NATIONAL BUREAU OF STANDARDS

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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Detection, Diagnosis, and Prognosis

MFPG

26th Meeting

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MFPG
Detection, Diagnosis and Prognosis

Proceedings of the 26th Meeting of the Mechanical Failures Prevention Group, held at the IIT Research Institute, Chicago, Illinois, May 17-19, 1977

Edited by

T. Robert Shives and William A. Willard

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FOREWORD

The 26th meeting of the Mechanical Failures Prevention Group was held May 17-19, 1977, at the IIT Research Institute in Chicago, Illinois. The program was organized by the MFPG committee on Detection, Diagnosis, and Prognosis under the chairmanship of Henry R. Hegner of GARD, Inc. The committee, the session chairmen, and especially the speakers are to be commended for the excellent program.

Most of the papers in these Proceedings are presented as submitted by the authors on camera ready copy with some minor editorial changes.

Special appreciation is extended to, Mr. H. G. Tobin Assistant Director, Electronics Division, IIT Research Institute for inviting the MFPG to use the very fine facilities of the Research Institute for this conference, Mr. Edward P. Fahy, Materials Manager at IITRI and members of his staff for the meeting arrangements, and to Robert M. Whittier of Endevco for meeting publicity.

Appreciation is also extended to the following members of the NBS Metallurgy Division: T. Robert Shives and William A. Willard for their editing, organization, and preparation of the Proceedings, Paul M. Fleming for handling financial matters, Todd Eudy for photographic work, Larry W. Ketron for drafting work, and to Marian L. Slusser for typing.

HARRY C. BURNETT
Executive Secretary, MFPG

Metallurgy Division
National Bureau of Standards

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The following registrants gave presentations at the symposium, but did not submit a manuscript for publication:

John Dunmore, "Updating Signature Analysis Techniques," Session II.

Jerry Allen, "Bearing Vibration Crest Detection," Session III.

Raymond Ehrenbeck, "Overview of Department of Transportation Sponsored Diagnostic System Development," Session IV.

David R. Sutliff* and Nicholas J. Darien, "Development of Data Collection System for Railroad Testing," Session IV.

J. E. Johnson* and Lloyd H. Emery, "Nondestructive Testing of On-Vehicle Tires Using Random Mechanical Excitation," Session V

* Indicates speaker when a paper had more than one author.

ABSTRACT

These proceedings consist of a group of twenty four submitted papers from the 26th meeting of the Mechanical Failures Prevention Group which was held at the IIT Research Institute in Chicago, Illinois on May 17-19, 1977. The central theme of the proceedings is detection, diagnosis and prognosis as related to mechanical failure. Papers are presented that discuss oil analysis, signature analysis techniques, new detection, diagnosis and prognosis techniques and equipment, railroad system diagnostics, and land vehicle diagnostics.

Key words: Failure detection, failure diagnosis; failure prevention; ferrography; land vehicle diagnostics; oil analysis; railroad system diagnostics; signature analysis; wear

UNITS AND SYMBOLS

Customary United States units and symbols appear in many of the papers in these proceedings. The participants in the 26th meeting of the Mechanical Failures Prevention Group have used the established units and symbols commonly employed in their professional fields. However, as an aid to the reader in increasing familiarity with and usage of the metric system of units (SI), the following references are given:

NBS Special Publication, SP330, 1974 Edition, "The International System of Units."
ISO International Standard 1000 (1973 Edition), "SI Units and Recommendations for Use of Their Multiples."
E380-76 ASTM/IEEE Standard Metric Practice (Institute of Electrical and Electronics Engineers, Inc. Standard 268-1976).

SESSION I

OIL

ANALYSIS

REVISITED

CHAIRMAN: J . M . PEREZ

CATERPILLAR TRACTOR COMPANY

STATISTICAL ANALYSIS OF WEAR METAL CONCENTRATION MEASUREMENTS IN OIL; CALCULATION OF SIGNIFICANT WEAR METAL PRODUCTION RATES

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The service life of aircraft engines and various other types of lubricated equipment in the Air Force is currently being monitored in the USAF Spectrometric Oil Analysis Program (SOAP) in which concentrations of wear metal in lubricating oil in the parts per million range are determined spectrometrically. These measurements generally ignore the effects of oil consumption and subsequent make-up and pay only qualitative heed to the rate of increase of wear metal concentrations. SOAP laboratories are provided with Wearmetal Tables to aid them in evaluating the significance of the wear metal concentrations. The Tables, particularized for each item of monitored equipment, recommend maintenance actions depending upon the wear metal concentrations of significant elements. It is not intended that the laboratory analyst use the Tables on an absolute go-no go basis. Recommendations are to be tempered in the light of the past SOAP and maintenance history of the equipment and its operating conditions, augmented by a healthy measure of the analysts SOAP experience and judgment in ascertaining the trend of the data. When this becomes difficult, it is suggested that a simple plot of wear metal concentration values against equipment operating time be prepared as an aid. For equipment such as the TF41-1 engine, which powers the A-7D aircraft, the lubricant capacity is small (ca. 3 gal) and the oil consumption rates are not infrequently as large as one quart per hour, with post-flight oil additions ranging up to 25% of the total oil volume. Under these circumstances the effect of oil consumption on measured wear metal concentrations is appreciable and must be considered in a proper evaluation of the data. This report discusses methods that have been proposed to simultaneously account for the effect of oil consumption and engine operating time in a quantitative manner. Attention has been focused on the TF41-1 engine because of its particular sensitivity to oil consumption effects. The techniques described and developed here are, of course, generally applicable to other engines and lubricated equipment.

The SOAP Wearmetal Table for the TF41-1 engine, shown in Figure 1, is typical of those for engines. Three different sets of guideline concentration values are given for the three types of instruments available at SOAP laboratories, Baird-Atomic A/E35U-1 and A/E35U-3 emission spectrometers and the Perkin-Elmer 303/305 atomic absorption spectrometer. Recommended action codes are listed to the left of the Tables and explained below them. For this engine, especial caution is urged in using the Table alone as a basis for evaluating the significance of wear metal data. Trend analysis in the form of a plot of analytical results against operating time is strongly recommended. Accordingly, typical SOAP records for iron in the oil from three TF41 engines are graphed in Figure 2. All are highly erratic in character and any trends deduced from them are subject to doubt. In a broad qualitative sense, one might assert that iron is increasing rapidly for Engine A, less rapidly for Engine B, and is substantially constant for Engine C. However, one must have misgivings about the repeated increases and decreases in metal content, particularly marked in Engine A. The immediate explanation that suggests itself for this behavior is the low precision of the measurements. Upon examination of this possibility, however, one learns that the instruments are required to have a repeatability (standard deviation) of 1ppm in this range of iron concentration and that they are checked frequently for conformance to this specification. Proceeding upon the premise that the data are within the required precision limits, the effect of oil consumption becomes the next likely candidate as the primary cause of the anomalous concentration variation.

Figure 3 illustrates the effect of oil consumption on the measured wear metal concentrations of an engine similar in characteristics to the TF41-1. Assuming the oil is absolutely clean initially and is sampled (and topped) at equal time intervals, the concentration will build up smoothly to an asymptotic limit of 7ppm for the given conditions. In contrast, if the engine were not consuming oil, the wear metal concentration would increase in linear fashion until the engine failed or the oil was changed. Thus after 100 hours of operating time, for example, the measured concentration would be 7ppm while the concentration indicative of the actual engine wear would be 35ppm, well above the guideline for removal. Of course, in a real case the sampling intervals are not equal and the measurements are only reproducible to ±1ppm; thus the concentration values would tend to fluctuate about their asymptotic limit much in the manner of that shown for Engine C in Figure 2, in which a limiting concentration appears to have been attained.

Since measured wear metal concentrations and their simple variance with time have serious deficiencies for use as engine serviceability criteria, particularly in the case of oil-consuming engines, the use of wear metal production rates (WMPR) has been proposed for this purpose. These may be calculated by the various approximate and one differential (and presumably more exact) relationship given in Figure 4, the latter described by Lotan (Ref. 1). All are derived from a simple material balance. The three approximate equations differ in their assumptions regarding the wear metal concentration in lost oil while Lotan's relationship assumes a constant rate of oil loss at a variable concentration and a constant wear metal production rate. The various formulas are applied to SOAP data for a TF41-1 engine in Figure 5. Results are calculated following the customary noted practice. As might have been expected, the approximation using the average value of the concentration yields the same result as the differential relationship while the assumption that the oil loss occurs at the final or the initial concentration gives a WMPR that is high or low respectively. In the interests of the simplest arithmetic, Approximation 2 was used for all further wear metal production rate calculations.

In certain situations, it may be of interest to calculate the wear metal production rate where the oil system is topped off several times between analyses. A method for accomplishing this is outlined in Figure 6. The relationship shown here is similar to the one found in Reference 1, though its derivation is different and much less elaborate than the latter. Though Air Force practice, sampling after each flight, virtually eliminates the use of this equation for its intended purpose, it has some utility in calculating average rates from a total elapsed time, a total oil volume added, a given number of fillings, and the initial and final analyses.

Concentration-time data and derived wear metal production rates are depicted in Figure 7 for a fairly typical SOAP iron record on a TF41 engine. The average oil consumption over the time period covered in the plot was approximately 0.25 quarts/hr (moderate and representative of the engines for which oil consumption data was available). The wear metal production rate graph proves to be both disappointing and disturbing. At best it mirrors the trend of the concentration curve in greatly magnified fashion, with some minor deviations due to the effect of oil addition (notably in the range from 23-29 hours where the concentration is constant). Its worst aspects are the numerous negative values of the WMPR and its highly erratic nature, varying widely from point-to-point. The physical interpretation of the negative WMPR values is that the engine is cleaning itself, an obvious impossibility. Hence they must be ascribed to the slight (and expected) variability in the concentration measurements. Since the concentration appears to be sensibly constant, one is led to determine the average concentration and the standard deviation of the measurements. The results indicate that the concentration is probably constant over the entire operating time and that the precision of the measurements is comfortably within the specified limit of 1ppm. Reasoning that since the concentration is constant, the WMPR might well be also, the same procedure is applied to these values with dismaying results. The precision of the calculated WMPR's is twice the mean value. The relative difference in the precision of the concentration measurements as compared with the wear metal production rates calculated from them is strikingly demonstrated in Figure 8, where the 95% confidence limits on both values are plotted to the same scale. These results are not unique to this engine but representative of others analyzed. The variability of the WMPR's is approximately an order of magnitude greater than the variability of the concentration measurements, if one assumes that we are obtaining a very imprecise estimate of a constant value.

As already indicated, the expression developed for calculation of the wear metal production rates for the case of n fillings between two analyses (Figure 6) may be utilized to derive an average WMPR. For this engine (SN 1670), it is found to be 2.45 for the recorded operating time and conditions. An estimate of this sort is somewhat reassuring in that it masks negative values and point-to-point variation in the averaging process. However, its precision (theoretically of the same order as the concentration measurements) cannot be deduced from a single set of data and its accuracy is indeterminate, since the calculated WMPR (r) is so highly dependent upon the final analysis (C_{B_n}). For a sufficiently large set of data points, the uncertainty of the estimate can be reduced by forming subsets of adequate size and number and obtaining the distribution of the rates calculated for each subset. In general, such a procedure is not very feasible, since an engine may well reach a critical condition before enough measurements are accumulated for a reliable analysis of the data.

An alternative procedure for extracting wear metal production rates from concentration measurements as a function of operating time is to perform a linear regression analysis upon the data on the assumption that the WMPR is reasonably constant. This method will yield a trivial and incorrect result (r=0) when the concentration is ostensibly constant (as in Figure 7). In most instances, however, the concentration measurements exhibit an increasing trend with time. A representative example of such behavior is shown in Figure 9. The rather wide fluctuations in concentration displayed by these data are undoubtedly due in part to the effects of oil consumption, which were not reported for this engine. Linear regression analysis produces a rather satisfactory correlation of the data as measured by the correlation coefficient of 0.941 as compared with unity for an exact fit. The wear metal production rate is deduced from the slope of the straight correlation line with the indicated standard deviation. By contrast, the graph of the WMPR follows its usual erratic course, magnifying the fluctuations in the concentration. It exhibits no discernible trend, is nowhere alarmingly large and even tends to decrease as the concentration climbs to a value high enough to signal maintenance action. Furthermore the average of the graphed WMPR values (2.45) is only 70% of that found from the linear correlation and its standard deviation is thirty times as large.

It is interesting to compare the relative trends in concentration and WMPR for an engine removed for teardown upon the basis of a SOAP laboratory recommendation. Such data are shown in Figure 10 for an engine used in Reference 2 to illustrate the utility of the WMPR concept. The concentration trends upward (with considerable fluctuation) rising from 6 to 12ppm in the interval between 5 and 38 hours of operation. In the next hour of operation it rises abruptly to 16ppm. The WMPR graph exhibits a magnified fluctuation but no discernible trend over the same time interval. In the last hour of operation, the WMPR jumps from 6 to 50 mg/hr. It is contended that this is a much clearer indication of engine deterioration than the jump in concentration, even though the prior WMPR history gave no indication whatsoever of abnormal wear. Before discussing this further, it is well to note that the entire range of WMPR values prior to the last hour of operation falls well within the 95% confidence belt (ca. -10 to 15 mg/hr), a fact that raises considerable doubt regarding their interpretation.

In order to assess the significance of a large increase in WMPR, it is necessary to obtain an estimate of the possible errors in the calculation. This problem is addressed in Figure 11, which outlines the procedure to be followed in estimating errors and tabulates their maximum possible values as a function of concentration. For the engine under consideration (SN 1175, Figure 10, operating interval of one hour, concentration of 15ppm), the maximum error at the 95% confidence limit can be as large as 39 mg/hr. Thus there is at least a 5% probability of calculating a WMPR of approximately 44 mg/hr on a random error basis and the significance of the value of 50 mg/hr actually obtained is open to question. Consideration of the large inherent error possible in calculated WMPR's and their inevitable erratic nature leads to the conclusion that they are not suitable indexes of engine wear and should not be used as a criteria for maintenance action.

One must next confront the problem of evaluating the significance of a large increase in concentration. A method for accomplishing this purpose is illustrated in Figure 12 for the data on Engine SN 1175 used in Figure 10. Assuming a constant WMPR, linear regression analysis yields the best least squares fit line to the concentration measurements. The correlation coefficient, R=0.92, indicates that the assumption is reasonable. Superposition of the 95% confidence limit belt on the linear regression line demonstrates that the final concentration measurement of 16ppm lies well outside these limits. Calculation of the probable deviation of a measurement from the least squares fit line indicates that there is less than a 1% chance of obtaining such a value as a result of random error. It is now justifiable to conclude that the engine has indeed begun to wear abnormally and to call for appropriate maintenance action.

Though the technique just described provides a satisfactory assessment of the concentration measurements and statistically valid wear metal production rates, it does not account for the effect of oil consumption. Certainly the wear metal production rate of 1.89 found for Engine SN 1175 (Figure 12) must be too low. To compensate for the oil consumption and dilution effects a corrected concentration may be calculated from the expression given in Figure 13. The corrected concentration is, of course, that fictitious value that would be measured if all the wear metal stayed in the system and only the oil were consumed.

The concentration measurements for Engine SN 1175, compensated for oil consumption in accordance with this procedure are depicted in Figure 14 together with their fitted linear regression line and superimposed 95% confidence belt. Comparison with Figure 12 indicates that the fit of the data has been noticeably improved (correlation coefficient increases from 0.92 to 0.96) and the wear metal production rate is approximately doubled and of higher relative precision. The most important conclusion to be drawn from this exercise is that oil addition data is necessary for a valid and meaningful assessment of engine wear from concentration measurements on oil-consuming engines.

To drive home further the importance of oil addition data, corrected and measured concentrations are presented in Figure 15 for Engine SN 1670 (previously discussed in Figures 7 and 8). The oil consumption effect is magnified in this instance by the condition that the contaminant level appears to have reached its limiting concentration. Correlation coefficients and derived WMPR's are given for the two sets of data, though the linear regression lines themselves are omitted for the sake of reduced clutter. As has been already stated, the virtually constant concentration results in a trivial and incorrect WMPR of approximately zero and a corresponding low correlation coefficient. Compensation for oil consumption dramatically increases the correlation coefficient and produces a plausible wear metal production rate.

In summary it may be stated that:

1. Linear regression analysis of wear metal concentration measurements offer a great improvement over current qualitative trending methods in evaluating engine service life.

2. Oil addition data is indispensable for the interpretation of concentration measurements from oil-consuming engines.

3. Proposed point-to-point calculation of wear metal production rates will not serve as a suitable index of engine wear due to their inherent low precision.

4. The techniques proposed here seem to account satisfactorily for the effect of oil consumption and engine operating time on wear metal concentration measurements.

References:

(1). Lotan, D., SNECMA Document MFTM No. 10564, "An Investigation into the Rate of Contamination of the Oil Circuit of a Turbojet Engine"

(2). Cuellar, J.P., Jr. and Staph, H.E., Southwest Research Institute Report No. RS-630, July 1975. "Task Report, Task 3 - Wear Metal Production Rate Compensation".

A/E35U-1

	Fe	Ag	Al	Cr	Cu	Mg
A	0-13	0-1	0-2	0-1	0-7	0-2
K	14-19	2-3	3-4	2-3	7-9	3-4
T	20+	4+	5+	4+	10+	5+

A/E35U-3

	Fe	Ag	Al	Cr	Cu	Mg
A	0-21	0-3	0-3	0-4	0-10	0-4
K	22-29	4	4	N/A	11-14	5-6
T	30+	5+	5+	5+	15+	7+

Atomic Absorption

	Fe	Ag	Al	Cr	Cu	Mg
A	0-10	0-2	0-2	0-2	0-5	0-2
K	11-14	N/A	N/A	N/A	6-7	3
T	15+	3+	3+	3+	8+	4+

Codes

A – Continue routine sampling.

K – Submit redtagged sample as soon as possible. Suspect possible discrepancy due to increasing wearmetal trends, recommend maintenance inspection. If aircraft has flown since last sample, ground unit until results of this sample are known.

T – Ground unit, examine for suspected discrepancy. Advise laboratory of findings.

Figure 1

TYPICAL SOAP RECORDS FOR IRON IN OIL FOR TF-41 ENGINES

(HIGH OIL CONSUMPTION, SMALL TANK CAPACITY)

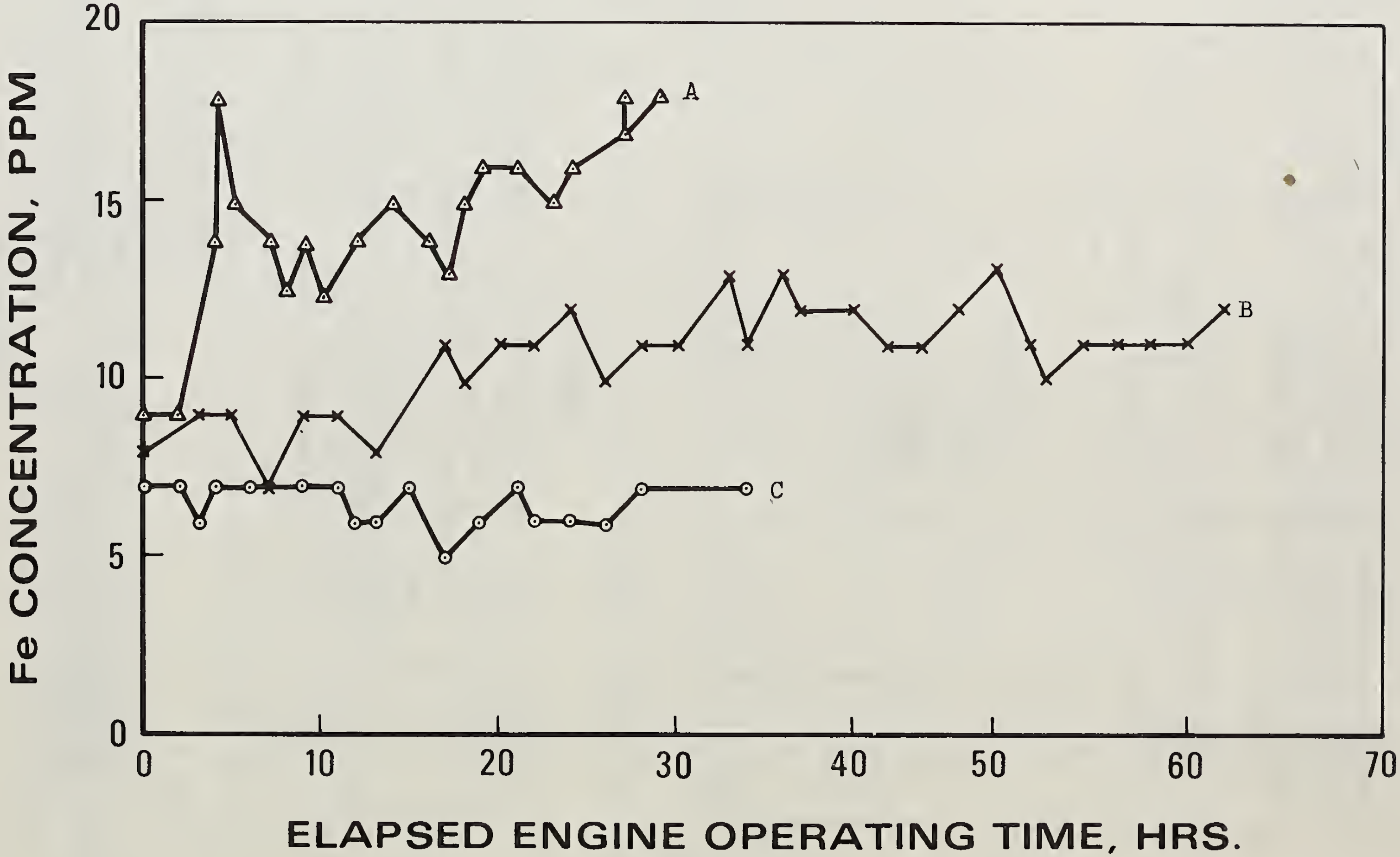


Figure 2

EFFECT OF OIL CONSUMPTION (AND ADDITION) ON MEASURED WEAR METAL CONCENTRATIONS

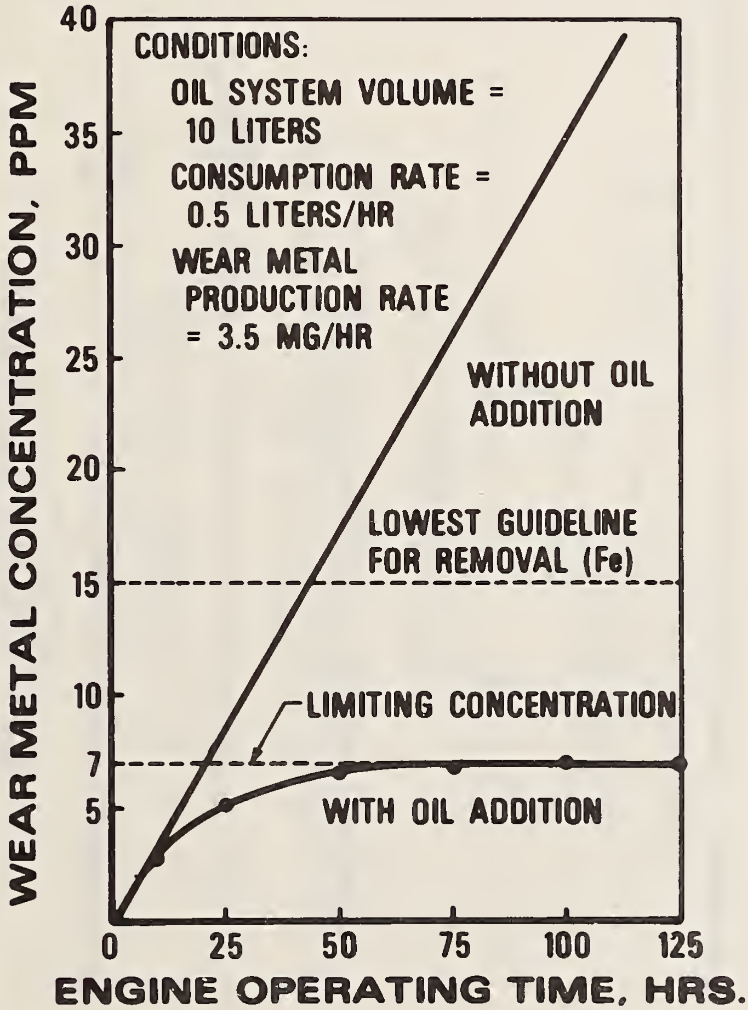


Figure 3

VARIOUS RELATIONSHIPS FOR WEAR METAL PRODUCTION RATE (r OR WMPR) CALCULATIONS

- APPROXIMATE, ASSUMING OIL LOSS OCCURS AT CONCENTRATION, C_A AFTER FILL-UP

CONDITIONS: $t = t_A$, $C = C_A$, OIL TOPPING VOLUME $= \Delta V_A$ V = SYSTEM VOLUME

$t = t_B$, $C = C_B$, OIL TOPPING VOLUME $= \Delta V_B$

THEN

$$C_A' = \left(1 - \frac{\Delta V_A}{V}\right) C_A$$

AND

$$V C_A' + r\Delta T = (V - \Delta V_B) C_B + \Delta V_B C_A' \qquad \Delta T = t_B - t_A$$

(1)

$$\text{WMPR} = r = \left(\frac{V - \Delta V_B}{\Delta T}\right)\left[C_B - C_A\left(1 - \frac{\Delta V_A}{V}\right)\right]$$

- APPROXIMATE, ASSUMING OIL LOSS OCCURS AT CONCENTRATION, C_B

(2)

$$r = \frac{V}{\Delta T}\left[C_B - C_A\left(1 - \frac{\Delta V_A}{V}\right)\right]$$

- APPROXIMATE, USING AVERAGE VALUE OF CONCENTRATION, $\dfrac{C_B + C_A'}{2}$

(3)

$$r = \left(V - \frac{\Delta V_B}{2}\right)\left[C_B - C_A\left(1 - \frac{\Delta V_A}{V}\right)\right]$$

- DIFFERENTIAL, ASSUMING A CONSTANT RATE OF OIL LOSS, $q = \dfrac{\Delta V_B}{\Delta T}$

$$r\,dT = (V_0 - qt)\,dc$$

AND

(4)

$$r = \frac{\dfrac{\Delta V_B}{\Delta T}\left[C_B - C_A\left(1 - \dfrac{\Delta V_A}{V}\right)\right]}{\text{Ln}\,\dfrac{V}{V - \Delta V_B}}$$

Figure 4

VARIOUS RELATIONSHIPS FOR WEAR METAL PRODUCTION RATE CALCULATIONS (CONT)

APPLYING ALL OF THE ABOVE TO THE FOLLOWING SOAP DATA:

$t_A = 33 \quad C_{Fe} = C_A = 13 \quad \Delta V_A = 0.8\text{qts.} \quad V \approx 11\text{qts.}$

$t_B = 35 \quad C_{Fe} = C_B = 13 \quad \Delta V = 2.5\text{qts.}$ (FOR TF-41 ENGINE)

NEGLECTING DIFFERENCE BETWEEN LITERS AND QUARTS AND TAKING PARTS PER MILLION (PPM) AS MG/LITER

FOR

$$(1) \quad r = \left(\frac{11-2.5}{2}\right)\left(13-\left(1-\frac{0.8}{11}\right)13\right) = 4.0$$

$$(2) \quad r = \frac{11}{2}\left(\qquad \right) = 5.2$$

$$(3) \quad r = \left(11-\frac{2.5}{2}\right)\cdot\frac{1}{2}\left(\qquad \right) = 4.6$$

$$(4) \quad r = \frac{2.5}{2}\cdot\frac{1\cdot}{\text{Ln}\frac{11}{11-2.5}}\left(\qquad \right) = 4.6$$

Figure 5

FOR THE SITUATION OF n FILLINGS BETWEEN 2 ANALYSES AND THE FOLLOWING RATHER RESTRICTED ASSUMPTIONS:

$$\Delta V_A = \Delta V_B = \Delta V_n = \frac{V_A}{n}, \quad V_A = \text{ TOTAL VOLUME OF OIL ADDED}$$

$$\Delta T_1 = \Delta T_2 = \Delta T_n = \frac{T}{n}, \quad T = \text{ TOTAL ELASPED TIME BETWEEN ANALYSES}$$

THEN FOR APPROXIMATION (2)

$$(V - \Delta V_n) C_{B_n} + \sum_1^n \Delta V_i C_{B_i} = \sum_1^n r_i \Delta T_i + V C_A'$$

ASSUMING CONSTANT r

$$\sum_1^n r_i \Delta T_i = rT = (V - \Delta V) C_{B_n} - V C_A \left(1 - \frac{\Delta V}{V}\right) + \Delta V \sum_1^n C_{B_i}$$

$$C_B = \left(1 - \frac{\Delta V}{V}\right) C_A + \frac{r \Delta T}{V - \Delta V} = K_1 C_A + K_2$$

IF $\Delta V << V$, THEN $K_1 \approx 1$

AND $C_{B_i} = C_A + iK$

$$\sum_1^n C_{B_i} = n C_A + \frac{n(n+1)}{2} K$$

AND $rT = V\left[C_{B_n} - C_A + \frac{V_A}{nV}\left(\frac{n+1}{2}\right)(C_A + C_{B_n}) - \frac{V_A}{nV} C_{B_n}\right]$

OR $r = \frac{V}{T}\left\{C_{B_n}\left[1 + \frac{V_A}{2V}\left(\frac{n-1}{n}\right)\right] - C_A\left[1 - \frac{V_A}{2V}\left(\frac{n+1}{n}\right)\right]\right\}$

Figure 6

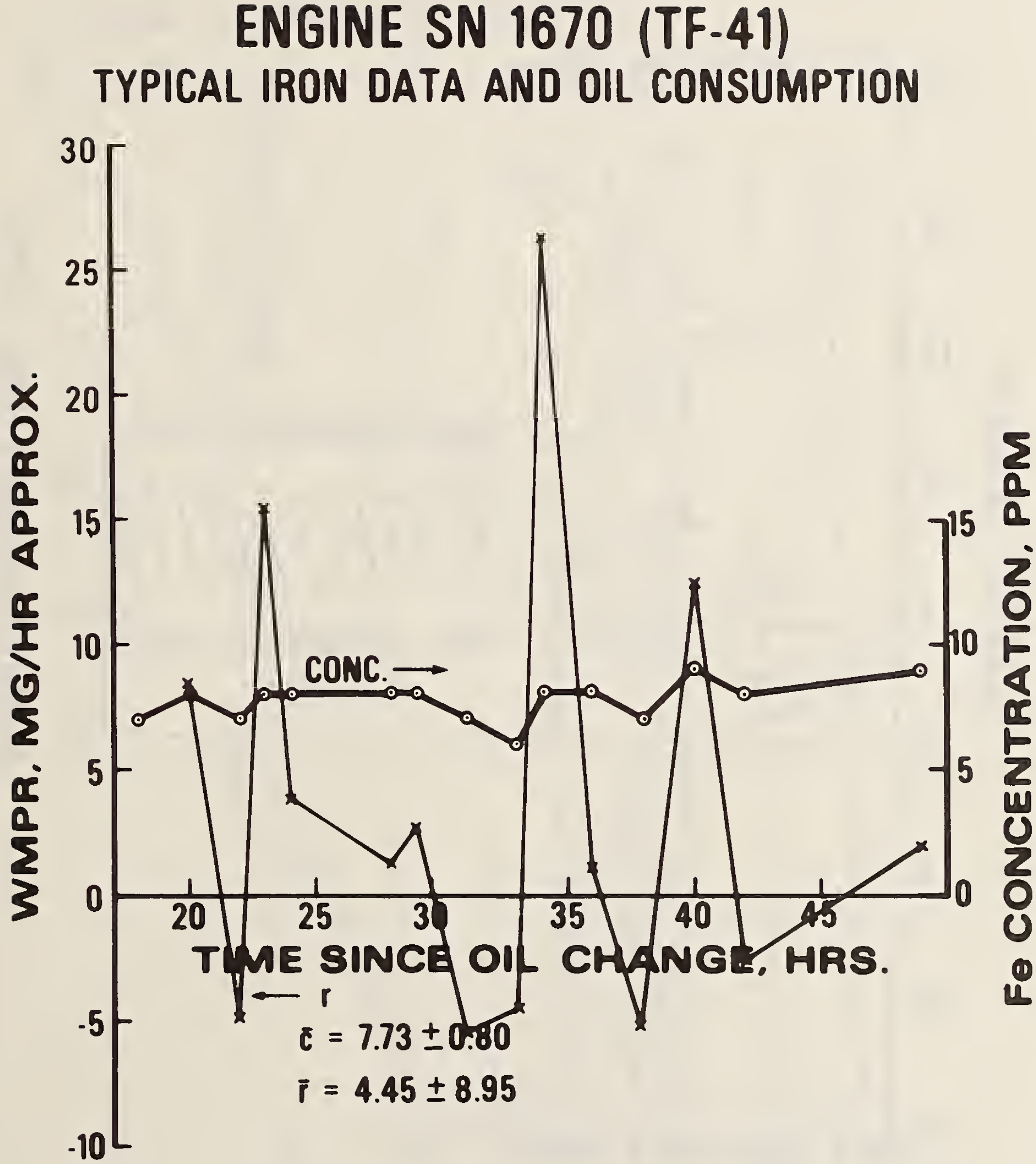

ENGINE SN 1670 (TF-41)
TYPICAL IRON DATA AND OIL CONSUMPTION
WMPR, MG/HR APPROX.
Fe CONCENTRATION, PPM
TIME SINCE OIL CHANGE, HRS.
CONC.
r
$\bar{c}$ = 7.73 ± 0.80
$\bar{r}$ = 4.45 ± 8.95
30
25
20
15
10
5
0
-5
-10
20
25
30
35
40
45

Figure 7

ENGINE SN 1670

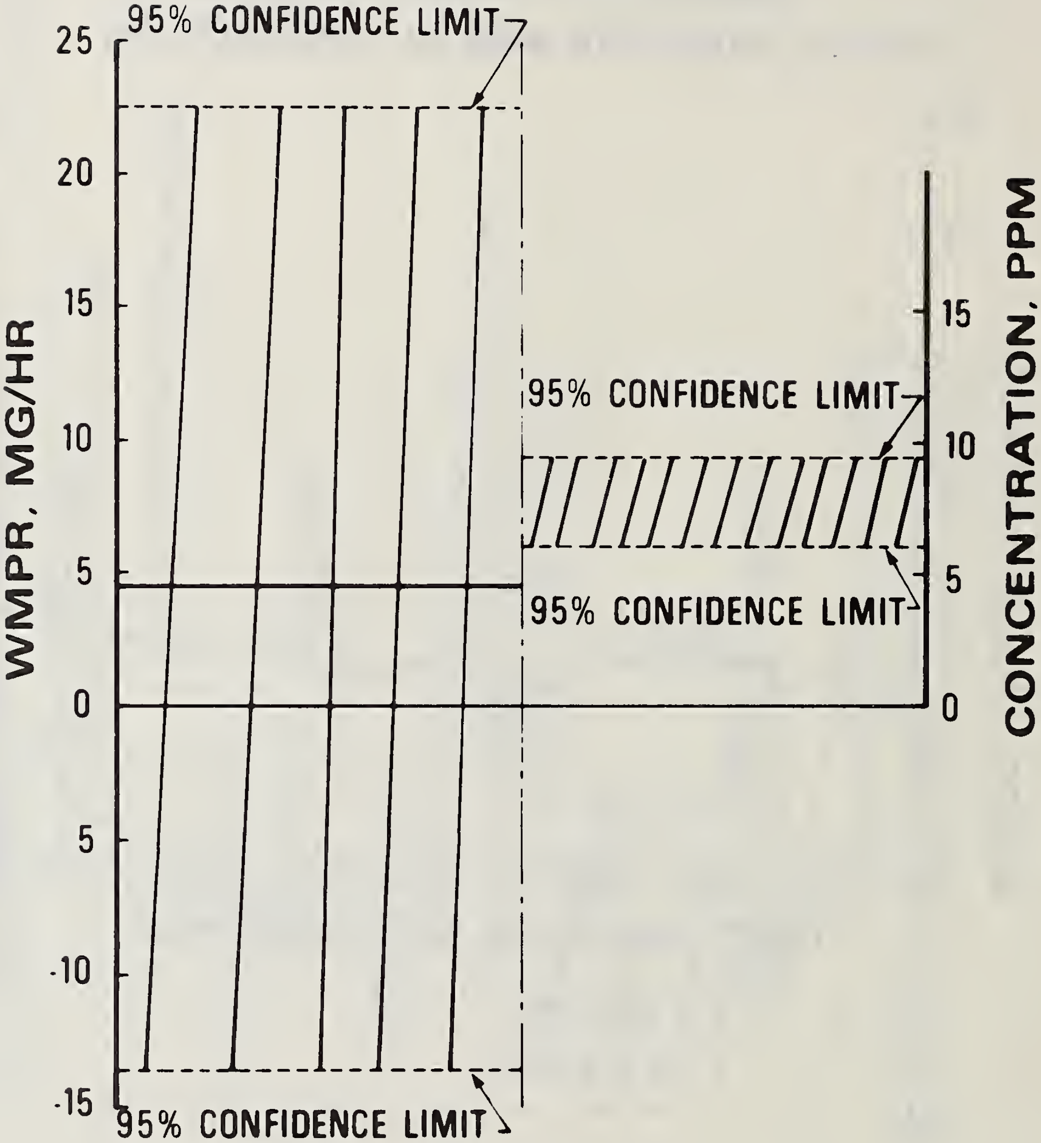


Figure 8

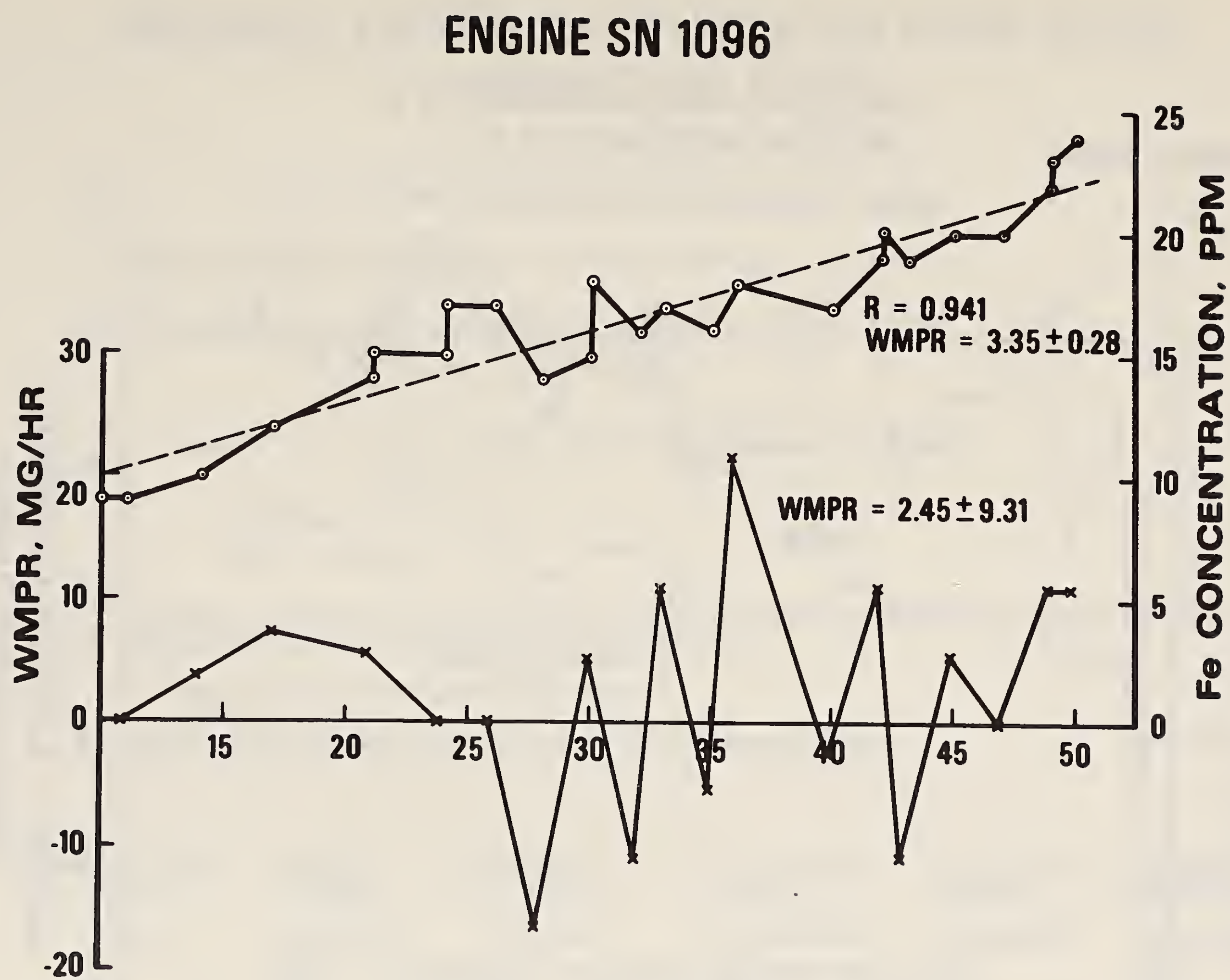
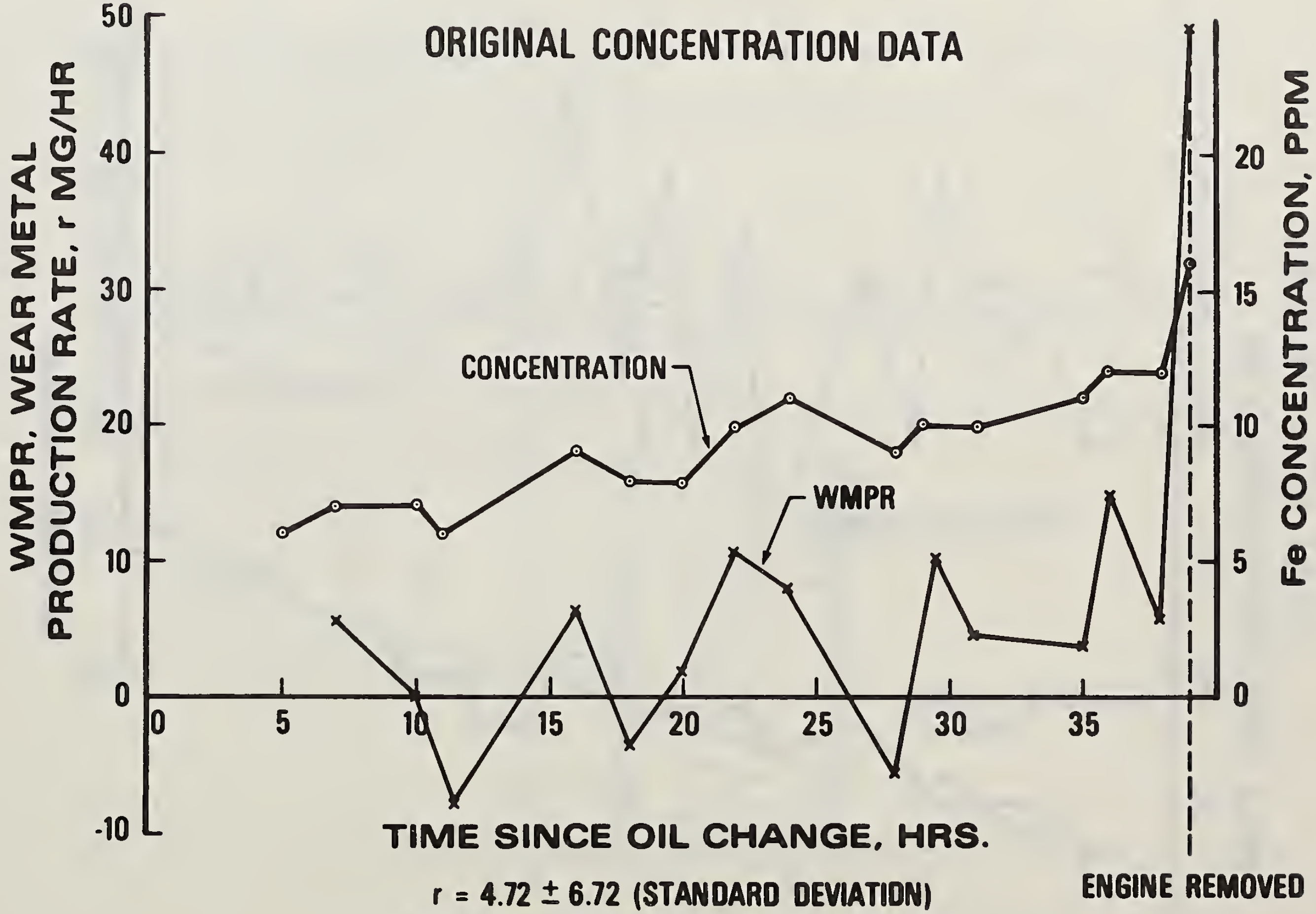

ENGINE SN 1096
R = 0.941
WMPR = 3.35±0.28
WMPR = 2.45±9.31
WMPR, MG/HR
Fe CONCENTRATION, PPM
30
20
10
0
-10
-20
25
20
15
10
5
0
15
20
25
30
35
40
45
50

Figure 9

ENGINE SN 1175



r = 4.72 ± 6.72 (STANDARD DEVIATION)
AT 95% CONFIDENCE LEVEL r = 4.72 ± 14.31

Figure 10

PROBABLE ERRORS IN CALCULATED WEAR METAL PRODUCTION RATES

$$r \approx \frac{V}{\Delta T}(C_B - C_A') = a(C_B - C_A')$$

IF P_R = ERROR IN r FOR GIVEN ERRORS IN C_B AND C_A'

THEN

$$P_R = \left[\left(P_{C_B}\frac{\partial r}{\partial C_B}\right)^2 + \left(P_{C_A'}\frac{\partial r}{\partial C_A'}\right)^2\right]^{\frac{1}{2}}$$

WHERE $P_{C_B} = P_{C_A'} =$ ERROR IN CONCENTRATION MEASUREMENT

HENCE

$$P_R = a\sqrt{2}\,P_{C_B}$$

MAXIMUM ERROR OCCURS WHEN $\Delta T = 1$, SINCE RECORDS INDICATE THAT SAMPLES ARE NEVER TAKEN AT LESS THAN 1 HOUR INTERVALS.

SINCE $V \approx 11$, MAXIMUM VALUE OF $a \approx 11$

USING SPECIFIED ACCURACY DATA FOR IRON DETERMINATIONS

CONCENTRATION IRON	ACCURACY INDEX	REPEATABILITY INDEX	MAX. STANDARD DEV. IN r	MAX. ERROR @ 95% C.L.	MAX. PROBABLE ERROR (50% C.L.)
5 (PPM)	2.08 (PPM)	1.04 (PPM)	16.2 (MG/HR)	32.4 (MG/HR)	10.9 (MG/HR)
10	2.24	1.12	17.4	34.8	11.8
15	2.50	1.25	19.4	38.8	13.1
20	2.83	1.42	22.0	44.0	14.8

Figure 11

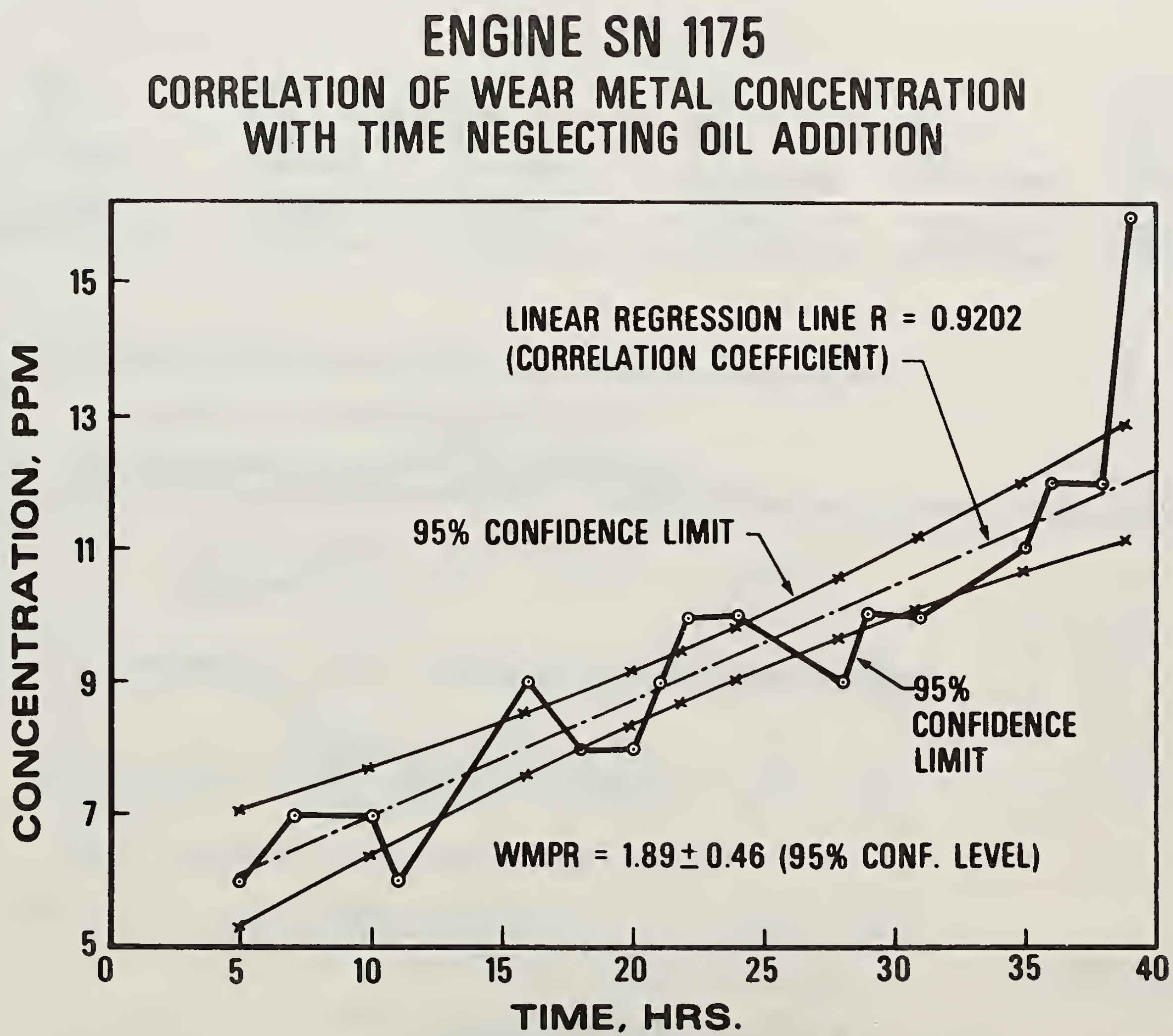

ENGINE SN 1175
CORRELATION OF WEAR METAL CONCENTRATION
WITH TIME NEGLECTING OIL ADDITION
LINEAR REGRESSION LINE R = 0.9202
(CORRELATION COEFFICIENT)
95% CONFIDENCE LIMIT
95%
CONFIDENCE
LIMIT
WMPR = 1.89 ± 0.46 (95% CONF. LEVEL)
CONCENTRATION, PPM
5
7
9
11
13
15
TIME, HRS.
0
5
10
15
20
25
30
35
40

Figure 12

CORRECTION FOR OIL CONSUMPTION (AND ADDITION)

LET ΔV_i = OIL LOST IN INTERVAL BETWEEN TWO SAMPLES

C'_{i-1} = CONCENTRATION OF WEAR METAL IN OIL AFTER TOPPING THE OIL SYSTEM FOLLOWING THE FIRST SAMPLE

C_i = CONCENTRATION IN SECOND SAMPLE

THEN FOR THE Nth MEASURED CONCENTRATION

$$C_{n(corr)} = C_{n(meas)} + \frac{\sum_{1}^{n} \frac{\Delta V_i}{2}(C_i + C'_{i-1})}{V - \Delta V_n}$$

WHERE

ΔV_n = OIL LOST IN INTERVAL BETWEEN (N-1)th AND Nth SAMPLES

THIS, OF COURSE, IS A FICTITIOUS CONCENTRATION WHICH ASSUMES THAT THE METAL LOST WITH THE OIL IS ADDED BACK TO THE LUBRICATING SYSTEM

Figure 13

ENGINE SN 1175

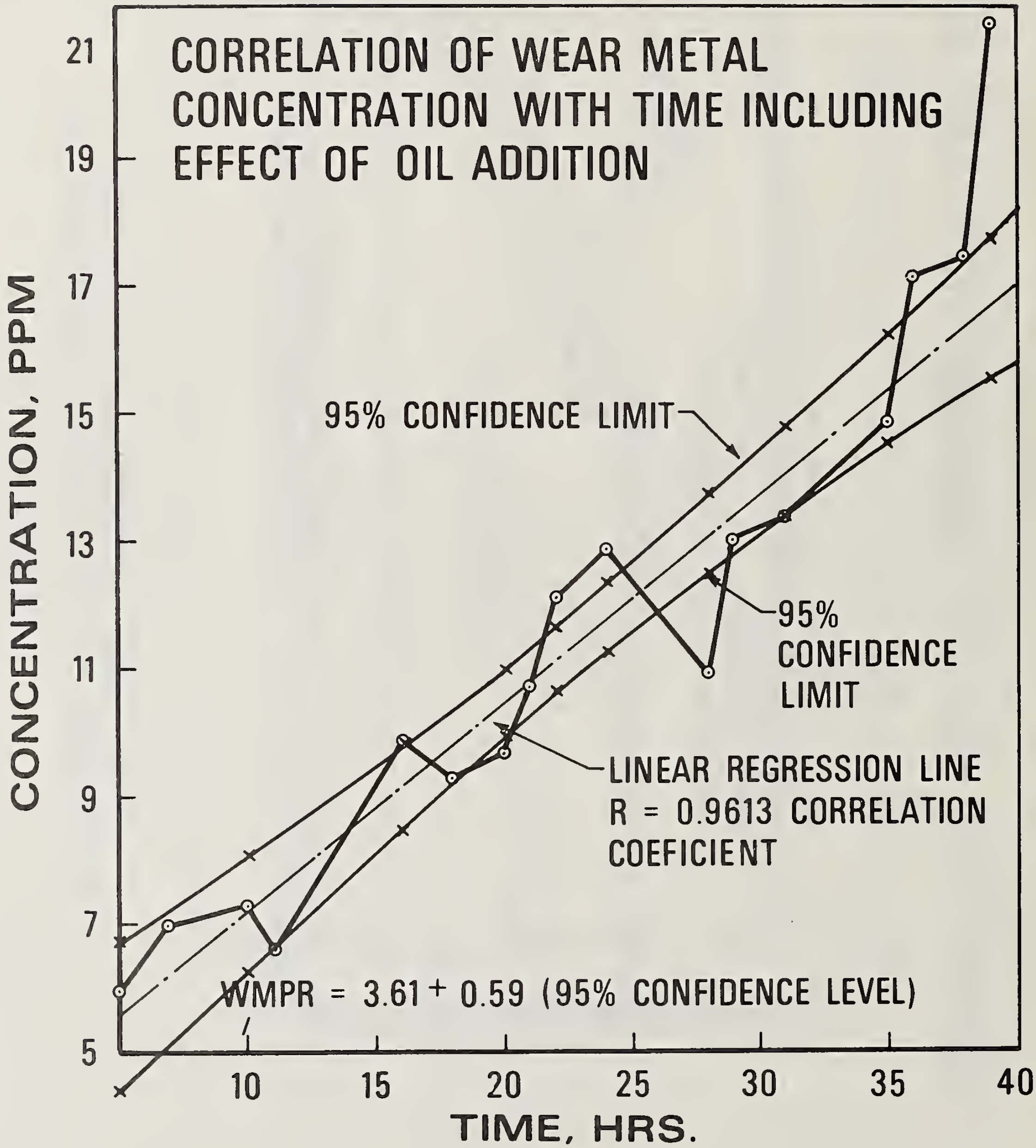


Figure 14

ENGINE SN 1670
HIGH OIL CONSUMPTION
COMPARISON OF MEASURED AND CORRECTED CONCENTRATION

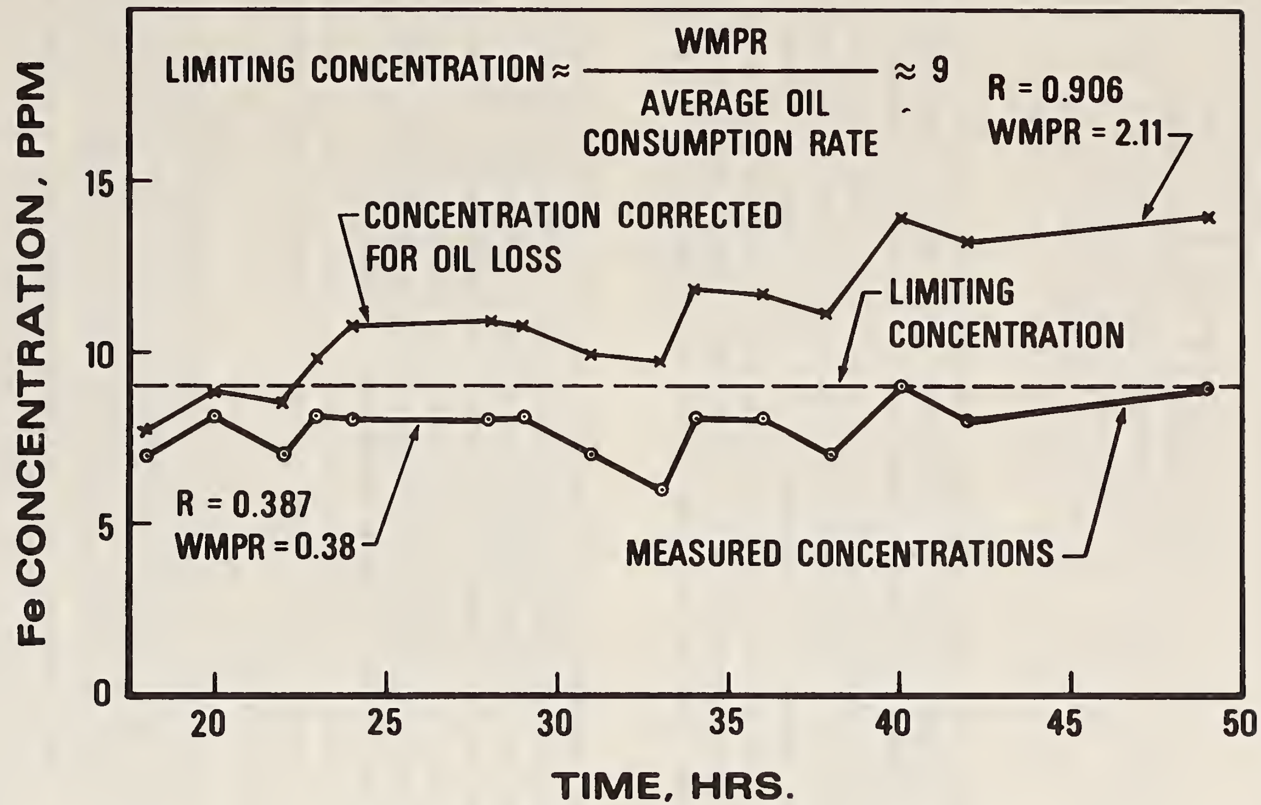


Figure 15

EFFECTIVE FLUID ANALYSIS OF OIL-WETTED SYSTEMS THROUGH PROPER PLANNING AND INTERPRETATION

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A major dilemma which has long faced engineers concerned with the prevention of mechanical failures is the early detection of such events. In the case of systems composed of oil-wetted components, the assessment of wearing processes is hampered by the necessity to contain the fluid. That is, the critical mating surfaces cannot be viewed directly to appraise deterioration. In general, there are three methods used for deducing the internal state of such components. The first approach and probably the most widely used is associated with external performance degradation (changes in leakage, heat level, vibration, noise levels, etc.). The second procedure involves the dismantling of the system to "pull an inspection." The third technique and the subject of discussion here is fluid analysis.

The use of fluid analysis for the detection and prevention of failures in oil-wetted systems has undoubtedly been spurred by the cost factor associated with maintenance and down time. As oil-wetted systems have grown in complexity, the cost of their maintenance and down time as well as their initial cost has increased. However, to be effective, any diagnostic program which relies upon fluid analysis must be properly planned and interpreted. The planning phase involves such aspects as sampling location, sample extraction, and sample container cleanliness. These aspects must be carefully considered to be certain that a representative sample is acquired. Once the analysis has been accomplished, it is necessary to interpret the results in terms of wearing processes occurring in the system components.

Basically, most fluid analysis techniques used today actually evaluate some portion of the contaminants entrained in the system fluid. The contamination level in an oil-wetted system is a dynamic parameter. For example, it can increase or decrease, depending upon the amount of ingression from the external environment and the rate of generation from internal surfaces. Also, the contamination level, in general, will be lower downstream of the system filter than it is upstream. Thus, it is important to consider these factors when obtaining a fluid sample.

The sampling procedure which is followed is another critical factor in the sample acquisition process. Since most contaminants of interest in an oil-wetted system will settle when the fluid is permitted to remain stationary, the sampling procedure most often recommended is called dynamic line sampling. This technique requires that the fluid be extracted from a turbulent region of the connecting lines while the system fluid is circulating. Reservoir sampling is also used effectively when care is taken to see that adequate mixing occurs within the reservoir. In addition, the location within the reservoir is important with such a technique.

Sample container cleanliness is very critical. All of the contamination in the container prior to placing the fluid in it will be added to that already entrained. Standard procedures are available for fluid sampling and evaluating container cleanliness. If proper consideration is given to sampling location, sampling technique, and container cleanliness, a sample of fluid will be acquired which is representative of the system fluid.

If oil-wetted systems are defined to include both hydraulic and lubrication systems, there are five fluid analysis techniques in widespread use: (1) particle counting, (2) gravimetric analysis, (3) pad comparison, (4) Ferrography, and (5) spectrographic analysis. These five methods can be divided into two categories. The first three techniques are concerned with the total particulate contamination present in the sample, while the latter two are normally used for wear debris evaluation. Thus, the interpretation which can be made from the data obtained from each of these methods is dependent upon the category into which it falls. That is, it is very difficult to assess the concentration and particle size distribution of the wear debris present in the sample from any of the first three methods listed.

Particle counting provides information relative both to particle size distribution and contaminant concentration. Obviously, a high concentration of very large particles will result in early failure of any oil-wetted component. Gravimetric analysis can only produce data relative to the total concentration of contaminant, while pad comparison relies upon the similarity between a membrane produced from the fluid sample and a standard membrane. Each of these three analysis techniques provides data upon which a diagnostic appraisal can be made; however, particle counting data are much more complete.

The two analysis methods which are primarily concerned with the type and concentration of wear debris provide acutely different information. Spectrographic analysis produces data relative to the concentrations of various elements, while Ferrography provides morphological results in regard to the wear debris. Both of these techniques have been and are being used effectively. The point to be made here is that the two methods offer different types of information, and the interpretation must take this into account.

The main objective of any diagnostic effort is to determine what, if any, corrective action should be taken. Replacing the system filter with one which is more efficient or reducing the rate of ingestion of external contaminants will reduce the contamination level of the system and, in general, extend the service life of the components. In addition, the severity of the operating conditions will directly influence the wear rate of oil-wetted components. Thus, if it is found through the process of fluid analysis that the system is being subjected to conditions which result in excessive wear, there are two obvious courses of action: (1) modify the duty cycle or (2) change to better components (filters, seals, pumps, etc.).

Modification of the operational duty cycle is usually not a satisfactory corrective action. Such a change means that the machine will not perform effectively at the intended power level. For example, in order to reduce the operating severity on a bearing, the speed or load or both must be reduced. In the case of a hydraulic system, the pressure can be reduced, which means that the system cannot transmit as much horsepower. Thus, corrective action normally takes the form of component replacement. However, merely changing a worn component with a new one will not remedy the cause of the potential failure. If the component life was not adequate, then something must be done about the conditions which caused the premature failure. In many cases, providing better contaminant protection is the answer. This can be accomplished by more effective filtration or by improving the seals and breathers to exclude contamination from the external environment. However, no matter what corrective action is deemed necessary, some consideration must be given to the cause of the failure if longer component life is desired.

OIL ANALYSIS/WEAR PARTICLE ANALYSIS

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INTRODUCTION

Oil analysis has been applied for many decades as a preventive maintenance concept utilized to predict impending mechanical failure through examination of used oil samples. Initially, physical properties of oil were considered indicators of equipment wear. However, meaningful results were not obtained until examination emphasis shifted to the analysis of oil carried wear particles. The term oil analysis has thus become synonymous with oil particle analysis or wear particle analysis.

The oil analysis concept is based on the premise that all mechanical systems experience the process of wear during operation. This wear process results in the production of wear debris or wear particles which are indicative of the respective wear surface condition. In the case of lubricated components these wear particles are picked up and circulated by the lubricant. Thus an examination or oil analysis of a lubricant sample can non-destructively reflect component surface wear condition.

Several oil analysis techniques are currently being utilized for government and industrial applications. These techniques, however, lack a firm technical basis. They are based on assumed monitored parameters and are applied, with varying degrees of success, by trial and error.

PROGRAM DESCRIPTION

In 1973, the Naval Air Engineering Center, under the sponsorship of the Naval Air Systems Command, initiated an ambitious research program with the goal of placing oil analysis on a firm technical basis. This goal was to be accomplished through an intensive correlation effort relating wear particle characteristics to component surface wear condition. Such wear particle correlations serve to hi-light critical characteristics/parameters which are directly relatable to component surface wear condition.

The Naval Air Engineering Center Program consists of two phases; a laboratory phase and a system application phase.

(1) Laboratory Phase

The laboratory phase of the program involves the bench testing of prime oil lubricated components. The objective of this phase is to monitor both the component surface wear condition and the respective generated wear particle characteristics throughout the life of the component. Correlations can then be drawn between surface wear progression and particle characteristic/parameter trends. Trend analysis will serve to identify critical particle characteristics which reflect the wear state of oil lubricated components.

(2) System Application Phase

The second phase of the program involves the application of laboratory findings to "field" operating systems. The objective of this phase is to verify laboratory component test results and conclusions.

Laboratory bench testing has been completed under the program and the system application effort is presently near completion.

PROGRAM RESULTS AND CONCLUSIONS

Oil analysis has traditionally been thought of as a one step, straight forward testing procedure. However, in actuality, oil analysis is a critical combination of techniques, test procedures, and analysis criteria. The total progression can be divided into five major elements; sample, detection, diagnosis, prognosis, and prescription.

(1) Sample

The sample element of the oil analysis process involves obtaining a timely, representative lubricant sample from a mechanical system.

(2) Detection

The detection element provides a first cut or preliminary determination as to the health of a machine. (i.e. is the machine wearing normally or abnormally?) If no abnormalities are detected, no future analysis is required. If an abnormality is detected or suspect, the lubricant sample is transitioned to the next oil analysis element.

(3) Diagnosis

The diagnosis element serves to further clarify the machinery wear abnormality. It provides a determination as to what machine component/ components are wearing and proceeds to define what wear mode/modes are present. Based on these determinations the analysis is transitioned to the next element.

(4) Prognosis

The prognosis element of the analysis process serves to define the course of the machinery wear abnormality. It provides a prediction of the residual life/time till failure based on the wearing component and the wear mode progression.

(5) Prescription

The last element of the analysis process serves to define a course of corrective action. It provides maintenance recommendations based on residual life, wearing component, and wear mode.

The sample element of the process is based primarily on technique. The elements of detection and diagnosis are based on monitored wear particle characteristics and/or parameters, and lastly, the elements of prognosis and prescription rely heavily on analysis criteria.

Primary objectives of the Naval Air Engineering Center research program is to define critical parameters that would effectively implement the detection and diagnosis oil analysis process elements. For this reason, discussion in this paper will be limited to these two elements.

Detection

As indicated above, the purpose of the detection element is to provide a determination as to the health of a machine. Based on the program testing, severe wear can be effectively detected by monitoring both wear particle quantity and size distribution. Particle quantity as well as the ratio of large (7-15 μm) to small (2-5 μm) particles increase substantially during an abnormal wear situation.

Diagnosis

Once the abnormality has been detected, it is the purpose of the diagnosis element to provide a determination as to what component/components are wearing as well as what wear mode/modes are present. Again, based on the program testing, further clarification of a severe wear condition can be accomplished by performing an elemental analysis and a morphology classification of the wear debris. It is obvious that elemental wear debris analysis can be directly related to wear component material. Wear particle morphology (i.e. shape, size, color, etc.) also can be related to a wear component and further serves to reflect the relevent wear mode. These morphology relationships have been thoroughly documented under the oil analysis research effort.

SUMMARY

Present oil analysis techniques are based on assumed monitoring parameters and applied by trial and error. The Naval Air Engineering Center has instituted a program with the goal of placing oil analysis on a firm technical basis. Oil lubricated components have been bench tested in order to formulate correlations between wear particle characteristics/parameters and surface wear progression. Critical parameters defined by bench testing and verified by field testing are:

- quantity
- size
- elemental composition
- morphology

OIL ANALYSIS DECISION PROCESS

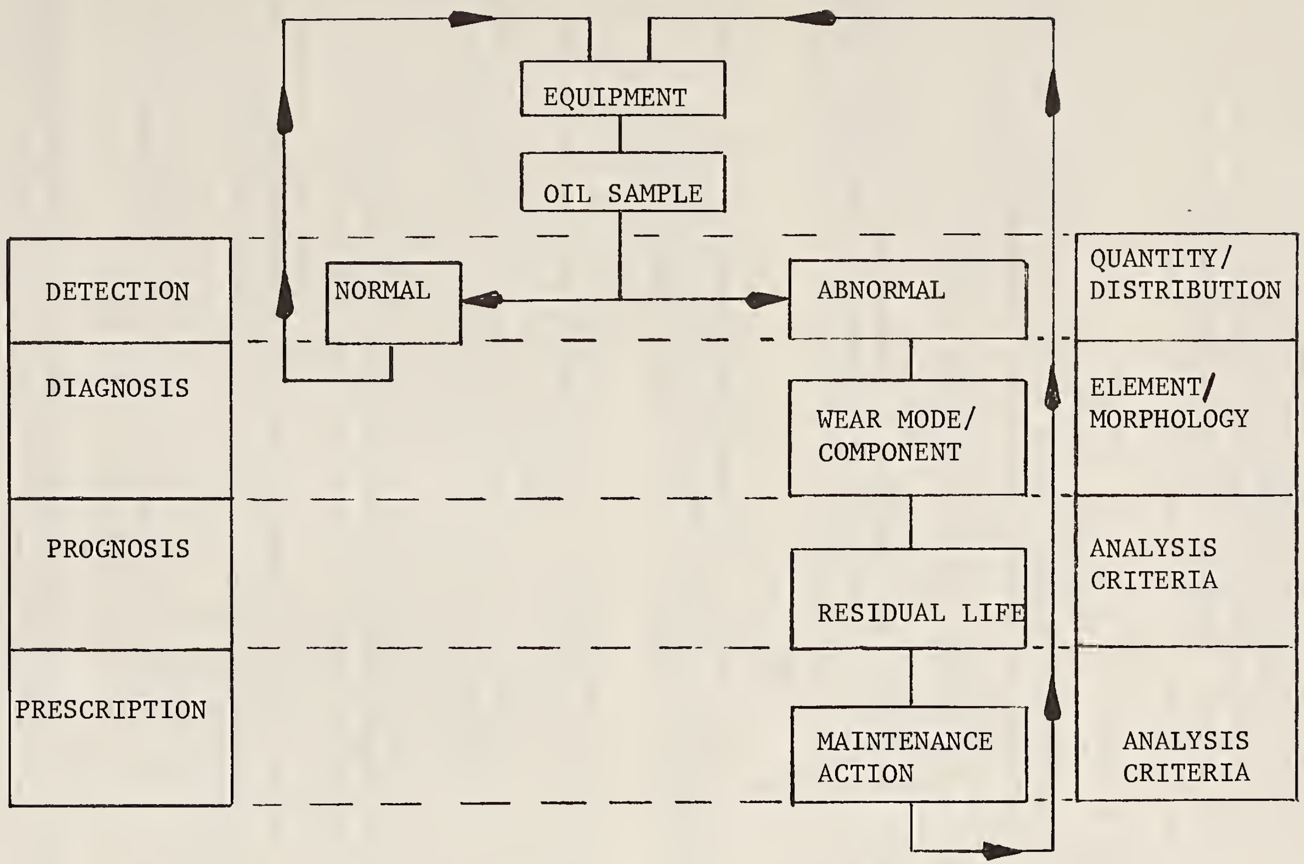

Figure 1

Based on the implementation of the above critical parameters, the overall oil analysis decision process can be summarized in figure (1).

The completion of this research effort will serve as a firm technical basis for the application of wear particle analysis to mechanical system diagnostics as well as mechanical system design. This application reflects great potential for substantial cost, material and manpower savings. Civilian and military sectors of society stand to benefit from wear particle analysis research.

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APPLICATION OF FERROGRAPHIC LUBE OIL ANALYSIS TO U.S.N. SHIP SYSTEMS

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Naval Ship Engineering Center (NAVSEC) has used Ferrographic Lube Oil Analysis on a production basis for two years and is firmly convinced of its effectiveness in predicting mechanical failure. The mission of Naval Ship Engineering Center is to perform engineering and material management functions for ship, system, equipment and material requirements in support of Naval Sea Systems Command. NAVSEC provides support of program requirements for ship design, system and equipment design, procurement, installation, material management and maintenance engineering. NAVSEC considers Ferrographic Oil Analysis a modern tool of maintenance engineering.

This paper will describe briefly the scope of NAVSEC's Ferrographic program, how it is used, and results of the program to date. It will also discuss briefly how criteria are set for making Ferrograms and the trade-offs resulting in the decision to place analysis capability on-site at the maintenance base.

NAVSEC's maintenance engineering program has established Ferrographic analysis at three intermediate maintenance activities, servicing three squadrons of ships, approximately ten ships per squadron. Each oil lubricated equipment in the program is sampled on an average of once every three months, normally following the quarterly refit. Sixteen equipments periodically sampled include four main feed pump motors, auxiliary diesel engine sump, main propulsion lube oil system, two ship service turbine generators, two refrigeration compressors, and the ship's air compressors. Air conditioning compressor lube oil samples and ship's hydraulic oil samples have recently been added to the program. An occasional grease sample is analyzed when it can be obtained when a bearing is being changed. Analysis and follow-up at one Intermediate Maintenance Activity (IMA) site, of approximately 160 samples per quarter, require about one third of the trained analyst's work time. It has been found to be well worth the time and expense.

Early sponsorship of further development of Ferrography at Trans-Sonics by the Office of Naval Research led to a program by Naval Air Propulsion Center and Naval Air Engineering Center. It involved collecting a number of samples of oil from different types of equipment and having them analyzed at Trans-Sonics. NAVSEC was asked to participate, and provided periodic samples from main feed pump motors from a number of ships. Results were so encouraging that in 1975, when this program was drawing to a conclusion, NAVSEC procured a set of equipment for one IMA site and had personnel trained in analysis. For reasons that will be discussed later, it was decided to locate the analysis capability on-site where sampling could be controlled and feedback and follow-up with ship's operating and maintenance personnel would be facilitated. This on-site analysis capability is backed up by engineering support at NAVSEC.

Following a year's evaluation at one IMA site, NAVSEC procured two additional sets of Ferrographic equipment and expanded the program to include approximately thirty ships at three sites. This application is truly a production use of Ferrography and is the largest production application known to NAVSEC within the Department of Defense.

