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IMPROVED QUANTITATIVE DEBRIS MONITORING CAPABILITY

Nicholas P. Maris
R. V. Kadyszewski
Aeroquip/TEDECO Division
24 E. Glenolden Avenue
Glenolden, PA. 19036

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AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6563

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This technical report has been reviewed and is approved for publication.

PHILLIP W. CENTERS, Ph.D.
Project Engineer
Lubrication Branch

HOWARD F. JONES
Chief, Lubrication Branch
Fuels and Lubrication Division
Aero Propulsion Laboratory

FOR THE COMMANDER

BENITO P. BOTTERI
Assistant Chief
Fuels and Lubrication Division
Aero Propulsion Laboratory

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This report describes the operation and performance evaluation results of a QDM® Mark II prototype fine ferrous debris monitoring system developed by TEDECO. The purpose of the QDM Mark II system is to continually measure the accumulation of wear - generated fine ferrous debris, as well as flake size debris. The QDM Mark II system employs an electronically driven probe which allows a continuous sensing of debris accumulation. The debris-related signal is detected and suitably scaled to provide a DC signal proportional to the mass of the accumulated debris. Since the system measures the mass of accumulated ferrous debris, its resolution is limited only by system and probe stability and allows detection of sub-milligram amounts of ferrous debris. The QDM Mark II prototype tested in this program provides only the mass-proportional DC signal as an output. The DC signal may be scaled to any range within the dynamic capability of the system and can be converted to a digital output format.

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Dr. Phillip W. Centers

22b. TELEPHONE NUMBER *(Include Area Code)*
(513) 255-6608

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System performance was demonstrated by detection of ferrous debris in the 10 to 50 micron size range. A test was also run to demonstrate the detection characteristics of 500 micron size flakes. The demonstration test was performed on the TEDECO oil test stand, which has the capability of simulating a turbine engine lubrication system. The tests were performed by injecting pre-measured amounts of the fine debris into the oil flow and observing the system output signal on an oscilloscope and a digital voltmeter. The tests were conducted on September 18, 1986 and witnessed by Air Force personnel.

The demonstration consisted of three tests using fine debris. In the first test, TEDECO supplied 10 to 45 micron debris samples were injected into the oil stream to illustrate general performance. In the next test, USAF-supplied 10 to 20 micron ferrous debris and USAF-supplied 45 to 50 micron ferrous debris were injected into the the oil stream. In the final test run, no further debris were injected into the oil flow and the probe was allowed to continue to collect as much debris as possible, from what was previously injected, in a reasonable amount of time. Before each test was run, the system output as shown by the digital voltmeter (DVM), was recorded as the "no-debris" signal. The flow was then started and accumulation allowed to occur until a certain output level (which reflected a desired amount of accumulation) was reached and recorded. At this point, oil flow was stopped and the probe removed from its housing. The accumulated debris was removed from the probe and weighed. The output level change in terms of millivolts was then compared to the actual weight of debris accumulation and the results plotted and analyzed to determine indication linearity. System stability was demonstrated in a clean oil system by observing the QDM Mark II output to remain at a fixed level (within an error range) over a 15-minute time period with no debris accumulation on the probe.

A test to demonstrate the output characteristic when 500-micron size flakes were accumulated was also performed. The results of this demonstration were not recorded, but visually observed. The 500-micron size flakes were injected and the output display on the oscilloscope was observed to indicate a substantial increase in the output voltage rate-of-change relative to that produced by the fine debris accumulation. This demonstration showed that the system could differentiate between accumulations of flakes and fine debris. Also, since the 500-micron size flake is on the order of 0.1 milligram, a system sensitivity to submilligram accumulations was clearly shown.

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1.0 INTRODUCTION

Engine oil monitoring has long been used to give early warning of the wear and impending failure of critical oil-wetted components. Traditionally, this has been accomplished by spectrographic oil analysis (SOA), which provided an elemental identification of the wear metal constituents on a parts-per-million of a sample of engine oil. While this method was relatively complete in its analysis, sampling and the logistic impact of remote area analysis of the oil sample present problems in the application of this technology. On-board systems developed to provide real-time monitoring of critical turbine engine wear modes often are not capable of detecting all failure modes present or possible in modern turbine engines.

An In-Line Ferrous Debris Monitor that provides real-time tracking of wear and failure modes must, to be effective, cover all significant failure modes of the turbine engine and preferably, should isolate the most serious ones to a module in a modular engine. While there will be failure modes specific to each turbine engine type, they will, in general, fall into two classes; those which produce fine particulate matter, such as early pitting and component rubbing; and surface fatigue failure resulting in small or large flakes. Often, the former will be an early indication of the occurrence of the latter failure mode. There are, however, some failures that produce only small debris right up to the time of catastrophic failure, such as roller end wear in a mainshaft bearing. Traditional airborne methods have concentrated on the latter large debris failure class, often to the exclusion of the former. This has largely been due to the debris size limitation of the sensing system. In contrast, ground-based systems, while sensitive to finer particulate matter, rely on sampling and are logistically limiting because of the slow response time of the analysis. Thus, an in-line debris monitoring system should include the following features:

1. Operate in a scavenge flow environment which contains a majority of the debris associated with both wear and surface fatigue spalling failure modes. The sensor assembly must function efficiently in the turbulent air/oil flow associated with the scavenge section of the oil system.

