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

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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:

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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

- 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

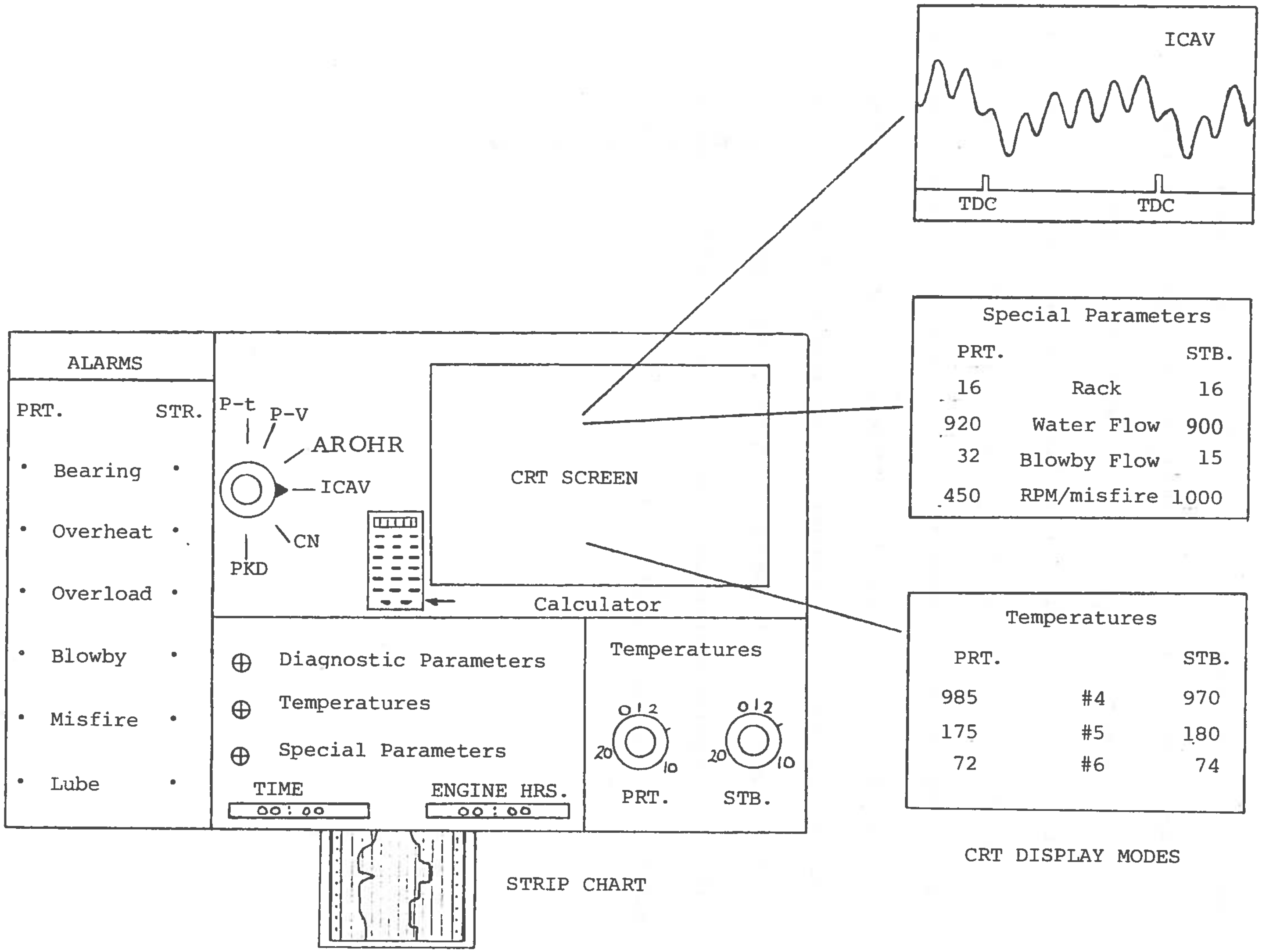

FIGURE 1.1 - SAMPLE LAYOUT OF PROPOSED ENGINE MONITOR

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

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.

