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METALLIC DEBRIS MONITOR FOR RECIRCULATING LUBRICATING OIL

By

Richard H. Hollinger

April 1972

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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13. ABSTRACT

The object of this program was to design, develop, and test an in-line metallic debris monitor for recirculating lubricating oil systems. The monitor was based on the removal of metallic debris by the action of centrifugal oil flow and filter screening, deposition of the debris in the annulus of a capacitor, and subsequent measurement of the change of capacitance compared to a reference capacitor of identical dimensions. The unit was found to respond to magnetic and nonmagnetic metallic debris and to changes in the rate of deposition of the debris. The principle of operation of the monitor is sound.

Difficulty with temperature drift was traced to unsymmetrical grounding of the monitor and reference capacitors. This condition can be corrected readily in any future work.

Details of illustrations in this document may be better studied on microfiche

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This report was prepared by the Franklin Institute Research Laboratories under the terms of Contract DAAJ02-71-C-0018. The work reported herein is part of a continuing effort to investigate and evaluate various techniques for determining the condition of aircraft components during flight.

The object of this program was to design, develop, fabricate, and test an in-line metallic debris sensor/monitor for recirculating lubricating oil systems, the rate of buildup of the metallic debris being a function of the degradation of oil-wetted components.

The design was based on a changing capacitor configuration to achieve retention of particles and stability of readout in varying flight attitudes.

The design unit demonstrated the ability to monitor the amount and rate of change of the amount of debris in a circulating lubricating oil system.

The results of this effort indicate the feasibility of monitoring circulating oil in flight.

The technical monitor for this contract was Meyer B. Salomonsky of the Aircraft Subsystems and Equipment Division.

Task 1F162203A43405
Contract DAAJ02-71-C-0018
USAAMRDL Technical Report 72-10
April 1972

METALLIC DEBRIS MONITOR FOR RECIRCULATING LUBRICATING OIL SYSTEMS

Final Report

by

Richard H. Hollinger

Prepared by

Franklin Institute Research Laboratories
Philadelphia, Pennsylvania

for

EUSTIS DIRECTORATE
U.S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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SUMMARY

The object of this program was to design, develop, and test an in-line metallic debris monitor for recirculating lubricating oil systems. The monitor was based on the removal of metallic debris by the action of centrifugal oil flow and filter screening, deposition of the debris in the annulus of a capacitor, and subsequent measurement of the change of capacitance compared to a reference capacitor of identical dimensions. The unit was found to respond to magnetic and nonmagnetic metallic debris and to changes in the rate of deposition of the debris. The principle of operation of the monitor is sound.

Difficulty with temperature drift was traced to unsymmetrical grounding of the monitor and reference capacitors. This condition can be corrected readily in any future work.

FOREWORD

This program was carried out for the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory under Contract DAAJ02-71-C-0018, Task 1F162203A43405. The electronic design portion of the program was conducted by Mr. Ramie Thompson of the Applied Physics Laboratory of the Franklin Institute Research Laboratories. Mr. Meyer Salomonsky of the Eustis Directorate served as Technical Monitor for the program and supplied useful information and encouragement.

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INTRODUCTION

Oil-lubricated surfaces, such as gears and bearings in a mechanical system, ordinarly fail through surface fatigue. The mechanism of failure appears to be the introduction of microcracks in the load-supporting surfaces because of the cyclic load application. The micro-crack structure spreads across and into the surface, and, eventually, portions of the surface which are bounded by the cracks are lifted from the part and are carried away by the lubricating oil. The surface portions which are removed have a flake-like appearance and are larger in size than normal wear particles which are simply abraded from the surfaces. Further surface disintegration occurs as the walls of the pit left by the lost material are broken down, and additional pits are formed. The process continues until the part is weakened structurally and fails, or until frictional forces are excessive and the system must be shut down.

A typical graph of metal content as a function of running time for a lubrication system is shown in Figure 1. It is convenient to refer to point C as the initial failure point, since surface fatigue and spalling begin at this point. The rate at which metal is generated by the system is reflected by the increase in metal content of the oil after the initial failure point. The rate of increase of metal content is generally at least double the rate of increase during normal operation of the system, and the increased rate results from the metal flakes being removed from the fatigued surfaces. With additional time, the breakdown of the surfaces accelerates, and the rate of increase of metal content in the oil becomes even larger until failure is reached.

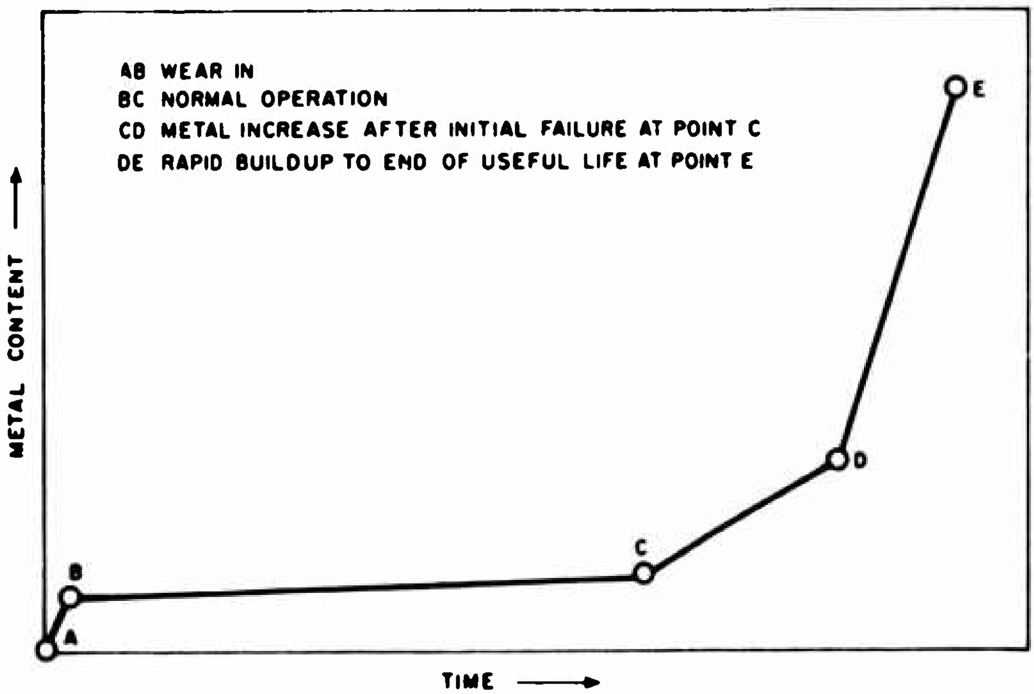

Figure 1. Metal Content vs. Time.

Analysis of lubricating oil from a mechanical system to determine the metal content might reasonably be expected to show when the system has reached the initial failure point. The Spectrographic Oil Analysis Program (SOAP) was instituted for this purpose. Since SOAP analyses require removal of an oil sample from the system and submission of the sample to a laboratory for testing, an undesirable time lag occurs between the taking of the sample and the receipt and interpretation of the analysis. A sensor which could be installed in-line in a recirculating oil lubrication system to show the amount of metal particles in the system and the rate at which metal particles were being generated would eliminate the need for taking and submitting samples and would also eliminate the need for plotting the analytical results against time to determine the rate of increase. It was the objective of this program to design, develop, and evaluate such a sensor.

DESIGN CONCEPT

PERFORMANCE REQUIREMENTS OF SENSOR

The following performance characteristics were desired for an operational in-line metallic debris sensor:

1. Must be sensitive to changes in the total amount and rate of generation of metallic particles both magnetic and non-magnetic, over a time span of 30 to 60 minutes.

2. Must be temperature insensitive, or must be easily compensated for temperature effects.

3. Must be insensitive to changes in flight attitude, or must stabilize rapidly to original readings upon return to level flight.

4. Must be small and lightweight.

5. Must present minimum restriction to fluid flow.

6. Must operate reliably in a vibration environment.

7. Must operate from aircraft electrical power source, and, in the event of power failure, must retain the last readings of total debris and rate of debris generation.