Sampling of oil from the various equipments is done by trained technicians in accordance with uniform standard established procedures. It is normally done during post refit sea trials - from equipment whose operation is secured for the sampling process. Uniformity in sampling is necessary to obtain consistent Direct Reading (DR) results for trending. When the ship returns from sea trials and prior to operational deployment, all samples are run through the DR Ferrogram Reader. This instrument, shown on the left side of the Duplex Ferrograph (Fig. 1), can be operated with little training. DR readings require about five minutes per oil sample. They represent a measure of the optical density of the particles deposited in the precipitator tube as oil is flowed through the highly divergent magnetic field. In general, the "Small" reading represents particles of normal wear and the Large DR represents particles of abnormal wear. A reading of 100 represents approximately 50% transmission of light through the particles to the calibrated photo cell. In normal wear, the "S" reading may exceed the "L" reading, but as the wear becomes severe and approaches failure, the ratio of DR_L to DR_S becomes large. Fig. 2 shows a plot of the DR readings from quarterly samples. This data is trendable, and NAVSEC has found that when DR_L exceeds a pre-established cut-off or threshold value, a Ferrogram slide should be made for further analysis. Setting of the cut-off values will be discussed later.

The right hand side of the Duplex Ferrograph is the Ferrograph Analyzer - used for making slides for detailed wear particle analysis. When the oil is gravity flowed down the slide (Fig. 3), over the highly divergent magnetic field, the particles of wear and some particles of contamination are deposited. After the Ferrogram is washed and fixed, it becomes a permanent record of the wear condition of the particular equipment on that date.

Analysis of the Ferrogram takes special training, and NAVSEC's on-site analysts have received it at the Trans-Sonics plant, as well as on-site. Using the Ferroscope (Fig. 4), a special microscope with a unique dual illumination system, the technician classifies the number and types of particles, and gives his judgement of the wear condition. This information, and comments, are filled in on the form shown in Fig. 5. Spectrometric results are inserted for later comparison when the data is received from the remote laboratory. The Ferroscope's illumination system (Fig. 6) selectively provides red reflective and/or green transmitted light. Thus color combinations reveal whether a particle is opaque metal or translucent salts, oxides or other contaminants. Other features include calibrated vernier focus adjustment to estimate particle thickness, and a filar eyepiece scale to estimate length and width.

It is well known that the material, size and shape of particles of wear give an excellent indication of the wear condition. Ferrography is the only method available to NAVSEC to determine size and shape of these particles. Site analysts in the NAVSEC Ferrographic program can and do make maintenance recommendations to the engineering officers of ships in the program. In a fifteen month period at the first IMA site using Ferrography, thirty such recommendations included 7 to change the oil, 15 to flush the sump and and change oil, 3 to change oil and place in standby, 4 to replace bearing (s) and 1 miscellaneous.

It is important to note that NAVSEC has found Ferrography to be such a sensitive indicator of wear that the analyst sometimes observes gradual bearing degradation over a period including several samples. He must exercise discretion not to recommend premature change of bearings. This maintenance action usually awaits evidence of bearing noise, as detected by NAVSEC's complementary vibration analysis program. Quarterly, each IMA site makes a report to NAVSEC, summarizing all samples taken, DRs and their plots, Ferrogram analysis reports, and recommendations made to ships. Site analysts often consult with NAVSEC engineers by telephone or message, and sometimes samples are sent to Trans-Sonics to confirm, or expand on, a finding. An engineer at NAVSEC evaluates results shown in the quarterly reports, and is developing techniques to apply statistical analysis to the data as the size of the data base increases.

In a fifteen month period, IMA site "A" made DR readings on 495 samples from the squadron it was servicing (Fig. 7). 121 (24.4%) of these samples were also made into Ferrogram slides, almost all 121 having exceeded the established cut-off values. Of the 121 Ferrograms, 51 were judged to show normal wear, 51 were in the "caution" area, and 19 were considered to be in a "very high" wear status. Thus 57.8% of the Ferrograms made (14% of all samples taken) showed wear above normal. It is interesting to note that all 19 "very high" wear samples were from drive motors for main feed pumps, four of which are on every ship. All four bearing change recommendations mentioned above were for these pump motors.

Except for special tests desired, Ferrogram slides are made only when large DR values exceed a predetermined cut-off value for each equipment. These values will vary between equipments because of differences in machine design and the operating environment. They are adjusted from time to time as the data base becomes larger and experience is gained. Equipment modification or operational changes can also cause a change in cut-off values. Cut-off values are set by NAVSEC by engineering judgement, based on:

- Average of previous readings
- Distribution of previous readings
- Percentage of samples that exceed the cut-off
- Consideration of the specific equipment and its maintenance and failure history

Statistical analysis was performed on the entire population of DR_L values for one type of main feed pump motor. It showed (Fig. 8) that the data is not normally distributed but is skewed to the right. Therefore the normal statistical formulae for prediction do not apply for this data. However, plots of distribution and relative cumulative frequency (R.C.F.) are useful to the engineer in setting the cut-off values. The R.C.F. plot for this motor (Fig. 9) shows that 70.6% of the readings fall below the cut-off value of 50 and therefore 29.4% of the samples would be made into Ferrograms for further analysis. From a sample of three ships during a fifteen month period, 25 Ferrograms were made from 73 oil samples from this particular pump motor. 24 of these Ferrograms were judged to show wear greater than normal. This indicates that the DR_L cut-off value was correctly chosen, as the time and cost for making Ferrograms was not expended needlessly on normal wear samples.

Following is a brief summary of trade offs involved in a management decision to place the analysis capability on-site at the IMA maintenance bases. The decision was necessary when the ONR/NAVAIR program was greatly reduced, and NAVSEC had made the decision to continue with Ferrography. It was felt that ultimately NAVSEC would desire support at three sites. However, establishing three labs, without first evaluating on-site operation of one, seemed a high risk option. Therefore the approach to on-site analysis was viewed from the standpoint of one site first and the other two later if results warranted. The other two approaches considered were: (1) to continue analysis at Trans-Sonics, and (2) to set up a Ferrography lab at an existing Naval laboratory where a technician would be trained for the job. Fig. 10, tabulating a trade-off of advantages, shows the on-site approach to be clearly superior. Sampling and analysis can be done by one technician, who is familiar with the equipment sampled, as well as its operation. He can discuss its maintenance history with the ship's crew, and be thoroughly familiar with any past problems. He can also follow up to see the effects of implementing his recommendations. When disadvantages are compared (Fig. 11), those of the on-site option are far less significant. A close look at costs considered a contract with the factory as compared to the costs of capital equipment, training, consumables, and cost for the analyst's time. On-site analysis turned out to be far less costly.

The recommendation was therefore made, approved, and implemented, to provide an on-site analysis capability at one site for evaluation, and follow-up with two additional sites when results were sufficiently encouraging. All three locations are now in a full production testing operation, and NAVSEC is completely pleased with the results.

In summary, this paper has discussed the scope of the NAVSEC Ferrographic program, how we use it, a summary of results, how large DR cut-off values are selected, and trade-offs leading to a decision as to where to put the analysis capability.

Finally, to those considering a production Ferrographic Lube Oil Analysis capability, NAVSEC recommends that every consideration be given to placing the analysis function as close to the maintenance activity as feasible. Technicians thoroughly familiar with the equipment sampled, and trained in Ferrography, make excellent analysts.

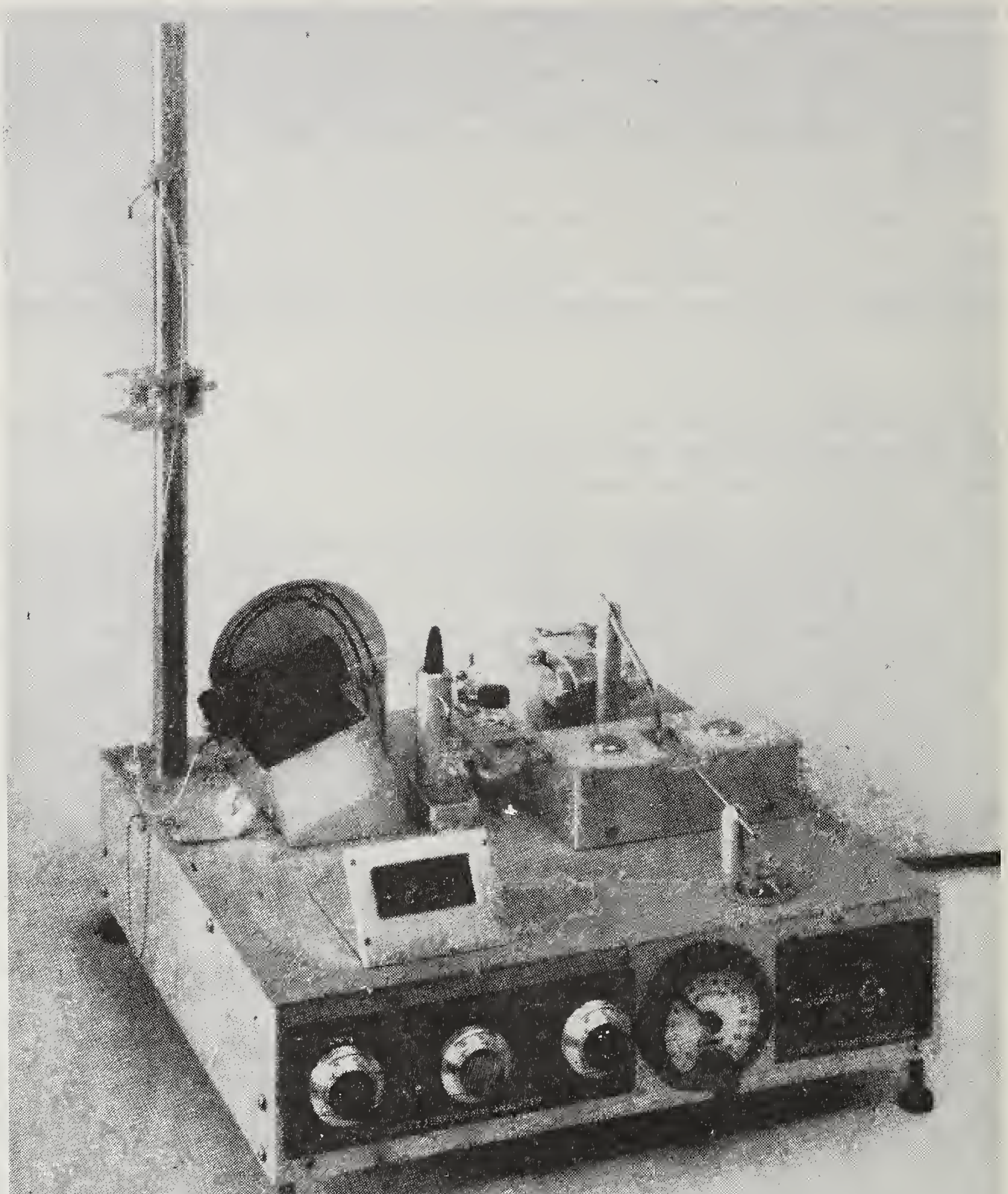


Figure 1

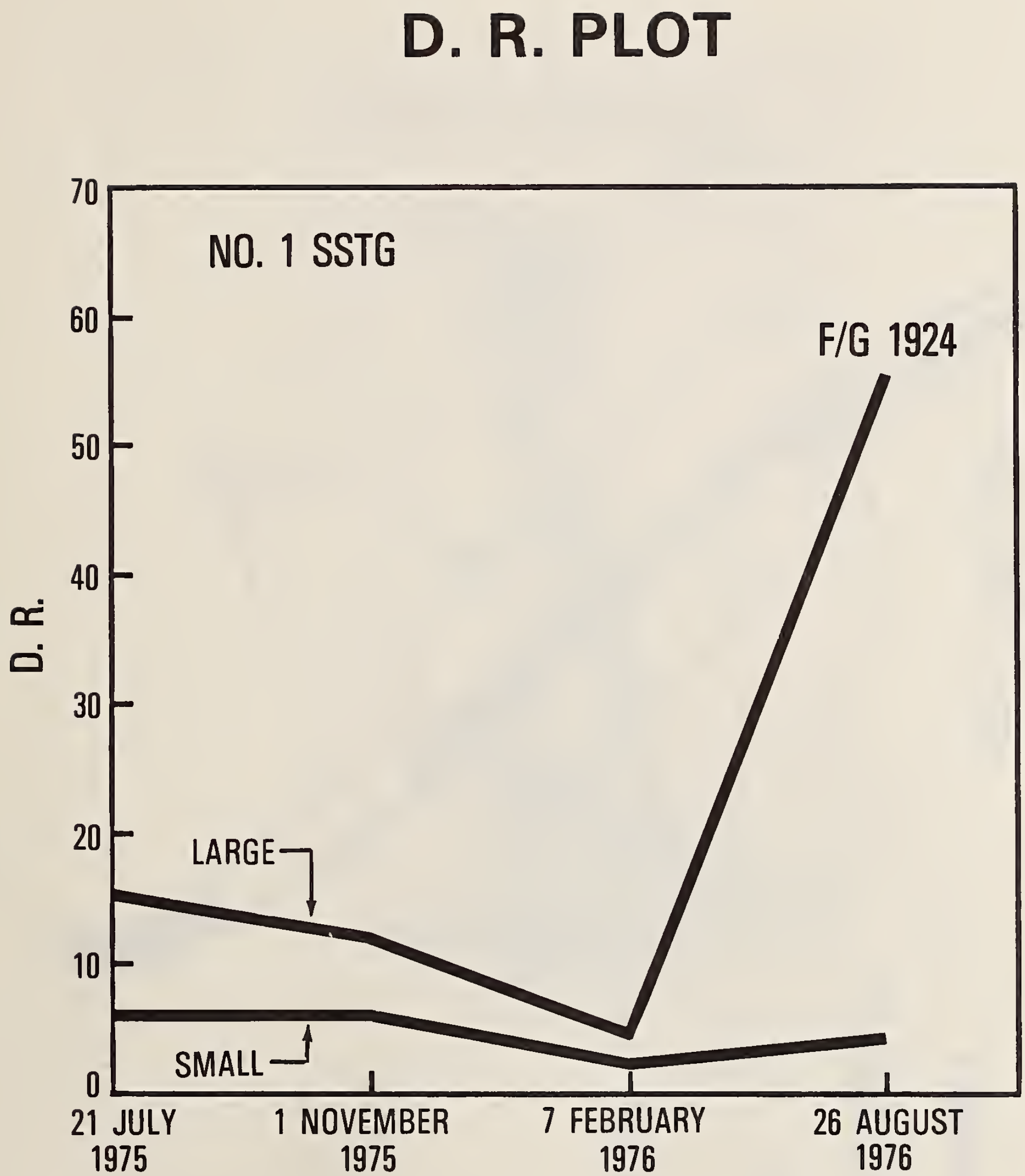
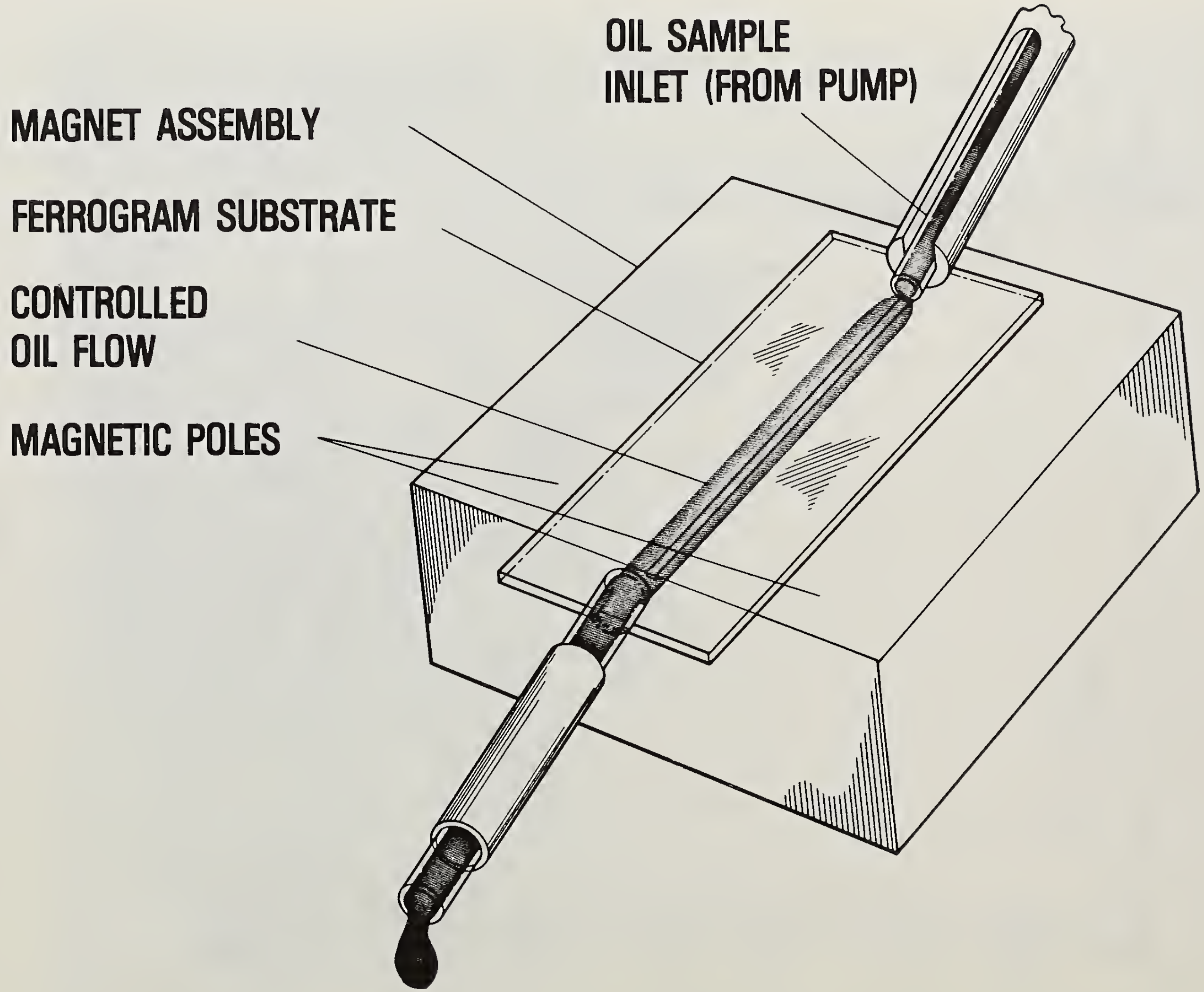

D. R. PLOT
NO. 1 SSTG
F/G 1924
LARGE
SMALL
D. R.
70
60
50
40
30
20
10
0
21 JULY 1975
1 NOVEMBER 1975
7 FEBRUARY 1976
26 AUGUST 1976

Figure 2



OIL SAMPLE
INLET (FROM PUMP)
MAGNET ASSEMBLY
FERROGRAM SUBSTRATE
CONTROLLED
OIL FLOW
MAGNETIC POLES

Figure 3

FERROSCOPE

Figure 4

FERROGRAPHIC ANALYSIS REPORT

SAMPLE NO. : 842 DATE : 1 SEPT 1976 SHIP :

EQUIPMENT : #1 SSTG DATE OF SAMPLE : 26 AUG 1976

D. R. RESULTS : 55/4 FERROGRAM NO. : 1924 DILUTION FACTOR : N/A

VOLUME OF OIL PASSED ALONG FERROGRAM : N/A HOURS ON OIL : N/A

TYPES OF PARTICLES	NONE	FEW	MODERATE	HEAVY
NORMAL RUBBING WEAR		XX		
FATIGUE CHUNKS		XX		
CUTTING WEAR		XX		
SEVERE WEAR	XX			
LAMINAR WEAR	XX			
SPHERICAL	XX			
OXIDE	XX			
DARK METALLO-OXIDE			XX	
NON-FERROUS, METALLIC		XX		
NON-METALLIC, CRYSTALLINE		XX		
CORROSIVE WEAR	XX			
NON-METALLIC, AMORPHOUS	XX			

CONSIDERED JUDGEMENT OF WEAR SITUATION :

XX NORMAL CAUTION VERY HIGH

SPECTROGRAPHIC RESULTS :

	FE	PB	CU	CR	AL	NI	AG	SN	SI	MG
PPM										

COMMENTS : FERROGRAM HAS FEW ABNORMAL WEAR PARTICLES - MOSTLY OXIDES.

Figure 5

FERROSCOPE BICHROMATIC ILLUMINATION

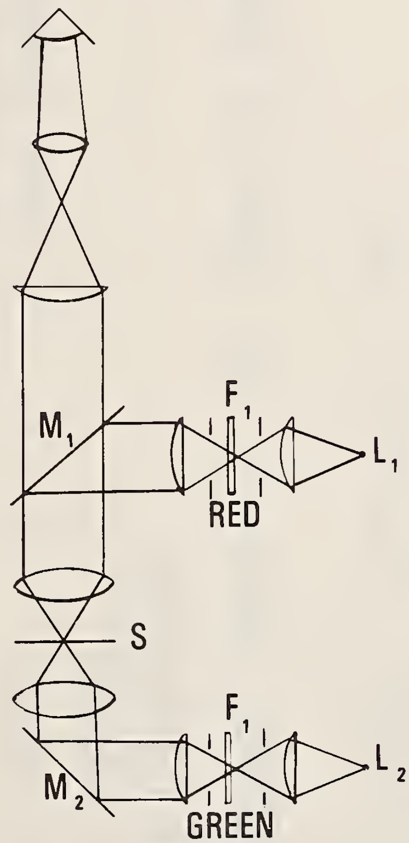


Figure 6

IMA SITE A
5 QUARTERS

TOTAL SAMPLES — 495

FERROGRAMS MADE – 121 (24.4% OF SAMPLES)

WEAR CONDITION

- NORMAL 51
- CAUTION 51
- VERY HIGH 19

Total: 121

CAUTION and VERY HIGH: ABOVE NORMAL 70 (57.8% OF FERROGRAMS)

Figure 7

DISTRIBUTION OF LARGE DR RESULTS
MFP MOTORS TYPE E

354 SAMPLES
JUNE, 1976

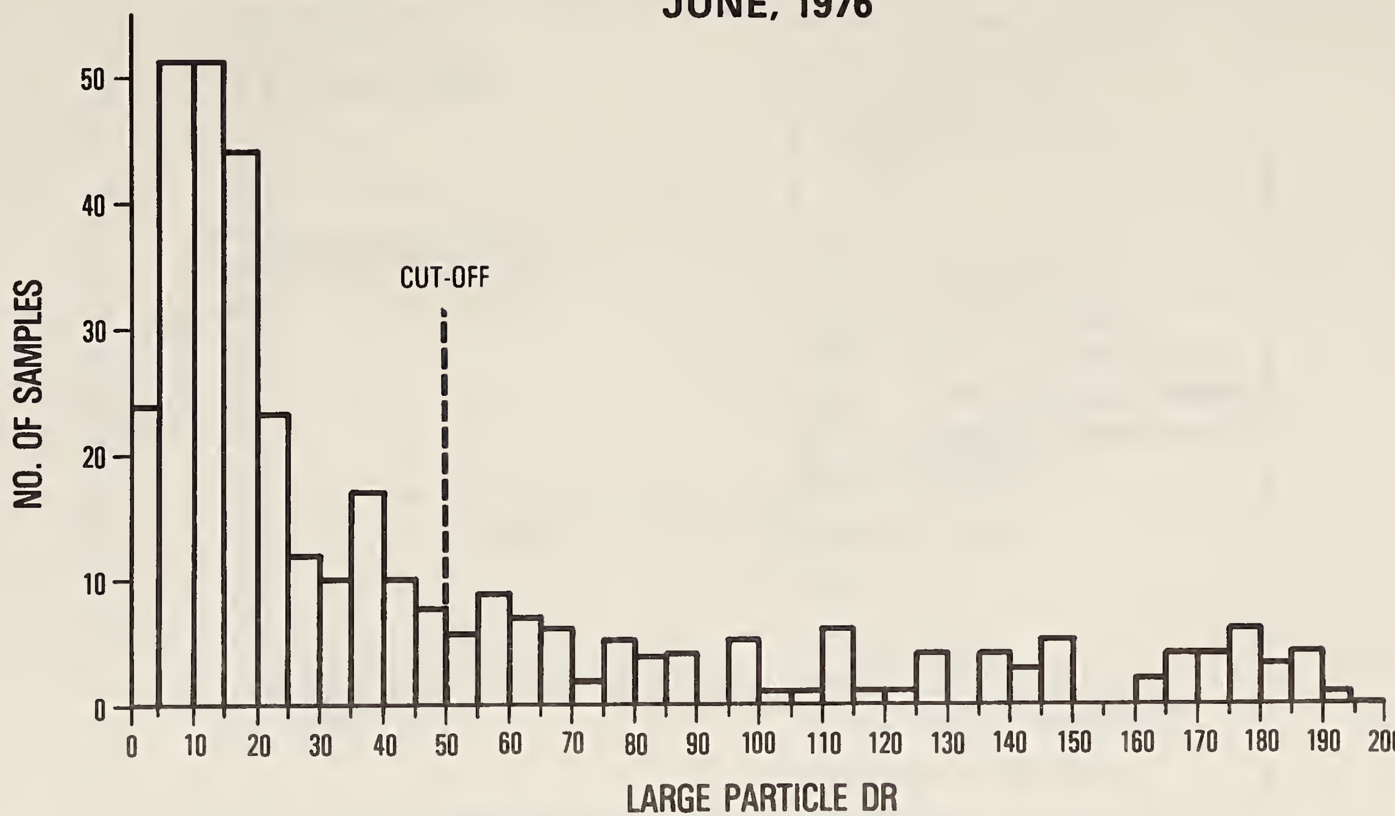


Figure 8

TYPE E
MAIN FEED PUMP MOTOR

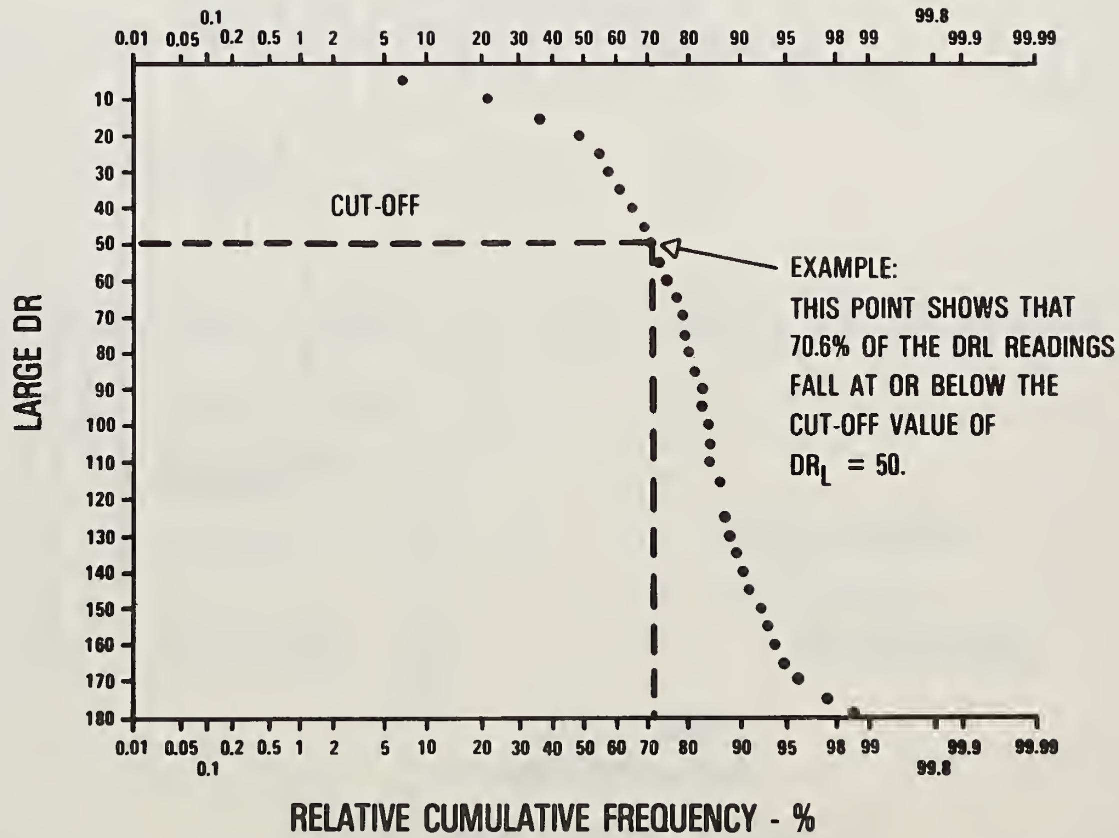


Figure 9

TRADE-OFF ADVANTAGES

APPROACH:	*ADVANTAGES*
(1) CONTINUE AT TRANS-SONICS	• ASSURED HIGH TECH. QUALITY • AVAILABLE IMMEDIATELY • LOW NAVSEC MANAGEMENT ATT'N REQ'D
(2) ESTABLISH ON-SITE	• TIMELY ANALYSIS RESULTS • COORDINATED WITH OTHER MAINTENANCE • ACCESS TO SHIPS/CREWS • ANALYST CURRENT SHIP EQUIP. EXPERIENCE • LOW PAPER WORK • LOWEST COST
(3) ESTABLISH AT NAVY LAB	• CLOSE TO NAVSEC, FACILITATING COORDINATION • CONTINUITY OF PERSONNEL

Figure 10

TRADE-OFF: DISADVANTAGES

APPROACH	*DISADVANTAGES*
(1) CONTINUE AT TRANS-SONICS	• ANALYSIS RESULTS EXCESS TIME TO OBTAIN • HIGHEST COST • ANALYST UNFAMILIAR WITH SHIP'S EQUIPMENT & OTHER MAINTENANCE
(2) ESTABLISH ON-SITE	• TIME LAG TO IMPLEMENT • TRAINING REQUIRED • NAVSEC & IMA SITE PERSONNEL TIME & ATTENTION REQ'D
(3) ESTABLISH AT NAVY LAB	• EXCESS TIME TO OBTAIN ANALYSIS RESULTS • TRAINING REQUIRED • FOLLOW-UP DIFFICULT • ANALYST UNFAMILIAR WITH EQUIP, OTHER MAINT, ETC. • HIGHER COST

Figure 11

EFFECTIVENESS OF THE REAL TIME FERROGRAPH AND OTHER OIL MONITORS AS RELATED TO OIL FILTRATION

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Abstract: A development model of an oil monitor known as the Real Time (R.T.) Ferrograph was evaluated on a bench tester to determine its effectiveness in detecting scoring and contact fatigue type failures, especially as influenced by various levels of oil filtration. Comparisons of the outputs were made with spectrometric oil analysis (SOA), a light scattering and attenuation device, an X-ray fluorescence device, a particle counter, and the analytical Ferrograph. Results of the testing showed the R.T. Ferrograph to be effective in detecting failures at or above the 40 micron filtration level. In addition it correlates well with the other oil monitors. Below the 40 micron filtration level the R.T. Ferrograph was found to be ineffective. An ancillary evaluation of a capacitive discharge chip detector placed in the oil loop was performed. The results showed that this was a promising method of reducing false failure indications by burning off non-failure related magnetic fuzz while at the same time maintaining its effectiveness in indicating a real failure.

Introduction: Ferrography is a technique for magnetically depositing metallic wear particles, by size, onto a glass slide or tube for examination. The application of Ferrographic oil analysis involves two steps, namely; 1) indicating a measure of the amount of both large (above 5 micrometers) and small microscopic wear particles in a sample of oil and 2) microscopically examining the wear particles' morphology. The first step indicates the wear severity or abnormality of oil wetted components while step 2 is used to identify the type of wear and possibly, the wearing component (bearing, gear, etc.). Step 2, being a time consuming and therefore relatively expensive process, is usually performed only when step 1 indicates an abnormal wear situation. Over the past several years Ferrographic analysis has been used successfully to aid in the prediction of failures of oil wetted components. In order to indicate failure on a more timely basis in critical equipment such as aircraft gas turbine engines, the Naval Air Propulsion Test Center has been active in developing, under contract to Foxboro Trans-Sonics, Inc., an airborne unit known as the Real Time (R.T.) Ferrograph which is capable of performing the step 1 function. Details of the development program are described in Reference 1. This paper will concern itself with the evaluation of a development model of the R.T. Ferrograph. This unit is suitable as an in-line device only on stationary equipment. Because oil filtration levels vary widely from one model engine to another as shown in Figure 1, the effect of this parameter on the effectiveness of the R.T. Ferrograph was considered important in the evaluation for purposes of defining its applicability or for determining that further development of the R.T. Ferrograph is required. For comparison purposes other oil monitoring devices were used at various times during the evaluation testing. They included:

a. an in-line X-ray fluorescence device developed by United Technologies, Inc.

b. a light scattering device developed by General Electric and known as the G.E.O.M.

c. an emission spectrograph.

d. a Royco particle counter.

In addition, a new type of chip detector designed to eliminate false failure indications by sparking or burning off undesirable metallic "fuzz" was placed in the oil circulating loop for a large portion of the test program.

Description: A bench tester, known as the Geared Roller Test Machine (GRTM), was used in the evaluation program. This machine is used primarily for disc scoring tests. A cross section of the test section is shown in Figure 2. The test specimens are two 3 inch diameter discs which are loaded against each other and are operated, each at a different peripheral velocity so that both sliding and rolling take place at the same time. The slide-to-roll ratio can be varied and controlled by varying the speed ratio of the phasing gears. In addition, elliptical phasing gears were available so that the slide-to-roll ratio over the circumference of the test discs will vary to simulate the action on a gear tooth surface. For the purposes of this evaluation the machine was modified so that, in addition to disc scoring tests, bearing rolling contact fatigue tests could also be run.

The lubrication system is shown schematically in Figure 3. The oil recirculating system was capable of being operated in filter by-pass so that different size filters could be inserted without shutting off the system. As shown in Figure 3, the R.T. Ferrograph has its own recirculating oil system in which it cyclically measures the large and small particle density. One complete cycle consists of a flushing phase and a precipitation phase. The internal operation of the R.T. Ferrograph is shown schematically in Figure 4. During the flushing phase the oil is pumped through the glass precipitator tube to back flush particles deposited from the previous precipitation phase. Once the flushing phase is complete the pump automatically shuts off and a variable density magnetic field is automatically turned on. At the same time the oil in reservoir above the precipitator tube flows by gravity through the precipitator tube to the main oil reservoir. Particles deposit by size along the glass tube. The measurement of the quantity of particles deposited at each location (large and small) is accomplished by measuring the attentuation of a beam of light passed through the glass tube by a fiber optic cable to a photo resistor which produces a voltage output that represents the percentage area covered. The percentage area covered at the large particle location is symbolized by A_L and the area covered at the small particle location by A_S. A third fiber optic cable is placed outside the magnetic field and is used to adjust the lamp voltage so as to maintain a constant electrical resistance through the photo resistors, i.e., this compensates for oil discoloration. For simplicity in the monitoring of machinery it is desirable to combine the two values (A_L and A_S) into one number (index) which will indicate that either failure or a high wear situation is in progress. Two such severity indices have been suggested:

1. $A_L (A_L-A_S)$ - This value reflects both a size distribution (A_L-A_S) and the influence of large particle generation which is thought to indicate the onset of abnormal wear.

2. $(A_L+A_S)(A_L-A_S) = A_L^2-A_S^2$ - This value indicates the influence of the total particle count (A_L+A_S) and the particle size distribution (A_L-A_S).

Test Results and Discussion

Disc Scoring Tests at Varying Slide-to-Roll Ratios - No Filtration

The purpose of this series of tests was to determine the R.T. Ferrograph's ability to distinguish among various severity levels of wear. Tests were run at five (5) different slide-to-roll ratios (0, 0.1, 0.2, 0.27, 0.33). The severity of the condition increases with increasing slide-to-roll ratio. The tests were run at a 4741N load. No filter was used in any of the tests. The tests were run for four hours or until scoring failure of the discs occurred. Figure 5 clearly demonstrates that there is a direct relationship between R.T. Ferrograph response and the wear severity level. In the three cases where no failures occurred, the Ferrograph readings increased slightly and then leveled off indicating a normal wear situation. The initial increase in level was probably a reflection of break-in wear in which the surface asperities were initially worn off. The two cases where failure occurred showed continuously increasing values of Ferrograph reading with time. The rate of increase was higher for the failure which experienced the more severe operating condition. In addition the Ferrograph correlated with the level of iron in the oil as measured by emission spectroscopy. Another disc scoring test using elliptical phasing gears was run in which the slide-to-roll ratio varied over the circumference of the test discs from 0 to 0.33. Data from this test was obtained for the R.T. Ferrograph, SOA, G.E.O.M. and the X-ray fluorescence units. The results are plotted in Figure 6. All units increased in their reading as the test approached failure. The increase in readings was sharp for all the methods except for the G.E.O.M.

Effect of Filtration - Disc Scoring Tests

A series of disc scoring tests were run at five different filtration levels; namely; filters having nominal ratings of 10, 25, 40, 75 and ∞ (no filter) micrometers. The purpose of these tests was to determine the effectiveness of various oil monitors with filtration level. A scoring test was run at each filtration level. After the completion of each test, the oil was recirculated through the system using a filter of the next finer level from that on which the test was run. Readings on the oil monitors were taken after 5 minutes of recirculation, after which the next finer filter was inserted into the system and again readings were taken after 5 minutes. This process finished with the use of the 10 micron filter. The results of the testing are shown in Figure 7. Scoring was made to occur several times during the course of each test. At the 10 and 25 micrometer level the R.T. Ferrograph showed no indication of failure or abnormal wear throughout the entire test. At the 40 micrometer filtration level there is some indication of wear at the time the first scoring occurred after which a leveling off in readings is indicated. Definite abnormal wear indications are evident for the 75 micrometer and no filtration levels at the time the first scoring occurred after which a leveling off of the reading occurred. The effect of reducing the reading by filtration is evident during the recirculating test. In the case where no filter was used, the recirculating tests show a severe drop in reading for filter levels below 40 micrometers, indicating that most of the particles are below the 40 micrometer level. Spectrometric oil analysis for iron and G.E.O.M. data as obtained during the scoring tests showed trends similar to the R.T. Ferrograph. However, during the recirculating oil test the effect of filtration was not nearly as dramatic in reducing the readings. The particle size distribution at the end of each test was measured using a Royco particle counter. The results are plotted in Figure 8. Examination of the case where no filtration is used will give an indication of the amount of particles generated within each size range. The majority of wear particles generated are in the 2-10 micron range. The second largest group of particles are in the 10-25 micron range. These two groups taken together constitute over 99 percent of all particles generated. Therefore the overwhelming majority of particles generated from a scoring type of wear process are below 25 microns in size. Use of the 10 or 25 micron filter did not substantially reduce the number of particles in the 2-10 micron range, but did for the 10-25 micron range. This fact, taken together with the previous data showing that the oil monitors could not detect failures using 10 and 25 micron filters, indicates that the monitors are (1) not capable of detecting particles in the 2-10 micron range,(2) are most sensitive at detecting particles in the 10-25 micron range.

Effect of Filtration - Bearing Fatigue Spalling Tests

A test series similar to that for disc scoring was run for rolling contact fatigue. An NJ212 roller bearing was run to initial spalling at each filtration level at a load of 18085N. After initial spalling the load was reduced and the bearing run to final failure. Initial and final failure are compared in Figure 9. The response of the various monitors with time at the various filtration levels are shown in Figure 10. Also shown are the recirculation tests. All test bearings failed by spalling as intended except the bearing which ran without filtration. This bearing failed because of excessive cage wear. In Figure 9 the arrow indicates when initial spall failure took place. The R.T. Ferrograph results show no indication of failure at the 40 micron level or below. At the 75 micron and the no filter levels, the increasing trend in reading level indicates a failure in progress. The effect of filtration on the Ferrograph readings is also obvious during the recirculation tests. The spectrometric results gave some indication of failure at the 40 micron level in addition to those detectable at the 25 and 10 micron levels. The G.E.O.M. scatter indication showed an increasing trend in reading at all filtration levels except for the 10 micrometer level. The recirculation tests show a reduction in readings with decreasing filter rating for both the SOA and G.E.O.M. However the effect is not as dramatic as with the R.T. Ferrograph. The UTRC X-ray oil monitor was run only in the case in which no filter was used. Comparison of the X-ray unit with the other monitors is shown in Figure 11. It can be seen that the X-ray unit showed the same trend in readings as did the other monitors. The PPM level of iron indicated by the X-ray unit was much lower than that indicated by emission spectroscopy. The particle size distribution at the end of each test was measured using the Royco particle counter. Again as in the disc scoring tests 99 percent of the particles generated are below 25 microns in size as shown in Figure 12.

Summary of Effectiveness of Oil Monitors at Various Filtration Levels

The data presented thus far was reviewed for each monitor and a subjective judgement was made to determine the effectiveness of each monitor at the various levels of filtration. These results are given in Table I for both the disc scoring and bearing fatigue tests. If a monitor was not evaluated at a particular filtration level an N/A (not applicable) is indicated in the Table. A question mark in the Table indicates that the data showed a possible, but not a clearly definable, trend toward indicating a failure.

The tests run at the coarser levels of filtration have all of the oil monitors clearly indicating a failure. As the levels of filtration become finer, the ability of all the oil monitors to detect a failure lessens as seen in Table I. This series of data shows that the oil monitors limit to decisively detect failure is a level of approximately 25 micrometers. Any filtration range above 25 micrometers, shows high correlation among the monitors when there are large concentrations of wear particles.

Correlation of R.T. Ferrograph with Analytical Ferrograph

The Analytical Ferrograph is a laboratory device which is used to precipitate wear particles from an oil sample to a glass slide for microscopic examination. The particles are precipitated according to size along the length of the slide in a manner similar to that of the R.T. Ferrograph. The resulting slide is called a Ferrogram. An important parameter of wear indication is the amount of build up of particles where the oil first contacts the Ferrogram substrate. This is called the height of the entry deposit. This would correspond to the A_L value on the R.T. Ferrograph. Ferrograms were made from oil samples taken from both disc scoring and bearing fatigue tests conducted at the 75 micron filtration level. In addition Ferrograms were made for the recirculating tests. Comparison between the percent large area covered (A_L) and the height of entry deposit on the Ferrogram is seen in Figures 13 and 14 for both tests. The two values are seen to give excellent correlation.

Capacitive Discharge Chip Detector

There is presently considerable interest by helicopter manufacturers, engine companies and the military in replacing presently used magnetic chip detectors with capacitive discharge (burn-off type) chip detectors in order to reduce the number of false indications caused by the accumulation of small magnetic particles and debris. The burn-off type chip detector operates by discharging an electrical spark after a build-up of magnetic particles causes bridging of the gap. If the particles are small enough to be burned off, no failure indication registers. The charge will be built up again on capacitors located internally in the chip detector. However, particles or chunks which are too large to burn off will continue to bridge the gap after discharge has taken place and will register a failure indication. For a given gap size, the size of particles which can be burned off depends on the magnitude of the electrical discharge which can be varied by the capacitance.

This type of chip detector was placed in the recirculating oil loop through all the disc scoring and most of the bearing spalling filtration tests. The output of the detector was monitored on a Viscorder to record any discharges which took place. The first discharge of the detector occurred during the bearing tests. The unit discharged 22 times in 25 minutes after which it indicated a failure. The unit had been in the system 44.3 hours before a failure indication occurred. Over that period of time 4 disc scoring tests and three bearing tests had been run to failure. During the test in which the discharges occurred the R.T. Ferrograph oil monitor showed a rapid increase in reading level as shown in Figure 15. The wear particles were removed from the chip detector, filtered and the size distribution estimated as shown in Table II. The distribution of particle size shows that the particles are relatively small. This indicates that small particles are capable of bridging the gap and indicating a failure without being "burned off". It is speculated that the increase in particle generation as the failure progressed (indicated by Figure 15) was so rapid that the small particles accumulated on the chip detector and bridged the gap before the capacitor could fully recharge to "burn off" the particles.

The fact that the chip detector indicated a real failure before the failure reached a point where large chunks of metal were being generated shows that its effectiveness is not substantially impaired by its burn off characteristics. On the other hand the fact that there were 22 discharges indicates that the chip detector is capable of burning off small particles.

To obtain optimum effectiveness from this type of chip detector the design (i.e. gap size, capacitor strength, magnet strength) should be tailored to the wear generating characteristics of machinery being monitored.

Conclusions

1. The R.T. Ferrograph, as presently configured, is effective in detecting bearing and disc scoring type failures, if the nominal oil filtration level is above 40 micrometers. At filtration levels below 40 micrometers the R.T. Ferrograph is ineffective. At the 40 level its effectiveness is questionable.

2. Under conditions when the R.T. Ferrograph is an effective (i.e. above 40 micrometers) failure detector, it correlates well with other detection methods i.e. analytical ferrograph, SOA, X-ray, and light scattering.

3. The preponderence (99 percent) of wear particle generation resulting from disc scoring and bearing fatigue spalling failure is in the size range from 2 to 25 micrometers.

4. Comparison of all the oil detection methods has shown the bench type light scattering method to be effective over the largest filtration range.

5. Capacitive discharge chip detectors offer a promising method of reducing false failure indication while at the same time maintaining an effective level of actual failure indication.

References

1. Obendorfer R.E., Lazarick R.T., "Development of a Real Time Airborne Ferrograph", Proceedings of the 25th Defense Conference on Non Destructive Testing, Sept. 1, 1976, Boston Mass.

FIGURE 1: NOMINAL MICRON RATING FOR VARIOUS ENGINE OIL FILTERS

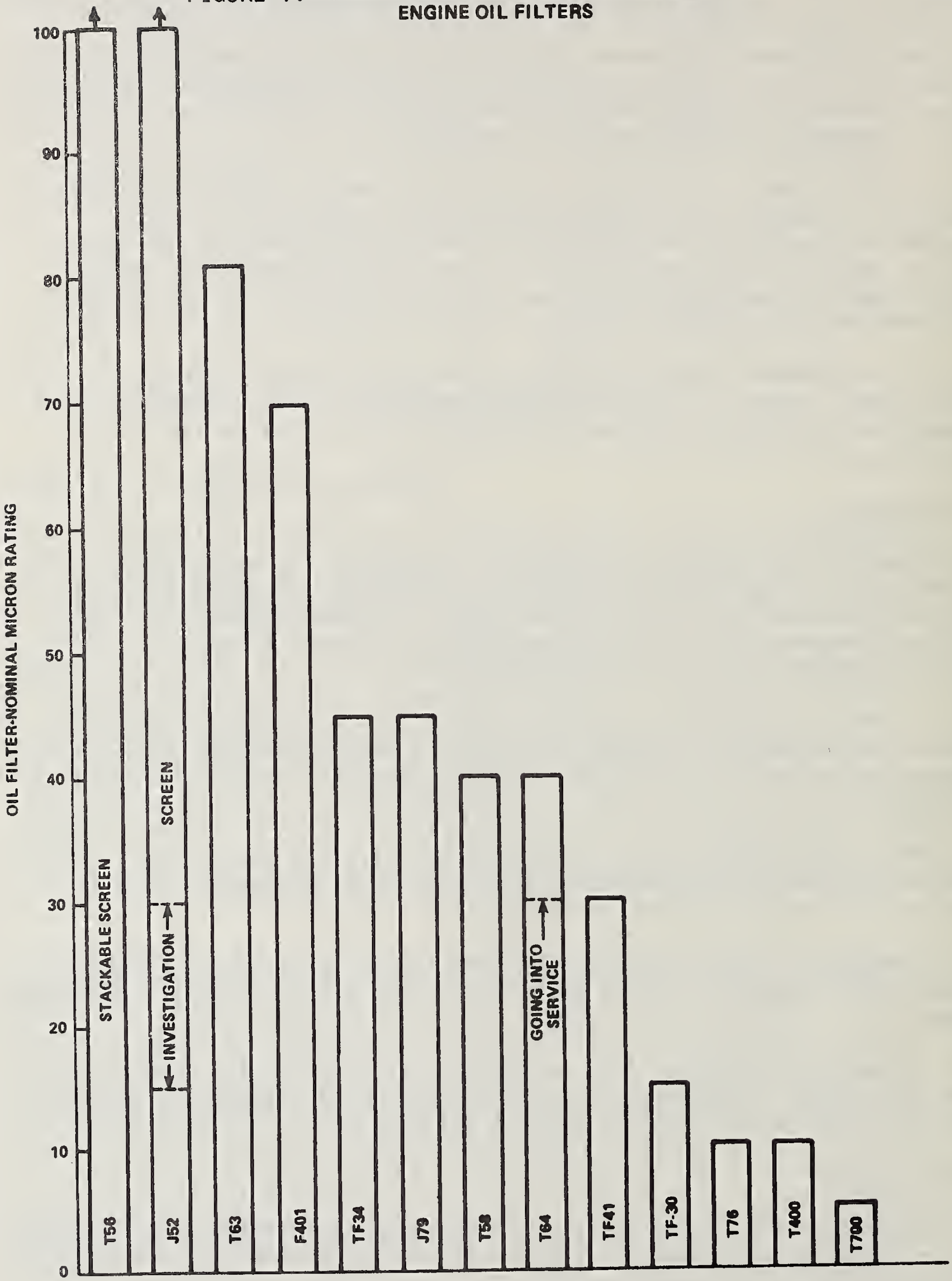


FIGURE 2: **GEARED ROLLER TEST MACHINE SCHEMATIC**

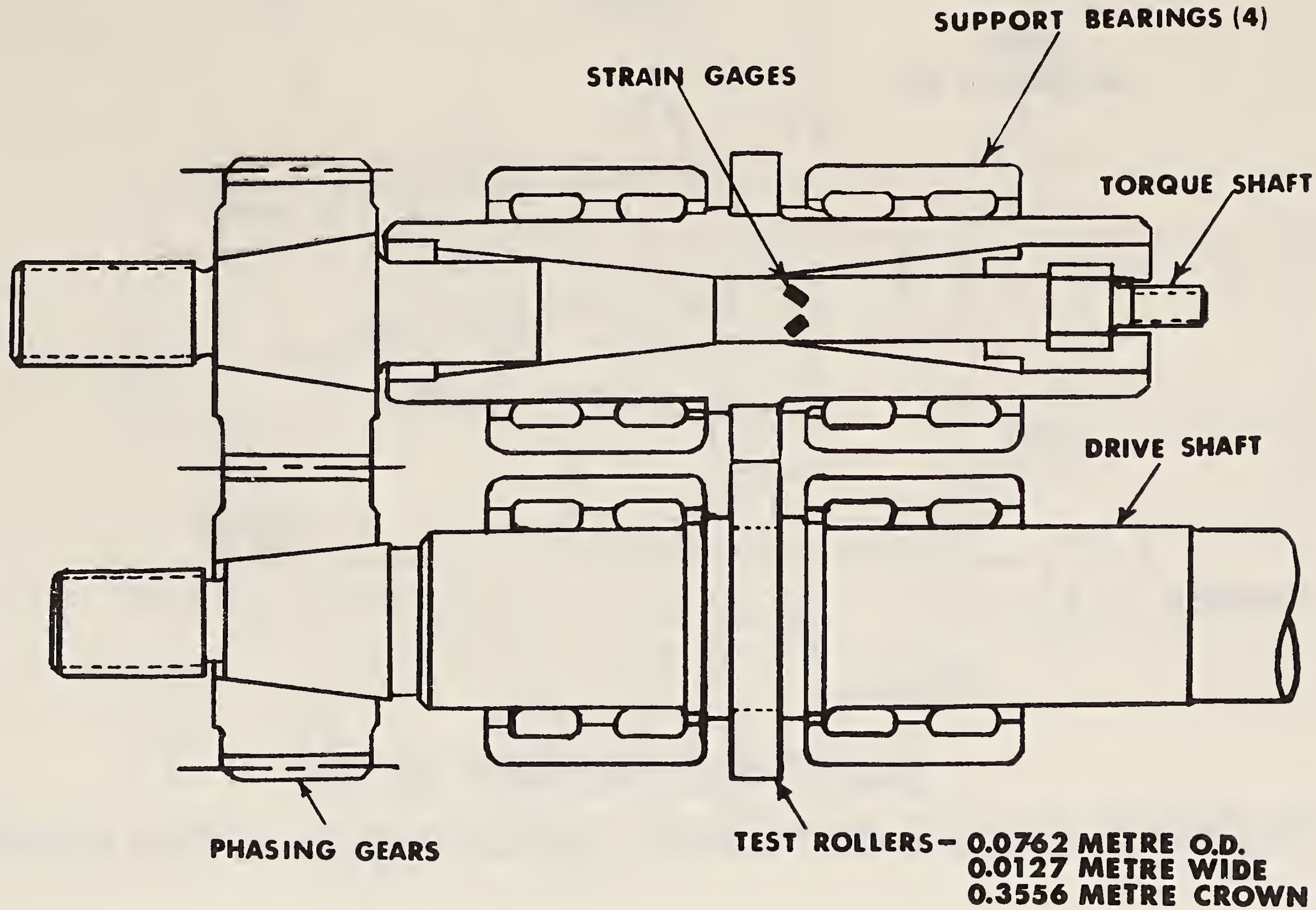
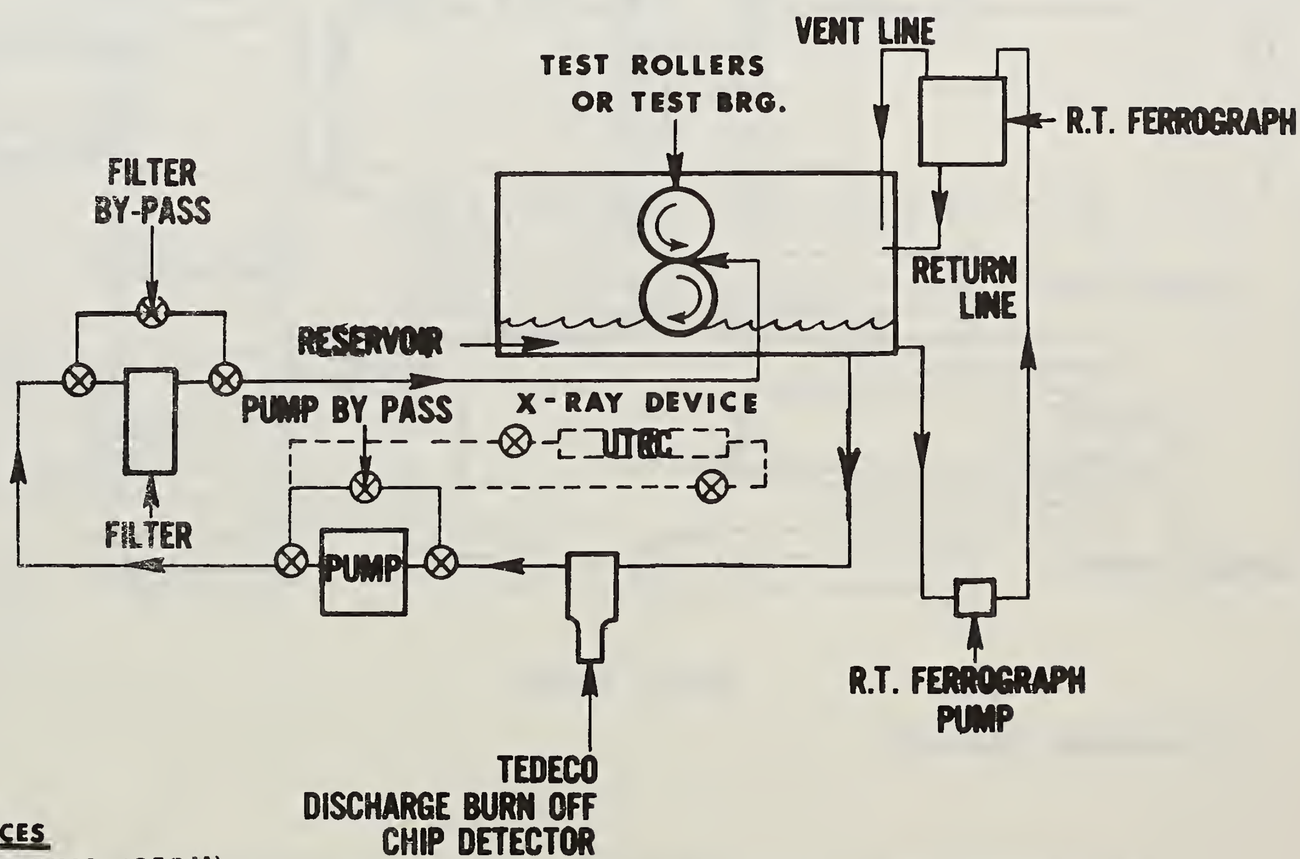


FIGURE 3

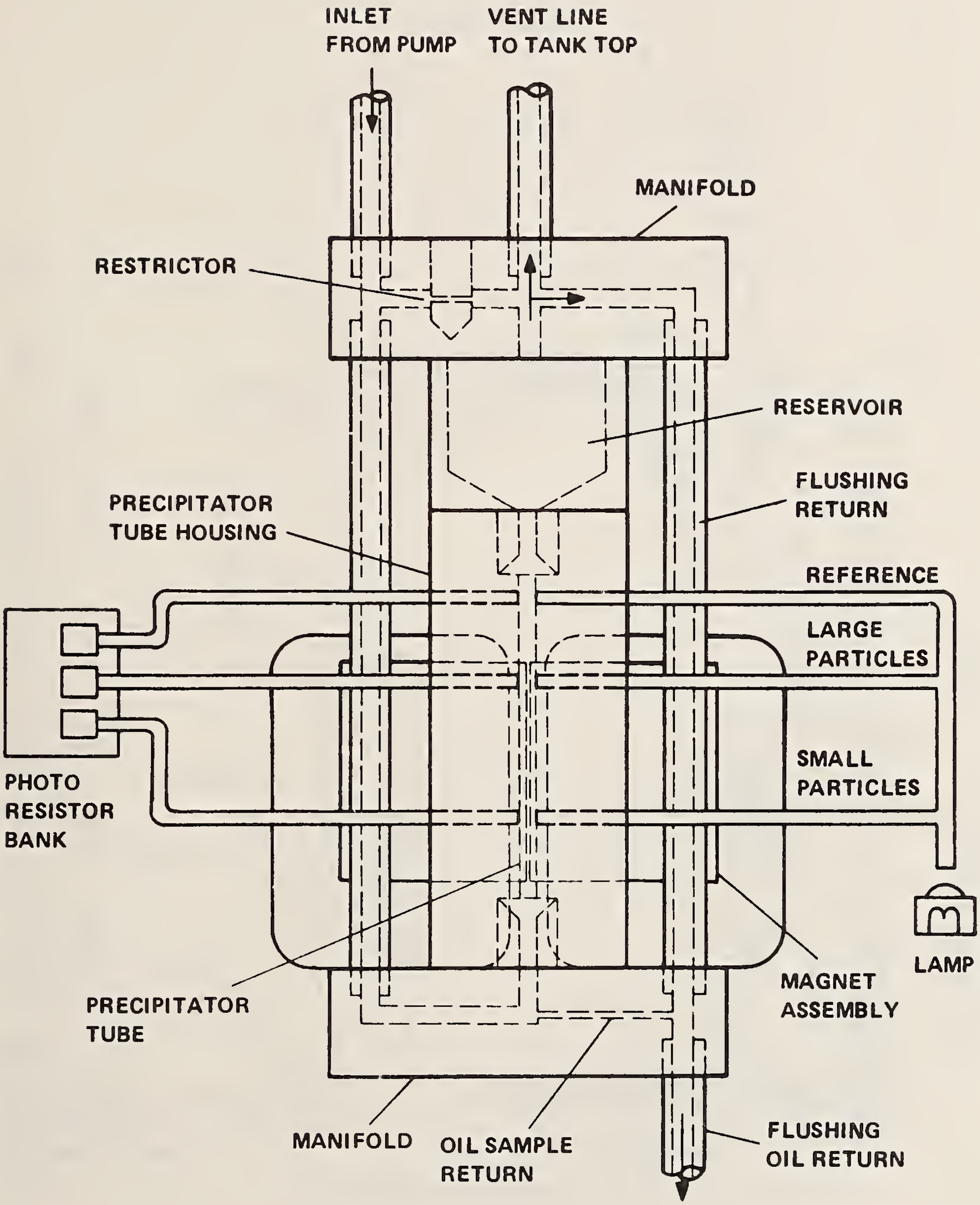
GEARED ROLLER TEST MACHINE LUBRICATION SYSTEM SCHEMATIC FOR OIL MONITOR EVALUATION



BENCH DEVICES

1. LIGHT SCATTERING (GEOM)
2. EMISSION SPECTROSCOPY

FIGURE 4



INTERNAL OIL FLOW & OPTICAL SYSTEM OF TYPE
7081 FERROGRAPH

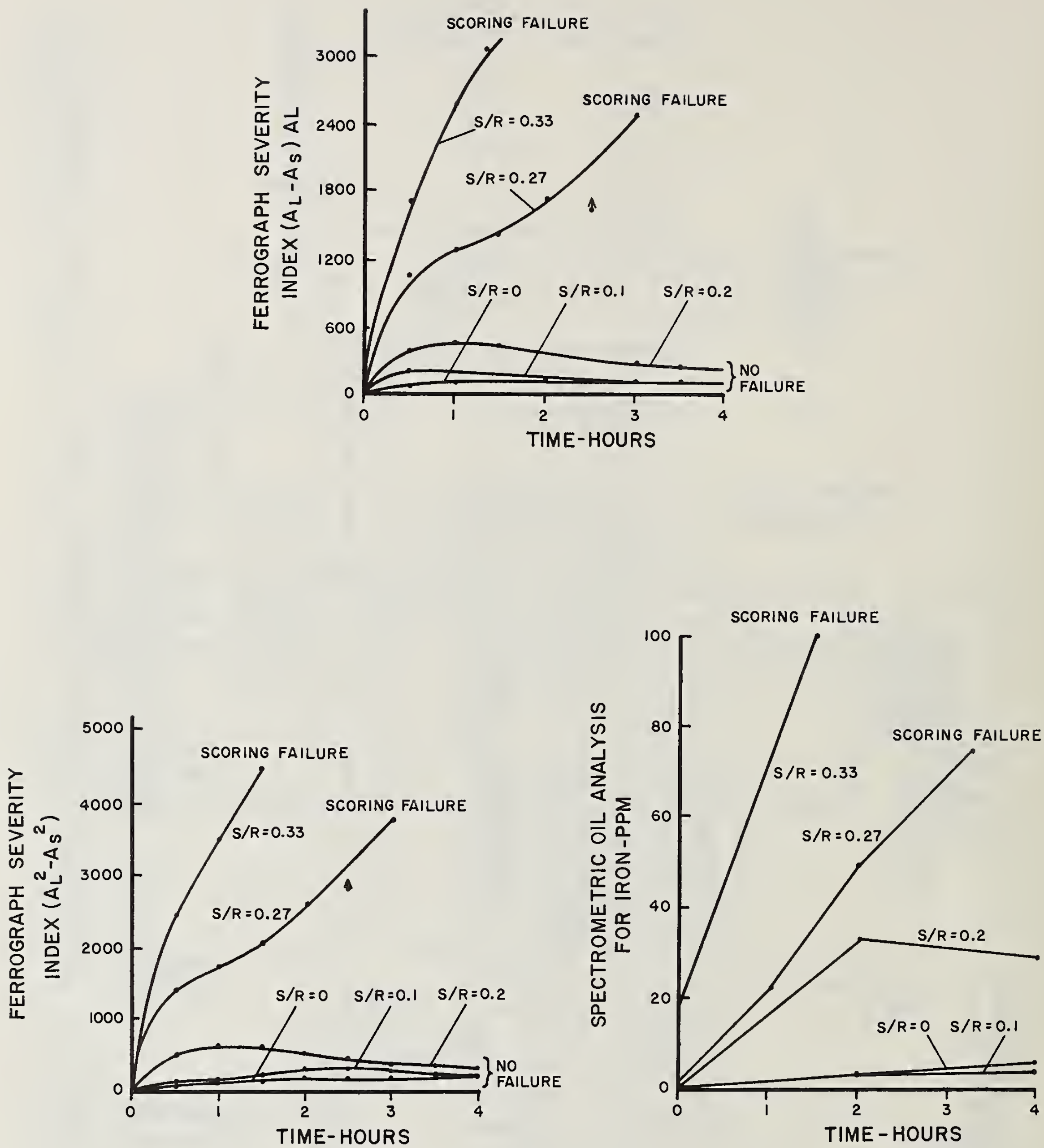


FIGURE 5 COMPARISONS OF THE R.T. FERROGRAPH READINGS AND SOA FOR VARIOUS SLIDE-TO-ROLL RATIOS ON THE GRTM

FIGURE 6

OIL MONITOR READING VS PERCENT RUNNING TIME FOR DISC SCORING TEST WITH NO FILTRATION

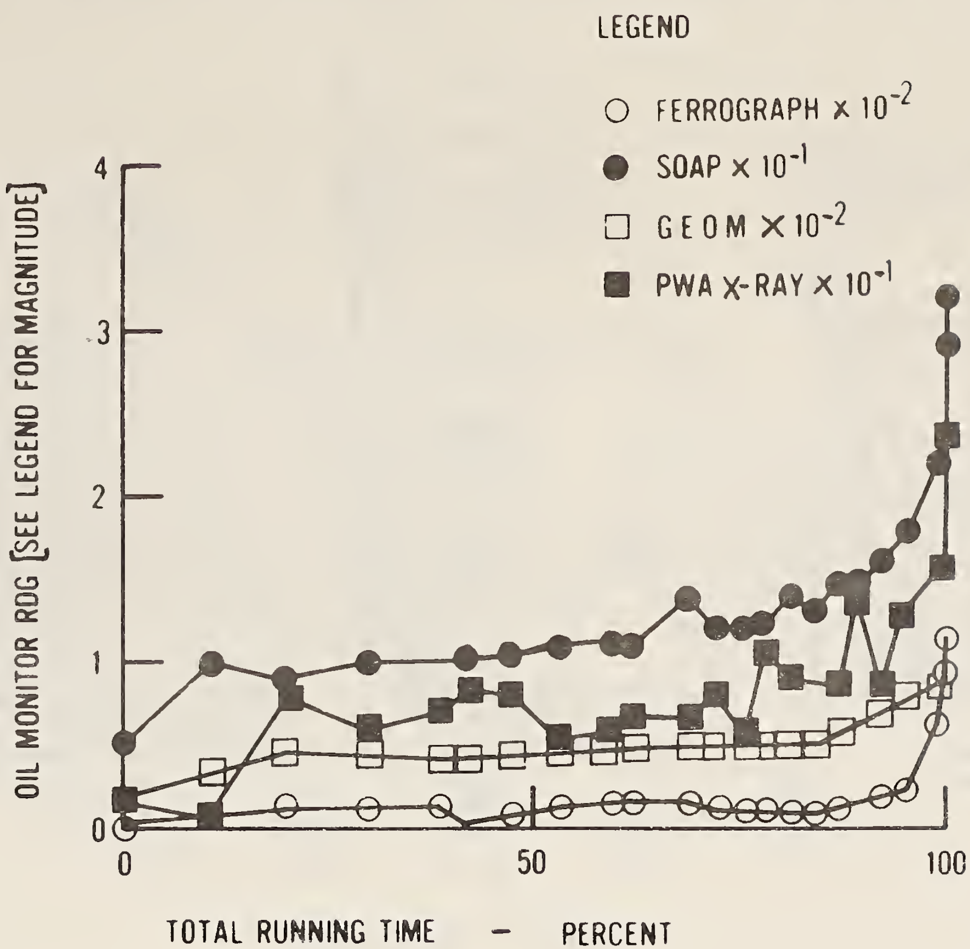


FIGURE 7 OIL MONITOR READINGS VS PERCENT RUNNING TIME FOR THE DISC SCORING TEST SERIES

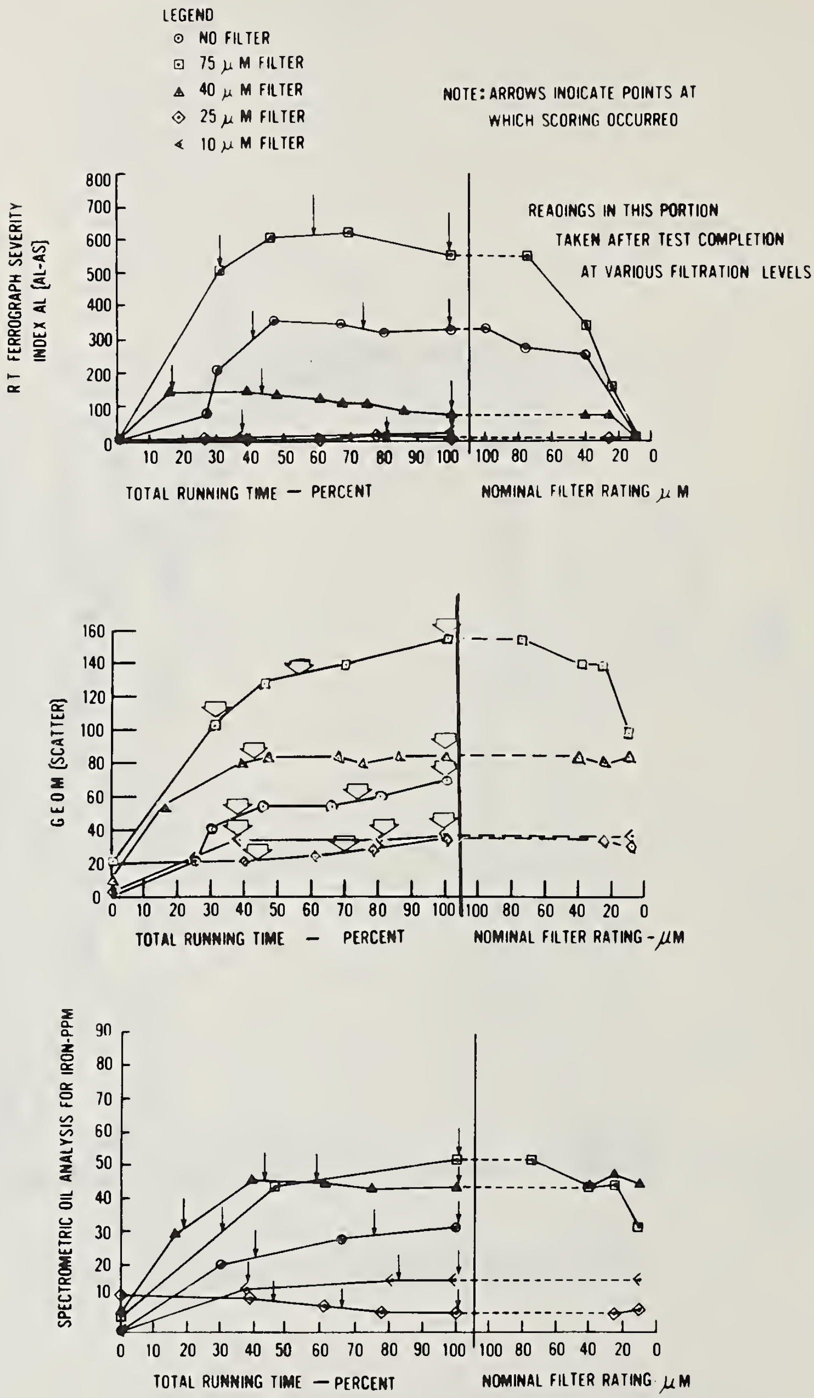
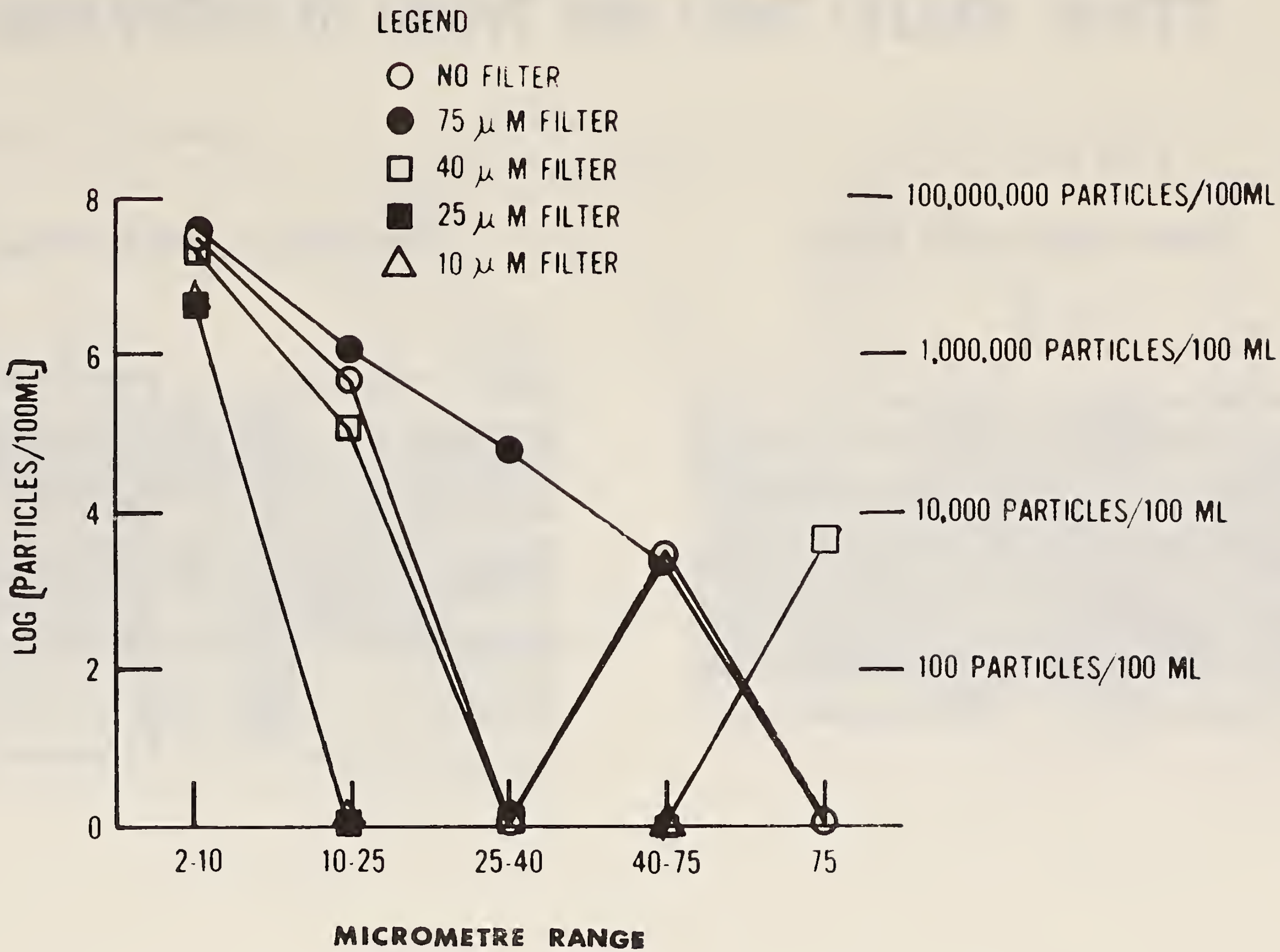
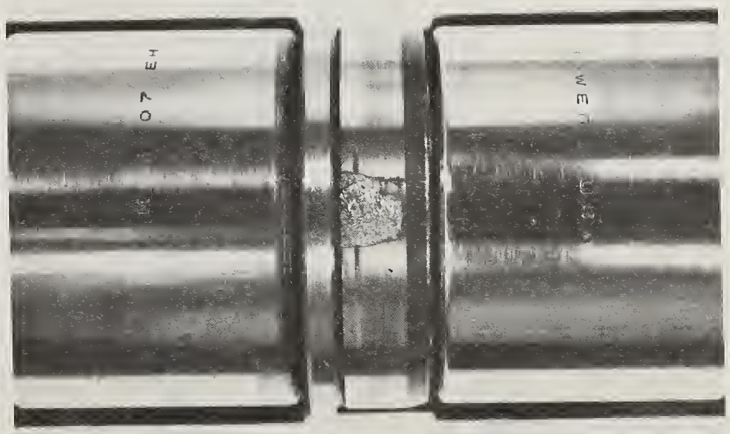
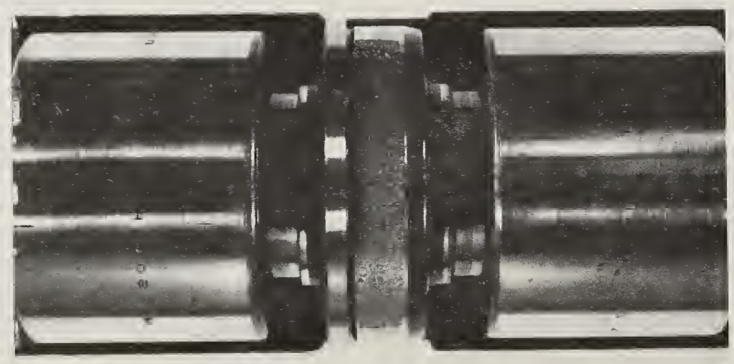