2. The system must provide reliable real-time information on the engine or mechanical system that accurately reports upon machinery health.

3. The sensing system should have the resolution and measurement capability for accumulations of ferrous debris extracted from the oil stream for particle sizes of 100 microns or less.

4. The sensing device should have the capability to operate over a wide range of lubricant system conditions with a high time between failures.

Because of its small debris size range capability, such a system should be capable of application as a long-term degradation monitor, as well as a short-term failure prognostication system. Thus, the in-line debris monitoring system should provide a marked increase in capability to detect wear in lubricating oil-wetted components and permit diagnoses (that are now being done off-line) to be functionally integrated into an on-line diagnostic system.

2.0 TECHNICAL DISCUSSION

2.1 Technology Approach. TEDECO has funded ongoing Research and Development programs to develop ferrous debris detection systems using actively-driven probe techniques.

Eddy current technology is employed in this QDM Mark II system design for the detection of ferrous debris by the QDM sensor.

The QDM sensor configuration consists of a coil wound about a ferrous polepiece, which in turn, is in contact with a permanent magnet. The magnet provides the capability to retain ferrous debris. In the electronically driven probe, the coil in the probe is supplied with a constant-current digitally controlled waveform signal. The probe coil is part of a parallel RLC network. For a given AC current level in the network, the voltage developed across the network is a maximum at the resonant frequency and decreases as the frequency of the driving current is increased or decreased about the resonant frequency (Figure 1(a)).

When the probe is driven by a constant current at a constant frequency below resonance, the voltage developed across the network will increase as debris accumulates (Figure 1(b)). This voltage, converted to a DC signal, is the output proportional to accumulated ferrous debris.

2.2 Prototype Description. The QDM Mark II fine ferrous debris detection system design (Figure 2) was internally funded by TEDECO nearly 3 years ago. The design guidelines set by TEDECO at that time were:

(A) System mass resolution in the submilligram range. The design goal was 0.1 milligram.
(B) The system will not have a debris size range lower limit.