CONCEPTUAL DESIGN

The approach used to design and develop the metallic debris sensor included two observations from previous test and development work in hydraulic and fuel systems. Experience in testing hydraulic filters has shown that a properly designed filter housing separates particulate matter from the hydraulic fluid by cyclone action. When fluid was introduced into the filter housing through a port exactly tangent to the curvature of the filter bowl, the particles were separated from the fluid and settled to the bottom of the filter bowl. Furthermore, the circular flow tended to wash the filter surface, causing particles which had been trapped there to be removed and settle in the filter bowl. Other test work on fuel system fuel level indicators had shown that capacitance probes could be used as fuel level indicators, even with electrically conductive materials, if one of the capacitor elements was coated with polytetrafluoroethylene. A sensor housing which used the cyclone and filter washing action to separate particles which, in turn, would settle into an annular capacitor where the quantity could be measured, would serve two purposes. First, since the particles would be removed from the fluid, the unit would act as a filter; second, the particles, on settling into the annular capacitor, would cause a capacitance change which would allow the unit to act as a sensor of particulate quantity.

In the concept drawing of Figure 2, lubricating oil enters the sensor chamber tangentially, thus setting up the cyclone and washing action. The separated particulate material settles into the annulus at the chamber bottom while the oil passes through the fine screen, and then through the outlet and through an annulus at the edge of the outlet port. The protected plate that forms the common wall between the two annuli is coated with polytetrafluoroethylene. The metallic debris that settles in the outer annulus alters the effective plate area of the capacitor formed by the outer plate and the protected plate. The capacitor formed by the inner plate and the protected plate has clean oil flowing through it and, suitably trimmed to compensate for the smaller plate area, serves as a reference capacitor.

The difference in capacitance for the two annular capacitors should then be only the result of the metal deposited in the outer capacitor, since any changes induced by temperature or water content in the oil should be equal for both capacitors.

The difference in capacitance could be determined by making the collecting and reference capacitors part of a bridge circuit. The bridge output would be proportional to the quantity of debris collected, and, in theory at least, the output signal could be differentiated to give the rate of debris collection. In practice, direct differentiation of the signal would cover too short a time span, so the difference between the amount collected at one point in time and the amount collected at some later time would be used to give the rate of collection.

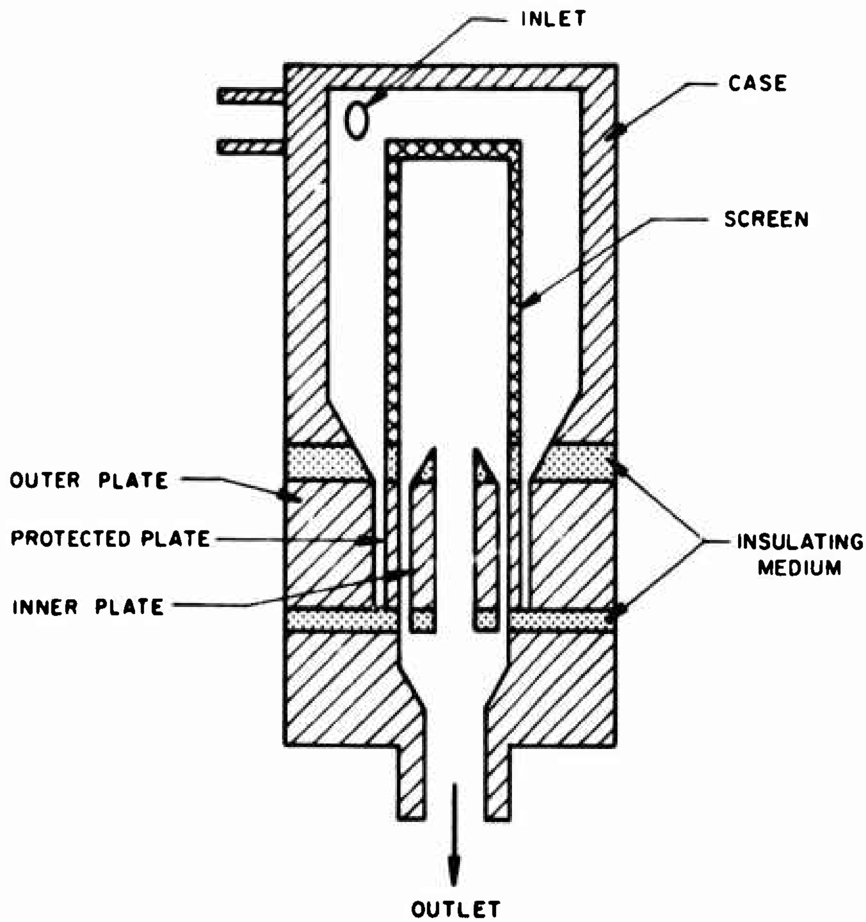

Figure 2. Concept Drawing, Metallic Debris Sensor.

FINAL DESIGN

CAPACITORS

The arrangement of the capacitors in the concept design made it extremely difficult to bring electrical leads to the capacitor plates. In addition, it was realized that the porting arrangement would make it more difficult to mount the sensor. For ease of manufacture and maintenance, it was decided to use two capacitors of identical dimensions, one of which would collect the particles and one of which would be downstream from the filter screen. The downstream capacitor would allow oil to flow through it and would be the reference capacitor. No large amount of trimming would be required for this configuration, since the plate areas of both capacitors would be very nearly identical.

In order to arrive at dimensions for the collector capacitor, calculations were made of the quantity of metal which the sensor might reasonably be required to collect. Data for the calculations were taken from previous bearing test data. Analysis of the lubricating oil (MIL-L-7808) from the bearing tests gave an average of 150 milligrams per liter or 150 ppm of metal contaminant near the end of useful bearing life. The contaminant, for purposes of calculation, was assumed to be steel with a density of 7.83 grams per cubic centimeter. Assuming a system nearing the end of useful life and having an oil volume of 4 gallons, the total weight and volume of debris at a concentration of 150 milligrams per liter is shown in the following calculations:

Total weight of steel debris

$$\frac{4 \text{ gal.}}{.2633 \text{ gal./l}} \times 1.50 \text{ gm/l} = 2.2701 \text{ gm}$$

Volume of steel in 2.2701 gm

$$\frac{2.2701 \text{ gm} \times 0.61 \text{ in.}^3/\text{cm}^3}{7.83 \text{ gm/cm}^3} = .017685 \text{ in.}^3$$

The capacitor should, then, be capable of collecting .017685 cubic inch of steel without overfilling.

The volumes of annular capacitors having a height of 1.00 inch and a plate separation of .010 inch were calculated for different plate radii by using the following equation:

$$V_{annulus} = \pi h \left(r_1^2 - r_2^2\right)$$

where $V_{annulus}$ = volume of capacitor, $in.^3$

h = height of capacitor, in.

r_1 = diameter of outer plate, in.

r_2 = diameter of inner plate, in.

Table I shows the capacitor volume for different radii and shows the degree to which the capacitor would be filled by .017685 cubic inch of steel debris. In calculating the degree of filling, no correction has been made for packing of the debris. In practice, the volume of steel debris would be the same, but since it would not pack to its full density, the height of the debris in the annulus would be greater than that calculated. A 75- to 77-percent degree of filling was selected, since the radii involved were not too large and the remaining 23 to 25 percent seemed sufficient to account for the packing of the debris.

TABLE I. CAPACITOR VOLUME AND PLATE RADII

r_1 (in.)	r_2 (in.)	$V_{annulus}$ ($in.^3$)	% Fill
.260	.250	.016022	110.04
.270	.260	.016650	106.21
.280	.270	.017278	102.35
.290	.280	.017907	98.76
.300	.290	.018535	95.41
.310	.300	.019163	92.29
.320	.310	.019792	89.35
.330	.320	.020420	86.61
.340	.330	.021048	84.02
.350	.340	.021676	81.59
.360	.350	.022305	79.29
.370	.360	.022933	77.12
.380	.370	.023561	75.06
.390	.380	.024190	73.11
.400	.390	.024818	71.26
.410	.400	.025446	69.50
.420	.410	.026075	67.82
.430	.420	.026703	66.23

A test capacitor was prepared for the purpose of measuring the change in capacitance incurred with different amounts of metal particles, the magnitude of the capacitor output, and the effect of excitation frequency on capacitor sensitivity. The capacitor was constructed by mounting hollow stainless steel cylinders concentrically as the capacitor plates in a black phenolic housing. The inner cylinder was coated with polytetrafluoroethylene before mounting. The capacitor dimensions used were:

Plate height	1.000 inch
Diameter, outer plate	.750 inch
Diameter, inner plate	.730 inch

The 1.000-inch height was later modified by beveling the top portion of both cylindrical plates. The parallel portion of the plates after beveling was 0.784 inch in height. The gap before coating the inner plate with polytetrafluoroethylene was 0.10 inch.