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.

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

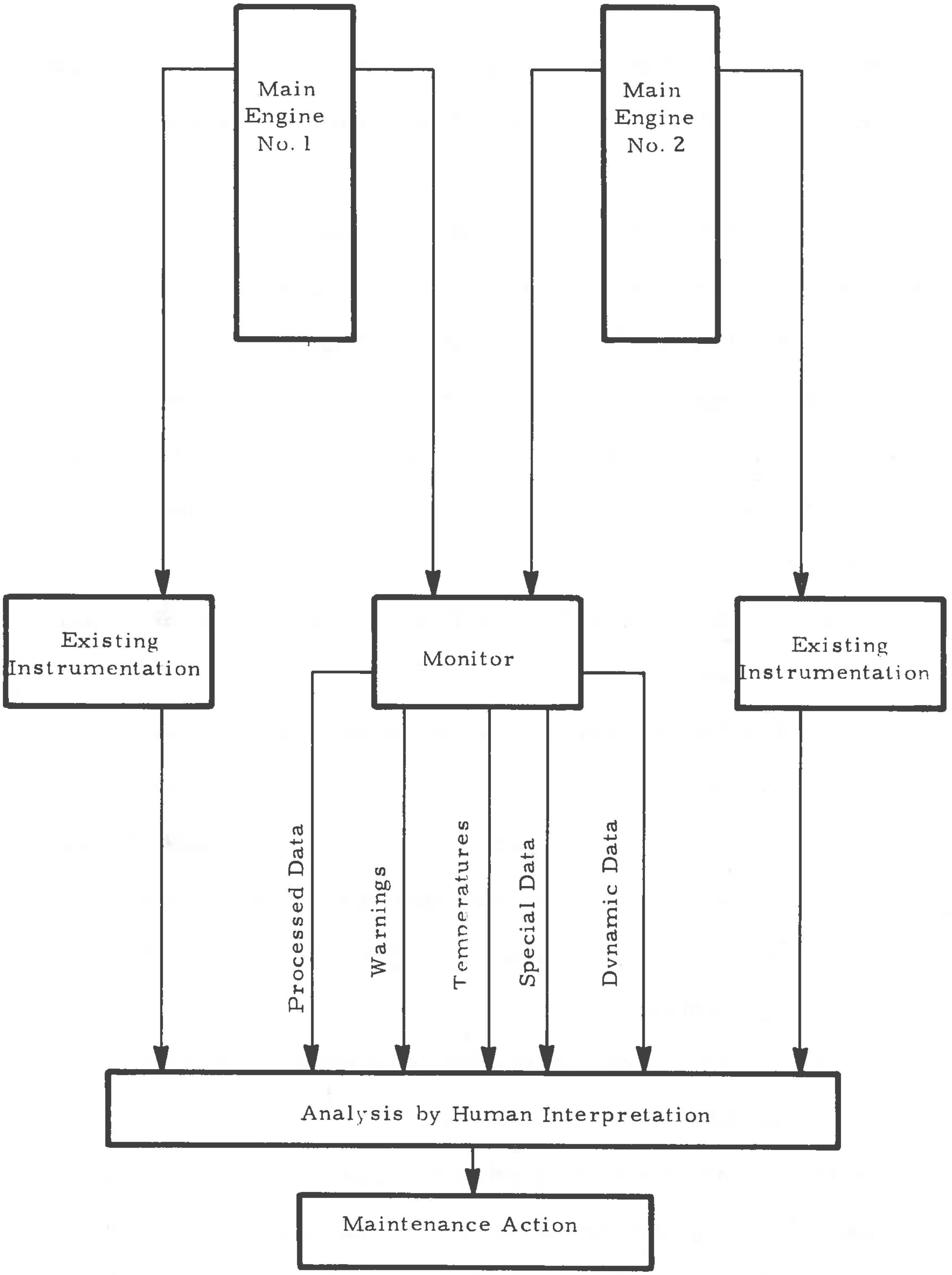


FIGURE 2.1 - FUNCTIONAL SCHEMATIC OF MONITOR INSTALLED IN ENGINE ROOM

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 - Concluded

aw Data	Processed From Raw Data	Use
3.	Sea Water Temperature	Heater exchanger defects
9.	Δt Water across Oil Cooler	Defective oil cooler-water side
0.	Water in Temperature	Cooling system diagnosis
1.	Water out Temperature	Cooling system diagnosis
2.	Δt Air across Intercooler	Defective intercooler
3.	Ambient Air Temperature	Reference, intercooler diagnosis
	Pressure (Gauges)	
.	Δp across Fuel Filter	Fuel filter analysis
.	Δp across Oil Filter	Oil filter analysis
.	Coolant Pressure	Water pump diagnosis
.	Oil Gallery Pressure	Lube oil system diagnosis
.	Sea Water Pressure	Sea water pump diagnosis
.	Fuel Transfer Pump Pressure	Fuel pump diagnosis
.	Turbocharger Pressure	Turbocharger diagnosis
	Lab Analysis Data	
.	Oil Analysis	Oil condition bearing condition piston ring liner wear
.	Coolant Analysis	Heat exchanger condition coolant condition

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.

(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.

TABLE 2.2 - Fault Detection Effectiveness Of Monitor

Fault	Automatic Monitor Selector	Manual Analysis 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
Low oil pressure	X	X		