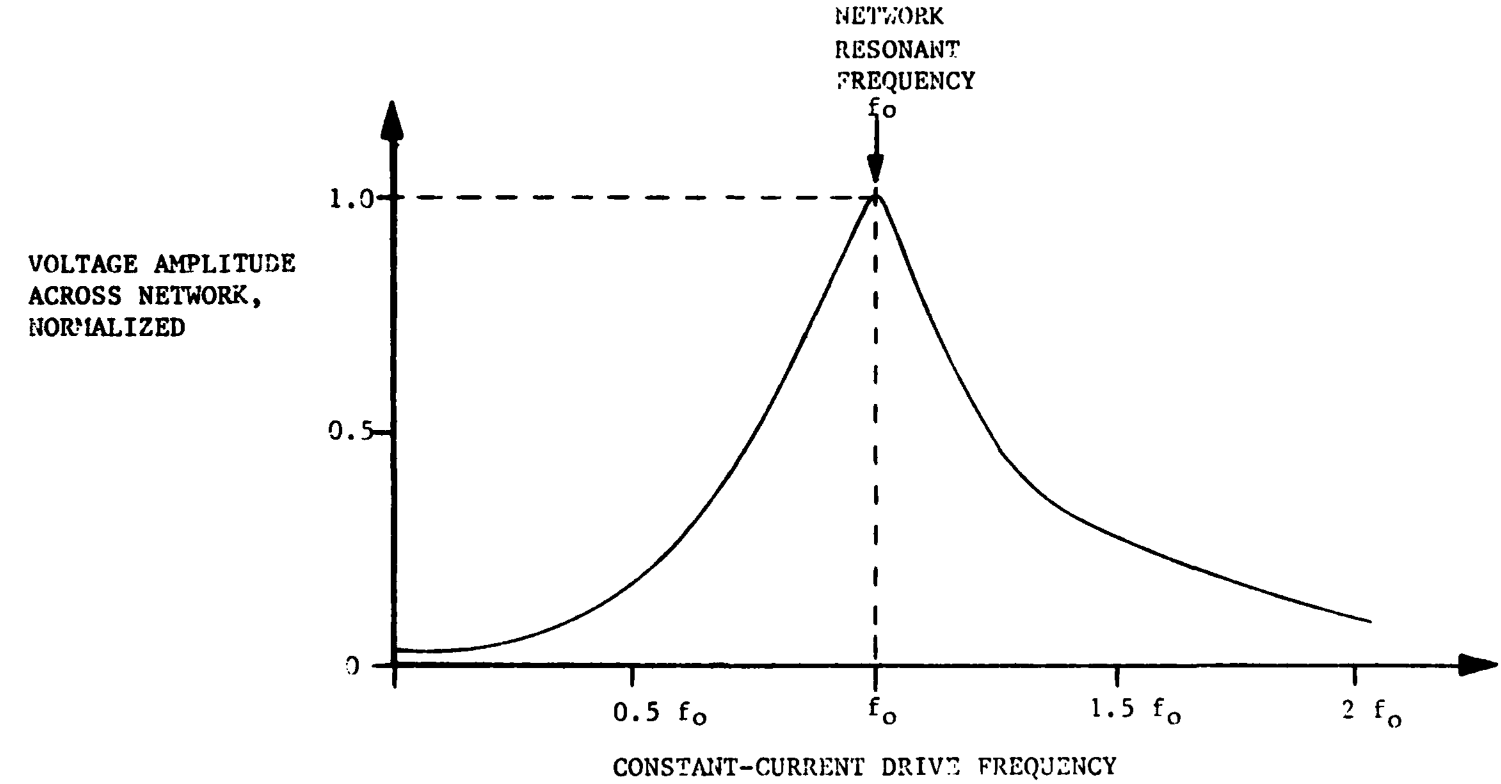


FIGURE 1a. VOLTAGE VS. DRIVE CURRENT FREQUENCY OF PARALLEL RLC NETWORK

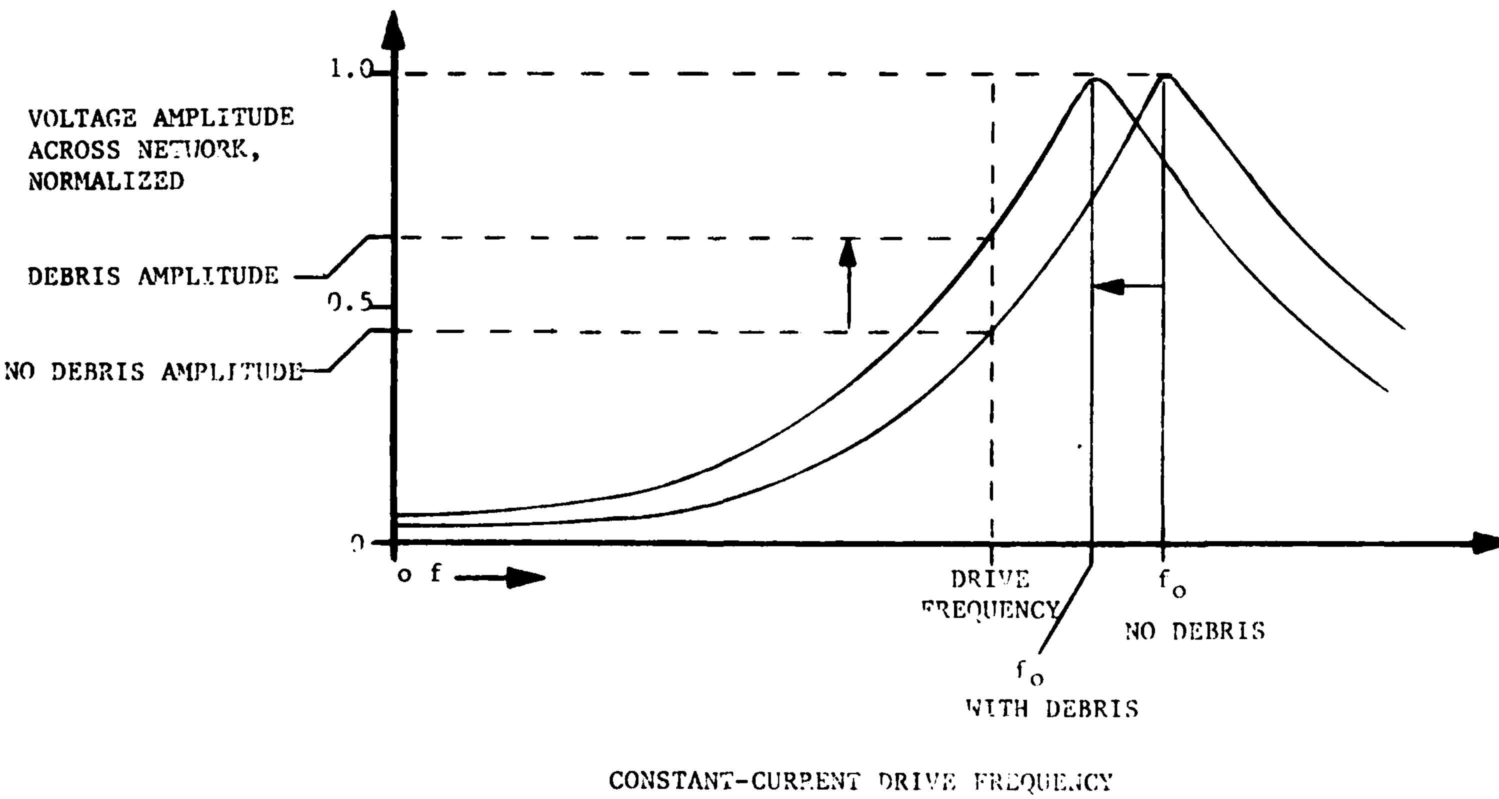


FIGURE 1b. EFFECT OF DEBRIS UPON RESONANT FREQUENCY AND AMPLITUDE

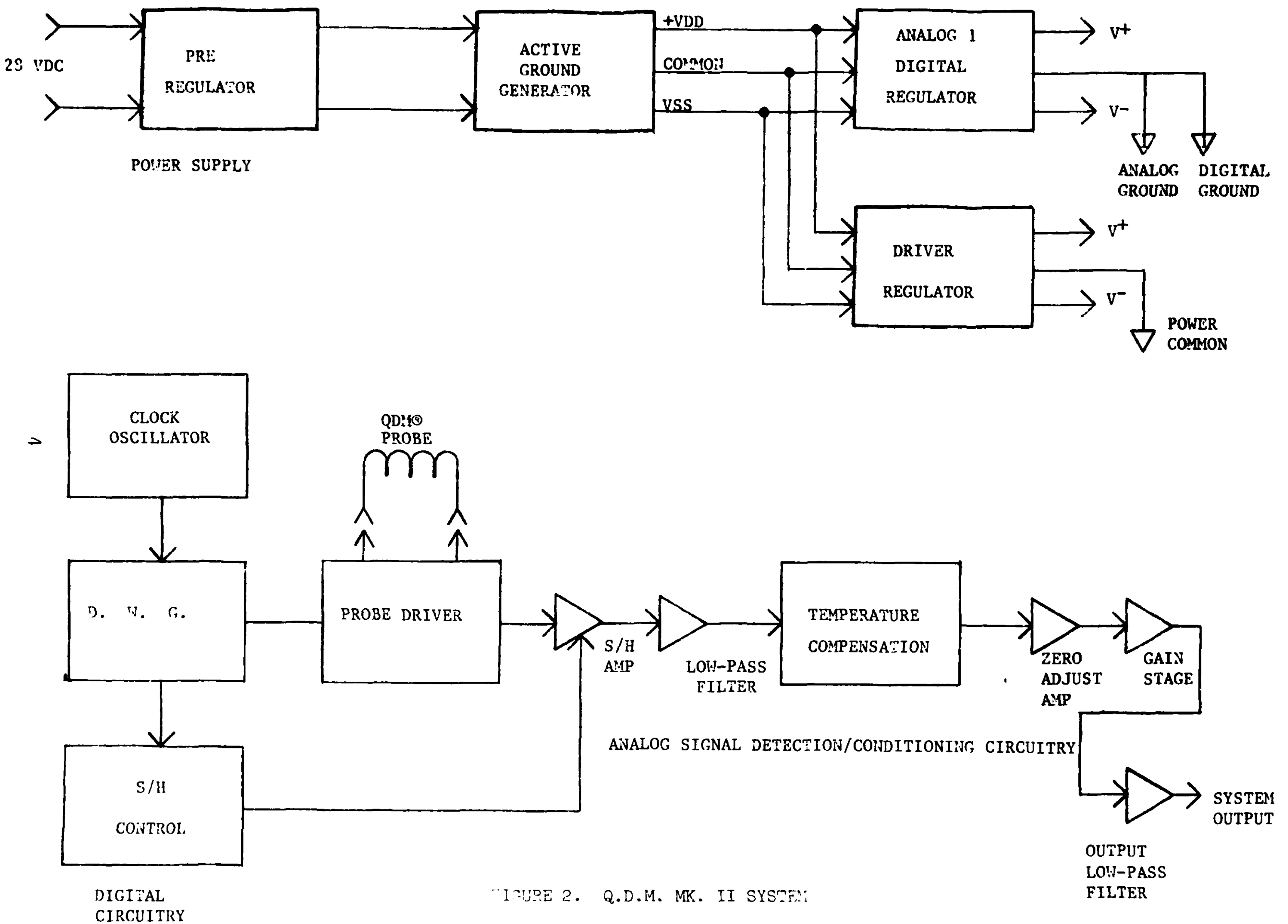


FIGURE 2. Q.D.M. MK. II SYSTEM

(C) The system will have inherent memory due to its debris retention capability.

(D) The system will have high electrical noise rejection capability due to its low frequency signal conditioning.

(E) The system will have high vibration noise rejection because of its very low frequency bandwidth.

The prototype electronic unit consists of four parts; power supply, digital circuitry, probe driver, and analog signal detection/conditioning circuitry.

2.2.1 Power Supply. The power supply provides a highly regulated, temperature-stable bipolar voltage source for the system. The power supply consists of three sections; a preregulator, an active ground reference generator, and two independent but identical precision voltage sources (also known as preregulators).

The main function of the preregulator is to regulate the incoming 28 VDC presented to the power input. It also provides accidental reverse polarity protection and minimizes the effects of transients or short-term undervoltages on the system.

The active ground reference generator is used to create a bipolar voltage supply. Since the bipolar voltages at this point are not sufficiently regulated for the low-level analog signal processing section and the precision waveform generator, another stage of regulation is performed by the post-regulators.

The post-regulators provide the precise, temperature-stable voltages required. One post-regulator set is dedicated to power the probe driver electronics, and one set to power the digital and analog electronics. Both post-regulator sets utilize the same low temperature coefficient band gap voltage reference. Temperature stability is enhanced by the use of a tempsistor in the feedback loop of each positive voltage regulator.

2.2.2 Digital Circuitry. The digital circuitry provides both an amplitude-stable waveform and control functions for the analog circuitry. The digital circuitry consists of three main sections; the system clock oscillator, the digital precision waveform generator, and the sample/hold control generator.

The heart of the system is the clock oscillator whose function is to synchronize the digital circuitry.