FIGURE 8: **WEAR PARTICLE DISTRIBUTION AT VARIOUS FILTRATION LEVELS FOR DISC SCORING TESTS**





TYPICAL INITIAL FATIGUE SPALL



TYPICAL FINAL FATIGUE SPALL

COMPARISON OF INITIAL AND FINAL FATIGUE SPALLS

FIGURE 9

FIGURE 10 OIL MONITOR READINGS VS PERCENT RUNNING TIME FOR THE BEARING TEST SERIES

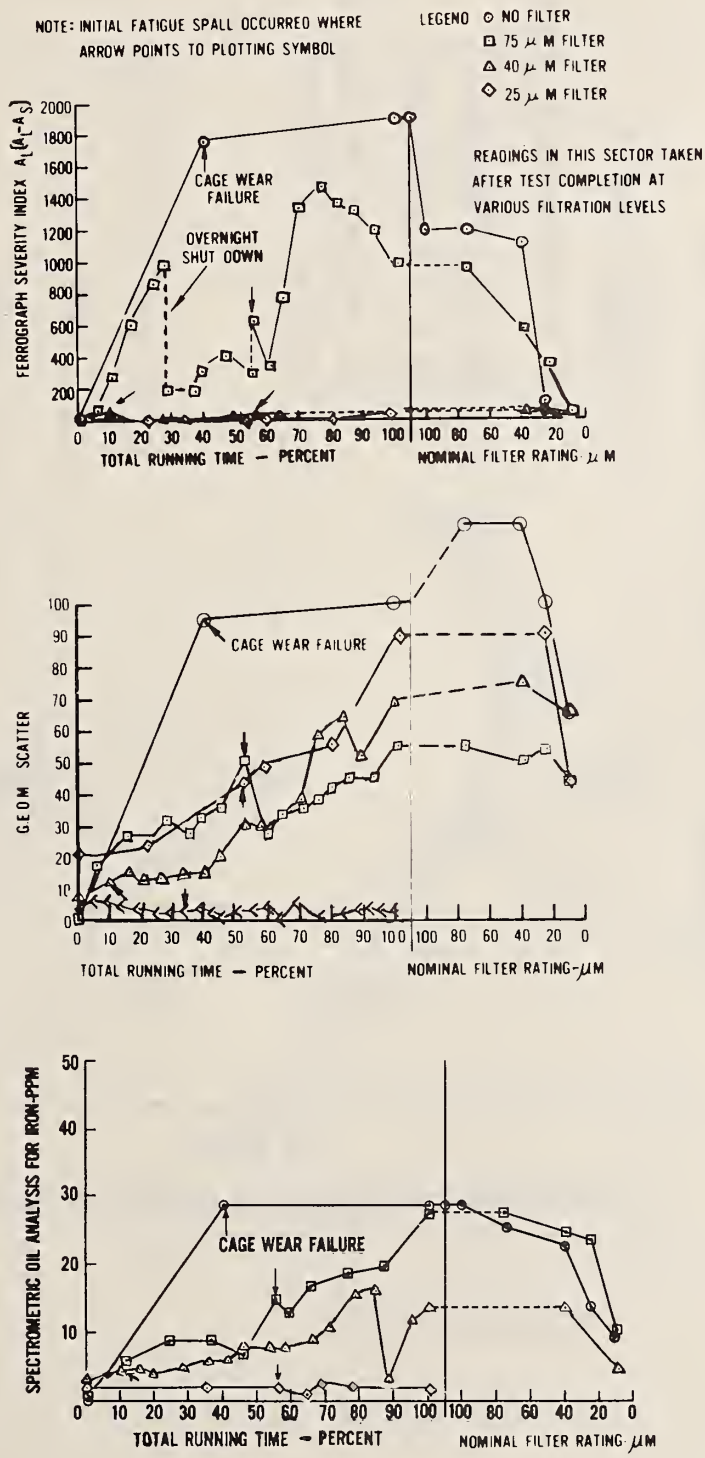


FIGURE 11

OIL MONITOR READING VS PERCENT RUNNING TIME FOR BEARING TEST WITH NO FILTRATION

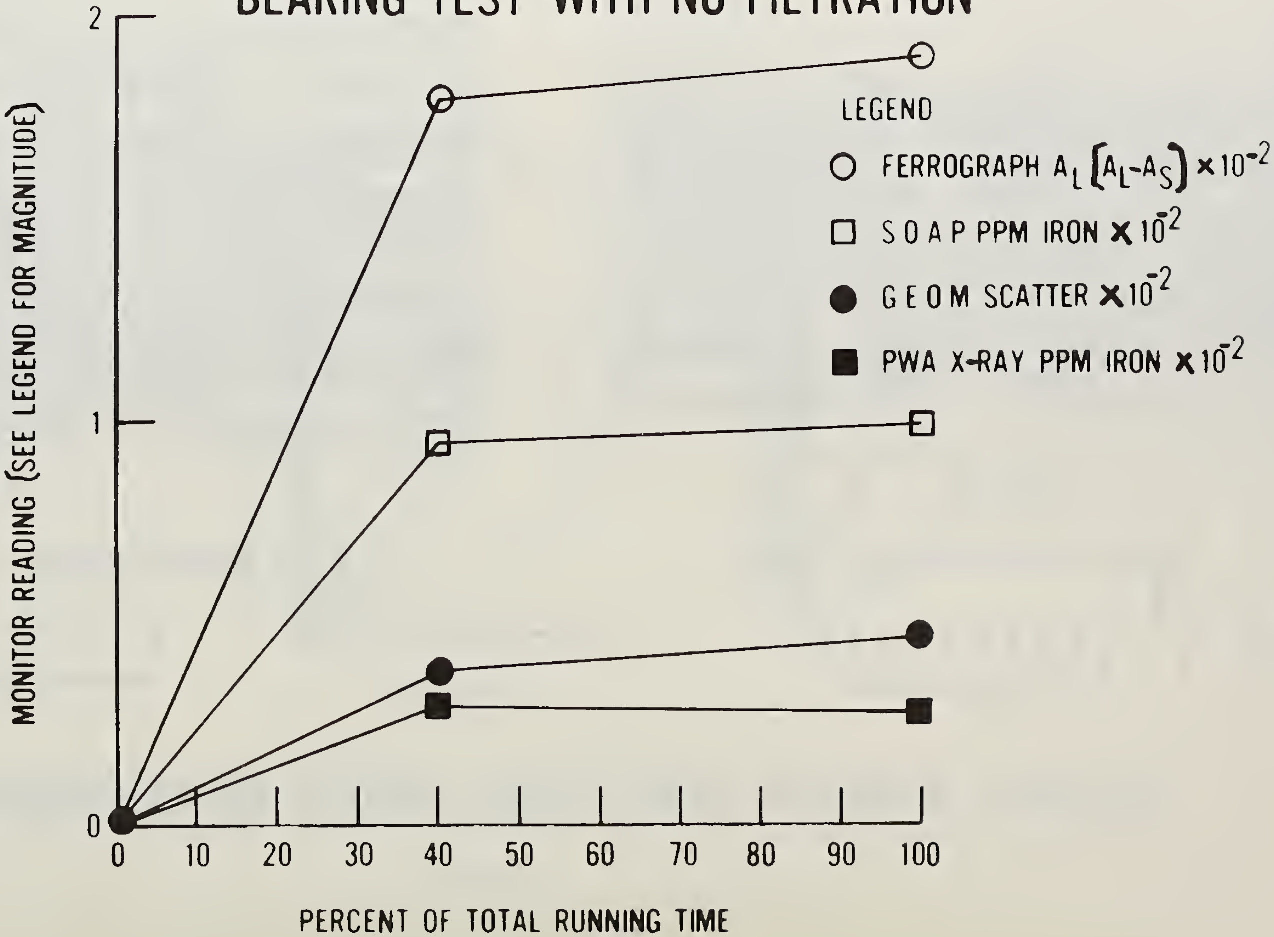


FIGURE 12

WEAR PARTICLE DISTRIBUTION AT VARIOUS FILTRATION LEVELS FOR BEARING FATIGUE TESTS

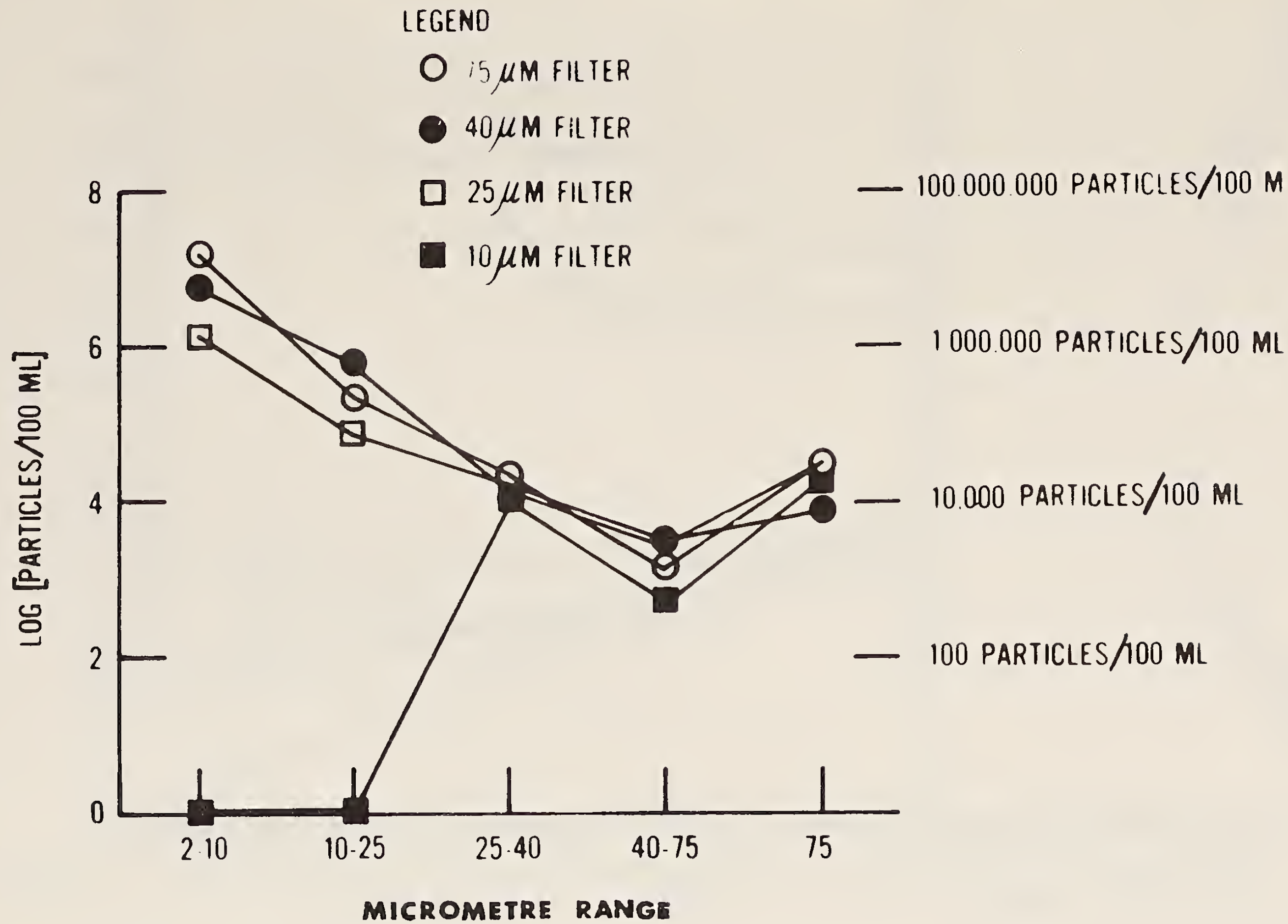


FIGURE 13: COMPARISON OF R.T. FERROGRAPH AND ENTRY DEPOSIT HEIGHT FOR BEARING RUN TO ULTIMATE FAILURE

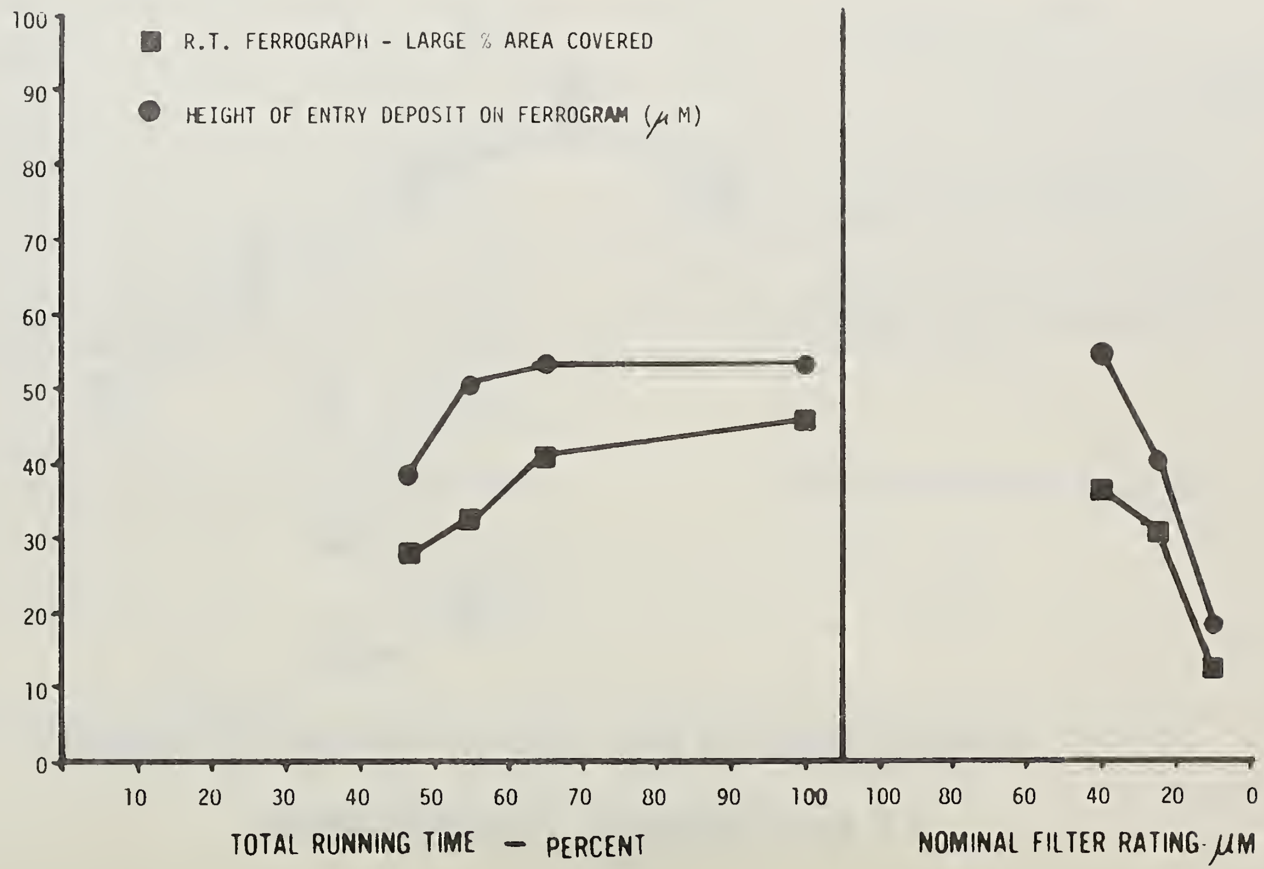


FIGURE 14: COMPARISON OF R.T. FERROGRAPH AND ENTRY DEPOSIT HEIGHT FOR A DISC SCORING TEST

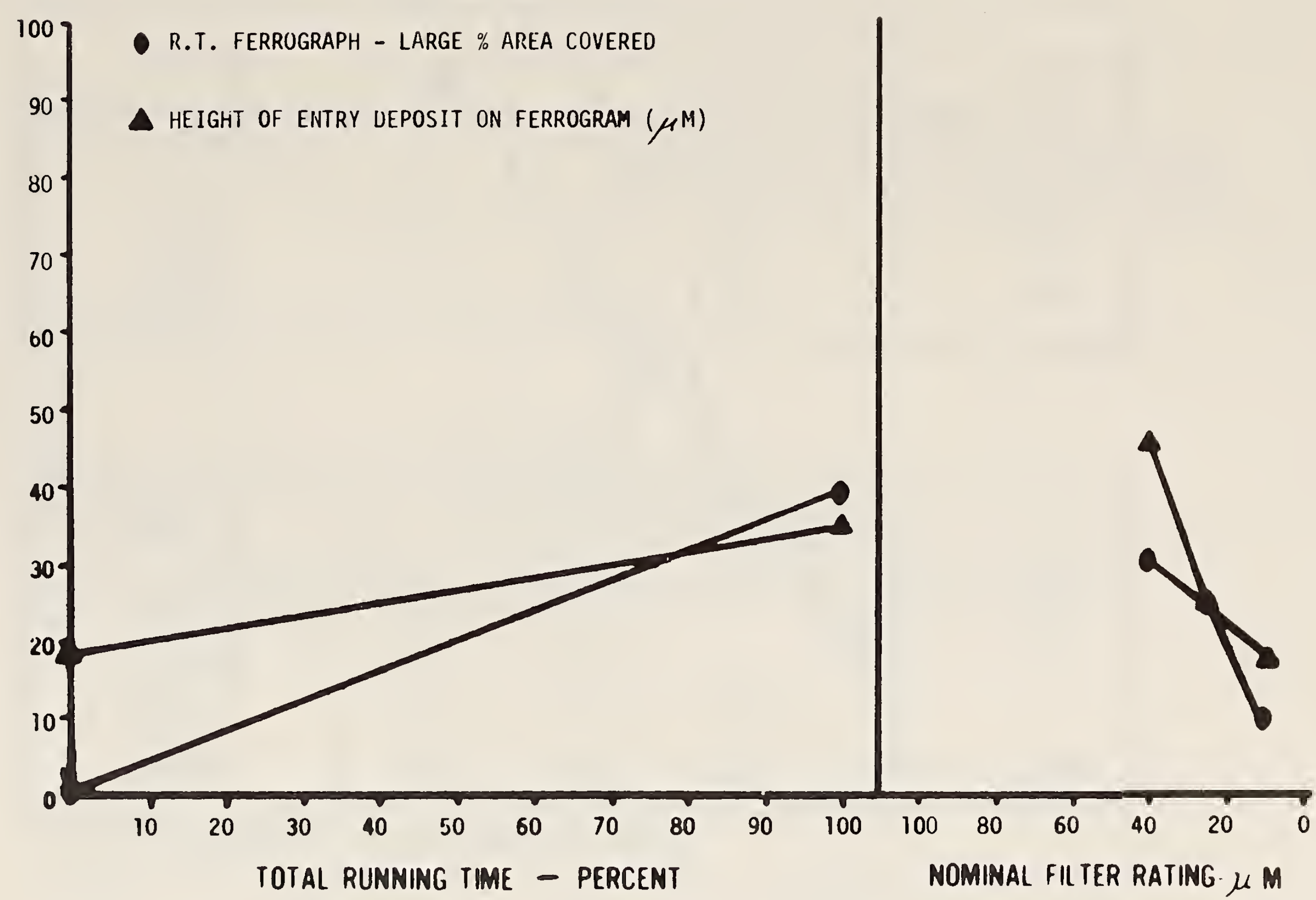


FIGURE 15: COMPARISON OF CAPACITIVE DISCHARGE PERIOD WITH R.T. FERROGRAPH READING

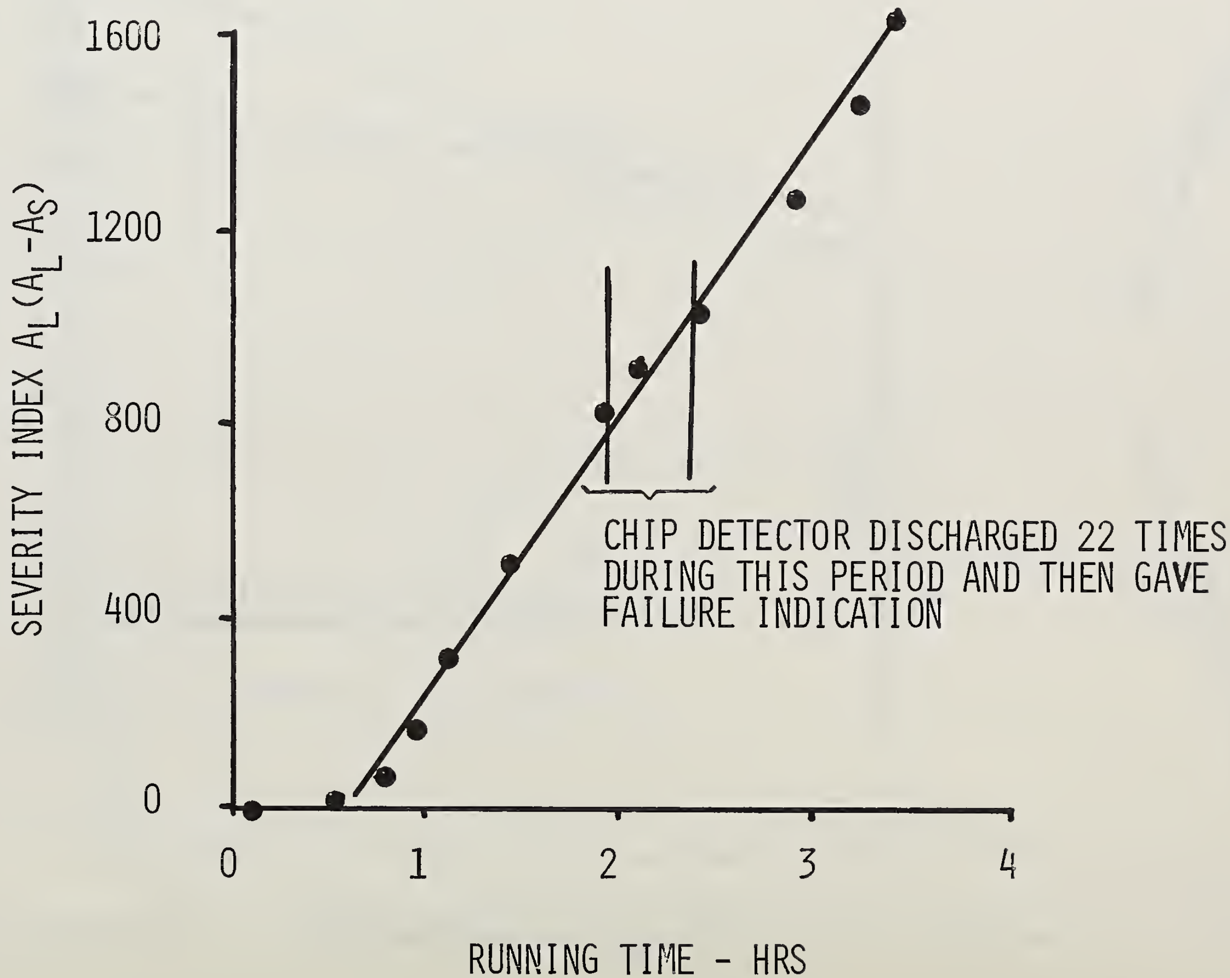


TABLE I: **EFFECTIVENESS OF OIL MONITORS AT VARIOUS FILTRATION LEVELS**

A. BEARING SPALL

MONITOR	FILTER SIZE (MICROMETRE)				
	∞	75	40	25	10
R.T. FERROGRAPH	YES	YES	NO	NO	NO
SOAP	YES	YES	NO	NO	NO
G.E.O.M.	YES	YES	YES	YES	NO
UTRC*	YES	N/A	NO	N/A	N/A

B. DISC SCORING

MONITOR	FILTER SIZE (MICROMETRE)				
	∞	75	40	25	10
R. T. FERROGRAPH	YES	YES	?	NO	NO
SOAP	YES	YES	YES	NO	?
G.E.O.M.	YES	YES	YES	?	?
UTRC*	YES	N/A	N/A	N/A	N/A

*X-RAY FLUORESCENCE

TABLE 2

PARTICLE SIZE DISTRIBUTION ON CHIP DETECTOR

RANGE μM	PERCENTAGE OF TOTAL
1 TO 10	75
10 TO 60	20
GREATER THAN 60	5

SMALLEST PARTICLE	1
LARGEST PARTICLE	125

FERROGRAPHIC SEPARATION OF ORGANIC COMPOUNDS

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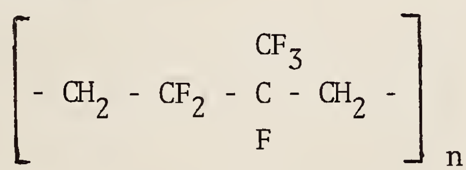
The separation of particles from a fluid medium by a magnetic force is analagous to separation by a gravimetric force. Any motion of a particle relative to its surrounding fluid medium due to a magnetic field as a function of the relative magnetic susceptibilities of both the particle and fluid, in much the same way as gravimetrically induced motion is a function of the relative densities. Consequently, for magnetic separation to be achievable, there must exist a difference in the magnetic susceptibility of the particle relative to the fluid medium.

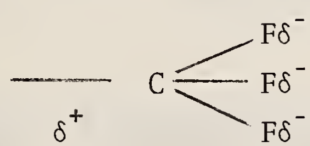
If a sufficiently high combination of field strength (B) and field gradient (∇B) exists, this difference in magnetic susceptibility need not be great. That is, it is neither fundamental nor necessary that the particles be ferromagnetic. Indeed, current Ferrograph Analyzers readily separate paramagnetic particles and non-magnetic particles which have induced magnetic moments due to attachment during the wear process of relatively small amounts of ferromagnetic material.

The following text briefly describes how chemical adsorption has been used to induce paramagnetism in certain organic materials.

The majority of organic compounds are polar in nature. That is, while the molecule is macroscopically electrically balanced, local imbalances exist within the molecule. For instance, the polymer viton has the following molecular structure:



While the overall structure is electrically balanced, the carbon-halogen side chains are polar. Consequently, although one cannot expect any ionic bonding, such structures might be expected to behave electrostatically.



Even theoretically non-polar polymers such as polyethlyene appear to exhibit polar characteristics, apparently due to macroscopic straining during extrusion and radiation induced cross-linking.

It has been found that when metal cations of magnetic elements such as iron or nickel are introduced into a mixture of organic particles and a liquid, sufficient metal cations are adsorbed onto the surface of the particles to raise the magnetic moment of the particles above that of the fluid medium. Thus, a magnetic separation is achievable. The cations are introduced as salts that are soluble in the fluid medium. In the case of aqueous solutions, this is relatively easy, while their use with oleophilic mistures may require the use of transitionary fluids such as an alcohol.

While the modes of attachment of these cations to the particles is understood, the precise magnetic moment of the attached cation and the parameters which influence that value as compared to the free cations in the fluid are unclear. Consequently, work is being undertaken to qualify the technique and establish its field of applicability.

The technique is currently being applied in two areas of research. Firstly, analysis of human synovial fluid for particles of bone and cartilage. Here there exists an excellent opportunity to significantly improve the diagnostic tools available for the examination of arthritis and other joint disorders.

Secondly, in the separation and examination of organic particles in machine hydraulic fluids. The particles are generated by the wear of seals and gaskets within the system. Currently, there are no indirect means of positively assessing the wear of these seals.

SESSION II

SIGNATURE

ANALYSIS

TECHNIQUES

CHAIRMAN: R. F. MISIALEK

NAVAL SHIP ENGINEERING CENTER

MECHANICAL SIGNATURE ANALYSIS AS A FIRST STEP IN QUANTIFYING THE CHARACTERISTICS OF OPERATING MACHINERY

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Although techniques are available to experimentally determine the characteristics of operating machinery they are generally precluded in all but extreme cases by considerations of time and cost. As a result, the most common method to analyze machinery depends on spectrum or signature analysis to quantify characteristics. From this point on machinery analysis is a learning process where components and characteristics are related to their generating mechanism or event. The knowledge thus gained then becomes the key to deciphering the performance of other machines and the process repeats.

The events and characteristics focused on during a typical analysis may be common to a machine type, common to a component such as an anti friction bearing, symptomatic of a problem such as bearing instability or coupling misalignment or perhaps even generated by a combination of the foregoing.

Assessing characteristics by machine type is relatively simple to execute and has been used for years on machinery such as jet engines where a large number of identical units can be sampled. Selecting the signature obtained from one unit as a norm to which others are compared is one technique, however, a more accurate method is to construct a statistical median signature from a large sample group. Although the median signature may not represent a specific unit it, plus some tolerances, provides a convenient baseline to gain a rapid and accurate assessment of the condition of similar machinery.

When the machines are not identical but only similar the problem becomes much more difficult. Gears, for example, may behave quite differently due to differences in design and construction. In a situation such as this it is necessary to seek out common factors, learn how they behave as a group, then attempt to extrapolate that knowledge to other units. A recent series of unconnected gear failures is a good illustration of the latter, for in each case the symptoms of failure were the same although the gears operated at different speeds. Although the commonalities may not be recognized until long after the actual occurrence the lessons learned will hopefully enable early recognition of future problems and thereby play a decisive role in preventing outright failure.

Identifying the characteristics of specific mechanical components such as blading and anti friction bearings is generally not difficult. The difficulty, however, arises when one attempts to assess condition from a vibration signature. In many cases the differences between a good component and a bad component are very subtle in nature and difficult to detect. Quite often the subtleties can be greatly enhanced by pre conditioning such as envelope detecting a high frequency signal prior to reducing it to its spectral representation.

The symptoms of common problems such as instability, unbalance or misalignment are generally very similar between machine types even though the machines themselves may be quite different. The general approach and fundamental rules of diagnostic analysis have been known for years and are only being refined by signature analysis.

Despite the fact that the instrumentation for signature analysis is highly refined and well understood interpretative skills are still in their infancy. Signature analysis provides the vehicle; what is needed now is study, comparison, extrapolation and of course learning through failures as well as successes to build a sound technology.

SPECTRUM ANALYSIS AND MACHINERY MONITORING

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Process industries have long recognized the value of applying trend analysis to the maintenance of expensive equipment. In its simplest form trend analysis embodies measuring certain specific variables from an operating machine at regular intervals throughout the life of that machine. Problems are frequently predicted before catastrophic failures occur by noticing unusual changes in the level of a monitored variable.

Initial trend analysis using vibration data was conducted by recording overall levels of vibration at specific locations on a machine. The most frequent choice trend variable for such simple studies is velocity measured around the bearing locations of the machine. A considerable body of historical information lends credence to the argument that machines in a similar state of health exhibit similar velocity levels regardless of their operating speeds. Although a somewhat simplistic assumption, this observation had lead to the widespread use of velocity trending as a "frequency independent" indicator of a machine's vibratory state.

More modern approaches to the problem involve recording spectra from measured variables rather than a simple overall level. In these more modern implementations, the most popular measurement variable is the relative displacement between rotating shafts and their fixed supports. Most frequently these measurements are made from proximity detectors permanently installed near the bearing caps of the monitored machine. Typically, two proximity probes (perpendicular to one another) are installed at each bearing location. In some installations, an additional probe is used to view the position of a thrust washer giving an indication of axial excursion of the shaft. Axial motion is also monitored in many programs by measuring axial direction velocity in the neighborhood of the bearing cap.

The signals from these fixed transducers are monitored by recording spectra in each position on a regular interval. Comparison of these spectra can indicate changes in the balance (due to rotor wear or loading) as an increase in the rotative speed component of the spectra. The long term operating speed stability of the machine may also be trended by the frequency location of the rotative speed component. An increase in harmonics of rotative speed is often indicative of misalignment or looseness between elements of the machine occurring due to changes in the foundation or thermal shifts. Additionally, sub-rotative components (as well as harmonics of rotative speed) are indicative of the state of health and clearance of fluid film bearings.

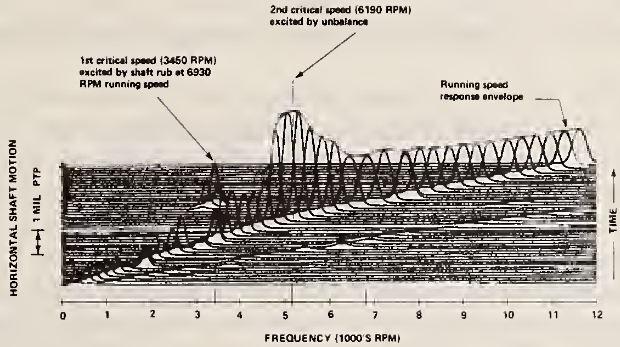
Such measurements generally fall in the "low" frequency category and are indicative of the condition of the machine at the time the measurements are taken. Prediction of machine failure is normally not done from such measurements, rather they are used to justify corrective action on a scheduled basis.

"Higher" frequency observations, normally made by measuring accelerations from the fixed system of the machine, are often indicative of gear and bearing wear. Such trending is based on changes at frequencies associated with the contact rate of gear teeth or rolling elements of bearings. In general, these measurements are used to "head off" problems before they display themselves in the lower frequency measurements as "today's problem".

Trending spectra of both types often permit the early detection of difficulties in the peripherals associated with large machines. Potential control system failures often give early warning in terms of the speed stability exhibited during the spectrum measurement. Observation of permanently installed transducers during typical operating cycle often disclose difficulties associated with peripheral plumbing, lubrication pumps, filters, etc.

Spectrum analysis can be particularly useful during the normal start-ups and shut-downs of a major machine. During initial commissioning of such a machine basic parameters such as the frequency of shaft critical speeds and local structure resonances can be identified. The start-up and shut-down operations often allow forcing functions to be applied to the machine that are not normally seen during the operating cycle. These forcing functions can disclose mechanisms of the machine that should be well understood as an aid to interpretation of possible difficulties indicated by trending spectra. Machine run-ups are particularly useful for determining the state of balance of the machine as well as shaft clearances from seals and fluid film bearings.

The following figure is a "stacked plot" of 45 spectra recorded in rapid sequence during the start-up cycle of a small machine. These spectra were recorded from a horizontally oriented proximity probe near one of the bearings of the machine. The rather dominant "mountain range" running from the lower lefthand corner to the upper righthand corner is the path line of the rotative speed of the machine. This path line generally discloses the critical speeds of the machine although it is often necessary to record two perpendicular transducers to be certain all criticals have been examined. This is especially true in machines that lack symmetry of bearing stiffness.



Below the rotative speed path line, a small "mountain range" can be seen. This is the path line of the second harmonic of rotative speed. A lack of significant amplitude in this path line indicates that no major misalignments or foundation looseness are present. In general, either of these conditions will cause the motion of the shaft to be non-sinusoidal, with a strong increase in the harmonics of rotative speed.

Of particular importance in the above figure is the very small "mountain range" occurring in the 3000-4000 RPM range above the rotative speed path line. This is an indication of sub-rotative speed excitation. Such excitations are normally indicative of an instability in the system. This is typical of a machine with a seal rub or bearing clearance problem. In this example, the instability was deliberately introduced by causing a metallic "rub" between the shaft and the housing of the machine. Although sufficient clearance existed to preclude any rubbing in the operating speed of the machine, during the run-up a particular set of circumstances formed that caused the sub-rotative excitation. These conditions are typical of those required for sub-rotative response. They are:

1. The machine must have some initial unbalance. In a practical sense all operating machinery have some residual unbalance.
2. A close clearance must exist between the fixed and rotating elements of the system.
3. The machine must be operating at a rotative speed that is approximately twice one of its critical speeds.

In the above figure, sub-rotative response occurred when the machine was running approximately twice its 3450 RPM first critical speed. Sub-rotative responses of this form are a very strong indication that the machine in question should be closely monitored on a frequent basis. Possible locations of interference should be identified. Appropriate components should be on hand prior to next scheduled stoppage of the equipment. Further, during the shut down of the equipment every effort should be made to pass through the "twice critical" speed regime as rapidly as possible to minimize the damage potential.

COMPARISON OF VIBRATION SIGNATURE ANALYSIS TECHNIQUES

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Many different approaches are used in the analysis of vibration data. Too often a machinery monitoring system will be developed that is based on a single approach. This reduces the value of the system because to extract the maximum diagnostic information usually requires a combination of analysis techniques selected on the basis of expected machine failure modes. This paper describes several techniques and briefly describes a machinery monitoring system to be installed in a nuclear power plant that combines all the techniques discussed.

Figure 1 displays spectra from the same machine for a displacement sensor, a velocity sensor and an accelerometer. It is obvious that if it is desired to monitor once per rev motions of a shaft in a slow machine that displacement probes offer significant advantages. On the other hand, if high frequency gear mesh signals are of interest then an accelerometer based system is favored. Velocity is a useful compromise between the two and many alarm systems are based on a velocity amplitude limit.

Many investigators are using accelerometers to provide data on very much higher frequencies than shown in Figure 1. Figure 2 shows the accelerometer output for a rub condition in a hydrogen compressor. The information that is useful here is the source of excitation for this high frequency resonance. An analysis technique to handle this high frequency vibration is shown in Figure 3. Amplitude pulsations are shown in the amplitude versus time displays and the resultant spectra before and after demodulation are also shown. The impact rate for the excitation is available from the frequency content of the low frequency demodulated spectrum.

Figure 4 compares two spectra, one from the low frequency vibration region and the other a spectrum of a demodulated high frequency resonance. In addition to higher signal levels, the demodulated spectrum allows the analysis of signals occurring at electrical noise frequencies.

The other extreme in vibration frequency response is information contained in the D.C. levels produced by displacement probes. Figure 5 shows the shaft locus in a bearing and shows that at low powers, the shaft rides against the top half of the bearing. In this particular case, the bearing is not designed for this type of operation and damage to the machine results in continued operation at this condition.

Another technique that is used to extract a signal from noise is time series averaging. Figure 6 shows the improvement in signal to noise ratio by synchronously averaging a signal buried in noise.

Synchronous signal sampling has other valuable side benefits. Runout errors in displacement probes may be removed by synchronously sampling the probe output at an N/rev rate at low speeds and subtracting this signal (again synchronously) at all higher speeds. Figure 7 shows the runout memorized and subtracted to remove the error. Figure 8 shows the benefits obtained by runout correction for an amplitude versus speed plot of the once per rev vibration component in a machine start up. Figure 8 could have been obtained by using a tracking filter if the machine acceleration were not too great. For very fast acceleration the data shown in Figure 8 can be calculated once for every revolution using the relationship shown in Figure 9 if an N per rev signal is generated by the machine.

Figure 10 is the block diagram of an automatic machinery monitoring system that employs all the techniques discussed above. Synchronous sampling is employed for machine start-stop data as well as runout correction. Spectral data is available for steady-state operation and an envelope detector may be inserted ahead of the FFT for high frequency analysis. The monitor provides continuous surveillance of the machines and alarms on velocity amplitudes for accelerometers. This portion of the system operates even if the computer malfunctions.

This system will be evaluated in a nuclear power plant in 1978.

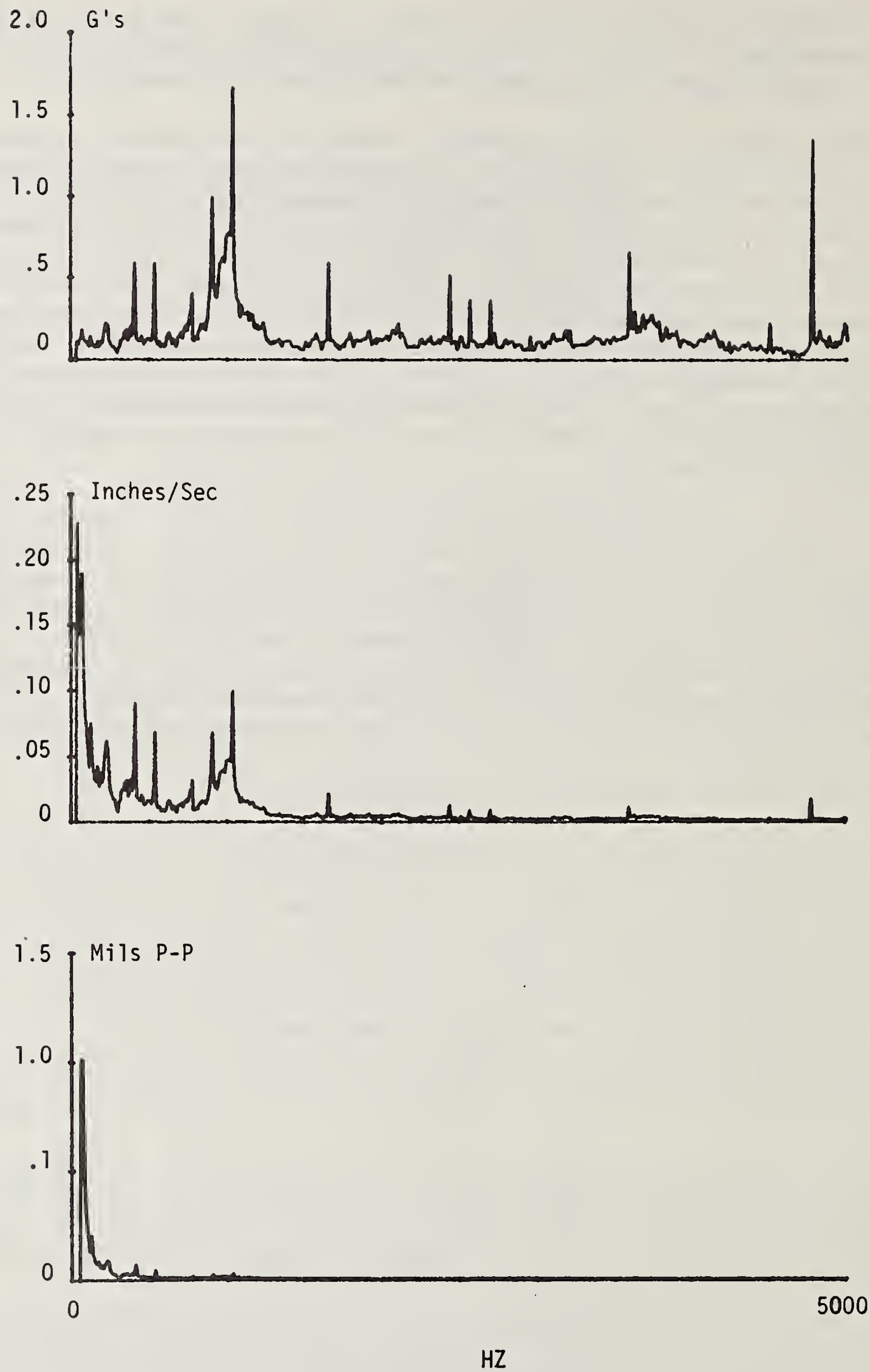


Figure 1 DISPLACEMENT VELOCITY AND ACCELERATION SPECTRA

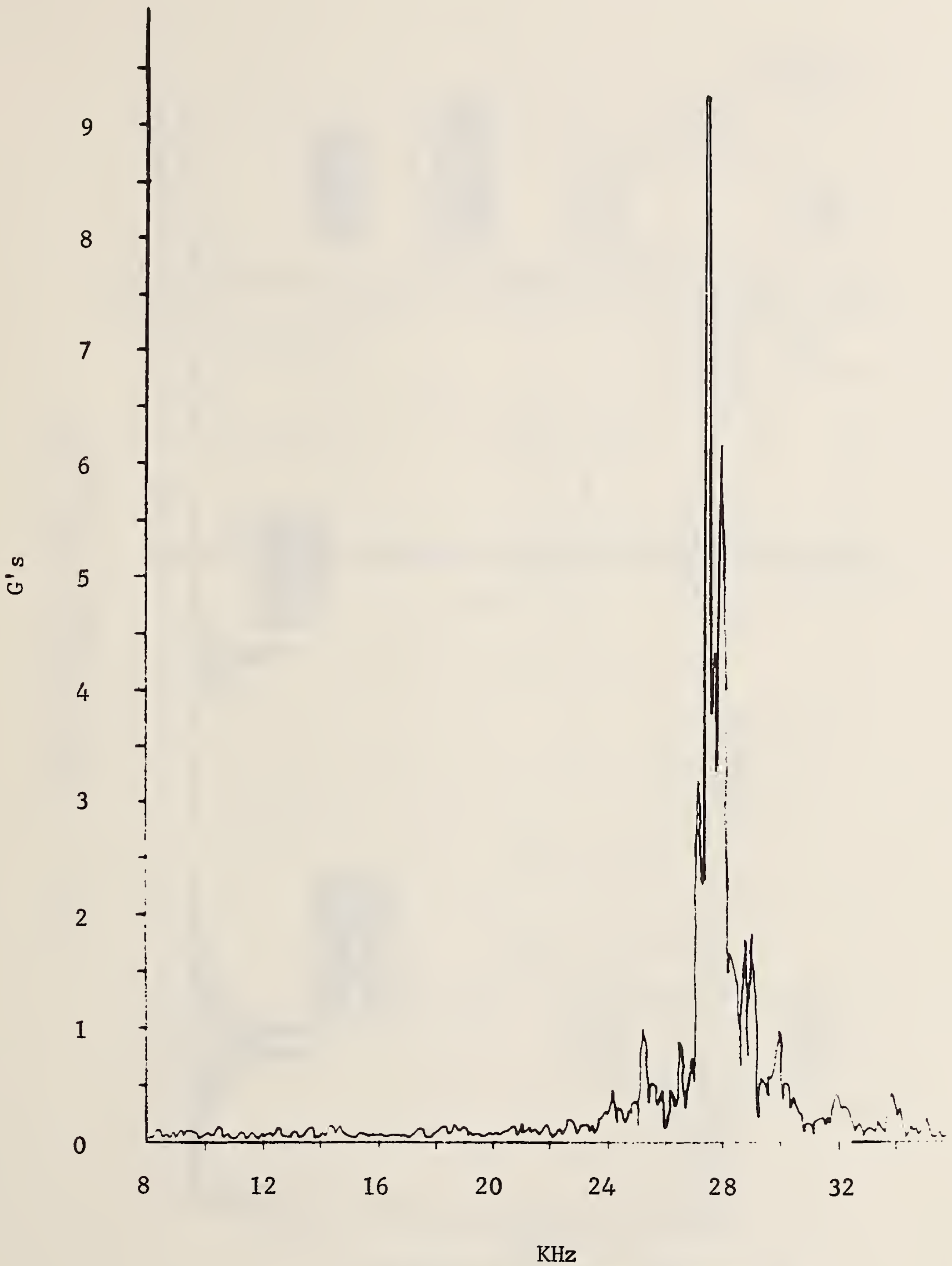


Figure 2 HIGH FREQUENCY VIBRATION

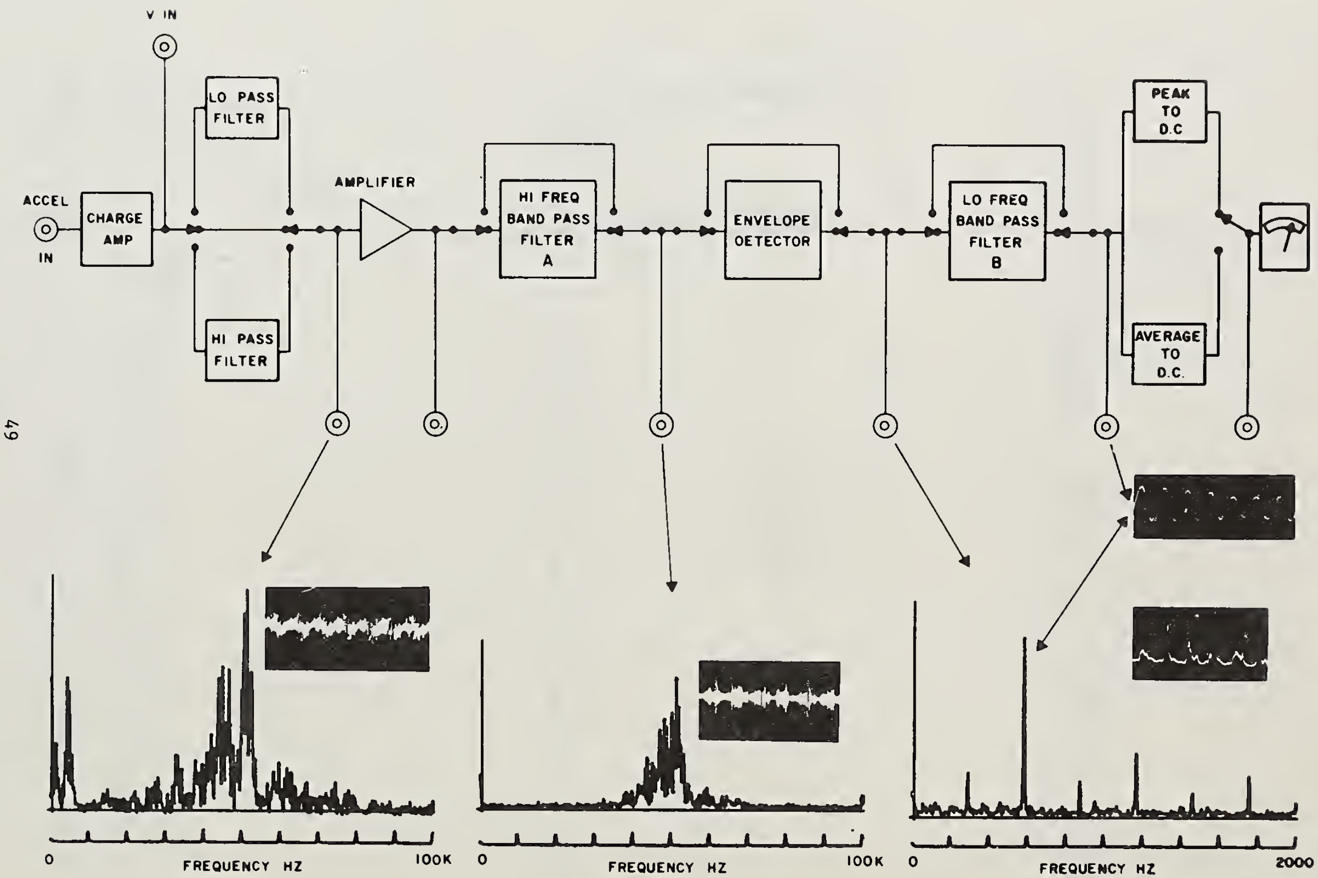


Figure 3 VIBRATION ENVELOPE DETECTOR BLOCK DIAGRAM & SIGNAL FLOW

49

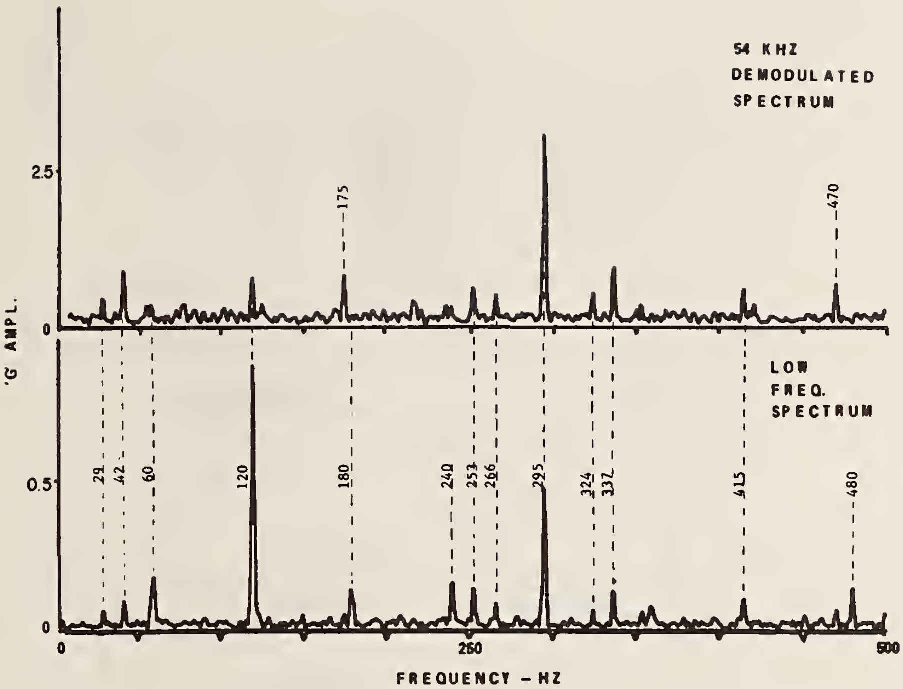


Figure 4 LOW FREQUENCY VIBRATION
VERSUS
DEMODULATED HIGH FREQUENCY

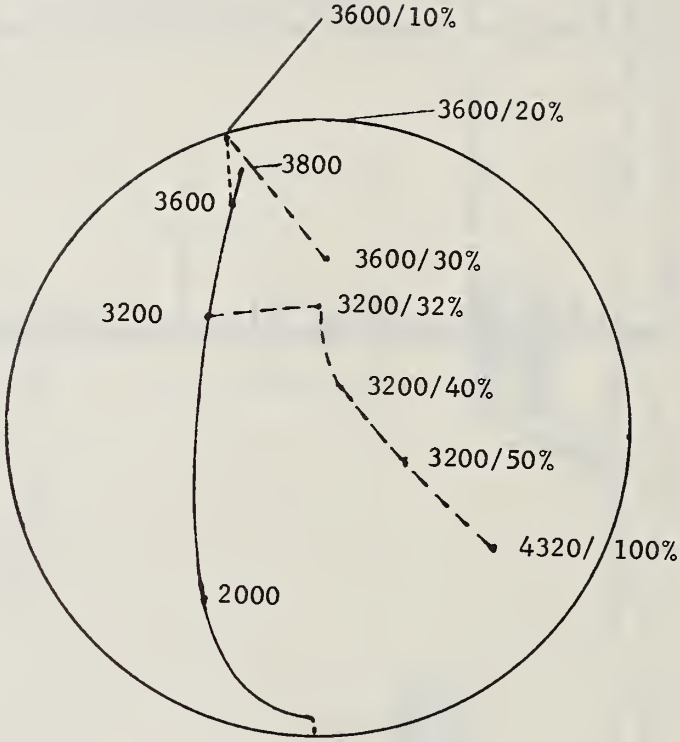
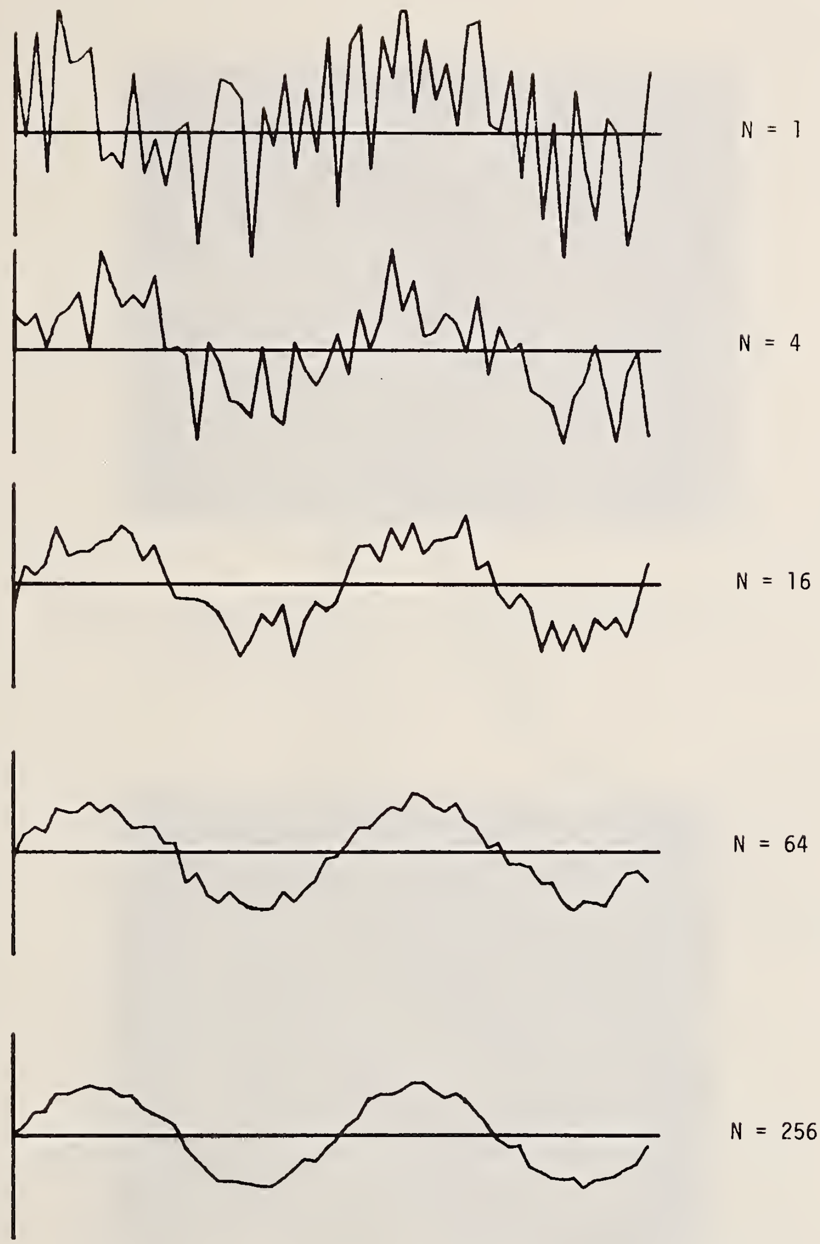


Figure 5 BEARING LOCUS FOR A PUMP UNDER VARYING LOADS AND SPEEDS



Signal = 0.5
Noise = 1.0

Figure 6 TIME SERIES AVERAGING

Figure 7a Top Uncorrected Probe Output Runout—Bottom Memorized Runout

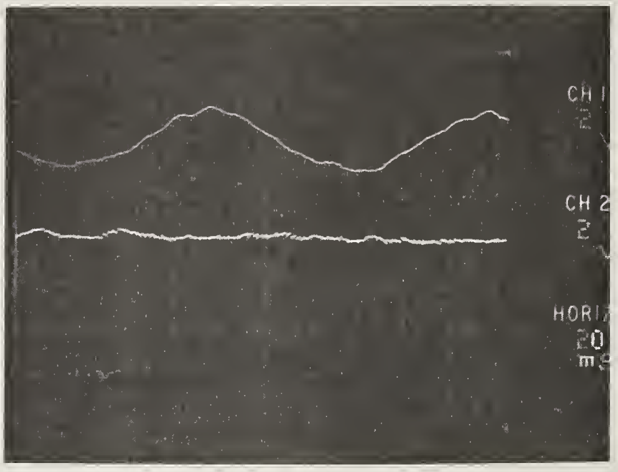


Figure 7b Top Uncorrected, Bottom Corrected Signal at Low Speed

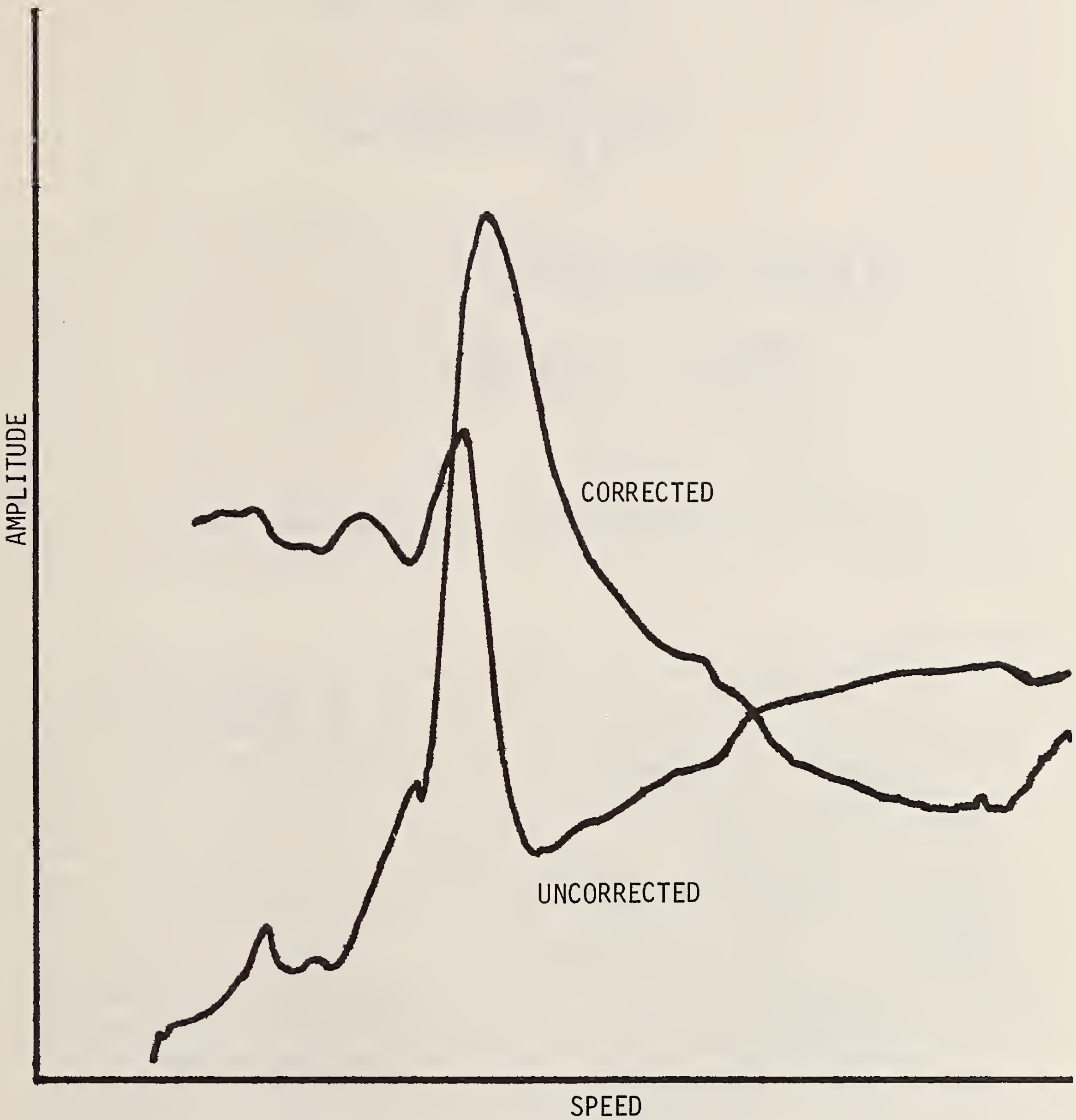


Figure 8 AMPLITUDE VERSUS SPEED
CORRECTED AND UNCORRECTED FOR RUNOUT

$$a_n = \frac{1}{T}\int_{-T}^{T} f(t)\cos w_n t \, dt$$

$$b_n = \frac{1}{T}\int_{-T}^{T} f(t)\sin w_n t \, dt$$

$$\text{AMPLITUDE} = \sqrt{a_n^2 + b_n^2}$$

$$\text{PHASE}_n = \text{Tan}^{-1}\left(\frac{b_n}{a_n}\right)$$

Figure 9 CALCULATION OF SYNCHRONOUS AMPLITUDE

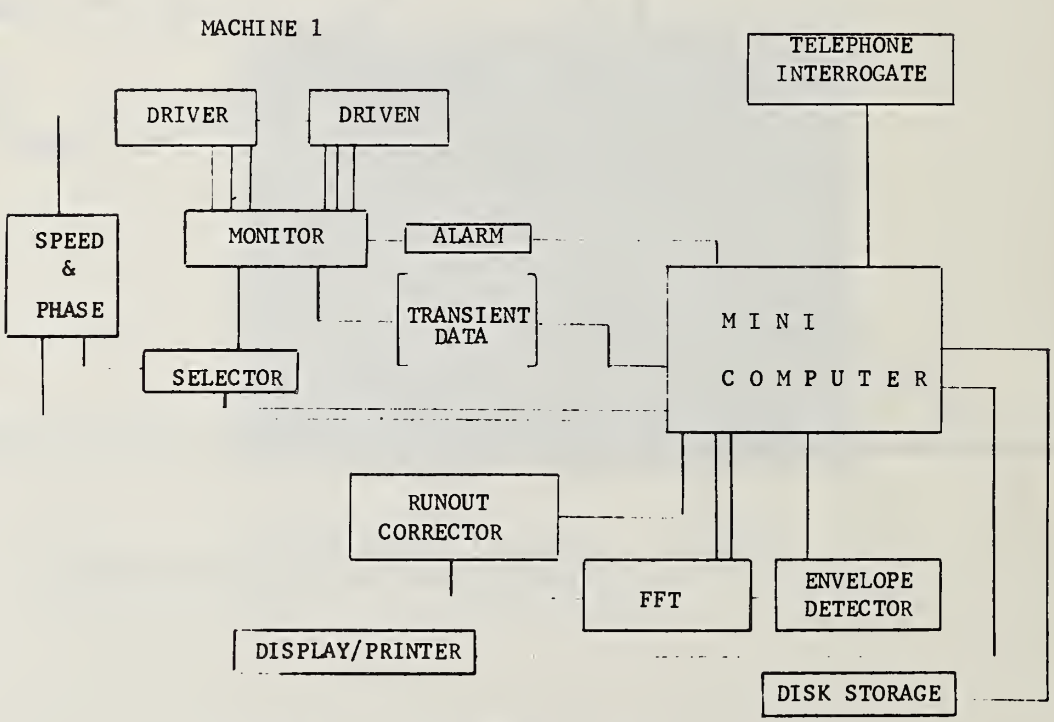


Figure 10 MACHINERY DIAGNOSTICS SYSTEM

THE ROLE OF SIGNAL PROCESSING IN MACHINERY VIBRATION ANALYSIS

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Machinery vibration analysis is an important tool in the diagnosis and prognosis of machinery problems, monitoring of vibratory conditions, acceptance testing, and modeling of machinery systems. With the increasing complexity of machinery systems, the more stringent noise criteria, and the continuing effort to improve operation, machinery vibration analysis is becoming very useful to the designers, troubleshooters, and users of such systems. The need to perform this type of analysis was pointed out by Messrs E. Weinert and R. Badgely in their article entitled, "Down with Vibration", when they reported that "between 20% and 40% of all casualties, forced outages and forced partial outages, are directly relatable to vibration". Statistics such as these certainly emphasize the need for more and improved machinery vibration analysis.

Since machinery vibration is generated by forces within the machine, proper measurement and analysis of the vibration permit the determination of vibration sources and their severity. As a result of this analysis, determination of the machine's health including mechanical deficiences and degradation is possible. The machinery vibration analysis technique used for accomplishing the above involves the integration of three major areas consisting of signal acquisition, signal processing, and data interpretation. Signal acquisition involves the sensing of the machine's vibration at specific locations using transducers which emit signals or waveforms representative of the vibration experienced. The signals are then conditioned using amplification, integration, or other techniques such that they may be processed directly or stored for later playback and processing. Signal processing, which will be discussed in more detail later, involves the processing of the acquired signals using techniques capable of providing required data or information in a desirable format. The third major area, data interpretation, involves analyzing the data provided by processing and identifying the sources of the machine's vibration. This is accomplished by comparing the data to the calculable forcing frequencies of the machine based on design characteristics. Once the interpretation of data for sufficient locations is complete, the vibratory condition of the particular system is known.

The role of signal processing in machinery vibration analysis is to provide the means by which we can obtain useful information or data about a machine from its vibration signals. These signals representing the machine's vibratory motion are complex in nature and are composed of many frequencies at different amplitudes related to the forces being generated by various components of the machine. In general, the processing will be performed such that the time varying signals are transformed into the frequency domain. Since design characteristics of the machine permit us to calculate forcing frequencies associated with the machine at various speeds, processing in the frequency domain gives us convenient relationships to use in the interpretation of the data. Processing in the time domain can also be very useful and, as we shall see later, has applications in machinery vibration analysis.

Processing of vibration signals will involve the basic functions of filtering, detecting, and displaying of the data. These functions may be accomplished using analog techniques, digital techniques, or a combination of the two. A concern of many people involved in machinery vibration analysis work is whether to use analog or digital techniques for processing vibration signals. The main considerations in making such a decision should be the particular processing requirements involved and anticipated future requirements. In general, digital techniques offer many advantages including decreased processing time required, ease of performing various operations, high resolution, good repeatability, and others. Processing systems are classified by the type of filtering used. The two basic types are Constant Bandwidth where the bandwidth is invariant with frequency and Constant Percentage Bandwidth where the bandwidth is variant with frequency. The specific type required will depend on the nature of the signals being processed and the intended application of the resulting data.

Many signal processing techniques and methods are conducive to machinery vibration analysis. Although most signals will be stationary and periodic in nature, many of the techniques are applicable to non-stationary signals as well. Primarily, most processing for machinery vibration analysis work is based on the Fourier Analysis concept or the representation of a complex waveform in terms of its various frequency components. Such processing will permit one to analyze the vibration amplitudes (displacement, velocity, acceleration) at specific frequencies. This concept and its many variations has given us signal processing methods which are utilized extensively in today's machinery vibration analysis work. Some of the more common methods include:

(a) Narrowband Analysis which provides vibration amplitude vs. frequency data using narrow filtering techniques.
(b) One-Third Octave Analysis which provides vibration amplitude vs. frequency data using filtering with bandwidths equal to 23% of specified center frequencies.
(c) Signature Ratio Analysis which provides vibration amplitude vs. orders of rotational data. This method has the advantages of compensating for speed variations of the machine and

of displaying orders directly which eliminates the need for many calculations.

(d) Frequency Translation which provides a means of separating a selected band of frequencies from the vibration signal and then translating that band to a lower frequency band. This method is very advantageous in achieving increased frequency resolution and in the analysis of modulated vibration signals.

(e) Order Tracking which provides a means of determining the response of a particular rotational order as a function of the machine's speed. This method also permits one to determine excitation sources for system resonances.

(f) Spectral Mapping including Time Spectral Mapping which provides representation of Amplitude vs. Frequency vs. Time and RPM Spectral Mapping which provides representation of Amplitude vs. Frequency vs. Speed (RPM).

A method of RPM Spectral Mapping which has become very useful in machinery vibration analysis is "Shades of Gray" processing. This is accomplished through the use of a computerized spectrum analyzing system with outputs displayed on a line printer/plotter. The spectra are condensed and plotted sequentially at selected RPM increments during the machine's speed varying or acceleration run. The RPM at which each spectrum was obtained is printed at the beginning of the spectrum. The vertical span for each spectrum is limited to preclude overlapping of the spectra giving a clearer and more useful display than normally achieved with other spectral mapping methods. The shades of gray effect giving the necessary contrast is achieved by automatically darkening the area under the spectra curves. Some of the more beneficial characteristics of this type of processing include:

(a) Provides a quick look at a machine's vibratory characteristics throughout its entire operating speed range.

(b) Provides easy identification of rotational orders and system resonances.

(c) Provides means for determining where to concentrate processing effort for more detailed analysis. This includes information such as which speeds spectrum analyses should be performed and which orders of rotational should be tracked.

It should be noted that this method overcomes shortcomings of some other spectral mapping methods by providing permanent printouts without using troublesome photographic methods, and by not limiting the number of spectra which can be displayed sequentially.

Other signal processing techniques widely used as a result of developments in Fast Fourier Transform analyzers include time domain techniques such as signal averaging and correlation. Signal averaging is useful in signal enhancement applications since it tends to eliminate or reduce non-related background noise signals. Correlation processing provides still another means of signal enhancement in addition to aiding in the determination of similarities between signals. Other techniques using the dual channel capabilities of the Fast Fourier Transform analyzers include cross spectrum, transfer function, and coherence function analyses. These are very useful in the comparison of spectra and, particularly, in the area of structural analysis.

Now that we have considered the role that signal processing plays and some of the applicable processing methods, it should be noted that the types of processing required for specific applications will depend on many factors such as characteristics of the machinery system being tested, the characteristics of the signals to be processed, and the specific requirements of the analysts or users of the data. Although this paper emphasized the more sophisticated processing methods, the most basic of processing methods may be sufficient to satisfy your requirements. Too often, those involved in processing work tend to "overprocess" and still fail to meet the requirements.

In summary, we have taken a brief look at machinery vibration analysis as to what it is and why it is necessary. We have also determined that the role of signal processing is to provide the means by which we can obtain useful information about a machine from its vibration signals. Finally, we have considered some of the many processing techniques available and some of their specific applications.

DIAGNOSTIC TECHNIQUES FOR STEAM TURBINES

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GENERAL DESCRIPTION AND OPERATING CONDITIONS

Diagnostic techniques discussed in this paper are for large steam turbines. An installed turbine-generator can be over 200 ft. in length and weigh over five million pounds. Several turbines, built to operate at specific steam pressures and temperatures, are connected in series to drive a generator which produces the electricity our society now takes for granted.

Units built in 1900 could generate 2 megawatts of electricity, less than a single multistory office building requires today. Some of the turbine-generators currently being built will be able to generate more than 1300 megawatts, or enough electricity to supply the residental needs of over 4 million people.

The basic design of the turbine is determined by the fuel used for steam generation. Normally used fuels fall into two categories namely, fossil (i.e., oil, coal or natural gas), or nuclear fission. Nuclear turbines require higher steam flow rates than fossil units because nuclear reactors do not make steam at temperatures and pressures as high as fossil boilers. A fossil fueled boiler may deliver 7×10^6 lb of steam per hour to a large fossil steam turbine, while a large nuclear steam turbine, Fig. 1, will require 17×10^6 lb of steam per hour. Depending upon the steam supply, inlet steam pressures can vary from 1000 psi to 3500 psi and expand the steam to more than 1000 times its original volume as it flows past the blades. When it leaves the final row of blades, its pressure has dropped to 2 to 3 in. of mercury, absolute.

For large units, reliability is of utmost importance in the economics of electrical energy generation. Modern turbine-generators operate with an availability of over 90 percent; that is, they are available to generate power 90 percent of the time. Unscheduled down time can be expensive as shown in Fig. 2. Using 1976 information, replacement power for a downed 600 MW unit could cost between $200,000 to $300,000 per day for make-up power from another unit within a utility. Replacement power purchased from a neighboring utility would cost more.

TYPES OF OPERATIONAL PROBLEMS

Steam turbines generate static and dynamic signals which are indicative of its operating performance. Measurements of temperature, pressure, force, flow, strain, displacement, velocity, acceleration, phase, etc. can be used to estimate the usable work and integrity of the machine. To develop a diagnostic technique that can be used to minimize unscheduled outages, it is necessary to understand some of the following operational problems:

- Rotor Unbalance

Rotating parts cannot be perfectly balanced during manufacturing, due to geometrical variances and the lack of perfect homogeneity of materials. Parts may also change their dimensions under operating conditions. Identifying frequency will be at the turbine's running speed.

- Rotor Bow

When the turbine has been shutdown, the rotor can bow if uneven cooling occurs within its cylinder. A distance detector can be used to measure the rotor's eccentricity when the unit is on turning gear and operating at minimal speed.

- Rotor Whirl

Uneven leakage of steam through or past seals, at certain load conditions, can cause an energy input to the rotor. This causes the rotor to vibrate at its own natural frequency, which is usually less than half of the turbine's running speed frequency.