Defective oil cooler		X		
Defective intercooler		X		
Defective turbocharger		X		
Fuel injection rack out of adjustment		X		
Defective heat exchanger		X		
Worn sea water pump		X		
Worn water pump		X		
Worn oil pump		X		
Scaled water jackets			X	
Defective vibration damper			X	
High bsfc				Not Feasible
High exhaust smoke				Not Feasible
Low absolute performance				Not Feasible
Defective valves			X	
Clogged fuel filter		X		
Clogged oil filter		X		
Clogged air filter		X		
Engine timing off			X	
Abnormal combustion			X	
Valve timing defective			X	
Defective coolant			X	Requires offboard tests & analysis
Defective lubricant			X	Requires offboard tests & analysis

Not detected by the monitor

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 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 3.2 - 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

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)

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).

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).

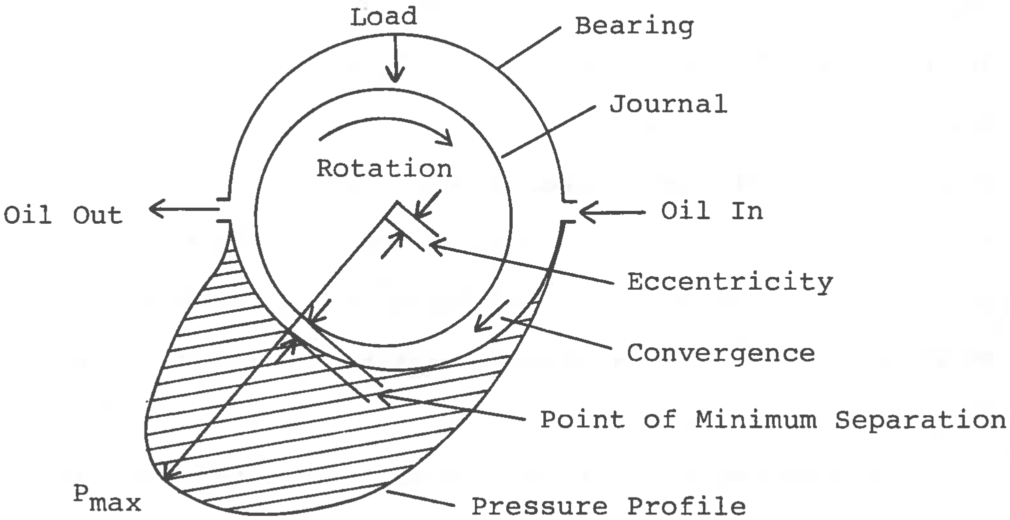


FIGURE 3.1 - HYDRODYNAMIC LUBRICATION OF CRANKSHAFT JOURNAL BEARING

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 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

f bearing temperature. That is, the warning period prior to catastrophic
ailure might be short (on the order of a few minutes) and hence allow time
or engine shutdown only.

