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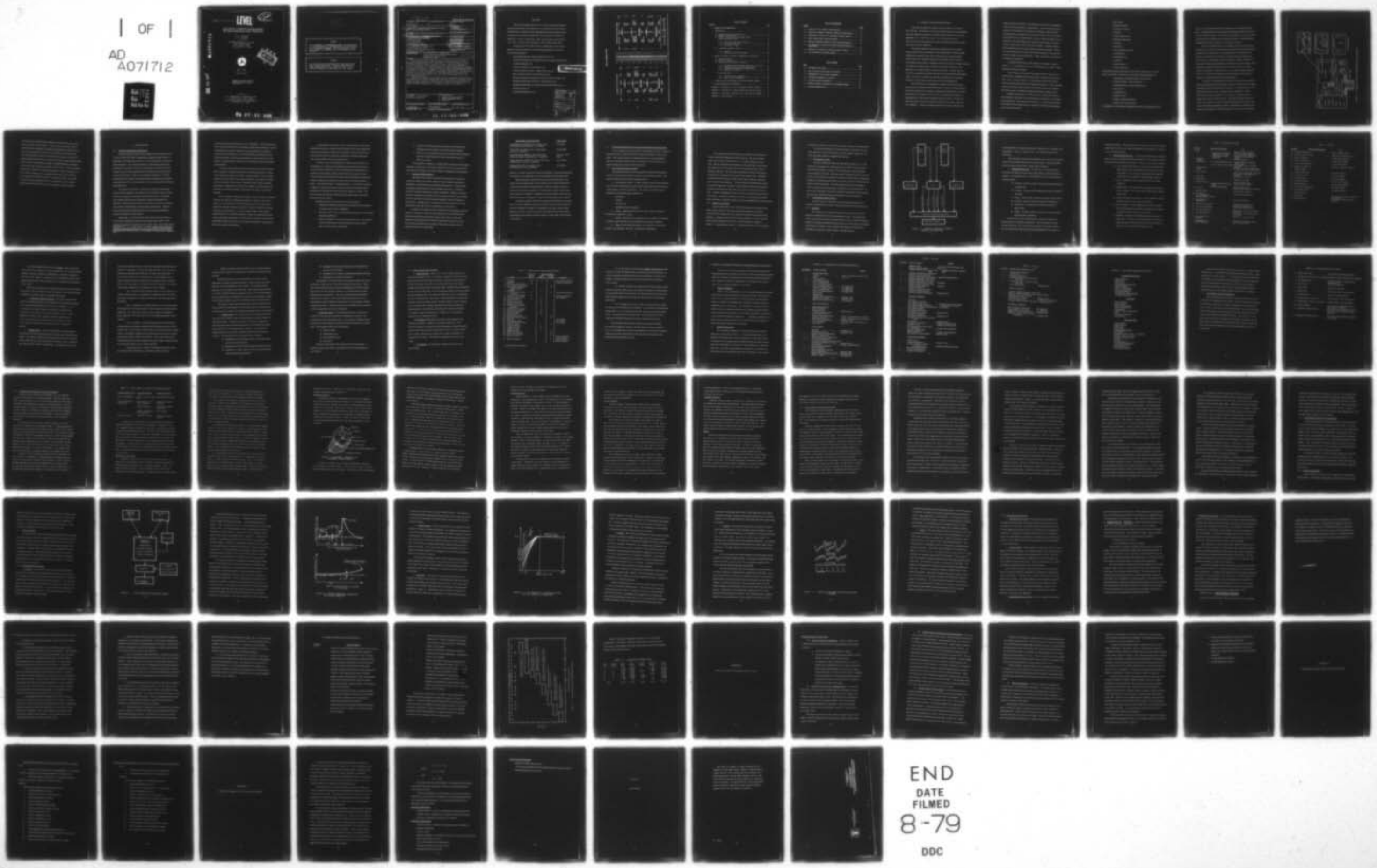

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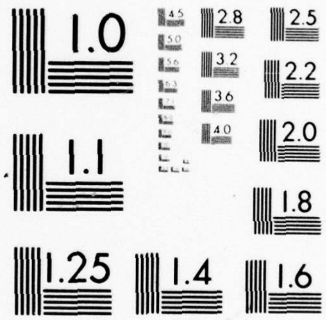

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SELECTION OF A PROTOTYPE ENGINE MONITOR FOR COAST GUARD MAIN DIESEL PROPULSION

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APRIL 1979

FINAL REPORT

Prepared by

U.S. DEPARTMENT OF TRANSPORTATION
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16. Abstract

A diesel engine monitor system has been synthesized from several parameter measurement subsystems which employ measurement techniques suitable for use on the main propulsion engines in U.S. Coast Cutters. The primary functions of the system are to monitor selected parameters, activate alarms or warnings when a critical failure mode is in progress, display all monitored data for hand recording by engineering personnel, and provide limited but adequate data-processing capability for analysis of these data. Diagnosis of existing engine problems and prognosis or prediction of incipient problems are accomplished by application of an interpretation rationale to the raw and analyzed data. The system works in conjunction with existing shipboard instrumentation, off-board laboratory analysis results, and crew inspection findings.

Parameter measurements such as blowby flowrate, main bearing block temperature, and rack position are made electronically using state-of-the art techniques. Unique electronic circuitry and data display devices are featured to permit analysis of engine diagnostic parameters. Final analysis of data for both diagnosis and prognosis is by human interpretation. The monitor system is not computerized.

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PREFACE

This work was performed for the U. S. Coast Guard and Transportation Systems Center of the Department of Transportation under Contract DOT-TSC-920. Members of these organizations who gave technical advice and guidance to the project include CDR. Barry Roberts and LCDR. Ken Wagner (C.G. Office of Engineering), LCDR. James Sherrard and Fred Weidner (C.G. Office of Research and Development), and Mr. Robert Walter (TSC).

Preparation of this report involved a considerable amount of data gathering, and the assistance of the following organizations in that task is hereby acknowledged:

Alco Engines Division, White Industrial Power, Inc.
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Cooper-Bessemer Division, Cooper Industries, Inc.
Electro-Motive Division, General Motors Corp.
Enterprise Engine and Compressor Division, Delaval Turbine, Inc.
Fairbanks Morse Engine Division, Colt Industries, Inc.
Mangone Boatbuilding Yard, Stewart and Stevenson Services, Inc.
National Marine, Inc.
Nevelle Island Shipyard, Inc.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

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1. SUMMARY AND RECOMMENDATIONS

This report provides the results of a part of Phase II of Contract DOT-TSC-920. The objective of the work reported herein was to recommend a suitable diagnostics system for use with the diesel engines used for main propulsion in U.S. Coast Guard cutters. The information upon which this work is based was obtained from various manufacturers and from SwRI experience in similar endeavors.

The primary difficulty encountered in this effort lies in the great range of solutions that are possible, and the consideration of these possible solutions in choosing the most effective system for the intended purpose. At the present time, diagnostic equipment is available (or in the process of development) that ranges in complexity from large computer-oriented automatic test equipment employing many sophisticated transducer systems, to the application of a simple portable measuring instrument. Between these extremes lies a multitude of possible solutions for the Coast Guard engine application. Our choice of system was based upon considerations of equipment reliability, operator skill, and the basic needs for this application.

The system that is recommended as a result of this work provides several types of information with different uses. First, the system monitors selected data inputs from the engine, compares these inputs with out-of-limit specifications, and signals an alarm to warn of conditions that indicate an impending failure that requires immediate corrective action. Second, the system provides a means for diagnostic evaluation of the engine, where the term "diagnostic " refers to the determination of the cause or location of a fault that exists in the engine. Such diagnostic evaluations are designed to reduce the time necessary for engine repair. Third, the system provides means for the formation of a prognosis of impending component failure. Such prognoses are pertinent to those types of failures that are associated with long-term wear or deterioration in which an engine parameter can be observed to vary consistently over a period of time towards a value that indicates engine failure (time-based trend analysis). Prognosis allows a failure prediction and accurate preventive maintenance planning. Fourth, the system displays certain engine performance parameters that provide a measure of engine output and efficiency. These parameters are useful both in diagnosis and prognosis.

A suggested panel layout of the diagnostic instrument is shown in Figure 1.1. A description of the use of the diagnostic instrument, without explanation of function, follows.

Alarm indicators are provided for engine overheat, overload, excessive blowby, impending main bearing failure, lubrication fault, and cylinder misfire or power imbalance. These alarms automatically function when the measured parameters exceed specified tolerances. Since tolerances may vary with engine speed and load, the instrument monitors both speed and load to provide a continuously updated performance tolerance limit.

Diagnostic information is contained in three subsystems of the unit: the temperature subsystem, the special parameter subsystem, and the diagnostic subsystem. The temperature subsystem is a straightforward temperature indicator with selector switch in order that the following temperatures may be visually observed:

- Main bearing
- Coolant into engine
- Coolant out of engine
- Oil sump
- Common exhaust duct
- Individual exhaust port
- Fuel inlet
- Ambient air
- Intake manifold or air box
- Air intercooler
- Turbocharger air
- Oil cooler
- Turbo oil return
- Sea water injection

The special parameter subsystem permits either continuous or, in some cases, intermittant monitoring of several unconventional parameters:

- Instantaneous crankshaft angular velocity (ICAV)
- Cylinder pressure - time relation (p - t)
- Cylinder pressure - volume relation (p - v)
- Rack position
- Coolant flow rate
- Blowby flow rate
- Dynamic crankcase pressure
- Apparent rate of heat release

The diagnostic or data analysis subsystem features an oscilloscope with the capability of retaining dynamic data for display for an indefinite period of time, a graphic plotting unit for permanent recording of pertinent data (some of which is plotted by hand), and a standard programable electronic calculator to facilitate basic mathematical processing of raw data. Such mathematical manipulation is kept to a minimum in this system, however.

Due to the complexity and cost of adapting currently available instrumentation to the engine room environment, the important engine performance parameters of torque/power, fuel consumption rate, and exhaust smoke density are omitted from the monitor, and in their place are parameters (rack position, engine speed, fuel and air densities, exhaust temperature) that permit ersatz engine performance and efficiency to be determined. This substitute or synthetic performance factor is used to inform of a sudden change in performance (warning function) or of a gradual change (prognosis function). In both cases, diagnostic steps can be taken to determine the cause(s) of the performance/efficiency deterioration.

In practice, the functioning of the monitor would proceed as follows. An alarm sounds only when a parameter associated with one of the six engine subsystems shown on the alarm panel in Figure 1.1 indicates that an out-of-limit condition exists. Such a condition must be remedied or at least ameliorated as soon as possible, even to the point of shutting down the engine until corrective action is taken. The same parameters monitored by the alarm system, all of the conventional parameters listed above, and the so-called special parameters of ICAV, rack position, coolant flow rate, blowby rate and dynamic crankcase pressure, are measured continuously.

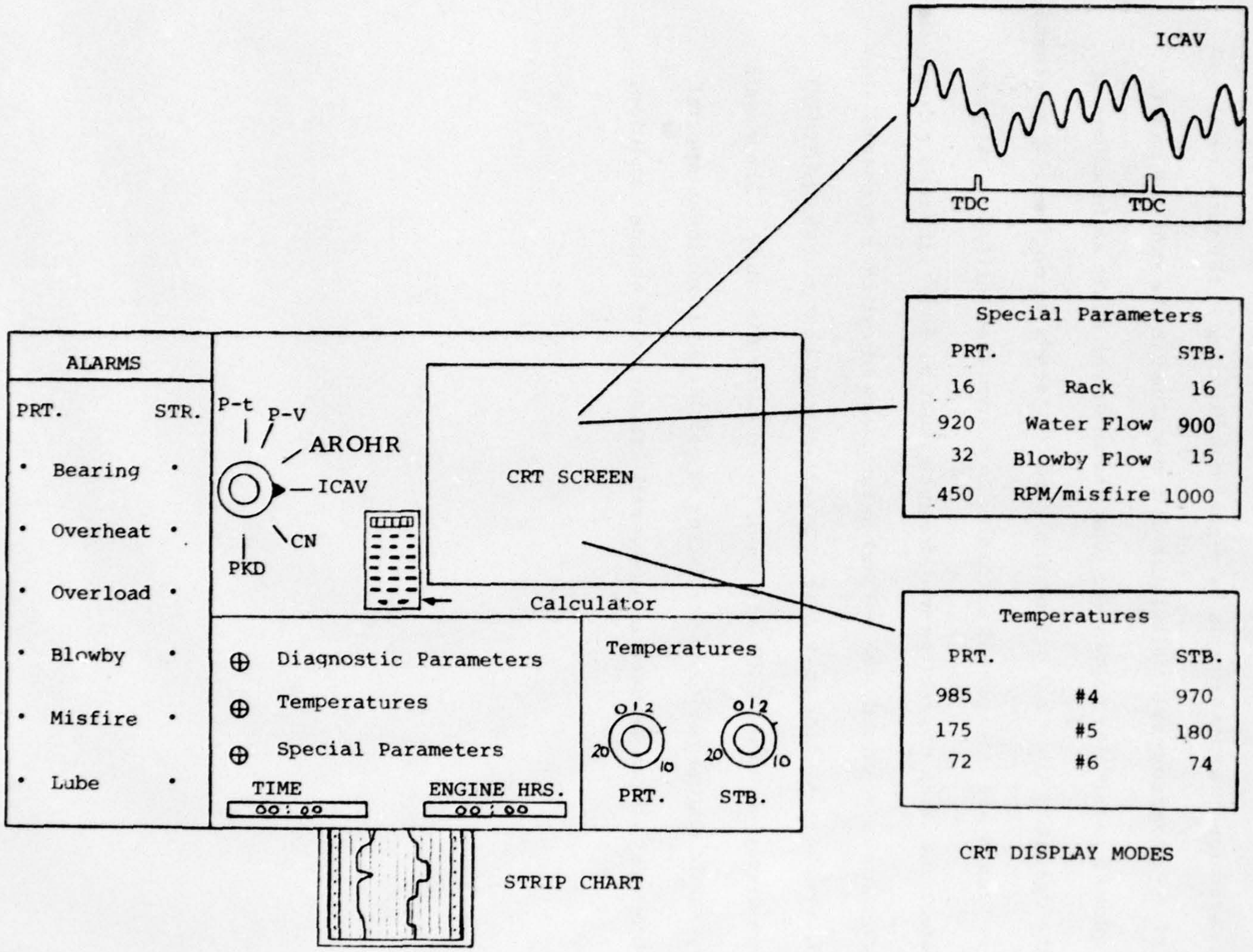

FIGURE 1.1 - SAMPLE LAYOUT OF PROPOSED ENGINE MONITOR

Their values are plotted (mostly by hand) at hourly intervals on the strip chart at the bottom of the monitor. These values are in either "raw" or processed form; processing is by signal conditioning in the monitor or by use of the programmable calculator unit contained in the monitor panel. The plotted parameter values are thus shown on the chart as functions of engine operating time and can be analyzed for trends by engineering personnel. These trends are interpreted according to a furnished method or rationale to determine when corrective maintenance must be done. If further diagnostic information is required, the special parameters of cylinder pressure-time (p-t), pressure-volume (p-v), or apparent rate of heat release (AROHR) can be displayed on the CRT screen of the monitor for study. The ersatz or synthetic engine performance factor is calculated from these special parameters and can be used in an overall evaluation of engine condition.