The digital precision waveform generator provides an extremely amplitude-stable driving waveform for the probe driver in the analog circuitry.

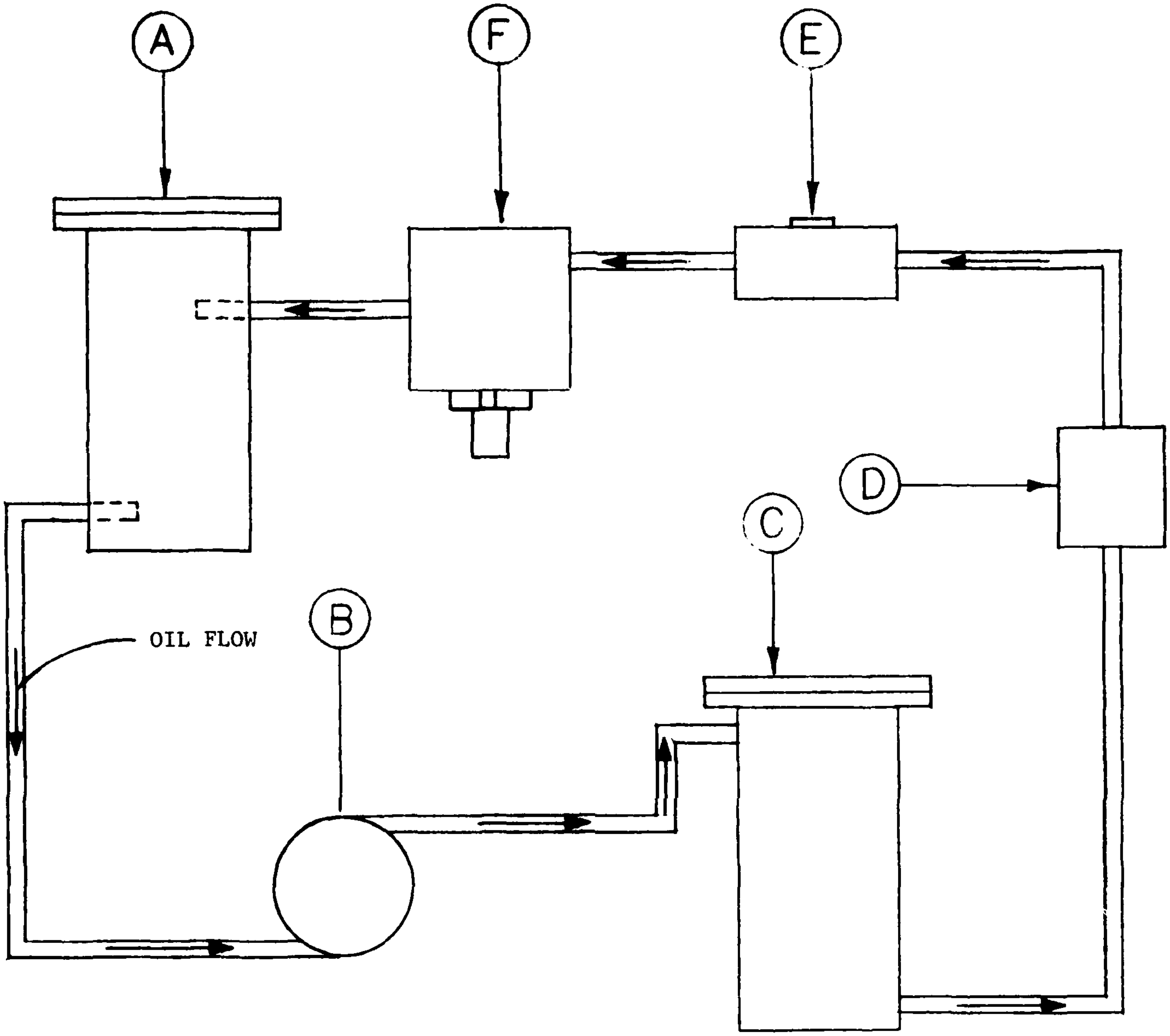
The control function section is responsible for controlling a sample-and-hold amplifier (SHA) further "downstream" in the analog circuitry section. The control function triggers the SHA to acquire the signal at a predetermined, repeatable position on the waveform.

Another function of the digital circuitry is to provide a power on reset of all the digital functions to provide proper start-up.

2.2.3 Analog Signal Detection/Conditioning Circuitry. The purpose of the analog circuitry is to drive the probe, detect the resultant signal, temperature compensate, and scale the debris signal as required. The detected debris signal is low pass filtered and then temperature compensated to minimize temperature induced variations of the probe over a wide temperature range. The resultant output signal is proportional to accumulated ferrous debris mass.

2.3 Test Program. The following describes the test setup, test procedure, and results of testing performed on the TEDECO oil test stand for the QDM Mark II fine ferrous debris detection system prototype. Results of the pre-demonstration test are included, as well as the demonstration test results.