rankshaft Vibration

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

ummary

Based on the discussion of the various bearing diagnostic parameters
iven above, it is concluded that the most effective (and cost-effective)
pproach involves a good oil spectrometric analysis program and continuous
onitoring of main bearing operating temperature. The former is potentially
apable of spotting incipient failure of bearings (as well as other components),
hile the latter is a method of avoiding severe crankshaft damage resulting
rom bearing failures that occur on a time scale that is shorter than the spectro-
etric analysis cycle time (sampling, submission of sample to lab, analysis, and
ata feedback to the ship). Main bearing hydrodynamic oil pressure is a para-
eter that, in theory, could yield important information as to bearing condition,
ut the measurement and monitoring of this parameter would require costly

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 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.

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

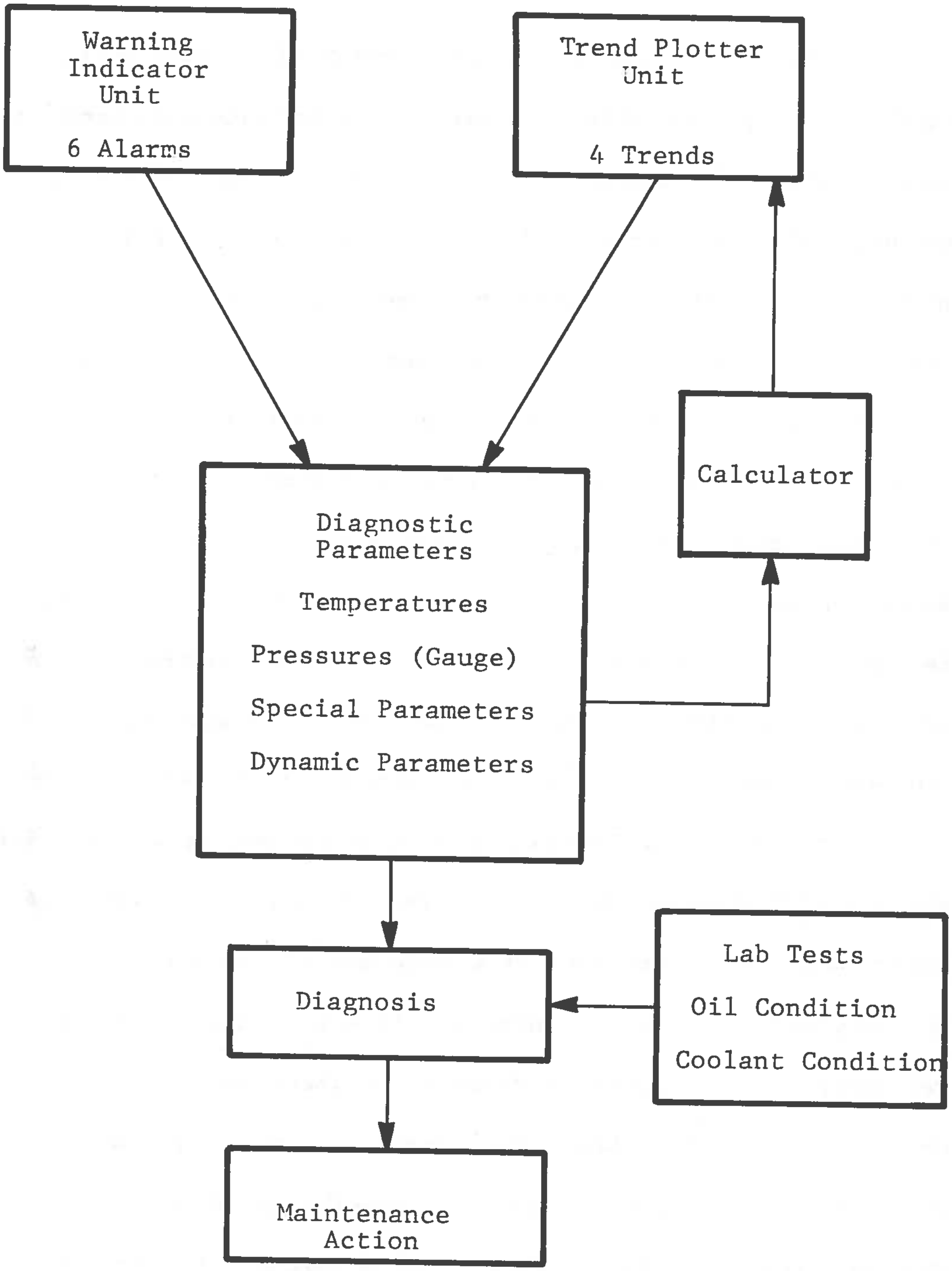
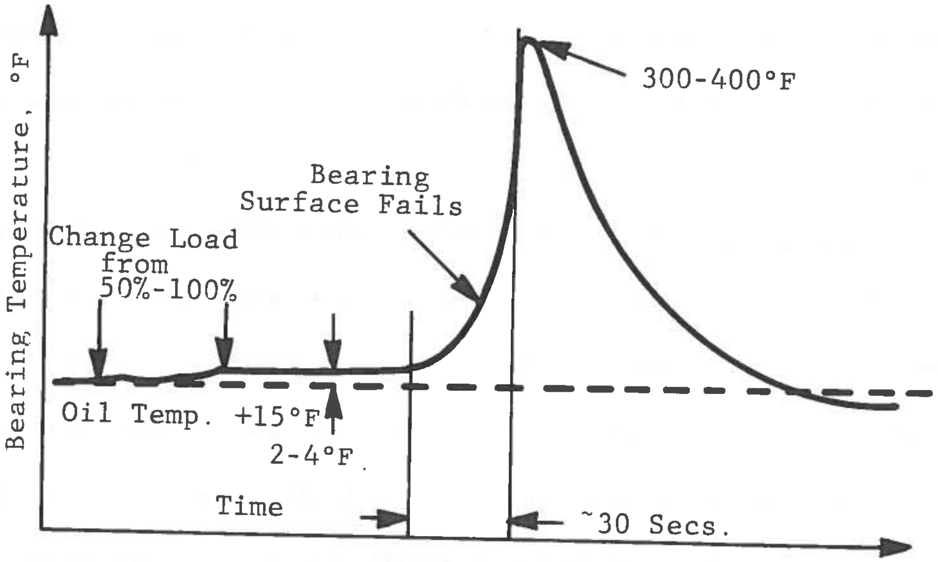
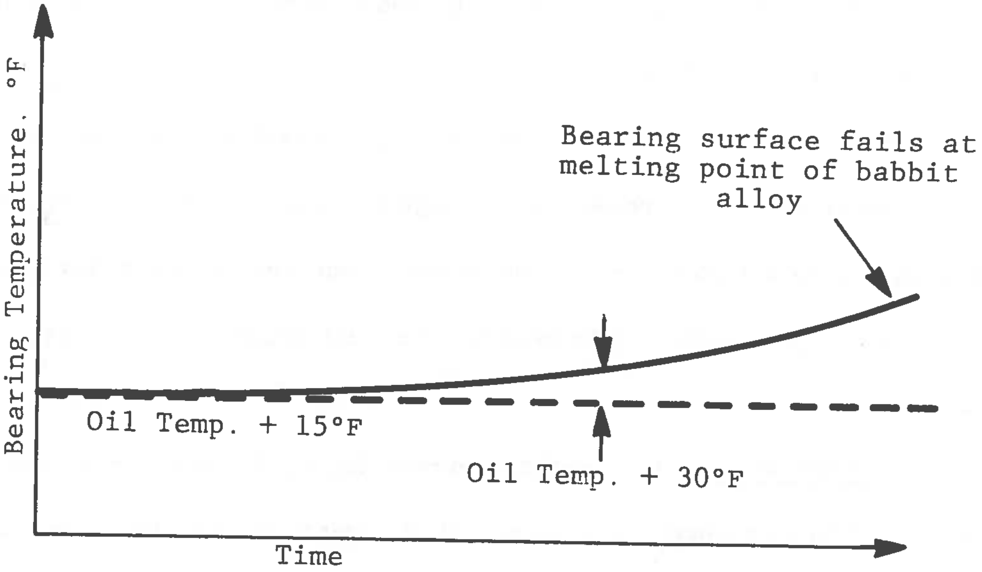