2. INTRODUCTION

2.1 Program Background and Objectives

Southwest Research Institute (SwRI) began work in November, 1974 on Contract DOT-TSC-920 for Transportation Systems Center of the U. S. Department of Transportation and the U. S. Coast Guard Office of Research and Development. The initial part (Phase I) of that program involved an investigation of methods to reduce fuel consumption and exhaust emissions of large in-service diesel engines used in locomotives and several classes of Coast Guard cutters. Phase I was completed in September, 1975 with the publication of a report (1) that summarized the findings and conclusions and presented a list of recommendations as to the course that future (Phase II) work should take.

One objective of the Phase I effort was to ascertain current maintenance practices applied to these engines and to evaluate the effect of these practices on engine fuel consumption and emissions levels. It developed that available information was insufficient to permit determination of a quantitative relation between the type of maintenance practiced by the engine users and the resulting effects on performance and emissions. However, this effort did produce valuable information on the types of maintenance programs employed with these engines.

Specifically, it was found that the Coast Guard at that time used an "as-required" maintenance program for the engine center section, which consists of all cylinder assemblies (pistons, piston rings, and cylinder liners),

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[1] Storment, J.O., C. D. Wood, and R. J. Mathis, A Study of Fuel Economy and Emission Reduction Methods for Marine and Locomotive Diesel Engines, Report No. DOT-TSC-OST-75-41, U.S. Department of Transportation, September 1975

main and connecting rod bearings, and the crankshaft(s). Under this program, the two principal methods used to determine condition and performance of these components are (1) periodic analysis of the spectrochemical and physical properties of the lubricating oil, and (2) monitoring of parameters such as crankcase pressure, exhaust manifold pressure, intake manifold or air box pressure, and exhaust gas temperatures for individual cylinders by standard instrumentation.

Values of these parameters, plus wear metal concentrations from the lube oil analysis, are plotted as functions of engine operating time to obtain a time-based trend analysis of the data. Another indicator of overall engine condition is the full-power trial, wherein the ability of the engine to develop rated load and speed is determined. Individual-cylinder values of exhaust temperature, firing pressure, and fuel rack setting are recorded during the full-power run and later analyzed to determine if the engine is performing normally.

The "as-required" maintenance program, which is entirely conventional in nature, was said to be working well in general. However, there were a number of cases reported that indicated there was room for improvement: engines that required overhaul at intervals of 7,000 to 12,000 hours of operation (about one-half the time for the same engine models in other marine applications) and, in at least two instances, engines that experienced severe, almost catastrophic deterioration of center section components without giving unambiguous indication of the fact in the values of performance parameters or lube oil wear metal concentrations.

It seemed likely to SwRI that if major engine problems could develop undetected, then other, at present minor problems could remain undetected. These minor problems not only have the potential to become progressively more serious, but also to cause fuel consumption and exhaust emissions (particularly smoke) to be above nominal levels.

Therefore, it was recommended that a primary task in Phase II of the program be to determine the parameters associated with performance of critical engine components, and to develop prototype instrumentation to monitor these parameters and the rationale needed to interpret the data. The information thus obtained would indicate when replacement or adjustment of these components was necessary, without the risk of either premature (hence, unnecessary) repair or component failure. It would then be possible to institute a maintenance program that would obtain both maximum useful component life and maximum efficiency from the engine as a whole. This last item would mean that fuel consumption and smoke opacity were maintained near optimum values.

Principal objectives of this program were the following:

a. Determine candidate parameters that are diagnostically significant for engine center section components.

b. Enumerate state-of-the art measurement techniques for the candidate diagnostic parameters.

c. Show how problems in other engine subsystems (e.g., fuel injection, cooling, lubrication) can cause excessive wear and premature failure of center section components.

d. Determine candidate diagnostic parameters and measurement techniques for these primary or causative engine problems.

e. Select the most promising parameters and measurement techniques and make recommendations for future development work in a follow-on program.

This program is, therefore, an initial survey and study to define engine diagnostic concepts that are potentially applicable to the Coast Guard's situation and that are thought to be worthy of further investigation and development.

2.2 Summary of Study Methods

Information on the topics of interest was obtained from a literature search and contacts with outside companies such as engine manufacturers, shipbuilders, and transducer and instrument manufacturers. Conversations with engine manufacturers have been primarily concerned with problems involving crankshaft bearings and cylinder assemblies. Builders of tugboats, which are often powered by engines used in Coast Guard cutters, have outlined the nature and extent of engine monitoring equipment currently installed in these vessels. Manufacturers of transducers and instruments have provided information on the state-of-the art developments in their areas.

In addition, the experience SwRI has gained in other programs involving diagnostic concepts for truck-size diesel engines has been used extensively. Information obtained in preparing the Phase I report has also been used, especially such information as concerns the main diesel engines of interest. The main diesel engines that are germane to this study, together with the cutters they power, are listed below.

Engine Make, Model and Type	Cutter Class
Fairbanks Morse 38TD8-1/8, two-stroke cycle, turbocharged, opposed-piston, 12 cylinders	378' WHEC
ALCO 251B, four-stroke cycle, turbocharged, V-block, 16 cylinders	210'B WMEC
Fairbanks Morse 38D8-1/8, two-stroke cycle, blower scavenged, opposed-piston, 12 cylinders	310', 290', 269' WAGB
Cooper Bessemer FVBM 12-T, four-stroke cycle, turbocharged, V-block, 12 cylinders	210'A WMEC
Enterprise DSR-46, four-stroke cycle, turbocharged, in-line, 6 cylinders	269' WAGB

However, it should be noted that the general diagnostic relations and principles discussed here are applicable to large diesel engines in many applications.

Engine problems considered in this study include those that (1) can result in serious engine center section damage if they remain undetected for a relatively short period of operating time, (2) allow an engine to operate, but with increased fuel consumption, decreased power output, and increased smoke opacity, (3) originate in component areas other than the center section, but that can induce or contribute to center section problems if not corrected.

Concepts of problem detection and diagnosis considered here are those that (1) have been applied (perhaps only in the laboratory) to diesel engines of any size and design, (2) appear to be adaptable to the large, medium speed engines of interest, (3) can be integrated, both physically and operationally, into existing cutters without extensive changes to either engine room hardware or procedures.

2.3 General Considerations of the Coast Guard Engine Monitoring System

It is our opinion that the Coast Guard would benefit from use of improved instrumentation in conjunction with their large main propulsion diesel powerplants. This section presents an expanded discussion of the design philosophy of the prototype monitor system, including the role of the monitor in a general maintenance scheme for the Coast Guard.

2.3.1 Functions of the Monitor System

The prototype design will feature improved and advanced instrumentation for the detection and diagnosis of faults in the main diesel engines. The monitor system will perform the following functions:

a. Automatically monitor a limited amount of selected data and alarm for out-of-limit conditions that could result in component failure and extensive engine damage or reduced performance. The monitor will indicate failure symptoms in the following engine subsystems:

Lubrication
Cooling
Fuel Injection
Mechanical Power Assemblies

b. Display diagnostic data that can be used to isolate or pinpoint the defective component or cause.

c. Display data that can be analyzed to form a prognosis or prediction of failure, which will allow accurate preventative maintenance planning.

d. Display performance parameters as an indicator of overall performance and efficiency, and allow optimization of adjustments.

The maintenance monitor system will aid engine room personnel in routine maintenance planning and trouble shooting. The data currently logged aboard ship is judged inadequate for thorough diagnosis and prognosis. Specific parameter measurements are described later in this report that supplement the existing data taken aboard ship and provide a logical prognostic approach. The data analysis equipment available aboard ship is not adequate for isolating several types of diesel engine faults. Equipment is described that will enable a detailed diesel engine diagnosis without the need for unusual test conditions. The procedures and methodology by which the currently logged data is used to render diagnosis and provide a prediction of failure is limited by the data being taken and by the limited utility of the data. A method of expanding the uses of the data is outlined in a later section of the report. It should be noted that the utility of the existing data and diagnostic techniques is expanded through use of new and supplementary measurements.

2.3.2 Degree of Automation

It was decided early on in the study that any program to develop a prototype monitor system for the Coast Guard should emphasize transducer selection and data usage rather than automation and advanced data processing hardware. Computer automation for fast data acquisition, automatic analysis and precision presentation of the data -- either by printers, displays or plotters -- is premature at this time. The automation task can be accomplished if desired or needed at a later date by numerous contractors, including SwRI.

The proposed maintenance monitor prototype is therefore to be manually operated to a large extent during the initial shipboard application. No tie-in with engine controls is suggested at this time.

2.3.3 Development of Data

The above conclusion leads to the next major conclusion, i.e., that exploratory evaluations are needed, beyond those achieved through straightforward study methods, to develop fully the diagnostic rationale pertinent to each parameter selected. While the several candidate parameters selected for use in this monitor are relatively well known and their usage in diagnostics, prognosis, and monitoring is familiar, more time is needed to develop the full utility of each measurement. The study program did not permit adequate time to be spent in the full data usage development of each measurement. In some cases, exploratory evaluations using full-scale engines and ship propulsion units are required for the full development of each measurement.

2.4 A Synthesized Monitor System

A monitor system is described in the following paragraphs that represents a summation of the general conclusions made in the previous section.

2.4.1 Hardware

The monitor will be a permanent part of the control room and is designed to accomodate both of the main propulsion engines. The system will require ship's power and electronic signals from sensors located on the engines. Figure 2.1 illustrates schematically how data from both the monitor and existing instrumentation combine to aid in diagnosis and prognosis of engine faults. Six subunits comprise the monitor system: Warning indicator,

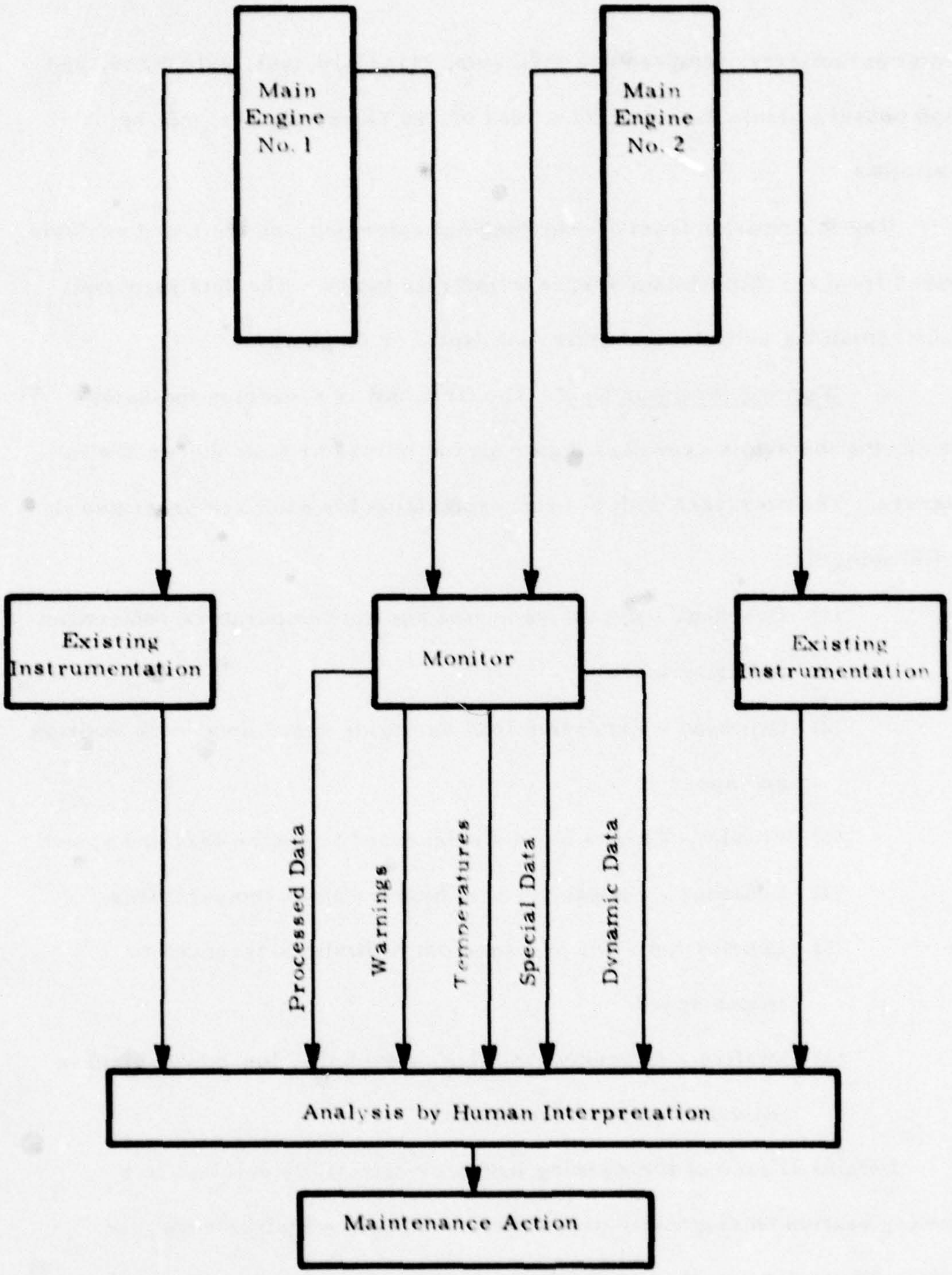


FIGURE 2.1 - FUNCTIONAL SCHEMATIC OF MONITOR INSTALLED IN ENGINE ROOM

special parameters, temperature indicator, diagnostic unit, calculator, and graph plotter. Table 2.1 identifies each of the parameters measured by these units.