2.3.1 Oil Test Stand Setup. Figure 3 is a simplified drawing of the test setup used. The oil reservoir (A) is filled with Exxon ETO 2380 synthetic oil. Reservoir oil capacity is 3 gallons. Oil then flows from the reservoir to the electric motor powered pump (B) into and through the filter container (C). The filter container uses a Rosedale strainer with a BETA bag filter rated at 50% for 12 micron and above and 95% for 37 micron and above debris. The bag is removed during testing, to allow any injected but not captured debris to recirculate through the system, and inserted during system clean-out. The oil flow then passes through a flowmeter (D) and the debris injector (E), which employs a self-closing valve to allow debris injection while the oil is flowing. The oil then flows into a 1F174-5 Lubriclone (F), which contains the 1G836 QDM probe used for the QDM Mark II testing, and then back to the reservoir. The Lubriclone was used to provide a more uniform and repeatable debris accumulation on the probe than can be obtained using a full-flow housing. Capture efficiency of the Lubriclone for small debris is also higher than that for the full-flow housing.



Ⓐ OIL RESERVOIR

Ⓑ OIL PUMP

Ⓒ FILTER CONTAINER

Ⓓ FLOWMETER

Ⓔ DEBRIS INJECTOR

Ⓕ 1F174-5 LUBRICLONE® WITH 1G836 QDM PROBE

FIGURE 3. OIL TEST STAND SETUP

The debris may be put into the system by the debris injector or dumped directly into the reservoir. The advantage of using the debris injector is that debris is put into the oil flow directly upstream of the probe which allows a more rapid rate of debris accumulation on the probe and hence a saving of test time. There is no provision for heating the oil in this test configuration. Heat is generated by frictional heat losses within the system itself. This setup was used for testing both prior to and during the USAF demonstration test.

2.3.2 General Test Plan/Procedure. The test plan used for the USAF demonstration test, as outlined in the following section, was derived from the test procedure used for predemonstration testing. The official test plan was as follows below.

2.3.2.1 Test Objectives. The tests are to be conducted to demonstrate the performance of the TEDECO QDM Mark (MK) II System Technology. In a closed-loop hydraulic flow stand environment, the capability of the QDM MK. II system to provide an analog output for fine debris is to be demonstrated. The sensitivity of the QDM MK. II system to detect fine ferrous material in the size range of 10 to 45 microns is to be demonstrated. Sensitivity to detect mass increments of 0.2 milligrams is to be demonstrated using the fine size debris. Linearity as a percent of full scale and repeatability of output response, is to be demonstrated by accumulating 5-milligram samples of the fine size debris.

2.3.2.2 Test Item Configuration Identification. The test item used in the demonstration tests consisted of one TEDECO QDM MK. II electronics module, a 1F174-5 Lubriclone, and a model 1G836 sensor.

2.3.2.3 Test Procedure.

2.3.2.3.1 Hydraulic Flow Stand Demonstration Test.

2.3.2.3.1.1 Prior to the demonstration, clean the flow stand oil by using a Rosedale strainer with a BETA bag filter rated at 12 micron (50%) and 37 micron (95%). With a solid oil flow condition, operate the test stand at 8 $\pm$2 GPM (gallons per minute) at room temperature until the oil is sufficiently cleaned.

2.3.2.3.1.2 Configure the TEDECO hydraulic flow stand with a QDM Lubriclone model 1F174-5.

2.3.2.3.1.3 Install the model 1G836 sensor in the model 1F174-5 Lubriclone.

2.3.2.3.1.4 Connect the sensor to the QDM MK II electronics. Connect a DC power supply to the QDM MK II electronics and supply power at 28 VDC (nominal).

2.3.2.3.1.5 Connect the output of the QDM MK II electronics to a digital voltmeter and an oscilloscope.

2.3.2.3.1.6 Adjust the flow stand for an air/oil ratio of 0/1 and an oil flow of 8 gallons per minute at ambient temperature (100 to 150 degrees F).

2.3.2.3.1.6.1 Run the test stand for approximately 15 minutes to demonstrate stability of the system in a clean oil condition.

2.3.2.3.1.6.2 Inject approximately 10 milligrams of fine size debris into the oil flow (inject additional 10 milligram quantities of debris as desired after the initial accumulation indication).

2.3.2.3.1.6.3 Observe the QDM MK II output on the oscilloscope and voltmeter. When the output indicates approximately 5 milligrams of fine debris accumulation, shut down the flow stand. Record the data.

2.3.2.3.1.6.4 Remove the model 1G836 QDM sensor from the model 1F174-5 Lubriclone.

2.3.2.3.1.6.5 Remove the accumulated debris from the sensor. Weigh the accumulated debris and record the data.

2.3.2.3.1.6.6 Install the model 1G836 QDM sensor in the model 1F174-5 Lubriclone. Reset the QDM MK II electronics and the instrumentation.

2.3.2.3.1.7 Repeat 2.3.2.3.1.6.2 through 2.3.2.3.1.6.6.

2.3.2.4 Test Schedule. The demonstration tests were conducted at the TEDECO facilities on September 18, 1986.

2.3.2.5 Instrumentation. The following instrumentation, or equivalent, with a current calibration was used to conduct the demonstration tests:

a. Digital Multimeter, Fluke model 8060A.

b. Digital Storage Oscilloscope, Phillips model PM305.

c. DC Power Supply, Power/Mate Corporation model B PA-40E.

d. Digital Scale, Mettler model AC100.