FIGURE 3.2 - FAULT DETECTION AND ISOLATION PROCESS



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

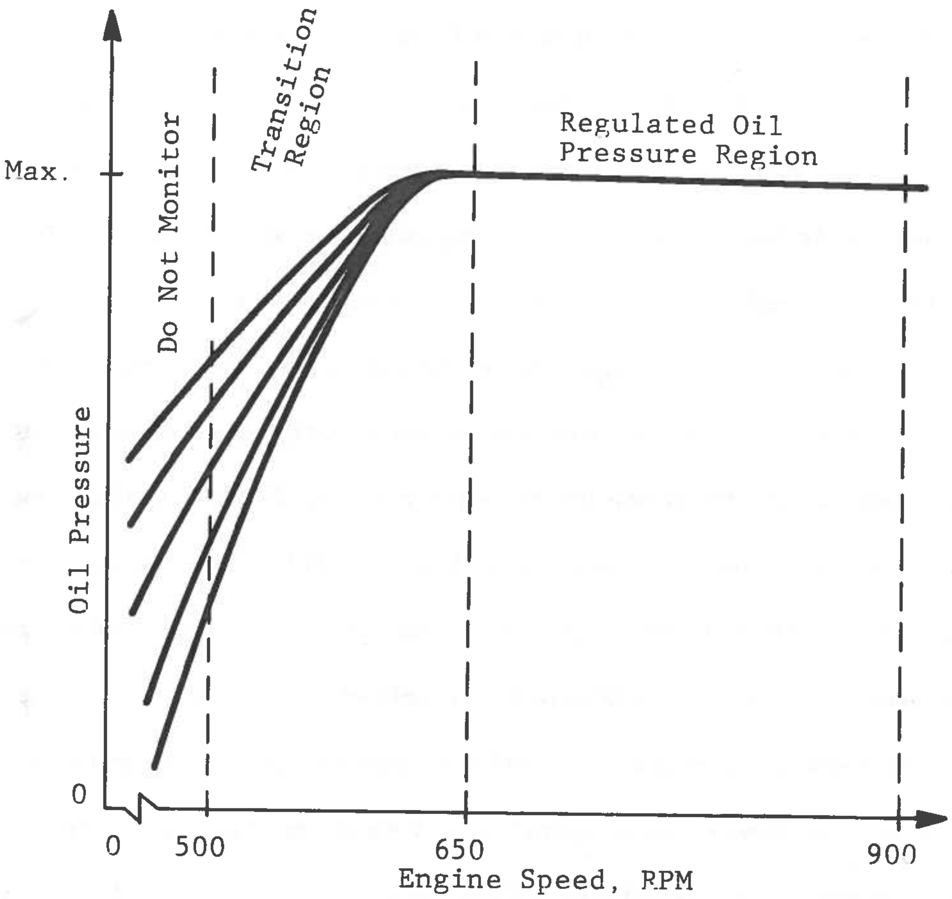


FIGURE 3.4 - OIL PRESSURE AS A FUNCTION OF ENGINE SPEED AND VARIOUS OIL TEMPERATURES

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 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.

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 $=(M_{\text{coolant}})(Cp)(\Delta t)$, 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.

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. 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

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.