Calculations of the probable electrical performance of the test capacity were made for the capacitor with a 0.0035-inch coating of polytetrafluoroethylene on the inner plate and a 0.0065-inch gap which would be filled with oil. The overall capacitance of the sensor, filled with oil but containing no debris, was approximated by considering the total capacitance to be the result of the series combination of the capacitances of the coating layer and the gap. Thus,

$$C_u = \frac{C_o\, C_t}{C_o + C_t} \tag{1}$$

where C_u = the sensor capacitance without debris

C_o = the oil filled gap capacitance

C_t = the coating capacitance

The capacitance variation as particles fill the gap was derived by consideration of Figure 3, which represents a parallel plate capacity analogy with metal particles filling the gap to a height x. If electrical field fringing is neglected, the total capacitance between plates A and B can be written as the parallel combination of the capacitance of the portion of the coating covered by metal debris, C_t (x/h), with the series capacitances of the remaining oil-filled gap, C_o (1-x/h), and the remaining part of the coating, C_o (1-x/h). Thus,

$$C(x/h) = C_t(x/h) + \frac{C_o\,(1-x/h)\; C_t\,(1-x/h)}{(1-x/h)\;(C_o+C_t)} \tag{2}$$

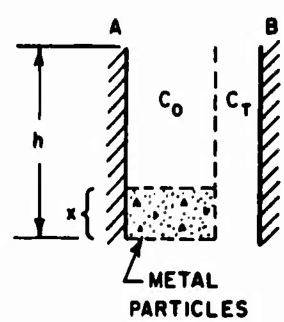

Figure 3. Parallel Plate Capacitor Analogy.

where C_o and C_t are as before,

$C(x/h)$ is the capacitance of sensor partly filled with debris

x/h is the fraction of the total height of the sensor occupied by debris.

By rearranging equation (2) and substituting from equation (1), a simplified expression for the partly filled capacitor is obtained.

$$C(x/h) = C_u \left[1 + (x/h)\ (C_t/C_o)\right] \tag{3}$$

Using a parallel plate approximation for the cylindrical capacitors and the dimensions given earlier, a value of 243 μμf was calculated for C_t. Similarly, a value of 62.3ε μμf, where ε is the dielectric constant of the oil relative to vacuum, was calculated for C_o. Consideration of the calculated values of C_t and C_o, when applied in equation (3), shows that the percentage change in capacitance will be approximately double the percentage change in the height of the deposited debris, provided that ε is near a numerical value of 2. The relative dielectric constant for MIL-L-7808 lubricating oil is near this value. From these calculations, it is apparent that the capacitance changes will be magnified as debris settles in the capacitor. In the foregoing calculations, the packing phenomenon for the metallic particles has been ignored.

The performance of the experimental test capacitor was evaluated under simulated conditions by filling it with MIL-L-7808 oil, to which varying quantities of carbonyl iron in the particle size range of 2 to 5 microns were added. The capacitance was measured as a function of the weight of carbonyl iron added to the oil. At high concentrations of carbonyl iron, difficulty was encountered, in that a thick slurry was formed which would not flow readily into the capacitor annulus. The capacitance of the oil-filled unit with no particles settled in the annulus was 146 μμf. This result was essentially independent of the excitation frequency; the excitation frequency selected for further use, based solely on convenience, was 1000 Hz. The results of the experiment are shown in Table II. The total change in capacitance is in the region of 80 to 100 μμf.

The capacitor was cleaned overnight in an ultrasonic cleaner after the conclusion of the experiment. The air-filled capacitance of the unit was 61 μμf compared to a pretest value of 58 μμf. The capacitance of the unit filled with 1.2 grams of dry carbonyl iron was 220 μμf.

The basic dimensions and performance of the capacitor were good and were retained as the basis for the capacitors to be made for the in-line unit. The gap dimension was increased to 0.013 inch in the final configuration to allow larger particles to enter the annulus.

TABLE II. CHANGE OF SENSOR CAPACITANCE

Total Grams of Carbonyl Iron Mixed With the Oil	Capacitance ($\mu\mu f$)	Notes
0.0	146	
0.1	148.5	
0.3	158	
0.5	176	
0.7	183	
0.7	196	After stirring and settling for 5 minutes
0.7	203	20 minutes settling
0.9	212	
1.1	217	20 minutes settling
1.3	222	20 minutes settling
1.8	232	1 hour settling
2.2	233	0.5 hour settling
2.5	239	20 minutes settling
2.9	242	20 minutes settling*
3.1	242	0.5 hour settling*
3.3	242	0.5 hour settling*

*Filling was a sticky paste.

SENSOR

The prototype sensor for in-line use consisted of three main parts:

1. Housing
2. Monitor and reference capacitors
3. Filter screen

A drawing of the sensor assembly is shown in Figure 4.

During operation, oil enters the sensor through the inlet tangentially. The centrifugal action so induced serves to separate particles from the fluid and to wash particles from the filter assembly. The separated particles fall into the annulus of the monitor capacitor at the bottom of the filter chamber, where they bring about a change in capacitance of the monitor capacitor. The oil, together with small normal wear particles, passes through the filter to the outlet port, but a portion of the flow is diverted through the annulus of the reference capacitor. The flow through the annulus enters the collector groove and combines with the main outlet flow. Provision was made to install an orifice between the

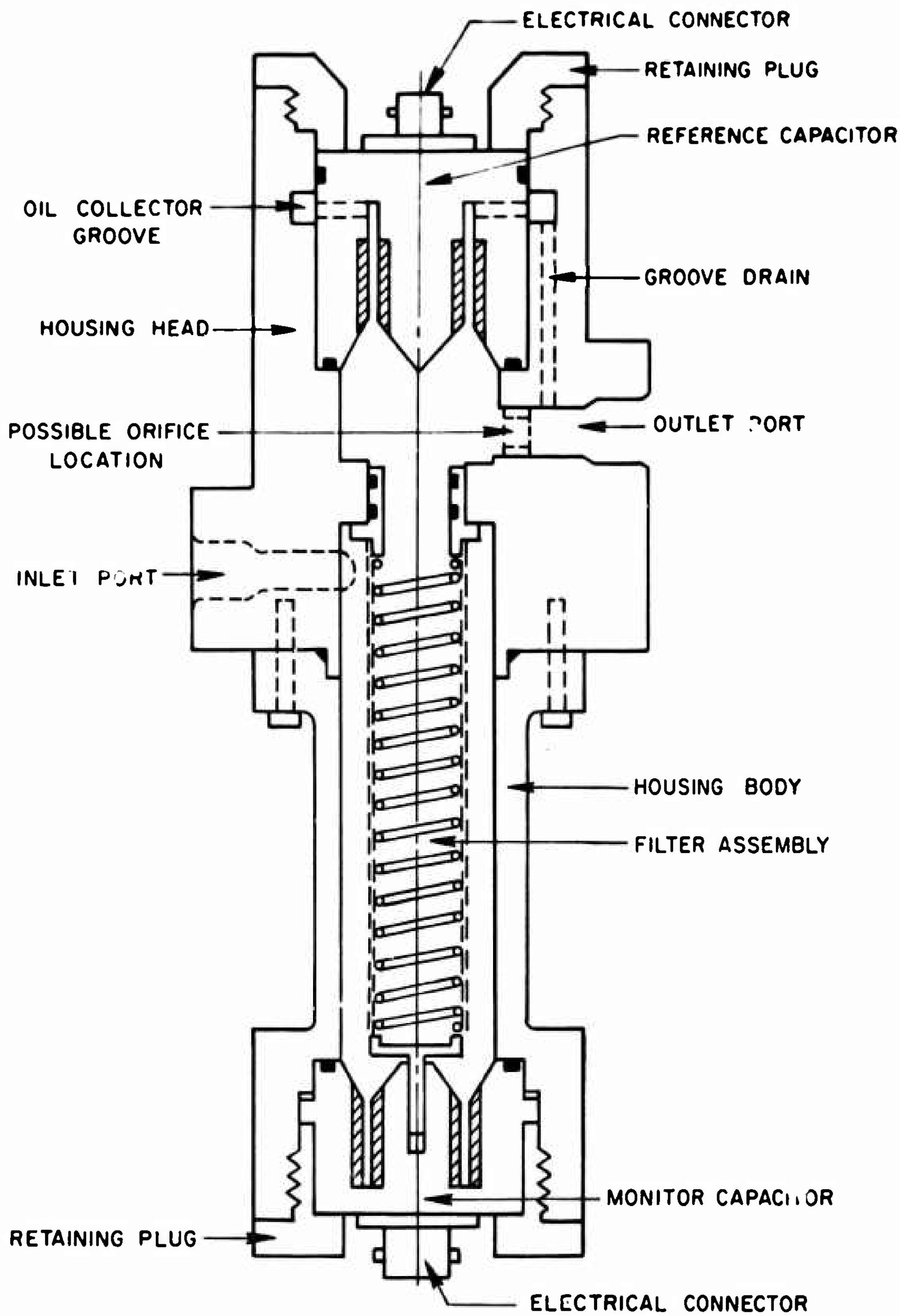

Figure 4. Sensor Assembly Diagram.