2.3.2.6 Data Requirements. Data were acquired during the demonstration tests from the oscilloscope and from the digital voltmeter. The oscilloscope displayed a real-time analog presentation of the QDM MK II output along with a coarse quantitative measurement. The digital voltmeter reading was a more accurate representation of the QDM MK II output data and was used in the data analysis. The debris mass was determined from the digital scale measurements.

2.3.2.6.1 Using the data obtained from 2.3.2.3.1, the output voltage was plotted as a function of the mass of the accumulated debris for all conditions. The data were analyzed to determine sensitivity, linearity, and repeatability.

2.3.2.7 Support Requirements. The TEDECO oil test stand facility was used for the hydraulic flow stand demonstration tests. TEDECO personnel made all preparation for the tests, conducted the tests, and analyzed the data. Air Force personnel witnessed the testing and presentation of the QDM MK II capabilities and test data analysis.

2.3.3 Test Results. The data summation of the test results for the pre-demonstration and the demonstration tests are tabulated in Tables 1 and 2 and plotted graphically in Figure 4.

2.3.3.1 Pre-Demonstration Test Conditions.

Debris size: 10-45 micron (TEDECO supplied).

Oil temperature: 110 degrees F $\pm$20 degrees F.

Oil flow rate: 8 $\pm$2 gallons per minute.

Air/oil ratio: 0/1.

Probe housing: model 1F174-5 Lubriclone.

Probe type: 1G836.

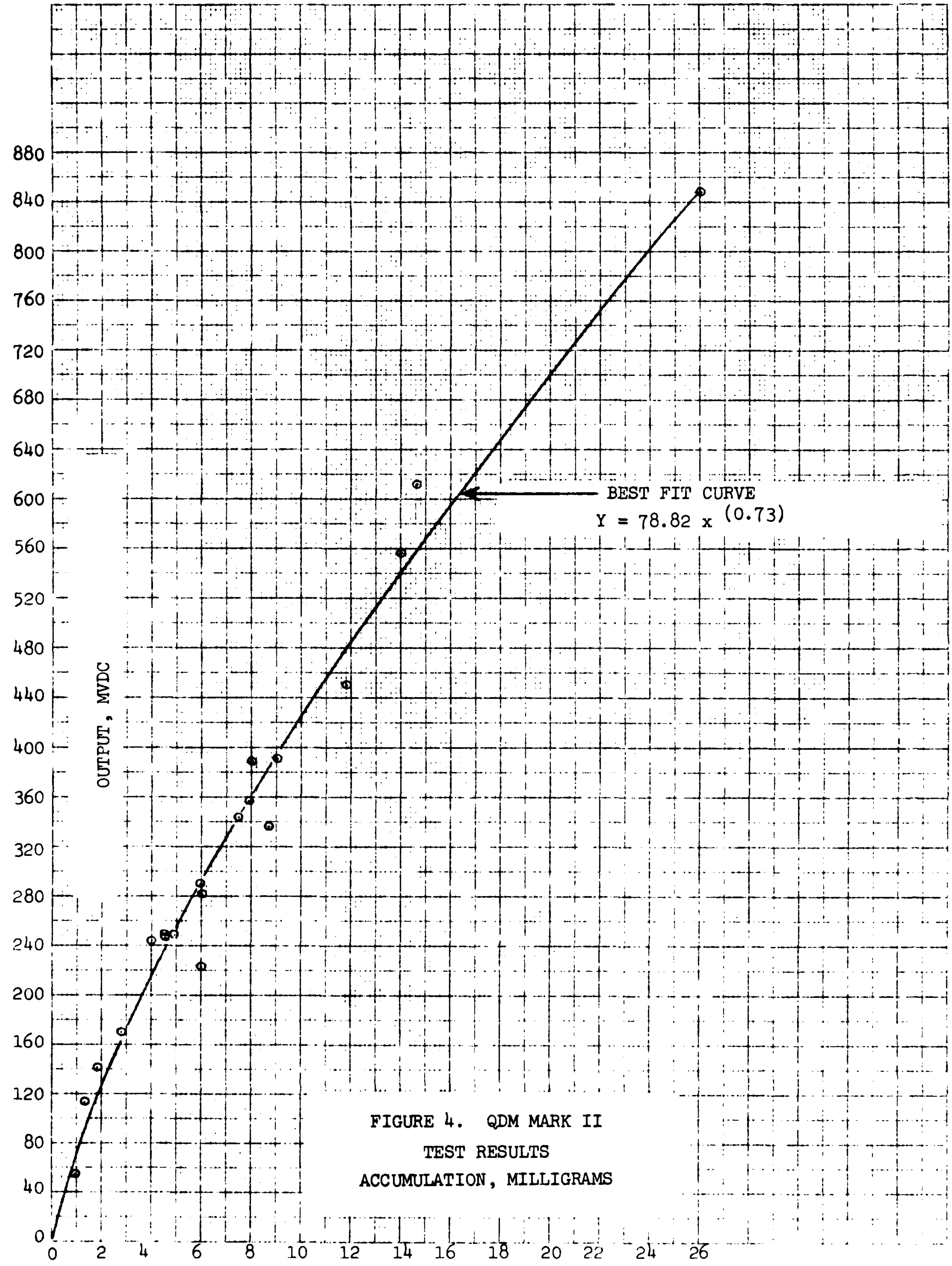


FIGURE 4. QDM MARK II
TEST RESULTS
ACCUMULATION, MILLIGRAMS

2.3.3.2 Predemonstration Test Results: see Table 1.

2.3.3.3 Demonstration Test Conditions: see 2.3.2.3.1.

2.3.3.4 Demonstration Test Results: see Table 2.

2.3.4 Test Results Evaluation. From the data plotted in Figure 4, a linear approximation for a limited scale of data (up to 15 milligrams) suggests a system sensitivity of 44 millivolts/milligram. Beyond this point, extrapolating the data suggests that saturation of the sensor with debris would occur at approximately 40 to 50 milligrams.