- Rotor Impacting

Impacting exists when rotating and stationary parts come into contact. The identifying frequency will be the subharmonic of the turbine's running speed which is the closest subharmonic to the rotor's fundamental natural frequency.

- Bearing Instability

This phenomenon occurs when the oil film between the journal and its bearing is not tapered as it should be for normal operation. A thicker wedge of oil acts to drive the journal within its bearing at less than half of the turbine's running speed.

- Rotor Non-Uniformity

If the flexibility of the rotor is not equal in all directions it will have different moments of inertia. A cracked rotor will have a double moment of inertia when the crack is deep enough to affect the shaft's flexibility. Identifying frequency will be twice the turbine's running speed.

- Short Circuit Torque

Electrical transients imposed on the generator will cause the turbine rotor to vibrate at 120 Hz. If the rotor has a torsional frequency near 120 Hz, large vibration amplitudes will occur.

- Thermal Expansion

When steam is admitted into a turbine, both the rotating and stationary parts will expand. Because of its smaller mass, the rotor will heat faster and expand further than the casing. Axial clearances between the various turbine parts are provided to allow for differential expansion in the turbine. Contact between rotating and stationary parts may occur if the allowable differential expansion limits are exceeded. Displacement measurements on the rotor, casing and a differential between the rotor and casing can be made.

- Blade Failures

When steam flow is increased and the turbine is loaded, natural sources of excitation cause blade vibrations. There are always some non-uniformities in the distribution of flow around the circumference resulting from the steam inlet, the exhaust, extraction slots and the variability of stationary blades which cause a variable loading on the blades as they rotate. Blade vibrations normally occur at a harmonic of running speed or at the nozzle passing frequency. (Examples of the type modes excited are shown in Figs. 3 and 4). An exception to this rule is a phenomenon called blade flutter which can occur to the last stage of low pressure blades at reduced flow and high exhaust pressure. In this case, the blade group's third natural frequency, a torsional mode, is excited.

• Water Induction

Severe internal damage to the turbine can occur as the result of unwanted moisture or water being emitted into the machinery. Slugs of water can be carried over from the boiler to the high pressure turbine or from heaters through the extraction lines to the turbine. Static water can also back up through the extraction lines from reheaters and feed-water heaters. Damage ranges from broken blades to rubbing, due to differential expansion between rotor and cylinder. When the problem first starts to occur there is no audible characteristic frequency which identifies the problem, but a temperature change will occur.

TURBINE SUPERVISORY INSTRUMENTATION

Turbine supervisory instrumentation is used to generate alarms and/or trips in the event of the turbine approaching certain defined limits which are indicative of turbine mal-function and/or failure. Measurements are compared with predetermined limits based upon either experience or calculations.

Turbine variables currently monitored are: rotor vibration, rotor axial position, rotor eccentricity, casing and differ-ential expansion, speed, governor valve position, and turbine metal temperatures. Each measurement requires a transducer, some recording means, and a package of circuits to make the transducer signal suitable for recording.

Vibration and eccentricity measurements include displays of phase angle as well as detection of the peak-to-peak magni-tudes of the displacement. Since a rotor will tend to bow due to uneven cooling, rotor eccentricity is monitored continuously while the unit is on turning gear and up to 600 RPM. Bowing of the rotor will appear as vibration over 600 RPM.

When specified, each measurement can be arranged to be scanned by a computer. Information could be displayed on a cathode ray tube as shown in Fig. 5.

AVAILABLE MEASUREMENT AND ANALYSIS TECHNIQUES

Since the advent of the first commercially available vacuum tube, electronic devices have been used to sense, condition, record, store and display static and/or dynamic measurements. Rapid advancement in electronics over the past decade has provided equipment on a commercial basis which is a definite assist for making on-line analysis of static and dynamic data.

The oldest type of detector is the ear and the oldest type of analyzer is the brain. Some mechanics can listen to an engine's airborne or structureborne sound (via a listening rod) and determine the malfunctioning part, however, this skill is more an art than a science.

Many types of sensors are available for detecting the performance of rotating machinery. These sensors may be either contacting or non-contacting types that are sensitive to displacement, velocity or acceleration. Examples of some of these sensors are a linear variable differential transformer for measuring static or dynamic movement, a coil moving in a magnetic field whose output is velocity sensitive, a crystal which produces a signal proportional to acceleration, and a capacitive, inductive, or eddy current proximity pickup. In addition, a fiber optics or photosensor can be used to determine displacement utilizing reflected light. Other types of sensors, some of which are still in the development stage, utilize ultrasonics, x-rays, RF noise, infrared radiation, and atomic radiation.

Once dynamic movement has been sensed, it must be analyzed so that the observer or control system, can take the appropriate action. A sound level meter or a voltmeter are examples of instruments that will indicate the gross signal level. If the signal happens to be of a single frequency, the reading is quite meaningful. When required, there are various size filters available to make a discrete frequency analysis as shown in Fig.6.

A popular instrument for making analyses in real time is a time-compression type spectrum analyzer. In this device, the analog signal is first passed through a low-pass filter after which it is sampled at a rate that is determined by the selected frequency range of the analyzer and then converted to a digital signal.

In addition, data reduction systems employing only digital techniques are available for performing Fourier transforms very quickly. Such instruments combine high speed processing ability with the flexibility of a mini-computer capable of many mathematical operations, to produce a variety of different analyses.

Probably, the greatest advance in experimental procedures over the past decade is due to the use of computers. The ability to reduce massive amounts of data in minimum time has made it possible to obtain a better understanding of the characteristics of complex machinery during various operating phases.

EXAMPLES OF DIAGNOSTIC TECHNIQUES USED ON STEAM TURBINES

Blade Failures

Tuned turbine blading is designed so that resonant frequencies of the blade do not coincide with multiples of the machine's running speed or the nozzle passing frequency. During its design stage the resonant frequencies of the blades are typically displayed in a Campbell Diagram, as illustrated in Fig. 7.

Final product verification can be accomplished in a customer's plant using radio-link telemetry. Miniature ratio transmitters, operating in the commercial FM band, are mounted in environmental, protective capsules in the balance weight holes in the low pressure end of the turbine. Resistance strain gages are cemented to the blading at specific locations to measure the strain amplitude and its frequency.

To date, telemetry has been used numerous times to evaluate the performance of low pressure turbine blades in the field. The strain gages and wire paths will survive at temperatures up to 500°F and centrifugal loading of 20,000 g's. The transmitters and power supply will operate satisfactorily at temperatures up to 300°F and centrifugal loads of 8600 g's in the presence of moisture.

The possibly does exist for using telemetry to extract information off the rotor for supervisory instrumentation. Long-term telemetry usage is currently limited by erosion from water droplets and the power supply.

Another example of detecting a blade problem is shown in Fig. 8. This spectrum illustrates the airborne sound levels obtained near a low pressure turbine during normal operation and after a fast transient condition which was a blade failure. Using normal supervisory instrumentation, the turbine did not shutdown automatically as a result of the blade breakage. The increased magnitude of rotor unbalance did not raise the vibration level at one or more of the unit's bearings high enough to produce an alarm or trip condition.

Use of external airborne or structureborne sound measurements to detect and decipher blade vibration is not as easy a task. It is certainly difficult to distinguish which row of blades may be vibrating when the frequencies of the various modes are similar. The important point, however, may not be which row of blades is vibrating, but that a frequency has appeared in the spectrum that could be critical to further operation.

Clearances

Stationary and rotating parts sometimes come into contact within a steam turbine. Normally, a rub is not detected until the machine is opened up for inspection.

In several instances, Westinghouse has been successful in pinpointing rubs associated with excessive clearance which allow the inlet connection between the inner and outer cylinders of a high pressure steam inlet to vibrate. From data, similar to Fig. 9, it was possible to decide when the bell seal used on these machines had excessive clearance. The turbines were dismantled and the clearances restored to normal. This action minimized the possibility of a future mechanical problem within the inlet cylinder. When the turbine returned to service, the characteristic vibration disappeared.

Rotor Thermal Cycles and Cracks

A change in blade-path steam temperature will produce thermal stresses in the rotor. Heating of the rotor surface followed by an equal cooling constitutes a thermal cycle and imposes on the rotor a cycle of alternating stress. Cracks will ultimately develop after a number of cycles which depends on the severity of the stress and the rotor's material.

The relationship between alternating stress and cyclic capacity is a known material property. Therefore, it may be possible to predict the number of stress cycles necessary to initiate a rotor crack.

Cracks usually propagate slowly and then have a exponential growth, with a final rapid acceleration of growth to a burst rotor. When the crack becomes large enough, the rotor will have a double moment of inertia which will produce a second harmonic of vibration. Of four field case histories of cracked rotors (not Westinghouse), the second harmonic was reported in two instances. In another case, the propagation of a thermal crack was accompanied by an increase in transient vibration during temperature decreases over a period of three months.

During a normal turbine outage, ultrasonic and other techniques can be used to inspect rotors for cracks and thereby eliminate the probability of a rotor burst on machines which have been in service for a number of years.

Water Induction

Water induction has been a major cause of forced outages of large steam turbines. Presence of water is first detected by changes in the measured temperature of the affected parts, as shown in Fig. 10. Use of metal temperature thermocouples to determine the presence of water or cool vapor in the turbine cylinder is an effective means of detection, but of no use in the prevention of water or vapor injection. Thermocouples placed at strategic locations within the piping system, however, might provide the necessary warning to the operator.

Westinghouse is currently investigating other methods of more rapidly identifying impending induction of water into turbines under an Electric Power Research Institute contract. The main objective is to sense the presence of water rapidly enough to close valves or take other action to prevent water from entering the turbine.

DIGITAL ELECTRO-HYDRAULIC CONTROL

The increased complexity of todays steam turbine generators and the significantly greater investment in each power plant demands a control and monitoring system, Fig. 11, which can maximize the protection and efficiency of the units operation. By combining the flexibility of the digital computer for handling complex logic decisions with the speed and high forces of hydraulics for valve positioning, the Westinghouse Digital Electro-Hydraulic (DEH) meets these needs.

The DEH automatically increases the turbine generator speed or load at a rate based on calculated critical rotor stresses, as shown in Fig. 12. All other critical turbine generator variables are also checked. Transducer outputs are monitored for failures. The speed channel has two out of three redundancy checking, with automatic channel switching in case of a contingency.

During synchronizing of the generator to the line and while loading the unit a set of control valves modulate steam flow to the unit under command from the digital computer. During initial loading even heating of the turbine inlet is obtained by opening each control valve the same amount. This is called single valve operation. Once the turbine is heated, higher unit efficiency is obtained by sequencing these valves to minimize pressure losses across the valves. If a control valve fails to respond, the digital computer will automatically sense this, switch the unit to single valve operation and compensate for the malfunctioning valve.

During operation, if there is a contingency in the digital computer the system automatically will switch to manual allowing uninterrupted power generation. Also incorporated in this portion of the system, is the overspeed protection controller. A second, redundant overspeed trip system also protects the unit.

During all phases of operation, the computer constantly protects the unit, not only by scanning the actual values of existing parameters, but also by anticipating future values. Corrective measures are taken to avoid alarm or trip conditions.

A modern centralized display provides communication between the turbine-generator and the operator. Through the use of control and display panels, a cathode ray tube, and a typewriter, the operator can digitally display information such as temperatures, pressures and vibrations. A continuous monitoring and alarm system assures effective and reliable operation by supplying the operator with timely information.

EXPERIMENTAL FACILITIES

The Westinghouse Steam Turbine Division has an array of laboratory and experimental facilities that are engaged in developing, analyzing and verifying steam turbine design. Some of the facilities available to help develop new diagnostic techniques include:

- Rotor Dynamics

This facility is a single mass rotor supported by two journal bearings, with precise speed control up to 7000 RPM. Bearing geometry, oil viscosity and rotor unbalance can be varied. The facility has been used to analyze response to rotor unbalance and study instability phenomena such as oil whip.

- Valve Test

To evaluate the acoustical, vibrational and flow characteristics of large control valves, a 7400 ft^3 reverberant chamber with permanent low-noise, high-capacity flow systems was built. Up to 140,000 lb of steam per hour at 1100 psia, or 200,000 lb of steam per hour at 600 psia, or 140,000 lb of air per hour at 130 psia, is available.

• Large-Scale Multi-Stage Turbine

Industry's largest steam turbine test facility, Fig. 13, was placed in operation by Westinghouse Electric Corporation during 1975 at the Chester Plant of the Philadelphia Electric Company. With a steam supply up to 750,000 lb per hour, low pressure turbines, with blade lengths of up to 40 in. can be evaluated at speeds up to 4320 RPM. Various types of diagnostic, supervisory, control and data instrumentation can be evaluated over a wide range of power plant operating conditions. Currently, 700 points of data and 100 points of control and supervisory instrumentation are available.

• Controls

For dynamic simulation of control system design and plant dynamics, advanced computer techniques are used in this facility, Figs. 14 and 15, to analyze frequency response, hysteresis and operating and stability characteristics. Prototypes of new control systems, operated in conjunction with computers simulating plant dynamics are tested for reliability, durability and dynamics to assure trouble-free operation in the field.

• Data Acquisition and Reduction

Several facilities are available for precise and responsive data acquisition, on-line data reduction, recording and storage for further analysis. Automatic traversing of probes can be computer-directed in preprogrammed steps. Pressure, temperature flow, speed, torque and frequency data can be printed out for performance monitoring. Vibration stress and amplitude levels, frequency and phase can also be printed out on a routine basis from a dynamic test.

Using a Fast Fourier algorithm technique, one system processes the dynamic data using standard calculation techniques and presents the results in terms of linear or power spectrum, auto-or-cross-correlation function, or coherence. This system has also been used to generate orbital plots of bearing data, decay curves of damping tests and analyses of acoustical data.

FUTURE DIRECTIONS

The high capital investment and need for extreme reliability in electrical power generation dictate expansion of the turbine generator monitoring and diagnostic funtions. Areas such as analysis of the vibrational characteristics of the rotor-bearing system, continuous monitoring of the chemical purity of steam,added water induction protection and increased long term recording and trending of machine behavior are prime candidates for future systems. Such systems could be incorporated into the existing DEH or structured in individual subsystems for retrofit to existing machines.

Completely automated actions will be in general reserved for those cases where the operator does not have sufficient time to react. Emphasis will be placed on giving the operator increased information relative to decisions he has to make.

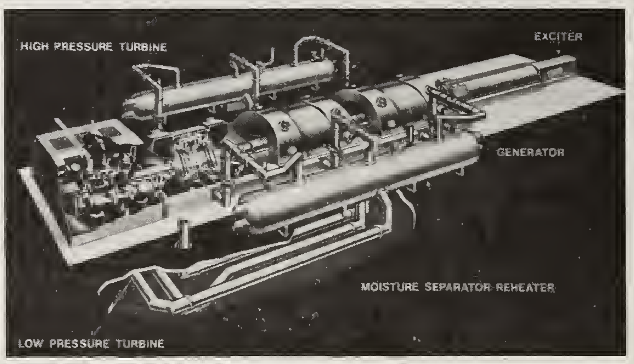

Figure 1. 1300 MW nuclear steam turbine generator.

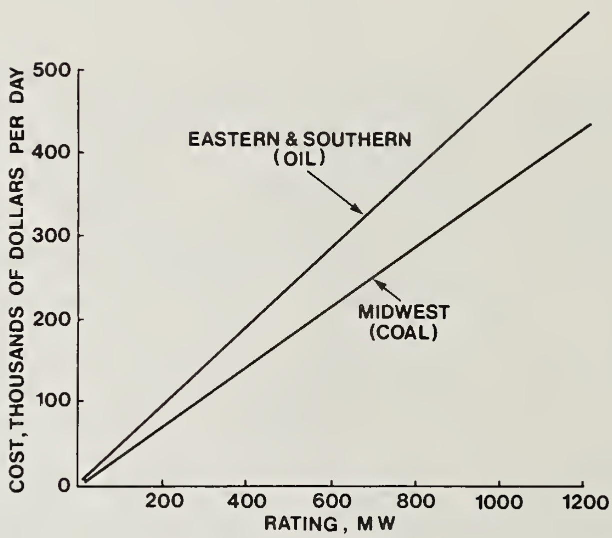

Figure 2. 1976 utility make-up power cost.

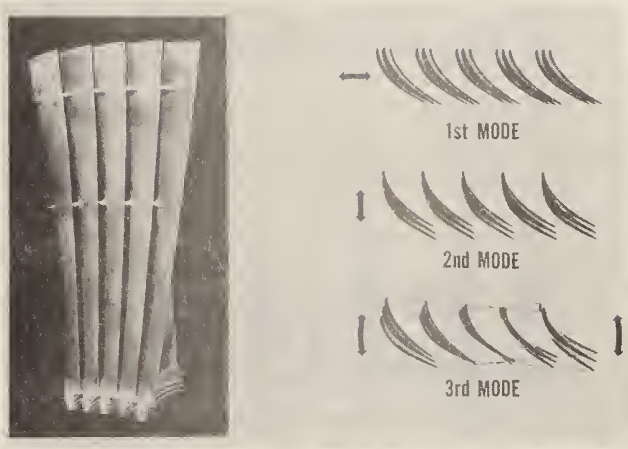

Figure 3. Typical first three modes of a group of last row blades.

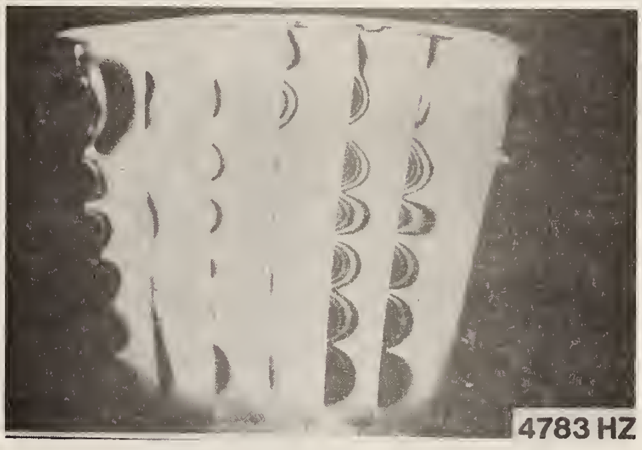

Figure 4. Hologram of last row blades showing deflection pattern at 4783 Hz.

```
PRESS(PSI)THR=2415   IMP = 1104      EXH=    2 IN.HG  REF= 324     RATE= 20 MW/MIN
TEMPS( F )THR=1000   IMP = 815       EXH= 102 LD RES(MW)INCR = 30  DECR=180
```

ATC ALARMS

```
7:30    HOLD LD HI VIB BRG  5
7:32    BRG MTL TEMP HI BRG 5
```

(message flashes until operator acknowledges)

ATC MESSAGES

```
0:31    1st STG STM TEMP SENSOR OUT OF SERV SENSOR #2
6:42    FTR STRESS INITIATES LD RATE DECR.
```

DISPLAY PAGE NO. 4 BEARING VIB AND METAL TEMP

```
VIB ALARM = 5.0 MILS TRIP = 10.0 MILS   MTL TEMP ALARM = 225F  TRIP = 235F
                                        TB MTL TEMP ALARM = 210 F  TRIP = 225
```

BRG NO	1	2	3	4	5	6	7	8	9	TBFF	TBRF
VIB(MILS)	0.9	0.9	0.8	2.7	5.5	3.1	1.6	1.1	0.9		
TEMP(F)-1	195	193	196	202	230	211	198	198	201	187	191
-2	195	192	196	201	229	211	198	197	202	188	193

Figure 5. Cathode ray tube display.

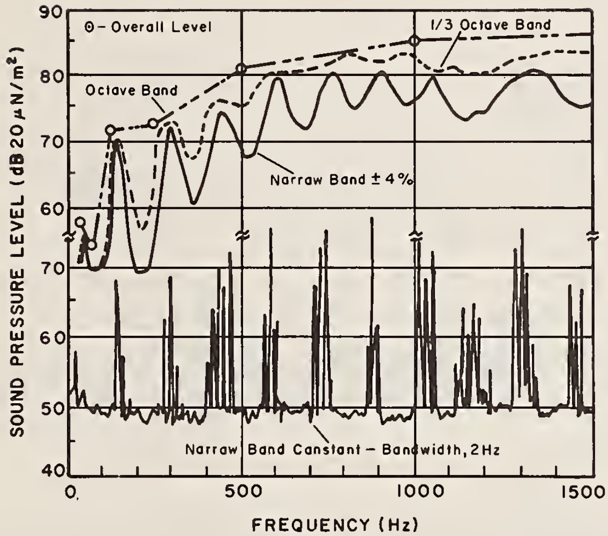

Figure 6. Analysis of sound signal using different bandwidth filters.

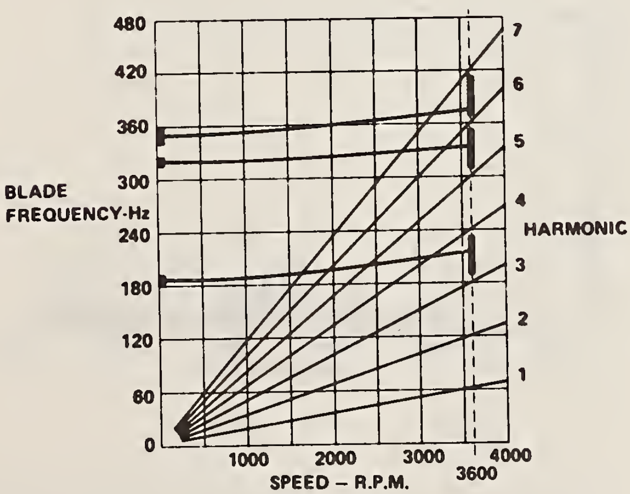

Figure 7. Typical Campbell Diagram for a group of low pressure blades.

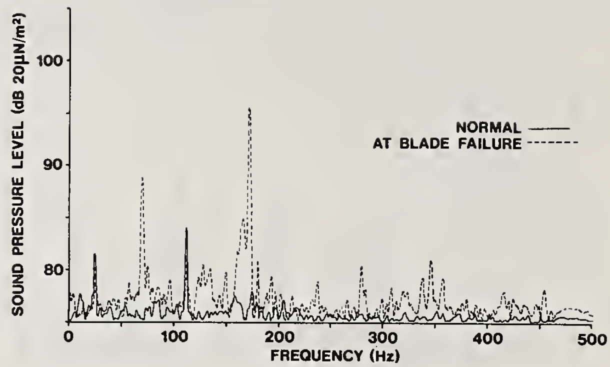

Figure 8. Airborne sound spectrum before and at a low pressure blade failure.

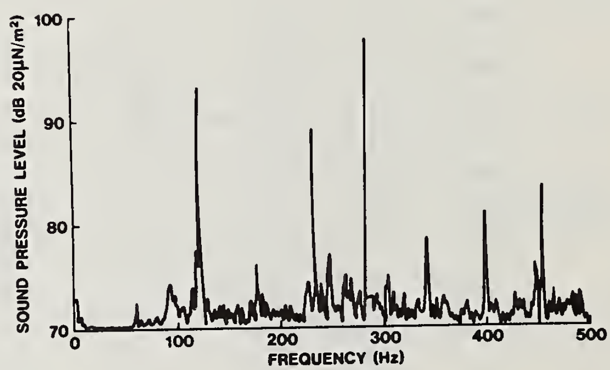

Figure 9. Airborne sound spectrum of a bell seal clearance problem.

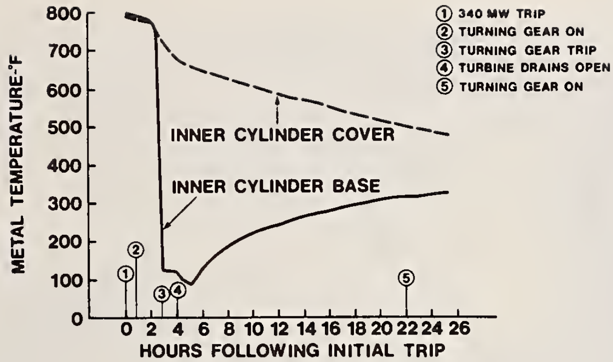

Figure 10. Abnormal high pressure - intermediate pressure turbine cylinder cooling due to water being induced accidentally into cylinder by flooding from a feed-water heater. Unit could not be placed on turning gear until there was an acceptable temperature differential at point 5 after a trip occurred at point 3.

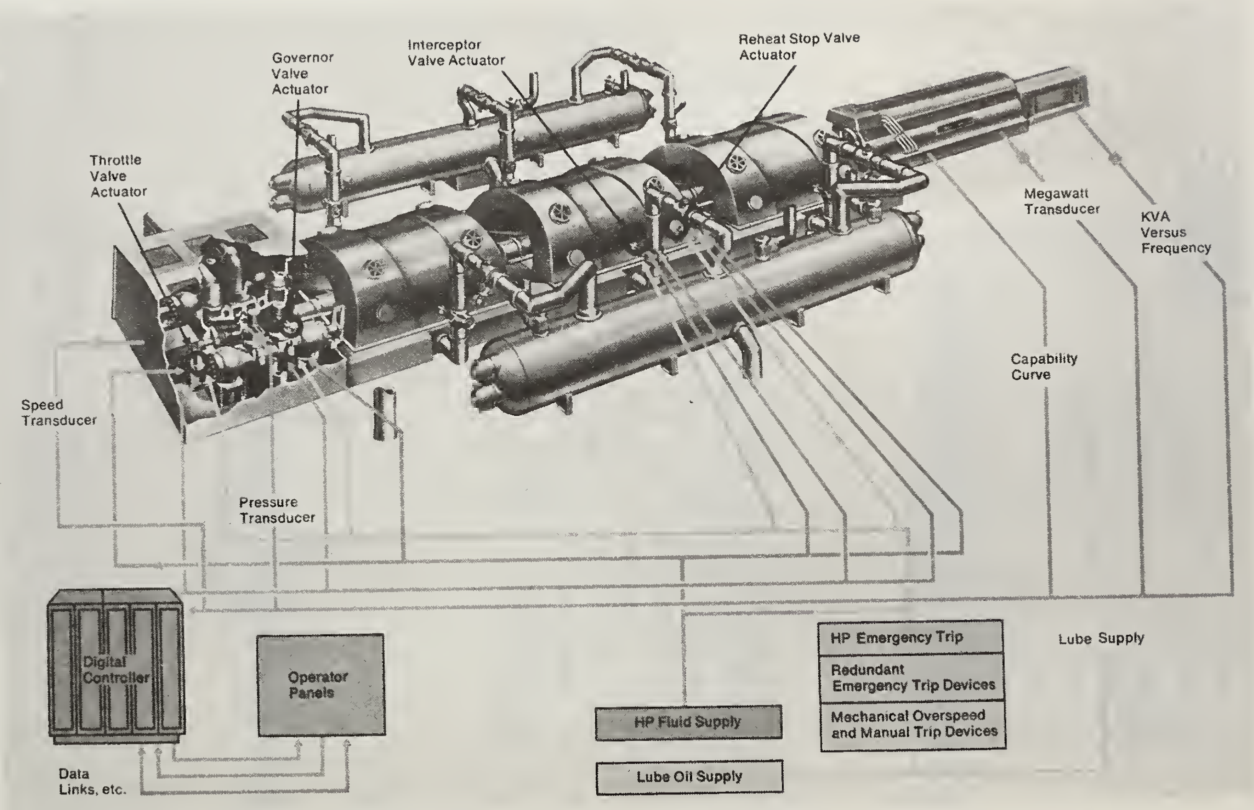

Figure 11. Digital electro-hydraulic control system.

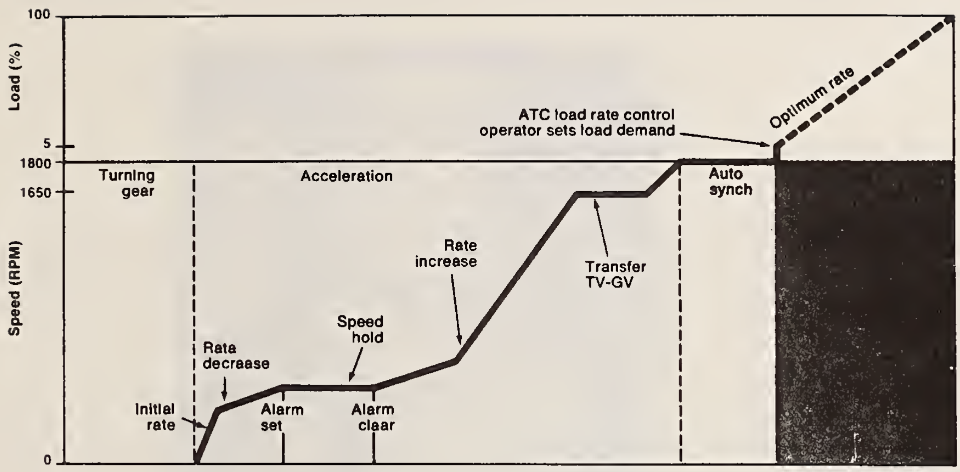

Figure 12. Automatic turbine control-speed/load profile.

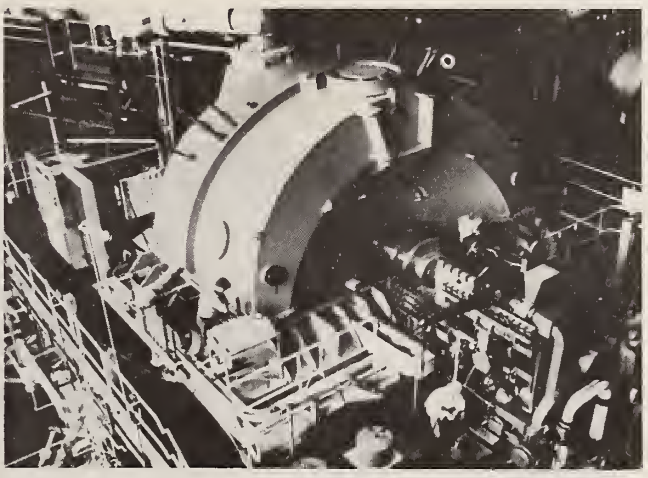

Figure 13. Industry's largest steam turbine test facility.

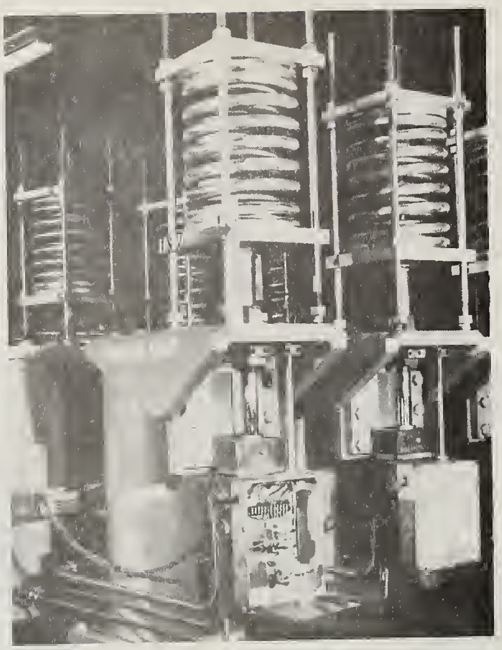

Figure 14. Controls laboratory test stand hydraulics.

Figure 15. Computer and simulation area in control laboratory.

EXPERIMENTAL DETERMINATION OF RADIAL MAGNETIC FORCES AS A FUNCTION OF ROTOR OFFSET IN A LARGE INDUCTION MOTOR

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Hundreds of motors, used to drive compressors in gaseous diffusion plants, have been uprated from 2000 HP to 3300 HP. Bearing failures have been experienced on some of these reworked motors and the Franklin Institute Research Laboratories (FIRL) was asked to assist in finding the cause.

Since the flux density in the gap had been substantially increased, the radial magnetic force, which acts in the direction of the minimum gap, and is proportional to the square of the flux density, became a prime suspect. Preliminary estimates from the motor rebuilder indicated that a radial force of 5,400 lb would result from only a 10 mil radial offset of the rotor within its stator. Computer analyses indicated that a radial force of less than half that estimated value could lead to bearing instability or to minimum film thickness failures depending upon its direction.

A test was run on one uprated motor to experimentally determine the radial magnetic force acting on the rotor, and to see how this force varied as the gap was changed. The test served to check not only the estimated magnetic force levels, but the resulting bearing behavior as well.

To determine the magnetic force reactions at the bearings, the horizontal and vertical displacements of each bearing housing were measured upon the sudden removal of the magnetic force. This was brought about by cutting the excitation to the motor at full speed.

In order to maximize these displacements, FIRL reduced the stiffness between each bearing housing and its mounting flange by machining away material so as to leave four supporting columns, two vertical and two horizontal. Optimum vertical and horizontal stiffnesses were targeted at 10^7 lb/in. This value is more than 5 times the maximum film stiffness of the bearing, thus not affecting rotor-bearing performance. Yet it is compliant enough to yield 1μ in. displacement for each 10 lbs of force. With each displacement sensor able to resolve less than 2μ in., force resolution would be 20 lbs. Since the anticipated forces were to be in the 2,000 lb range, this resolution was felt to be more than adequate. The actual stiffness values as determined by calibration tests on site were 1.4×10^7 lb/in for the horizontal stiffnesses, and 0.5×10^7 lb/in for the verticals.

The displacement sensors were noncontacting eddy current probes. They were affixed to the mounting flange and they "looked at" copper target buttons bonded to the bearing housings in the plane of the mounting flange. Copper was used due to the higher sensitivity so obtained, 500 mv/mil vs. 200 mv/mil for steel. The price paid for doing this is reduced linear range and smaller gap setting, neither of which was a problem in this case.

A Brush 6-channel strip chart recorder was used to plot the change of the vertical and horizontal displacement components of each bearing housing that resulted from the loss of magnetic force when the excitation to the motor was cut. In order to eliminate the high level vibration portion of these four signals, they were passed through sharp cutoff (48 dB/octave) low pass filters set at 1 or 2 Hz. The filters also had 20 dB gain, thus raising the sensitivity to 5 volts/mil or 5 mv/μ in. The fifth channel of the strip chart recorder displayed the analog speed output of the motor so that coincidence with motor cutoff could be noted.

Other sensors mounted on the motor included orthogonal shaft probes in each bearing for journal position and orbits, and horizontal and vertical accelerometers on each bearing housing. Another proximity probe was used to sense motor rotational speed by looking at the passing of a keyway. Still another probe was used to sense the rotational speed of an oil ring by looking at the passing frequency of a steel insert.

All the sensor outputs were recorded with a 14-channel FM tape recorder allowing for relative amplitude and phase determinations during subsequent playback. Two dual-channel oscilloscopes were used for continuous observation of both journal orbits. Also, a single channel FFT spectrum analyzer was used to view various frequency spectra and time domain wave forms, and these were recorded for later analysis using a digital cartridge tape recorder.

The moving of the bearing housings to vary the air gap was accomplished with jack screws mounted to the end bells. Flats were provided on the mounting flanges for the jack screws to act upon.

Measuring shims were used to measure rotor to stator air gaps at the quarter points at each end. The flange mounting bolts were loosened and using the jack screws, each bearing housing was moved till the measuring shims indicated the rotor to be approximately centered. The bolts were then retightened, the air gaps rechecked, and plastic tipped locking bolts, which were used to hold the bearings tight in their seats, were snugged down. In addition, using a telescoping gage and micrometer, the gaps between the jack-screw mounting blocks and the flats on the mounting flanges were measured and recorded. This entire procedure was to be repeated each time the rotor to stator air gap was changed.

The motor was now ready for its first run (rotor centered), following calibration which was accomplished by applying a 100 lb force in the vertical and horizontal directions at each bearing.

All the initial tests were made with the motor sitting on rubber pads on the test floor, running with no load, for various rotor to stator air gap conditions. Later a coupling would be put on and the motor moved to a test stand where it was coupled to a load generator and run under full load.

The sequence of testing was as follows: Rotor "centered"; 10 mils low; 20 mils low; 10 mils high; 20 mils high; 10 mils right (looking at brake end of motor, having CCW rotation); 15 mils left; 15 mils left under full load.

Figure 1 illustrates the resulting horizontal and vertical magnetic force components for each of these conditions. The forces generally follow what would be expected. That is they act in the direction of the rotor offset (minimum gap direction) and they increase as the offset increases. However, the magnitude of these forces is far below what had been predicted by the motor rebuilder, approximately 20 lbs per mil-of-rotor-offset vs. 270 lbs per mil, both of these on a per bearing basis.

For the full load condition, the very high vertical couple is believed to be the result of coupling misalignment and represents actual forces under load due to misalignment. When the excitation is cut, the coupling no longer transmitting torque experiences sudden tooth to tooth freedom and these misalignment forces disappear in rapid fashion just like the magnetic force in question. Thus they show up as apparent magnetic forces.

This contention is supported by the spectrum of the coupling end vertical shaft sensor which indicates a 2X running speed displacement component 10 dB higher than the 1X running speed component while running under load.

Measured journal orbits indicated little effect from gross (20 mil) rotor offsets, and no discernable shift in the position of these orbits upon the sudden removal of the excitation to the motor. This supported the conclusion that the magnetic forces were small.

While this test was showing that the magnetic force was not the culprit, it indicated that the bearing oil rings were. The rings were seen to operate erratically and far too slowly at best. The worst were new perprint rings, as had been put in the uprated motors. New, better operating, redesigned rings are now being installed as the motors are reworked.

This technique of filtering displacement signals to determine low frequency or step application forces on "spring" structures in high vibration environments can probably be used to good advantage in many diverse applications.

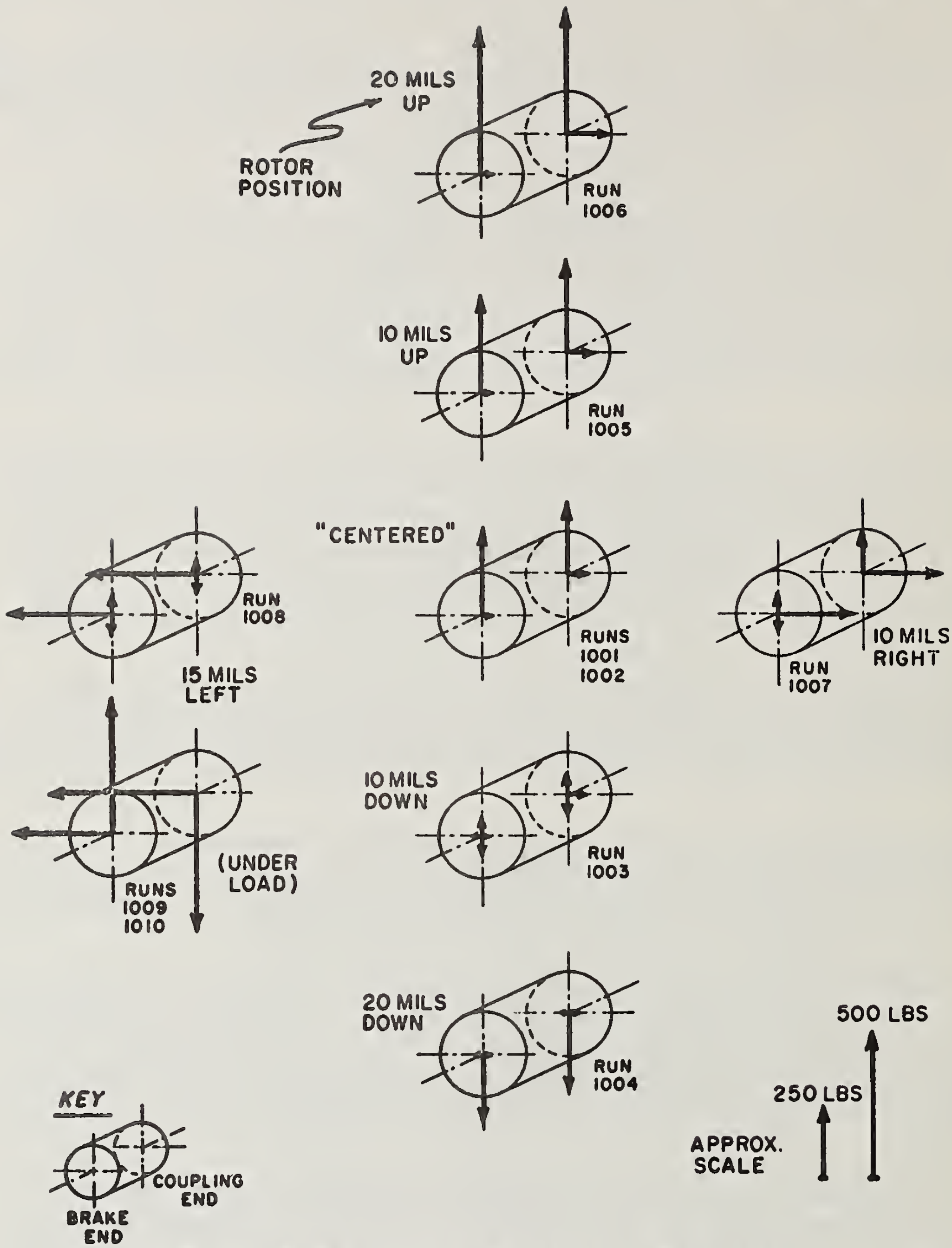

Figure 1. Magnetic Force Components at the Bearings

SESSION III

NEW DETECTION, DIAGNOSIS AND PROGNOSIS TECHNIQUES AND EQUIPMENT

CHAIRMAN: R. A. COULOMBE

NAVAL SHIP ENGINEERING CENTER

A NEW CHIP DETECTOR - RELIABLE, VERSATILE, AND INEXPENSIVE

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For over a decade, electric chip detectors have been installed in virtually all helicopter transmissions and engines and in many propulsion and drive systems of military fixed-wing aircraft. They contain a magnet which attracts the ferrous debris shed into the lube system by failing components and retain it for later visual inspection and failure verification. The debris particles which fall across the gap between two electrodes act like a switch and activate a chip warning light (see figure 1).

Electric chip detectors are surprisingly reliable indicators of incipient failure. For example, during a two-year period studied by the Army, chip detectors on a part of the UH-1/AH-1G fleet scored 75 "hits" (indications followed by component removal) against 9 "misses" (component removals without chip warning) for an overall success rate of 88%. For the transmission chip detectors, the success rate was even higher with 40 hits and one miss, corresponding to 97.5% success. This indication reliability is comparable to ASOAP experience overall and outscores it considerably for the transmissions.

Unfortunately, as is widely recognized, conventional chip detectors are subject to a large number of "nuisance" indications which are not caused by failure-related debris. The same study shows that in addition to the 75 correct indications, there were 529 nuisance indications; 305 or 58% of them were reported as being due to "wear fuzz" and 130 or 25% due to electrical failure of the chip detection system. The remaining cases were the result of moisture in the lube system (4%), carbon and other metal contamination (6%) and 7% were due to unknown causes.

Such statistics have made chip detectors controversial over the last few years, despite the high reliability of failure indication mentioned earlier. In order to eliminate the nuisance indications and make chip detectors more dependable, their causes must be understood more clearly.

It goes without saying that the electrical failures which accounted for 25% of those indications are avoidable by using state-of-the-art connectors and test circuits. Clearly, the "wear fuzz" indications are the most important category to be eliminated.

A model for the development of the debris spectrum reflecting a typical fatigue-type failure (bearing or gear spalling) is shown in figure 2. Under normal operating conditions, a background consisting of appreciable quantities of particles usually less than 30 microns in diameter are continuously being produced by normal wear processes. In the diagram, the particle production rate in mg/hour is plotted on the vertical axis rather than the accumulated total. Therefore, the debris spectrum would remain unchanged along the time axis if no failure occurred.

As a spall develops as a result of a local fatigue crack and then propagates across the load-bearing surface, more and more debris particles of larger and larger size are being produced. This causes both the spectral maximum and the large-particle threshold to move to the right. Simultaneously, the production rate of small particles also increases, permitting indentification of the failure by spectrographic analysis. The production of debris particles of approximately 500 micron and over leads to failure indication by the chip detector.

In lube systems with very fine filtration (e.g., the newer 3 micron-absolute filters), most debris particles of the 10 micron class are removed as quickly as they are produced. With coarser filtration, these particles slowly accumulate in the oil and, being mostly ferrous, are deposited on the chip detector. Gradually, a conductive path forms across the chip gap and the chip warning light comes on. This process seems to be the origin of most "wear fuzz" nuisance indications. In addition to other strong evidence, this is indicated by the fact that during the development program of the T-700 engine, which has a 3-micron absolute filter, no such "wear fuzz" indications were reported.

Unfortunately, many chip detector installations, especially but not exclusively in engines and transmissions of older design, add greatly to this problem. Figure 3 shows a typical lube system schematic of an engine, with the chip detector installed in the main scavenge line. For any given size of debris particle, there is a finite probability e_1 that the particle will be transported to the vicinity of the chip detector (point A). For a large number of particles, this probability becomes the debris transport efficiency of the lube system. In the system shown, this quantity would be zero for particles larger than the openings in the pump inlet screen.

Once the debris is transported to the vicinity of the chip detector, some provision must be made to either slow down the oil flow so that it can settle out or a screen must be used to capture, retain and deposit it on the chip detector. In many installations, neither is the case and the result is a low debris capture efficiency e_2.

Finally, the indication efficiency e_3, the probability that a particle, once deposited on the chip detector, will be indicated, corresponds to the sensitivity of the chip detector and is largely determined by its gap size. If $e_1 \cdot e_2$ is low for failure-type debris, the chip detector sensitivity must be high to compensate for this. In practice, this means a small gap size which, in turn, leads to more nuisance indications. This is due to the fact that the transport efficiency of any lube system is practically equal to one for particles smaller than 50 microns.

It becomes obvious that a conventional chip detector cannot successfully cope with this problem, at least not in lube systems with coarse filtration. The reason is clearly that a chip detector responds with an indication each time the chip gap is bridged, regardless of whether the gap consists of large quantities of small or small quantities of large particles, or even of a fine, long sliver.

This problem can be resolved by sending a strong current pulse through the chip gap every time there is electrical continuity. The pulse is generated in a small capacitor network which can be located in the chip detector (see figure 4) or elsewhere. It causes a local melting of the kind of particles that are responsible for these indications which interrupts the current path. Since this process occurs within a few milliseconds, local lubricant temperatures and flow conditions have no influence on this process. On the other hand, debris particles with more substantial cross-section conduct the current pulse unharmed and the continuity remains.

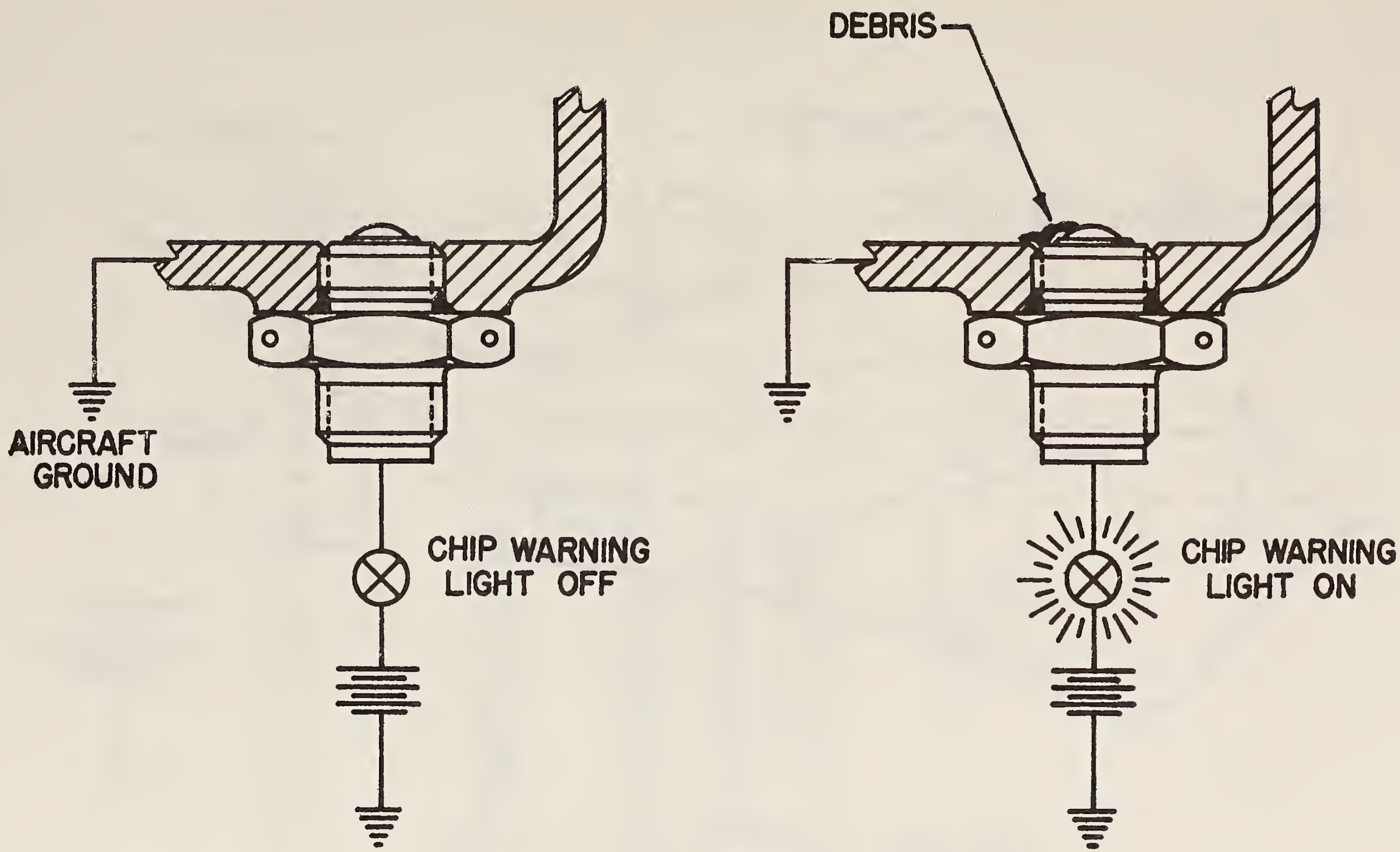
This method can be applied in several different ways. Firstly, the current pulse discharge can be initiated automatically every time continuity occurs. The chip light is therefore not activated, unless the debris survives unchanged the effects of the pulse. The result is a chip detection system with a greatly reduced tendency to nuisance indications. For example, the Hughes YAH-64 helicopter, whose transmission is equipped with such a system, experience no "wear-fuzz" type indication through 500 hours of flight tests. The Sikorsky S-76 helicopter is also equipped with such a system. A full-flow chip detector with screen located in its transmission is shown in figure 5.

Secondly, the current pulse can be initiated by the pilot ("manual" system). In this case, the chip light comes on each time debris bridges the chip gap, regardless of its cross section. The pilot initiates the pulse by pushing a panel switch and makes the usual precautionary landing only if the chip light stays on. If the chip light goes out but comes on again after a short time, this indicates the continuing generation of fine debris particles. This may be associated with an early stage of a bearing spall, with a gear-scoring type of failure or with excessive spline wear. If the current pulses are continued, this type of debris eventually saturates the chip detector and the chip light can no longer be extinguished. This point corresponds to the onset of the chip indication in the automatic system discussed earlier. If desirable, it can be set at an arbitrarily low threshold by selecting gap size and capacitance for high sensitivity.

With this method, prognostic information can be obtained about the developing failure. This can be made more practical by incorporating a counter into the chip detection system which records each successful current pulse. This technique can be used for both automatic and manual systems. Figure 6 shows a four-channel chip detection system for a helicopter installation (only one of the chip detectors is shown). The panel switch is activated when a chip indication occurs and if the current pulse successfully removes the indication, the corresponding counter advances.

The pulsed chip detection system is very flexible. For example, it is equally adaptable to full-flow and to sump-type lube systems and is easily retrofittable into aircraft with existing chip detector installations. It also retains one of the most important positive characteristics of most conventional chip detectors, the quick access to the collected debris for visual failure verification without lubricant drainage.

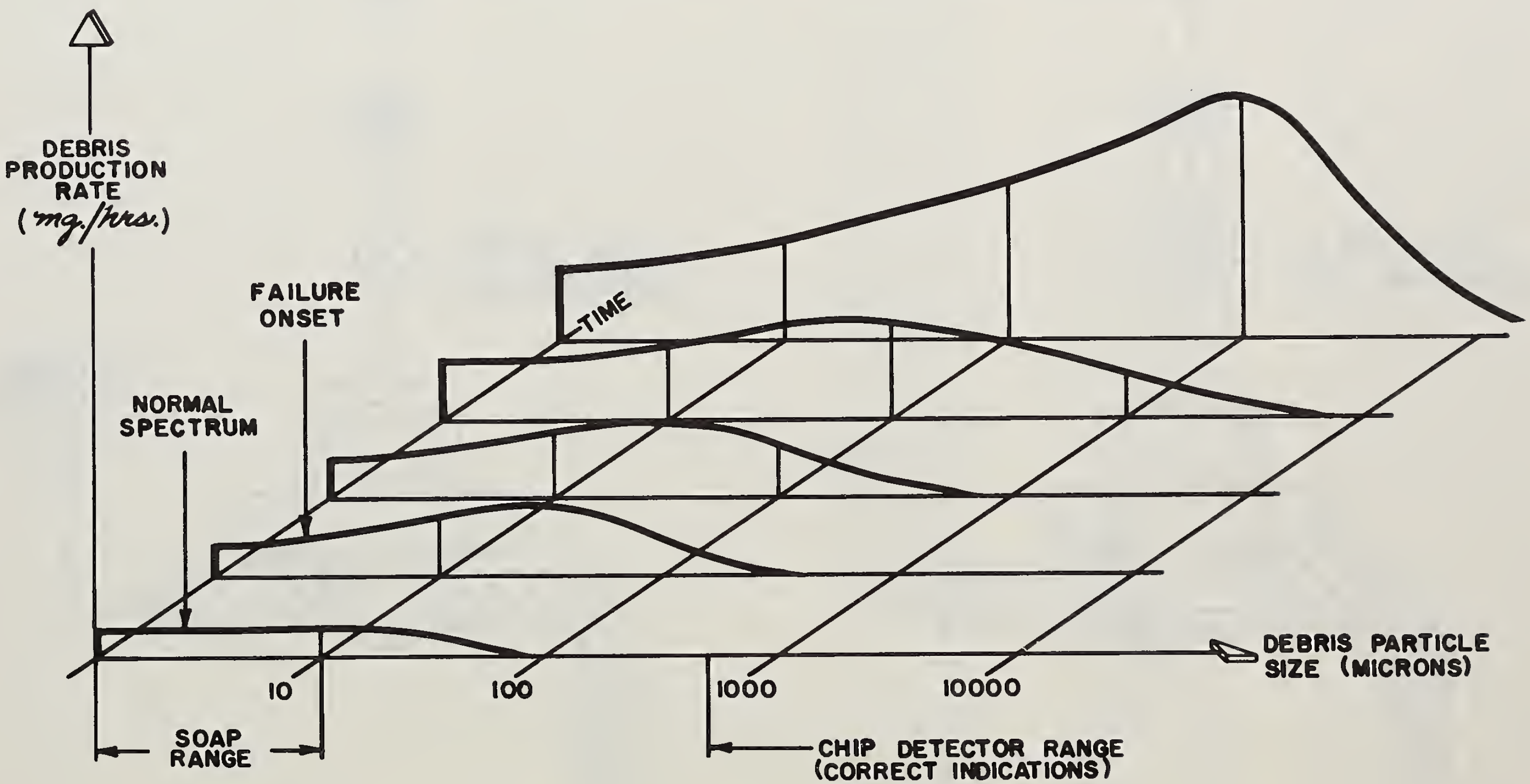
Furthermore, operational experience in several flight test programs has shown that the pulsed chip detector offers greatly improved dependability and reliability over conventional chip detectors. Its comparatively low cost therefore qualifies it uniquely for future real-time, airborne debris detection requirements.

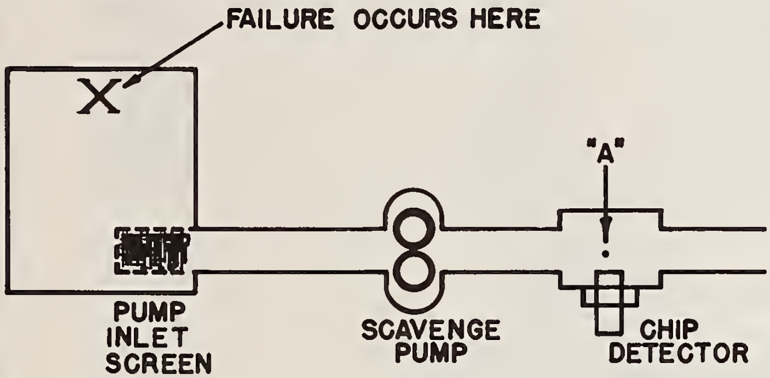


CHIP DETECTOR OPERATING PRINCIPLE

FIGURE I

FIGURE 2: DEBRIS PARTICLE SPECTRUM





TRANSPORT EFFICIENCY $e_1 = \dfrac{\text{PARTICLES TO POINT "A"}}{\text{PARTICLES GENERATED}}$

CAPTURE EFFICIENCY $e_2 = \dfrac{\text{PARTICLES ON CHIP DETECTOR}}{\text{PARTICLES TO POINT "A"}}$

INDICATION EFFICIENCY $e_3 = \dfrac{\text{PARTICLES INDICATED}}{\text{PARTICLES ON CHIP DETECTOR}}$

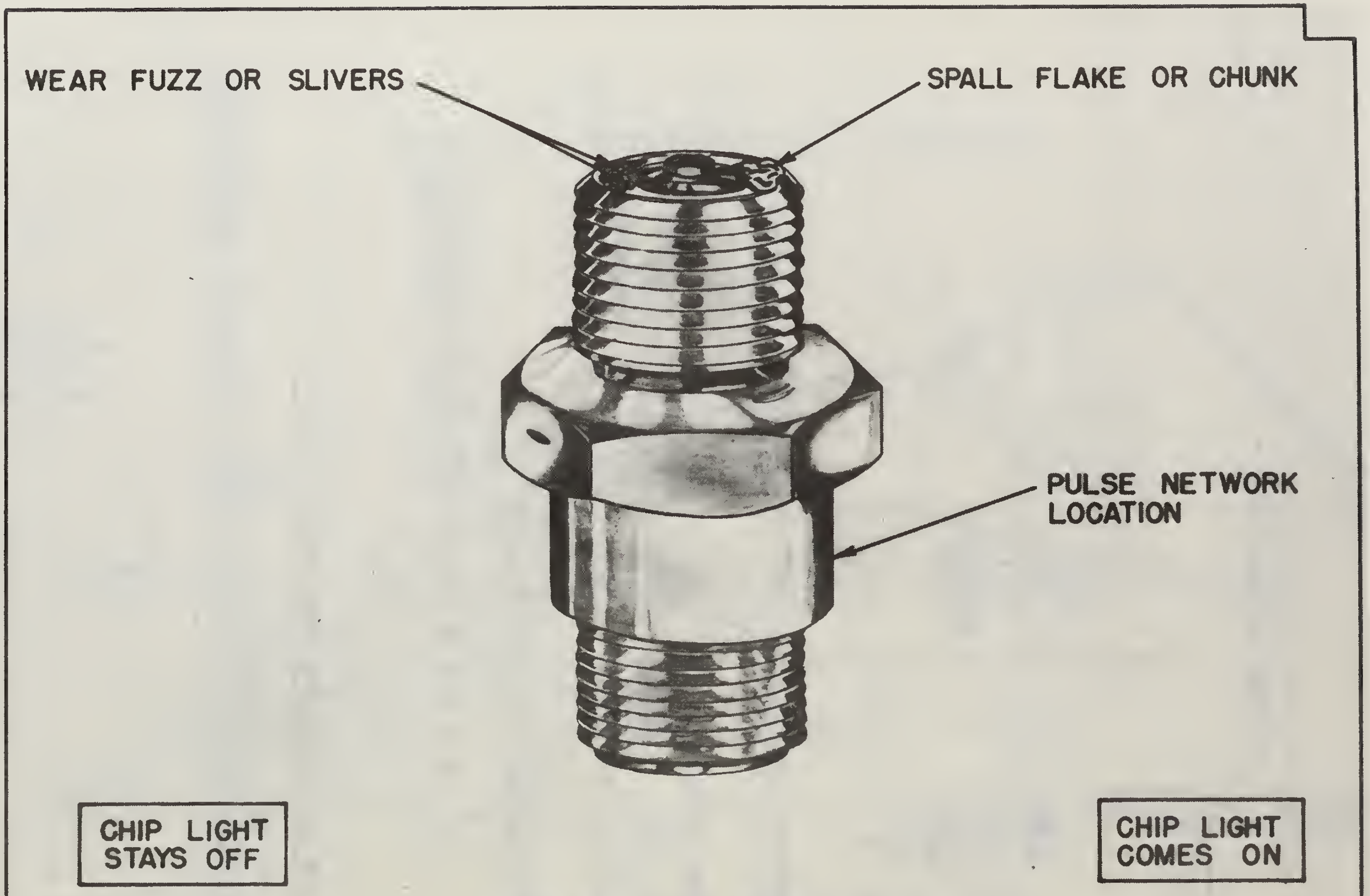
FAILURE INDICATION PROBABILITY

$$e = e_1 \cdot e_2 \cdot e_3 = \frac{\text{PARTICLES INDICATED}}{\text{PARTICLES GENERATED}}$$

<u>LOW $e_1\,e_2$ REQUIRE HIGH SENSITIVITY!</u>

<u>HIGH SENSITIVITY CAUSES MORE NUISANCE INDICATIONS!</u>

FIGURE 3



PULSED CHIP DETECTOR

FIGURE 4

Figure 5

Figure 6

ANOTHER LOOK AT TIME WAVEFORM ANALYSIS

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Determination of the mechanical condition of machinery through the use of vibration measurement most often involves amplitude versus frequency analysis. This type analysis generally provides sufficient information to permit diagnosis of a machine's condition, but there are times when it is desirable to supplement such analyses with additional information. Although there are many analysis techniques available to provide additional information, the use of time waveform measurements provides a number of advantages, not the least of which is the ease of acquisition.

While it is possible to obtain time waveform data with standard, or storage oscilloscopes, the real time analyzer with its capability to easily store and display time waveform patterns provides the real impetus for taking another look at time waveforms as a source of diagnostic information.

Amplitude versus frequency analysis provides information as to the distribution of the vibration energy across the frequency spectrum of interest. In addition, if such analyses are taken at short time intervals to produce a "waterfall" display a plot of amplitude versus frequency versus time is developed. As a supplement to this information, the time waveform data can provide the following:

1. a physical description of the vibration which shows whether the vibration is steady or intermittent, constant amplitude or varying, periodic or non-periodic, etc.,

2. the relation between the vibration and physical events such as valve closure,

3. the peak overall amplitude,

4. the phase as it relates to mechanical unbalance, as well

as to mode shapes and harmonics,

5. the symmetry of the signal which relates to the characteristics of the forcing function and the vibrating structure,

6. the damping associated with the vibrating structure, and

7. the direction of initial excitation which can be used to infer the direction of the force and the source of vibration.

When time waveform measurements are taken of different types of machines it is immediately obvious that in many cases interpretation is aided by the use of filtering. Depending on the specific data, high pass, low pass, or band pass filtering can greatly clarify a time waveform which would otherwise be difficult to interpret. In addition, it has also been found that it is desirable to display the data over two different time intervals. Displaying a relatively "long term" time sample provides information as to general trends of amplitude and phase; whereas a "short term" time sample, i.e., a few cycles of the primary frequency of interest, shows the details of the vibration which can be used to determine phase angles, direction of excitation, etc.

Although time waveform data is particularly valuable for analysis of non-steady state and transient vibrations, it can also prove useful in analysis of steady state vibration. By way of illustration, several examples are given.

Investigation of the vibration characteristics of a six cylinder 50 H.P. air conditioning motor driven compressor using time waveform displays provided information beyond that yielded by the standard amplitude versus frequency analyses. In all these tests band pass filtering was used to eliminate vibration frequencies above and below that band containing the fundamental and second harmonic of the compressor.

The amplitude versus frequency analysis taken on the compressor for the range of 0-6000 CPM, showed that the signature was dominated by the fundamental rotational vibration plus what appeared to be the second harmonic. The words "appeared to be" are used because it is not possible to determine from an amplitude versus frequency plot whether the higher frequency is in fact the second harmonic, or merely a frequency close to that of the second harmonic.

The long term time waveform pattern for these same signals showed that the amplitudes of both signals were quite steady and that the phase between them was essentially constant which confirms that the higher frequency was harmonically related. By looking at the short term time waveform analysis it could be seen that the harmonic was in fact the second, since the phase angle did not change with time, and consisted of a "jog" in what otherwise would appear to be a sine wave.

For comparison an amplitude versus frequency analysis was made for a different point on the compressor. Again the two dominant frequencies appeared to be the fundamental and second harmonic, although at this position there were also some low level random vibrations. For this position the long term time waveform amplitude and phase trends showed an entirely different picture from the other measurement point. The amplitude fluctuated widely from instant to instant, and the phase changed with time.

The short term time waveform plot also showed the random amplitudes and confirmed that the phase was changing. From this it could be determined that the upper frequency was not a harmonic, and, therefore, most probably related to looseness rather than misalignment or reciprocating forces.

Thus, the time waveform analyses specifically provided information as to amplitude variation, phase variation and confirmation of the harmonic relationship between frequencies.

The investigation of time waveform analysis also included a study of a two stage, belt driven reciprocating air compressor. The compressor was driven by a 1750 RPM induction motor through a belt reduction of 1.75/1 to give the compressor a speed of 1000 RPM.

The vibration characteristics of this machine could be divided into two frequency ranges of interest. The first was the low frequency range which included the fundamental and second harmonic of the compressor. These compressor frequencies are typical of unbalance and reciprocating forced vibrations found in this type machine.

These vibrations when measured at the compressor base, and displayed as a time waveform, showed the characteristic pattern of a fundamental plus second harmonic vibration with a 180° phase angle relationship between the fundamental and second harmonic. Additional measurements made over the bed-plate and the compressor cylinder suggested that the entire compressor assembly was in a rocking mode of vibration at the frequency of the second harmonic; having a nodal, or pivot, point approximately coincident with the centerline of the compressor crank shaft. A measurement taken at the top of the compressor cylinder in the same direction as that taken at the base showed that although the fundamental and second harmonic were still dominant, their phase relationship was 0°, rather than the 180°, indicating that the cylinder top was moving opposite to the base which is characteristic of a rocking vibration. It should be noted that to provide positive confirmation of this rocking vibration, a once-per-revolution pulse from an electromagnetic pickup should be superimposed on the time waveform.

The second frequency range of interest covered the high frequencies, (i.e., above 100 Hz (6000 CPM) although these were modulated by the relatively low rotational frequencies and their harmonics. The time waveform was measured vertically on the top of the cylinder head, and showed the repetitive pulses of the vibration caused by the opening and closing of the air intake and discharge valves. The periodic vibration pulses from this valve action could be seen in somewhat more detail in a short term analysis, namely the sequence of: open intake, close intake, open discharge, close discharge. A further expanded time waveform display of one of these pulsations provided further information as to direction of the pulse excitation and rate of decay of the vibration.

This same measurement displayed as an amplitude versus frequency analysis showed two dominant peaks: one at about 5000 Hz (300 KCPM) and the other at 11,670 Hz (700 KCPM) which suggested excitation of two natural frequencies. This provides an interesting comparison between amplitude versus frequency and time waveform and indicates the value of the time waveform in supplementing information from the standard amplitude versus frequency analysis.

From the above examples involving the steady state operation of two types of reciprocating compressors, it can be seen that the time waveform does provide significant information beyond that obtained from amplitude versus frequency analyses alone.

THE ADVENT OF SOPHISTICATED FLUID POWER SYSTEMS AND ITS IMPACT ON PREVENTATIVE MAINTENANCE IN THE MILITARY

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ABSTRACT

Over the years we have witnessed advances in many areas of fluid power contamination control. These advances have been made in many laboratories with the aid of the automatic particle counter.

Although we are slow to see transition from laboratory to field use, where applied, the automatic particle counter has shown to be a valuable preventive maintenance tool. The United States Military and many commercial firms realize the importance of contamination monitoring, however preventive maintenance programs remain somewhat limited.

In the discussion which follows, a brief review is made of the need for contamination monitoring and the specific programs that have addressed those needs. Further application of the automatic particle counter in preventive maintenance is examined in future trends.

INTRODUCTION

Fluid power systems today are much more sophisticated than their predecessors of ten or twenty years ago. Why are they more sophisticated? Because we demand better performance. Fluid power systems must react quicker, with more precision, and definitely more reliability than earlier systems. Perhaps the greatest impact on today's fluid power system has been caused by computerized control. In effect the introduction of computer interfaced fluid power has required tighter tolerance limits in both the fluid power system and system components.

What the designer has gained in fluid power design through improved feedback systems, precise control, computerization, and reliability; he has given up the high tolerance of fluid power systems to withstand contamination from various sources including particulates of wear, ingestion of sources external to the fluid power system, as well as dirt, water, and hydrocarbons.

Where screens or chip monitoring had sufficed before, highly engineered filters are now a requirement to prevent contamination from fouling the hydraulics.

Where the use of cotton bags to gather weld beads and debris was sufficient in the past, vast filter banks and flushing requirements are specified for initial clean up procedures, followed by a preventive maintenance program of monitoring hydraulic and lube oils for unacceptable levels of contaminents.

REVIEW

A brief review of design philosophies of various hydraulic applications will give us a good background to help understand why fluid power contamination plays an important role today.

Surface ships, for example, are evolving from the concept of several hydraulic systems to a more centralized system. It used to be that a ship had separate systems for steering, capstan, winches, elevators and so on. Filtration was either nonexistant or minimal. Contamination related problems were avoided by designing the fluid power system to operate on a slurry of hydraulic fluid, sand, and sea water. Perhaps this is an exaggeration, however, even today we see many of these old ships operating with the same dirty old sump. Break downs still occur of course.

Recently, the U.S. Navy has initiated a program to clean up some of these ships. The hydraulic fluid is cleaned up by removing water and particulates, filters are installed or improved. Not surprisingly, the performance of that system is improving too.

There has always been some concern for subsurface craft as far as fluid power reliability. A submarine may have two pumps to ensure a source of fluid power, however it has only one distribution system. Over the past decade an ambitious program has been developed to monitor contaminant levels of hydraulic and lube oils.

Aircraft control systems are another example of a high risk environment where a man's life depends on a reliable hydraulic system. Again the U.S. Navy has recognized this and has perhaps the most aggressive and rewarding preventive maintenance program in airborne fluid power.

It is true that a properly designed hydraulic system would have filters in all the "right" places and thus avoid contamination problems. In fact one might then argue that "aircraft hydraulics do not become contaminated," but they do. That is why in 1969 when the U.S. Navy initiated its control program to monitor aircraft hydraulics, sixty-six reports of hydraulic system contamination were received of which nearly a third implicated damage to components. Moreover, six deaths resulted and fourteen aircraft could not be economically repaired. The total cost that year essentially due to contaminated aircraft hydraulics was $28,481,000 (1).

Missle systems owing to their overall function, design and purpose, have always demanded the most of current fluid power technology. The hydraulic fluid must be very clean, for operation pressures are high and a sticking valve or even altered response time could mean mission failure. Once the missle is in the field the hydraulic system cannot be opened up again until it comes back to the rework facilities for periodic inspection. Owing to the size and cleanliness level required, on-line contamination monitoring is the preferred means, and works quite well with the HIAC Contamination Control Monitor. Particle counts can be taken without regard to test stand vibration, fluid temperature or viscosity changes. All this can be done while putting the system through dynamic check out as well.

CONTAMINATION AND PREVENTIVE MAINTENANCE

Thus far I have addressed contamination monitoring without detailing the reason behind the practice. The idea is very simple, and perhaps taken too lightly by Engineers, Designers, and Maintenance people: "The end result of the presence of particulate contamination ... is to accelerate wear (2)." Thus if we can monitor and control the amount of particulate contamination in a system, we have a means for determining and controlling the useful life of the hydraulic system.

Contamination and its control is not really new. For we have known for some time now the effects of particles on bearings (3). In recent years the fluid power industry has made significant improvements in associated areas for contaminant monitoring including instrumentation, standards, and techniques (4,5).

We know that contamination control generally addresses four areas:

1. Source
2. Amount
3. Tolerance
4. Control

From a preventive maintenance point of view each area is important. If one is to achieve contamination control of a system, one must have a knowledge of source, amount present, and the tolerance of the system.

Recently much work has been done in addressing source contaminants, especially "tribocontaminants," or wear particle contamination. In fact the study has been specialized and termed Tribology. The term originated from the Greek "tribos," meaning "rubbing" and is defined as,

> "The science and technology of interacting surfaces in relative motion and of the practices relating thereto (6)."

A tribocontaminant is still a particle however, and as such, the rate of generation can be monitored using a particle counter in a regular preventive maintenance program. The end result would be a histogram of the system under inspection. Over a span of time the system would indicate, by means of the particle count histogram, its transition from break-in wear to normal operating wear, and finally, transition to abnormal or degenerating wear; indicative of imminent failure of the system.

It is relatively easy to access the benefits of particle counting in preventive maintenance. Two areas of improvement can immediately be seen:

1. Better scheduling of normal maintenance functions.
2. Foresight as to when a system digresses from normal to abnormal wear, at which point proper action can be taken.

The concept of particle histograms is not totally new, and has been used in various independent maintenance programs and in research. I would predict that this is an area in which we will see future growth in preventive maintenance.

The amount or level of particulate contamination a system can endure has also been an area of great study. There are two general ways for quantifying amount of contaminant, i.e., a particle size distribution (7), and a gravimetric measurement (mg/l). While the particle size distribution gives detailed information over a series of size ranges (in essence a multivariable) the gravimetric is only a single variable. Particle size distributions are hence a more sensitive measure to changes in wear patterns. Nevertheless, gravimetric analysis is used in various lubricants as a measure of contaminant level. In certain low risk or low cost applications the measure is adequate. But where a break down in the lubricating system can be economically disastrous, or risk human life, a particle count distribution should be taken as a preventive maintenance guideline.

For example, the large turbines used in power generation by utility companies are monitored periodically to evaluate the condition of bearings. Should the lubricant indicate bearing degeneration of an abnormal nature, the turbine can be scheduled for proper maintenance. The utility avoids an emergency shutdown and such costs involved during the emergency situation.

Many studies have been done to determine what contaminant level the system can tolerate. Generally the studies have been done on individual components used in a hydraulic system (8). The results look rather encouraging for future designers as reported by Fitch (9). It is very possible Engineers may some day design complete systems with a product or component normally rated for their sensitivity or lack of it to contamination.

As stated earlier, control of particulate contaminants is a multidimensional task incorporating source, amount present, and tolerance of the system. I have discussed very briefly each of these dimensions. A great amount of work has been done in each area and research continues.

Secondly, contaminant control is more than hardware. It is a well thought out Maintenance Plan to monitor systems, access their various states for contaminant levels and trends. Such a program can pay off in terms of less down time, better reliability, safety, and especially improved Maintenance Management. Improved such that one changes from managing a maintenance program on a crisis by crisis basis, to a well managed working schedule which forecasts when a hydraulic system will come in for work to be done.

Finally, filtration is also very important in contamination control. Ideally we would like the filter to offer the following characteristics:

1. Infinite restriction to the passage of particles.
2. Exhibit zero resistance to the flow of fluid.
3. Provide unlimited capacity for retaining particles.

Obviously we can only come close to the ideal. HIAC has aided manufacturers of filters with the development of the Model 6+6 for determining Beta ratios. With this instrument, manufactures are able to make particle counts and have Beta ratios automatically printed out in accordance with adopted multipass evaluation standards (10).

FUTURE TRENDS

Looking to the future of contamination analysis in terms of preventive maintenance, we see great possibilities in several areas.