The information from the warning indicator unit and the trend analysis derived from the plotted data serves to indicate faults. The data provided by the remaining units is used to isolate faults or diagnose.

a. Warning Indicator Unit - The first unit is a warning indicator that alarms the ship's crew that major engine failure or fault modes are in progress. The messages with a brief explanation for each are presented in the following list.

(1) Overheat - Excessive engine coolant temperature referenced to engine load.

(2) Overload - Excessive load on engine based upon rack position and speed.

(3) Blowby - Excess blowby referenced to engine load and speed.

(4) Bearings - Excessive main bearing block temperatures.

(5) Lubrication - Oil pressure out of limits referenced to engine speed.

(6) Misfire - Excessive misfire, slow burn, low power yield in individual power assemblies.

Details of each of the warning indicator circuits is detailed in a following section on diagnostic parameters. The six warnings cover the cooling, lubrication, fuel, and mechanical systems of the engine in such a way as to indicate the most serious and damaging faults that can occur in a catastrophic manner. These six alarms were selected on the basis of problem analysis and interviews with engine manufacturers, ship operators, and fabricators of monitor systems.

b. Special Parameters Unit - Six special parameters are measured that are unique to the ship's existing instrumentation. The following identifies each parameter and its use in the monitor system as a trend analysis parameter:

(1) Fuel Injection Rack Position - allows a sensor reading which when combined with speed yields a function related to engine output power. This is used in referencing those parameter limits that vary in proportion to engine torque or power.

(2) Time - absolute day, hour, minute time for data logging reference.

(3) Engine Hours - the running time of the engine since the last major overhaul. The clock runs when engine rpm is greater than 50 rpm.

(4) Crankcase blowby, gas flowrate - used to establish a relative measure of piston, ring, liner wear condition.

(5) Water flowrate - used to establish the rate of heat transfer of the cooling system and is used in conjunction with coolant temperatures and lab analysis of the coolant.

(6) Misfires - a display of the running average of the ratio of engine rpm to "misfires" which establishes the misfire condition and allows determination of any increase with time or change due to preventative maintenance actions.

TABLE 2.1 - The Monitor Data Inputs

Raw Data	Processed From Raw Data	Use
1. RPM		Engine reference condition
	a. Instantaneous Crankshaft Angular Velocity (ICAV)	Misfires, cylinder imbalance due to low power on compression
	b. Instantaneous Cranking Speed (CN)	Compression analysis during cranking
2. Combustion Pressure (As Required)		Cylinder compression
	a. Pressure-Volume Traces (PV)	Abnormal combustion, indicated cylinder power
	b. Rate of Heat Release (AROHR)	Fuel injection faults, abnormal combustion
3. Top Dead Center Signal		Reference for dynamic measurements to allow isolating defective cylinder
4. Rack Position		Calculation of approximate fuel rate, calculation of approximate load, reference
5. Clock Time		Reference for trend data
6. Engine Hours		Elapsed time on engine
7. Crankcase Pressure		(No direct application)
	a. Dynamic Crankcase Pressure (PKD)	Compression fault analysis
	b. Blowby Flowrate (MBB)	Cylinder assembly wear
8. Oil Level		Safety monitor, maintenance indicator
9. Coolant Flowrate		Cooling system condition
10. Oil Pressure with Standardized Pressure Regulator Position		Lubrication system condition
11. Main Bearing Cap Temperatures		Main bearing condition
12. Exhaust Port Temperatures		Cylinder power balance, fuel injection pump adjustment
13. Δt across Turbo Turbine		Turbocharger turbine defects
14. Fuel Inlet Temperature		Reference for fuel rack calculation of fuel flow
15. Oil Sump Temperature		Reference for oil pressure analysis of oil pump
16. Δt Oil across Heat Exchanger		Defective oil cooler-oil side
17. Turbocharger Oil Return Temperature		Turbocharger bearing defects and lube oil system defects

TABLE 2.1 - Concluded

Raw Data	Processed From Raw Data	Use
18.	Sea Water Temperature	Heater exchanger defects
19.	Δt Water across Oil Cooler	Defective oil cooler-water side
20.	Water in Temperature	Cooling system diagnosis
21.	Water out Temperature	Cooling system diagnosis
22.	Δt Air across Intercooler	Defective intercooler
23.	Ambient Air Temperature	Reference, intercooler diagnosis
	Pressure (Gauges)	
24.	Δp across Fuel Filter	Fuel filter analysis
25.	Δp across Oil Filter	Oil filter analysis
26.	Coolant Pressure	Water pump diagnosis
27.	Oil Gallery Pressure	Lube oil system diagnosis
28.	Sea Water Pressure	Sea water pump diagnosis
29.	Fuel Transfer Pump Pressure	Fuel pump diagnosis
30.	Turbocharger Pressure	Turbocharger diagnosis
	Lab Analysis Data	
31.	Oil Analysis	Oil condition bearing condition piston ring liner wear
32.	Coolant Analysis	Heat exchanger condition coolant condition

An optional readout in this section is oil level. This is based upon the fact that several engines do not have provisions for oil level sight glasses and there would be no method of establishing oil consumption during long periods at cruise condition. In many cases oil consumption correlates with engine blowby flowrate, and an estimate for oil consumption can be obtained in this manner.

Each of the instrumentation techniques used for measuring the special parameters, and a discussion of how the data applies to the monitoring tasks, is detailed in a section to follow on diagnostic parameters.

c. Temperature Measurement Unit - The unique measurements made by the temperature unit are the individual main bearing block temperatures and differential temperatures across heat exchangers. All of the temperatures currently measured by shipboard instrumentation are now measured by the monitor's temperature measurement section. This is suggested since some current temperature measuring equipment aboard ship is not of the quality available today and the addition of inputs to the temperature indicating unit would not present a significant expense.

d. Diagnostic Unit - This unit is based upon a standard memory oscilloscope with custom designed circuits for input signal conditioning and display. The operator simply selects the diagnostic parameter of interest, and the proper vertical scale factor and time reference is made available to him without need for a series of adjustments. The diagnostic unit is used in the event a malfunction in one of the power assemblies is indicated by the "misfire" warning light. The unit will enable the ship's crew to isolate the faulty power assembly and to determine the cause of the malfunction. In the event that simple fuel rack adjustments or valve adjustments can be made to remedy the fault, the analysis unit can again be used to check the effects of the maintenance action upon the observed symptoms. The specific measurements displayed on the diagnostic unit are as follows:

TDC - Top Dead Center reference marks for each cylinder, No. 1 cylinder top dead center is accompanied by an additional mark at 5° ATDC. This signal is displayed as a reference below each of the remaining dynamic parameters.

ICAV - Instantaneous Crankshaft Angular Velocity measurements allow examination of the engine speed to locate low power-producing cylinder assemblies. The cause of the low power can be related to compression faults, aspiration, or fuel injection by use of the following parameter measurements.

PT, PV, AROHR - These measurements are all based upon the cylinder pressure information available from the blowdown petcocks on each cylinder head. (PT is Pressure versus Time, PV is Pressure versus cylinder Volume, and AROHR is Apparent Rate Of Heat Release derived from cylinder pressure and cylinder volume measurements.) The cylinder pressure and volume parameters are used to diagnose fuel injection faults, aspiration faults and compression defects in each cylinder assembly.

Cranking speed (CN) analysis is used during the instant of start up to isolate faulty compression in a particular cylinder assembly.

Dynamic Crankcase Pressure (PKD) is used to isolate defective compression due to defective rings, piston or liners in an individual cylinder assembly.

The diagnostic unit is in use only when there is a need to isolate faults unique to specific cylinder assemblies. However, power and sensor input data is always available to it when needed. The cylinder pressure transducer is an exception to this statement. When a fault has been isolated to a specific cylinder assembly by analysis of ICAV, CN or PKD parameters, then a pressure sensor is installed in the petcock of the appropriate cylinder and the dynamic analysis can proceed to further isolate the problem cause.

The scheme by which these parameters are used in conjunction with other parameters in the diagnosis of diesel engine faults is presented along with specific sensor details in the diagnostic parameter section of this report.

e. Calculator Unit - The calculator unit is a common programable electronic hand calculator similar to those produced by Hewlett Packard or Texas Instruments. It enables the operator to do several computational tasks that would take up an excessive amount of time if performed by hand using a slide rule or a non-programable calculator. The calculator is adapted and built in to the monitor hardware and is wired for battery recharging. The following tasks are performed by the calculator:

(1) Computation of heat exchanger factor for the engine using water flow and temperatures.

(2) Computation of the load factor using rack position and rpm.

(3) Computation of engine efficiency factor using rack position rpm and operating temperatures.

(4) Computation of indicated cylinder power by integration of pressure-volume display.

(5) Calculation of the change of prognosis parameters with time.

(6) Extrapolation of prognosis trend data.

The calculator is a built-in feature of the monitor system and is preprogramed to handle the above mentioned mathmatical operations. Advantages of this scheme are that sea trials and shakedown tests of the monitor may indicate that some program changes to accomodate particular engine idiosyncrasies are necessary. If so, they could be performed with little impact upon the monitor. Use of either hardwired electronic logic or a minicomputer system at this point would prove to be very expensive should changes be necessary. Changes of this sort are anticipated since all aspects of each data parameter are not now well known.

f. Graph Plotter Unit - A conventional strip chart recording unit is used to record rpm and rack position continuously at all times. The recorder has a slow chart speed of about .25 in. per hour. Prognostic trend parameters are hand-plotted on the plotter at hourly intervals during operations. The prognostic trend data is listed below:

(1) Blowby flowrate

(2) RPM/misfire ratio

(3) Heat exchanger factor

(4) Load factor

The plotter represents a time-saving device that will produce a satisfactory data record while not presenting an extreme burden upon the watch-stander.

2.4.2 Faults Detected and Procedures

a. Faults Detected - Table 2.2 is a list of faults common to each of the diesel propulsion units. The monitor's capabilities in detecting these faults are indicated in the adjacent columns. Automatic monitor detection includes those faults indicated on the warning indicator unit and usually includes several faults under one indicator light. Manual detection techniques include review of logged data, review of prognosis graphs, and human analysis using the diagnostic unit. The analytical complexity involved in diagnosing the fault is indicated in the next column. "Easily Diagnosed" involves items as simple as limit checking, whereas "Complex Analysis" involves making several measurements, making comparisons with normal standards for those parameters, and following a flow diagram to obtain the diagnosis. For example, analysis considered to be complex is the comparison of trend data over a long period of time.

The Remarks column deals with the state of development of the interpretive rationale, transducers, and signal conditioning. If the detection technique is feasible but the data interpretation requires development, then the term "rationale development" is used. If sensor development or signal conditioning is required, then "sensor development" is indicated in this column. "Not feasible" is explained in the body of the report.

b. Procedures - The Maintenance Monitor will be utilized in several ways:

TABLE 2.2 - Fault Detection Effectiveness Of Monitor

			Manual Analysis		
	Fault	Automatic Monitor Selector	Easily Diagnosed	Complex Analysis	Remarks
1.	Overheat	X	X		Rationale Development
2.	Overload	X			Sensor Development
3.	Defective Cylinder Seals	X			
4.	Low Cylinder Compression			X	
5.	Worn Rings, liner, piston (single cylinder)			X	
6.	Overspeed		X		
7.	Low power in one power assembly	X		X	Rationale development
8.	Defective main bearings	X	X		Sensor Development
*9.	Defective rod bearings				Not Feasible
10.	Low oil pressure	X	X		
11.	Defective oil cooler		X		
12.	Defective intercooler		X		
13.	Defective turbocharger		X		
14.	Fuel injection rack out of adjustment		X		
15.	Defective heat exchanger		X		
16.	Worn sea water pump		X		
17.	Worn water pump		X		
18.	Worn oil pump		X		
19.	Scaled water jackets			X	
20.	Defective vibration damper			X	
*21.	High bsfc				Not Feasible
*22.	High exhaust smoke				Not Feasible
*23.	Low absolute performance				Not Feasible
24.	Defective valves			X	
25.	Clogged fuel filter		X		
26.	Clogged oil filter		X		
27.	Clogged air filter		X		
28.	Engine timing off			X	
29.	Abnormal combustion			X	
30.	Valve timing defective			X	
31.	Defective coolant			X	Requires offboard tests & analysis
32.	Defective lubricant			X	Requires offboard tests & analysis

* Not detected by the monitor

(1) An out-of-limit alarm from the warning indicator unit prompts the use of the data and analysis units to isolate the fault and would prompt the review of prognosis data plots and hourly logs to determine the origin of the problem. Necessary engine inspections are performed and maintenance action is taken.

(2) Periodic analysis of the prognosis data trends using the graph plotter will indicate faults in their early stage of development and maintenance can be scheduled when most convenient. At this point special data can be obtained using the diagnostic unit on a periodic basis to enhance the normally plotted data.

(3) The diagnostic unit can be used on a periodic basis to search for defects in the individual power assemblies. The cylinders can be examined during standard cruise conditions and the data, along with oscilloscope photographs, recorded with the conventional data. Over a period of, say, six months each cylinder assembly will have been examined at least once.

The prototype monitor system includes the hardware described, the structured diagnostic rationale, and some degree of human interpretation. It is anticipated that the structured diagnostic rationale will be enhanced, refined and otherwise streamlined by SwRI during the development of the monitor system and during sea trials.

3. REVIEW OF CANDIDATE DIAGNOSTIC PARAMETERS AND TECHNIQUES

This section reviews the parameters associated with typical diesel engine problem modes, presents our selection of the most promising candidate diagnostic parameters, and outlines the reasoning that underlies this selection. Finally, the method of interpretation (or rationale) of the data furnished by these candidate parameters is discussed.