outlet and the filter (as shown in Figure 4) if it became necessary, in order to increase flow through the reference capacitor. The sensor assembly was designed so that the parts, including the capacitors, could be removed for cleaning or servicing without disconnecting the housing head from the lines.

Figures 5 and 6 show the sensor housing and an exploded view of the sensor with dummy, all-aluminum capacitors. Figure 7 shows the actual monitor and reference capacitors in black phenolic plastic mounts. The weight of the sensor in the form shown is 2.7 pounds, which could be further reduced by using thinner housing walls and capacitor retaining plugs.

Since it was expected that the filter screen size would have an effect on the pressure drop across the sensor, three filter screens with the following opening sizes were prepared:

50 microns (325 mesh)
135 microns (100 mesh)
215 microns (60 mesh)

The screens were silver soldered to a slotted, stainless-steel, cylindrical screen support.

READOUT UNIT

The signal processing and display electronics consisted of a bridge circuit and a servo loop in a portable carrying case. The readout from the unit is by means of two meters which show the total amount of debris collected in the monitor capacitor and the difference in the amount collected between a given reading time and the reading time immediately preceding it.

The bridge circuit was evolved from the following equation governing bridge circuit response:

$$\left|\frac{V_o}{V_a}\right| = \frac{(x/h)\ (C_t/C_o)}{2\ (2 + (x/h)\ (C_t/C_o)}$$

where V_o = output voltage

V_a = excitation voltage

x/h = fraction of capacitor filled with debris

C_t = coating material capacitance

C_o = oil layer capacitance

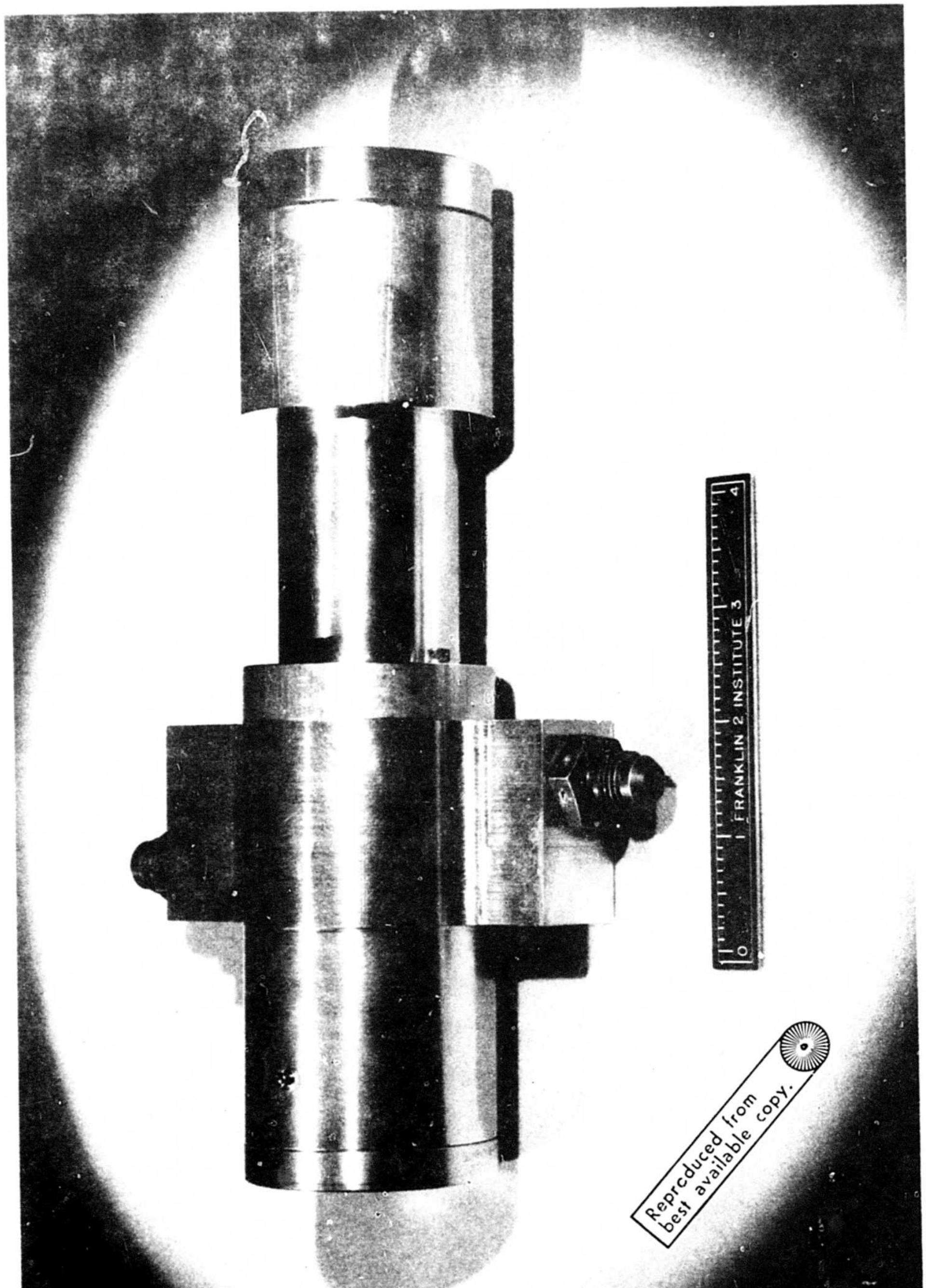

Figure 5. Sensor Housing.