Computer interfacing of hydraulic systems and contamination monitoring is an area of great potential. By maintaining historic data in the computer, trends can be analyzed and predictions made. Not only might it be possible to predict system failure, this information would also further the organized management of preventive maintenance by scheduling components for inspection and system checkout.

We will no doubt see improved interfacing of hydraulic test stands and contamination monitoring. There are many instances where the test stand adds contaminants to essentially clean systems. Hence the incorporation of contaminant monitoring on-line within the test stand offers advantages over current contamination monitoring techniques.

Finally, I believe we will see the use of particle counting extended for use in monitoring critical lubricating oils. The method of weight measurement of contaminants is not sensitive enough in many applications. Nor can many groups afford a spectrometer to analyze wear metals. We are seeing enough evidence today to seriously consider particle counts as an excellent means of predicting bearing failure.

CONCLUSIONS

After many years of study of both particulate contamination and its effects, we are finally seeing the use of the automatic particle counter make its transition from experimental labs to the shops for use in successful preventive maintenance programs. While the acceptance of the automatic particle counter has been widespread for laboratory studies, practicle use in the field has been slow.

For those commercial industries that have made use of the particle counter, the initial investment has paid off in many ways: longer life of hydraulic systems, improved reliability and forecast of potentially hazardous hydraulic systems.

A large variety of sophisticated fluid power systems have seen the use of the automatic particle counter as a preventive maintenance tool. The applications are expanding, and the use of the particle counter is gaining acceptance in the field of preventive maintenance.

Through improved solid state electronics, HIAC has designed an automatic particle counter which is fairly easy to use. The use of sample bottles for gathering samples of hydraulic fluid necessitates an understanding of practical techniques for obtaining reliable data. However, the recent introduction of the HIAC Flow Control Monitor for on-line monitoring of contaminants eliminates almost all possibilities of human errors in technique. The Monitor is pressure and viscosity insensitive and hence ideal for in-line applications.

We will indeed see further use of the particle counter and computers. Through further research we will be able to confirm trend analysis toward system or component failure. It is very possible that the automatic particle counter/ computer interface will become one of the most important tools in lubrication and hydraulic systems for detection, diagnosis and prognosis of bearings in hydraulic component failure. The payoff will be safety, reliability, and an efficient plan of preventive maintenance action.

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TIRE DEGRADATION MONITORING

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GARD, INC. has been performing nondestructive testing of tires for the U. S. Army for over 4 years. Based upon this work, which included:

a) a detailed 500 tire ultrasonic scanning test,
b) casing water wicking tests,
c) correlation peel tests,
d) on-vehicle road test monitoring, and
e) ultrasonic inspection technique development,

it was concluded that a quick and simple nondestructive measurement of tire casing fatigue (degradation) could be made, and that such a measurement would pay for itself in allowing a retreader to:

a) reduce in-process failures, and
b) reduce on-the-road, retread tire failures.

This saves money for both the owner and the retreader of the tires, and provides increased safety for the user.

What do we mean by casing fatigue? It is the degree of bond between the cords and surrounding rubber in the body of the tire. This bond changes during the life of the tire from "tight" in a good, new tire, to "loose" as the tire body grows during use, to "casing separation" - a failure which is characterized by cord showing on both sides of what remains of the tire at the end of its life.

Fatigue detection is more practical as a nondestructive test of tires than separation detection because the presence of a separation does not necessarily mean the tire will soon fail. <u>Large</u> separations would be critical to casing failure in retreaded tires. However, they are normally found during the standard retreading process, which includes inspection in spreading, buffing, and molding. <u>Small</u> separations, which are not now readily found, lead to many casing failures. However, they do so only in weak casings. A strong casing, with typical small defects, will not fail until weakened by use. As an example, many new tires are fabricated with small separations and still provide miles of use: thus, alone, the presence of small separations is not a practical indicator of tire suitability for retreading. The state of casing fatigue must also be known.

Monitoring casing fatigue eliminates the need for emphasis on the detection of small defects (and the elaborate scanning needed to find them). It provides a quick, simple, and practical way to improve tire quality and safety.

Empirically, GARD was able to establish that pulse-echo ultrasonics could provide an indication of casing fatigue. Ultrasonics measures the increased porosity in a casing due to cord loosening. The sensing signal decreases, due to sound scatter, as the tire degradation increases.

Since pulse-echo is a single-sided inspection, on-vehicle inspections can be performed. Figure 1 shows such readings for new tires as a function of mileage on a truck. The data is plotted as an average of axle readings. As expected steering axle fatigue is greater than rear axle fatigue which is greater than intermediate axle degradation.

Figure 2 shows an averaged population of new-unused, "new" retread-candidate, newly retreaded, and retreaded retread-candidate tires plotted against average miles as figured by the U. S. Army. As can be seen the degradation curves in Figure 1 and 2 follow each other well.

GARD, INC. has built and is marketing a pulse-echo ultrasonic Tire Degradation Monitor (TDM) which allows the above type of measurement to be made. (Figure 3) Its electronics are specifically designed to provide digital readings which relate to degradation in both steel and textile, truck and passenger, tires: readings which range roughly from 20 to 0, 20 normally being a good tire, and 0 being a weak tire to be rejected for retreading.

Degradation occurs uniformly around a tire, because tire use is circumferential: age, mileage, load, temperature, and pressure affect the tire everywhere. So a tire can be sampled to get degradation information. Scanning does not have to be performed; the inspection is quick and simple. One measurement would theoretically be enough. However, several measurements must be made so that local effects, such as bruises or splices, do not give erroneous readings.

A pulse-echo reading is sensitive to geometry. It is based upon sound being reflected back to the probe. Thus to make an inspection practical for most tires, a mid-line tire inspection is recommended. Readings in the shoulder area of a tire are not reliable because tires have many different shoulder geometries, and worn tires add another significant geometry variable.

Can this technology predict shoulder problems? (A big concern with retreaders.) There is obviously a relationship between mid-line and shoulder fatigue in a given tire. How consistent is it from tire to tire? A TDM user has found he can eliminate 100% of his top ply and 50% of his shoulder casing adjustments by the mid-line degradation inspection.

This reduction in failure rates comes about because of two factors: a) an increased casing rejection rate due to the elimination of weak casings which would have previously been retreaded and b) grading of rejected casings for use. The above retreader increased his casing rejection by 4% in reducing his casing failures as indicated. The failures accounted for about 50% of his adjustments, which in turn accounted for about 5% of his total retreading. He now grades his retreaded casings for about 50% heavy and 40% light use (see Figure 4).

Figure 4. - Inspected Tires

Disposition	Distribution
Reject*	4
Trailer Use	46
Any Use	50

* This rejection is before normal visual inspection.

The retreader is saving money. The trucker has less road failures, saves money, and has a safer road operation.

In summary, government-financed research work has uncovered a new failure prognosis technique for tires: that of predicting casing residual life by measuring its overall integrity, independent of existing local anomalies. This is much like a life insurance underwriter predicting a person's remaining lifetime based upon his current age. The insurance companies have found this to be a sound statistical basis for doing profitable business. We feel the tire industry will now be able to do the same.

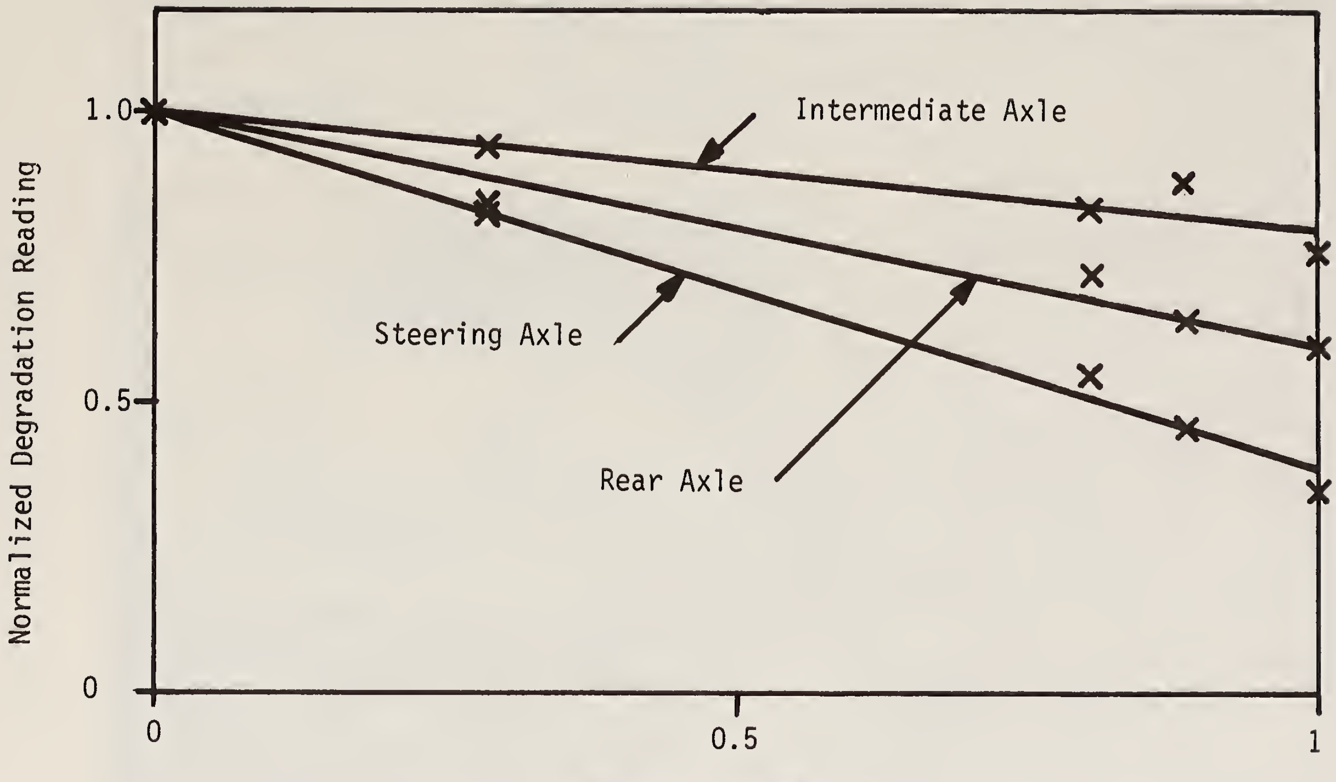

Figure 1 - On-Vehicle Degradation Readings

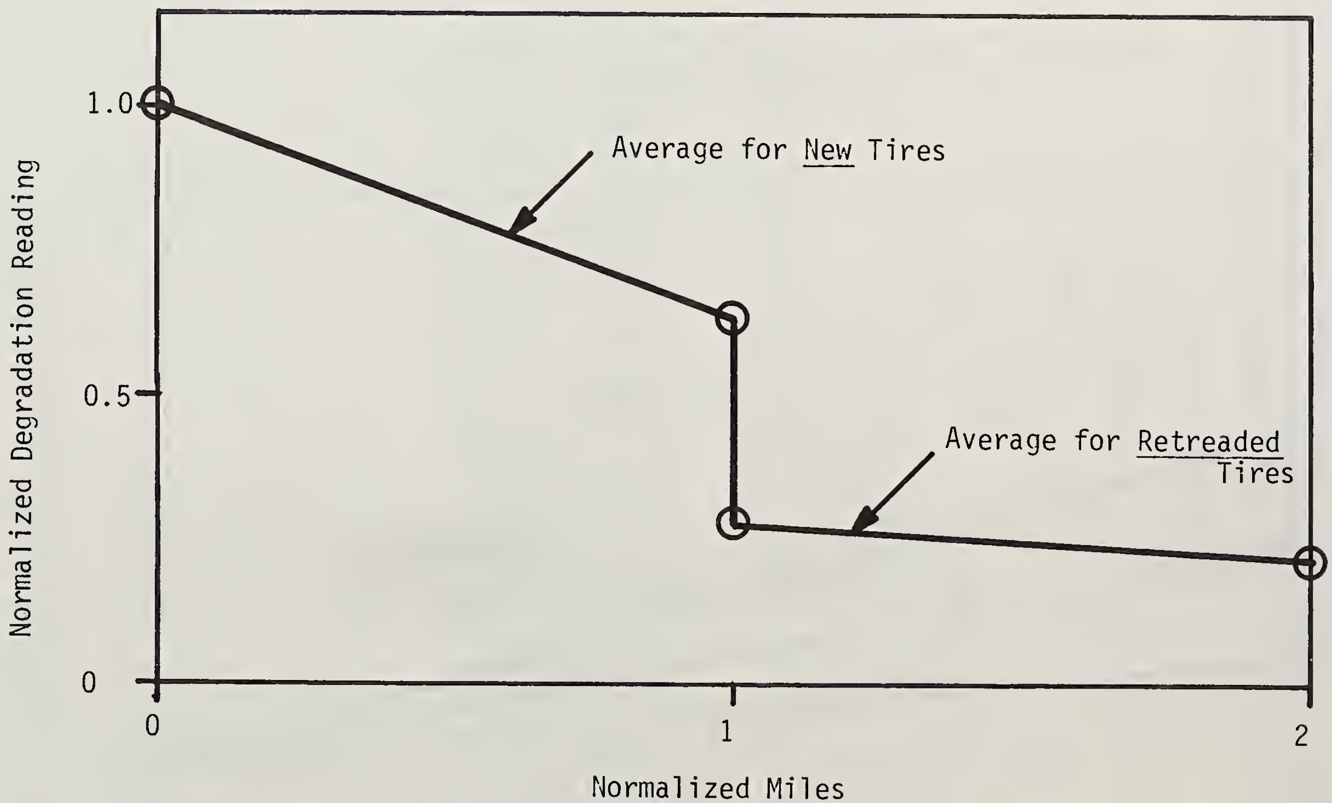

Figure 2 - Population Degradation Readings

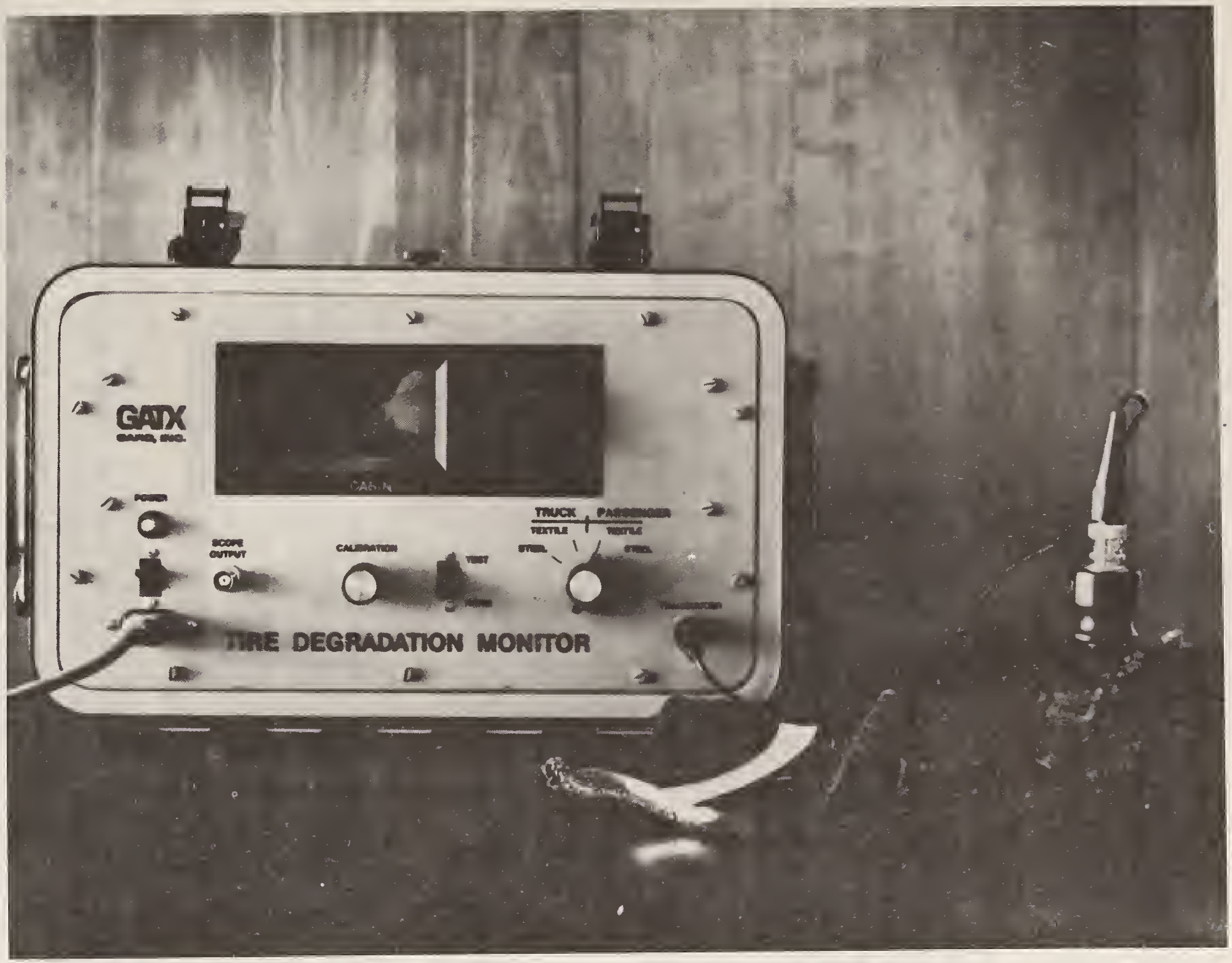

Figure 3. TIRE DEGRADATION MONITOR

USE OF MICROPROCESSORS IN ANALYSIS OF ACOUSTIC EMISSION WELD MONITORING DATA*

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Abstract: The use of Acoustic Emission as a nondestructive technique for real time weld evaluation creates a need for supporting analysis equipment. This equipment is needed to extract the information required for setting parameters on acoustic emission weld monitors as well as exploring the application of Acoustic Emission to various welding materials and processes. The equipment requirements are fast analysis turnaround time, simplicity of operation, and maximum information extracted from the weld. The authors are developing a system for this analysis using wideband tape recordings from a modified video tape recorder and a microprocessor-based computer. Analysis is made of amplitude frequency content and pulse-realted information of the acoustic emission bursts, and presentation of the analysis is designed for simplicity and efficiency in the operator-computer interaction. The paper presents current results of this procedure, a description of the analyzer system and associated equipment, and possibilities for future work using microprocessors in this and in other areas.

Introduction

The study of Acoustic Emission Weld Monitoring at GARD began in 1971 with an effort aimed at real-time NDE of railroad tank car welding. Our goal was to minimize radiography, particularly the shooting of multiple radiographs of the same weld. We hoped to do this by performing "on-the-spot" inspection of welds as they were completed to allow immediate repair and correction of welding problems. Acoustic Emission is by its nature an "on-the-spot" phenomenon, and was determined to be a suitable solution to this problem.

Many researchers have shown that useful information may be obtained acoustically from stressed metal specimens.[1] The welding of metals produces a unique situation where stress is generated by the thermal contraction of the cooling weld bead. As the weld cools, stress causes the growth of flawed areas, particularly cracks. Since the release of energy in a growing flaw is mechanical in nature, it is also acoustic in

* Some of the data presented in this paper was acquired as a direct of indirect result of work done under U. S. Nuclear Regulatory Commission Contract No. AT(49-24)-0187.

nature, with the frequencies of interest ultrasonic and generally lying between 100 KHz and 1 MHz.

Many problems are involved in Acoustic Emission Weld Monitoring, however. These are generally due to extraneous and interfering noise. This noise is due to a multitude of sources, including the noise of the electrical arc, cooling slag, and mechanical scraping or pounding noises. These noises tend to mask the useful information which comes from the weld.

GARD has demonstrated that Acoustic Emission Weld Monitoring can take place even in the presence of interference, by the use of signal processing techniques.[2,3] The first such techniques were discovered by trial and error, and involved many hours of manually adjusting parameters and replaying taped data. Our experience is now sufficient to allow a more sophisticated approach to data analysis, and we felt that future use of Acoustic Emission Weld Monitoring was sufficient cause to develop an automatic data analysis system to fulfill our needs. It would allow us to efficiently study new welding materials and new welding processes, to establish parameter settings for Acoustic Emission monitoring for particular applications, and to improve settings for systems in use, such as at our tank car manufacturing facility. To do this economically, such a data analysis system would have to:

1. Use either live or tape recorded weld data as an input.

2. Have the capability of holding large amounts of data obtained during one weld and to conveniently store data on all welds observed for subsequent reprocessing.

3. Have sufficient flexibility in formatting data input and output both to the convenience of the developer and for efficient operation of the processor.

4. Offer simplicity of programming for efficiency in altering the way the data is processed.

5. Be capable of gathering data in an uncontrolled environment, such as weld lab or production floor.

We would have been forced to use a large-scale computer as the core of our system if microprocessors hadn't been developed. The small size, low cost, and programmability provided by microprocessor systems enabled us to more than meet the above requirements of Acoustic Emission analysis. They have allowed us to develop a small, on-line, programable monitor which will be discussed later.

The introduction of the microprocessor to the electronics industry ranks as one of the most exciting things to happen in recent years. The development of Large Scale Integration (LSI) manufacturing techniques allows the reduction of all of the necessary functions of a computer system to the size of a few tiny integrated circuit "chips".

In addition, mass production of the chips can and has brought the cost down dramatically. For example, the Motorola 6800 microprocessor, which has more computing power than many early computers that cost hundreds of thousands of dollars, can be bought for $35.00. This low cost allows the equipment designer to consider applications which he may otherwise have rejected, or for which he would have used fixed, hardwired logic elements.

The microprocessor may be thought of as a universal logic element whose function may be changed by means of a stored "command". A series of these commands is called a program, or simply "software". The programmer may remove an instruction, and insert another in the program and easily change the function of the microprocessor. Thus modifications are easily made, and mistakes easily corrected.

In an application such as ours, turn-around time on a large-scale machine is, at best, a matter of minutes. At worst, it can be up to a half a day. Microprocessors allow one to conveniently set up a processor that is dedicated soley to ones' project and can reliably give turn-around times in seconds. Large scale machines are still the data storage champions, but with mass storage peripherals (floppy disc, cassette) microprocessors are able to retain more data than we can presently conceive of gathering.

In the formatting of data exchange, the microprocessor has a definite advantage. To suit many diverse users, large scale general purpose machines are programmed to accept input according to a limited number of formats. Each user must therefore organize his data toward the processor's preference rather than to his individual situation. The microprocessor allows one to easily construct his own computer and to wire and/or program it to accept data in a format convenient to his individual requirements.

Programming a microprocessor is no more difficult than programming a large scale machine. Our processor was easily programmed in assembly language, but systems are on the market that allow programming at higher levels, such as BASIC, PL/1, etc.

An area in which microprocessors are better for our applications than a large-scale machine is in their greater mobility and tolerance to environmental variance. Large-scale machines are set in air-conditioned rooms. You go to it, it doesn't come to you. Microprocessors are portable and capable of being run anywhere a human will be comfortable.

Finally, when a large-scale machine is programmed, any further use of that program must be done on that or a similar machine. When a microprocessor is programmed, the job of building a dedicated processor is virtually complete. The computer can now exist as a field-portable electronic device by hardening the programs into PROMS.

The present configuration of the acoustic emission data processing system is shown in Figure 1. The following discussion of its operation refers to the block diagrams in Figures 2 and 3.

Data Gathering and Preprocessing

The function of this portion of the analyzer (Figure 2) is to:

1. Acquire acoustic emission information from the weld,

2. Break the analog information down into characteristics of interest and

3. Put these characteristics into a digital format compatible with the digital processor.

Information is gathered from the weld by means of (A) a piezoelectric transducer or transducers sensitive to surface mode vibrations in the ultrasonic range. Our experience has shown that the range of frequencies of interest is about 100 KHz to 1 MHz. Although information is probably present above 1 MHz, it becomes very difficult to get useable real world data in this region. We are continuing with our investigation in the >1 MHz region.

The analog signals are amplified after leaving the transducer(s), and may be tape recorded at this point (B). We use a Sony Video tape recorder, AV3650 which is modified to defeat the servo system on the rotating head deck, but other equipment may be used. An audio control track is added at this time to facilitate location of various areas of the weld, or changes in welding conditions. This information is put in by voice to allow addition of pertinent comments. The signal from either "live" weld or tape recorder is then amplified and is simultaneously broken down into frequency and energy characteristics.

Frequency characteristics are determined by (c) a set of 8 band pass filters which break the band of interest into equal percentage portions. Each portion is rectified, filtered, and the average peak value determined. A packaged "data acquisition system" (Burr-Brown MP7208) is used to multiplex the analog signals, digitize, and feed them to the processor system on command.

Energy characteristics of the burst are determined by a common acoustic emission technique called "Ring Down Counting". The signal bursts of interest are approximately exponentially damped sine waves. It can be shown mathematically[4] that if a threshold level is set, and if the number of cycles of an acoustic burst exceeding that threshold are counted, then the energy contained in the burst is approximately related to the count total by the following relationship.

$$\text{Log (energy in burst)} = K \cdot \text{(total of counts)}$$

This method of analog to digital conversion is ideal for acoustic emission bursts, because it tends to average out fluctuations due to extraneous resonances, etc. The ring down counting equipment (d) includes appropriate amplifiers, 1KHz-1MHz bandpass filters, and gain adjustments and consists of a modified Dunegan/Endevco (model 301) totalizer.

Additional circuitry is employed to supply the totalized ring down count to the processor, along with information as to our currently used thresholds for energy levels for purposes of display selection. (e.g., we may select all bursts exceeding the current low energy threshold). The information is fed to the processor on command.

Data Processing and Display

After the data is preprocessed, it is presented to the microprocessor system. This system (Figure 3) does the following:

1. Accepts data in both compressed and multiplexed modes and processes it.

2. Continuously displays 7 types of processed incoming data in real time, if desired.

3. Allows changes of display type, scale, or grouping without disrupting the data acquisition.

4. Simultaneously stores incoming data to mass storage, if desired.

5. Recalls data from mass storage, if desired.

6. Prompts the operator in everyday English through the various data acquisition and display options available to him.

In essence, the data processor used for acoustic emission analysis is programmed to operate as an on-line, operator-adjustable organizer of data derived from acoustic emission waveforms. At the heart of its operation is the Motorola M6800 microprocessing unit (MPU). This MPU, which contains all the arithmetic and decision-making capabilities of the system, is completely contained in one 40-pin IC chip. It is this compactness that makes the microprocessor system so portable and so environmentally tolerant. The MPU responds to and controls the system by means of a 16-line address bus, an 8-line data bus, and a number of control lines, represented in Figure 3 as one line.

The set of instructions which the MPU uses to operate the system as a data organizer is stored in several Motorola M6810 random access memory units (RAM). Other items stored in RAM are the English language text by which the system and the operator communicate, the processed data, the current display, and results of calculations directing the system through its operations.

A key feature of this system for our application is the aforementioned English text the system uses to prompt the operator and the operator uses to alter the system's operation. This was implemented so that data analysis could be done by someone who had no understanding of computers. An example of a system operator exchange is shown in Figure 4. This "dialogue" is conducted using a CRT with keyboard or a TTY unit receiving and transmitting data to a Motorola M6850 asynchronous interface adaptor (ACIA). This adaptor, and the Motorola M6820 peripheral interface adaptor (PIA) discussed below, are the keys to the microprocessor system's ability to adapt to the data formats desired by the operator. The physical structure of these devices is sufficiently undefined so that an appropriate command from the operator, through the microprocessor, can configure it to accept and/or transmit in a variety of formats. These devices are different in that the ACIA receives and sends serial data whereas the PIA receives and sends parallel data. The CRT-keyboard combination used in our system transmits and receives serial data in a preset format (RS232). Thus, upon operation initiation, our program instructs the ACIA to operate in an RS232 format. The ACIA can then present keyboard text to or receive CRT text from the data bus, thus creating an operator-MPU information exchange.

The preprocessed acoustic emission data are put on the data bus via two modes. The multiplexed frequency band data (A) is placed directly upon the bus upon command sent along a control line from the MPU. The ringdown count, threshold, and energy criteria data (B) are presented to the bus in parallel form through a peripheral interface adaptor (PIA) instructed by the MPU to be a 16-bit data acceptor. In addition, this PIA is instructed to initiate, upon receipt of a control signal from the pre-processor, a high-priority temporary interruption of the MPU's normal display and dialogue routines so that the MPU can receive, process, and dispose of the incoming data. The way the MPU disposes of the data in our system illustrates the versatility of the PIA.

If desired by the operator, the processed data can be displayed as it is received, thus giving a real-time analysis of the current weld acoustic events. This display is accomplished by presenting display coordinate data to a PIA instructed to be a data transmitter (C). The output of this PIA is put through a digital-to-analogue and operational amplifier circuit and presented, at the operator's selection, to either an oscilloscope for online previewing of event trends, or to an x-y plotter for the creation of hard copy of an analysis. Simultaneously, if so desired, unprocessed data can be stored in mass storage for further retrieval and analysis. This data is presented to a PIA instructed to operate both as an 8-bit data acceptor and an 8-bit data transmitter (D). This PIA, by use of its four accessory control lines and an additional PIA for 12-bit control line capacity, directs the traffic of digitized data to and from a floppy disc mass storage system. Thus, the versatility of our acoustic emission weld data analyzer is based on the versatility of the microprocessor and its family units.

Some Typical Results

To demonstrate the type of output the data processor gives, the results from three weld specimens are presented in Figures 5. The type of flaw induced in these welds was that of incomplete penetration. Dye penetrant was used to provide immediate confirmation of these flaws.

The processor generated histograms shown in Figure 5 are those of the number of acoustic events of a given ringdown count plotted on the vertical axis against the value of the ringdown count plotted on the horizontal axis. In effect, the analysis corresponds to that of an energy distribution. This method of analysis creates patterns that allow the eye to pick out subtle variations as well as continuous emission sources such as electronic or weld arc noise.

Figure 5b shows the analysis display acquired during weld number 1, a weld in which incomplete penetration was very slight and intermittant. Very little acoustic emission activity is present with a widely scattered energy distribution. Incomplete penetration in weld number 2 (Figure 5c) was nearly 100%. Note the dramatic increase in activity. Weld number 3 (Figure 5a) was generated as a control having good penetration, and the analysis shows the least activity of all. Figure 6 shows variations in the frequency spectra of the above three welds. The differences in frequency characteristics are also obvious to the eye. We are presently at the stage where similar analyses are being done on a mass production basis to create a large acoustic emission data base.

Summary

To summarize, the use of microprocessors in general allows one to construct a dedicated processor according to his specific needs, take that processor anywhere he goes, and use it with a minimum of turn-around time. In addition, programming a microprocessor amounts to the "wiring" of an electronic device dedicated to a desired process.

In our specific application, we are able to use the processor to display distributions of ring-down count (energy) and frequency bands during a weld or the play-back of one. Through operator interaction, we are able to search for a promising flaw-candidate pattern and follow it through sequences of good and bad welds. By this means, we can not only find background noise and flaw patterns, but are able to ascertain what adjustments of monitor parameters are necessary to exclude or enhance these patterns. This will result in a better "signal-to-noise ratio" in the detection of weld flaws. In addition, it is our hope to be able to tune the monitor parameters finely enough to allow not just detection of flaws, but indications of flaw type and extent.

In addition to the analyzer system that has been described above, GARD has constructed a new acoustic emission weld monitoring system for particular field applications which also contains its own microprocessor system. The development of this system followed exactly the same lines as the development of the data processor but, whereas the processor had been developed up to the software development stage, this system has been carried through to the stand alone stage. Besides allowing easy adjustment, through software, of monitoring parameters as determined by the analyzer system; the microprocessor also allows this system to perform other functions in its idle time. The microprocessor determines, by means of difference of arrival time, the location of an AE source along a weld length; it controls the display of such information, and allows the system to run on totally unattended operation. Figure 7 shows the system.

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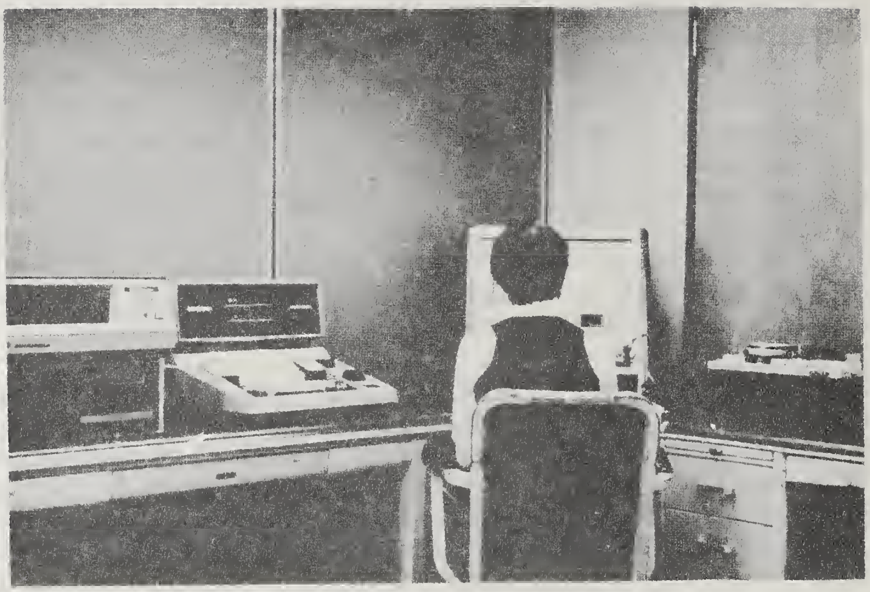

Figure 1. THE ACOUSTIC EMISSION DATA PROCESSING SYSTEM IN OPERATION

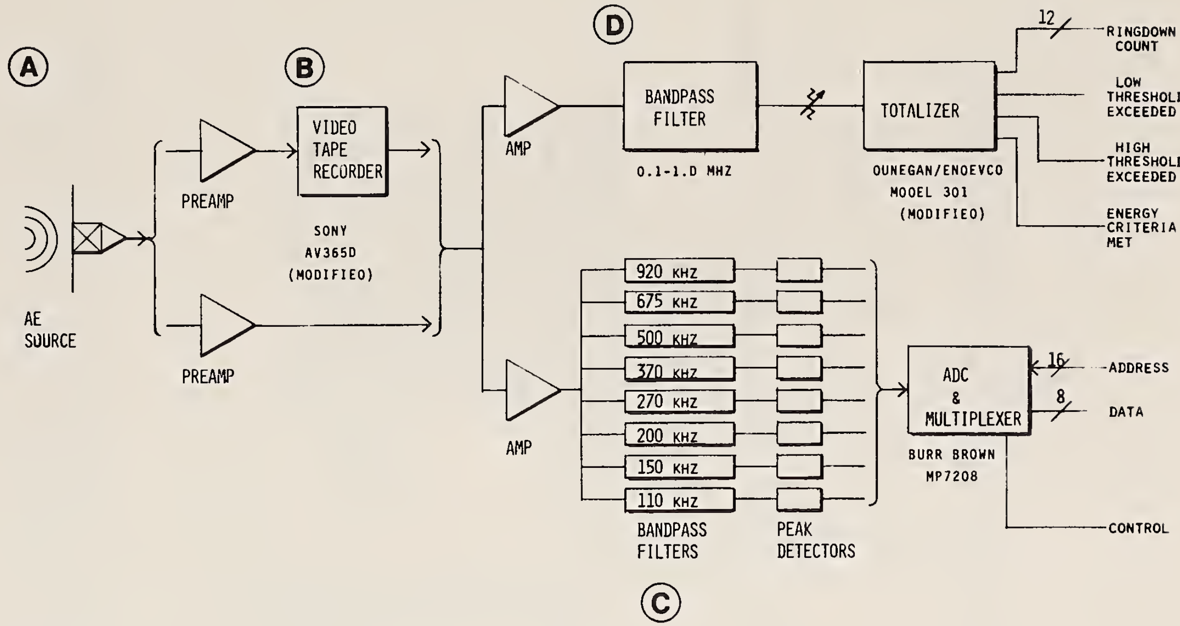

Figure 2. DATA GATHERING AND PREPROCESSING BLOCK DIAGRAM

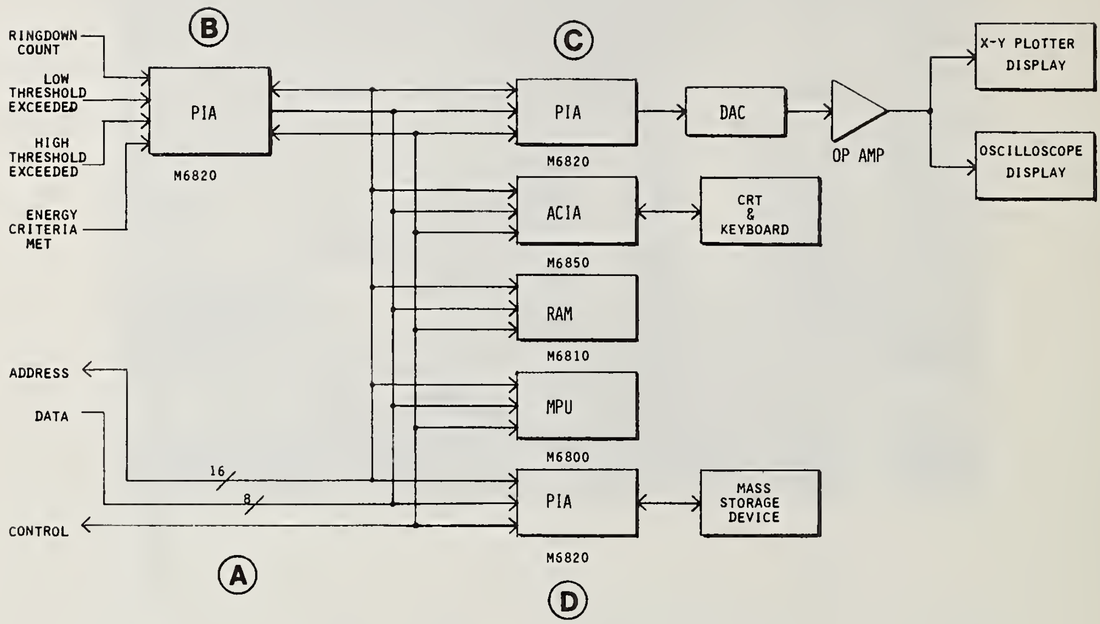

Figure 3. DATA PROCESSING AND DISPLAY BLOCK DIAGRAM

```
READY FOR OPERATION:

     TO RUN         KEY R
     TO RESTART     KEY S ... R



DATA RECALL FROM FILE NUMBER:
    01  STANDARD 10-16-21 DB    00500
NUMBER HISTOGRAM DISPLAY ON OSCILLOSCOPE
     001 X SCALE FACTOR
     001   LINES/CELL

TO CHANGE STATE, KEY 'C' ... C

     ERASE DISPLAY              KEY E
     SUSPEND DATA INPUT         KEY M
     MASK BAND CHANGE           KEY B
     SCALE CHANGE               KEY S
     CELL SIZE CHANGE           KEY C
     DISPLAY MODULE CHANGE      KEY D
     TYPE HISTOGRAM CHANGE      KEY H
     FILE NUMBER CHANGE         KEY F
     PROCEDURE CHANGE           KEY P ... E
```

Figure 4. AN EXAMPLE OF SYSTEM-OPERATOR EXCHANGE

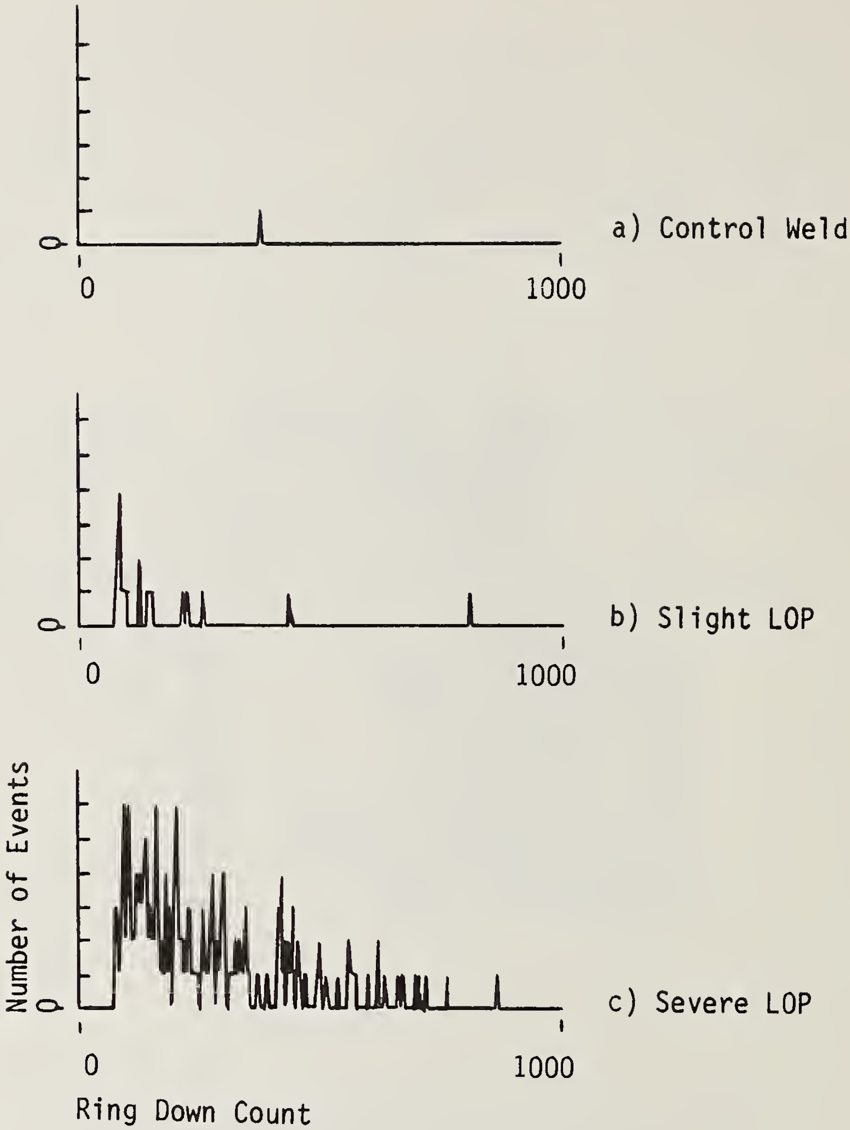

Figure 5. ACOUSTIC EMISSION ANALYSIS SYSTEM PLOTS - ENERGY DISTRIBUTION

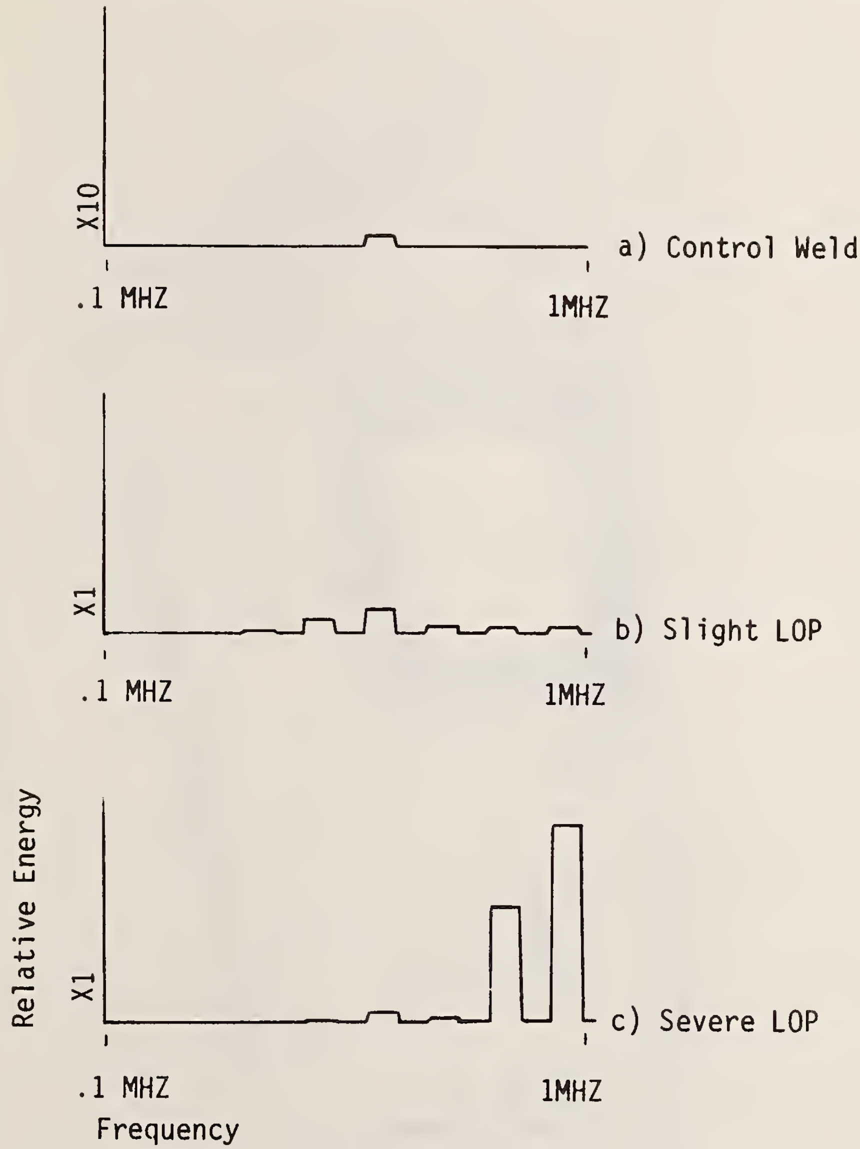

Figure 6. ACOUSTIC EMISSION ANALYSIS SYSTEM PLOTS - FREQUENCY SPECTRA

Figure 7. AN ACOUSTIC EMISSION WELD MONITOR CONSTRUCTED USING THE M6800 MICROPROCESSOR

PICTORIAL HISTORY OF THE DEVELOPMENT OF PROXIMITY PROBES FOR USE IN HIGH TEMPERATURE LIQUID METALS ENVIRONMENT

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Introduction

In the development and condition monitoring of machinery, it is common practice to use any number from a large variety of sensors that provide operational and/or monitoring information. Fortunately, in many applications the physical environment in which the sensors operate tolerates the use of materials of moderate physical properties with regard to temperature and contact exposure capability.

However, often in those instances where the internal environment of machinery is hostile to many engineering materials, the need for data is most urgent. The designers of such machinery and the designers of sensors for use in the hostile environment present inside the machinery, face much the same problem. Their design freedom is severely limited by:

1. Lack of choice of materials, types of construction and fabrication methods.
2. Need for long life, due to difficult access and replacement.
3. Lack of information on long term physical properties of composite structures (e.g., electrical connections, metal-ceramic components).

Nevertheless, as the need arose, such sensors as proximity probes, pressure transducers, accelerometers, strain gages, microphones and others were developed and used. Almost without exception, these were for a long time laboratory devices, due to the very limited demand for field installations. Of those sensors that have become available commercially very few if any are shelf items. The commercial quantities made of the various sensors are generally very limited. Overall quality ranges from poor to excellent. Prices are up to five times higher than those paid for comparable devices used in less severe environments. Continuity of availability of sensors from commercial sources has been good.

When at Mechanical Technology Incorporated (MTI) development work on sodium lubricated bearings began, it turned out that there was no commercial source for suitable proximity probes or pressure probes. As a result, MTI developed those sensors for its own use as well as offering them commercially. For one of these sensors, the inductive proximity probe, the development is traced as it can be seen in photographs of sections of actual probes. Before presenting the picture exhibit, the principle of operation of this class of probes is described and the major design parameters are identified. The inductive proximity probes are separated in two groups:

1. Eddy Current Proximity Probe
2. Magnetic Reluctance Proximity Probe

Eddy Current Proximity Probe

The principle of the inductive proximity sensor (eddy-current type) is shown in Figure 1. This sensor consists of a coil powered with alternating current, resulting in an alternating EM* field around the probe. If a conducting (nonmagnetic) surface is brought near the coil, the relationship between $\bar{E}$ and $\bar{I}$ changes. This change is the result of alternating currents (eddy currents) generated in the target by the external EM field of the probe. The eddy currents in turn generate an EM field which opposes that of the coil.

The opposing effect of the eddy current field causes the total field inside the target to become weaker with increasing distance from the surface. The depth at which the intensity is about 60% down from that on the surface is defined as the depth of penetration.

The effect of the target is to reduce the inductance (L) and to increase the AC series resistance (R).

If part of the gap is filled with a conducting medium, the field of the coil is attenuated in the same way as by the target. If the field attenuation in the partially filled gap is small (< 10%), the probe can still function. This is of importance when using the probe in a corrosive environment where hermetic sealing is necessary. For that application, the probe is mounted in a hermetic envelope, typically of austenitic stainless steel. The thickness of the stainless steel in the gap must be such that no excessive attenuation of the field occurs. Thus, it is important to know what factors determine the depth of penetration. The depth of penetration is inversely proportional to the square root of the electrical conductivity (ρ), the magnetic permeability (μ) of the target material and the frequency (f) of the AC field, as is also shown by the graph in Figure 3.

At a given operating frequency, the depth of penetration can vary two decades between the nonmagnetic resistive materials and the magnetic materials. Figure 3 can be used as a guide in selecting a usable combination of target material, probe envelope material and operating frequency.

Magnetic-Reluctance Proximity Probe

The principle of this probe is illustrated in Figure 2. The field generated by the alternating current through the coil causes magnetic flux

*EM = Electro-Magnetic

in the ferromagnetic core. The flux density with a core is from two to three decades higher than without a core.

The flux passes from the core through the gap back into the core. The air gap constitutes a major part of the magnetic reluctance of the probe. The typical increase in probe inductance when placing a ferromagnetic target in contact with the probe is 50 - 100%.

The effect of a nonmagnetic target on this probe (Figure 2) is similar to that on the probe in Figure 1. That is, a nonmagnetic target causes a decrease in inductance (L) and an increase in the AC series resistance of the probe with the core. When operated with a nonmagnetic target, the probe with core is an eddy current probe. When operated with a magnetic target, it is a magnetic-reluctance probe.

Discussion of Section Photographs

Liquid metal bearing research and development requires reliable measurement of shaft orbit. Without exception, the orbit measurement is made with noncontacting probes. All probes are of the inductive type, of two classes:

1. Magnetic Reluctance Probe
2. Eddy Current Probe

The reluctance probe consists of a pot core, with a coil inside it. The eddy current probe consists of only a coil.

The construction of both types of probes is a compromise between the need to electrically insulate the coil windings (and the entire coil) and the need to mechanically secure the coil to the housing either directly or first to the core and then to the housing.

The need for a practical and controllable assembly sequence of the various parts, including making electrical connections to the mineral insulated lead, and sealing the entire envelope hermetically, leads to additional compromises in the entire design.

With the foregoing as an introduction, a number of actual realizations of high temperature probe designs will be described briefly, using photographs of metallographic sections of transducers or assembly drawings identifying the various parts.

The metallographic specimens are made by first vacuum impregnating the entire assembly, followed by a gradual removal of material by grinding in a surface grinder. When the desired detail is exposed, the section is lapped and polished and macro and micro photographs are taken. The sections selected here are most representative of the arrangements of probe components in the various designs.

Figure 4 shows a design developed by the U.K.A.E.A. in 1967*. It has the basic elements of the reluctance probe, coil and core. To assure that the core is maintained in a fixed position with respect to the housing, it has a sliding center part. This part is kept fixed forward axially by an austenitic steel pin (matching the housing in thermal expansion). The core is carried through the face of the probe to eliminate the effects of an austenitic steel cover. The lead terminations are brought out to the side, to be accessible during assembly.

This probe was used in pairs, in push-pull, with a magnetic target ring and with a carrier frequency of 800 Hz. Push-pull operation assures linearity and temperature compensation. This design has given satisfactory service for many hours in the English bearing research programs. It has not been commercially available.

At about the time that the design in Figure 4 was being developed, a very different design was made commercially. Samples of it are shown in Figures 5 and 6 and Figures 7 and 8.

Both of these designs use a core composed of a bundle of ferromagnetic alloy wire. The wire passes through the center of the coil and is bent around in a U-shape to provide a return path for the flux on the outside of the coil. Figure 5 shows a section on the probe center line. Figure 6 shows a section off the center line, where the outer part of the core is visible.

Figure 7 shows a design similar to that in Figure 5, except for the use of a sturdy coil form. It is mounted in a holder that permits (later) installation of a sealing diaphragm.

The designs in Figures 5 and 7 are for high temperature use, but are not hermetic. Details of the probe from Figure 7 are shown in Figure 8. The designs in Figures 6 and 8 were obtained commercially and were prototypes. Their performance was inadequate.

The designs in Figures 6 and 8 were followed by the design in Figure 9. It has also a wire core. Two identical inductors are mounted in one housing. The second inductor is used to obtain temperature compensation.

The function of the temperature compensating inductor is discussed in connection with the following design. The design in Figure 9 was a commercial prototype. Its performance was adequate, but the manufacturer discontinued further development efforts. This led to the development of the inductive proximity transducer at MTI in 1969 to be

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*S. A. Dean, B. G. Ferguson, E. Harrison and A. Stead
"A TRANSDUCER FOR MONITORING THE RADIAL CLEARANCE AT A SODIUM-LUBRICATED PUMP BEARING"
United Kingdom Atomic Energy Authority
The Reactor Group - 1967 - TRG Report 1472(R)

used in sodium bearing research.

A derivative of the probes shown in Figures 5-9 is shown in Figure 10. This probe has been made commercially for about 7 years by a succession of English companies, all under the direction of the originator of the basic probe design. It has been used successfully in substantial quantities by a large variety of users. The laminated core permits operation at a carrier frequency of as high as 50 kHz without serious degradation of the Q (Quality*) of the probe. The probe is being used in sodium and steam environments to a temperature of 1100°F (600°C). Overall, quality control and performance of the probes have been moderate to good over the years. No long term data has been published.

An X-Ray of this probe is shown in Figure 11. It shows the form and the location of the lead terminations before they were disturbed by the lead end removal.

The probe in Figure 10 operated in half-bridge configuration can be used to make a single-ended gap measurement with a dielectric medium in the gap. Temperature compensation is provided by the second inductor, which has a dummy target of the same material as that of the active (outside) target. If a conducting medium is present in the gap, and if a nonmagnetic target (and dummy target) is used, temperature compensation is degraded severely. No application of the latter type has been reported.

A probe similar to that in Figure 10 with a single (active) inductor is shown in Figure 12. It is generally used in pairs in push-pull to obtain temperature compensation and linearity over a wide temperature range. The section in Figure 12 shows a cracked coil form. The cracking was probably caused by thermal stresses. The coil was wound wet (with application of liquid ceramic cement during winding) and became solid after firing of the ceramic cement. Subsequent axial expansion of the wire caused the coil flange to crack away. The coils in the transducer in Figure 10 are not wet wound, and no cracking occurred.

All designs shown thus far have a coil of a length roughly equal to their diameter placed in a magnetic core, resulting in a high inductance and a very directional and well defined external flux pattern. The design in Figures 13-14 is a radical departure from that concept. It only contains a very flat coil ("pan-cake" coil) and no core.

The field of the coil reaches a distance of approximately one half coil diameter radially and axially (front and rear). The design in Figure 13 shows a coil held in a dielectric mass. The dielectric mass is held in a metal case at a distance from the coil where the field is sufficiently weak. Around the coil no metal can be tolerated to within

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*Ratio of inductive reactance to series resistance.

a distance equal to the coil radius, as otherwise the coil becomes inductively partially shorted and the probe is proportionately desensitized.

The probe design shown in Figure 14 is widely used in many applications. It is operated with a carrier frequency of 1-3 MHz. The probe is not hermetic. It is used at low temperatures (< 300°F). Similar probes are also made for high temperature service, without or with a hermetic envelope.

When operated at a very much lower carrier frequency, and when held in a housing made of a resistive alloy, with only a thin face cover, the probe can be made hermetic. Under these circumstances, sufficient flux remains to permit sensing of a metal object outside the probe housing. However, the absence of a core, and in its place the presence of a conductive housing degrades the signal generating capability of the probe somewhat, and hence increases the chance of drift and noise. Also, the small section of the coil necessitates the use of very fine wire to obtain sufficient turns (and hence inductance) to off-set the inductance loss due to the absence of a core.

To circumvent the problems of stresses due to differential expansion, and to locate the coil windings firmly in the transducer, the ceramic coil form is sometimes replaced with a metallic coil form. The metal form is coated with a ceramic coating by flame spraying to provide the necessary insulation to ground for the coil wire.

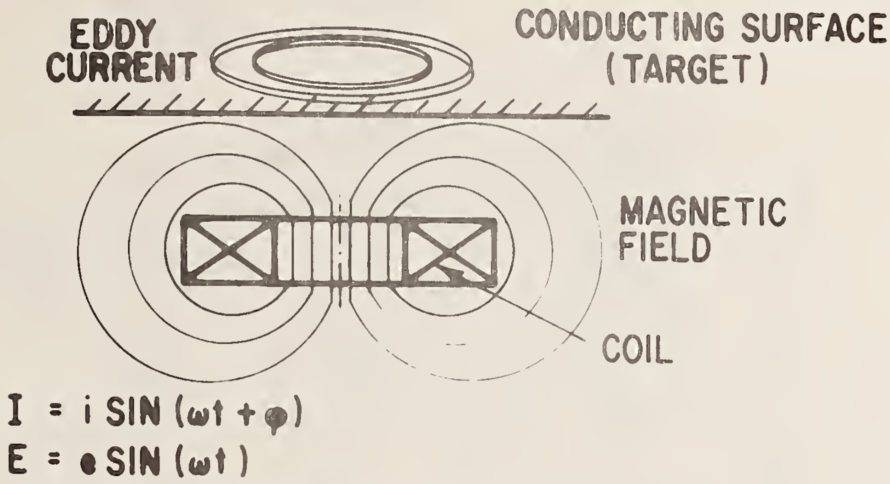
The metal coil form causes additional losses that further reduce the probe's signal to noise ratio.

<u>Summary</u>

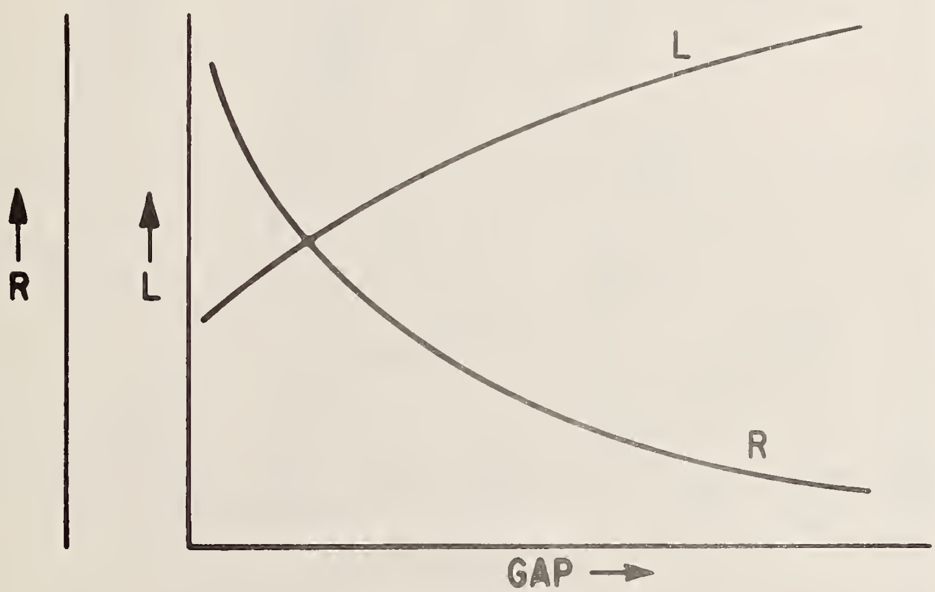
Development of liquid metals lubricated bearings created a need for proximity probes capable of measuring bearing orbits in sodium at high temperature. In a nearly parallel effort, such probes were developed by U.K.A.E.A. and by the AEC at MTI. Both probes became commercially available. The U.K.A.E.A. probe has led to the current design as shown in Figures 10 and 12. The MTI probe design has remained the same, except for minor changes in lead connections made in 1976 and a different choice of coil wire alloy.

The probe sections shown illustrate the many design concepts that were tried to satisfy the functional requirements of the measurement. When comparing the number of components used in the various designs with core, and the necessary assembly operations and sequence of operations, the MTI design appears superior to any of the preceding or parallel designs.

The present state of proximity probe technology permits the fabrication of reliable high temperature hermetic devices suitable for long term monitoring of machinery in a sodium environment.

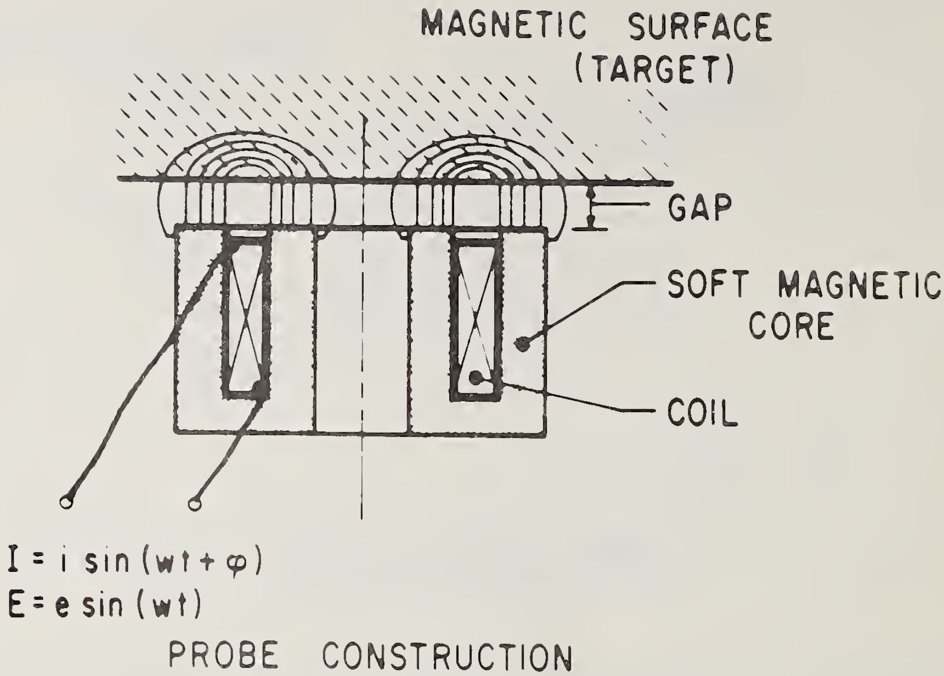


PROBE CONSTRUCTION



TYPICAL PROBE RESPONSE

Fig. 1 - Inductive Proximity Sensor -
(eddy current type)



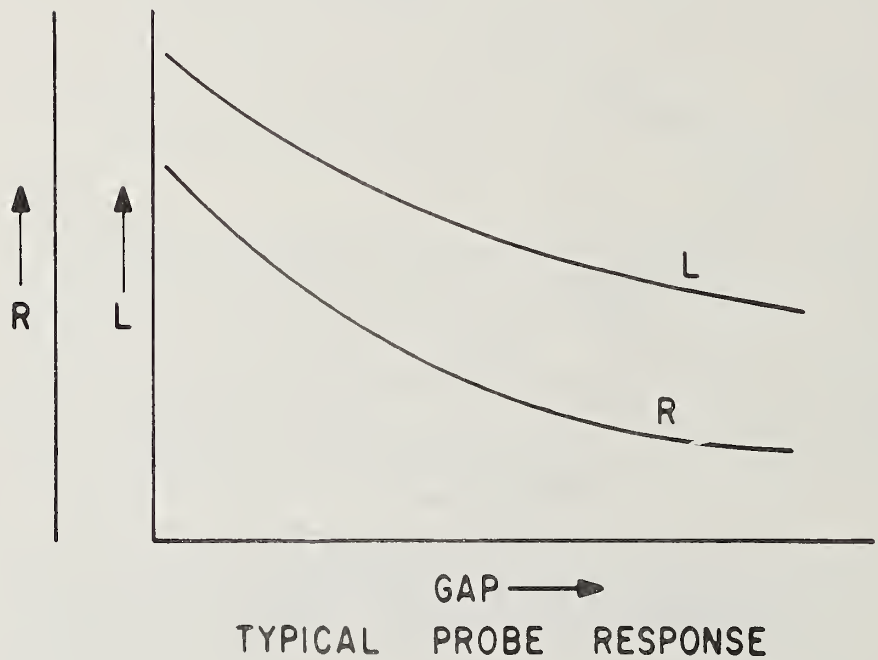


Fig. 2 - Inductive Proximity Sensor
(magnetic reluctance type)

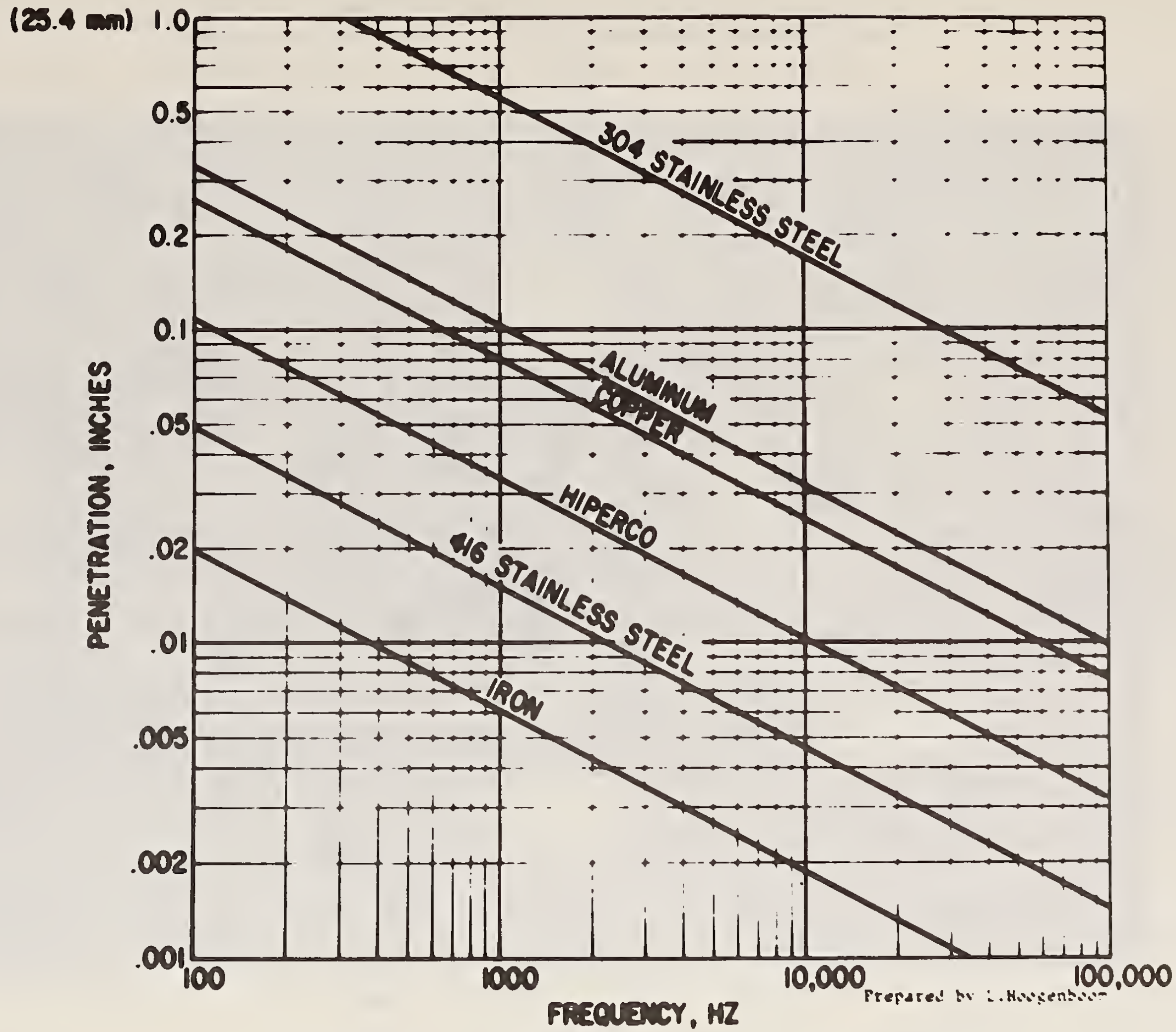


Fig. 3 - Electromagnetic Field Penetration versus Frequency

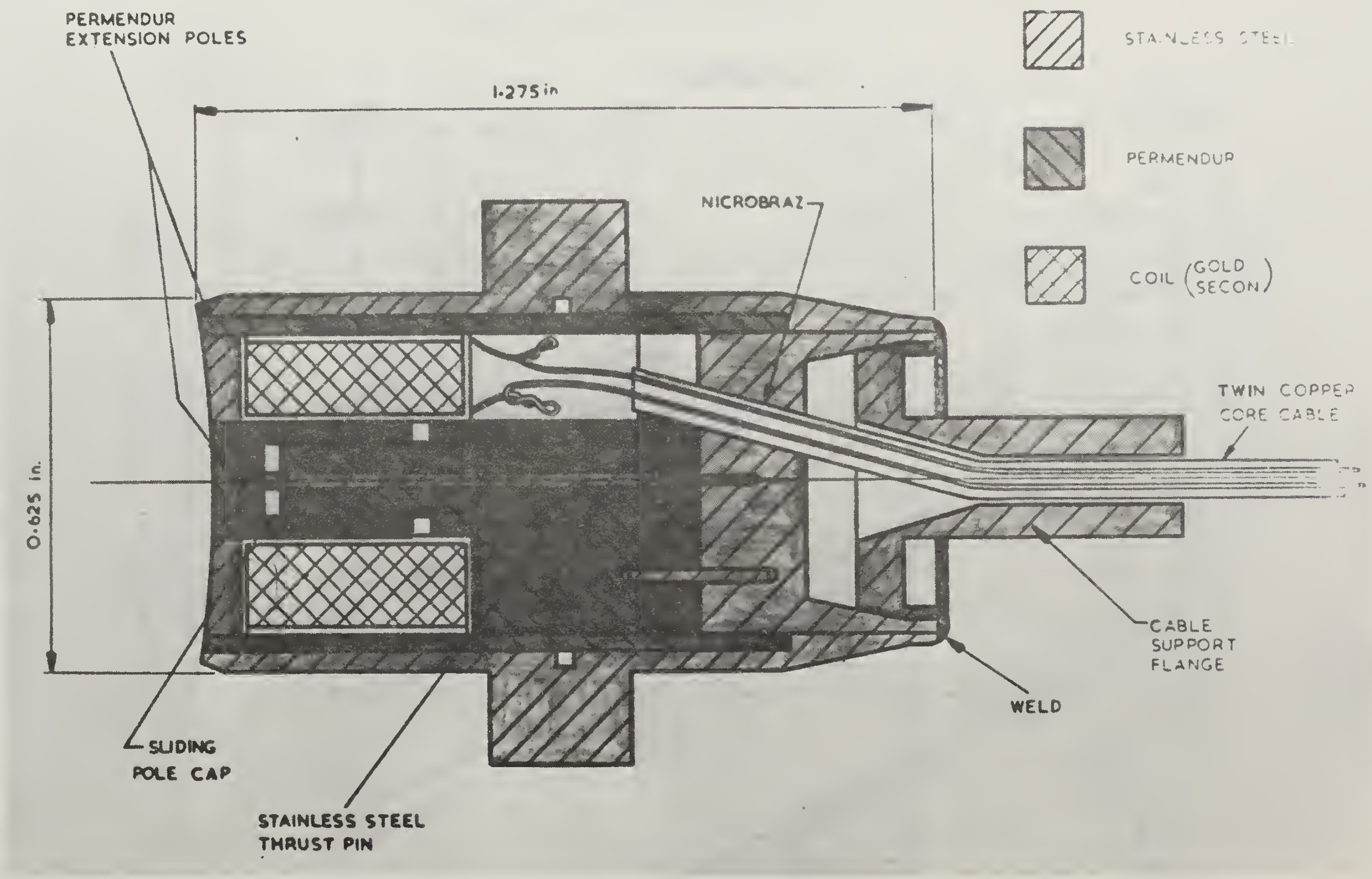


Fig. 4 Liquid Metals Proximity Probe Used to Measure Bearing Clearance in Developmental Sodium Pump (1967) to Maximum Temperature of 400°C (750°F)

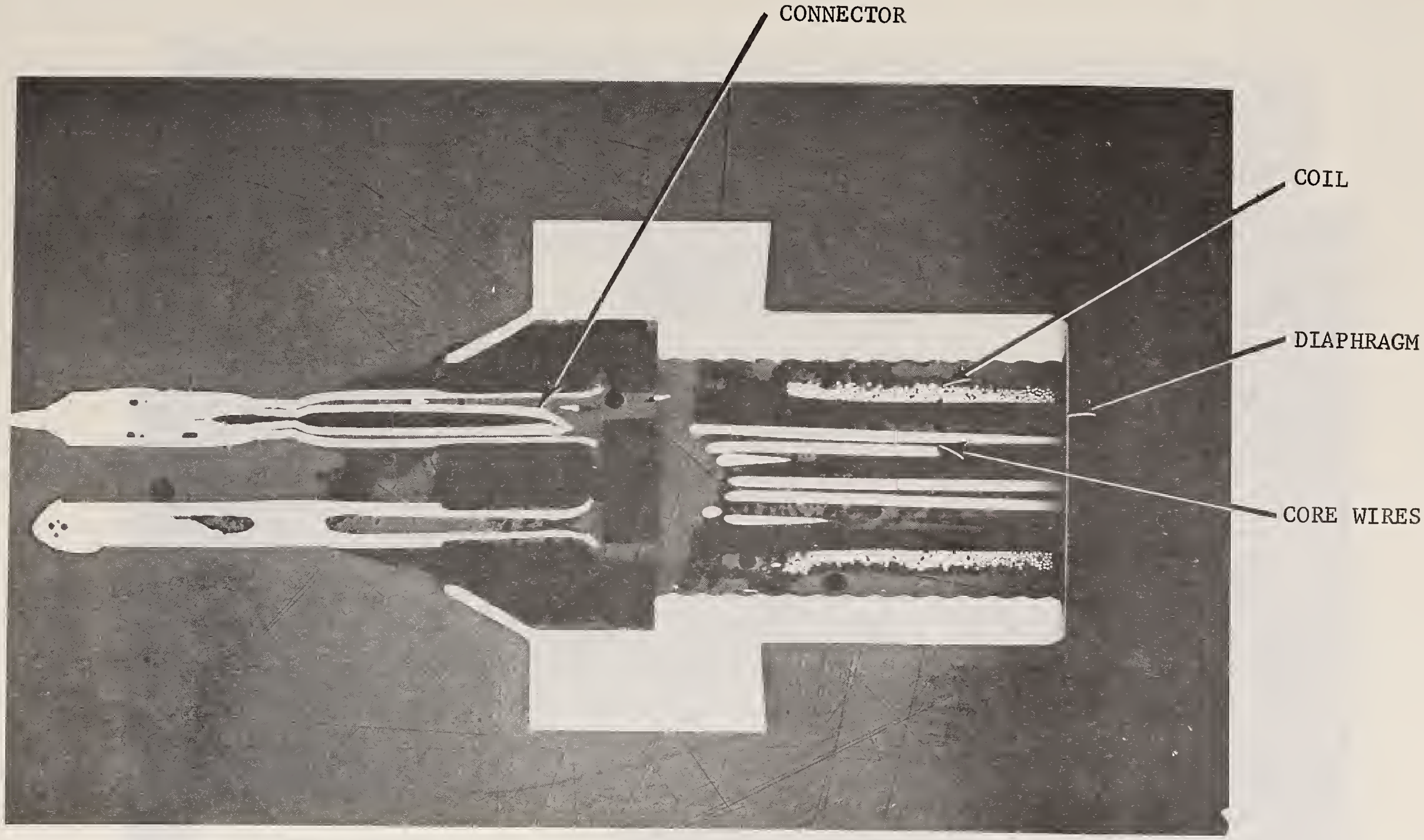


Fig. 5 Axial Section through Probe with Wire Core.
Probe Diameter .28 inch (7mm)