3.1 Engine Parameters

Table 3.1 is a comprehensive list of all measurable engine parameters that have been considered during the course of this study. The columns adjacent to the list indicate whether or not each parameter measurement is deemed acceptable in this application according to the general criteria of feasibility and cost effectiveness. (By "feasibility" we mean the ability to obtain an accurate, usable measurement in the engine room environment.) A brief comment is given beside each unacceptable parameter to explain why it was rejected from further consideration. Analogous comments are not made for those parameters that were not rejected since their significance will be discussed in detail later in this section.

3.2 Candidate Parameters

The parameters considered to be most promising for the subject application are presented in Table 3.2. This list includes many of the pressures and temperatures currently measured on Coast Guard cutters. The parameters are grouped under headings that represent units of the prototype monitoring system: Warning data, Trend Analysis data, and Diagnostic data. Note that a given parameter may appear in more than one of these groups, which are listed in their order of importance to the monitor.

TABLE 3.1 - Comprehensive List Of Engine Parameters

Acceptable	Overall Parameter	Comment
*	Engine speed (rpm)	
	Torque	Complex on-board measurement (See Sec. 3.3)
*	ICAV	
*	TDC reference	
*	Combustion presure	
*	Avg. cranking speed	
*	Dynamic cranking speed	
	Avg. cranking current	Not applicable
	Dynamic cranking current	Not applicable
	Avg. cranking voltage	Not applicable
	Dynamic cranking voltage	Not applicable
*	Time of day	
*	Engine hours	
	Cylinder liner temperature	Marginal value
	Starting air pressure	Marginal value
	Engine room acoustic noise	Not applicable
	Fuel System Parameter	
*	Supply pump pressure	
*	Inlet temperature	
	Moisture in fuel	Marginal value
*	Transfer pump pressure	
*	Filter pressure drop	
	Dynamic injection pressure	Complex instrumentation and analysis
	Dynamic needle lift	Complex instrumentation and analysis
	Fuel return temperature	Marginal value
	Fuel consumption	Complex on-board measurement (See Sec. 3.3)
*	Rack position	
	Inlet Parameter	
	Humidity	Marginal value
	Barometric pressure	Marginal value
*	Engine room air temperature	
*	Intake air temperature	
*	Intake manifold air temperature	
*	Air box air temperature	
*	Temperature drop across intercooler	
	Pressure drop across air filter	Marginal value
	Air flowrate	Complex instrumentation
*	Intake manifold pressure	
*	Air box pressure	
*	Turbocompressor pressure	
	Turbo wheel speed	Marginal value
	Dynamic intake manifold pressure	Marginal value
	Intake air opacity	Not applicable

TABLE 3.1 Continued

Acceptable	Exhaust Parameter	Comment
	Exhaust smoke	Complex on-board measurement (See Sec. 3.3)
	Dynamic exhaust smoke	
	Exhaust emissions (CO, CO_2, O_2, NO_x UBH)	Complex instrument, marginal value
*	Individual exhaust port temperature	
*	Exhaust stack temperatures	
	Dynamic exhaust gas temperature	Complex instrumentation
*	Exhaust temperature before turbo	
*	Exhaust temperature after turbo	
	Exhaust back pressure in stack	Marginal
*	Exhaust pressure before turbine	
	Dynamic exhaust pressure	Marginal
*	Crankcase pressure	
*	Dynamic crankcase pressure	
*	Crankcase blowby flowrate	
	Crankcase blowby temperature	Marginal value
	Lubrication Parameter	
*	Oil level	
	Oil condition viscosity	Obtained from periodic tests; of marginal value if taken in real time
	Oil condition wear metals	
	Oil condition additive depletion	
	Oil condition oxidation concentration	
*	Oil pressure gallery	
*	Oil pressure after filter	
	Oil pressure at top end	Marginal value
*	Oil sump temperature	
	Oil gallery temperature	Marginal value
*	Temperature drop of oil across oil cooler	
	Oil debris	Marginal value
	Oil flowrate in gallery	Complex instrumentation
	Moisture in oil	Complex instrumentation
*	Oil temperature at turbo return	
	Oil consumption	Complex instrumentation
*	Bearing temperatures	
	Engine vibrations	Complex instrumentation
	Oil pressure to turbocharger	Marginal value
	Cooling System Parameter	
*	Coolant level	
	Coolant consumption	Marginal value
	Coolant condition - solids concentration, pH	Obtained from periodic tests
*	Sea water pump pressure	
*	Coolant pump pressure	
*	Coolant in temperature	

TABLE 3.1 Concluded

Acceptable	Cooling System Parameter (cont'd)	
*	Coolant out temperature	
*	Coolant flow	
*	Seawater temperature	
*	Temperature rise of coolant across oil cooler	
*	Temperature rise of coolant across intercooler	
	Water pump suction	Marginal value
	Combustion Parameter	
*	Dynamic cylinder pressure versus time	
*	Dynamic cylinder pressure versus cylinder volume	
*	Apparent rate of heat release	
	Cumulative heat release	Marginal value
	Fuel injection flowrate	Complex instrumentation
	Average cylinder pressure variations	Marginal value
	Miscellaneous Parameter	
	Electromagnetic interference	Not applicable
	Radio frequency interference	Not applicable
	Mapping of surface temperatures	Marginal value
	Radioactive tracer wear of various components	Marginal value

TABLE 3.2 - The Monitor Parameters By Priority

Warning Indicator Data

Blowby flowrate
RPM (ICAV)
Rack position
Main bearing temperatures
Coolant flowrate
Water in temperature
Water out temperature
Oil gallery pressure
Turbocharger return pressure
Oil sump temperature

Trend Data

Blowby flowrate
Water flowrate
Water in temperature
Water out temperature
Rack position
Common exhaust temperature
RPM
Fuel inlet temperature
Rack position

Diagnostic Data

Water flowrate
Blowby flowrate
Misfire rate
Rack position
Cranking speed-dynamic
RPM (ICAV)
Combustion pressure (Pt, PV, AROHR)
Dynamic crankcase pressure
Exhaust port temperatures
Oil level
Top dead center
Conventional temperatures
Conventional pressures
Used oil analysis
Used coolant analysis

One part of the monitor system will be devoted to so-called "unique" parameters; i.e., those that are somewhat unconventional in nature. These parameters are listed in Table 3.3. The second column in this table gives the transducer that is required for the measurement. The most unconventional of these parameters is apparent rate of heat release (AROHR), a measurement based upon a new electronic circuit developed by SwRI. A detailed discussion of the AROHR technique is presented in Appendix C.

3.3 Justification of Parameter Selection

Many of the parameters in Table 3.1 have been eliminated from consideration for the application under study. In most of these cases the reason for elimination is obvious or, at least, not significant to the discussion at hand. However, some of the rejected parameters are so closely associated with a diesel engine's state of performance that their elimination from the monitor system should be discussed more fully. Also, the roles of some other parameters need to be analyzed in more detail. Therefore, this section is offered as justification of our parameter selection and to inform the reader about some conventional and unconventional parameters and their measurement.

TABLE 3.3 - The Unique Monitor Parameters

1.	RPM, (ICAV, CN)	60 tooth gear & proximity detector
2.	Combustion Pressure (Pt, PV, AROHR)	Dynamic pressure transducer (as required)
3.	Top Dead Center	Proximity detector in register with flywheel marks
4.	Rack Position	Linear potentiometer
5.	Clock Time	Electronic clock chip
6.	Engine Hours	Mechanical counter off rpm signal
7.	Coolant Flowrate	Venturi meter & pressure
8.	Main Bearing Cap Temperatures	Thermocouple in main bearing caps
9.	Turbocharger Oil Return Temperatures	Thermocouples in oil return tube
10.	Coolant Analysis	Lab analysis of suspended particles and depletion of inhibitor
11.	Crankcase Blowby Flowrate	Orifice plate and differential pressure transducer with oil debris trap and surge tank
12.	Dynamic Crankcase Pressure	Fail strain gauge pressure transducer (as required)

3.3.1 Crankshaft Bearing Parameters and Their Measurement

Crankshaft main and connecting rod bearings are at once among the critical and inaccessible of all engine components. They are critical because a bearing failure can result in severe engine damage that will require the greatest cost and downtime to repair of any engine problem. Their inaccessibility means that detection of incipient or existing bearing problems is, at best, difficult. In addition, the parameters associated with crankshaft bearing performance and condition are few in number. A brief discussion of these parameters and methods of measuring them will put the situation in perspective.

The characteristic which renders a bearing unsuitable for further service is its clearance with the crankshaft journal. If enough bearing metal has been worn away to increase this clearance beyond a certain point, then oil leakage from the bearing will be excessive and it will not be possible to obtain the condition necessary for hydrodynamic lubrication. The lack of hydrodynamic lubrication will increase friction and lead to higher bearing operating temperature, greater bearing wear rate, and, hence, to an even larger clearance. Therefore, the situation deteriorates at an accelerated rate as the various problem factors interact in a "vicious cycle" manner. In a relatively short period of operating time, catastrophic damage to the crankshaft will result.

Fortunately, there are parameters associated with the problem factors that at least have a potential for yielding diagnostic information about the critical bearing-lubricant-crankshaft journal interface. However, accurate, reliable measurement that produces interpretable data is necessary before this potential is realized in a manner suitable to practical application. The following table and discussion summarize the situation for these parameters.

TABLE 3.4 - Bearing Diagnostic Parameters And Measurement Methods

Bearing Problem Factor	Associated Parameter	Measurement Method
Rate of bearing wear	Amount of metal in lube oil	Spectrometric analysis
Lack of hydrodynamic lubrication	Oil pressure in lower-half of bearing	Conventional average pressure
	Bearing temperature	Conventional average temperature
	Acoustic emission from contacting parts	Not developed
Excessive clearance	Crankshaft vibration	Vibration signature analysis

It should be noted that application of these parameter measurements range from commonplace (in the case of spectrometric oil analysis) to rare (for crankshaft vibration analysis) or nonexistent (for bearing oil pressure) in current engine maintenance practice. (Of course, only spectrometric analysis is used by the Coast Guard at this time.) Furthermore, two of the measurements (oil pressure in bearing and bearing temperature) are definitely not applicable to connecting rod bearings due to measurement difficulties, while one parameter (acoustic emission) is of doubtful utility with either type of bearing because of a present lack of instrumentation and test rationale development. The measurement and analysis of acoustic emissions remain theoretically possible however.

Spectrometric Oil Analysis

Spectrometric analysis is not yet an on-board test procedure. Oil samples must be periodically obtained according to a specified procedure and forwarded as soon as possible to the oil analysis laboratory. There, the metals resulting from wear of several components (not just bearings) are identified, and the individual amounts are measured in parts per million (ppm).

When these results are plotted as functions of engine operating time, a rate of wear is established for each wear metal component group (since a given wear metal may have more than one potential source in an engine).

The usefulness of spectrometric analysis derives from the fact that all critical center section components are oil wetted, and the potential therefore exists for determination of their rates of wear. Since the failure of a given component is (theoretically) preceded by a steadily increasing wear rate over a fairly lengthy period of operating time (say, several hundred hours), it is in principle possible to detect incipient component failure far enough in advance to schedule appropriate maintenance action and, hence, prevent a catastrophic failure.

The limitation of spectrometric analysis is that catastrophic component failures can and do occur suddenly or, at least, on a time scale that is too short for the incipient failure to be detected by lube oil analysis. In addition, a cutter on extended cruise or patrol could accumulate several hundred hours of engine operation without being able to submit oil samples for analysis. Such a delay could deprive engineering personnel of this information during the crucial time between the onset of accelerated wear and actual component failure. Also, a mistake in the oil sampling procedure can render the best laboratory analysis inaccurate and useless.

Since spectrometric analysis of bearing metal is currently the only indicator of main and rod bearing condition, it is important to set up and operate a reliable spectrometric analysis program. This the Coast Guard is attempting to do by transferring all lab work, data analysis, and record keeping to the U.S. Navy Oil Analysis Program (NOAP). However, the potential problems outlined in the preceding paragraph cannot be eliminated (or even minimized) in all cases. Therefore, it is advisable to consider the other parameter measurements given in Table 3.4.

Bearing Oil Pressure

The general condition of hydrodynamic lubrication for a crankshaft main bearing is shown schematically in Figure 3.1. Oil pressure between the journal and bearing is greatest near the point of minimum separation in the lower half of the bearing. When clearance reaches a certain critical value, leakage of oil from the bearing end becomes so great that the convergence of the two components cannot generate an oil film that will maintain complete separation of the two metal surfaces. Contact will then occur under some or all operating conditions (defined by load, speed, temperature, and oil viscosity).

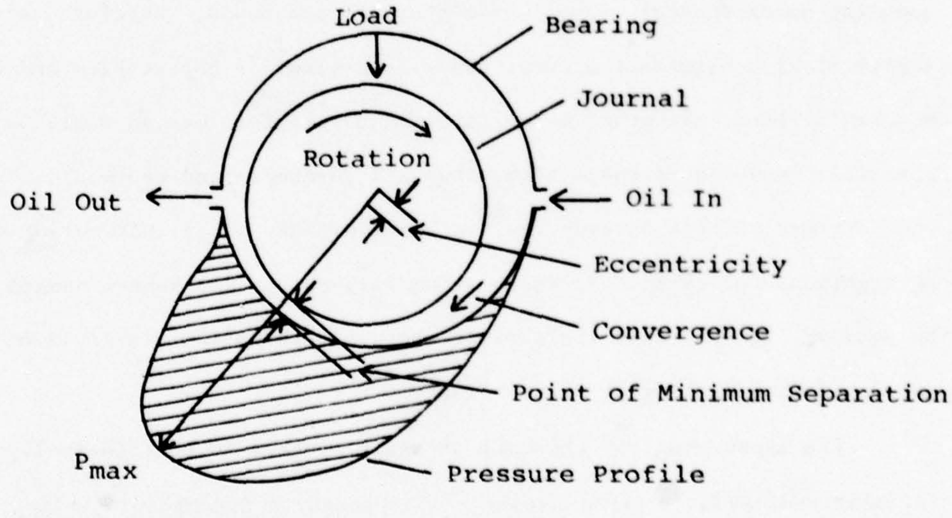


FIGURE 3.1 - HYDRODYNAMIC LUBRICATION OF CRANKSHAFT JOURNAL BEARING

The drop in oil pressure in the region of hydrodynamic lubrication is the parameter of potential interest. (Note that this is <u>not</u> the pressure in the oil gallery that feeds the bearing.) Deterioration of the load-carrying ability of the oil film or wedge will be reflected as decreased pressure in this region. If the clearance increases slowly with time, hydrodynamic pressure will decrease slowly and monitoring of this pressure might provide significant diagnostic and prognostic information concerning the condition of the bearing.