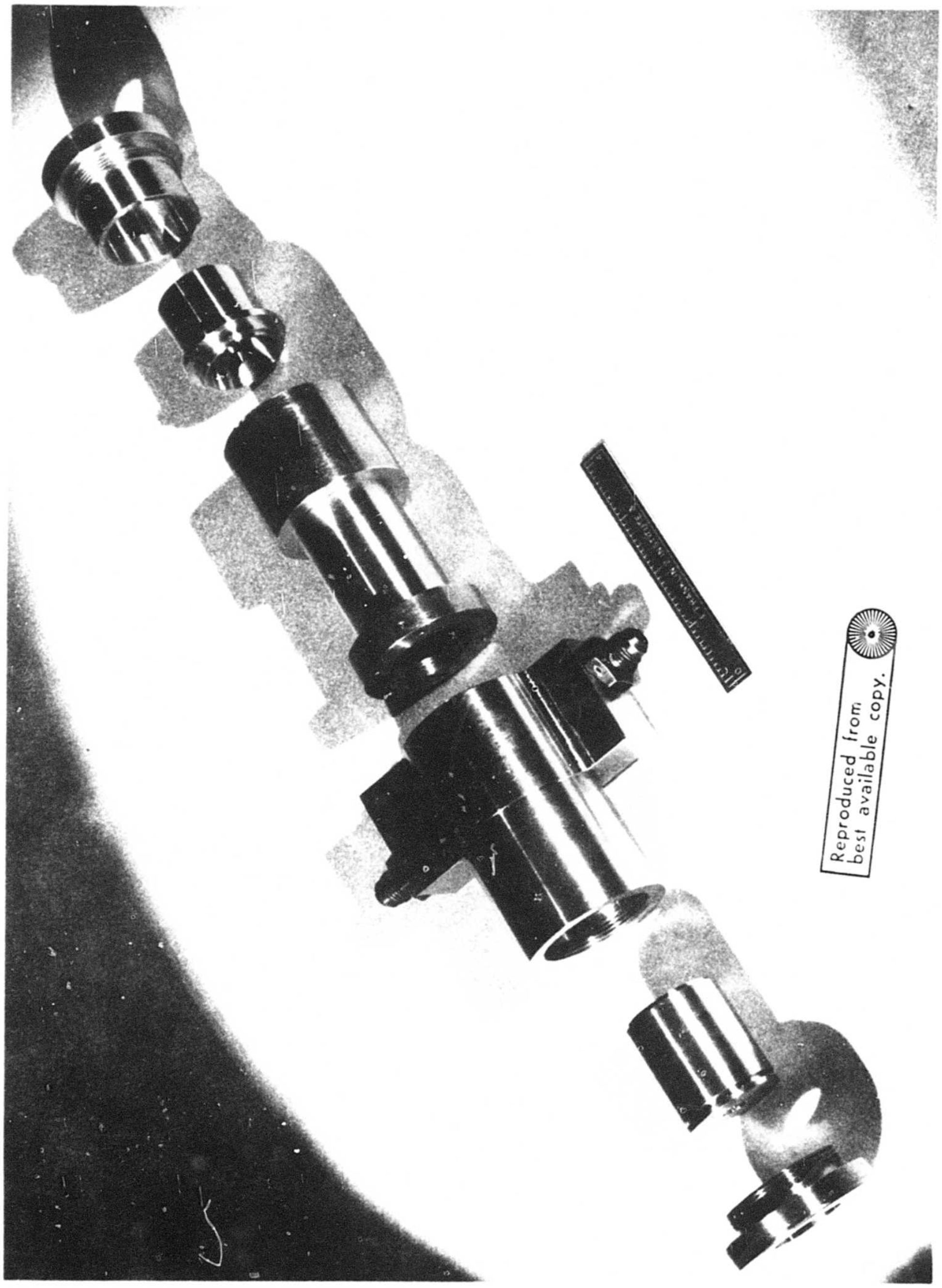

Figure 6. Exploded View of Sensor Housing.

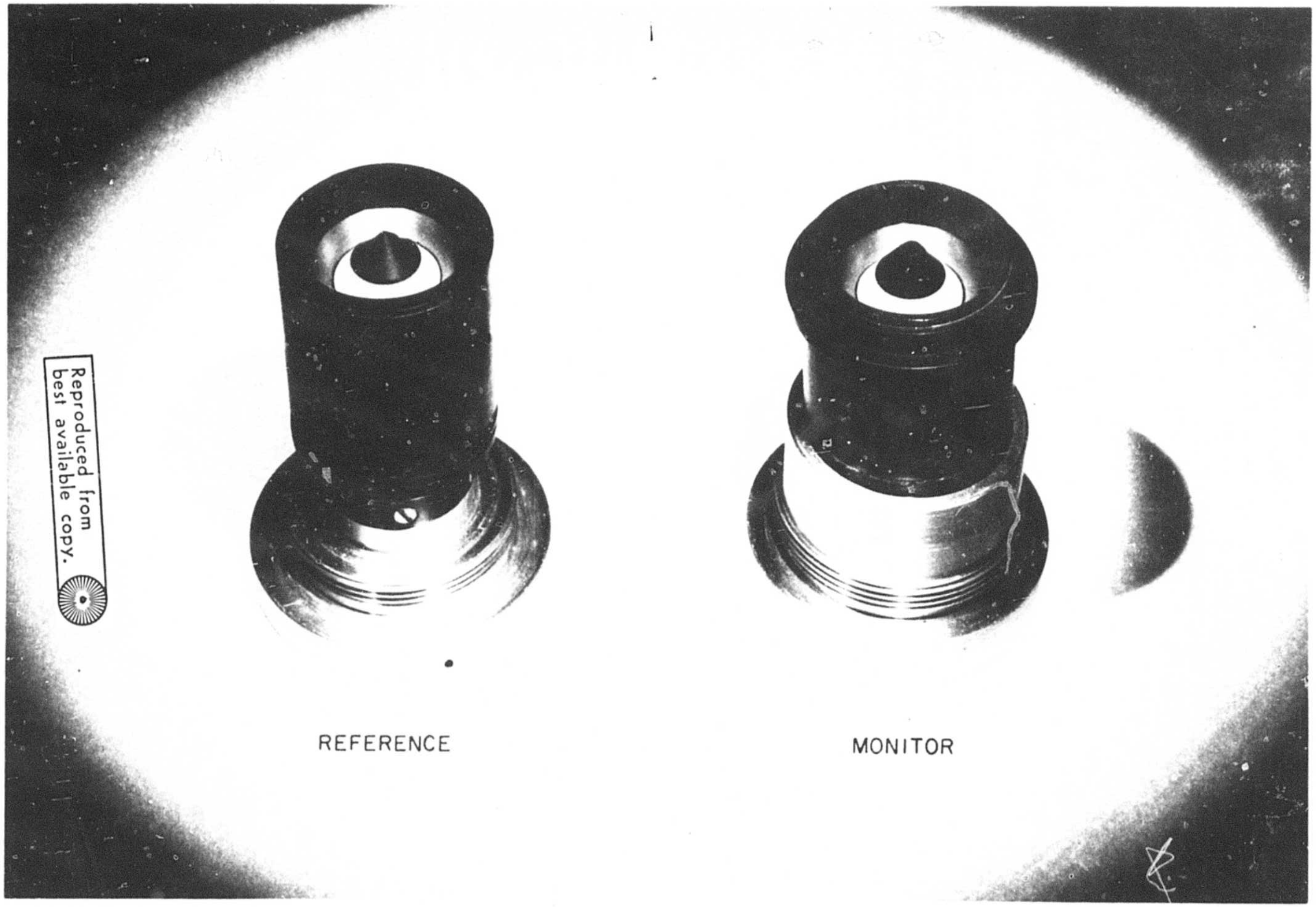

Figure 7. Monitor and Reference Capacitors.

The response of a typical bridge circuit is in Figure 8. At values of $(x/h)\ (C_t/C_o)$ greater than 1, the output will be approximately linear, but values of $(x/h)\ (C_t/C_o)$ of less than 1 will give readings which will indicate a lessening derivative (rate of accumulation) for equal increments in debris. Since the value of C_t/C_o is near 2 for the sensor capacitor, the value for the fraction filled (x/h), which would be the minimum for linearity, is about 50 percent. In practice, maximum meter deflection for the meter measuring the amount of debris collected was obtained for an x/h value of .13 or an $(x/h)\ (C_t/C_o)$ value of about .26. In this narrower range, the deviation from linearity is minimized, and the derivative should be uniform for the same increments of debris.

The bridge circuit which was developed for the readout unit is shown in Figure 9. The oscillator, on the far left of the figure, generates about 20 volts peak-to-peak at 1100 Hz. All operational amplifiers were Fairchild 741 units with the base wiring as shown in the inset. Bridge output varied from 0 to 15 volts dc, depending on the degree of filling of the monitor capacitor.

The display portion of the readout unit is shown in block diagram form in Figure 10. The amplified dc signal from the capacitance bridge is used to drive a servomotor, which in turn drives a feedback potentiometer. The potentiometer output is compared to the bridge signal at the operational amplifier, and the servomotor continues to drive the feedback potentiometer until the signals balance. The feedback potentiometer signal is also displayed on the totalizer meter to show the amount of debris in the annulus of the monitoring capacitor. The signal from the feedback potentiometer continues to be shown on the totalizer meter until there is, again, a change in signal from the bridge. By removing the 28-volt dc driving power from the servomotor, the bridge output signal is effectively locked into the potentiometer. During operation, the 28-volt dc servomotor power is removed from the servomotors until they are activated by push-button switches. When the differential indicator switch is depressed, the previous reading from the bridge circuit which is locked in the totalizer potentiometer is compared to the current reading of the bridge circuit, and the servomotor attached to the differential potentiometer drives until the difference signal is balanced. The potentiometer reading is displayed on the differential meter. Since the difference can be either positive or negative, the meter reads both positive and negative. Depressing the second switch updates the totalizer loop by activating its servomotor as explained before. The wiring schematic for the servo loop is shown in Figure 11. The complete sensor and readout unit is shown in Figure 12.