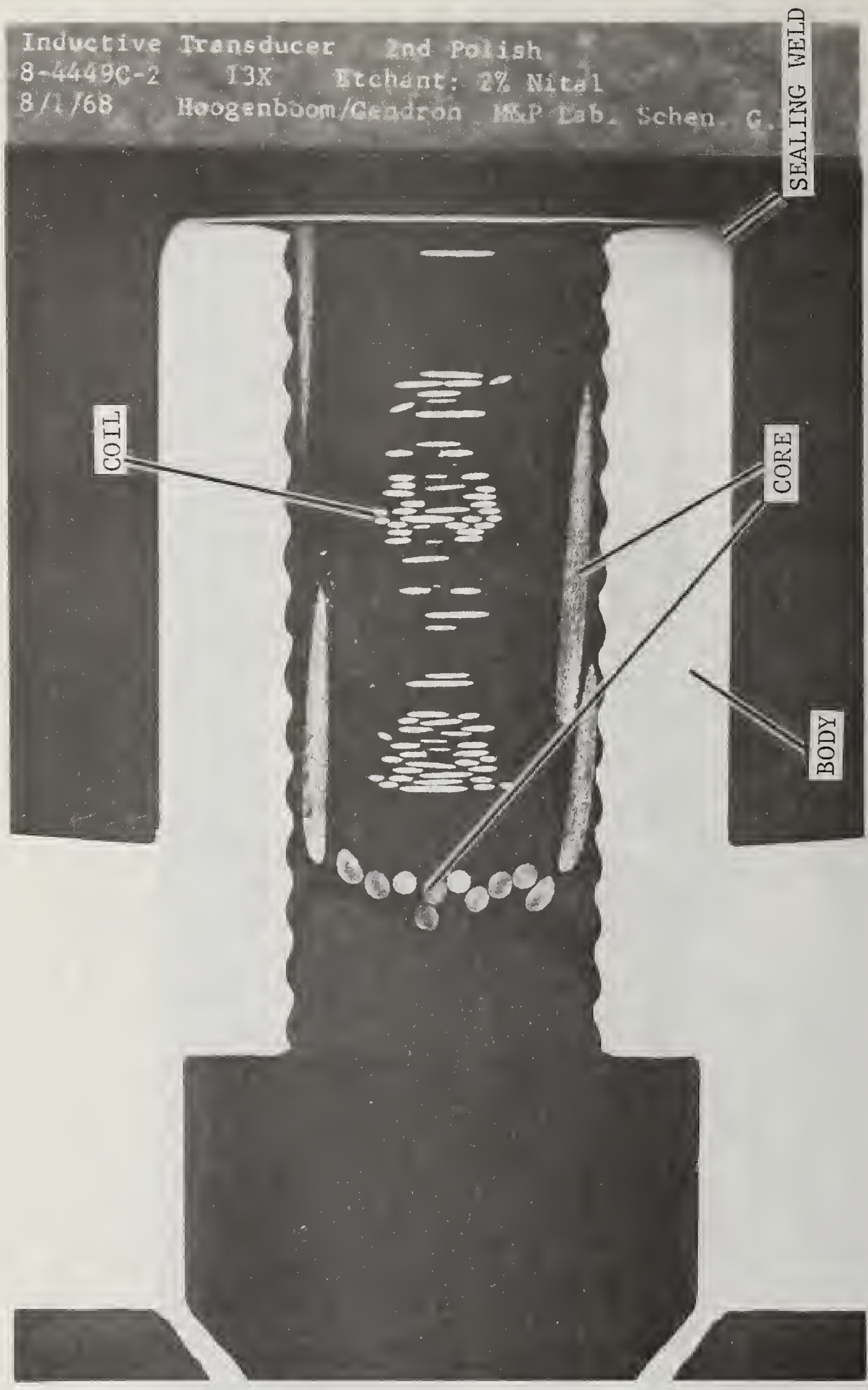


Fig. 6 Off-Axis Section through Probe with Wire Core (Photographed Before Reaching Axial Section in Figure 5)

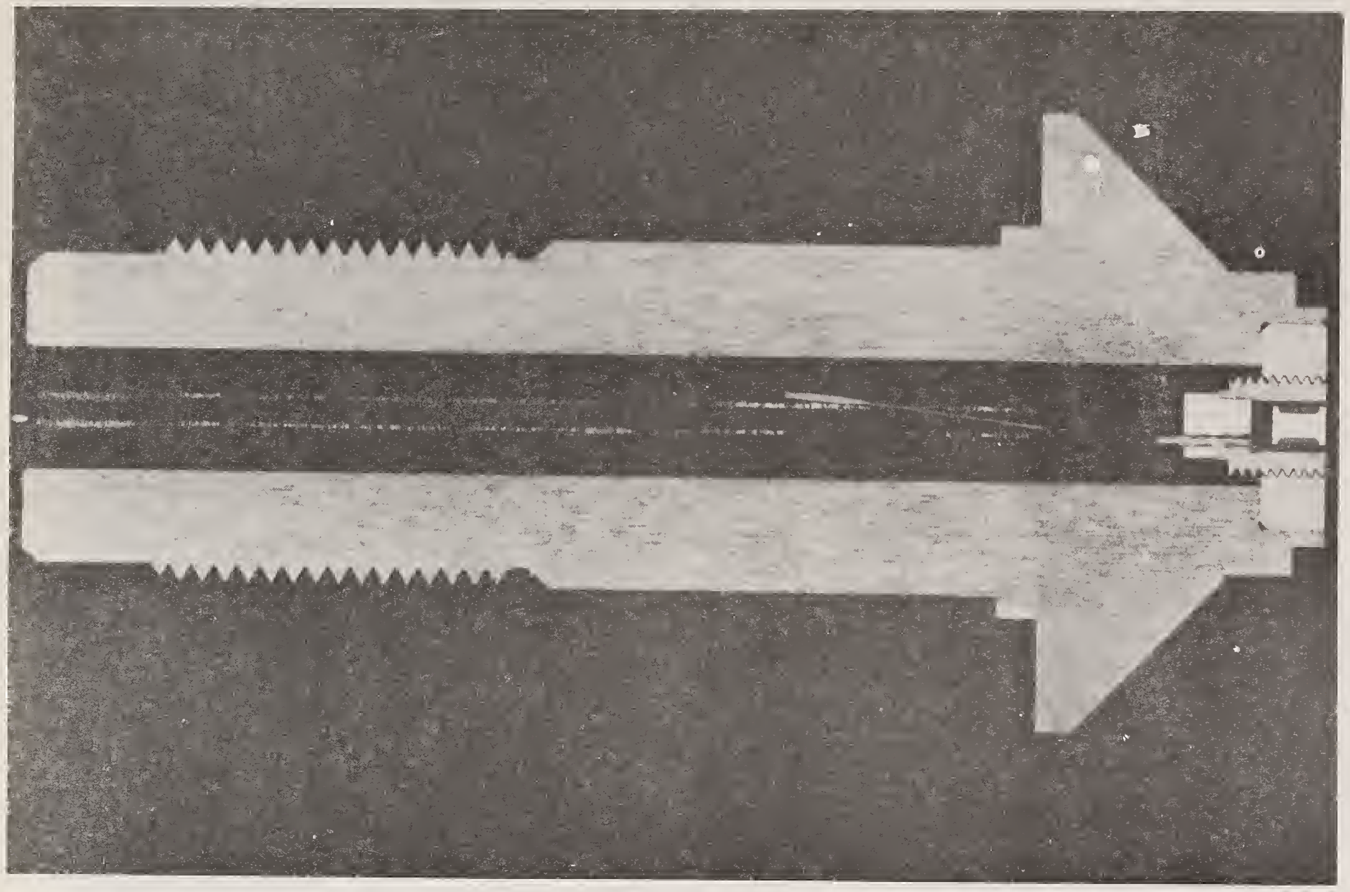


Fig. 7 Section through Probe with Wire Core.
Probe Diameter .28 inch (7mm)

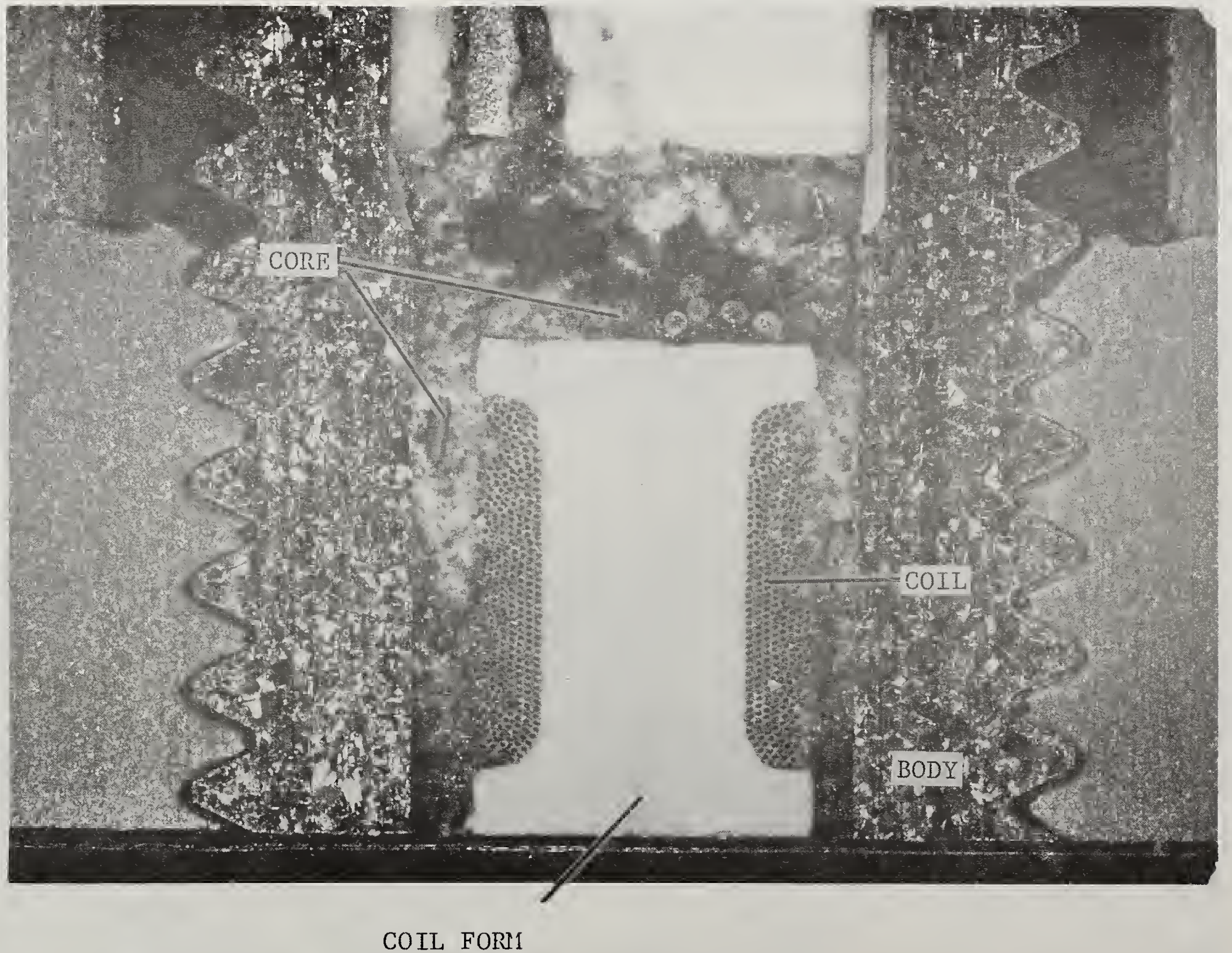


Fig. 8 Detail of Probe Section in Figure 7

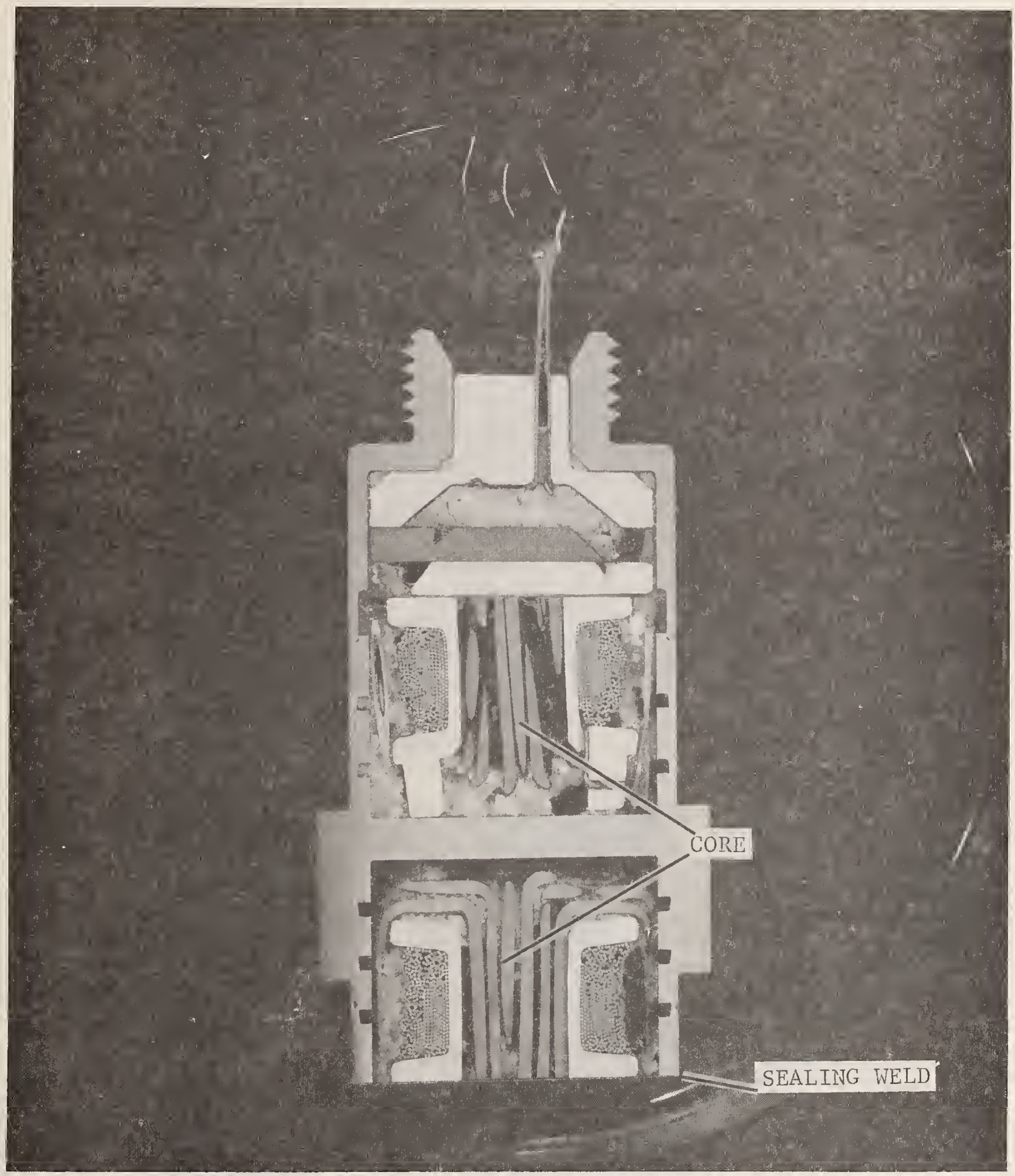


Fig. 9 Section through Probe with Wire Core, with Built-In Temperature Compensating Inductor. Probe Diameter 1.0 inch (25mm)

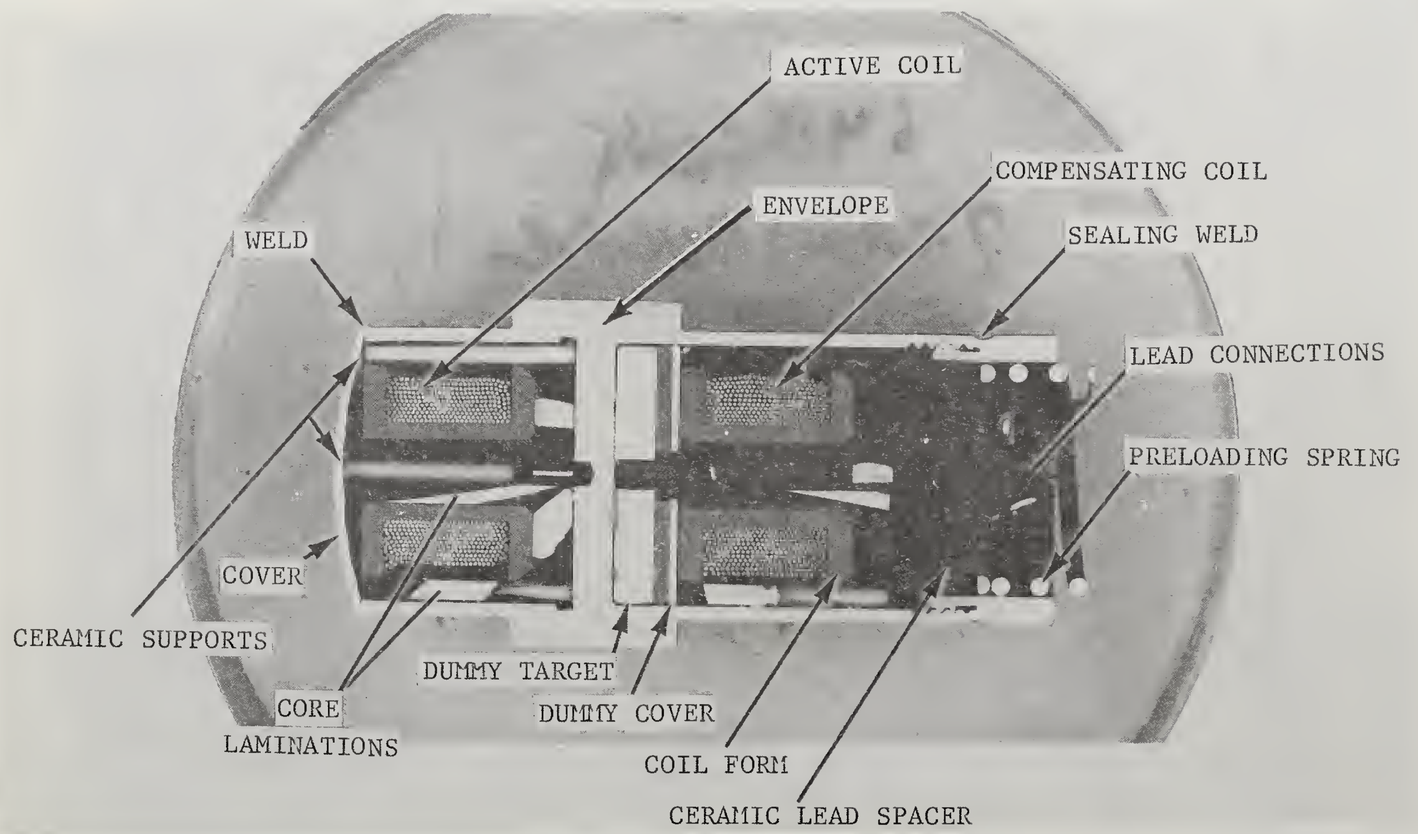


Fig. 10 Metallographic Section of High Temperature Proximity Probe with Internal Compensating Coil and Target.

The Cover Became Bulged Due to (unintentional) Internal Pressure Buildup. Lead End of Case was Removed for Separate Sectioning.

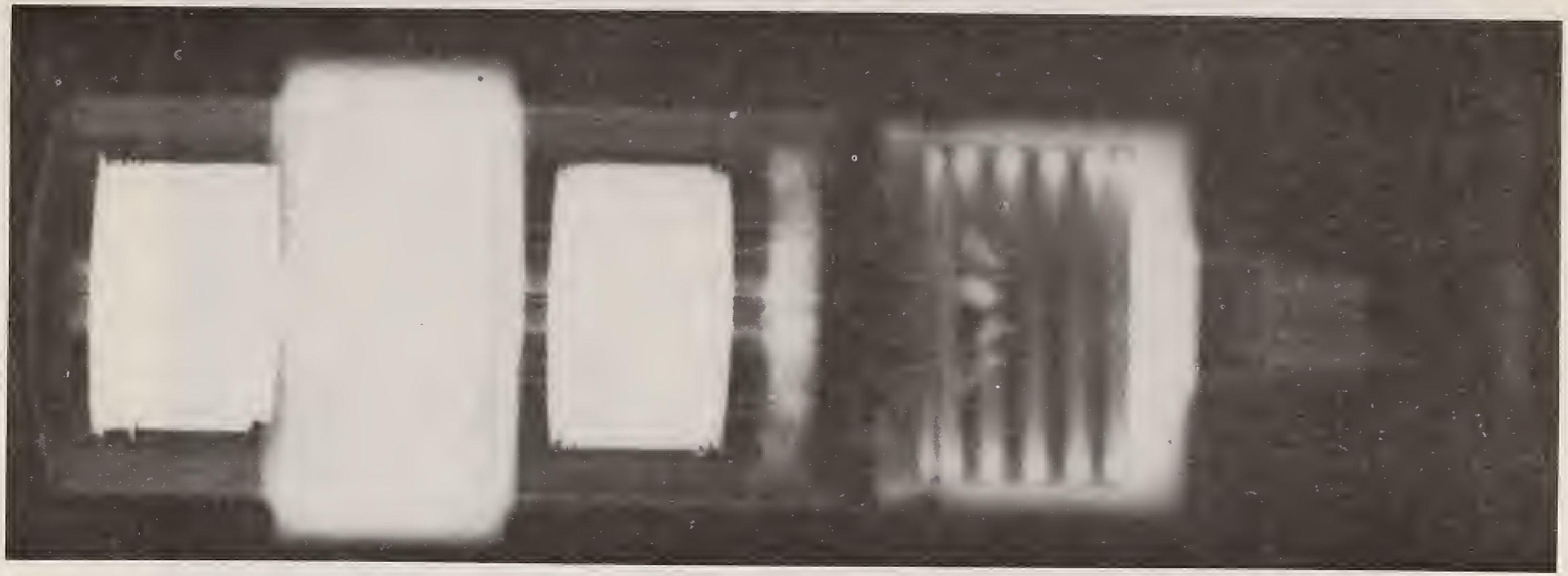


Fig. 11 X-Ray of the Probe in Figure 10, Before the Lead End was Removed and Before Sectioning

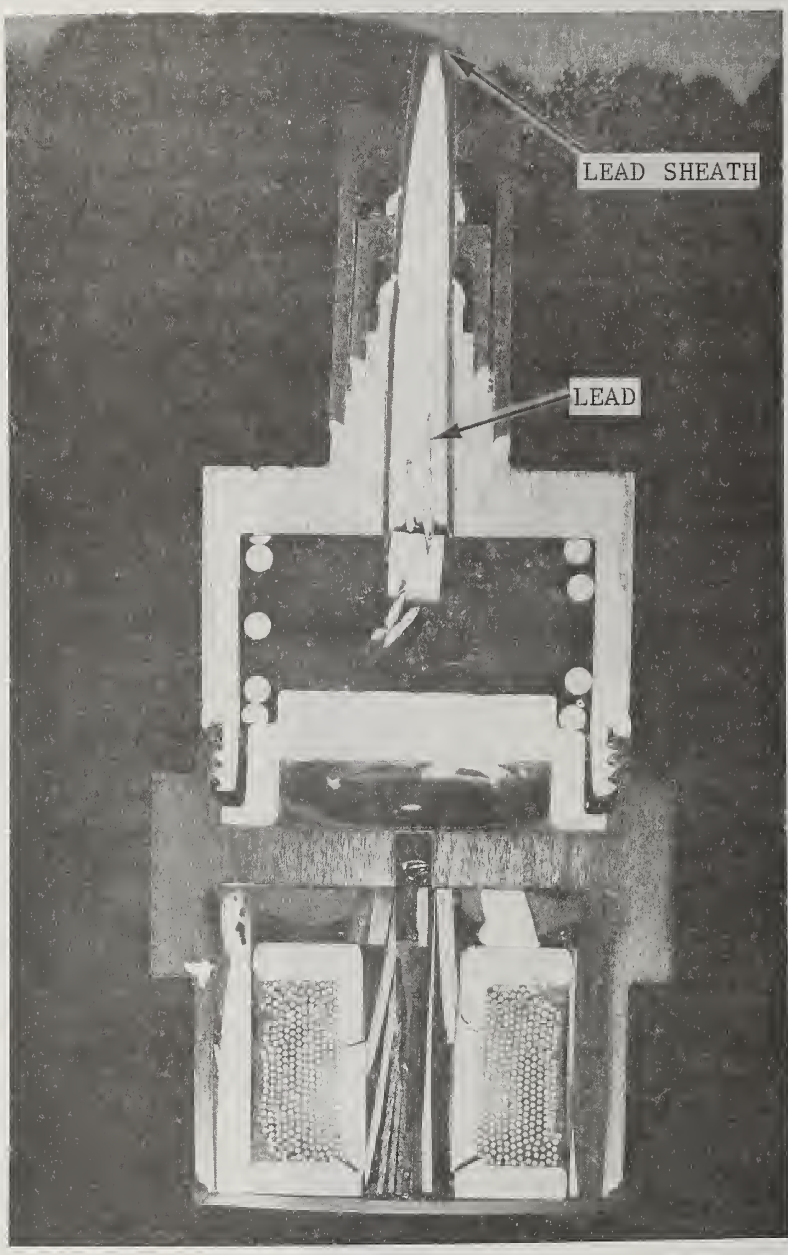


Fig. 12 Proximity Probe Similar to that in Figure 10, without the Compensating Inductor. Probe Diameter is .75 inch (19mm)

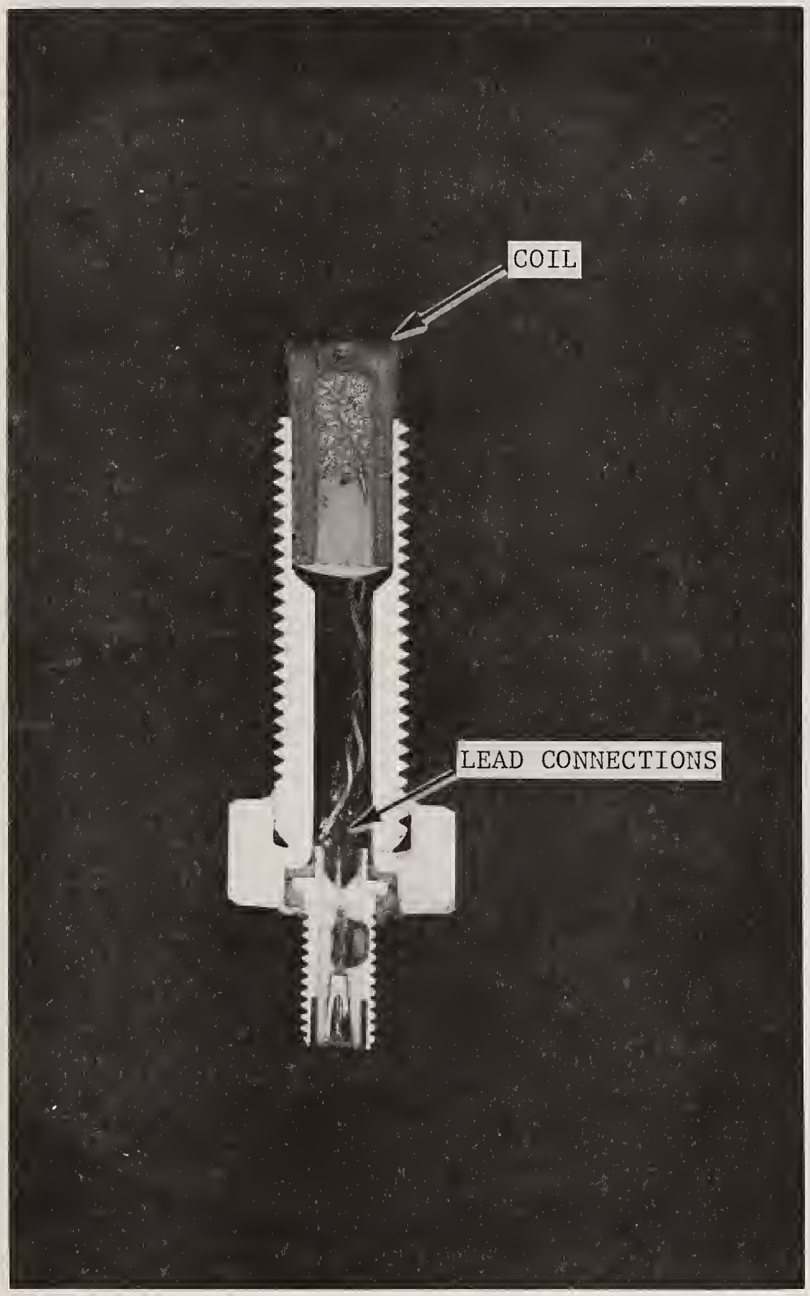


Fig. 13 High Frequency Eddy-Current Proximity Probe (Room Temperature Operation)

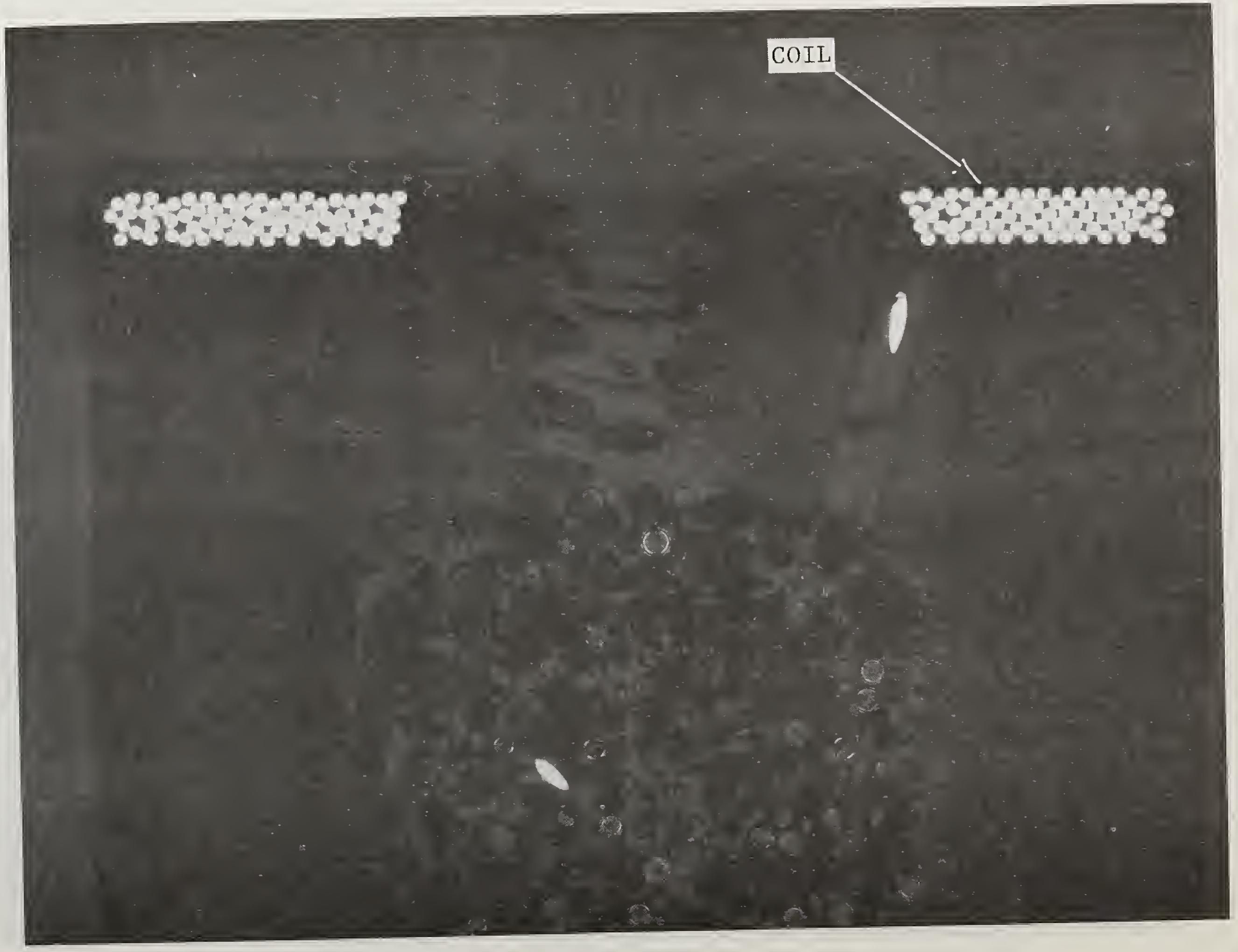


Fig. 14 Detail of Probe in Figure 13

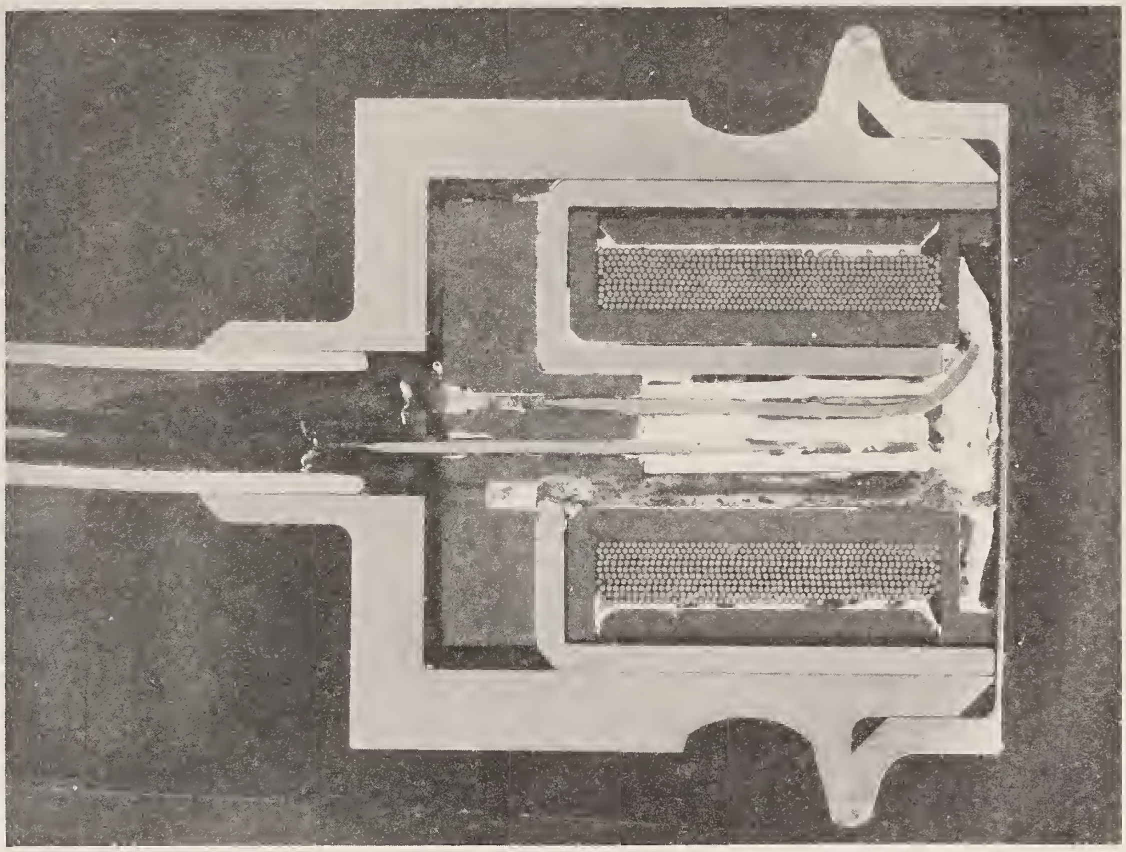


Fig. 15   High Temperature Proximity Probe Developed at MTI in 1969

SESSION IV

RAILROAD SYSTEM DIAGNOSTICS

CHAIRMAN: J. L. FRAREY

SHAKER RESEARCH CORPORATION

DEPARTMENT OF TRANSPORTATION SYSTEM FOR TRAIN ACCIDENT REDUCTION (DOT-STAR)

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White Oak Laboratory
Silver Spring, MD 20910

In the course of 30 billion miles traveled each year, the two million American railroad freight cars suffer thousands of derailment accidents, 5602 in 1970. These derailments are due to numerous causes, but historically approximately half are due to failures of equipment or roadway. The cost of these derailments is not accurately known. But estimates for equipment and roadway-caused accidents total approximately 60-65 million dollars for direct railroad losses, with total losses estimated at 180-330 million dollars per year.

The largest single category of equipment-caused derailments are due to broken or overheated journal bearings (hotboxes), which accounted for 409 derailments and 45-75 million dollars in estimated total damages. Other major equipment-caused derailment sources are broken truck components and car dynamics. Similarly, the majority of roadway-caused derailments are attributable to broken rails, joints, or switches and to improper maintenance of the roadway.

The Naval Surface Weapons Center (NSWC) became involved in this railroad problem as a part of the Navy's Technology Transfer Program. The Federal Railroad Administration funded NSWC to investigate possible solutions to their problem, due to NSWC's experience in the development of high production, low cost, and high reliability sensors.

Considering the large amount of damage attributable to equipment and roadway-caused derailments and the relatively limited number of major causes, it is intuitive that an economically feasible solution to this problem exists. The three most viable solutions to the prevention and/or reduction of damage from derailment accidents for the existing fleet are: preventative inspections and maintenance; wayside monitor systems; and on-train monitor systems.

Each of these methods provides a cost-effective solution to part of the derailment problem. However, the most functional and cost-effective solution to the total problem would be a nation-wide system using all three methods in conjunction.

The on-train monitor system is perhaps the least researched and definitely the least deployed method of derailment prevention. On-train systems offer substantial advantages in the detection of failure modes that are rapid and offer little advance warning. Monitoring of potentially hazardous failure modes during every second of a vehicle's life is the major advantage of on-train systems. However, providing an economically viable system for railway freight cars is a substantial challenge. Objectives for such an on-train monitor system would include:

- o low cost
- o very low false alarm rate
- o very low maintenance
- o self-sufficient
- o monitors multiple accident causes

Such an on-train monitor system is the Department of Transportation System for Train Accident Reduction, DOT-STAR.

Preliminary studies for the DOT-STAR System evaluated the equipment and roadway-related derailment causes that were monitorable by on-train systems. The most economically viable equipment-related causes were journal and roller bearing hotboxes. In both cases derailments are prevented by an on-train monitor system. Prevention of roadway-related derailments is not economically viable with an on-train system. However, it was determined that local derailments could probably be detected by an on-train system which could in turn prevent a general derailment (train wreck).

In a portion of derailments, an initial local derailment of one wheel, one axle, or an entire truck will take place and the train will proceed some distance without further disturbance. No one will be aware of the local derailment until an obstruction or further damage to the derailed equipment leads to a general derailment, the magnitude of which is directly related to train speed.

The number of such two-stage derailments is not readily determined from FRA accident data. However, review of all National Transportation Safety Board derailment accident reports between 1969 and 1976 indicate that up to 30 per cent of all derailments are of the two-stage type. Therefore, an effective on-train local derailment detector could substantially reduce derailment damage.

The objectives of the DOT-STAR System are three-fold. First, the system is to detect incipient or actual derailments and provide for action to prevent or mitigate resulting damage. Second, the system must provide a minimum life cycle cost, require minimum maintenance, and be compatible with railroad industry operating and maintenance procedures. Third, the system must be capable of expanding to include additional hazards such as fire and rock-off.

The DOT-STAR System is an on-train safety system that monitors and automatically activates the train's brake system upon the detection of a wheel derailment or excessive axle bearing temperatures. The braking action stops the train before either an axle bearing failure develops into a derailment or a minor derailment develops into a major wreck.

Currently, the basic system consists of continuously-monitoring self-powered thermal and derailment sensors connected via a wiring network to an electro-explosive valve attached to the car brake line (figure 1). The activation of any sensor produces a pulse of electrical energy that in turn fires the explosive valve, thereby venting the brake line and activating the braking system.

The on-train location allows for rapid and automatic response to derailments caused by failures of either equipment or roadway. The system on each car is independent of the other cars on the train; this makes the system compatible with present railroad industry operating procedures.

The system is designed with low cost, long service life, maintenance free components to provide both minimum initial and life cycle costs. The sensor assembly (sensors and integral power supplies) and the electro-explosive brake venting valve are both one-shot maintenance-free devices (figures 2,3, and 4). The wiring network is rugged, shielded, and does not affect normal car or truck maintenance. Expansion of the basic system is easily provided by coupling of additional sensors (fire, rock-off, etc.) into the wiring network.

The DOT-STAR thermal sensor is designed to continuously monitor the temperature of either journal or roller bearing assemblies. At or below the maximum normal bearing temperatures, the sensor remains inert. If a bearing assembly rises to a temperature above this normal maximum, the sensor fires and transmits an electrical signal that activates the train braking system.

Functionally, the sensor consists of three parts: a spring-loaded "cocked" firing pin held in the ready position by a "C" configured release pin and a thermal battery power supply (figure 5). The heart of the sensor, the "C" configured release ring, is made of an NSWC-developed alloy called NITINOL. This nickel-titanium alloy has a memory property such that at a given temperature NITINOL objects can be restored to their original shape even after being "permanently" deformed out of shape. When this closed "C" release ring is heated to its thermal transition temperature by an overheating bearing, this release ring springs to an open "C" configuration, releasing the firing pin which in turn activates the thermal battery power supply.

The continuing development of the DOT-STAR thermal sensor was broken into two sequential efforts: journal and roller bearing applications. The journal bearing work has been completed through a full field demonstration. This demonstration consisted of two phases. The first phase was the successful demonstration of hotbox detection and train brake application on two intentionally-caused hotboxes at a train speed of 35 mph (figures 6 and 7). The second phase, which is in progress, is designed to demonstrate a low false alarm rate. To date 32 sensors have each seen greater than 40,000 miles of actual service without a single false alarm. The roller bearing application work is presently preparing for a similar demonstration test with the expectation of similar results.

The method used to attack both problem applications is identical. It consists of finite element computer simulations of bearing heat generation and conduction (figures 8 through 14). These are used to predict normal over-the-road temperatures, thermal gradients through structural members, and temperature rise-time characteristics during hotbox conditions. These data were used in conjunction with actual measured over-the-road and hotbox temperatures to optimize the thermal sensor design and sensor contact location.

Most of the work on derailment sensors to date has involved studying both normal over-the-road and derailment environments. Two possible detection techniques have been determined: direct rail contact and seismic detection. In order to eventually compare the two techniques, substantial seismic over-the-road and derailment data have been collected.

From this data, we have found that under extreme winter frozen-ground conditions, over-the-road environments such as rough track, rough switches, etc. often exceed derailment conditions during the summer (figures 15 and 16). This is true for both acceleration and velocity. Shock spectra analysis has also revealed no significant differences between these two environments (figures 17 and 18). Discrimination between the two environments will require filtering and integration of the velocity signature. NSWC is currently exploring this approach.

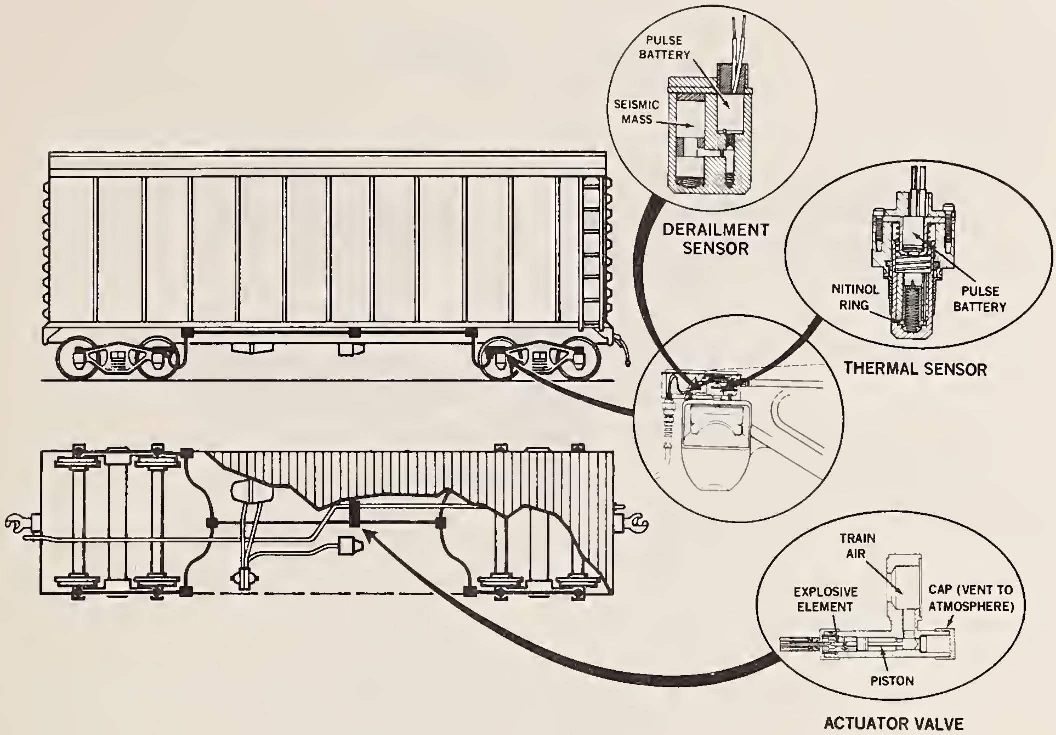


figure 1: D.O.T.-System for Train
Accident Reduction

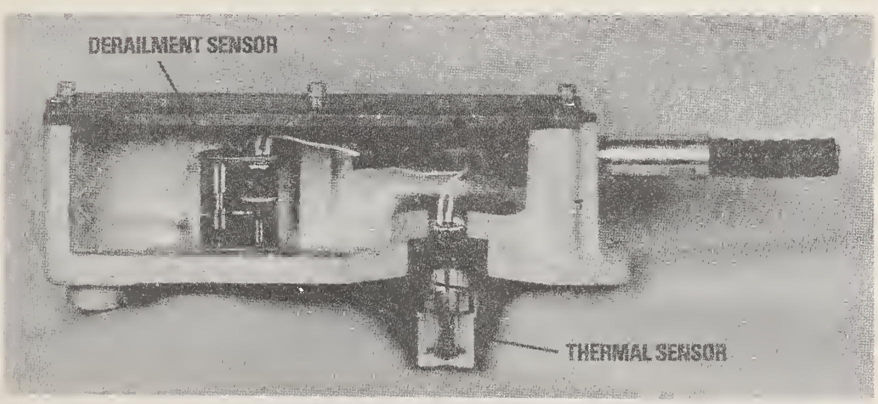
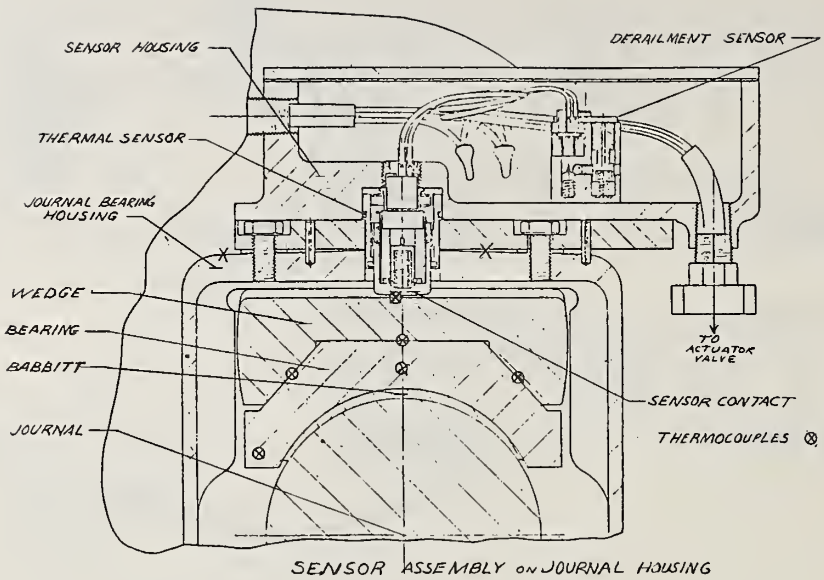


figure 2: Sensor Assembly



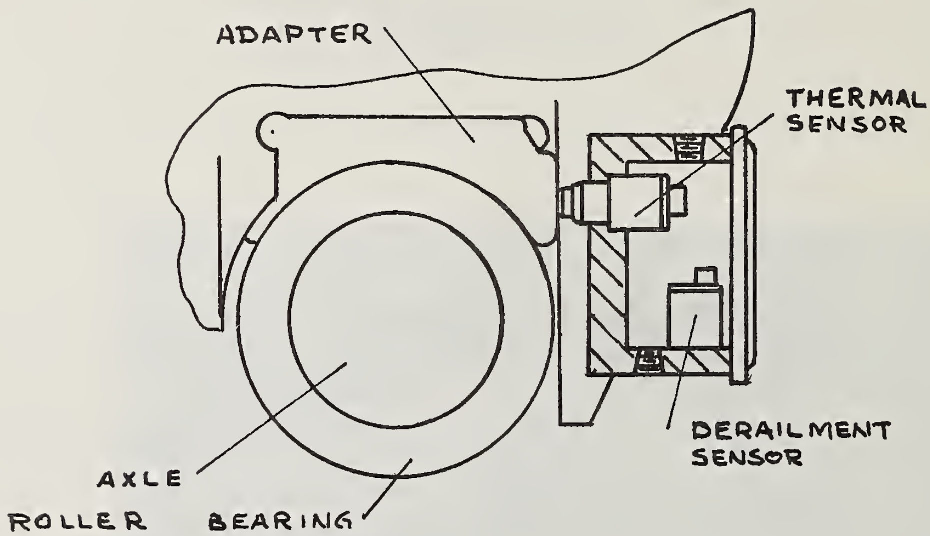


figure 3: Sensor Assembly Mounting
Locations

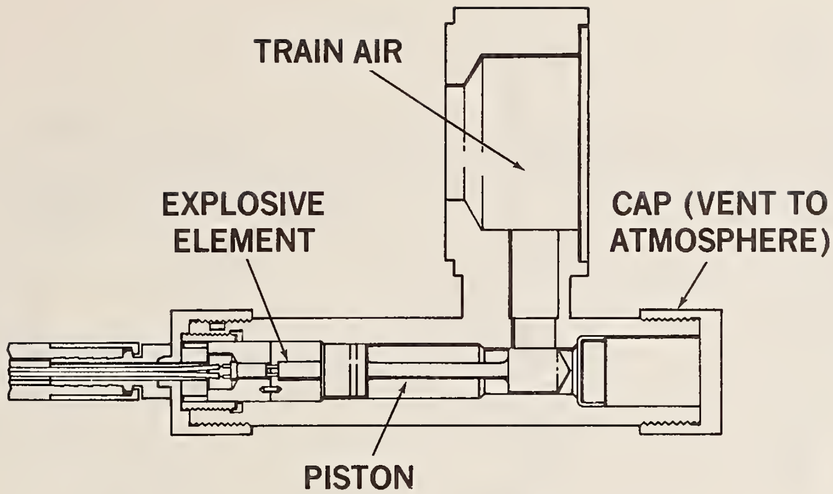


figure 4: Electro-explosive Valve

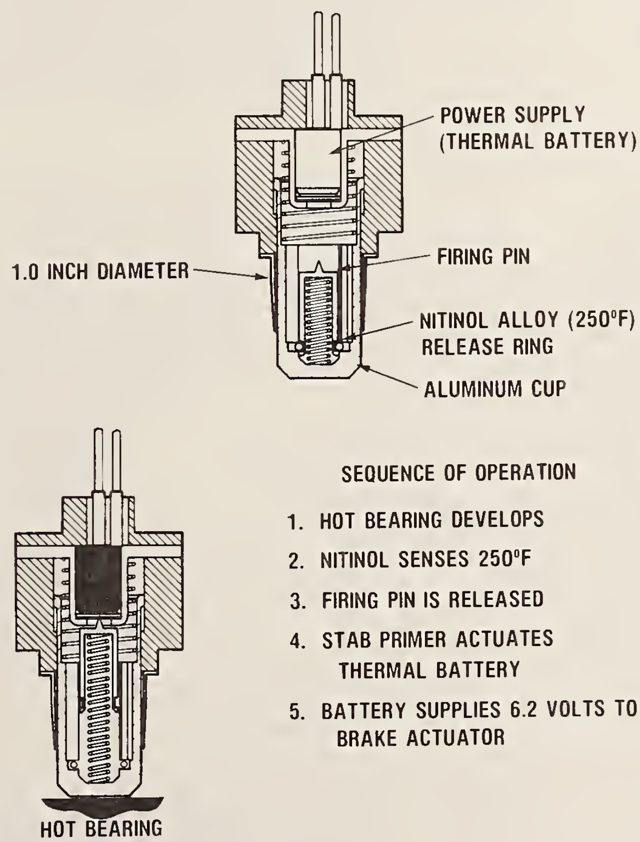


figure 5: D.O.T.-S.T.A.R. Thermal Sensor

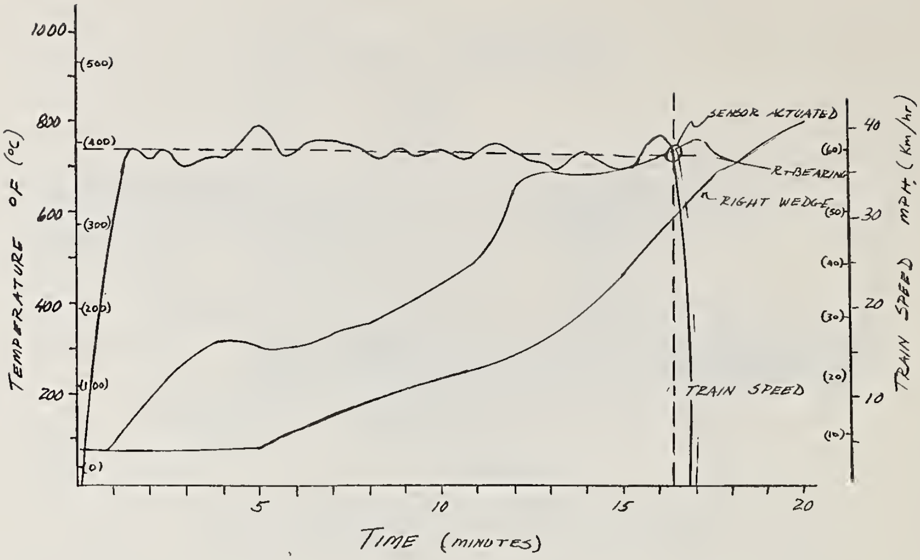


figure 6: Field Test Demonstration of
D.O.T.-S.T.A.R. System.
Journal Bearing Hotbox Detected
and Train Stopped. Right Side.

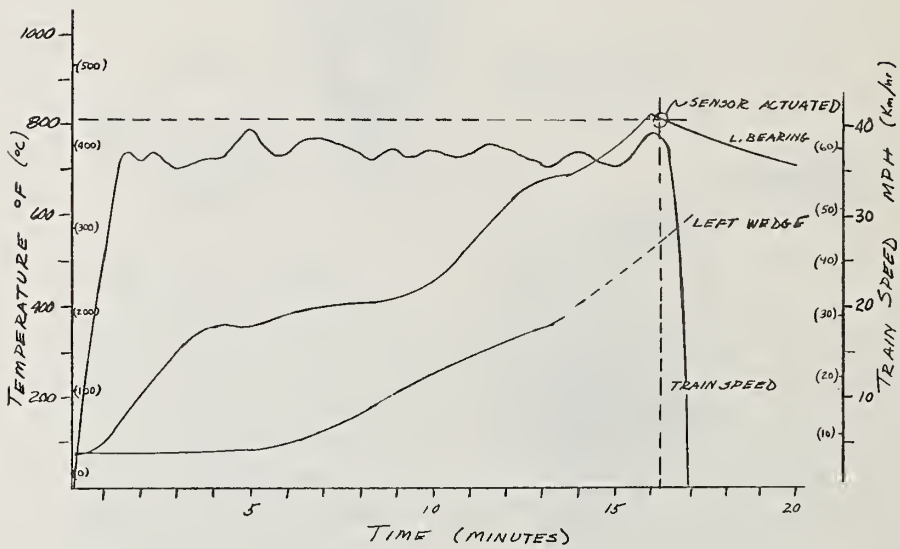


figure 7: Field Test Demonstration of
D.O.T.-S.T.A.R. System.
Journal Bearing Hotbox Detected
and Train Stopped. Left Side.

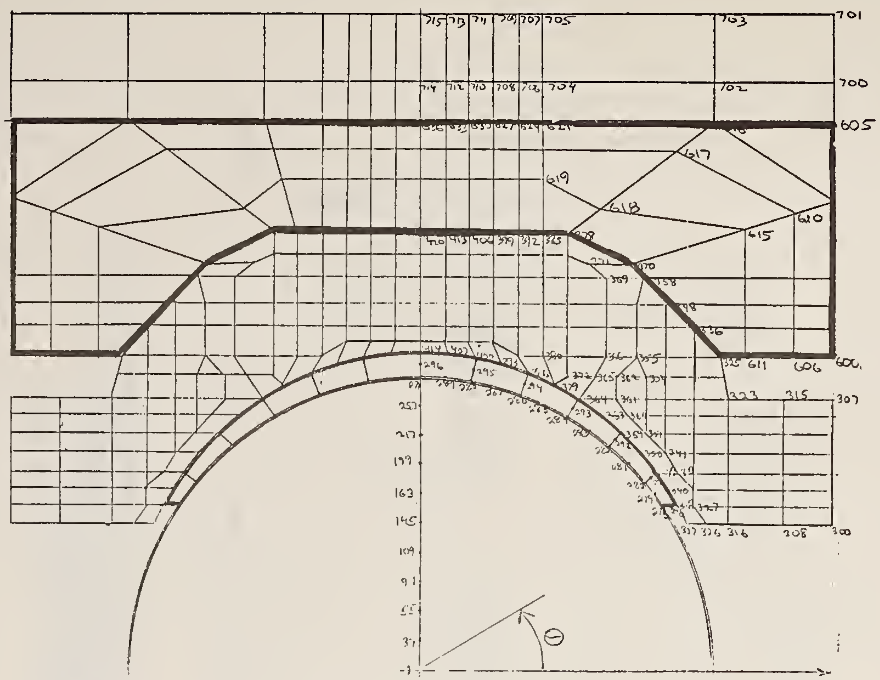


figure 8: Typical Journal Bearing Finite Element Net for Heat Production and Conduction Analysis.

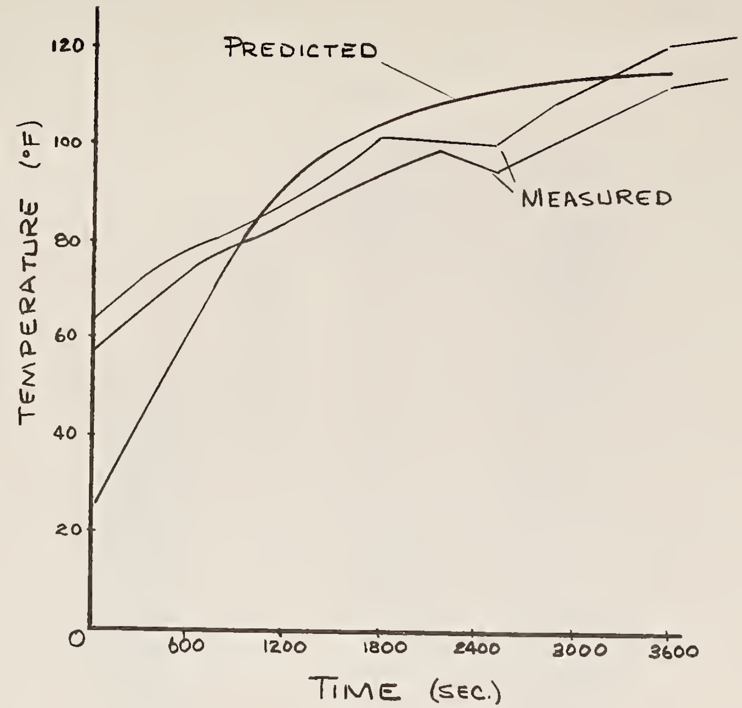


figure 9: Comparison of Predicted and Measured Full Car Over-the-Road Journal Bearing Wedge Temperatures.

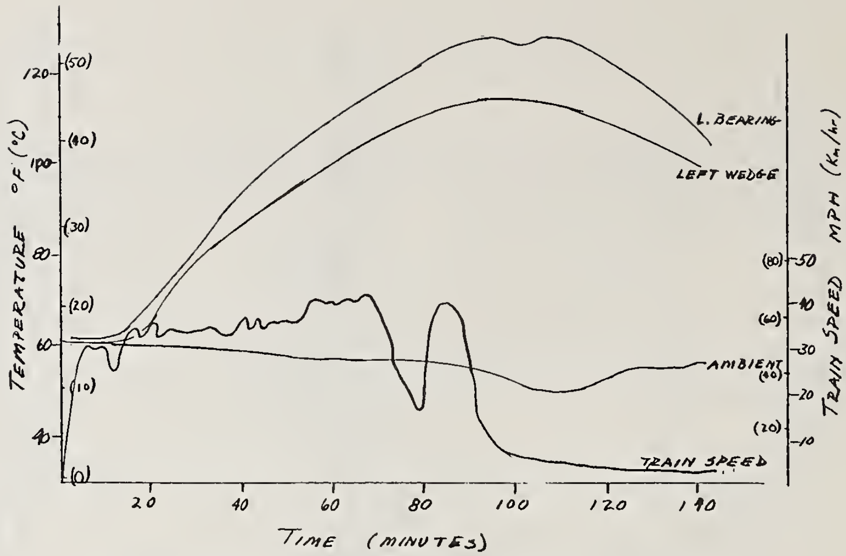


figure 10: Measured Empty Car Over-the-
Road Journal Bearing
Temperatures.

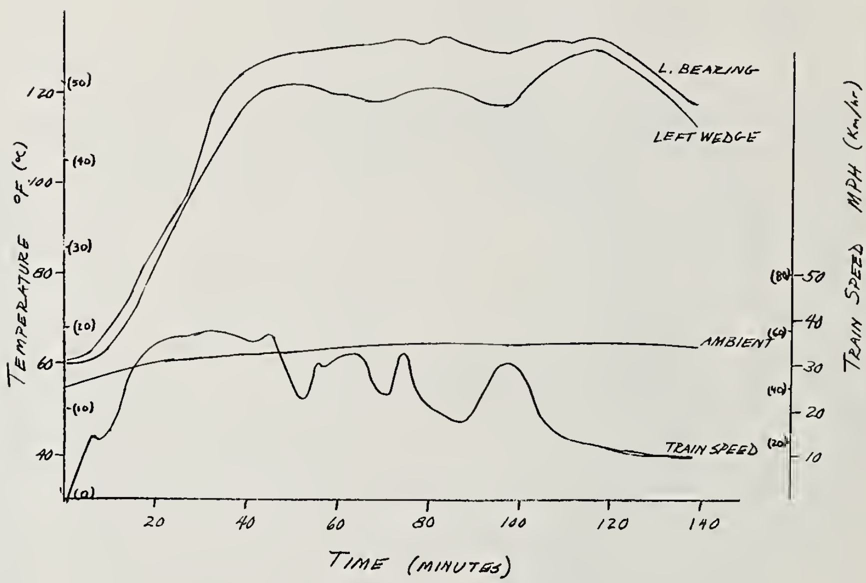


figure 11: Measured Full Car Over-the-
Road Journal Bearing
Temperatures.

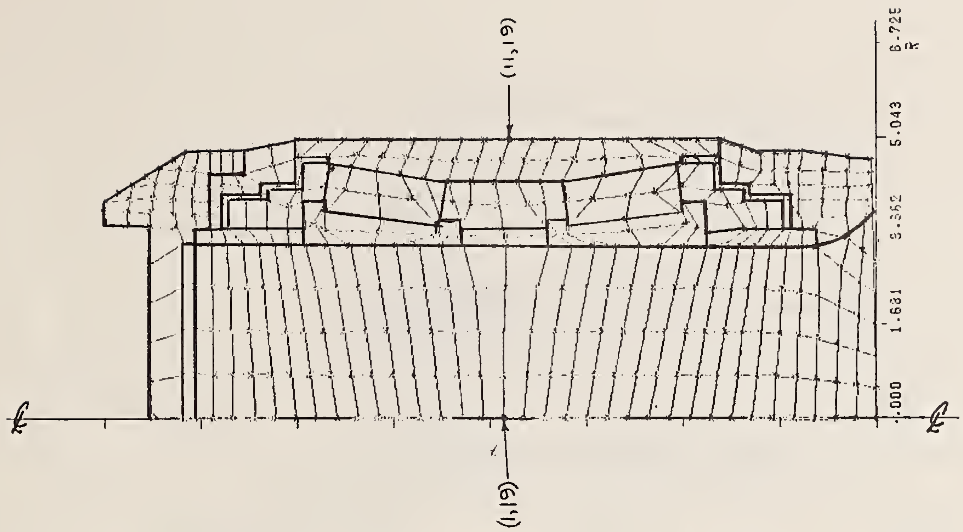


figure 12: Typical Roller Bearing Finite Element Net for Heat Production and Conduction Analysis.

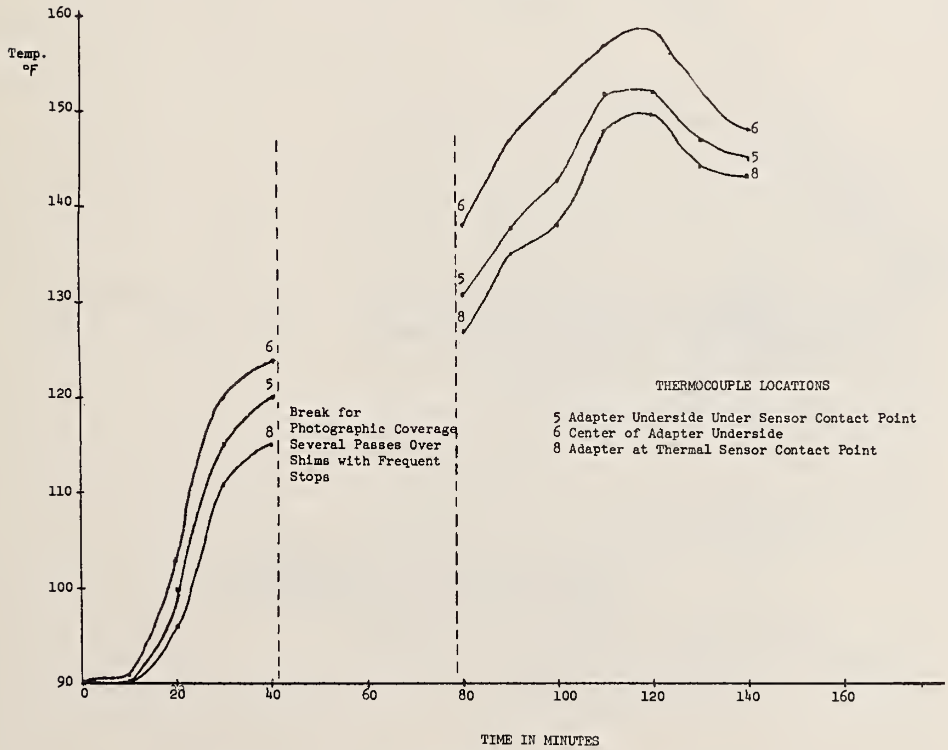


figure 13: Measured Full Car Roller Bearing Operating Temperatures at 45 MPH, 90° Ambient Temperature.

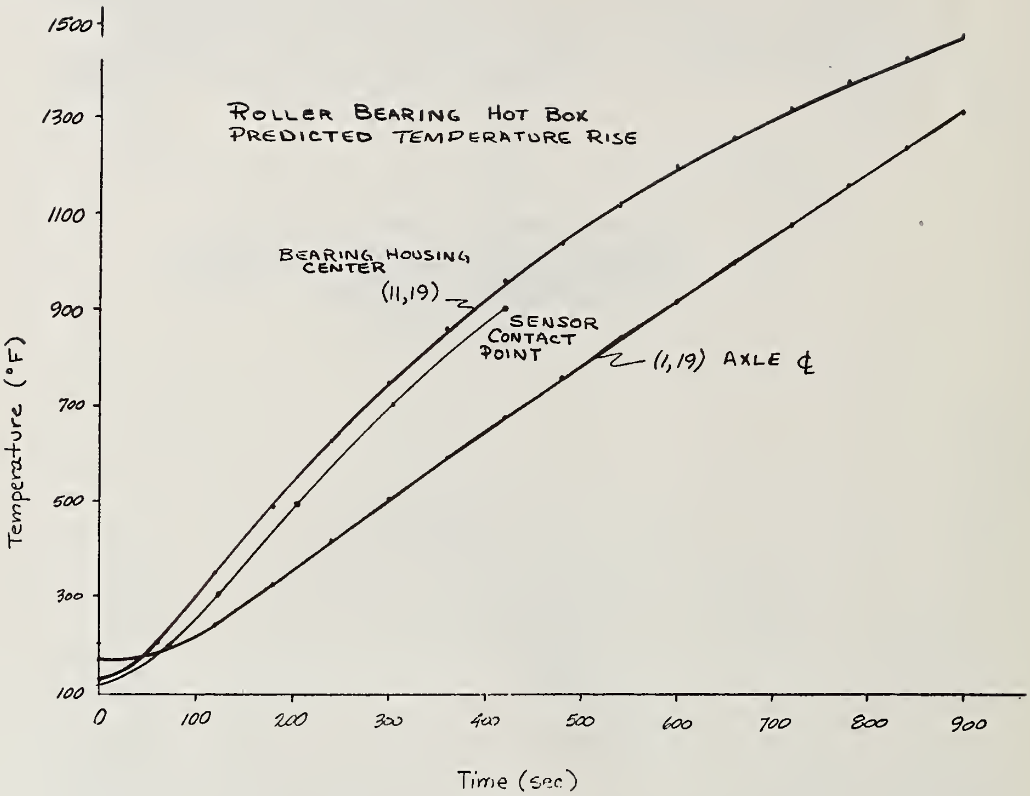


figure 14: Typical Predicted Roller Bearing Hotbox Temperature Rise Characteristics

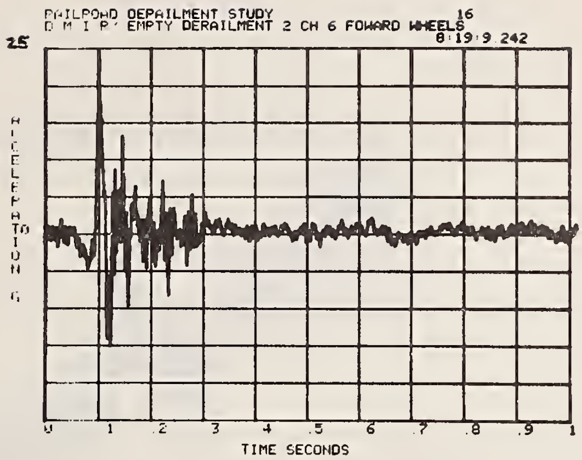


figure 15: Typical Side Frame Accelerations During an Empty Car Derailment.

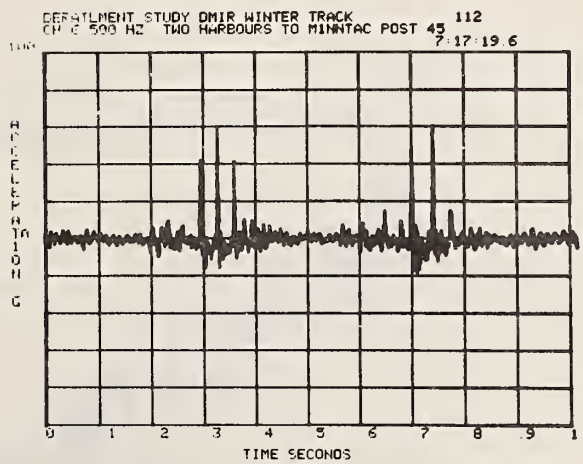


figure 16: Typical Side Frame Accelerations Traversing Rough Track.

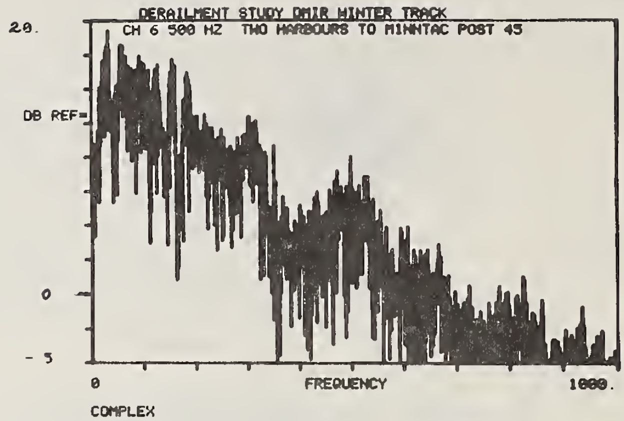


figure 17: Shock Spectrum Frequency Analysis of Typical Side Frame Accelerations Traversing Rough Track.

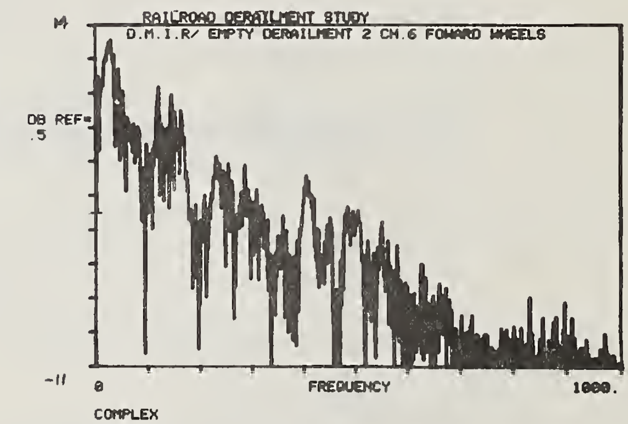


figure 18: Shock Spectrum Frequency Analysis of Typical Side Frame Accelerations During an Empty Car Derailment.

COMPARISON OF VIBRATION ANALYSIS TECHNIQUES FOR RAILROAD ROLLER BEARING DIAGNOSTICS

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This paper summarizes recent work at Shaker Research Corporation involving railcar roller bearing defect diagnostics utilizing high frequency vibration techniques. The general objectives of the work are summarized in Figure 1.

Although both objectives are addressed to the same component - railcar roller bearings, and both employ the same basic raw data - high frequency vibration, they have vastly differing requirements. A track side or wheel shop device requires ruggedness, simplicity (minimal operator training), and a sensitivity high enough to identify defects that are easily recognizable to the naked eye. A device used for certification testing, on the other hand, must be able to discern minute defects and can utilize more sophisticated techniques as it would be inherently a laboratory device. The three basic levels of sophistication used in analyzing the raw accelerometer data are summarized in Figure 2.

Three test vehicles or rigs were employed to evaluate the high frequency vibration approach using bearings with varying types and degrees of surface defects. The test rigs are shown in Figures 3 through 5. Four separate types of diagnostic system tests were performed (using the three test rigs).