Some main bearings undoubtably experience a gradual increase in clearance, but a large number (perhaps most) of the bearings probably suffer a sudden increase, without warning. Such a situation might occur, for example, in a bearing which was momentarily overloaded or deprived of an adequate flow of oil, or that experienced a high rate of abrasive wear for a short period of time. A comparatively sudden increase in clearance would result in a corresponding quick decrease in oil film pressure and would, therefore, shorten the length of time between the onset (and indication) of the problem and actual bearing failure. In other words, the prognostic information would be substantially reduced--perhaps eliminated all together--and one would be left with the information that bearing failure was imminent. This information would be highly useful since complete bearing failure and crankshaft damage could be avoided, but no means would exist whereby bearing failure could be accurately predicted with any degree of certainty.

The measurement of this oil pressure appears to be technically feasible for main bearings. A usual average (as opposed to dynamic), highly damped measurement would probably suffice; this approach eliminates the problem of short lifetimes for dynamic pressure transducers under conditions of rapid cycling. It would be best if the measurement was made for each main bearing. However, this would involve a complex system for only one parameter and would add greatly to the cost. Therefore, in practice only two or three bearings would be included; this number should provide an adequate picture of the condition of all such bearings in the engine.

Bearing Temperature

Another parameter of interest (again, for main bearings only) is the temperature of the bearing material itself. This temperature is at its minimum value when full hydrodynamic lubrication is in effect. As the hydrodynamic condition deteriorates, metal-to-metal contact occurs and bearing temperature increases. However, the prospect must again be faced that the temperature will not increase gradually over a long period of time, but will increase suddenly as a result of a brief but destructive contact between the bearing and journal. Furthermore, temperature will remain high for only a few minutes as bearing metal is being worn away. Once a certain amount (corresponding to a few thousandths of an inch) of metal has been removed, the flow of oil through the greater clearance will increase, thereby carrying away the extra heat and lowering the temperature back to normal (or even lower).

Thus, the monitor must look for a characteristic temperature "spike" that would have a width corresponding to a few minutes' duration, out of perhaps thousands of hours of engine operation. The monitor would then signal engine room personnel that catastrophic failure was about to occur. The length of time between warning and failure would be inversely proportional to the load and speed of the engine at that particular time; in any case, enough time should be available to reduce load and speed to a safer level or, if desired, to shut down the engine.

The monitoring of main bearing temperature is a relatively straightforward matter. Thermocouples specially designed for this application are readily available, and the design of the monitoring circuit is uncomplicated. Again, two or three bearings could be instrumented to give a representative picture of all the bearings. However, the simplicity of the measurement and its apparently excellent cost-benefit ratio make instrumentation of all main bearings an attractive proposition.

Acoustic Emission

The other parameter associated with a general lack of hydrodynamic lubrication is acoustic emission resulting from contact between the journal and bearing. Such contact occurs with both main and connecting rod bearings and, in principle, the sound signature resulting from this contact should be detectable by suitable transducers and analyzable by appropriate instrumentation.

This sound can be in either the audible (to the human ear) range of about 15 Hz to 20 kHz or the extra-audible range above 20 kHz. Recent research has concentrated on higher-order harmonics in the range of several hundred kHz. The reason for this is that the lower frequencies (including those in the audible range) are difficult to analyze electronically because of the "trash" inherent in such signals. If the sound is presented to the ear (and brain) for analysis, then it is necessary to take into account the experience of the observer in interpreting the signal in terms of a unique engine malfunction such as bearing failure. Furthermore, every human perceives the same sound in a different manner, and many people have "dead spots" in their hearing which preclude hearing sounds of certain frequencies.

The aforementioned research into engine acoustic emissions of higher frequencies has the potential to detect malfunctions. However, the feasibility of this technique has not been demonstrated to be practical or cost-effective in field operation since the instrumentation is complex and expensive and the signal analysis and test rationale are lacking for the engines of interest. In addition, it is not known if the information that might be obtained by this technique would be any more prognostic in nature than would the simple parameter of bearing temperature. That is, the warning period prior to catastrophic failure might be short (on the order of a few minutes) and hence allow time for engine shutdown only.

Crankshaft Vibration

Crankshaft vibration signature analysis is not considered to be practical for diagnosing or predicting bearing problems. The reason behind this assessment is that crankshaft vibration arises from fairly large unbalanced forces acting on the crankshaft, and the two principal causes of these forces are unbalanced firing pressures among the cylinders and a faulty vibration dampener, The slight vibration resulting from even several bearings operating with excessive clearance and without hydrodynamic lubrication would probably not be detectable by any instrumentation system that could be termed cost-effective. In addition, there is a lack of the specialized experience and test rationale that would be needed for operation of such a system on board a vessel.

Summary

Based on the discussion of the various bearing diagnostic parameters given above, it is concluded that the most effective (and cost-effective) approach involves a good oil spectrometric analysis program and continuous monitoring of main bearing operating temperature. The former is potentially capable of spotting incipient failure of bearings (as well as other components), while the latter is a method of avoiding severe crankshaft damage resulting from bearing failures that occur on a time scale that is shorter than the spectrometric analysis cycle time (sampling, submission of sample to lab, analysis, and data feedback to the ship). Main bearing hydrodynamic oil pressure is a parameter that, in theory, could yield important information as to bearing condition, but the measurement and monitoring of this parameter would require costly development and, in the end, might provide no better information than bearing temperature. Analysis of acoustic emissions and crankshaft vibration is not fully developed and/or cost-effective at this time.

3.3.2 Standard Diesel Performance Measurements

In the laboratory, the three parameter measurements that are indispensable in evaluating basic engine performance characteristics are flywheel torque or power (BHp), fuel consumption rate, and exhaust smoke density (opacity). And, in the laboratory, no fundamental problems are encountered in making these measurements.

Typically, dynamometer beam load (in lb) is measured by a load cell connected to a digital readout. Torque and power are usually calculated from these two quantities; however, a simple electrical circuit can be used to present torque or power values directly, with digital readout. Fuel consumption rate is measured on a mass basis (lb_m per hour), either directly, by means of a weigh scale-and-timer arrangement or a linear mass flowmeter, or indirectly, by means of a volume flowmeter and knowledge of temperature-compensated fuel density. Mass fuel rate is desirable for calculation of brake specific fuel consumption (BSFC), the primary measure of engine efficiency: lb_m of fuel consummed per hour of useful work delivered. Smoke opacity is measured by light-obscuration smokemeters that are mounted either at the end of the stack or duct or in the duct itself.

There is little question that any diagnostic system or engine monitor would benefit from measurement of power, fuel rate, BSFC, and smoke opacity. However, there are special difficulties involved in adapting these measurements to the shipboard environment of the Coast Guard. The problems have been discussed to some extent in the Phase I report; they are reviewed here for convenience.

The use of a linear mass fuel flowmeter is definitely preferable since it is capable of producing accurate data in the desired form (lb_m per hour). The instrument is not affected by fuel density or viscosity, and the data need no correction or compensation. Furthermore, this flowmeter is able to accurately measure fuel consumption over the large range (as much as 50 to 1) from rated speed and load to idle. As used in the laboratory, the linear mass flowmeter is a commercially-available unit with a reasonable price. However, they have not been used on board a moving ship.

Adapting the linear mass fuel flowmeter to a Coast Guard engine is complicated by the operating conditions present when the vessel is underway. That is, the pitch, roll, and vibration present will produce undesirable effects on the operation and accuracy of the flowmeter in its present configuration. The problem centers around the recirculating (or "make-up") fuel tank that receives fuel from the main supply tank and the fuel that is returned from the engine. Fuel from the main supply enters the recirculating tank through a float-controlled valve similar to that used in a carburetor. The flow through this valve is equal to the fuel that is consumed by the engine; hence, the consumption rate displayed on the readout device is determined by the position and movement of the float valve assembly.

It is well-known that the instrument is sensitive to motion of the recirculating tank and float valve. Therefore, it will be necessary to modify this part of the flowmeter to render it less susceptible (even, perhaps, impervious) to the effects of vessel motion. Conversations with a manufacturer of such a flowmeter indicates that several options are available to minimize the effect of motion, and that a cooperative effort might be established between the manufacturer and SwRI to modify the device further and make it truly suitable for shipboard measurement. However, a considerable effort would be needed to adapt the unit to the Coast Guard situation.

Drive shaft-mounted horsepower transducers are currently installed on Class 378 high-endurance cutters. However, these transducers are reputed never to have worked properly and now have apparently fallen into disuse. They are of the "contacting" type; i.e., strain gauges are applied to the drive shaft and the resulting electrical signals are brought out through slip rings to the readout device. The transducers became inoperative due to an oil film on the slip rings that prevents good electrical contact. This is a common problem with this type of transducer. Class 210 medium-endurance cutters are not equipped with horsepower transducers. However, the amount of exposed, accessible drive shaft is sufficient to allow most types of transducers to be installed.

A survey of commercially available horsepower transducers has turned up several models of the noncontacting type. These transducers, which also utilize small strain gauges mounted on the drive shaft, rely on solid state electronic circuitry to transmit the signal from the rotating member to a suitable receiver mounted in proximity to the shaft. An accuracy of ±1.0 percent is claimed. However, the instruments all produce a relative torque readings in their present configuration, although it may be possible to calibrate them to give absolute data. Calibration would involve applying a known torsional load to the shaft and observing the transducer reading. Several such loads that span the torque range of the engine would be necessary to verify the accuracy and linearity of the transducer and its read-out device.

Installation of the transducer does not require any modification of the driveshaft and is generally a straightforward procedure. However, the calibration procedure appears to be a formidable problem. The chief difficulty is to apply very large, but accurate, pure torsional loads to the locked driveshaft within the confines of the engine room. It may be acceptable to forego onboard calibration and utilize instead the relative power data to compute and display a relative BSFC. This approach is feasible in a monitoring and diagnostic system that does not have to provide the absolute data required for a laboratory-type test program. Accuracy would not be sacrificed by use of relative data since the horsepower transducer could be checked for linear response characteristics before being installed on the shaft. However, even under these conditions a substantial effort would be required to obtain these data from two large engines.

As mentioned previously, smoke opacity can be determined by either end-of-stack or inline smokemeters. For a permanent installation on board a Coast Guard cutter, only the inline model need be considered. The instrument would be located in the exhaust duct at a point between the exhaust manifold (and turbocharger, if present) and the duct outlet. Readout would be by means of a meter and/or strip chart recorder in the monitor panel. The smokemeter could be modified to measure the average smoke opacity (i.e., for all cylinders) and dynamic opacity (the smoke "puffs") from individual cylinders. The former data is best suited to continuous monitoring, while the latter type of data would be used to isolate a combustion-related problem to a particular cylinder.

The installation of the inline smokemeter presents no fundamental problem; the light transmitter and light receiver (or photocell) are diametrically mounted in the walls of the exhaust duct, and they must be carefully aligned to obtain the proper output signal. Vibration of the duct may necessitate realignment, but it is uncertain how often this would be required. However, it is known that inline smokemeters need frequent cleaning of the optical surfaces of soot. This is a routine maintenance item performed, say, every 50-100 hours of engine operation, and it is a relatively simple procedure since the smokemeter itself is not removed from its mounting.

A much more difficult problem is posed by calibration of the smokemeter. This step should be done at intervals no longer than a few hundred hours of engine operation. Calibration requires that two or three optical filters of different opacity be placed in the light beam path to check both the absolute opacity reading and linearity of the smokemeter and readout device. Since the smokemeter and exhaust duct are a closed system, it is necessary to remove the smokemeter from its mounting, set the unit up on a test bench, and perform the calibration there. It is therefore necessary to realign the optical system when the unit is reinstalled in the duct.

It is thought that the above procedures, performed on two smokemeters (one for each main diesel engine), would constitute an unacceptable burden on a ship's engineering personnel. Therefore, we concluded that smoke opacity data must be exluded from the Coast Guard monitor system.

The preceding discussion of engine room measurement of fuel consumption, shaft power, and smoke opacity is only meant to bring problems associated with these measurements into perspective in regard to the proposed engine monitor. The data are most certainly important and could be obtained if questions of current cost effectiveness (including time utilization of engine room personnel) and reliability could be disregarded. And it may be desirable to begin separate research into the problems involved. However, it is our opinion that the solution of these problems would substantially increase the development time and cost of the monitor.

3.3.3 Conventional Pressures and Temperatures

Conventional pressures currently measured by bourdon tube gauges will not be replaced by pressure transducers for two reasons. First, the cost of a single pressure transducer of average accuracy, with readout power supply, cables, connectors, signal conditioning, and installation costs on a naval vessel ranges from $1000 to $1800. When multiplied by the required number of pressure measurements, the cost exceeds the electronics in the monitor. Also, the pressure information needed is not dynamic and is not absolutely necessary at all times. Hence, a gauge observed periodically is entirely adequate for an initial prototype of the monitor.

In an advanced monitor, the use of pressure transducers would still be highly selective, again based upon cost, as well as reliability. The pressure transducer is generally unreliable unless carefully protected from the normal engine room environment of temperature fluctuations, vibrations and moisture.

3.3.4 Temperature Indicator

A single indicator or readout device is suggested for all temperature measurements. The existing thermocouples will be disconnected from their indicator and wired to the indicator supplied in the monitor, along with additional temperature measurements such as bearing blocks and turbocharger return oil. One unit calibration will be necessary and all temperatures will have a common reference junction and the same linearization circuit. The ship's instrumentation for temperatures will not be used.