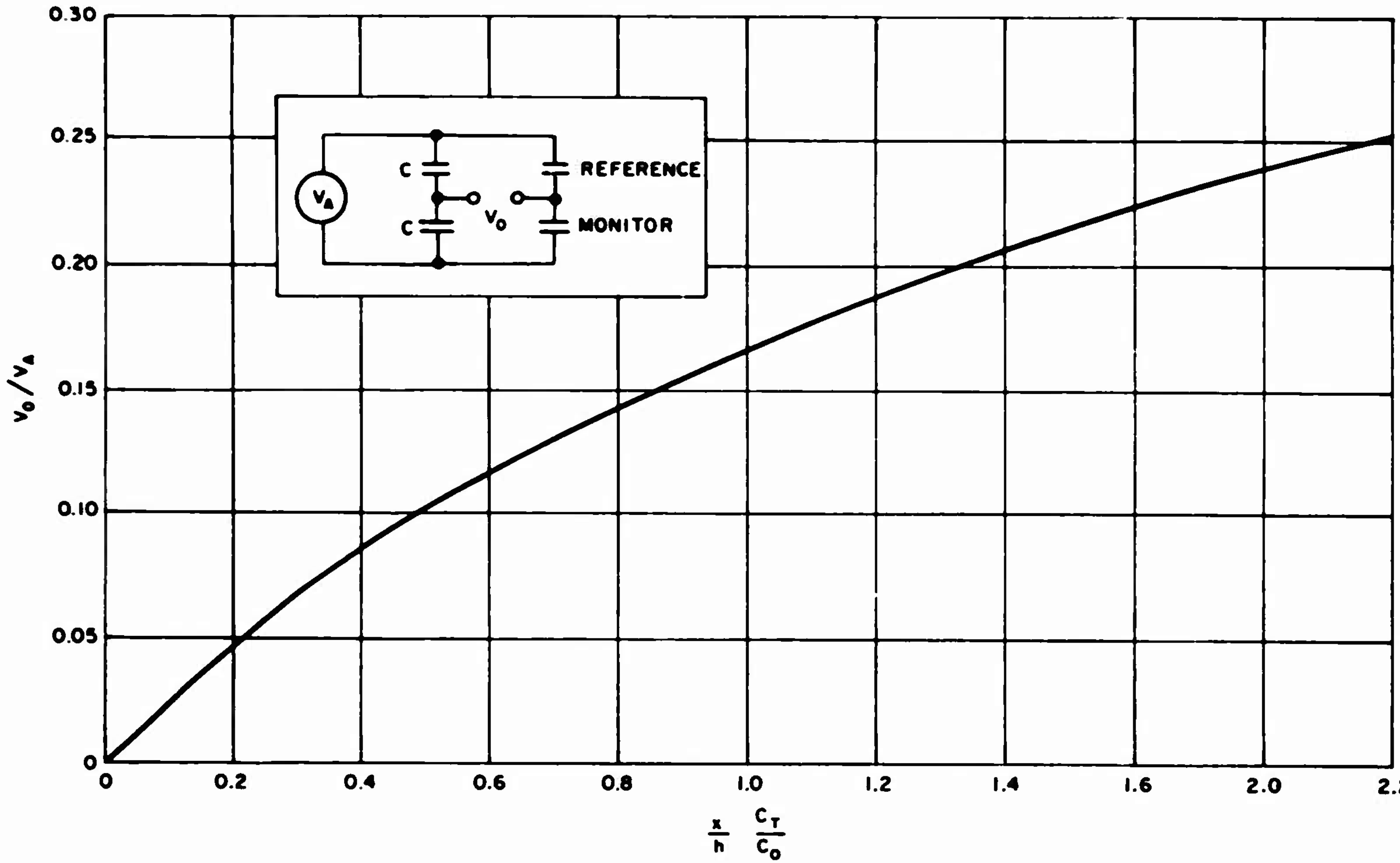

Figure 8. Response for Bridge Circuit.

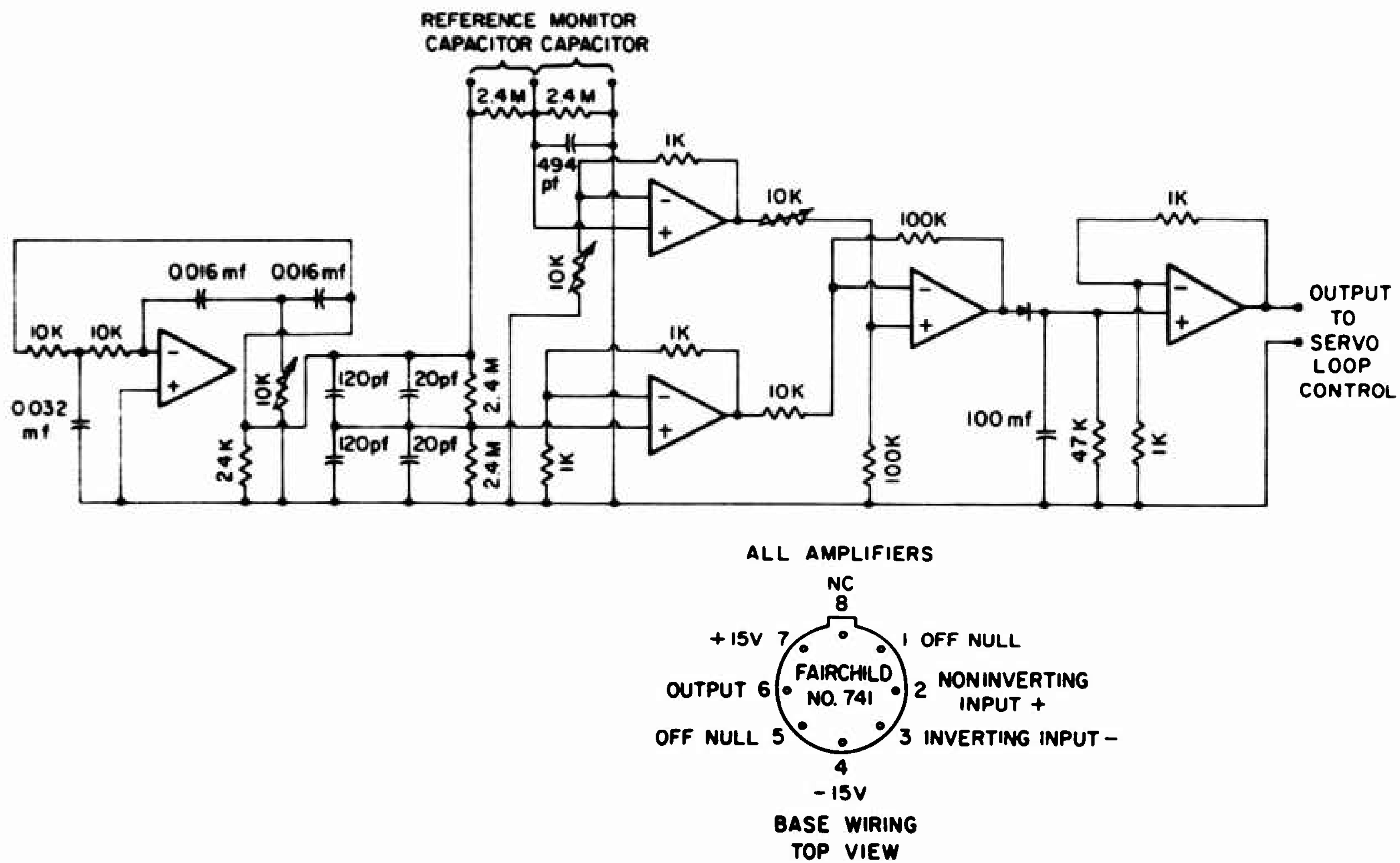

Figure 9. Bridge Circuit.