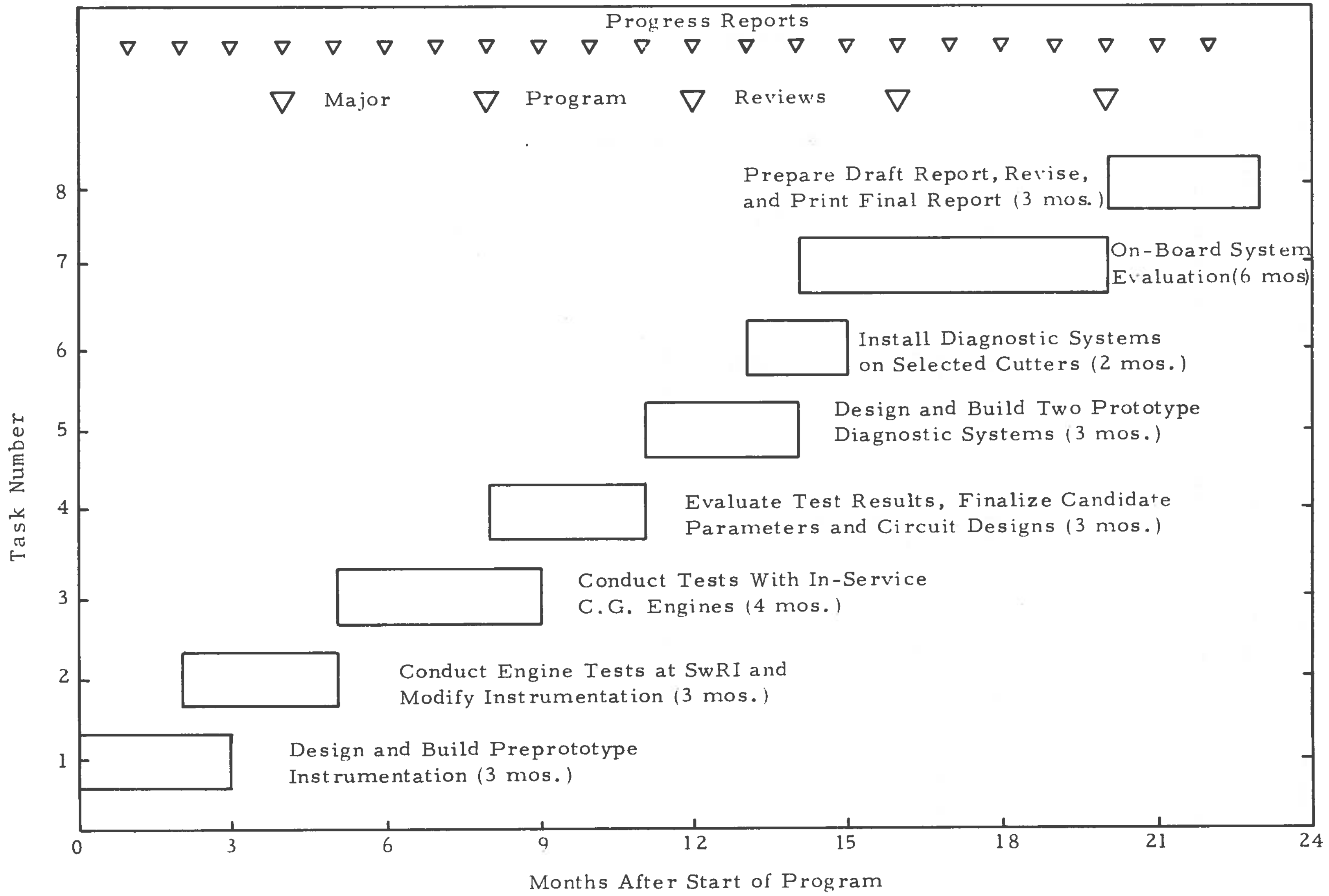


FIGURE 5.1 - TASK SCHEDULING OF PROPOSED PROGRAM

APPENDIX A

Discussion Of Types Of Diagnostic Monitor Systems

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.

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:

APPENDIX B

Existing Data Logging On WMEC 210A And 210B Cutters

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)

$$Q = W + \Delta U$$

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.

APPENDIX D

New Technology