3.4 System Rationale

The method of the monitor system operation suggests that the warning indicator parameters and the trend parameters will be the primary method of detecting the presence and cause of faults. Maintenance actions can be prescribed when the fault has been isolated to specific engine subsystems and components. The fault isolation or diagnosis is accomplished by using the remaining parameters. The following sections detail use of the warning indicator parameters and the trend parameters and indicate how faults are then isolated by use of the diagnostic parameters. Figure 3.2. indicates this process by block diagram.

3.4.1 Warning Indicator Parameters

a. Bearings - If any individual main bearing block temperatures exceeds 270° F the associated warning light will blink once per second and a corresponding audible alarm will sound at the same frequency. This action continues until the temperature falls below the preset limit. Once below this limit, the light continues to burn steadily until a manual reset button (located inside the cabinet) has been actuated. The reset button is accessible by unlocking and opening the monitor panel. This technique insures that the incident will be logged by the watch stander.

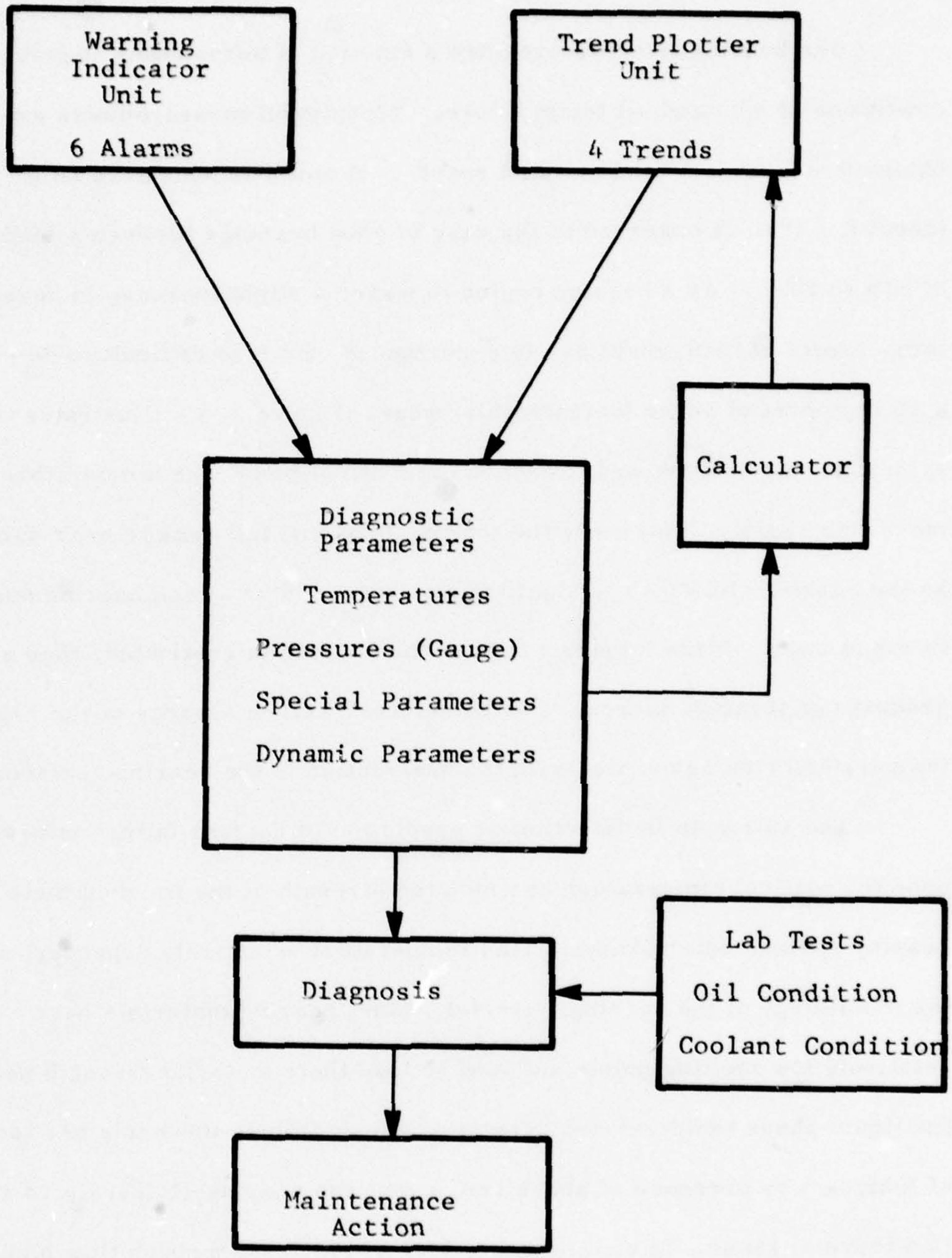
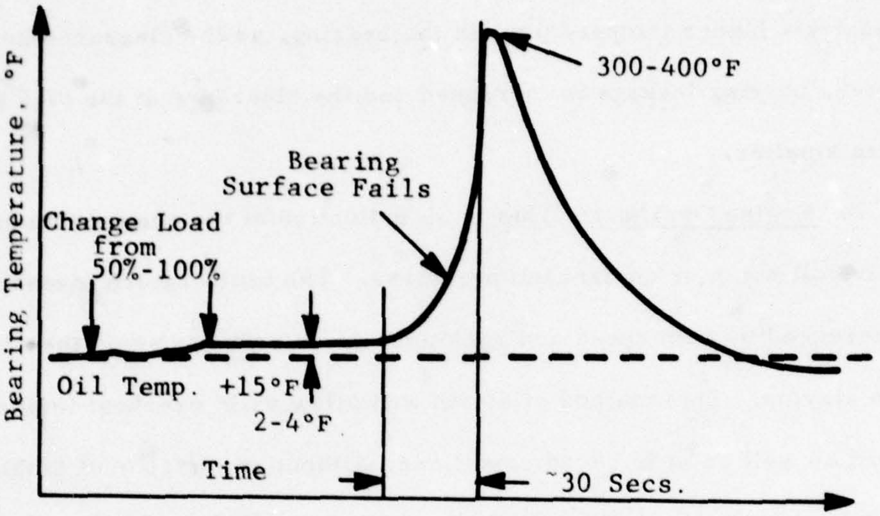


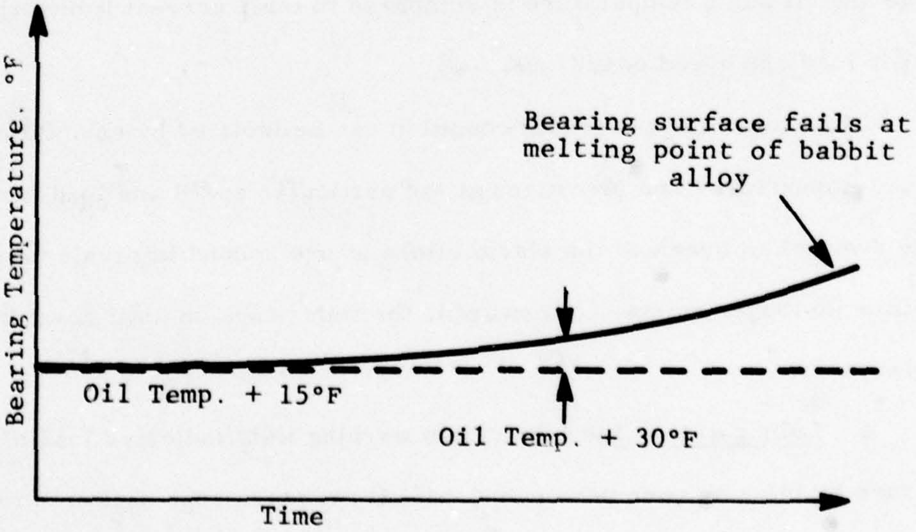
FIGURE 3.2 - FAULT DETECTION AND ISOLATION PROCESS

The bearing temperatures are a function of horsepower at given conditions of rpm and oil temperature. Meaningful measurements are obtained at above 50% load at rated speed . A small temperature shift (about 2 - 4° F) is observed in the case of good bearings between a load change of 50% to 100%. As a bearing begins to wear, a slight increase in bearing temperature at load conditions is experienced, but it is difficult to detect until the onset of sever (catastrophic) wear. Figure 3.3 illustrates this principle. As bearing wear reaches the critical point, the temperature increases rapidly. Normally the temperature will fall back to near normal as the bearing clearance is significantly increased or as the bearing surface is wiped away. If the lubricant flow to the bearing is restricted, then a gradual temperature increase can be detected well in advance of the rapid temperature rise associated with the destruction of the bearing surface.

The rationale in detection or prediction of bearing failure is based upon the critical temperature at which the strength of the finished metal bearing surface deteriorates. This temperature is entirely dependent upon the metallurgy of the bearing material. Most bearing materials have relatively low melting points and tend to lose their material strength near the liquid phase temperature. The two bearing failure mechanisms, loss of lubricant or presence of abrasives, cause the bearing ultimately to fail in a thermal sense. In one instance, loss of lubricant through flow blockage or pump failure upsets the bearing heat balance and causes a temperature increase which reduces the oil viscosity and causes (too) small bearing clearances at the load point. In the case of abrasives in the oil, the bearing



Case of Rapid Destruction of the
Bearing Surface



Case of Restricted Flow of Lubricant
to the Bearing

FIGURE 3.3 - BEARING TEMPERATURE INCREASE FOR
TWO FAILURE MECHANISMS

clearance at the load point is worn away relatively slowly. This results in progressively higher temperatures in the bearing, as the clearance geometry is altered, bearing leakage is increased and the clearance at the load point becomes smaller.

b. Engine Overheat - This is an indication of the occurrence of either excessive oil sump or coolant temperatures. The temperature measurements are referenced by both speed and rack position in order to avoid the occurrence of false alarms. This method of alarm will allow valid overheat indications at part load as well as at full load conditions, without an instance of ambiguous data. A load factor is computed electronically using rack position and the speed of the engine. The measured value of coolant temperature out of the engine and oil sump temperature is compared to their correct limit values at specific load and speed conditions.

The cause of the overheat condition can be isolated by examining the engine temperatures and pressures at the particular speed and load condition. In the event of an overheat the alarm blinks at one second intervals until the condition no longer exists. Afterwards, the light stays on until reset by the watchstander.

c. Lubrication - The lubrication warning light indicates loss of oil pressure by blinking once per second. If oil pressure goes back into tolerance the light stops blinking, but continues to burn until reset. The oil pressure is compensated to a standard value using both oil temperature and engine speed parameters. Figure 3.4 illustrates the map of possible oil pressures at various conditions of speed and oil temperature. A simple comparison limit

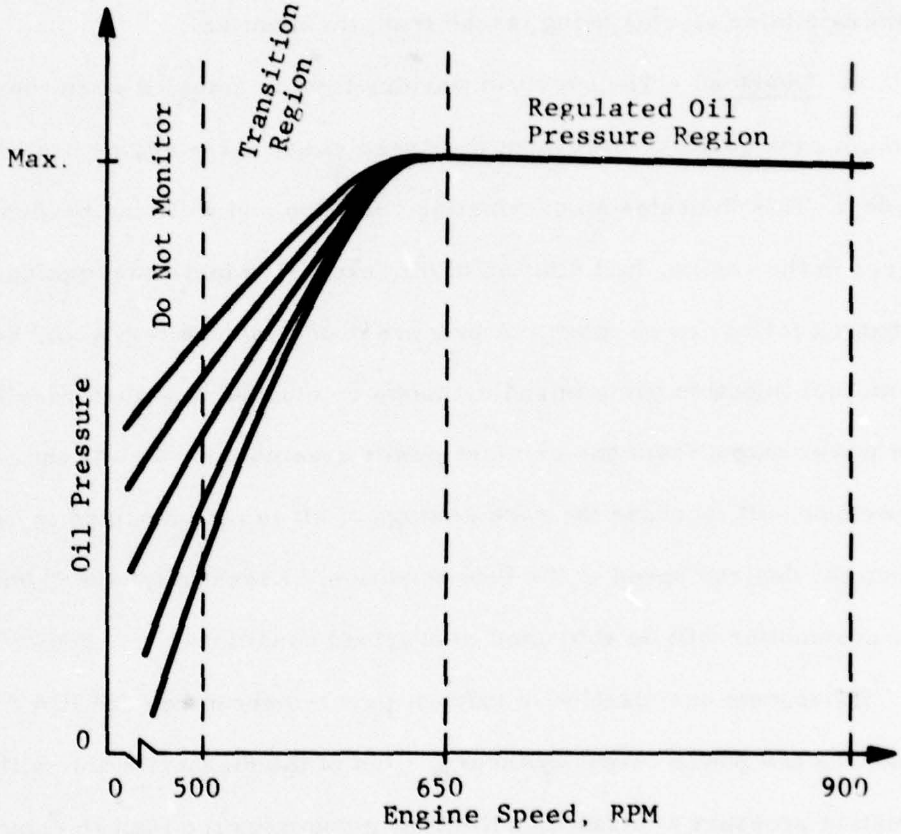


FIGURE 3.4 - OIL PRESSURE AS A FUNCTION OF ENGINE SPEED AND VARIOUS OIL TEMPERATURES

cannot be applied to all cases. When engine speed exceeds a particular value, a single low oil pressure comparison limit can be established without ambiguity. Note that at speeds below this value the low limit is dependent upon both oil temperature and engine speed. The compensation is again included to eliminate false alarms being issued from the monitor.

d. Overload - The overload warning light is actuated when the normal maximum rack position throughout the speed range of the engine has been exceeded. This indicates an overfueling condition and will lead to high thermal stresses in the engine, fuel dilution of oil, excessive fuel consumption, and fuel deposit formation on rings. A precursor of this condition would be individual fuel injection pump misadjustments or plugged injectors resulting in low power output from one or more power assemblies. In this instance the governor will increase the rack settings of all injection pumps in order to attain the desired speed at the load condition. Essentially, the "good" power assemblies will be subjected to overload conditions.

Subsequent examination of exhaust port temperatures and ICAV data will indicate the low power output cylinders. Use of the diagnostic unit with the combustion pressure transducer will allow pinpointing the fault to compression, fuel injection, or aspiration problems.