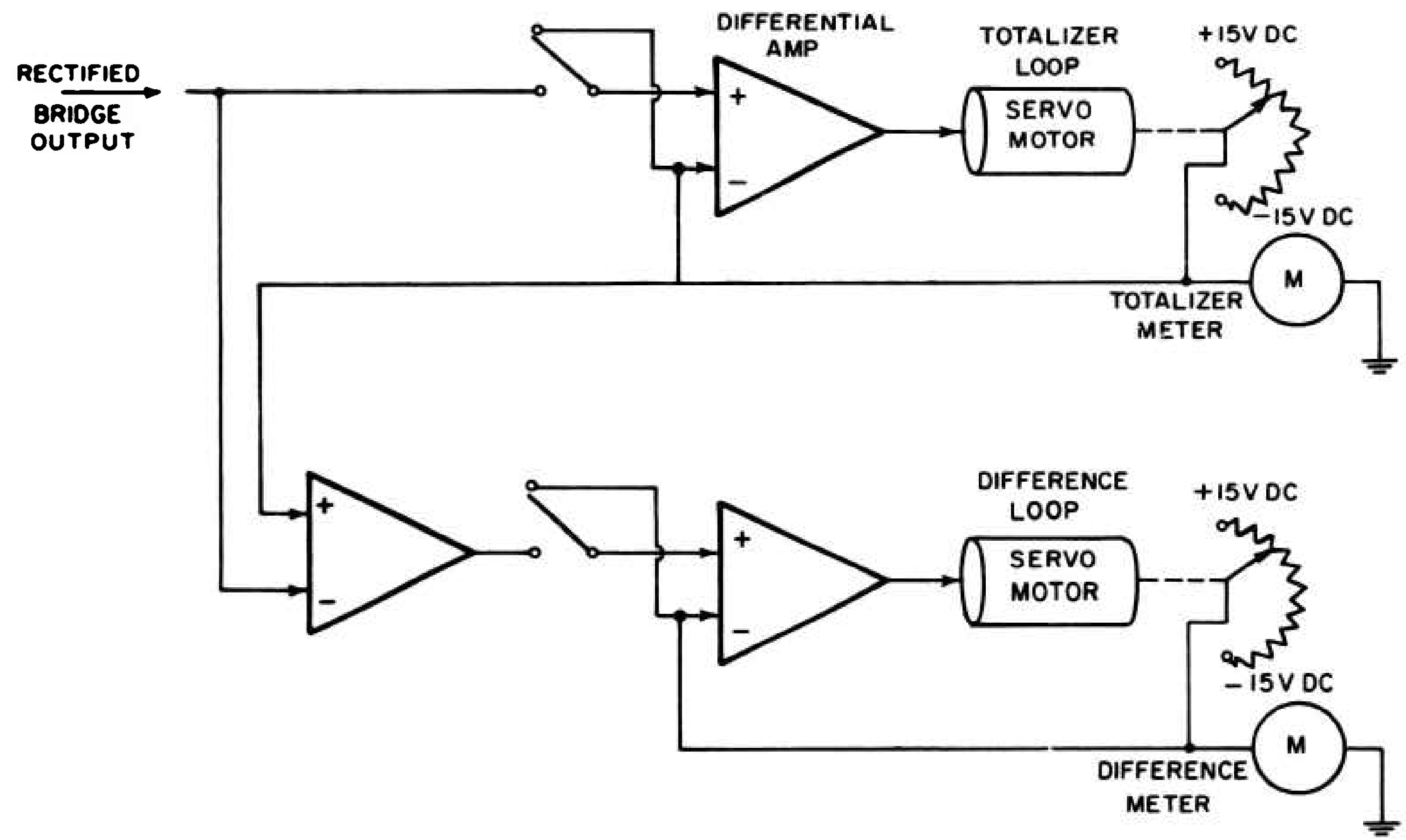

Figure 10. Servo Loop Block Diagram.

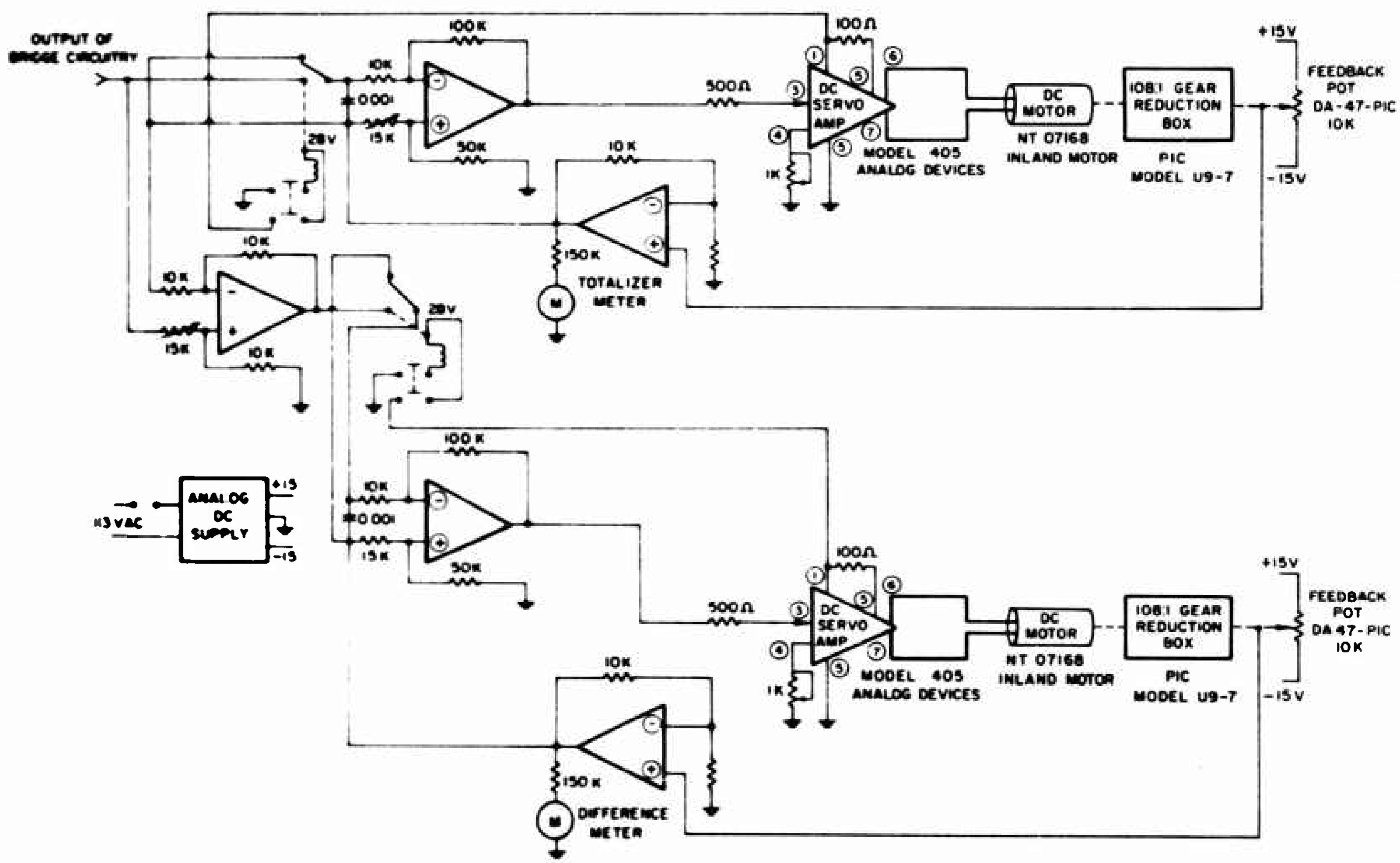

Figure 11. Servo Loop Schematic.