The primary diagnostic system objectives and conclusions for each of the tests are summarized in Figures 6 through 9. In addition to diagnostic system evaluation, the failure progression and certification tests were designed to study bearing failure mechanisms and times to failure of various defect modes.

Figures 10 through 14 summarize the results of each test in terms of bearing condition versus peak amplitude and, in the case of the certification tests (Figure 14), the signal to noise ratio of the discrete defect frequency contained in the demodulated signal. Specific conclusions with regard to each test were given in Figures 6 through 9. In general it is seen that:

1. If "peak" amplitudes exceed two "g's", the bearing was unquestionably defective.
2. Below two g's, amplitude level was an unreliable indicator of bearing quality.

3. Using a spectrum analyzer to analyze the low frequency (0-200 Hz) demodulated signal, made it possible to rate bearings in the region below two g's.

For the wheel shop tests a modified crest factor approach was also used as a bearing condition rating factor. In this case, approximately five seconds of useful magnetic tape recorded raw acceleration data for each of the 90 bearings tested was available (useful in the fact that both load and speed were constant). For each bearing a modified crest factor was created by manually dividing the peak by the average of the demodulated signal at the same "instant" in time. The results of this approach is shown in Figure 15. The plot shows the percentage of the total number of good bearings that would be rejected, the number of defective (yet not condemnable by AAR rules) that would be rejected, and the number of condemnable bearings that would be accepted versus detection level (modified crest factor). For example, if the detection (rejection) level was arbitrarily set at 1.0, approximately 20% of the good bearings and 50% of the defective bearings would have been rejected, and 20% of the condemnable bearings would have been accepted.

Thus, it is seen that the addition of a rather simple data processing technique (crest factor) greatly improves the discriminating power of the high frequency variation diagnostic approach. By performing the crest factor function electronically and improving the drive system to attain better speed consistency, the discriminating power should be greatly enhanced.

General conclusions with regard to the feasibility of high frequency as a railcar roller bearing diagnostic tool are summarized in Figure 16.

GENERAL OBJECTIVES OF WORK

EVALUATE FEASIBILITY OF DIAGNOSTIC SYSTEMS:

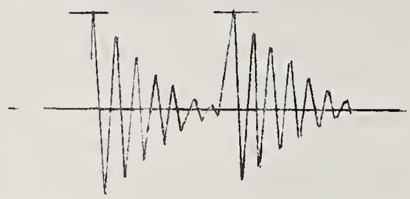
- o FOR DEPLOYMENT AT A WHEEL SHOP OR AT TRACK SIDE

- o FOR USE DURING CERTIFICATION TESTS TO INDICATE THE "INITIAL" OCCURRENCE OF A SURFACE DEFECT.

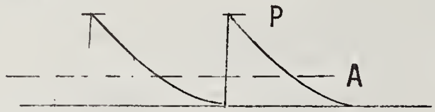
Figure 1

HIGH FREQUENCY (OVER 10 KHZ) TECHNIQUES UTILIZED

o PEAK ACCELERATION AMPLITUDE

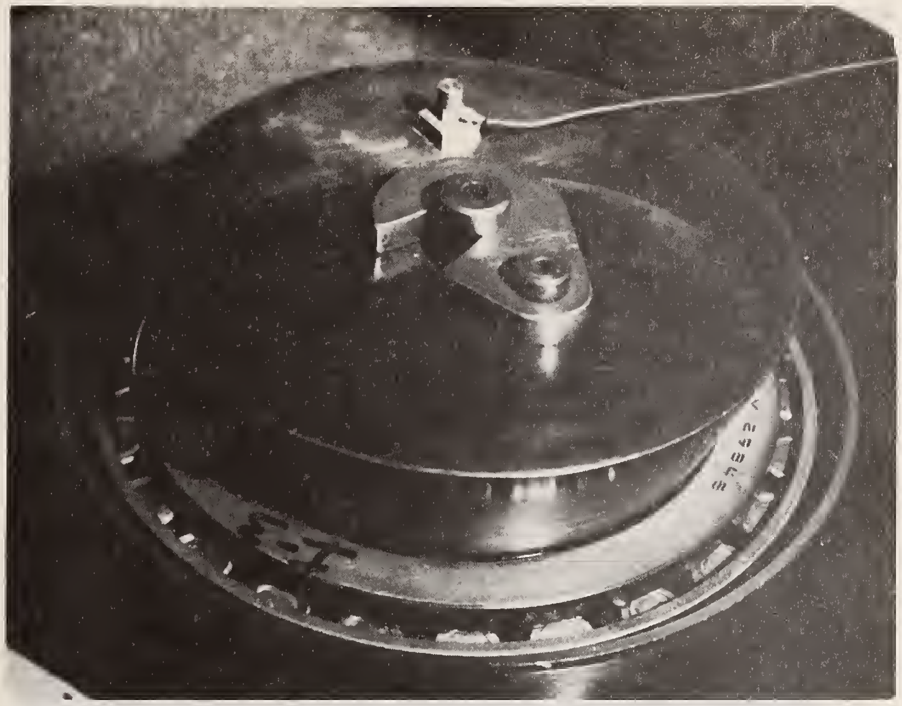


o PEAK/AVERAGE AMPLITUDE OF DEMODULATED HIGH FREQUENCY SIGNAL



o FREQUENCY DOMAIN ANALYSIS OF DEMODULATED SIGNAL IN THE RANGE OF ROLLER PASS FREQUENCIES (0-200 HZ)

Figure 2



- ROTATING OUTER RACE
- MODERATE AXIAL LOAD
- VARIABLE SPEED
- UNGREASED BEARINGS

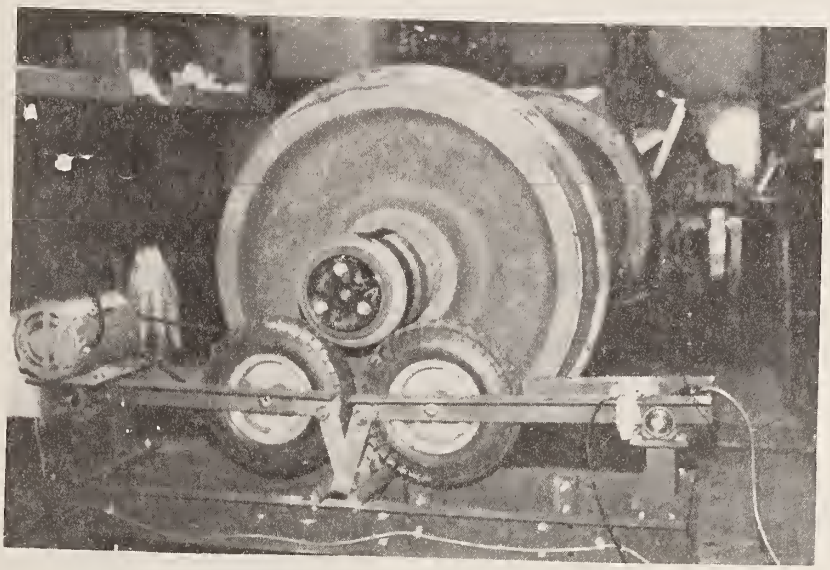
Figure 3

FAILURE PROGRESSION AND CERTIFICATION TESTS

- o ROTATING INNER RACE
- o HIGH SPEED (65 MPH)
- o USED TO EVALUATE BEARINGS WITH MULTIPLE DEFECTS

Figure 4

WHEEL SHOP TESTS



- o ROTATING OUTER RACE
- o MODERATE SPEED (45 MPH)
- o USED TO EVALUATE A "RANDOM" SAMPLE OF BEARINGS OF UNKNOWN QUALITY

Figure 5

OBJECTIVES AND CONCLUSIONS — COMPONENT TESTS

ESTABLISH FEASIBILITY

- o AMPLITUDE @ 10-40 KHZ GOOD INDICATOR OF GROSSLY DEFECTIVE BEARINGS

- o POOR DISCRIMINATION BETWEEN NEW, GOOD, AND "MARGINAL" BEARINGS

EXAMINE ROTATIONAL SPEED EFFECT

- o AMPLITUDE DECREASES MARKEDLY BELOW 30 MPH

DEFINE SYSTEM CONCEPT

- o H.F. (10-40 KHZ) PEAK AMPLITUDE APPROACH RECOMMENDED

Figure 6

OBJECTIVES AND CONCLUSIONS — FAILURE PROGRESSION TESTS

MONITOR DEFECTIVE BEARING DEGRADATION

- o DEGRADATION EVIDENT AND CONSISTENT WITH INCREASING AMPLITUDES

FURTHER QUANTIFY AMPLITUDE/DEFECT SIZE RELATIONSHIP

- o AMPLITUDE PER SE NOT ALWAYS INDICATIVE OF DEGREE OF DAMAGE

EVALUATE EFFECT OF GREASE

- o UNCHANNELED GREASE ATTENUATES AMPLITUDES BY 2 TO 3
- o 30 TO 50 HOURS REQUIRED TO STABILIZE (VIBRATION AND TEMPERATURE) A NEWLY GREASED BEARING

EXAMINE RADIAL LOAD EFFECT

- o LOAD HAS MINIMAL EFFECT ON VIBRATION AMPLITUDES

Figure 7

OBJECTIVES AND CONCLUSIONS — WHEEL SHOP TESTS

ESTABLISH FEASIBILITY OF TESTING WHILE INSTALLED ON AXLE

- SYSTEM CLEARLY ADEQUATE FOR IDENTIFYING "NON-REPAIRABLE" BEARINGS

IDENTIFY LIMITATIONS OF RECOMMENDED APPROACH

- ADDED SOPHISTICATION NEEDED TO SEPARATE DEFECTIVE FROM GOOD BEARINGS

- MECHANICAL APPARATUS NEEDS TO BE MORE POWERFUL AND MASSIVE

EVALUATE ATTENUATION EFFECT OF WHEEL SET INERTIA

- AXLE MOUNTED ACCELEROMETER ADEQUATE

Figure 8

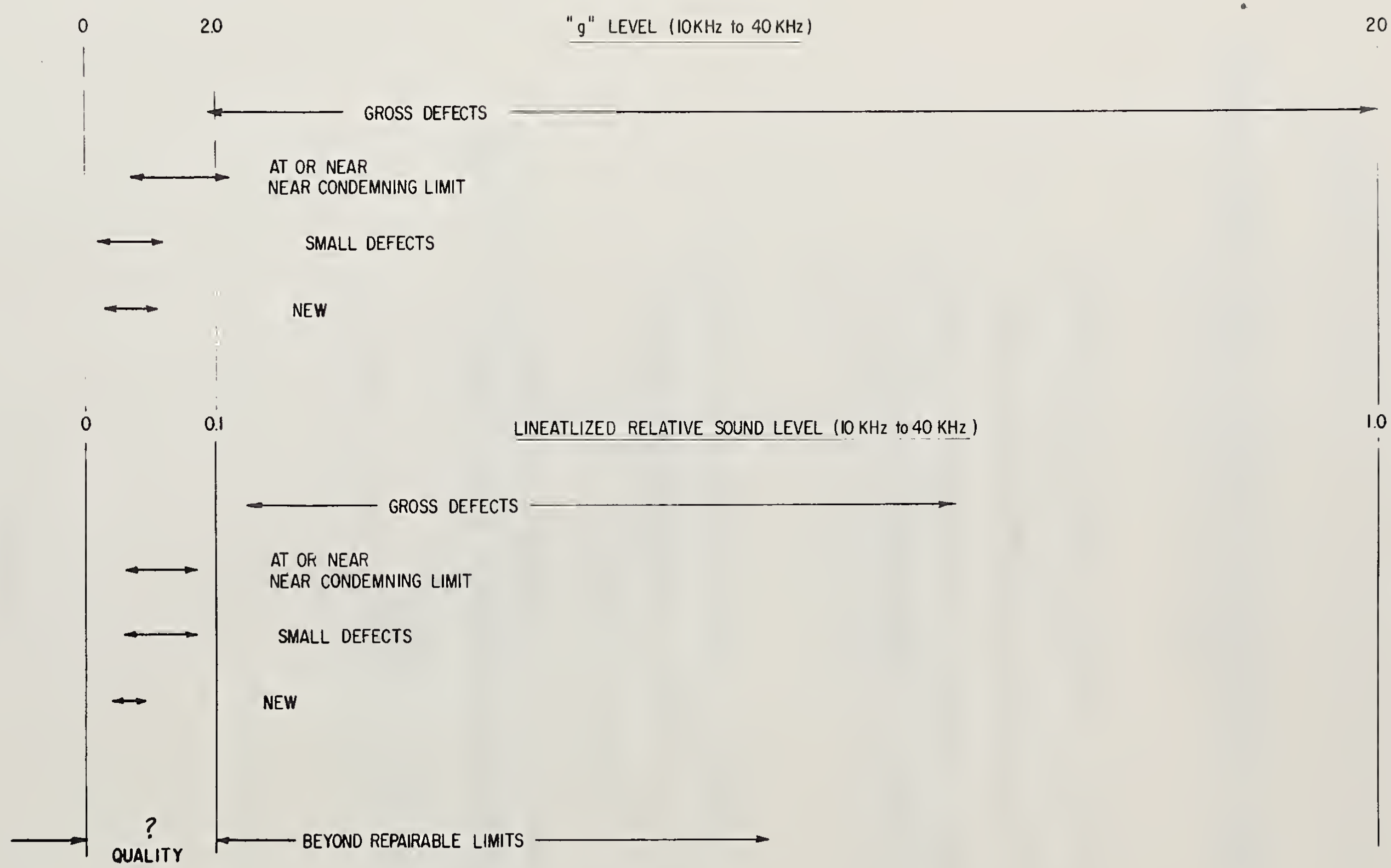
OBJECTIVES AND CONCLUSIONS — CERTIFICATION TESTS

EVALUATE POTENTIAL APPROACHES TO IDENTIFY "FIRST" SIGNS OF DEFECT

- CREATION OF A MINUTE DEFECT WAS REPEATABLY IDENTIFIED USING SPECTRUM ANALYSIS (VERY NARROW FILTERING) OF AN ENVELOPE DETECTED HIGH FREQUENCY ACCELERATION SIGNATURE

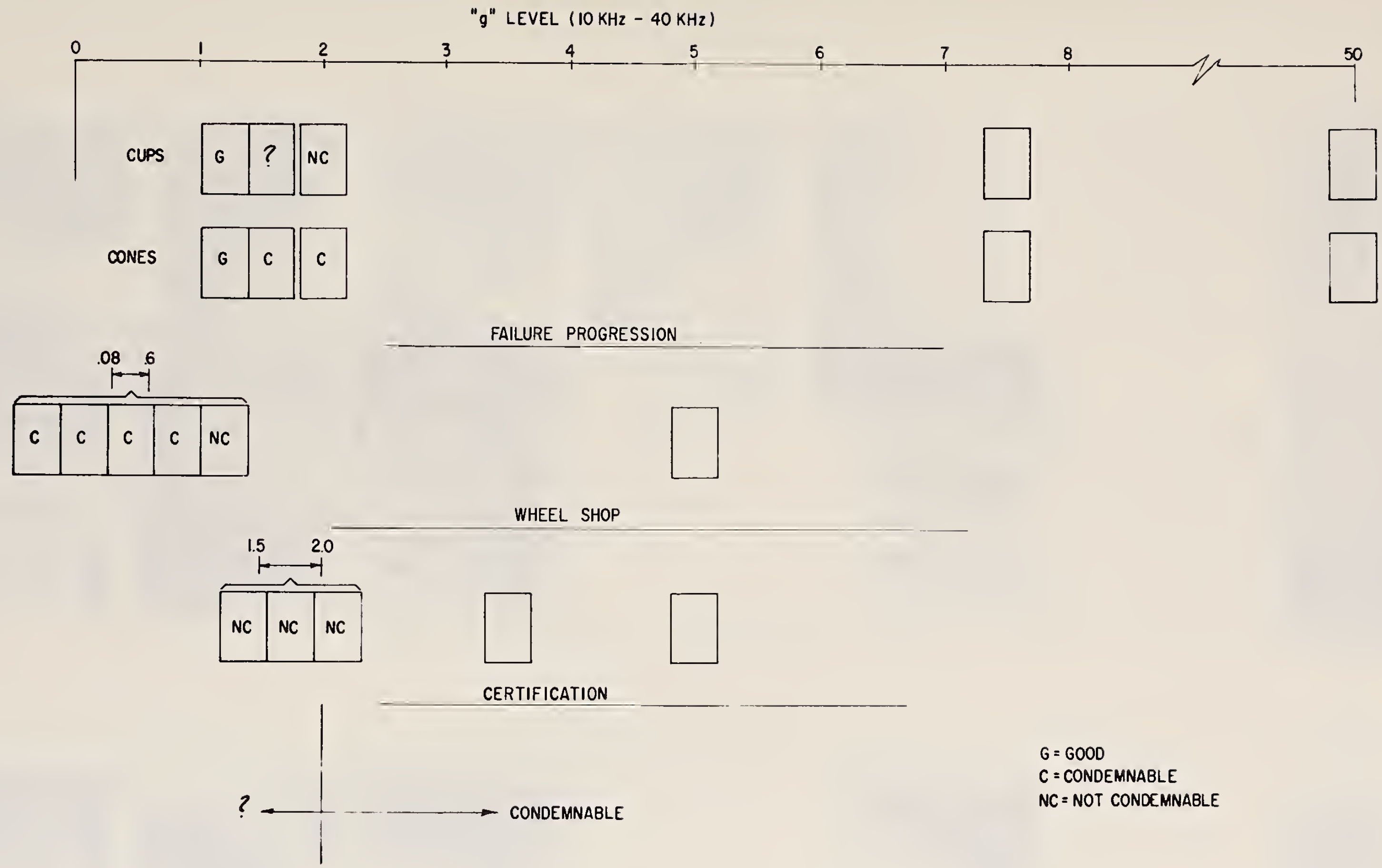
- HIGH PASS (OVER 10 KHZ) OR BROAD BAND (10 to 40 KHZ) FILTERING OF THE RAW SIGNATURE PRIOR TO ENVELOPE DETECTION PROVIDED MORE CONSISTENT RESULTS THAN NARROW BAND FILTERING

Figure 9



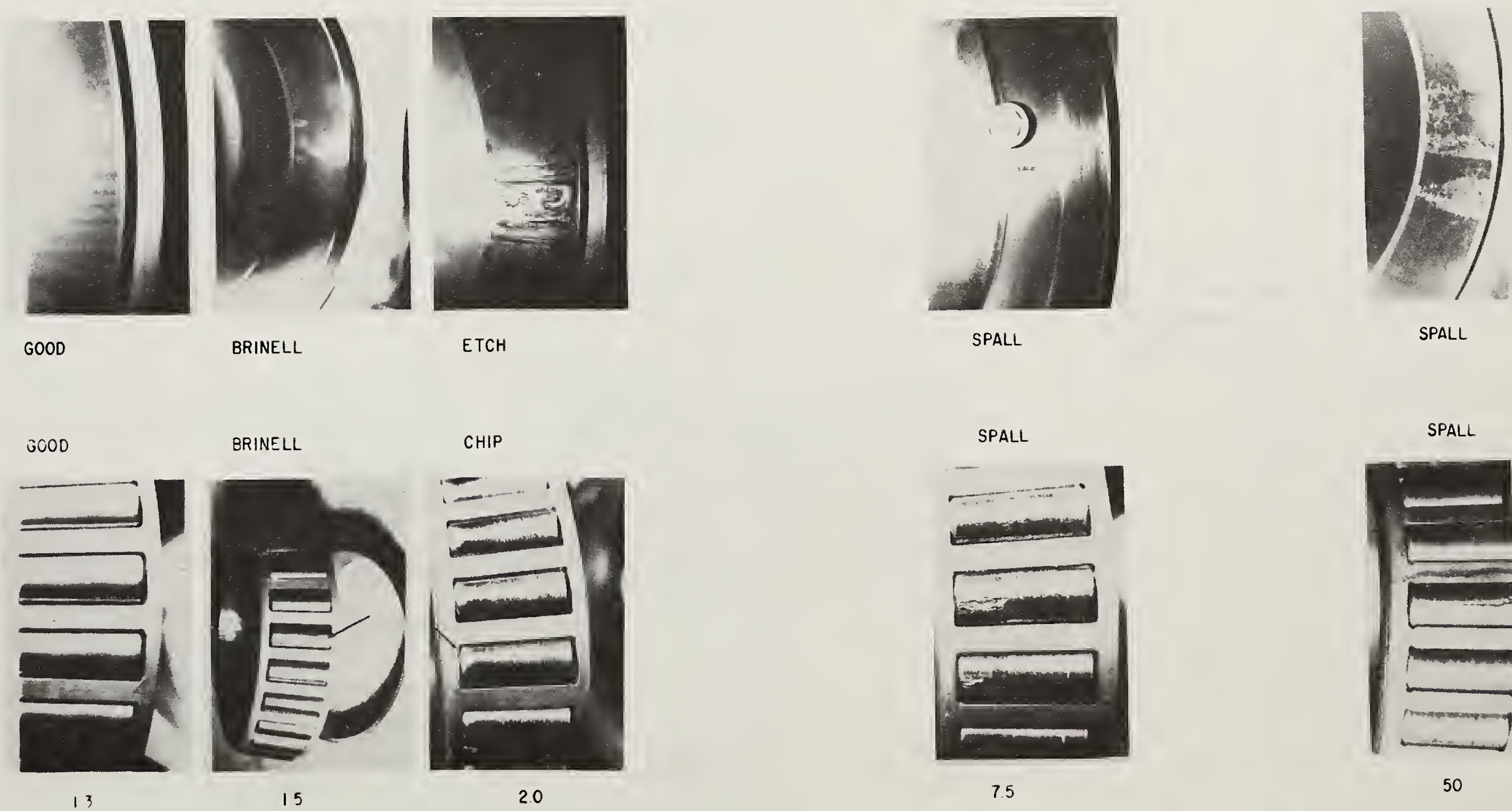
SUMMARY OF SINGLE COMPONENT TESTS

Figure 10



SUMMARY OF DEFECT VARIETY

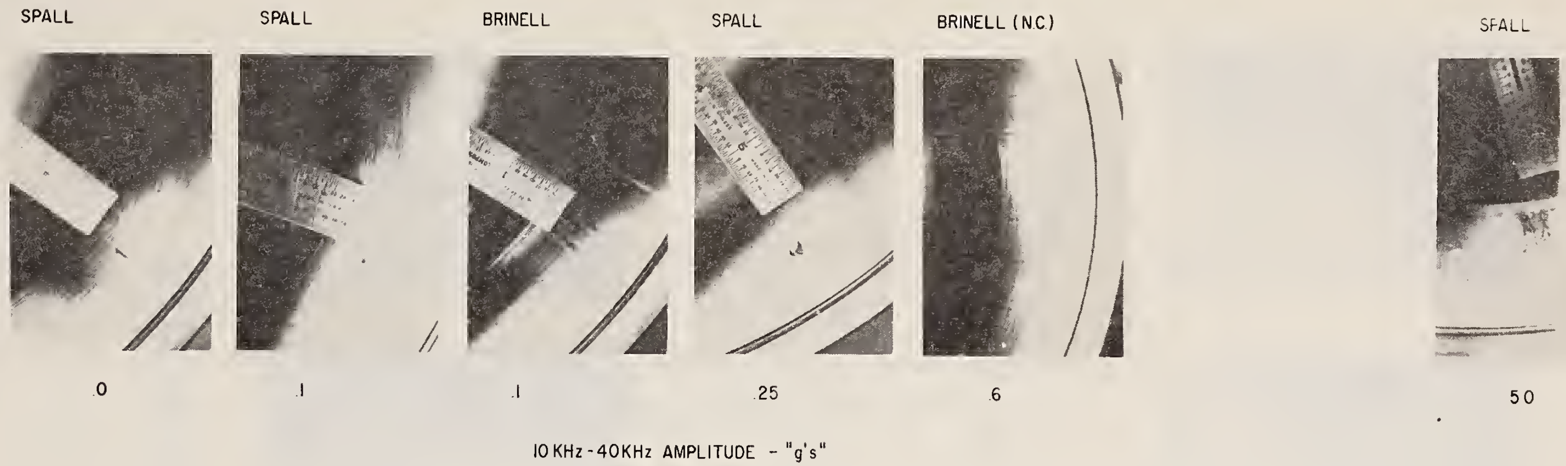
Figure 11



10-40 KHz AMPLITUDE - "g's"

CONDITION AND AMPLITUDE - FAILURE PROGRESSION TESTS

Figure 12



CONDITION AND AMPLITUDE - WHEEL SHOP TESTS

Figure 13

←	1.5 - 2.0	→	3.5	5.0

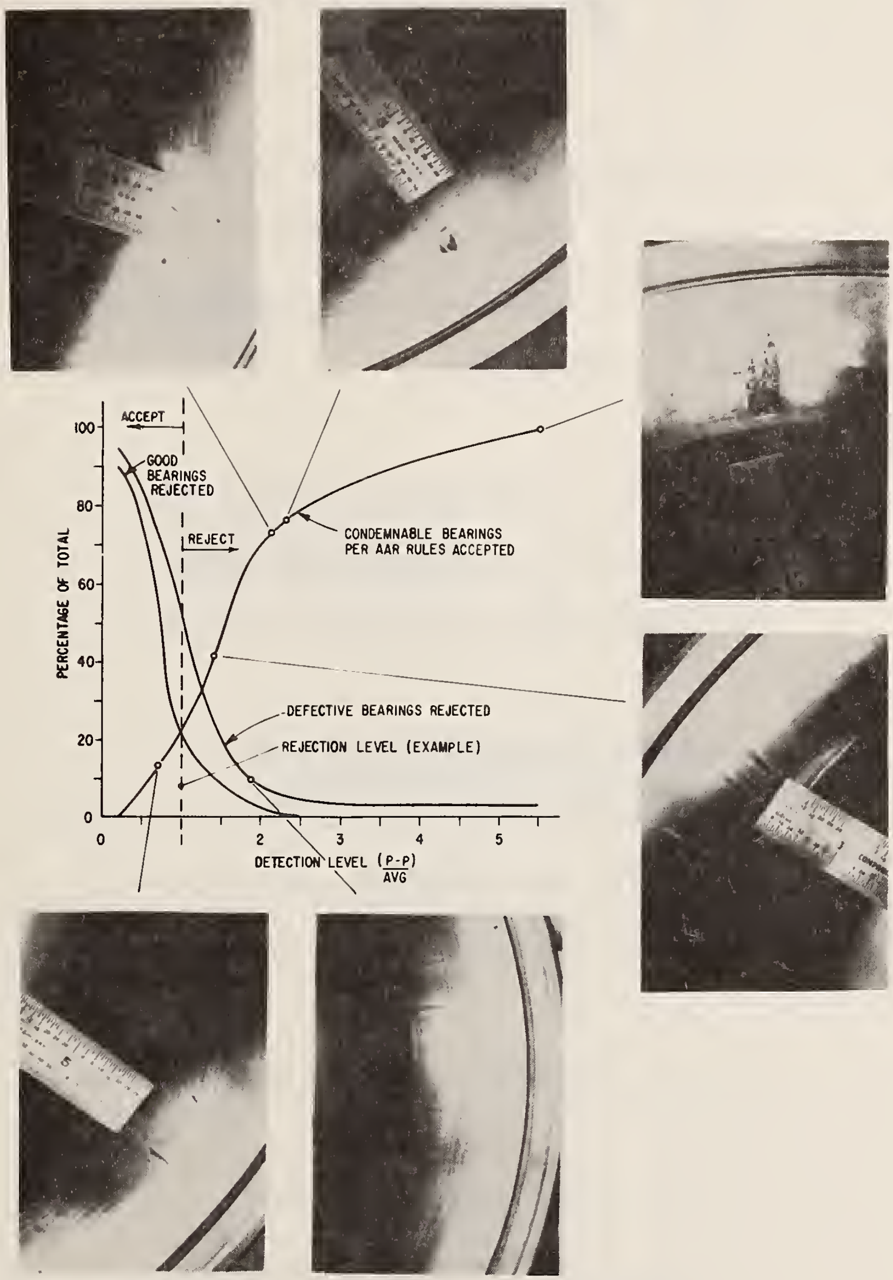
10 - 40 KHz AMPLITUDE - "g's"

1.3	1.3	3.0	12.6	6.7

SIGNAL - NOISE OF DISCRETE DETECT FREQUENCY
DEMODULATED FROM 10 - 40 KHz (FROM 0-200 Hz SPECTRUM ANALYSIS)

CONDITION AND AMPLITUDE - CERTIFICATION TESTS

Figure 14



RESULTS OF TESTS AT SOUTHERN RAILROAD
WHEEL SHOP SHOWING TYPICAL DEFECTS

Figure 15

SUMMARY OF CONCLUSIONS

- HIGH FREQUENCY PEAK AMPLITUDE DETECTION NEAR 2 "g" LEVEL SIMPLE AND INEXPENSIVE METHOD OF WEEDING OUT BEARINGS THAT SHOULD BE REMOVED FROM THE POPULATION

- SOME FORM OF CREST FACTOR APPROACH AFTER DEMODULATION APPEARS PROMISING TO BETTER DISTINQUISH GOOD FROM MARGINAL BEARINGS

- IF BEARING DIAGNOSTIC SYSTEMS ARE TO BE SUCCESSFULLY INTEGRATED INTO THE R.R. SYSTEM, AAR REMOVAL AND CONDEMNING LIMIT RULES WILL HAVE TO BE RE-EVALUATED WITH REGARD TO:

    - FREQUENCY AND PLACE OF INSPECTION

    - QUANTIFICATION OF DEFECT (EYE VERSUS AMPLITUDE)

Figure 16

SESSION V

LAND VEHICLE DIAGNOSTICS

CHAIRMAN: J. A. GEORGE

PARKS COLLEGE OF ST. LOUIS UNIVERSITY

MAINTENANCE MANAGEMENT THROUGH DIAGNOSIS

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MILITARY LAND VEHICLE MAINTENANCE*

The high cost of military vehicle maintenance has caused an increasing interest in the development of improved vehicle designs and diagnostic aids and procedures, with the objective of reducing costs. The Defense Advanced Research Projects Agency (DARPA), Vehicle Maintenance Program is currently addressing the question of whether advanced technology can contribute the opportunity for reducing these costs.

Current Army vehicle maintenance procedures include a scheduled maintenance program consisting of preoperation checks and periodic servicing. Also, corrective vehicle maintenance is performed in response to overt failures. Experience in the realm of stationary equipment maintenance suggests the need for an added component in the Army's operational scheme--periodic health screening.

HEALTH SCREENING

There are a number of benefits attendant to the ability to anticipate the need for maintenance rather than just reacting to the occurrence of failure. Failures tend to occur in a sequence or cascade of events, with each stage increasing the probability of the catastrophic event. The ultimate occurrence of this event can also precipitate secondary failures. If the sequence of events, or a significant decay function within that sequence can be detected in the early stages before failure has occurred, a systematically planned intervention can preclude the failure occurrence. The process, termed here health screening, can also provide the basis for reducing the scheduled maintenance program where screening can detect the need, and the lack of need, for servicing. A final benefit is the capability for a more reliable determination of the probability of a given vehicle successfully completing a future mission increment, leading in turn to a quantifiable fleet readiness prognosis.

Necessary to the implementation of a comprehensive health screening program is an understanding of the significant generic failure models for each vehicle type in the fleet. These models encompass the significant wear and condition decay functions as well as the failure cascades in

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*Section titles in this paper are keyed to the briefing charts attached.

which these functions play a role. Maintenance decision criteria can be derived from both the absolute level of the decay phenomenon and the rate at which decay is progressing.

A number of test equipments types can be employed to determine the progression of the decay phenomenon. Standard shop test equipment (TMDE) can be employed but requires a skilled mechanic and a shop setting. A significant hookup effort and the need for experience in interpretation of results has resulted in a reticence of Army mechanics to employ this equipment, even in the fault isolation function. The Army is currently developing an improved unit known as STE-ICE. This equipment is portable and can be used with a diagnostic connector if the vehicle is so equipped, or with a transducer harness which improves the hookup problem over the TMDE. STE-ICE provides the mechanic with testing logic but not with diagnostic interpretation. The Army's ATE-ICE equipment, now in the experimental stage, adds the capability for interpretive logic. A limiting feature of this technique, however, is that faults must be corrected as they are discovered or the subsequent decisions by the device may be in error. This limits the capability to perform a complete assessment before repair is initiated.

Dynamometers allow loading of the vehicle throughout the complete dynamic range of the vehicle and in theory make possible a more complete determination of vehicle condition. Another approach to dynamic evaluation would involve the miniaturization of the test equipment so that tests may be conducted on the road, thus eliminating the high costs of stationary energy absorption equipment. Such onboard equipments may be either connected just for the period of the test (strap-on) or may ultimately be built into the vehicle.

A final technique for screening tests is the detection and analysis of selected vehicle radiated signatures. The current state-of-the-art, however, suggests that this technique is only a long-term possibility. The radiated signal/noise characteristics from complex vehicle systems as their condition varies is poorly understood at this time. Given that vehicle signatures can be remotely detected, that condition/diagnostic signals can be discriminated and that machine intelligence can yield comprehensive assessment of vehicle condition, the technique may be considered a candidate ultimate system. Difficulties, however, beyond the problem of the capture and interpretation of signals from a complex vehicle may include the costs and logistics of the necessary equipment, particularly for a battlefield environment.

FAILURE MODELS

Actual vehicle failures result from a cascade or sequence of events or circumstances which ultimately lead to a catastrophic event. An example of such a sequence model may be developed around the cylinder failure associated with overtemperature operation. Basic causes can be of several types. Coolant loss may result from afterboil due to short cooldown procedures or from a system leak. Inadequate frequency of pre-op inspection would allow this loss to progress. Or, reduced coolant circulation could result from a clogged radiator on the coolant side, or faulty pump operation due to a loose belt. Or, debris in the radiator on the air side could cause reduced heat rejection. Each of these circumstances, or combinations of them, could cause an increasing operating temperature trend above the thermostat control point. The shape of this trend is important to its detectability. If this trend is undetected due to instrumentation resolution and/or infrequent observation, it can progress to the point where a severe overtemperature condition (boil over) results. If this condition is not observed in time, catastrophic cylinder failure results.

FAILURE/DECAY FUNCTIONS

Ideally, a time decay function, to be useful in a screening program, should be a graceful monotonically varying curve with a first derivative that increases in a continuing progression. If the derivative changes very slowly and then suddenly increases, precipitously, the short time available to be alerted to the change will preclude intermittent sampling and will require continuous monitoring of the function, with an alarm to signal the "break point." In this case only built-in test equipment can be considered competent to detect the phenomenon since off-board periodic inspection cannot practically inspect with the necessary frequency. If significant condition phenomena exist, however, which exhibit graceful decay functions, intermittent screen testing can be viable.

IMPLEMENTATION PROBLEMS

The difficulty, however, is that field failure model data for Army vehicles are woefully inadequate. The current understanding of those models is manifest in the design and qualification test criteria currently in use. It is apparent from experience with current vehicles which survive their qualification tests but don't perform to these levels when deployed in the field that the field deployment failure models are poorly understood. Certain vehicles, for example, require up to five (5) engines when deployed in the field to complete the qualification-endurance time requirement. The lack of understanding of these models means that we are ignorant of the prospects for a necessary set of graceful decay functions, and therefore a means to determine the viability of screen testing as a means to reduce maintenance costs.

Another inadequate resource, necessary to determining this viability, is consistent and reliable maintenance costs data for the existing fleet. Without such data it is impossible to make meaningful cost-effectiveness comparisons of candidate system alternatives with current practice. A principal difficulty, as usual, is the reliability of data source documentation.

VEHICLE MONITOR SYSTEM (VMS)

A key component of the DARPA Vehicle Maintenance program is the VMS Demonstration project. The demonstration objectives include determination of the capability of current and near-term technology to provide effective vehicle-borne instrumentation technology, and to demonstrate the effective use of such a device in the Army field environment. In connection with this latter objective, we expect the pilot data developed during the demonstration to provide significant insights for the recommendation of future productive courses of action.

Participants in the demonstration in addition to the DARPA Tactical Technology Office (TTO) are The Rand Corporation (program coordination, test design/supporting analysis), the U.S. Army, TARADCOM (contract administration, test planning and logistics) and RCA, Government and Commercial Systems Division (hardware/firmware development).* The current program schedule includes engineering/vehicle tests at TECOM beginning in FY 1978 and the field demonstration test beginning in FY 1979. The results of the demonstration should allow improvements to vehicle design and qualification criteria and a refinement in the understanding of cost effective future Army maintenance equipments and procedures.

VMS DATA DEVELOPMENT

The VMS is conceived to provide data from the actual field operating environment on deployed vehicles. The types of data to be developed are vehicle use patterns, vehicle condition progressions, and maintenance action patterns. Use pattern and condition data are derived from instrumented sensing of vehicle variables in a time context. Maintenance actions are derived, primarily from inputs by maintenance personnel, with attendant but unavoidable reliability questions.

In addition to developing a general understanding of the distribution of vehicle employment patterns, failure and decay correlations will be developed. Short-term failure processes will be developed from high resolution, real time data displays** showing causative stress excursions among concurrent data variations. Long-term failure correlations will be derived primarily from cumulative stress prediction variables. Analytical techniques to be used in developing these correlations will include LOGIT analyses (employing logistic progression failure probability model) and exponential failure probability regressions.

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*Bill Stewich of RCA will describe this development in the following paper.

**In general, data is compressed for storage by time stamp recording the event of threshold crossings. Each data domain is partitioned into bands of appropriate resolution.

As data is accumulated, quantitative failure models will be developed. Generic decay functions will be described such that the form of maintenance threshold criteria can be determined and the criteria values for specific vehicle types estimated. These functions, together with the use and maintenance pattern data, will be used to describe the significant failure model cascades with steps in the sequence given probability allocations and individual cascades assigned frequency functions.

ANALYSIS COMPONENTS

The partition of the analysis of results is required for the isolation of independent, or mostly independent, failure mechanisms. Physical components include the upper cylinder, engine mechanical, cooling, fuel, starting, charging, chassis electrical, drive line and braking subsystems. Operating components include the duty cycle (including the fraction of inoperative time, off-road operation, etc.), the stress pattern to which the vehicle is subjected, and the actual implementation of the scheduled maintenance actions.

UPPER CYLINDER VARIABLES

In the design of a data collection plan for use in long-term statistical failure correlation studies, it is necessary to anticipate which variables will predict failures of the type anticipated. For example, it has long been part of the conventional wisdom that the engine piston-speed history is the primary predictor of the cylinder wear phenomena--time at speeds above 2000 feet per minute increases wear rate at increasing exponential rates, rapidly reaching a power of four (4). I have estimated a preliminary set of independent cumulative stress variables for purposes of initial test design. These include the time histories spent at excess rpm, overtemperature, low temperature/high EGT* (loading while cold), high rpm/high EGT (heavy load condition--inertial and pressure forces both high, but balanced), high rpm/low EGT (unbalanced inertial forces), total cumulative hours (perhaps partitioned by rpm threshold domains) and the duty cycle portion of time the vehicle is dormant. Experience accumulated in early testing will help refine this variable list.

Dependent variables will include the trend in power capacity of the engine and imbalance among cylinders in power production (and compression). In addition, the collection of failures as defined by the need for maintenance are also defined as independent variables.

PRELIMINARY TEST DESIGN

As a preliminary starting point in the refinement of the test design and sampling plan, logit analyses are being employed to determine the failure profile, sample size and sampling rate implied by various stress predictors. For example, an occurrence 3 percent of the time

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*Exhaust Gas Temperature

(in 7.5 hrs/month operation) resulting in a 3-year mean time to failure suggest a progressive trip failure probability of 0.0014 initially (zero hours on vehicle), 0.0028 after 4.5 hours of stress (1 1/2 years of duty), and 0.0056 after 8.1 hours of stress (3 years). In order to be 80 percent sure that this profile, rather than a constant rate of 0.0028 prevails, a data sample of 30 vehicle-years of experience is necessary, if the various explanatory variables are uncorrelated. If they are correlated (with a factor of 0.7), the experience requirement is 100 vehicle-years. If the MTBF is doubled, the sample required is reduced by 30 percent, and if quadrupled, the sample required is reduced by 50 percent. These parameters would also imply a sampling rate resolution of approximately one data point per vehicle trip.

As the program progresses and experience and data are accumulated (both within and outside the VMS effort) on the vehicle types to be tested, analyses of this type will be used in refining the test design and ultimately the interpretation of the field demonstration results.

The engineering vehicle tests will be conducted so as to benefit the test design process as well as the proof test of the VMS design. This will be accomplished by recovering data from the VMS on a schedule to insure a continuous high resolution record and to accumulate the maximum vehicle test experience on an M60 tank and an M35 2 1/2-ton truck. Our data analysis computer code for use in evaluating these data will emphasize the accessibility to high resolution data and the manipulation of that data into explanatory variables for long-term correlations. The results of the correlation studies of these variable combinations will enable refinement and specification of the system firmware (PROM) including the allocation of the memory capacity among high resolution, trip data, periodic summation/histogram data, special power test data, and maintenance action input data. Some minor redesign of the sensor suit is also possible.

BUILT IN DIAGNOSTICS--AN ULTIMATE CONCEPT?

It is interesting to speculate, even if not highly productive as yet, on what form an ultimate system might take in the future of Army vehicle maintenance. An immediate candidate is the VSA concept but with the recognition that such systems are probably far in the future. There is also the added problem of using intermittent inspection in conjunction with precipitous failure behavior. Only continuous monitoring with warning alarm plus periodic readout can satisfy the total screening function regardless of the distribution of failure model shapes.

If we examine the prospect for eventually implementing continuous monitoring, we find reasons for optimism. The form of system involved is built-in diagnostics and it will derive naturally from the experience the automotive industry is now developing as a result of imposed emission and fuel consumption regulations. These developments will assuredly produce inexpensive and survivable sensors and on-board microcomputers such that the addition of the diagnostic function is a relatively small, incremental complication.

Diagnostics will require additional computation and memory, as well as on-board status and warning displays and a data readout feature. The diagnostic logical analysis and limit testing can be accomplished by means of either the on-board system or by the data recovery device--depending on cost effectiveness tradeoffs.

The benefits of such a system include two features of particular importance in the combat environment, in addition to the general benefits of fault warning and screen testing. One of these features is the ability to diagnose the repair requirements of a "dead" vehicle. This capability can be readily used to determine the resources necessary to regenerate the vehicle to service so that optimized maintenance resource allocation can maximize total fleet readiness. The other feature is a benefit of the programmed diagnostic logic and the ease of access to quick diagnostics at the operational level. This feature enables the company commander to rely on his motor sergeant to optimally schedule the maintenance of his vehicle fleet such that the fleet readiness is maximized. In a combat situation, this close coupling of the tactical commander with the quantitative understanding of the readiness of his vehicle fleet could greatly enhance his unit's combat effectiveness.

MILITARY LAND VEHICLE MAINTENANCE

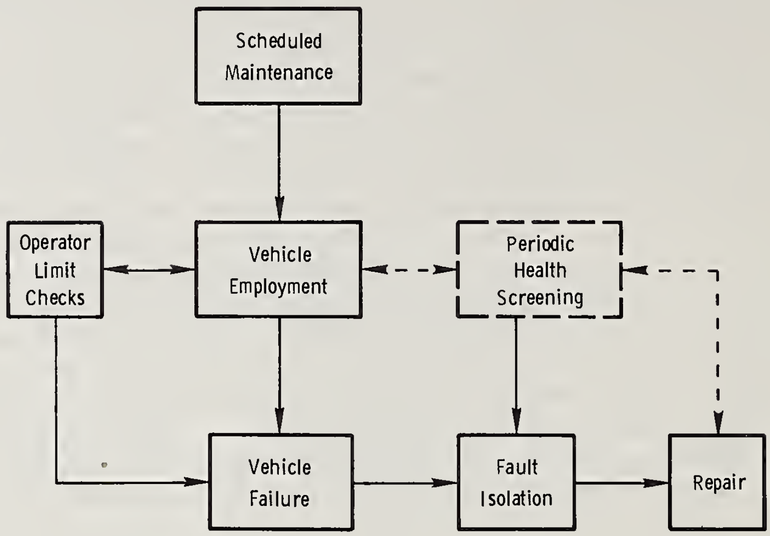

CHART 1

HEALTH SCREENING
(ANTICIPATORY MAINTENANCE)

- BENEFITS: REDUCE CATASTROPHIC FAILURES
  REDUCE SECONDARY FAILURES
  REDUCE UNNECESSARY MAINTENANCE
  BASIS FOR VEHICLE READINESS PROGNOSIS
- REQUIREMENT: GENERIC FAILURE MODELS
- CRITERIA: ABSOLUTE DECAY
  DECAY RATE
- TEST EQUIPMENT: STANDARD SHOP
  STE-ICE (DCA)
  ATE-ICE
  DYNAMOMETER
  STRAP-ON
  BUILT-IN
  VSA

CHART 2

FAILURE MODEL

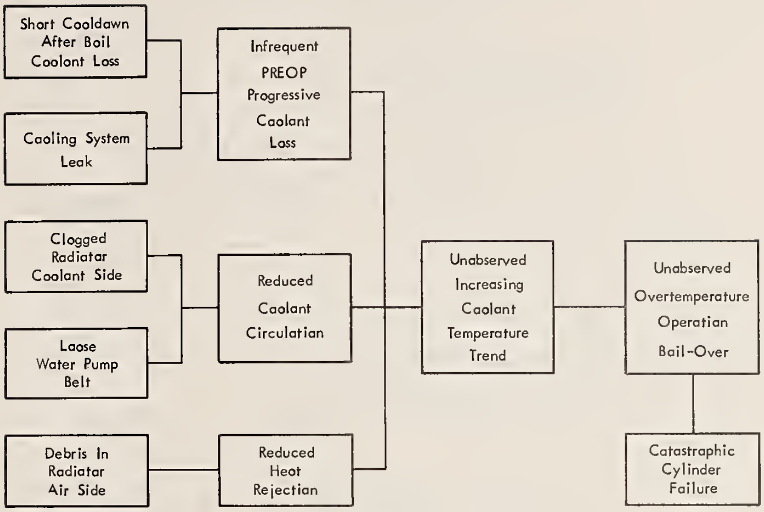

CHART 3

FAILURE / DECAY FUNCTION

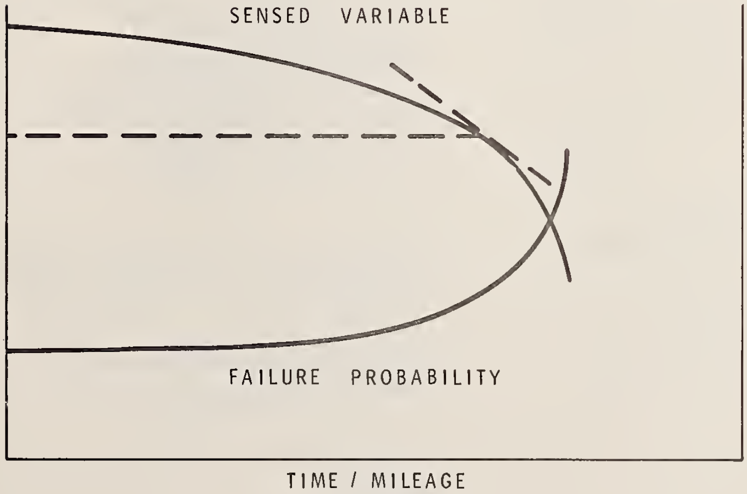

CHART 4

IMPLEMENTATION PROBLEMS

- FAILURE MODEL DATA
  - DESIGN / QUALIFICATION CRITERIA
  - AMENABILITY TO TRENDING

- MAINTENANCE COST DATA
  - INCONSISTENCIES
  - SOURCE RELIABILITY

CHART 5

VEHICLE MONITOR SYSTEM

● OBJECTIVES	VEHICLE-BORNE DIAGNOSTIC TECHNOLOGY CONCEPT DEMONSTRATION-PILOT DATA
● PARTICIPANTS	ARPA - DEMONSTRATION PROGRAM RAND - PROGRAM COORDINATION Test Design/Analysis TARADCOM - CONTRACT ADMINISTRATION Test Planning/Logistics RCA - HARDWARE DEVELOPMENT
● SCHEDULE	ENGINEERING VEHICLE TESTS - BEGIN FY 1978 FIELD DEMONSTRATION TESTS - BEGIN FY 1979
● RESULTS	VEHICLE DESIGN/QUALIFICATION CRITERIA ISSUE EQUIPMENTS/PROCEDURES

CHART 6

VMS DATA DEVELOPMENT

- DATA TYPES: USE PATTERNS
  CONDITION PROGRESSIONS
  MAINTENANCE REQUIREMENTS
- FAILURE CORRELATIONS: SHORT TERM -- STRESS EXCURSIONS
  LONG TERM -- CUMULATIVE STRESS
- TECHNIQUES: LOGIT ANALYSIS (LOGISTIC PROGRESSION)
  EXPONENTIAL REGRESSION
- FAILURE MODEL: DEVELOPMENT — DECAY FUNCTIONS
  CASCADES

CHART 7

ANALYSIS COMPONENTS

- VEHICLE SUBSYSTEMS
  - UPPER CYLINDER
  - MECHANICAL/LUBRICATION
  - COOLING
  - FUEL
  - STARTING
  - CHARGING
  - CHASSIS ELECTRICAL
  - DRIVE LINE
  - BRAKING
- OPERATING INFLUENCES
  - DUTY CYCLE
  - STRESS
  - SCHEDULED MAINTENANCE

CHART 8

UPPER CYLINDER VARIABLES

CUMULATIVE STRESS	DECAY / FAILURE
— EXCESS RPM	— POWER TREND
— OVER TEMPERATURE	— CYLINDER BALANCE
— LO TEMP / HIGH EGT	— FAILURE REQUIRING MAINTENANCE
— HI RPM / HI EGT	
— HI RPM / LO EGT	
— CUMULATIVE HOURS	
— DORMANT FRACTION	

CHART 9

PRELIMINARY TEST DESIGN

EXAMPLE 3% OCCURRENCE, 7.5 HRS / MONTH, 3 YR MTBF

FAILURE PROFILE

CUM. HRS.	TRIP FAIL. PROB.
0	0.14%
4.5	0.28%
8.1	0.56%

SAMPLING RATE - DATA POINT / TRIP

SAMPLE SAE

- 80% SURE OF PROFILE:
  - UNCORRELATED - 30 VEHICLE-YRS
  - CORRELATED - 100 VEHICLE-YRS
- 1.5 YR MTBF - 0.7 (SAMPLE)
- .75 YR MTBF - 0.5 (SAMPLE)

ENGINEERING VEHICLE TESTS

- CONTINUOUS HIGH RESOLUTION DATA
- MAXIMIZE VEHICLE UTILIZATION
- USE TO REFINE DEMONSTRATION TEST DESIGN
  - Prom
  - Sensors
  - Memory Allocation

CHART 10

BUILT - IN DIAGNOSTICS
AN ULTIMATE CONCEPT ?

- EMISSIONS AND FUEL CONSUMPTION REGULATIONS
  - INEXPENSIVE / SURVIVABLE SENSORS
  - ON - BOARD MICRO COMPUTERS
- DIAGNOSTICS
  - INCREMENTAL REQUIREMENT
  - ON - BOARD WARNING / DISPLAYS
  - READ - OUT DIAGNOSIS / REPAIR INSTRUCTION
- BENEFITS
  - MINIMUM MAINTENANCE COSTS, MAXIMUM READINESS
    Anticipate Short and Long Term Failure Progressions
  - "DEAD" VEHICLE DIAGNOSIS
  - MOTOR SERGEANT READINESS MANAGEMENT

CHART 11

VEHICLE MONITORING SYSTEM

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RCA Government Systems Division is developing a Vehicle Monitoring System (VMS) under contract to the Tank-Automotive Research and Development Command (TARADCOM) and the sponsorship of the Advanced Research Projects Agency (ARPA). The system will be a flexible research instrument to be installed in selected military vehicles for the purpose of collecting data supporting an ARPA-TARADCOM investigation into the high cost of operating and maintaining the land vehicle fleet. The VMS will supply comprehensive data describing the true use, condition and maintenance exposure of its host vehicle. This data will impact future vehicle designs and maintenance procedures.

A prototype development contract has been awarded to RCA following a Phase I design study during the summer of 1976 and design is now in progress. The prototype will be installed in two high density vehicles: the M35A2 2-1/2 ton truck and the M113A1 armored personnel carrier. Future plans call for installing a number of these systems in a variety of vehicles including the M151a2 1/4 ton truck (jeep) and the M48A3/M60A1 tank.

Hardware consists of a VMS Electronics Assembly (VMSEA) and a harness assembly, both installed in the vehicle, a Maintenance Action Input (MAI) device, and Data Retrieval Equipment (DRE).

During the course of the investigation, the on-vehicle assemblies will automatically collect and store vehicle generated data and maintenance data inputted by a mechanic via his MAI whenever he services the vehicle. Following nominal one month intervals, a contact team participating in the investigation will rendezvous with the vehicle, connect the DRE, extract the accumulated data and service the on-vehicle assemblies as necessary. Special vehicle tests may also be performed at this time and their results automatically compiled with the accumulated data. The data, encoded in digital format and requiring no human inputs other then those of the mechanic, will then be forwarded to a processing center for reduction and analysis.

Data Acquisition

The data acquisition scheme is based on collecting vehicle data which can be processed to evaluate a specific set of Vehicle Indicators. The indicators, which result from the first order reduction of raw VMS data at the processing center, quantiatively describe vehicle use, condition and maintenance exposure throughout the data collection interval. They combine all the VMS generated data into a structured data base available for further analysis. Table 1 lists the indicators that have been established.

The raw VMS data is acquired by monitoring key Vehicle Parameters during normal operation or special tests and by accepting coded inputs from a mechanic. The parameters which will be monitored for four high density vehicles are listed in Table 2.

The selection of vehicle parameters and the design characteristics of the VMS Electronics Assembly are critically related. The assembly is not merely a recording device. With its internal microprocessor, it manages the acquisition of parameter data and performs data reduction to a level where the indicators' raw data requirements are met with a minimum transducer count and on-vehicle memory capacity. This is illustrated in Figure 1. For example, the on-vehicle processor can insure that the value of some particular parameter is recorded only when it carries some specific significance, or it can determine some critical relationship among several parameters and enter this single result into storage rather than the values of the individual parameters themselves.

Table 1. Vehicle Indicators

Usage Indicators

Engine starts	Engine RPM
Failed starts	Engine overspeed
Push starts	Road speed
Jump starts	Front wheel drive engagement
Cranking in gear	Engine load
Oil Temperature out of range	High Load periods
Ambient Temperature	Terrain exposure
Electrical load	Coasting mileage
Fuel consumption	Total mileage
Parking brake engagement	Brake application
Warm up time	Cool down time
Engine blipping*	Vehicle acceleration/deceleration
Total revolutions	Gear ratios
Clutch operation	Tracked vehicle turning

*Mechanic's term for pulsing accelerator pedal

Table 1. Vehicle Indicators (Continued)

Condition Indicators

Health of -	Fluid Levels -
Starting system	Engine Oil
Charging system	Brake
Fuel system	Coolant
Lubrication system	Electrolyte
Breathing system	Drive train slippage
Cooling system	SI engine firing condition**
	Diesel power**
	Compression balance**

Maintenance Action Input Indicators

Engine Compartment Openings
Action Codes
Component identification codes
Elapsed maintenance time

** Special Tests

Data collected during special tests are obtained by monitoring the same parameters providing data during normal vehicle use. These tests consist of a CI engine power test, an SI engine idle misfire test and a compression balance test, all of which are significant in describing engine condition. They are special in that they require unusual operator vehicle interaction which may not occur during normal operation and, therefore, will be performed by the contact team at the time of data retrieval. The CI power test requires that the engine be brought from idle to governor speed at full acceleration, followed by fuel shutoff while at governor speed; power is calculated from the acceleration and deceleration rates. The SI engine idle misfire test is performed on a warm engine running at idle. The time intervals between 101 successive point openings are precisely measured and misfires are detected from irregularities in these intervals. The compression balance test requires that the engine be cranked while fuel or ignition are "off"; compression balance is calculated from the starter current waveform.

Hardware Overview

Figure 2 illustrates the hardware configuration.

The VMSEA is the core of the system. It interfaces with the vehicle harness assembly which terminates in transducers and switches installed

Table 2. Parameters and Input Channels

System Channel Number	Channel Type	VMS Electronic Assembly	PARAMETER SOURCE — HARNESS ASSEMBLIES: M35A2	M48A3/M60A1	M151A2	M113A1
1	PDIC		Engine RPM	Engine RPM	Engine RPM	Engine RPM
2	PDIC		Road Speed	Road Speed	Road Speed	Road Speed
3	ATIC		Road Speed	Road Speed	Road Speed	Road Speed
4	ATIC		Ignition Switch	Master Switch	Ignition Switch	Master Switch
5	ATIC		Starter Voltage	Starter Voltage	Starter Voltage	Starter Voltage
6	ATIC		Hood Switch	Hood Switch	Hood Switch	Hood Switch
7	ATIC	Clock Trigger				
8	ATIC	Tampering Sw.				
9	ATIC	MAI Connect.				
10	ATIC	DRE Connect.				
11	ATIC	(Spare)	(Spare)	(Spare)	(Spare)	(Spare)
12	SIC		Brake Switch	Brake Switch	Brake Switch	Brake Switch (L)
13	SIC		Park Brake Switch	(Spare)	Park Brake Switch	Brake Lock Switch (LxR)
14	SIC		Front Wheel Dr. Sw.	Turn Switch	Front Wheel Dr. Sw.	Brake Switch (R)
15	SIC		Oil Level	Oil Level	Oil Level	Oil Level
16	SIC		Coolant Level	Engine Oil Overfill	Coolant Level	Coolant Level
17	SIC		Brake Fluid Level	Brake Fluid Level	Brake Fluid Level	Pivoting Brake Fluid Level (LxR)
18	SIC		(Spare)	(Spare)	Choke Switch	Pivoting Brake Switch (LxR)
19	SIC		(Spare)	(Spare)	Fuel Pressure Sw.	(Spare)
20	SIC		(Spare)	(Spare)	(Spare)	(Spare)
21	FADC	Engine RPM				
22	FADC	Road Speed				
23	ADC		Battery Voltage	Battery Voltage	Battery Voltage	Battery Voltage
24	ADC		Battery Current	Battery Current	Battery Current	Battery Current
25	ADC		Alternator Current	Alternator Current	Alternator Current	Alernator Current
26	ADC		Fuel Level	Fuel Level	Fuel Level	Fuel Level
27	ADC		Oil Pressure	Oil Pressure	Oil Pressure	Oil Pressure
28	ADC		Air Filter ΔP	Turbo Pressure No. 1	Intake Manifold Vac	Air Box Pressure
29	ADC		(Spare)	Turbo Pressure No. 2	(Spare)	(Spare)
30	ADC		(Spare)	Air Filter ΔP No. 1	Air Filter ΔP	(Spare)
31	ADC		(Spare)	Air Filter ΔP No. 2	(Spare)	(Spare)
32	ADC-RTD		Engine Oil Temp.	Engine Oil Temp.	Engine Oil Temp.	Engine Oil Temp.
33	ADC-RTD		Ambient Temp.	Ambient Temp.	Ambient Temp.	Ambient Temp.
34	ADC-RTD		Coolant Temp.	Cyl. Head Temp.	Coolant Temp.	Coolant Temp.
35	ADC-RTD		Trans. Oil Temp.	Trans. Oil Temp.	Trans. Oil Temp.	Trans. Oil Temp.
36	ADC-RTD		Diff. Oil Temp. (1)	Final Drive Temp. No. 1	Diff. Oil Temp.	Diff. Oil Temp.
37	ADC-RTD		(Spare)	Final Drive Temp. No. 2	(Spare)	(Spare)
38	ADC-TC		Exhaust Temp. No. 1	Exhaust Temp. No. 1	(Spare)	Exhaust Temp. No. 1
39	ADC-TC		Exhaust Temp. No. 2	Exhaust Temp. No. 2	(Spare)	Exhaust Temp. No. 2
40	ADC-TC		(Spare)	(Spare)	(Spare)	(Spare)
41	ADC-C		Water in Fuel	Water in Fuel	(Spare)	Water in Fuel
42	ELEC		Battery Level #1	Battery Level #1	Battery Level #1	Battery Level #1
43	ELEC		(Spare)	Battery Level #2	(Spare)	(Spare)
44	ELEC		(Spare)	Battery Level #3	(Spare)	(Spare)
45	ACCEL		Vertical Accel.	Vertical Accel.	Vertical Accel.	Vertical Accel.

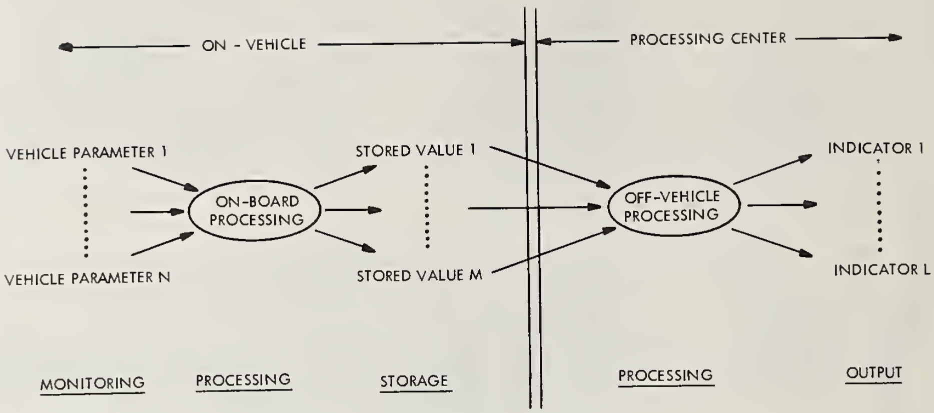

Figure 1. Data Acquisition Process

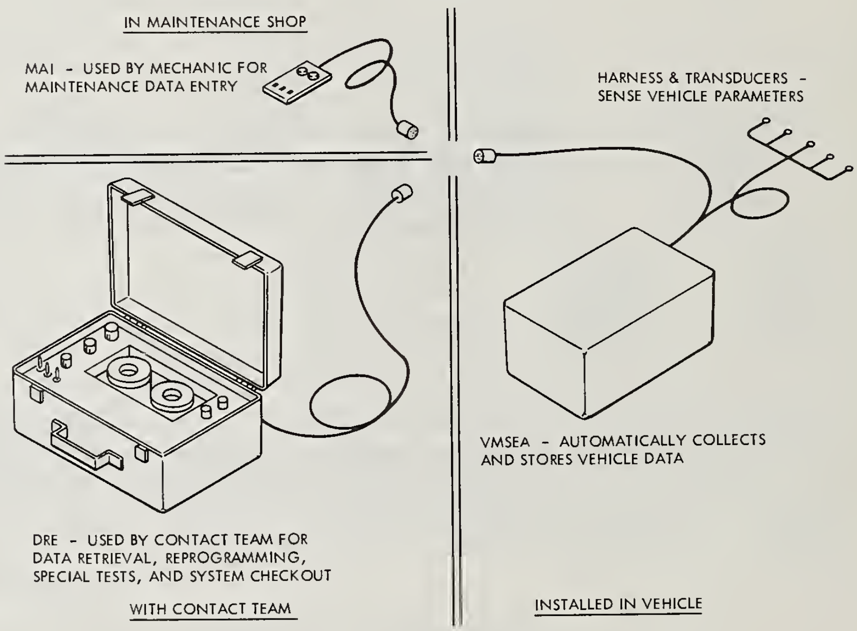

Figure 2. VMS Hardware Configuration

throughout the vehicle. It also interfaces with the DRE/MAI connector which will be mounted at a location readily accessible to the mechanic and contact team.

The MAI device will be a simple hand held unit kept at the vehicle maintenance shop. It will be equipped with three digi-switches via which the mechanic can enter a maintenance action code, a component identification code and the elapsed maintenance time. For example, replace/fuel injectors/thirty minutes = 001/016/030. Lights will be provided to indicate that the VMSEA is ready to accept a code and acknowledges an entry. A small code booklet will be furnished with the device.

The DRE equipment will be housed in a suitcase sized transport case carried by the contact team. It will contain a cassette type digital tape transport to record the data retrieved from the VMSEA memory and to reprogram the VMSEA program memory as required. Controls and a digital display will also be provided to enable the contact team to verify data transfer, determine the health of on-vehicle VMS assemblies and fault isolate as required, and record results of the special tests.

<u>VMSEA Design Features</u>

The VMSEA, from both hardware and software standpoints, is the critical system element. It is being designed for unobtrusive installation in the vehicle, to resist tampering and record evidence of such, and to operate in the environment of the tactical military vehicle with minimum servicing. It will serve its function in any vehicle; only the program instructions in the VMSEA and the harness assembly will be vehicle dedicated. Physical characteristics are presented in Table 3.

The VMSEA will contain an RCA 1802 CMOS microprocessor with 30K bytes (8 bit) of CMOS RAM memory: 12K bytes program memory, 2K bytes scratchpad memory and 16K bytes data storage memory. Signals will enter the VMSEA over forty-five input channels allocated among the four vehicle types as shown in Table 2. Dependent upon the nature of the signals, e.g., switch position, analog voltage, pulse train, they will be inputted through status registers, analog multiplexer to ADCON, or handled on an interrupt basis.

Certain of these inputs are referred to as <u>Action Triggers</u>. The action triggers, which are comprised of vehicle produced stimuli, tampering sensors, an internal clock, or connection of the DRE or MAI, cause the VMSEA to switch between operating modes and/or to record, process and store data.

The operating modes are active, standby, and backup. In the active mode, the VMSEA collects, processes, stores and dumps data as directed by its internal instruction set, action triggers, and commands received from the DRE. In the standby mode, power is applied only to those circuits nec-

Table 3. VMSEA Design Characteristics

Weight

18 pounds

Size

13.5" x 9.2" x 6.8"

Power Consumption (10 to 32 volt input from vehicle)

Standby Mode	-	0.3 watts
Active Mode	-	15 watts
Life on Backup Battery	-	at least two weeks

Environment

Temperature, Operating: -40° to 145°F
Non-Operating: -70° to 185°F
Humidity: 95% condensation, occasional splashings
Altitude: to 15,000 Ft. operating, to 40,000 Ft. non-operating
Vibration: 3G (5 - 500 Hz), 50G (10 - 1500 Hz)

Design Features

Microprocessor:	RCA 1802 CMOS
Memory:	30K Byte CMOS RAM

Flexibility

Programmability:	Program loading via DRE
Expandability:	Two spare boards with power, output channels for transducer conditioning circuitry and memory expansion
Applicability:	Applicable to all vehicle transducer sets

Maintainability

Internal self check with status display to contact team
Isolation to component level replaceable by contract team
No field calibration required

Reliability

Verification of data transfer at retrieval
MIL-STD established reliability parts
MTBF: 1030 Hours (30 months for heavy usage vehicle)

essary to maintain storage and recognize action triggers which switch the VMSEA to the active mode. The backup mode is an emergency mode in which only the clock and memory circuits are powered in the event that prime power, normally drawn from the host vehicle's batteries, is interrupted. The internal battery will sustain the clock and memory for at least two weeks.

VMSEA Data Memory

Major attention has been given to the architecture of the VMSEA data memory. It will be implemented with solid state CMOS devices to take advantage of their reliability and low power consumption. A 16K byte (8 bit) capacity is feasible given the density of current LSI devices and the constraint that the VMSEA be of unobtrusive size. In order to compress all of the significant vehicle data generated during a thirty day interval into this capacity, a scheme has been devised in which a portion of the data, particularly that surrounding a significant event, is retained in high resolution format while all of the data is retained in a "binned" format.

The high resolution format will consist of time-ordered data samples entered into storage at the sampling rate peculiar to each parameter. Engine speed will be sampled at a 0.1 second rate and, in the absence of a uniform acceleration, a time-tagged entry will be made for each 200 RPM change. Should a uniform acceleration be detected, only the end points will be recorded. Engine oil level will be sampled at a much lower rate. The level will be measured following each shutdown and the first "low" indication of the day will be recorded.

The sampling algorithms and high resolution format will permit a detailed reconstruction of the vehicle operating profile when necessary. However, the storage capacity required to retain all data in this format could become unwieldly, particularly in the case of a vehicle exposed to heavy use. The bulk of a vehicle's operating profile can be adequately reconstructed with less temporal resolution. The microprocessor will be used to reduce all data, originally sampled at high resolution rates, to the compact "binned" form.

A "bin" will consist of a reserved memory segment for recording some specific result computed between selectable time limits. The contents of each bin will be a single entry: a count of events, an accumulated time, etc. A typical bin for storing engine speed data will contain the total time that the speed lay between, say, 2000 and 2200 RPM during a specific week. Another example is engine oil level; a bin will contain the number of days that the oil was found to be low during the week. The actual bin structure is more complicated and is designed to extract the maximum information from each parameter. Twenty-five bins will be allocated to engine speed data for a nominal one week interval: (a) total time between

0+ and 400 RPM, (b) total time in 200 RPM increments, 400 to 5000 RPM, (c) number of 400 RPM crossings. The entire bin structure will be software adjustable.

A definite amount of storage capacity, independent of vehicle usage, can be allocated to storing binned data. Once this allocation has been made, the remainder of the memory can be allocated to storing high resolution data detailing some portion of the vehicle's operating profile.

In operation, all sampled data will be both entered into high resolution storage and processed into bin storage. When the memory capacity allocated to high resolution storage is filled, the memory contents will be overwritten on a first in/first out basis; binned data will never be overwritten, only updated. At any given time, the memory will contain all the binned data accumulated since the start of the collection period plus the most recent high resolution data.

The process will continue as described to the end of the collection interval unless some significant event occurs which will cause overwrite to be inhibited. The VMSEA can be programmed so that any event which it can detect can be used as an inhibit trigger; fifteen triggers can be set at any one time. Should overwrite be inhibited by some event, e.g., a mechanic's entry that he replaced the engine, predetermined amounts of high resolution data surrounding the change will be protected.

Figure 3 shows the memory that has been allocated for the different forms of storage. In addition to those discussed, fixed storage areas have been allocated for maintenance action data (forty-eight mechanic entries plus dated detections of forty-eight compartment openings), trip data (a set of eight data entries for one hundred automatically recognized trips), dynamic variables of the VMSEA operating system, special test results and confidence test results.

The 13.3K bytes of data memory remaining after allocation of fixed storage, along with the type of vehicle and the usage which it receives, determines the percentage of total high resolution data generated in a nominal thirty day interval which can be retained. This is summarized in Table 4. The quantitative estimates of vehicle activity were developed by defining use elements - a minimum monthly element, a cruise element, and a tactical off-road element - of specific duration and activity content. The quantity of data produced by each element was calculated and combinations of these elements were used to estimate monthly totals.

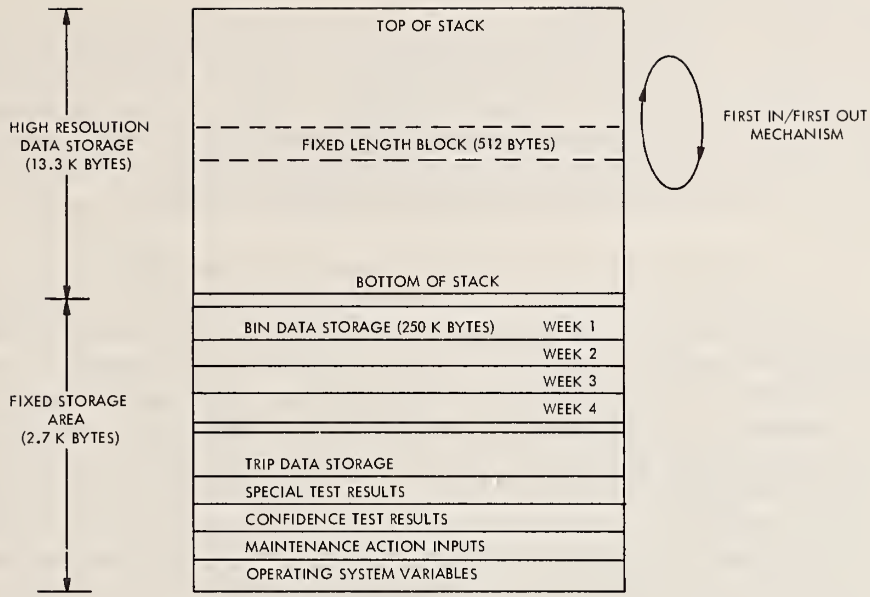

Figure 3. Data Memory Organization

Table 4. Estimated Amount of Monthly Data Retained in High Resolution Format

Vehicle Type and Monthly Use	Hours	Data Generated In Month	Percent Retained In High Resolution Format
Wheeled (M151, M35)			
Light	7.7	9.8K Bytes	All
Moderate	23.4	26.3K Bytes	50%
Heavy	41.7	46.1K Bytes	29%
Tracked (M113, M48/M60)			
Light	0.8	2.9K Bytes	All
Moderate	10.7	15.9K Bytes	84%
Heavy	24.8	33.6K Bytes	40%

Data Memory Size: 16K Bytes (8 bit)
Allocated for High Resolution Storage: 13.3K Bytes

Confidence Tests and Fault Isolation

The VMSEA will conduct routine confidence tests to assess its own health and that of the vehicle harness assembly. Test results will be acquired automatically during unattended operation. The bulk of the data will be stored and transferred to the DRE at data retrieval for forwarding to the processing center. There it will be used to determine long term health and calibration trends, e.g., transducer offset drifts.

A portion of the results will be processed in the VMSEA and stored in a format which can be displayed to the contact team when the DRE is connected. This will enable the contact team to make on-the-spot corrections: replacement of internal battery, entire VMSEA, defective transducer and repair of cables. As a typical example, the DRE might display a code which indicates the presence of a fault in channel 32. The contact team will then substitute a dummy harness assembly for the real one and determine if the fault persists. If it does, the VMSEA will be replaced. If it does not, channel 32 harness wires will be checked and repaired as required. Finally, the channel 32 transducer (oil temperature RTD) will be replaced. Replacement of certain malfunctioning transducers may be beyond the capability of the contact team. In this case, they will call for support.

Program Schedule

The prototype VMS system will be completed for acceptance testing during June 1978. It will then undergo a period of testing on selected vehicles to determine what changes should be incorporated in production units to optimize data acquisition. When finally operational, the VMS is expected to furnish data impacting the design, operation and maintenance policies of military vehicles.

Potential Applications

The VMS is potentially applicable to all classes of vehicles - land, marine and air. The exploitation of microprocessor technology provides flexibility and adaptability through software changes rather than hardware re-design. In addition, it minimizes data memory requirements, thereby allowing the use of relatively small, but relaible and rugged, solid state memories which are well suited to application in hostile and space limited vehicle environments.

Acknowledgement

The authors wish to acknowledge the contributions to the development of the VMS provided by Major T. Covington, ARPA, Mr. D. Sarna, TARADCOM, their staffs and their consultants from Rand and Battelle.

SYSTEMIZED DIESEL ENGINE DIAGNOSTICS

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Introduction

The advent of today's electronic systems brings engine manufacturers and engine owners new concepts which allow non traditional methods for improving engine maintenance techniques. Economics of engine operation and government environmental regulations are additional motivating factors which are influencing the current interest in reducing maintenance costs and improving engine performance. A study of past maintenance practices reveals an inconsistency in procedures utilized for diagnosing engine problems and a pattern of standard repair procedures which are employed when a particular operational problem is reported. The repair procedures generally result in replacement of several engine components without seriously attempting to isolate the faulty component. The basic problem may or may not be solved utilizing these procedures and therefore additional maintenance may be required in a second attempt to solve the problem. These methods are inefficient and costly, a cost which is borne by the owner or a warranty program.