Should the turbocharger fail to deliver the required amount of boost air, then a similar effect would take place. The governor will increase the rack positions beyond normal to compensate for the lack of power caused by the low boost pressure. Examination of the logged data will indicate that boost pressure and exhaust temperature are low in the same bank of cylinders. Further examination of the air and exhaust temperature data would isolate the specific turbocharger failure mode: worn compressor, worn turbine, or defective bearings. Should the turbocharger failure be due to a bearing problem, then a thorough examination of the engine lubrication system would be in order.

e. Misfire - The misfire warning light is an indicator of relative power output magnitudes from the individual cylinder assemblies. Figure 3.5 illustrates the information as it would appear on an oscilloscope screen for a six-cylinder engine. Any defect that would cause low power in an individual power assembly will disrupt the signal as indicated. Low compression, poor aspiration and defective fuel injection are typical faults that can be detected. The faults range from total loss of power to slow and incomplete burns.

As the electronic circuit detects instances of misfire during normal operation, the indicator light will blink. If the misfire is synchronized and occurs at all times, such as in the case of a completely plugged injector nozzle, then the indicator light burns continuously.

The special parameters indicator unit displays a running average of the ratio of misfires to revolutions and is logged and recorded data. If the watch stander does not see the misfire indicator working, he can review the plotted misfire ratio data trends and come to conclusions about the engine condition. If either the trend data or the warning light indicate a severe misfire condition, then the diagnostic unit is used to isolate the cause of the problem. Examination of the instantaneous cranking speed (CN) during starting will detect compression defects. The cylinder pressure transducer applied to the cylinder petcocks of a few cylinders will confirm the lack of

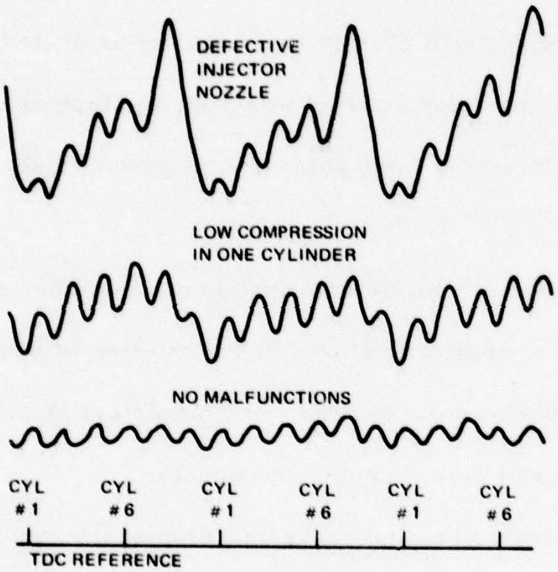


FIGURE 3.5 - MISFIRE OR LOW POWER FOR INDIVIDUAL ENGINE CYLINDER

compression indicated by the cranking speed analysis. Should compression be defective, an analysis of the dynamic blowby pressure will isolate the cause to either upper end or lower end faults. If no compression fault is detected, then the ICAV signal is reviewed to locate the defective cylinder. Once located, PV and AROHR data can be displayed using the cylinder pressure transducer in both a good cylinder and the suspected cylinder.

f. Blowby - The blowby indicator light functions whenever the crankcase blowby gas flow rate exceeds a preset limit established for the engine. This is used to indicate an excessive wear condition in the piston, rings, and liner section of the engine or broken rings and burned pistons. The flowrate value is compensated for both oil temperature and engine speed to prevent false alarms. The blowby data is evaluated at a load range from about 50-to 100-percent power. The blowby flowrate has been observed to change normally with changes in engine load for some engines. Other engines exhibit more significant changes in blowby flowrate with engine speed than with engine load. This behavior is thought to be a function of ring design. The method of compensation of the blowby data may be different depending upon engine type. However, the diagnostic rationale for blowby flowrate is the same for all engines. High blowby indicates worn pistons, rings, or liners, or in rare instances a lubricating oil problem involving defective lubricant or poor oil distribution. The blowby flowrate is plotted for trend analysis purposes. An exceeded limit or a definite trend towards an out-of-limit condition would prompt diagnostic evaluations using the dynamic crankcase pressure techniques described in the earlier misfire section.

3.4.2 Trend Analysis Parameters

a. Blowby Flowrate Trend - Blowby flowrate trend analysis is a straightforward observation of the blowby flowrate versus time from one-half engine load to full load. The blowby trend can be extrapolated in time to allow judging when the blowby will be out of tolerance and a detriment to engine life. If a high rate of increase is observed prior to exceeding the limit, then some diagnostic investigation as outlined in the previous sections should be made to determine the causes and hopefully perform maintenance to correct the problem.

b. Misfire Trends - Misfire trends are logged in the form of a ratio of engine revolutions to misfires. The ratio gets smaller as the misfire becomes more apparent and eventually is synchronized with every cycle. The use of trend analysis on this parameter is justified since the misfire could occur only at high loads in the initial stages. The data is high speed and is difficult to display in a quantitative manner other than by plotting.

Fault isolation techniques outlined in previous sections are used to isolate the misfire and initiate maintenance or adjustments to eliminate the cause of the misfire. An example of this would be misfiring due to a sticking fuel injector nozzle. The misfire might occur at low speeds occasionally, but not at load conditions. If detected early the nozzle could be removed, cleaned and replaced before a tip burned beyond repair or before a total misfire developed and caused loss of power, overfueling of the remaining cylinders, or excessive oil consumption.

c. Heat Exchanged Factor Trend - This is a computed factor based upon the cooling system parameters of coolant temperature and coolant flow rate. The theoretical heat rejected to the coolant can be computed using the following equation: Heat rejection to coolant = Rack Pos. x RPMx K, where $K = \frac{(\text{Temp of fuel obs.})}{(\text{Temp. of fuel ref.})} \frac{(\text{reference})}{(\text{fuel density})}$ obtained from work-up table for the engine. The heat transferred from the engine to the heat exchanger is equal to the theoretical heat rejected to the coolant and can be calculated from the following equation. Heat transfer from engine =($M_{coolant}$)(Cp)(Δ t), where $M_{coolant}$ is the coolant flow rate measured by flowmeter,

Cp is specific heat of coolant,

Δt is the temperature rise across engine .

There should be virtually no difference between these two calculated values. They are calculated and the differential is plotted periodically. If the differential increases in time, then there is an effect within the cooling system that is reducing the heat transfer effectiveness. This could be scaled water jackets, loss of pump output, or high sea water temperatures.

The increasing heat exchanger trend prompts diagnosis of the cooling system to isolate the fault. It may be that the trend will be observed long before there is an overheat condition indicated. The fault isolation of the cooling system involves analysis of the conventional pressures and temperatures along with consideration of the coolant condition. Each element of the cooling system has a temperature differential measurement that can be observed. The water pump has both pressure and flowrate information for its checkout. Sea water temperature can be used with the heat exchanger temperature rise to isolate the cause of reduced heat exchanger performance.

d. Efficiency Factor Trend - An overall performance efficiency factor is needed to monitor the overall performance of the engine, especially regarding parasitic losses that may not be detectable by any other monitored parameters, at least in the early stages of deterioration. One example of this would be high friction in rod bearings, blower bearings, valve train, pumps and fuel injection equipment. Combustion air pumping losses can also consitute a parasitic loss and can be made up of several slight faults such as air filter restriction, reduced intercooler efficiency, and valve leakage.

The measurement of engine output torque, speed and engine fuel consumption would allow calculation of brake specific fuel consumption (BSFC), an ideal overall performance and efficiency factor that could be compared to established limits and would indicate performance deterioration. Previous discussions indicated that we will not measure fuel flow or torque due to the problem of transducer complexity and reliability.

Rack position multiplied by rpm and a density correction factor based upon fuel input temperature is an approximate substitute for conventional fuel flow measurements. A computed value based upon average exhaust temperature, engine speed, and oil temperature can be derived for a substitute brake horsepower figure. Some development of this relationship may be necessary to accomodate differences between the various engines used by the Coast Guard. The two calculated quantities are used to derive an efficiency factor which is then plotted and observed for deviations over long periods of time:

$$\text{Efficiency factor} = \frac{\text{Fuel Consumption (Calculated)}}{\text{Brake Horsepower (Calculated)}}$$

Both of the calculated values used in the efficiency factor are functions of engine condition, and are not considered as an exact representation of brake specific fuel consumption. The parameter is intended to serve only as an indicator of changes in several of the parameters that are indicative of performance deterioration. The efficiency factor serves this purpose by being sensitive to performance deterioration, and it is a comprehensive way of prompting further diagnosis using the dynamic parameters and the conventional temperatures and pressures.

4. PROGRAM PLAN FOR DEVELOPMENT OF PROTOTYPE MONITOR SYSTEM

Development of the prototype diagnostic system will be accomplished in the following manner:

1. Measurement techniques for the candidate parameters will be incorporated into individual modules, one for each parameter. These modules will utilize preliminary electrical circuits (breadboards) that can be easily modified, if necessary. Appropriate readout devices (meters, gauges, digital displays) will be incorporated in each module, or, where needed, preliminary data will be read out on a chart recorder or oscilloscope.

2. The pre-prototype instrumentation will be evaluated by use with two large, medium speed diesel engines available at SwRI: a two-stroke cycle, blower-scavenged EMD 2-567 and a four-stroke cycle, turbocharged, six-cylinder Enterprise. A series of tests - with the test engine operating both normally and with selected induced malfunctions -- will be conducted over a wide range of speed-load values so that the instruments' responses can be optimized for the medium speed engines. Such optimization will probably entail relatively minor modification of the circuits.

3. The (possibly) modified instrumentation will then be used in a similar series of tests with actual Coast Guard cutter engines. It would be preferable to conduct tests with both Fairbanks-Morse and Alco engines since they are of primary interest to the Coast Guard. The acquisition of data from in-service engines, in their normal operating environment, would be especially valuable in this evaluation. Further slight modification of the instruments may be necessary during these tests.

4. Results of these tests will be analyzed to establish the diagnostic significance of the parameter measurements. Criteria used to establish this significance will include the unambiguousness and consistency of the measured parameter change when the associated malfunction is present, and the ability to interpret the data according to a set rationale.

5. Next, two prototype synthesized systems, consisting of the selected parameter measurement instrumentation in final design form, will be designed and built. Prime consideration in the design of the synthesized systems will be the integration of the units into the existing physical and operational engine room situation on the selected cutters. Instruction manuals will be written to explain system operation, check out, and any required maintenance procedures. The rationale needed by Coast Guard personnel to interpret the data will also be provided.

6. The synthesized systems will be installed on two cutters designated by the Coast Guard. It is recommended, however, that one cutter be of the WMEC 210B class (Alco 251 engines) and the other be of the WHEC 378 class (Fairbanks 38TD8-1/8 engines). The engines are of different designs, and the cutters have different mission profiles. Hence, the prototype systems would be involved in highly contrasting application and this situation would be desirable in evaluating their performance and design.

7. The data from the two systems will be recorded either by recording devices or by hand, according to the design of the prototypes and analyzed in depth by SwRI program personnel. The analysis will indicate operational status of the instrumentation and transducers and will be used to determine

which parameters are most (diagnostically) significant on a long-term basis. This information will, in turn, indicate how the prototype design should be modified to achieve the final system. A maximum of six (6) months is allotted for this trial period and data analysis; the length of time could be somewhat less if the test vessels are under high utilization.

8. The final step in the program will be to prepare a final report that will summarize findings, draw conclusions and make recommendations for the finalized diagnostic system. Also included in the report will be engineering design drawings and wiring diagrams for the system, cost analysis for construction, installation and maintenance of the final design, and examples of ways in which the capabilities of the unit may be upgraded as the state of the art advances.

5. MASTER PROGRAM AND COST SCHEDULES

Task No.	Task Description
1	Design and construct preprototype individual instrumentation modules for each recommended candidate diagnostic measurement. Performance period: three (3) months.
2	Employ modules to make parameter measurements with available (at SwRI) large medium-speed diesel engines in normal operation and with induced malfunctions. Optimize instrument performance by design modification, if needed. Performance period: three (3) months.
3	Employ modified instrumentation to make measurements with selected Coast Guard cutter engines in normal operating and induced malfunction modes. Performance period: four (4) months.
4	Evaluate test results from Task 3 to finalize candidate measurement techniques and electronic circuit designs. Establish basic rationale for data interpretation. Performance period: three (3) months.
5	Design and build two (2) prototype synthesized systems and perform check-out at SwRI. Performance period: three (3) months.

6 Install prototype systems on two (2) selected Coast Guard cutters. Check out installation and instruct crew members in system operation. Performance period: two (2) months.

7 Analyze acquired data to determine its diagnostic significance and system performance. Performance period: six (6) months.

8 Prepare final report to summarize program and to make recommendations for design of final diagnostic system. Report will also contain an updated rationale for interpreting data and updated cost estimates for construction and installation of final system. (At the present time, the estimated cost of a monitor/diagnostic system similar to that presented in this report is approximately $55,000 per ship). Performance period: three (3) months.

Total period of performance is 23 months. These tasks and their timing within the total performance period of the program are shown in Figure 5.1. Note that monthly progress reports and major program reviews every four months are scheduled to keep the sponsor informed. The major reviews are envisioned to include meetings between Coast Guard and SwRI personnel at Coast Guard Headquarters, Southwest Research or, possibly, on board the cutters equipped with the prototype monitors.