The variation of the data about the linear approximation in terms of standard deviation, from the 44 millivolts/milligram sensitivity, is on the order of 1 gram or 6.6% of the 15-milligram (limited) scale. The maximum deviation is measured to be +1.6 milligram, -1.8 milligram or approximately ±10% of the 15-milligram (limited) scale.

A best fit power curve of the form $Y = k\ x^{(p)}$ was determined for the data using k = 78.82 and (p) = 0.73. This curve is included in Figure 4 to illustrate its correspondence with the data.

Variation of the measured data points from this curve is within a reasonable scatter of limited test data. Errors in data point determination include those introduced by the testing controls and the data acquisition instrumentation. The power-law shape of the curve may be indicative of the effects of debris accumulation as a function of distance from the sensor pole piece surface.

The system stability was demonstrated by observing the system output for a clean oil flow condition (no debris accumulation) for 15 minutes. The output level variation during that time was within ±2 millivolts. This is approximately equal to a ±50-microgram variation.

When 500-micron size flakes were detected, the output change was approximately equivalent to a step function. The output level change was on the order of 4 to 5 millivolts. The 500-micron flake test was performed to demonstrate the difference in output characteristics between flake and fine debris accumulations. The output voltage for fine debris was a smooth, slowly-ascending ramp over time, while the output voltage for flakes was a step increase. An attempt was also made during the demonstration to differentiate between 10 to 20 micron and 30 to 45 micron sized particles on the basis of rate-of-change of voltage increase. A rate increase of the output was expected. The results were inconclusive because the oil contained a large amount of the 10 to 45 micron debris mixture from previous tests. However, a slight increase was noted for a very short period of time after the 30 to 45 micron debris was injected.

2.4 Conclusion. The QDM Mark II fine ferrous debris detection system prototype, in general, fulfilled the project requirements. Detection, quantitative measurement and analog output representing submilligram accumulations of fine ferrous debris, as well as flake size debris by the QDM Mark II system, have been demonstrated. The QDM Mark II system, as configured, has a system linearized sensitivity of 44 millivolts/milligram. This is equal to 8.8 millivolts/0.2 milligram and represents an acceptable and usable output level for the sub-milligram debris accumulation. The 0.2 milligram is approximately equivalent to a 500- x 500- x 100-micron size debris particle which is equivalent to a double thick 500-micron size flake. The goal to demonstrate sensitivity to accumulation of fine ferrous debris in the range of 10 to 45 microns was met by tests where 15 mg of 10 to 45μ debris were accumulated and accurately indicated.

The system exhibits a power-law output variation with a reasonable linear approximation range for debris accumulation up to approximately 15 milligrams. The data suggest that saturation of the system output does not occur until approximately 40 to 50 milligrams of debris are accumulated. The plotted data show the (limited) full scale linear approximation of the system to be approximately ±10%. The average deviation of the plotted data from the power-law curve is approximately +4%, -3% over the 26 milligram range. (+7%, -5% over a limited 15 milligram range.) The effects of temperature variation on the system linearity were minimum due to compensation and nearly constant test temperatures. Therefore, the output deviations are for the most part due to other parameters. Continued investigation to improve the output linearity is an ongoing effort by TEDECO.

TABLE I

Pre-Demonstration Test Results
10 to 45 Micron Debris Size

Actual Accum. (mg)	Vout (mVDC)	Equivalent Accumulation at 44 mv/mg (mg)	Output Deviation (mg)
0.9	55	1.25	+ .35
1.3	116	2.64	+1.34
1.8	141	3.20	+1.40
6.0	222	5.05	-0.95
4.0	242	5.50	+1.50
4.5	246	5.59	+1.09
4.9	249	5.66	+0.76
4.5	250	5.68	+1.18
4.5	251	5.70	+1.20
6.0	281	6.39	+0.39
8.7	339	7.70	-1.00
7.5	344	7.82	+0.32
7.9	358	8.14	+0.24
8.0	390	8.86	+0.86
11.8	452	10.27	-1.53
14.0	558	12.68	-1.32
14.6	615	13.98	-0.02
26.0	846	N/A	N/A

TABLE 2

Demonstration Test Results
10 to 45 Micron Debris Size

Actual Accum. (mg)	Vout (mVDC)	Equivalent Accumulation at 44 mv/mg (mg)	Output Deviation (mg)
2.8	174	3.95	+1.15
6.0	275	6.25	+0.25
9.0	415	9.43	+0.43

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