An approach for engine maintenance which shows considerable promise for success utilizes the concept of systemizing the diagnostic procedures for identifying problem causes and directing the mechanic to a particular repair procedure. A system for the maintenance of gasoline engine powered vehicles is now in production. A second generation of this system which is called Autosense[R] has been developed for diagnosing diesel engine malfunctions. The basic Autosense[R] unit is utilized for both the gasoline and diesel engine test systems and therefore minimizes equipment costs because of the economies resulting from fabrication in production quantities. The commercial truck market is the primary market for which the diesel test equipment has been configured. However, the test techniques which have been developed are suitable for application to marine, agriculture, construction, and off-highway diesel engine maintenance.

In addition, since the system is tape controlled its uses are not confined to testing engines. Inclusion of the proper sensors and diagnostic program on tape cassette allows expansion for testing transmissions, vehicles and other types of equipment requiring sophisticated diagnostic procedures.

System Description

The diagnostic system is a computerized tool for fault isolation of diesel engines and their subsystems. It consists of a computer console and a hand held controller. The computer console contains a data acquisition unit, teletypewriter, computer and a tape drive system. The transducer and solenoids for handling pneumatic and hydraulic signals are contained in a transducer box which is mounted to the rear panel of the console (Figure 1). The control program, test sequences, tests, test limits and specifications are contained on a small tape cassette which is placed into a tape reader. Reprogramming of the tape cassette allows for specification changes or expansion for testing additional engines and other types of equipment.

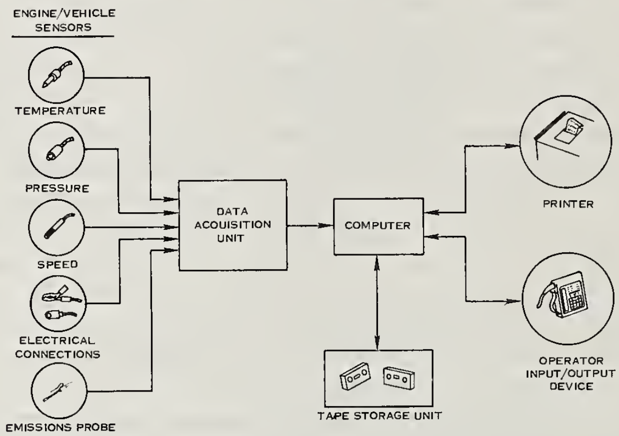

Figure 1. Diesel Diagnostic System Block Diagram

Sensors and sensor location was a significant consideration when configuring the system. The desirability to utilize engine mounted transducers is apparent, however, we selected the approach of using a transducer mounted in an enclosure at the unit. The primary reasoning which influenced the decision was cost, durability and performance of transducers commercially available for the possible applications. If sensors were to be specifically designed for the application, the engine mounted sensors would be preferred.

Operation

The HTS scheme for testing is to perform all tests on the engine without requiring a dynamometer. The non-dyno test techniques are relatively new and can be run quickly in both the steady state and dynamic test modes. A comprehensive approach to diesel engine diagnostics must include the ability to test for particular recurring problems, engine subsystems and individual tests independently. To implement this approach complaint oriented and subsystem sequences have been established which, when selected as the desired sequence for testing, automatically lead the operator through the testing cycle (Figures 2 & 3).

Complaint Oriented

Slow Crank
No Crank
Cranking/No Start
Hard Start - Hot
Hard Start - Cold
Low Power
Miss or Rough Running
Fast or Slow Idle
Smoke
Oil Pressure High or Low
Overheating

Figure 2. Diesel Diagnostic Sequences

Subsystem Sequences

Fuel System
Lube System
Cooling System
Air Intake System
Turbocharger
Air Charging System
Electrical System

Individual Tests (Partial Listing)

Engine Power
Power Contribution
Relative Compression
Blow-By
Gage Accuracies
High & Low Idle
Battery Condition
Fuel Pump Calibration

Figure 3. Procedural Test

The system is designed to diagnose engine problems with test sequences that are executed without external loading of the engine. By analyzing results of several tests a recommendation for a repair procedure is made to the operator.

Low Power Diagnostic

A common complaint of diesel engine operators is low power. An example of a diagnostic sequence for low power with its truth table and repair codes is illustrated in Figure 4. The tests selected for the sequences are listed on the left and the test results, pass or fail, are contained within the matrix. As a result of the engine performance when the diagnostic sequence is run, a pass or fail is recorded for each test. The pass-fail results for an individual test may not reveal the problem by itself. However, when included in a sequence containing the results of several tests, a determination of the problem cause can be established. The sum of the test results in a sequence will refer the operator to a repair code which defines the problem cause and recommends a repair procedure.

TRUTH TABLE

TEST											
COMP	P	F	F								P
POWER	P										
AIR IN FUEL	P			F							
CH PT 2	P				F						
CH PT 1	P										
PEAK PRESS	P						F				
GOV CUT OFF	P							F			
BLOW-BY	P	P	F								
AIR FILTER	P								F		
TURBO	P									F	
POWER CONT	P										F
DIAGNOSTIC CODE	151	152	153	154	155	156	157	158	159	160	161

DIAGNOSTIC MESSAGES

CODE	MESSAGE
151	ENGINE NORMAL
152	VALVE LEAKAGE
153	CYLINDER OR PISTON DAMAGE
154	AIR IN FUEL
155	FUEL PUMP OUT OF CALIBRATION. RUN 928
156	SAME AS 155
157	SAME AS 155
158	SAME AS 155
159	EXCESSIVE INLET RESTRICTION
160	SLUGGISH TURBOCHARGER
161	INJECTOR PROBLEM

Figure 4. Low Power Diagnostic

<u>Horsepower</u>

The horsepower test is a dynamic test developed for the diesel diagnostic system (Figure 5). Data are gathered during the free accel mode of engine operation. During a full throttle acceleration, the engine accelerates with its own inertia as a load. Torque is determined by the rate of acceleration times the engine inertia, $T = I\alpha$. Horsepower is obtained from the torque at any speed, $HP = KTN$. Actually, the torque generated during the accel is related to the specified torque, and by applying an algorithm developed for this purpose, torque which the engine is capable of producing can be determined.

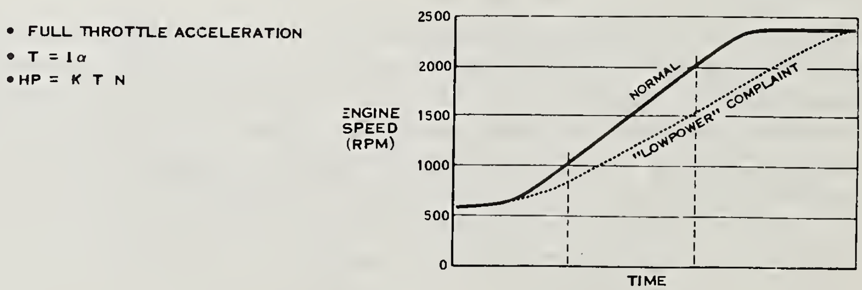

Figure 5. Diagnostic Techniques - Power

Turbocharger

Tests such as the turbo tests do not require full loading but do require a snap accel from idle to high idle and a hold at high idle for about five seconds (Figure 6). During the snap, inlet manifold pressure data are collected which when compared with previously established dynamic limits provides an assessment of turbo condition. The characteristics of turbo performance which are used in the analysis are the inlet manifold pressure depression, time of depression, pressure rise as a function of time and max value of inlet manifold pressure.

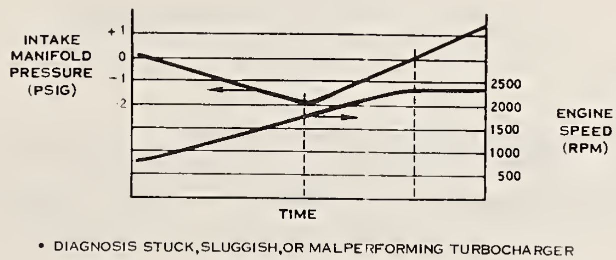

Figure 6. Turbocharger Health

Cylinder Health

A sound indicator of cylinder health is the relative compression test (Figure 7). By monitoring the battery current drawn during engine cranking, an evaluation can be made as to the work required during compression for each cylinder. By selecting the cylinder requiring the most work for compression and comparing that with the work required during the compression stroke for each of the other cylinders, an evaluation of relative compression can be established.

This test in itself will not identify the fact that a valve, ring or piston must be replaced. However, if other tests such as blow by are run in conjunction a more definite analysis can be concluded. The system output can, therefore, differentiate between ring/cylinder problems and valve and gasket problems.

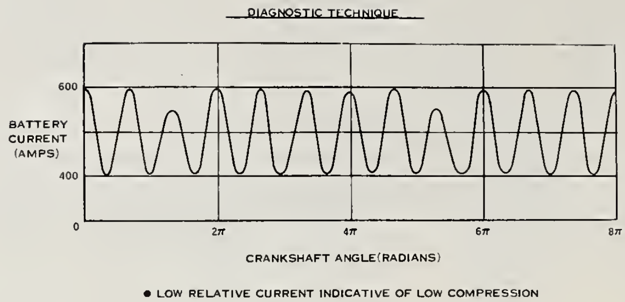

Figure 7. Relative Compression

Fuel Pump Calibration

A calibration check of the Pressure-Time (PT) type fuel pump can be achieved by sampling fuel pressure at predetermined reference points during a snap acceleration of the engine. These results contribute significantly to analysis of fuel system and low power complaints (Figure 8).

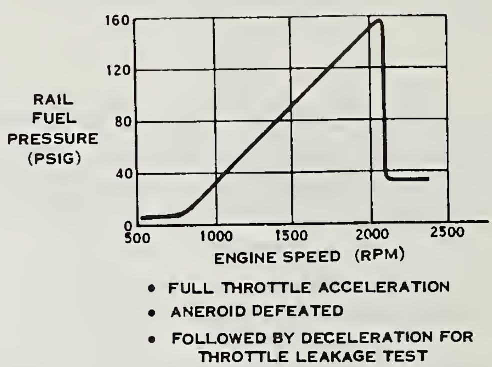

Figure 8. Fuel Pump Calibration

Lubrication System

By locating a transducer at a point downstream of the pump and regulator but before the oil filter, an assessment of the lube system can be determined. During a snap accel the pressure can be tracked and the time to reach regulation and the regulation pressure can be established

(Figure 9). This information, when compared with functional data from a properly operating system, can be used to determine pumping performance, regulation, lube system flow capacity, and in some systems, the point when piston cooling commences.

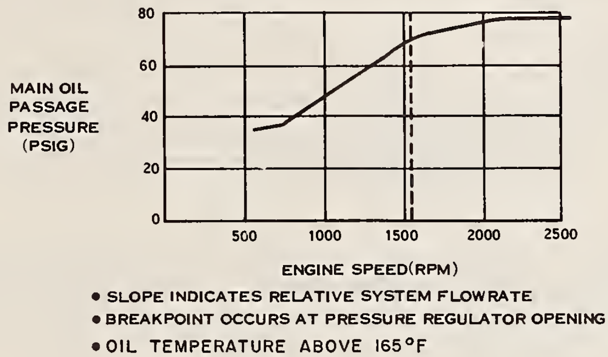

Figure 9. Lubrication System Criteria

Lube system flow capacity can indicate a stoppage in flow passages. This may mean a clogged filter or passage.

Relative Power Contribution

The relative power contribution test is one in which the power being delivered by each cylinder is determined and compared against the power being contributed by each of the other cylinders. The cylinder found to be delivering the most power is rated 100 percent and each of the other cylinders is compared to it in percent of power contribution (Figures 10a & 10b).

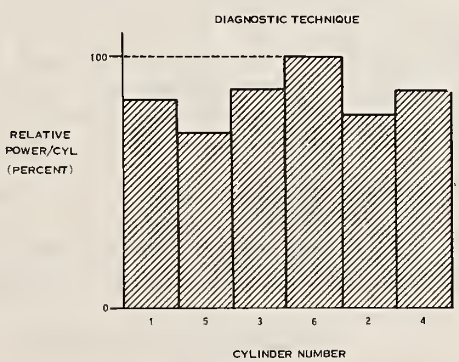

Figure 10a. Power Contribution

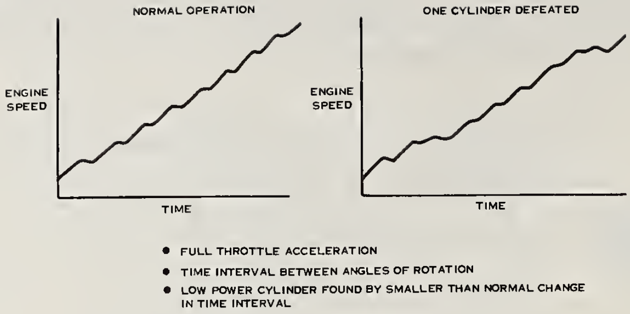

Figure 10b. Diagnostic Technique - Power Contribution

Cooling System

The cooling system diagnostics presents some interesting problems which do not enter into diagnostics of other engine elements. This is due to the fact that the engine cooling system is not complete in itself. It must interface with a radiator or cooling system which is not provided by the engine manufacturer. At this time the cooling system discussion pertains to the engine cooling system and most of the testing will be completed with the thermostat closed.

The use of one pressure transducer and one temperature sensor can provide data to determine general system characteristics. The use of a second pressure transducer will allow for further analysis.

Using a pressure sensor and a temperature sensor just upstream of the thermostat and running the engine at idle and high idle, thermostat operation, pump performance and shudderstat sequence operation can be determined, and whether the thermostat is functioning properly. Also, by running the engine at idle and high idle with the thermostat closed, an indication of pump performance can be determined (Figure 11).

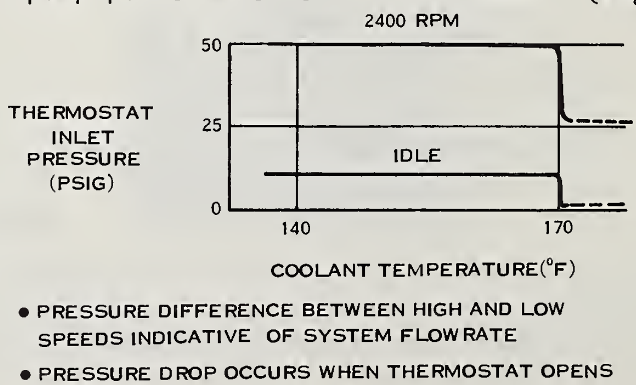

Figure 11. Cooling System Criteria

Diagnostic System/Engine Interface

The time required for making the necessary engine connections for diagnostic testing is an important consideration which has a significant impact on total test duration. Total test duration is that time required to connect signal lines to the engine, conduct the test and disconnect from the engine.

Electrical connections consist of attaching metal clips to various locations in the electrical system. These connections are made quickly and easily. The hydraulic and pneumatic connections are more time consuming to make unless a quick disconnect method is utilized.

On the initial testing of the engine male quick disconnect fittings are installed at the desired locations on the engine. These fittings remain on the engine to minimize set up time for future diagnostic testing. The diagnostic system is equipped with mating quick set up time that can be reduced further by manifolding all hydraulic and pneumatic signals to a conveniently located panel (Figure 12). To implement a manifolding scheme cooperation is required by the engine and vehicle manufacturers and the vehicle owner.

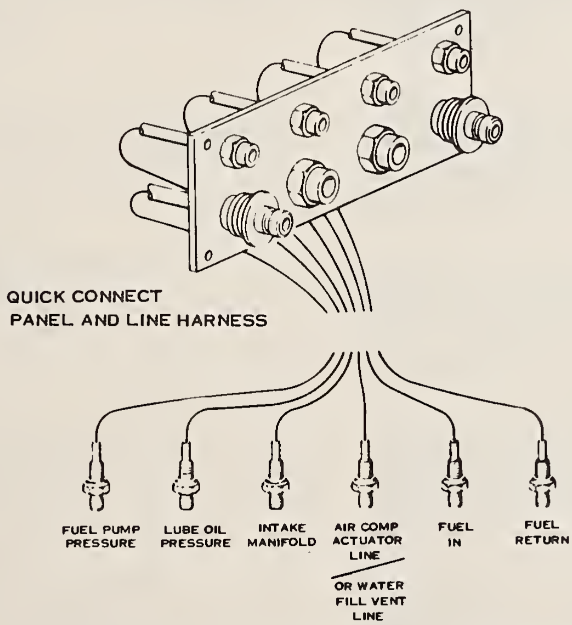

Figure 12. Installation Interface

Summary

The implementation of a diagnostic product requires an awareness of what diagnostics are and the depth of diagnostic penetration desired. The following is the diagnostic definition which best describes the HTS approach:

> Diagnostics are those methods used to isolate causes for performance and hardware malfunctions in engine systems. The diagnostic objective is to isolate faulty subsystem components involved in malperformance or failure so that repair is direct and accurate.

Therefore, diagnostics (fault finding) has the objective of isolating internal faults. Overall performance is not the governing criteria but is used as an indicator to determine faults.

The diagnostic system then provides for the profit conscious user a tool which will enhance his ability to increase engine productivity, reduce maintenance costs and effect a savings in warranty costs for the engine manufacturer.

To configure the diagnostic system and establish diagnostics the manufacturer must comprehensively utilize mechanical, hydraulic, pneumatic, electrical and electronic technologies together with a strong systems engineering effort.

MECHANICAL FAILURES PREVENTION GROUP

26th Meeting

Detection, Diagnosis and Prognosis

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APPENDIX

REMOTE DIAGNOSTIC TECHNIQUES
USED IN VIKING LANDER OPERATIONS*

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Abstract: The problem of monitoring performance and diagnosing malfunctions on the Viking Landers while operating on the Surface of Mars was complicated by severe data rate and volume restrictions. This paper describes the combination of flight hardware, flight software and ground operations software used for planning, prediction and telemetry data analysis functions which allowed the Viking Flight Team to successfully operate the landers for a combined 548 Martian days to date although many malfunctions have occurred. To illustrate the use of this system, a specific anomaly is discussed in detail.

Summary of the Problem

The design of the Viking Landers and their subsequent operations on the Martian surface have been greatly constrained by the distances over which the radio signals must travel and the limited view periods which are available.[1] The round trip light time from Earth to Mars to Earth is approximately 40 minutes at distances of approximately 220 million miles. Each lander has a view period to Earth of about 10 hours, and although the Earth can view Mars nearly continuously through the Deep Space Network Stations at Goldstone, California; Madrid, Spain; and Canberra, Australia; these stations must be shared between the two landers, the two orbiters and other projects such as Helios, Pioneer, and Voyager. These constraints coupled with antenna size restrictions and electrical power limitations of the spacecraft, combine to produce very low rates and low total volume for data return when compared to

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*This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS7-100, sponsored by NASA.

[1]This paper will address certain aspects of operating the Viking Landers on Mars from July 20, 1976 through May 19, 1977. The interplanetary cruise phase (while the landers were attached to the orbiters) and the descent to the Martian surface will not be discussed, although many of the same points apply.

earth based on near-earth telemetry systems. In order to maximize scientific data return, engineering data required to assess proper operation or diagnose malfunctions was kept to a minimum. Therefore, the Viking Flight Team was faced with a difficult challenge in attempting to deal with the following questions:

1. How could the lander performance be monitored so that malfunctions could be detected quickly and with a high probability?

2. How can problems be anticipated and prevented?

3. How should problems be corrected once they are discovered to prevent compounding the problem by acting hastily or conversely waiting too long to respond?

The lander system designers provided capabilities within the landers which allowed these questions to be answerable. The most important capabilities derived from the redundancy requirement of the Viking Project Specification which states,

> "No single malfunction shall cause the loss of all data return from more than one science investigation or the loss of all engineering data."

As a result of this directive, the landers were designed to have parallel or block redundancy, or alternate functions for every critical component. In addition, fuses and automatic safing modes were provided to isolate malfunctions to a specific component and terminate operations of that component until the VFT could reconfigure the system via commands from earth. As a result, the lander could be expected to survive until the corrective action could be taken, which could be no faster than 40 minutes and more typically several days. The remainder of the diagnostic capability required to answer the questions is provided by the lander telemetry subsystem, the operational planning and performance prediction techniques used by the VFT, and the telemetry data analysis conducted by the VFT, which are summarized in the following sections.

Figures 1 and 2 are provided for reference in these discussions. Figure 1 shows the lander functional block diamgram, including cruise and entry subsystems. Figure 2 is a sketch of the lander after it is deployed on the surface of Mars.

Telemetry/Communications Description

The communication links to a lander are depicted in Figure 3. Earth can communicate to the VL through the direct link (S-band) at 4 bits/second. The lander can return data over the direct link at 250, 500, or 1000 bits per second on the "high-rate" subcarrier and at 8-1/3 bits/second over the low-rate engineering subcarrier. The primary downlink method is the relay link (UHF) through which the lander can transmit data to either of the two orbiters (when they are in view) at 16000 bits/second. The orbiter stores the data on its tape recorder for transmission to earth typically a few hours later.

The data is gathered on the lander by the Data Acquisition and Processing Unit (DAPU). The DAPU either provides the data directly to the UHF or S-Band systems for real-time transmission, or stores it into the Data Storage Memory (DSM) or on the tape recorder for later transmission. All of these modes are controlled by sequences stored in and executed by the Guidance Control and Sequencing Computer (not shown) which issues commands to all other VL components to acquire, transfer and transmit data. The types of data that are collected are shown in Figure 2. The System Test Equipment interface was not used after launch nor the Viking orbiter interface after VO/VL separation. Each of the science instruments supply data in frames of various lengths to the DAPU. These data contain measurements pertinent to the instrument hardware status (current, voltage, temperature, mode discretes, etc.) as well as the desired scientific information. No on-board diagnostic processing of these data is done. The GCSC provides readouts of selected portions or all of its memory (up to 18432 twenty-four bit words) when scheduled in its stored sequences. This memory readout contains important information for status monitoring and diagnostic analysis such as: a count of the number of commands received from earth, the values of all sequencing times and subsystem commands which have been or will be issued until modified by the next earth uplink, all instructions of the flight program, and a table called the R1 table, which is a record of the last 2000 commands and the times that have been issued through GCSC register R1 to all science instruments and the DAPU. The R1 table typically spans the last 3 to 6 days of operation.

The engineering data collected by the DAPU for landed operations (exclusive of the science and GCSC data) is formatted into two formats (termed Format 4 and Format 5). Format 5 consists of frames of 768 bits containing 79 different measurements. Format 5 is designed for continuous data acquisition during direct links although it is occasionally used at other times and recorded in the DSM or directly to the tape recorder. Format 4 consists of frames of 768 bits and contains 74 measurements. It is collected one frame at a time and is scheduled by the GCSC to provide spot sampling throughout the day between downlinks. The engineering formats (1, 2, 2A, 2P, and 3) used prior to landing are continuous formats and were constructed similarly to Format 5 but contained other measurements pertinent to those phases. All engineering formats are time-tagged by the GCSC software clock, (except the cruise Format 1 which used earth received time).

The normal method of data collection used during the landed mission is to store all data except imaging and Format 5 to the DSM. The DSM holds

196608 bits and when it fills, the DAPU issues an interrupt to the GCSC causing the GCSC to command the DAPU to dump the DSM contents to the tape recorder. In this way runup and rundown of the tape recorder is minimized. Imaging and Format 5 may be written to the DSM at 8-1/3 bits/second for special purposes. Normally, imaging and Format 5 are put out directly to the UHF or S-Band links or written directly to the tape recorder. GCSC data is always transmitted real-time over the links.

Table 1 illustrates the data content of a typical relay link and a typical direct link. During its primary mission a lander would have a relay link every Martian solar day (1 SOL = 24 hours 39 minutes) and a direct link every other SOL. During the extended mission (after November 1976) the typical data return is two relay links and two direct links per lander per week.

The Planning/Prediction Process

A fundamental prerequisite to proper performance monitoring or diagnostic analysis of an operating system is to understand thoroughly what the nominal performance will be. Particularly in a system such as the Viking Lander where the visibility into operating characteristics is limited by the small data volume and intermittant data samples, the prediction must be as complete and accurate as possible. Furthermore, if the operating environment is unknown or unpredictable with time, the prediction system must be constructed so that the new information from telemetry analysis may be factored in.

The Viking Lander Mission Operations software system was designed according to these concepts. Figure 5 shows the uplink preparation software which is run in order to implement and verify a segment (typically 6 to 10 SOLs) of the lander mission. The events leading up to and the overall strategy employing this software system are discussed in reference 1 and will not be repeated here. However, the simulation and prediction functions used for performance monitoring and diagnostic analysis will be discussed.

LSEQ (Lander Sequence of Events) generates a sequence of events at a one-second granularity from user level inputs (1)* (i.e., time and type of pictures to take, duration of relay link, meteorology sample number and duration). It is a functional simulation of the VL data generation

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Reference 1: Lee, B. G. and Porter, Dr. J. D.; Design and Implementation of Viking Mission, AIAA Paper No. 77-270, January 10, 1977.

* The numbers in this discussion refer to the numbered points in Figure 3.

subsystems and the on-board GCSC software. It provides a sequence of events listing and discrete events file (2, 4, 8) for use by other programs, a detailed prediction** of all data to be returned (10) on each scheduled downlink, and saves a map of the DSM and tape recorder contents.

The LSEQ sequence of events is also passed to the COALES (Combined Orbiter Lander Sequencing) program to generate the operational timeline for mission controllers and DSN personnel (9). LCOM (Lander Command) generates from the LSEQ files a Hamming Coded message file which will be transmitted to the appropriate lander after the verification process is complete. LCOMSM (Lander Command Simulation) is a complete bit-for-bit model of the GCSC and contains the flight program which executes the planned mission period in the ground computer system at JPL. This program produces a listing of all GCSC input/output to the millisecond level which it compares to the LSEQ predicted events (3), thus verifying that the flight software after receipt of the command file will execute the planned sequence. In addition, it creates a file of what the GCSC memory readout data will contain during the direct and relay links.

Power management on the lander is a significant problem because the Radio Isotope Thermal Generators only provide about 80 watts of power to recharge the 4 lander batteries, although the system loads may reach peaks of 400 watts. The LPWR1-LTEMP-LPWR2 program set allows this problem to be analyzed prior to committing the vehicle to sequences which may totally discharge the batteries or thermally stress components. LPWR1 (4) converts the LSEQ sequence of events into a predicted system load (watts vs time) which LTEMP uses to predict lander temperatures at about 400 nodes within its thermal model. Since some components have thermostatically controlled heaters or temperature sensitive efficiency, LTEMP provides the predicted thermal history back to LPWR (6) for the final energy balance prediction. From these programs, the values of all lander temperature measurements and the system voltage/current measurements may be predicted. Various mode discretes (tape recorder on, etc.) are also related to these predicts.

Two other programs, LDLINK and RLINK, are used to predict direct and relay link communication performance.

From the products of these programs, it is possible to predict every command which will be generated on board the VL if the sequence is executed nominally, the amount and type of data vs time is known, the RF signal strength of each is known, and a complete power and thermal

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**The data type and volume is predicted but the value of each individual measurement is not.

history is available. The factors which cause deviations from these predictions are caused by planning errors, changes in the Martian environment, or hardware degradation. It is the task of the downlink analysis people to find these factors.

Downlink Analysis Process

The downlink data from one of the spacecraft are received at a DSN station and transferred via high speed data lines to the Jet Propulsion Laboratory where it is processed and displayed. Figure 6 illustrates this system. The TLMP program operates on the data real-time and provides decommutated data to the Ground Display video tubes. Real time operations personnel monitor this data for quick-look status as it is received. Important measurements are bounded by alarm limits which will flash a warning if they stray outside of limits so that the monitor person can notify other analysts of problems quickly. For routine analysis, typically the next day, the data is run through DECSET to product prints and plots of all engineering data. DECSET strips out all science data by type and provides files to each science team for analysis using their software. DECSET compares the GCSC memory readout to the predicted memory readout from LCOMSM and generates a list of non-compares which are later analyzed by Flight Software experts for anomalous conditions. The R1 table previously described is provided in this printout and may be compared against the LCOMSM discrete event listing in problem diagnosis. The system data record from TLMP is also run through a program called Mark IV which provides a frame by frame listing of all data received. This listing is useful in checking tape recorder performance and to insure consistency between the planning-LSEQ data prediction process and what the vehicle actually returns to earth.

Although it is not shown in Figures 5 or 6, both LPWR and LTEMP are capable of reading files of downlinked power and temperature data to use in comparison with the predicted values. In doing this, the analysts may refine their lander models of these functions to either upgrade accuracy or account for changing Martian environments. This is especially important in thermal predictions since they are affected by the optical depth of the sky, the Mars-Sun distance, time of year, winds, and dust coating on lander surfaces.

Laboratory Support

Two important laboratories were used during Mission operations for prediction, analysis, and diagnostic purposes. The first was located at Martin Marietta in Denver and was connected to JPL by high-speed data lines. The facility contained a complete real-time simulation using guidance and control hardware and flight software which was used to verify the landers descent trajectories prior to separation. For cruise and landed operations the Proof Test Capsule (PTC) was used to checkout sequences and analyze unusual hardware modes of operation. The PTC is a complete functional lander using qualified flight hardware, but connected to the ground checkout system. This laboratory was useful in verification of flight software changes and diagnosis of the battery charger failure that occurred during interplanetary cruise.

The second laboratory is located at JPL and contains a full-size mockup of the lander with actual flight-type cameras, surface sampler and X-ray, GCMS and Biology soil inlet systems. This lab is still in use for design and verification of all surface sampler sequences. Since the lander views Mars non-linearly through its cameras, it is not a straight forward process to acquire a soil sample at a specific location. The sequence of commands (extend, elevate, azimuth, rotate, vibrate, etc.) that the surface sampler needs can be worked out using this mock-up and the Martian surface as modeled from lander pictures. Then if the real VL surface sampler has a "no-go" either due to hardware malfunction or unexpected environmental factors, a detailed sequence baseline has been established for failure analysis. This laboratory was essential during operations and allowed quick recovery from several surface sampler problems.

Analysis of an Anomaly

On January 19, 1977, the Lander Performance Analysis Group DECSET analysts, H. Fuquay and J. Murphy, noticed that the VL-2 SOL 131 relay link (which had been processed the previous night) did not contain all the meteorology data that had been predicted. In reviewing the Mark IV listing of all data frames received it was quickly determined that the meteorology instrument had stopped providing data on about SOL 130, 13:42 local lander time. Management was quickly notified and an anomaly meeting convened. At that meeting it was apparent that all the prediction products had not yet been compared to the downlink received so the meeting was adjourned after an action item list was generated aimed at localizing the problem, with a status report meeting scheduled for 9 a.m. the next day, January 20. In the meantime, the SOL 132 relay link DECSET run had been completed and found to contain no new meteorology data. Figure 7 shows a timeline of VL-2 downlinks during this period.

However, in reviewing the LSEQ-LCOMSM predictions versus the data received from the Mark IV listing and the R1 table from the GCSC, R. Bender, the LPAG Deputy Chief, found the cause of the problem in a few hours of analysis and discussion with subsystem experts. Figure 8 shows the predicted versus actual timeline. The actual downline confirmed the predictions exactly until 14:03:49 when the DSM filled and was dumped to tape. This dump occurred about 30 minutes earlier than predicted. It was followed by a Format 4 to DSM which is always done automatically by the flight software to mark the start of data in the DSM since all the science data is not time-tagged. Then the low rate format 5 to DSM continued and all further sequencing was normal except no meteorology data was collected, indicating that either the instrument had failed or its data collection electronics was struck.

Using the Mark IV listing which provides a bit-by-bit accounting of data received, R. Bender was able to construct the timeline of Figure 9. This figure shows that when the Format 5 to DSM at 8-1/3 mode was started, the DSM contained 189288 bits. At 190464 bits the DSM/DAPU generates an interrupt to tell the GCSC "I am nearly full, dump me to tape". However, from discussions with the LPAG telemetry subsystem analyst, C. Seese, it was found that the DAPU would not generate the interrupt until the mode in process completed (at 14:03:48 on the timelines). In the meantime, the GCSC had received an interrupt from the meteorology instrument at 13:57:33 saying "my buffer is full, dump me to the DSM". However, the GCSC says to itself, "the DAPU is busy putting Format 5 in the DSM, I will hold the MET request until Format 5 is done". At 14:03:48 the GCSC then terminates the Format 5 to DSM mode by issuing the command to dump MET to DSM. Milliseconds later, the GCSC received the request from the DAPU to dump the DSM to tape which the GCSC issued at 14:03:49, allowing the standard 1 second for the MET data transfer to complete. However, the MET data frame is long enough to overflow the DSM past its upper limit, 196608 bits, at which point the DSM automatically puts the DAPU to standby, terminating the data shift pulses to the MET instrument before the 5156 bit frame is totally transferred. Since the MET instrument resets its "data ready" flag after the transfer is complete, it is hung-up waiting for a shift pulse which never comes. The GCSC never receives another MET data ready to command a MET dump to DSM, so MET is forgotten. The hardware design characteristics were confirmed through discussions with MET instrument engineers and DAPU/DSM engineers and the flight software operation reviewed with the Lander Command and Sequencing analysts, S. Lowrie and J. Kerekes, so R. Bender's diagnosis was complete.

The next step was to design the recovery plan. In this condition, the MET engineers and LPAG power analysts confirmed that only 3 to 6 watts extra power was being consumed. This level was to small to be of concern to loss of battery capacity and it was confirmed by comparison of LPWR predicts to downlink measurements on the SOL 132 relay link that an additional power load of this size was present. The temperature increase was too small to be detectible by LTEMP/downlink comparisons. There was no critical concern to lander safety, however, the meteorology science team wanted to reinitiate data collection as soon as possible. By this time it was Thursday morning, January 20, and too late to command the lander via the SOL 134 direct link. It was decided to build another separate command fild for the SOL 137 uplink already scheduled for Saturday, January 22. The solution was to simply issue via real-time command, the GCSC to DAPU command to dump MET to DSM. Low rate format 5 to DSM data collections which did not have a DSM to tape dump commanded immediately before them were eliminated to prevent recurrence of the problem.

This anomaly was an interesting test of the VL data monitoring and analysis system because it was very subtle and used most of the prediction tools. Normally, a problem such as this would have been caught by the real-time analyst monitoring the SOL 131 relay link. Unfortunately, due to a problem at the DSN station, a portion of the relay link data was lost between the station and JPL and had to be recalled which usually takes 1 to 2 days. Since the analyst did not receive all the planned data, his analysis of data received versus predicted (total frame counts) was incomplete, but agreed closely enough that he did not suspect a lander problem. The SOL 131 direct link contained a DSM dump which would have shown no MET data, but since it is the first 1K data received on the ground in a direct link, it is usually not acquired for the first 5 minutes, and in this instance, worse than that. Therefore the problem was obscured again. It was caught by the DECSET analyst very early in his process of evaluating the SOL 131 relay link results. If he had missed it, it would have been caught by either the meteorology team or the LPAG tape management analyst in later reviews.

The second interesting aspect of this problem is that it is not a hardware failure (the hardware has operated perfectly since the command fix) but a system design deficiency which excaped detection through extensive pre-launch testing and never occurred in mission operations for 175 SOLs of VL-1 and 130 SOLs of VL-2 operations. It only occurs when the DSM is used for continuous data collection (normally imaging or format 5) and would not be a problem if the DAPU issued the GCSC interrupt immediately rather than at the completion of the mode. Since it is inherent in the hardware design, the Lander Command and Sequencing team has had to work around it by taking the following actions:

1. LSEQ has been upgraded to model all data. The reason the DSM dump occurred early was that the Format 5 to DSM during ranging in the direct link was not modeled by the SOL 130 version of LSEQ.

2. Whenever low rate continuous data is put into the DSM, it is dumped just prior to initiating this mode and the data volume checked to be less than 190,000 bits.

3. If (2) cannot be done, the science instrument buffers are dumped after completion of the continuous mode to remove any unexpected hangups.

4. The real-time operations personnel have been instructed to check downlink time tags of science data to insure no instrument has

stopped. (This cannot be done for XRFS, GCMS or Biology, since they do not time tag their data).

Conclusions and Recommendations

This paper has attempted to illustrate how diagnostic failure analysis is applied to the Viking Landers operating on the surface of Mars over 220 million miles from earth using a very constrained telemetry return. At the date of this writing, Lander 1 has operated for 296 SOLs and Lander 2 for 252 SOLs (1 SOL = Martian day of 24 hours 39 minutes) and achieved all major science objectives planned before landing. Between them, the landers have experienced 23 major problems all of which were detected quickly by the Viking Flight Team and all of which were corrected in time spans of 2 to 7 days, resulting usually in minor data loss or delay of plans.

The system used to detect these problems and continue mission operations is a complex ground and flight hardware and software system summarized herein which requires expert and dedicated people to operate. The Viking Flight Team was made up of this type of people, most of whom had been hand-picked from the design development and test teams who put these systems together. Most projects having a similar remote diagnostic task will not have this luxury, either due to cost, or because normally the system designers are not involved with the operation of the system after it is delivered. Therefore, it is of interest to discuss the strengths and weaknesses of the Viking system.

First, in order to do remote performance monitoring and diagnostic analysis an accurate prediction system is required. This was achieved on Viking through use of ground computer simulations which ultimately performed very well. However, the development of this system was more expensive than need be because of the following factors:

1. The flight software for the lander computers was developed as an independent program until launch (when it came under control of the Flight Team) making the command software (LSEQ, LCOM/LCOMSM) difficult to design.

2. The data system was not standardized, and was difficult to obtain modeling information for. All science data had different formats, different frame lengths, and several did not time tag their data. This complicated both the prediction and downlink analysis software and caused many uncertainties in analysis.

3. Some of the science teams had not designed their software requirements to include all the modes of operation they intended to use so the ground software could not model these modes, necessitating changes "on the fly" during operations.

Second, in order to optimize data return for science, engineering data return was kept at the minimum required for nominal performance monitoring. This could have been alleviated by making more use of dual channel transmission and recording, one low rate channel for engineering and high rate channel for science. The Viking orbiters made much better use of this approach than the landers.

The Viking lander data system, on the other hand, had a near optimal design for maximization of data return over constrained downlink opportunities. After LSEQ modeling was shown accurate enough, tape recorder content could be predicted to less than 15 seconds out of 40 minutes record time at 16000 bits/second. Therefore, the downlink could be designed to contain a minimum of "margin" of filler data. This was accomplished by buffering each instrument so that it did not have to be serviced immediately when it had collected data, by using the DSM as temporary storage and the tape recorder as long-time storage. Data could be saved on the tape for several downlinks and played back later; however, the engineering data for status monitoring would be delayed with it. This collection technique allowed many experiments to run and collect data simultaneously with a minimum of interference and conflict resolution.

It is a very useful technique for diagnosis to record on-board all commands (and their times) issued by the on-board computer. This technique was partially developed on the VL but could have been enhanced by including all commands and doing an automatic compare of predict vs actual results.

Finally, it is desirable to automate the prediction versus actual data comparison as much as possible to reduce operation at manpower and increase the probability of detection of malfunctions early. The Viking Lander process was semi-automated but required expert review of all results. Standardization of the data system and the ground processing software files and timing could have allowed simpler compare processes with more automatic discrepancy detection.

TABLE 1

TYPICAL RELAY AND DIRECT LINK CONTENTS

A. SOL 281 Relay Link (VL-1 to VO-1)

Format	Frames New	Old	Wrap	New Data Percent of Total
4	444	58	43	2
5	630	19	21	2
SSCA	41	0	0	.02
BIOL	21	2	1	.2
MET	660	113	22	16
XRFS	1134	118	50	2
IMAGE 1	3549	0	0	55
IMAGE 2	1200	0	0	18
GCSC	296	0	0	4

Mission Period Recorded SOL 276/13:30:00 to SOL 281/11:50:00
Efficiency = New Bits/(Total Bits) = 96%
Total Data Returned 22611333. bits
Link Duration 25 minutes 52 seconds

B. SOL 283 Direct Link

Format	Frames New	Old	Wrap	Comment
4	37	0	46	DSM Dump Usually Lost
MET	32	0	64	DSM Dump Usually Lost
5 (Hi)	37	0	46	DSM Dump Usually Lost
GCSC	253	0	0	
5 (Lo)	15	0	0	93 Seconds Between Samples

Mission Period: Real Time SOL 283/17:20:00 to SOL 283/17:44:00
Total Data Returned 1189376. bits

ABBREVIATIONS

bps	- bits per second
COALES	- Combined Lander Sequencing Program
DAPU	- Data Acquisition and Processing Unit
DECSET	- Downlink Decommutation Decalibration Set program
D/L	- downlink to earth from VL
DSM	- Data Storage Memory
DSN	- Deep Space Network
FOVLIP	- First-order Viking Lander Imaging Program
GCMS	- Gas Chromatograph Mass Spectrometer
GCSC	- Guidance, Control, and Sequencing Computer
HGA	- High Gain Antenna
IRU	- Inertial Reference Unit
JPL	- Jet Propulsion Laboratory
LCOM	- Lander Command Program
LCOMSM	- Lander Command Simulation Program
LDLINK	- Lander Direct Link Program
LGA	- Low Gain Antenna
LPWR	- Lander Power program
LSEQ	- Lander Sequence of Events program
LTEMP	- Lander Temperature program
MET	- Meteorology Instrument
MV	- millivolts
PCM	- Pulse Code Modulation
PTC	- Proof Test Capsule
R1	- Register 1 of the GCSC
RLINK	- Relay Link program
RPA	- Retarding Potential Analyzer
RTG	- Radio Isotope Thermal Generator
SOL	- Martian mean solar day (24 hours, 39 minutes, 35.25 seconds)
TLMP	- Telemetry program (Lander real-time)
UAMS	- Upper Atmosphere Mass Spectrometer
UHF	- Ultra-High Frequency
U/L	- Uplink to VL from earth
V	- volts
VFT	- Viking Flight Team
VL	- Viking Lander
VO	- Viking Orbiter
W	- watts
XRFS	- X-Ray Fluorescence Spectrometer

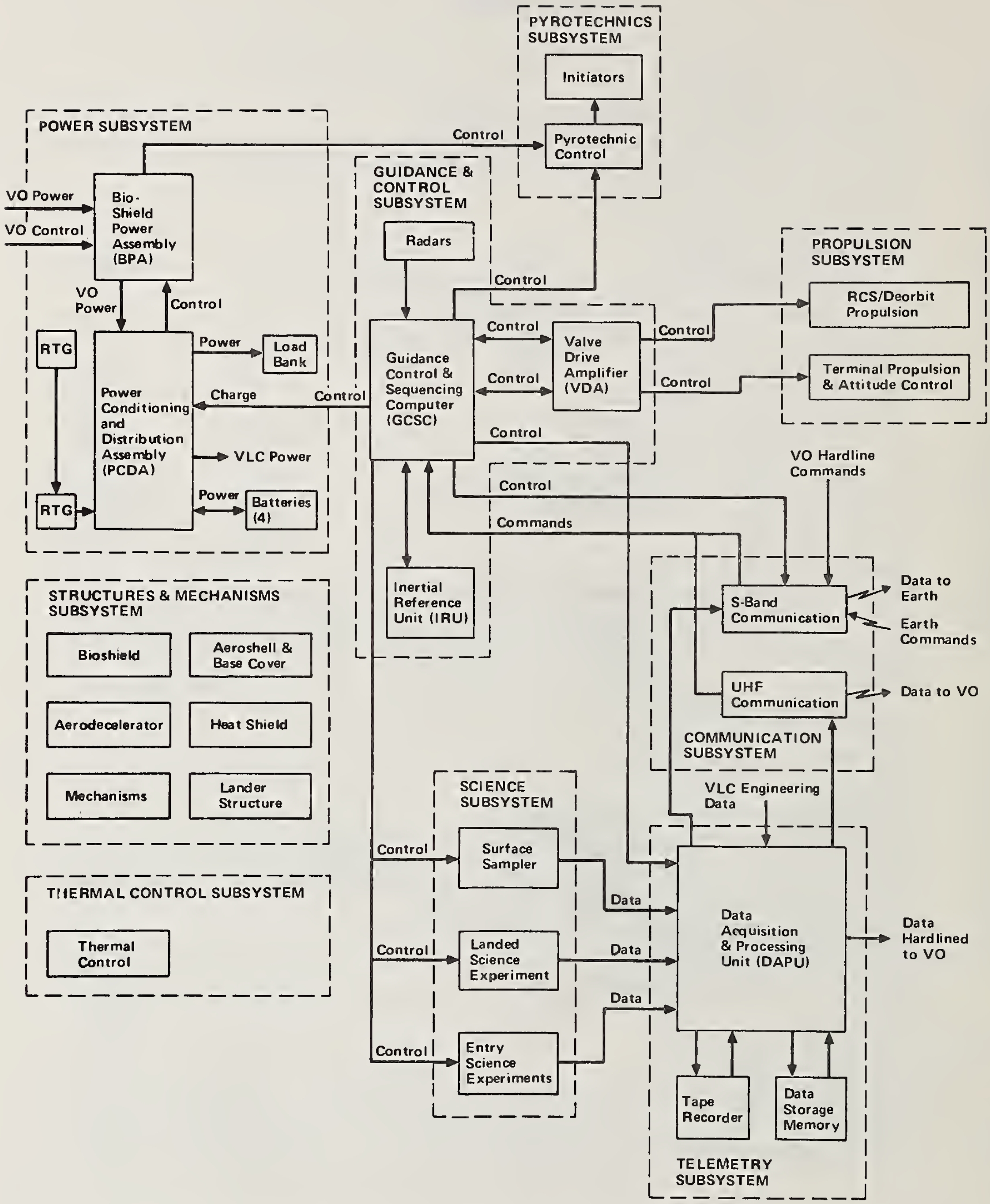

Figure 1 VIKING LANDER CAPSULE FUNCTIONAL BLOCK DIAGRAM

Lander

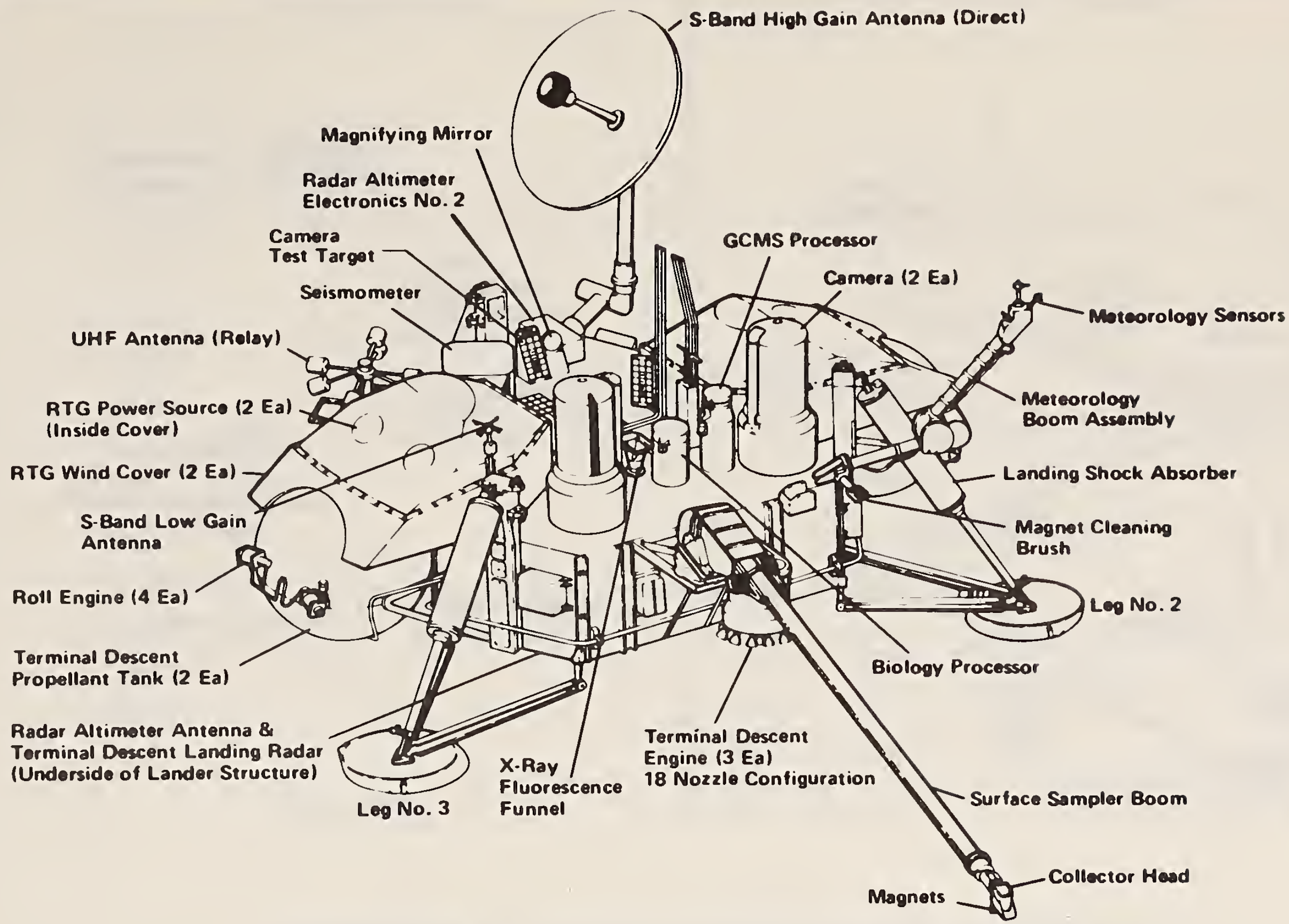

Figure 2

TELEMETRY/COMMUNICATIONS INTERFACE

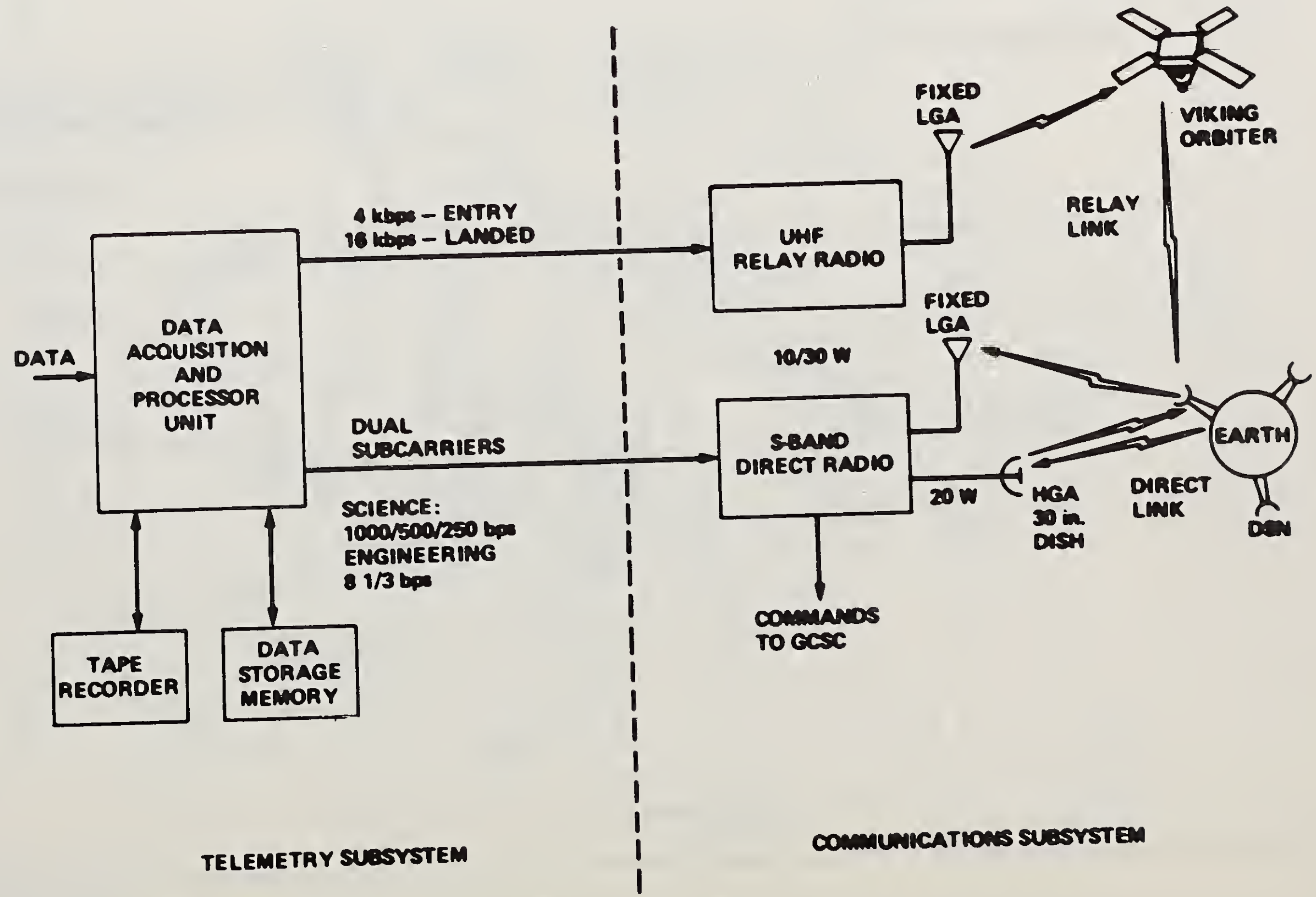

Figure 3

Telemetry Data Interfaces

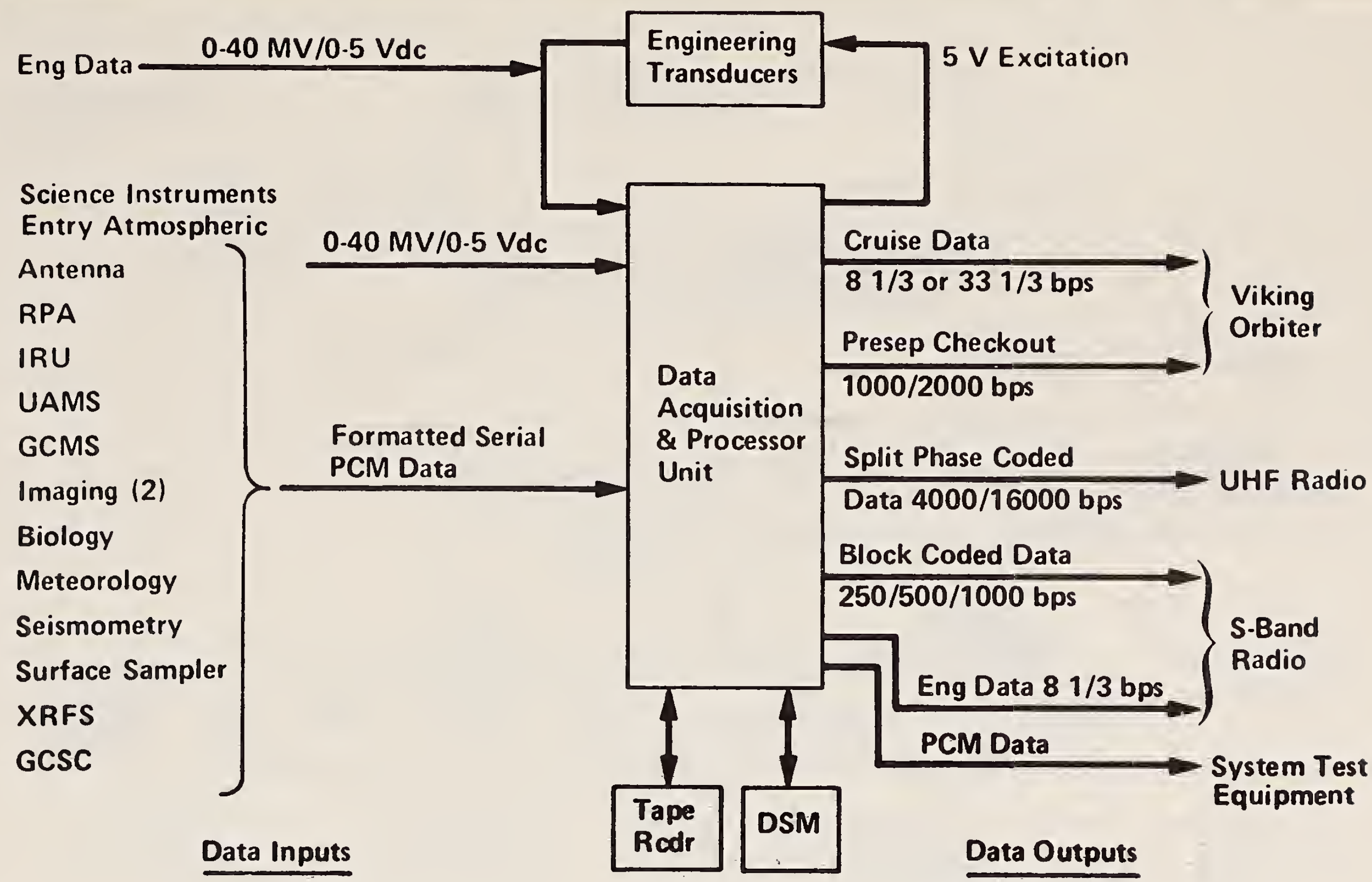

Figure 4

VIKING LANDER UPLINK PROCESSING SOFTWARE

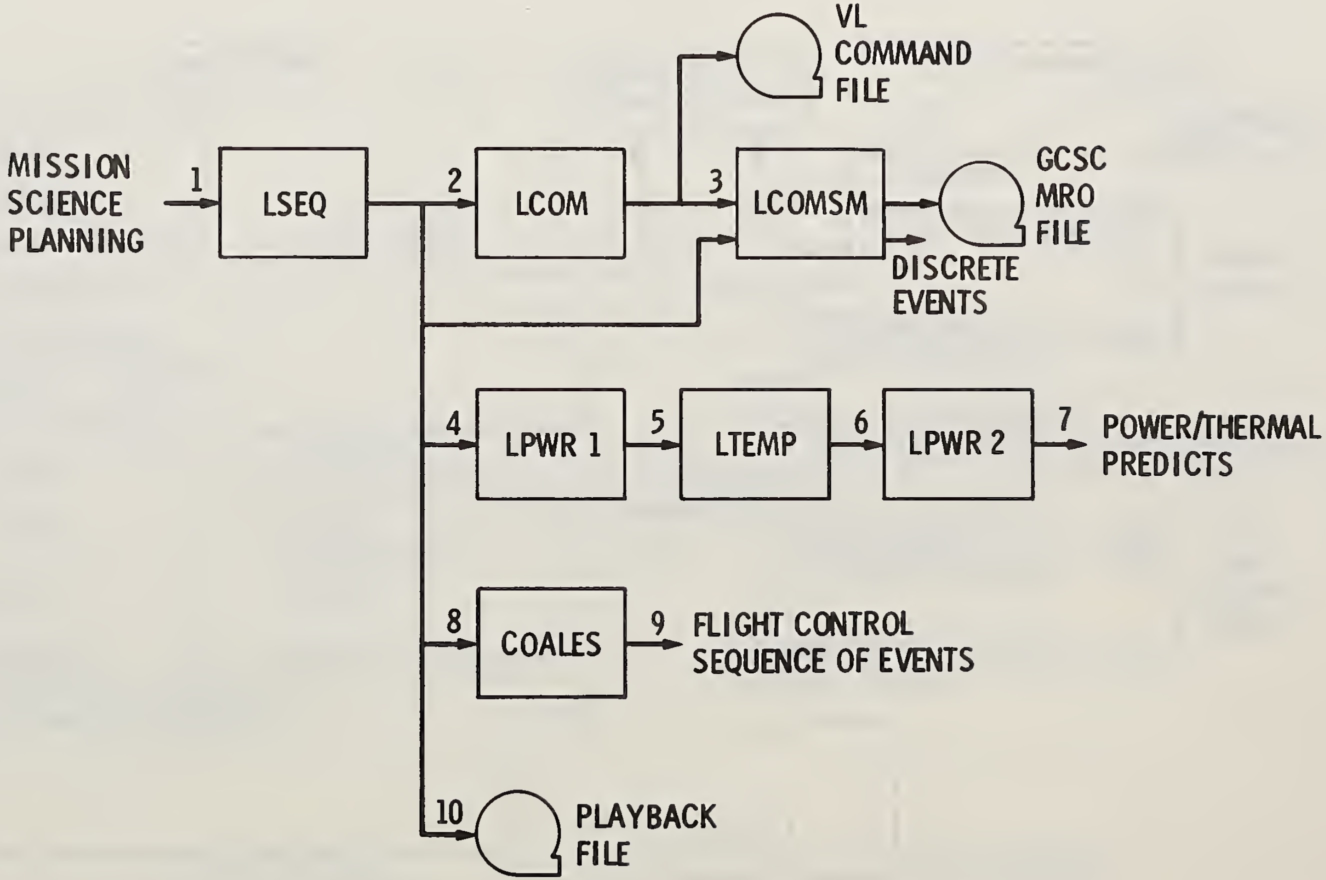

Figure 5

DOWNLINK PROCESSING SYSTEM

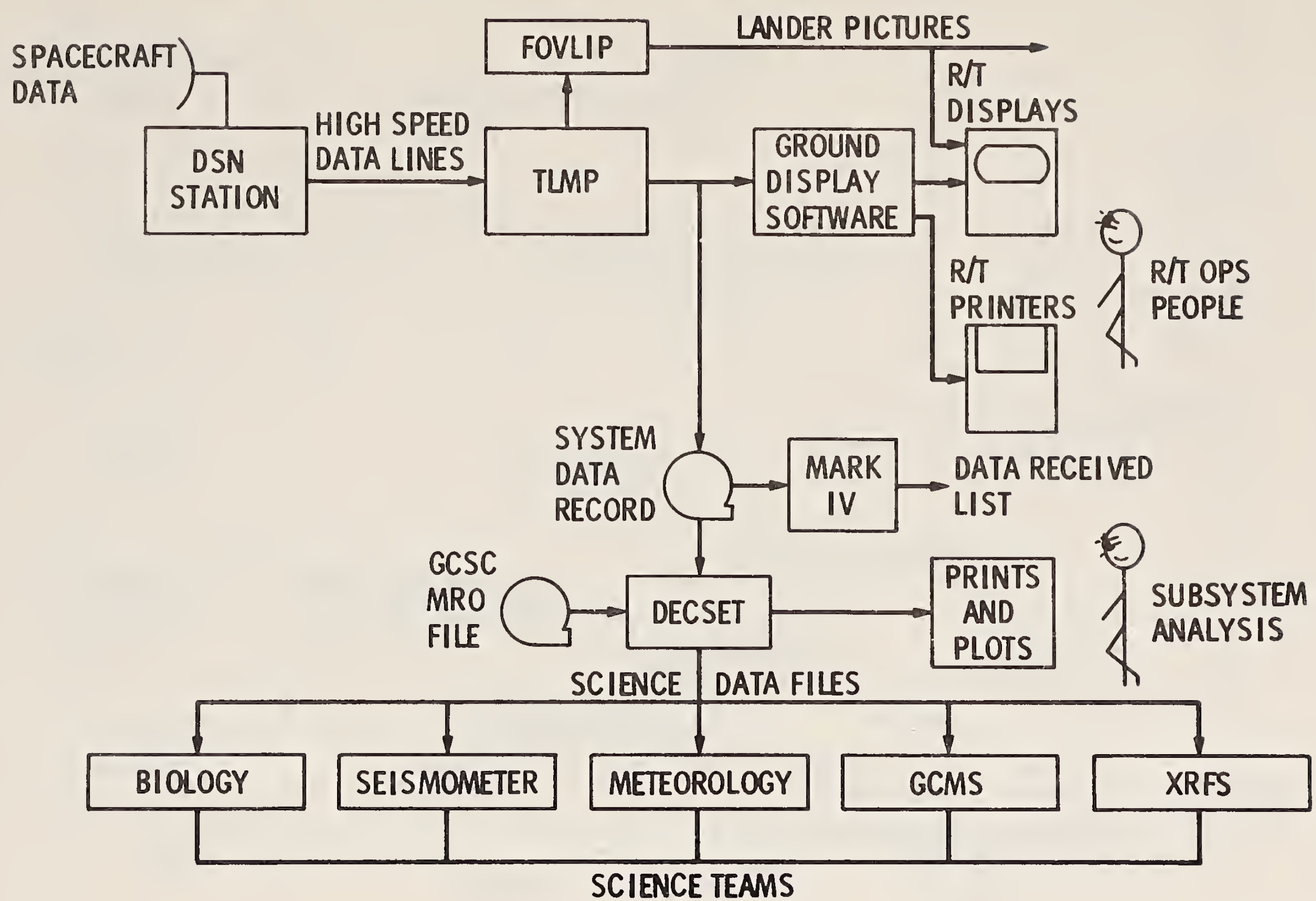

Figure 6

VL-2 UPLINK/DOWNLINK SCHEDULE DOY 15-22, 1977

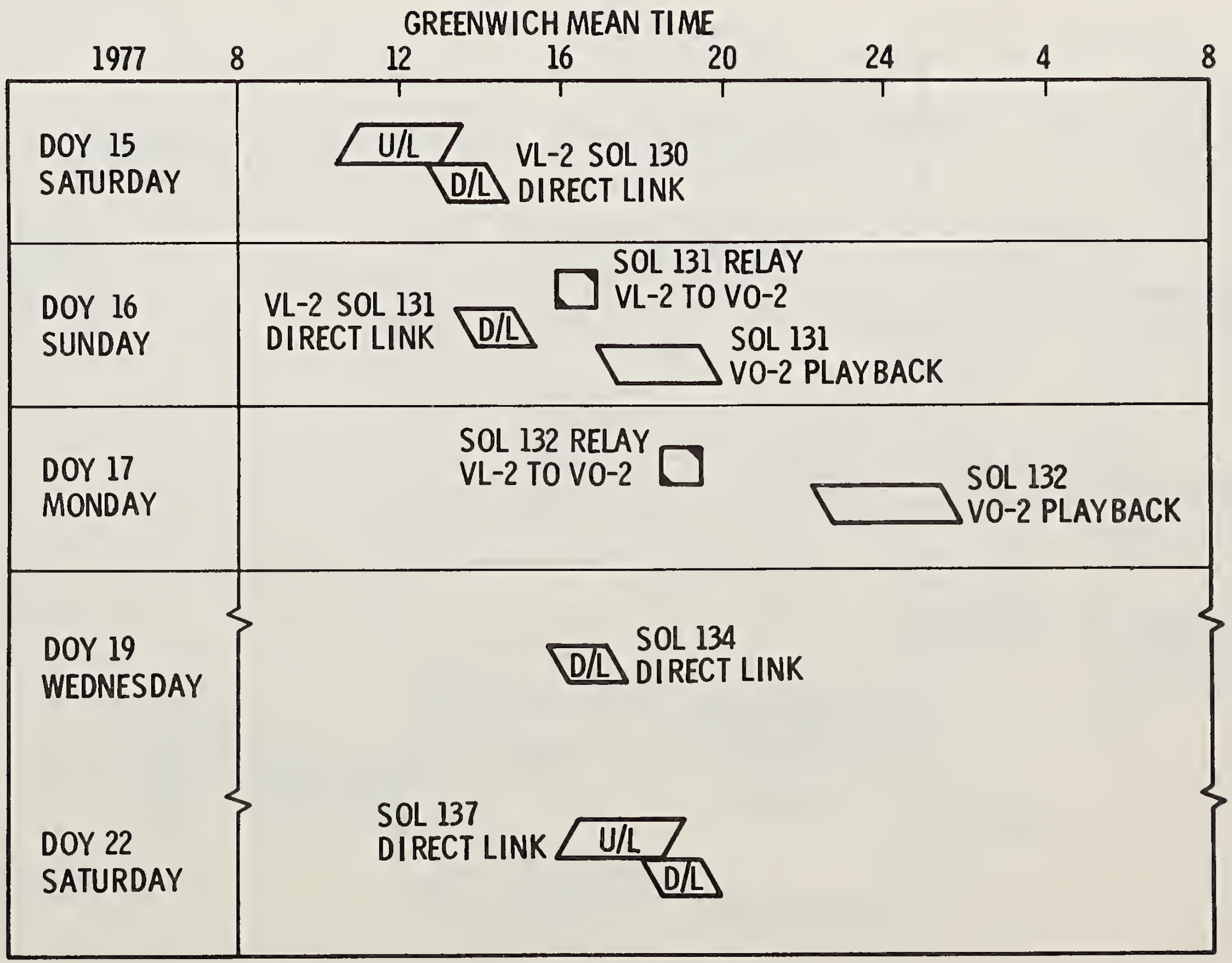

Figure 7

VL-2 SOL 130 TIMELINE PREDICTION vs ACTUAL

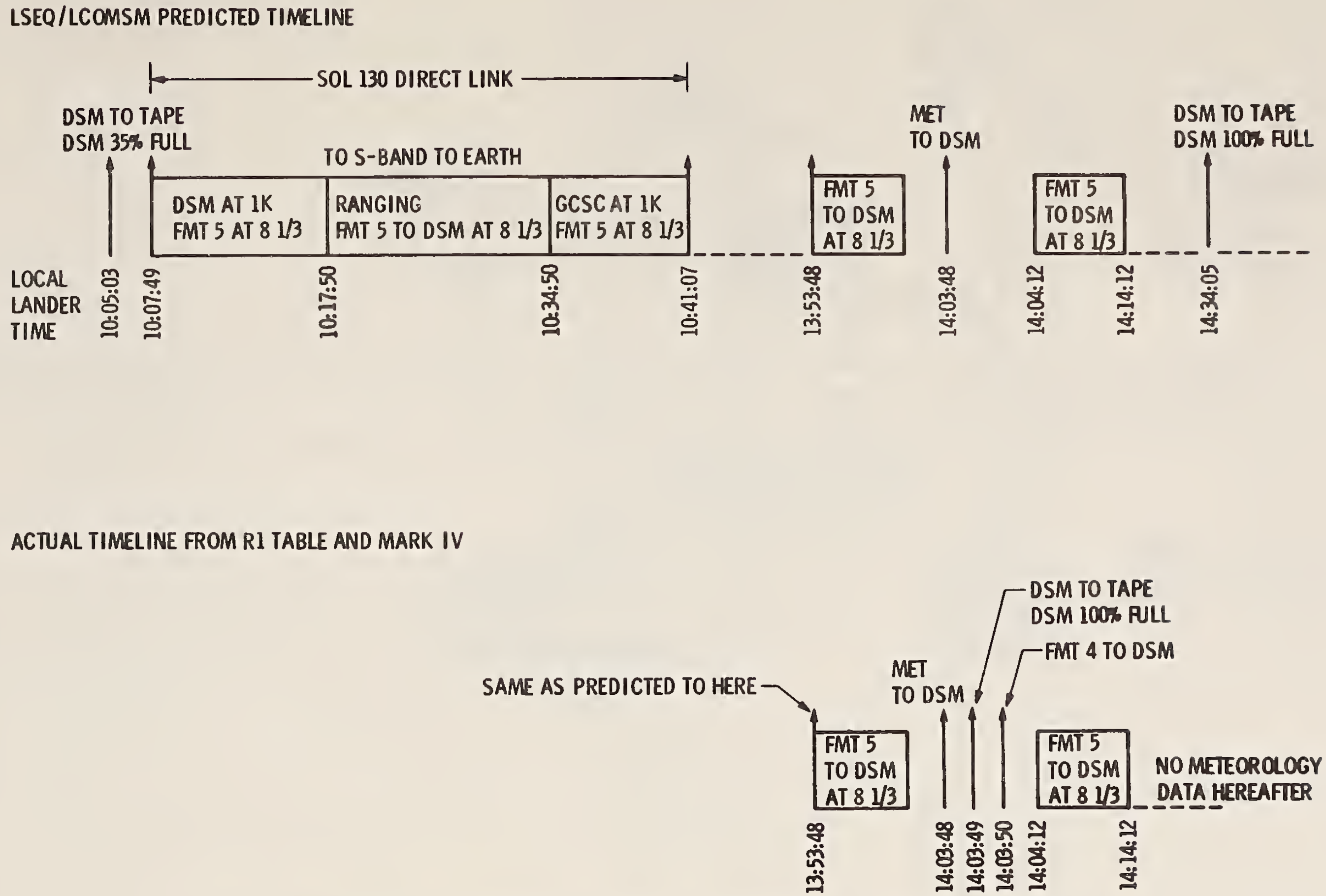

Figure 8

VL-2 MET DATA LOSS ANOMALY TIMING

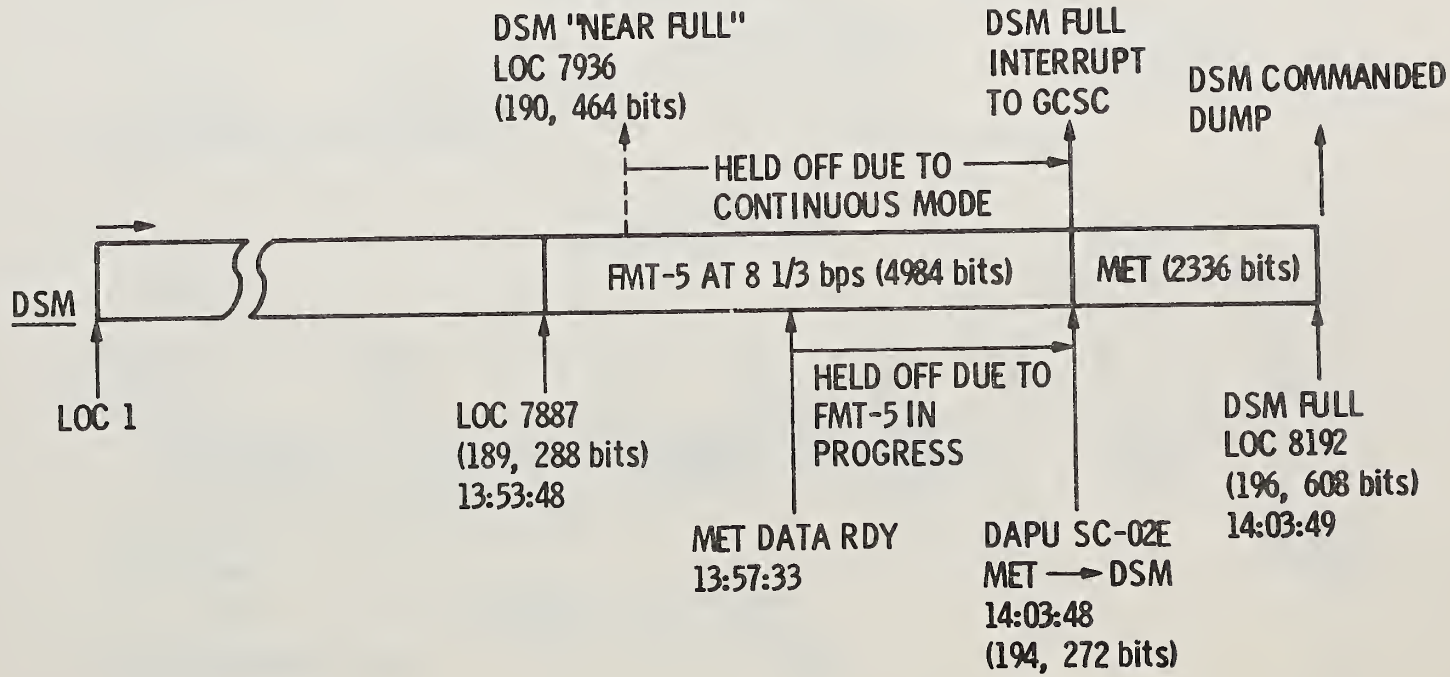

Figure 9

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

These proceedings consist of a group of twenty-four submitted papers from the 26th meeting of the Mechanical Failures Prevention Group which was held at the IIT Research Institute in Chicago, Illinois on May 17-19, 1977. The central theme of the proceedings is detection, diagnosis and prognosis as related to mechanical failure. Papers are presented that discuss oil analysis, signature analysis techniques, new detection, diagnosis and prognosis techniques and equipment, railroad system diagnostics, and land vehicle diagnostics.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Failure detection; failure diagnosis; failure prevention; ferrography; land vehicle diagnostics; oil analysis; railroad system diagnostics; signature analysis; wear

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