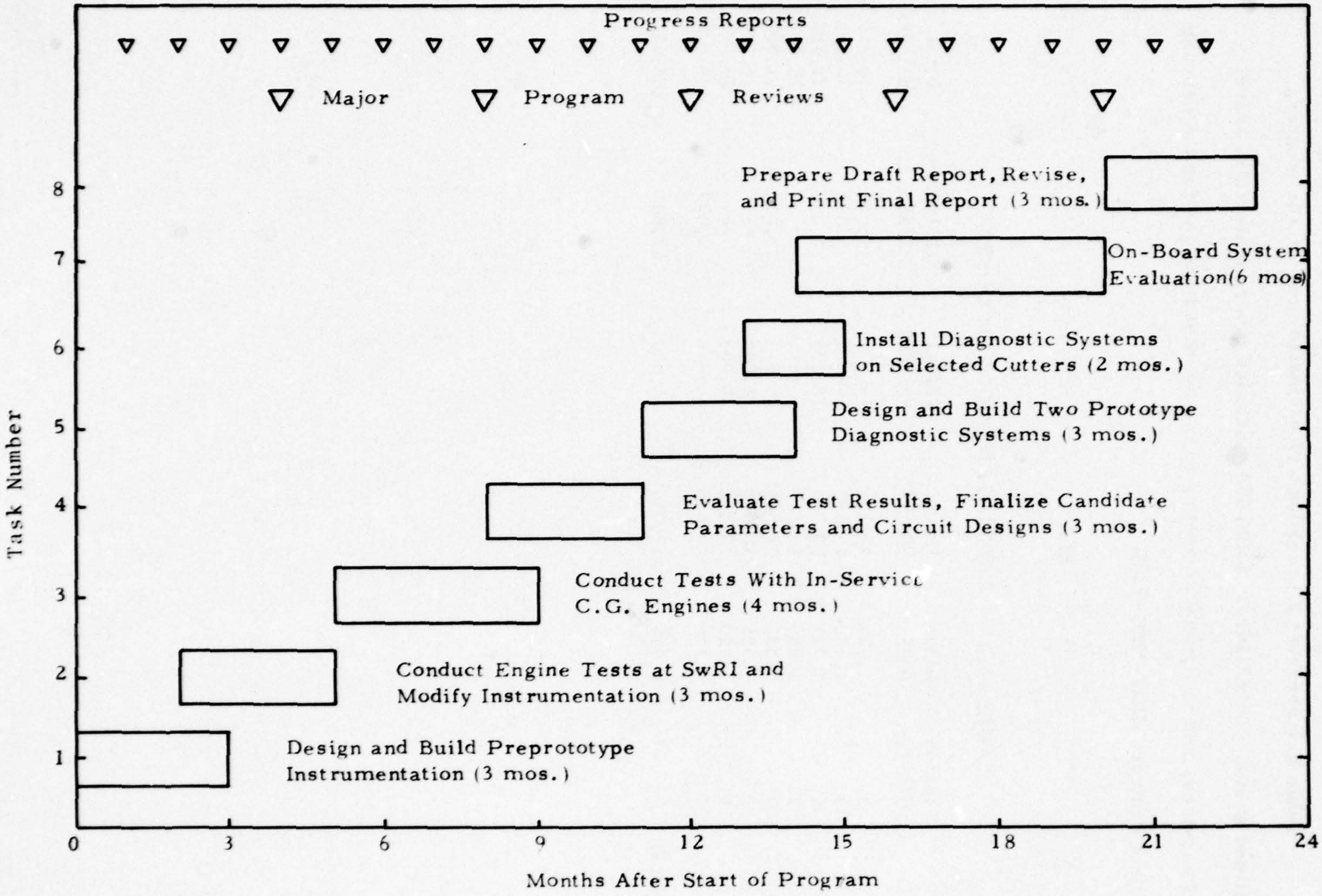


FIGURE 5.1 - TASK SCHEDULING OF PROPOSED PROGRAM

Table 5.1 presents a breakdown of estimated cost of the program outlined above. This figure, $288,454, includes labor, materials, travel and services, and is figured according to the overhead and fee for the existing subject contract (DOT-TSC-920).

TABLE 5.1 - ESTIMATED PROGRAM COSTS

Task Nos.	Duration Months	Labor Hours	Labor Dollars	Travel Dollars	Mat'l Serv Dollars	Total Dollars
1	3	1,284	25,854	--	15,000	40,854
2	3	1,500	29,382	--	5,000	34,382
3	4	1,252	22,750	12,000	5,000	39,750
4	3	1,064	26,556	--	--	26,556
5	3	3,572	71,304	--	20,000	91,304
6	2	556	10,550	6,000	--	16,550
7	6	1,320	23,388	6,000	--	29,388
8	3	396	7,670	--	2,000	9.670
Total		10,944	217,454	24,000	47,000	288,454

APPENDIX A

Discussion Of Types Of Diagnostic Monitor Systems

Present Hardware Configurations

A1. Carry-On "Suitcase" Equipment - usually a compact, self-contained system with various degrees of data acquisition and processing automation.

a. Carried -on with system and placed on engine

b. Permanently installed on engine and accessible to monitor through a centrally located connector panel.

c. A combination of built-in sensors and carry-on sensors. Usually these configurations are for diagnostic purposes, where several similar engines are serviced by a single crew of technicians. By virtue of the fact that it is portable, it cannot be used as a real-time monitor except in special cases where the system is left connected to a machine or engine for some time to obtain data.

A2. On-Board Monitor Panel, or Monitor Board - a junction box placed on or near the engine with sensors placed on the engine and whose leads run to the monitor panel. Power supplies and sensor signal conditioning is located in the monitor panel. The panel has visual displays for the engine operator; some have printed outputs. Usually performance, status and diagnostic information is displayed. Alarms are installed. Sometimes, manned controls and automatic controls are integrated into the monitor board.

The monitor panel located at the machine can output selected information to remote locations such as control rooms, bridge, master control boards, and so forth.

A3. Monitor Panel with Auxiliary Diagnostic Equipment - This system is the same as that mentioned in A2. above, but with electronic connectors for the output of critical parameters. Special analytical tools are hooked up to the monitor when in-depth diagnosis is needed. Typical example would be a monitor panel indication that engine speed was non-stable or erratic. An oscilloscope could be connected to the monitor panel and display the rpm signal dynamically and also show top dead center reference marks. This approach serves to reduce monitor panel cost and complexity. Another example involves the relocation of a pressure transducer normally mounted in the monitor panel for blowby pressure. If a misfire is suspected, the transducer can be disconnected from its panel location and placed directly in communication with the crankcase to measure dynamic crankcase pressure. Again, an oscilloscope is used to analyse the engine data in synchronization with the TDC reference marks to isolate the defective cylinder. This technique allows a high reliability remote sensor location for most of the time and allows short term, direct engine placement of the sensor when needed.

A4. Console Mounted Monitor System - The monitor board can be mounted with engine controls and conventional operational instrumentation in a standard electronics console and interfaced with a minicomputer. This system could be located in the main engine control room. It is an advanced system design that requires considerable knowledge of the engine data and control characteristics. Systems like this have been prototyped and are designed to perform predictive functions regarding the remaining life in a machine or the estimated time to failure. Most of the diagnostics involves considerable data processing and uses truth tables or logic trees. Safety alarms and shutdowns are integrated into the ship controls in some prototypes.

Sensors in this system are usually routed to local junction boxes near the machinery being monitored. The junction boxes can perform intermediate signal conditioning tasks using simple electronic circuitry or microprocessors. The preprocessed sensor information is then transmitted in digital format to the control room console. This system is a logical expansion of the on-board monitor panel described in A2. above. The watch standers can observe engine information at the main console location or they can observe a limited amount of data in unprocessed form at the local monitor boards (j-box).

Control functions, data processing, decision making and prognostication adds some cost to the hardware of monitor systems, but most of the cost is involved with software development and the prerequisite engineering studies that define the relationships between parameters and the failure and operational modes.

A5. Degree of Automation - The various hardware configurations discussed above can have degrees of automation. The systems can be totally manual, which means human observation and interpretation of the data. An example of this approach is an automotive instrument cluster with gauges. A slight amount of automation may include pressure and temperature limit switches, similar to automotive "idiot lights".

Semi-automatic features involve the use of pressure transducers with signal conditioning capable of displaying the electronic signal converted to engineering units. Once the data is converted to an electronic signal, it can be used in electronic circuits that turn on lights, provide warnings and alarms, and otherwise inform the operator of a change in engine status. Also, the signal can be compensated, corrected or referenced to other parameters. Once corrected, the signal can be compared to a predetermined limit which if exceeded will cause the appropriate alarm.

Automatic methods usually employ a computer processor for data signal conditioning, compensation, filtering, referencing and comparison to standard limits in a digital mode rather than by the analog methods employed in most "semi-automatic" monitors. More automation implies use of computer memory for the purpose of making long-term trend analysis and subsequent prognosis. Still more automation would involve not only predetermined limits for comparison, but also a logical analysis network of many data channels in order to arrive at a diagnosis. The next step in automation would involve the display of instructions or course of action to be taken by the observer.

An almost total transfer of knowledge and skill from the observer to the monitor requires the monitor system to assume control of the engine, in addition to its data acquisition, data processing, monitoring, diagnosis, prognosis and instructional tasks. Systems like this are being built for shipboard use that will have collision avoidance capability, optimal navigation, power plant optimization, and maintenance scheduling based upon selected sensor data. The Navy is also suggesting mission planning, using predicted machinery endurance and the mission profile as inputs. The Navy proposal is for those low mission, essential combat ships that will have reduced manning in maintenance functions. The comprehensive shipboard monitor will be observing all major machinery and equipment.

The key problems in achieving this high degree of shipboard maintenance monitoring has been outlined recently by a joint industry and military task force. They are listed below in order of priority:

1. Increase sensor endurance to prevent the sensor from becoming a major maintenance item itself.
2. Enhance the technology and data base for many kinds of machines so that the minimum number of sensors are applied, thus reducing system cost and increasing system reliability.
3. Develop appropriate hardware.
4. Develop appropriate software.

APPENDIX B

Existing Data Logging On WMEC 210A And 210B Cutters

EXISTING MEASUREMENTS ON 210B CLASS CUTTERS (Alco Engines)

Daily -

1. Run lube oil viscosity test on all operating MDE's. (Test utilizes a viscosity comparator which compares samples of used and new oil)

2. Run diesel engine cooling water test. (Consists of tests for chromate concentration, alkalinity, and chloride content.)

Underway -

Record hourly readings of the following parameters:

1. Shaft speed (RPM) by tach. gen.
2. Crankcase pressure by U-tube manometer
3. Fuel transfer pressure by gauge
4. Lube oil pressure by gauge
5. Seawater cooling pressure by gauge
6. Fresh water (coolant) pressure by gauge
7. Lube oil temperature by TC
8. Coolant in temperature by TC
9. Coolant out temperature by TC
10. Seawater temperature by TC
11. Lube oil level by sight glass
12. Lowest and highest exhaust temperatures by TC
13. Combined exhaust temperature (before and after turbo) by TC
14. Intake manifold pressure by gauge
15. Exhaust backpressure by U-tube manometer or gauge

EXISTING MEASUREMENTS ON 210A CLASS CUTTERS (Cooper Bessemer Engines)

Daily -

1. Lube oil viscosity test conducted as on 210B cutters.
2. No information on frequency of cooling water test.

Underway -

Record hourly readings of the following parameters:

1. Shaft speed (RPM) by tach. gen.
2. Engine room air temperature by TC or thermometer
3. Seawater in temperature by TC
4. Seawater temperature from oil cooler by TC
5. Seawater temperature from coolant heat exchanger by TC
6. Fresh water (coolant) in and out temperatures by TC
7. Lube oil temperature in and out of engine by TC
8. Lowest and highest exhaust temperatures by TC
9. Combined exhaust temperature (at turbo?) by TC
10. Seawater pressure from pump by gauge
11. Coolant pressure to engine by gauge
12. Lube oil pressure before and after filter by gauge
13. Lube oil pressure at engine (gallery?) by gauge
14. Fuel pressure before and after filter by gauge

APPENDIX C

Discussion Of Apparent Rate Of Heat Release (AROHR)

In much engine work of the research and development variety, the combustion pressure transducer is a primary tool. Certain combustion events are , however, difficult to discern from a pressure trace, primarily because the piston motion produces pressure changes independent of combustion, and subtle combustion-related effects are sometimes obscured. For instance, the degree of burning that occurs during the expansion stroke can not be very well determined from an inspection of the pressure trace.

As an alternate to the combustion pressure transducer, another procedure is to digitize the pressure data and compute the cumulative heat release or the rate of heat release. This operation is now done by many laboratories through the use of high-speed digital data acquisition and electronic computation of values derived from these data. This method is a very powerful one but entails a considerable capital investment.

For various types of engine experimentation conducted at SwRI, pressure-time or pressure-volume records provided less information than was required, and digital data acquisition with computer manipulations was not cost-effective. In such cases, the Analog Heat Release Computer has proven to be an effective device. This instrument receives analog cylinder pressure information from a high-speed pressure transducer along with cylinder volume inputs from a signal generator attached to the engine crankshaft. It then performs analog computations upon these inputs and produces an analog signal proportional to instantaneous heat release rate, integrated heat release, and other parameters. In this case, "heat release" is defined by the first Law of Thermodynamics applied to the mass of gas in the engine cylinder:

$$Q = W + \Delta U$$

where

$$W = \int P \, dV$$

and

$$\Delta U = C_V \Delta T$$

This defines Q as the net heat added to (by combustion) and subtracted from (by heat losses) the cylinder gas to produce the measured pressure history during the cycle.

Because the instrument is an analog device, the heat release data is produced in real time and may be displayed or recorded simultaneously with other measured engine parameters. A more detailed description of the instrument is given as follows:

Instrument Input Signals

Cylinder pressure - Scale factor adjustable, normally 100 psi/volt.

Cylinder volume - Obtained from Tetronix P/N 015-0108-01 function generator (or equivalent) attached to the crankshaft.

Instrument Output Signals

Cylinder pressure - Measured cylinder pressure plus atmospheric pressure (adjustable).

Cylinder volume.

Degrees crank angle - This signal is in the form of one pulse every 10° CA.

Piston displacement from TDC.

Cycle work; cumulative and instantaneous.

Integrated (cumulative) cycle heat release.

Instantaneous cycle heat release.

Adjustments and Calibration

Adjustable cylinder pressure gain.

Volume signal adjustable for engine displacement and clearance volume.

Adjustable gas specific heat ratio.

APPENDIX D

New Technology

This report is a summary of existing techniques for the diagnosis of diesel engine faults. However, a unique concept is proposed (Section 3) that combines many known techniques into a monitoring system for the main diesel engines of the U.S. Coast Guard cutters to determine the cause of location of a fault that exists in an engine. The unique electronic circuitry and display devices (described in pages 48-61) present engine performance parameters useful in both diagnosis and prognosis.

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