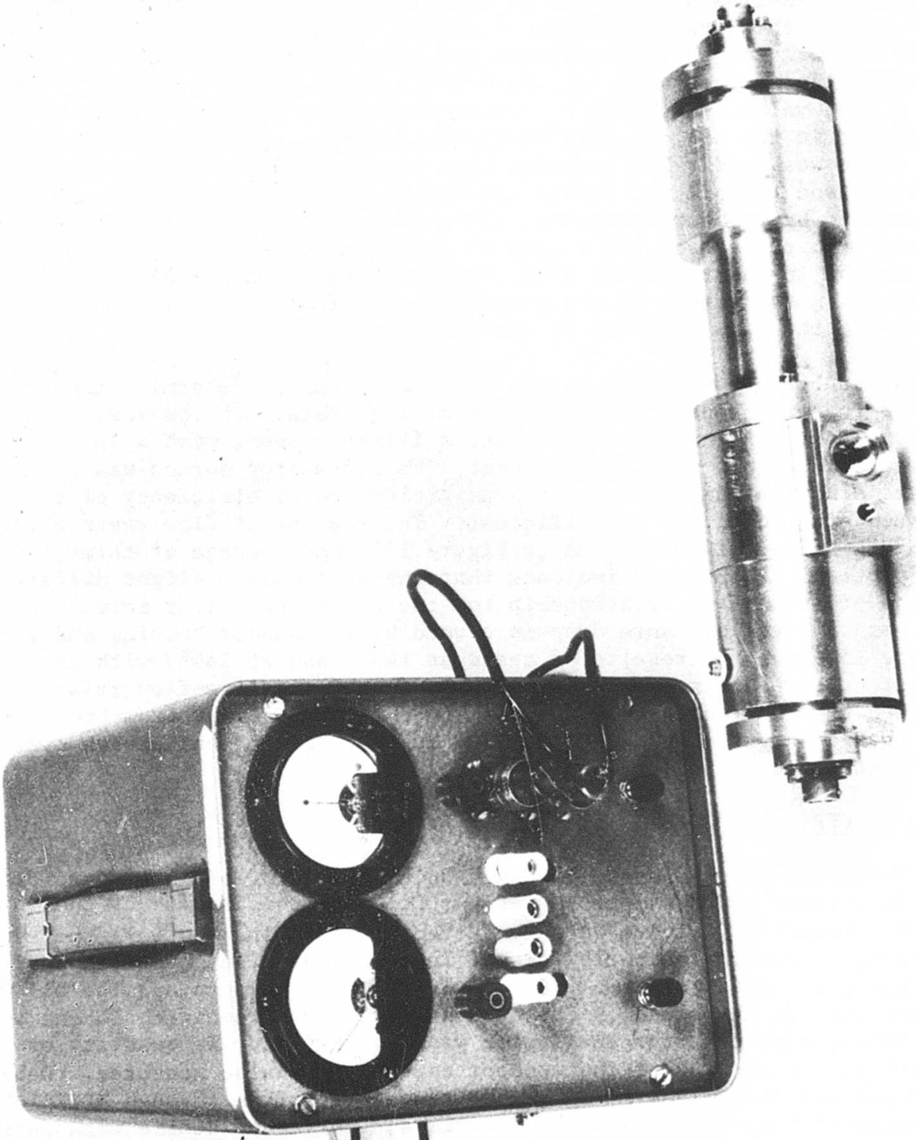

Figure 12. Sensor and Readout Unit.

TEST PROGRAM

FLOW TESTS

In order to conduct tests of flow as a function of differential pressure across the in-line sensor, and to test the sensor for particle removal efficiency, the apparatus shown in Figure 13 was constructed. During opertion, the oil to be passed through the test sensor was placed in the mechanically stirred sump (A), which had a sight level indicator, heaters, and a vent valve. A charge of contaminant could be added to the sump and dispersed in the oil, or, for simple flow versus pressure drop tests, the oil alone was used. The sump was then pressurized from the nitrogen tank (B), and the oil was forced through the test sensor (E) at a flow rate determined by the sump pressure. Pressure gages (D), upstream and downstream from the sensor, were used to determine pressure drop. The oil was caught in the receiving tank (G) which rested on a load cell (F). By plotting the output of the load cell as a function of time on an X-Y recorder, the flow rate was determined.

Tests were first performed on the in-line sensor to determine the pressure drop across the sensor as a function of flow rate. The sensor, with dummy capacitors, was tested without a filter screen, with a 135-micron screen, and with a 50-micron screen. The 250-micron screen was not tested since it was felt that the particle-removal efficiency of a screen of such size would not be sufficient. The results of flow tests at 140°F with MIL-L-7808 oil are shown in Figure 14. The average of three tests was plotted The curves indicate that there is only a slight difference in the pressure-flow relationship for the different filter screens and that most of the pressure drop is caused by the sensor housing and fittings Figure 15 shows the results of tests at 140°F and at 250°F with the two different screen sizes. The difference in the pressure-flow relationship between the two temperatures is slight; this must result from the fact that the change of viscosity of MIL-L-7808 is less than 6 centistokes over the temperature range indicated.

REMOVAL EFFICIENCY TESTS

The operation of the sensor is based on the removing of metal particles from the fluid and the settling of particles in the annulus of the monitor capacitor. Tests were conducted to determine how well the sensor could carry out the particle removal function. Various quantities of iron filings were added to MIL-L-7808 oil in the stirred sump, and the oil was passed through the sensor. The quantity of debris remaining in the sump and tubing upstream from the sensor was measured, and the quantity of debris in the annulus of the monitor capacity was also measured. Debris quantity was determined by filtering the oil residues through preweighed filters, washing and drying the filters and collected debris with petroleum ether, and, finally, drying and weighing the filter with the collected debris. It was found that errors were incurred largely as a result of the

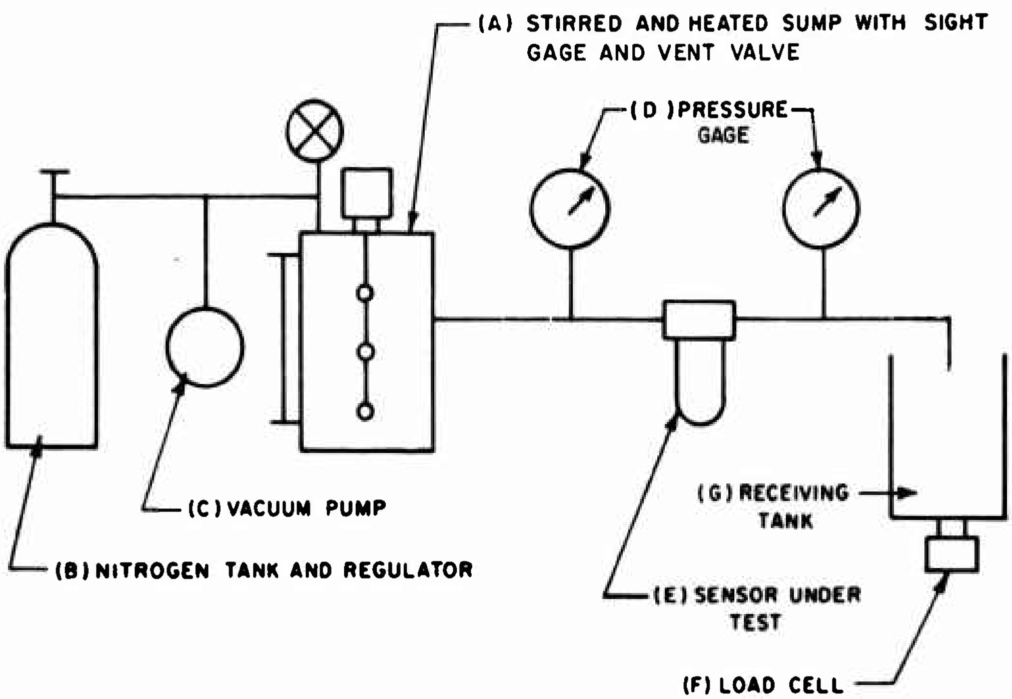

Figure 13. Flow Test Apparatus.

inability to wash the remaining particles completely from the sump. Thus, in some tests, particles remained in inaccessible places in the sump and caused lower particle-removal efficiency results to be calculated. During a later run, some or all of these particles would be swept out and caught by the sensor, thus causing artificially high particle removal efficiency results.

Efficiency of removal is calculated from the following:

$$\frac{\text{Weight of Metal in Detector}}{\text{Weight Added - Weight Remaining Upstream}} \times 100 = \text{Efficiency}$$

The first test series was carried out using iron filings which were unsized. The 135-micron filter screen was used in the sensor, and 2.00 grams of the iron filings was added to the sump. The test results are shown in Table III.

A second test series was conducted using iron filings in the following four size ranges: 44 to 73 microns, 73 to 145 microns, 145 to 177 microns, and 177 to 297 microns. The tests were conducted as noted before, but the quantity remaining in the tank was not determined. The omission of the quantity of particles remaining was dictated by the loss of oil during each determination. Between one pint and one quart of oil remained

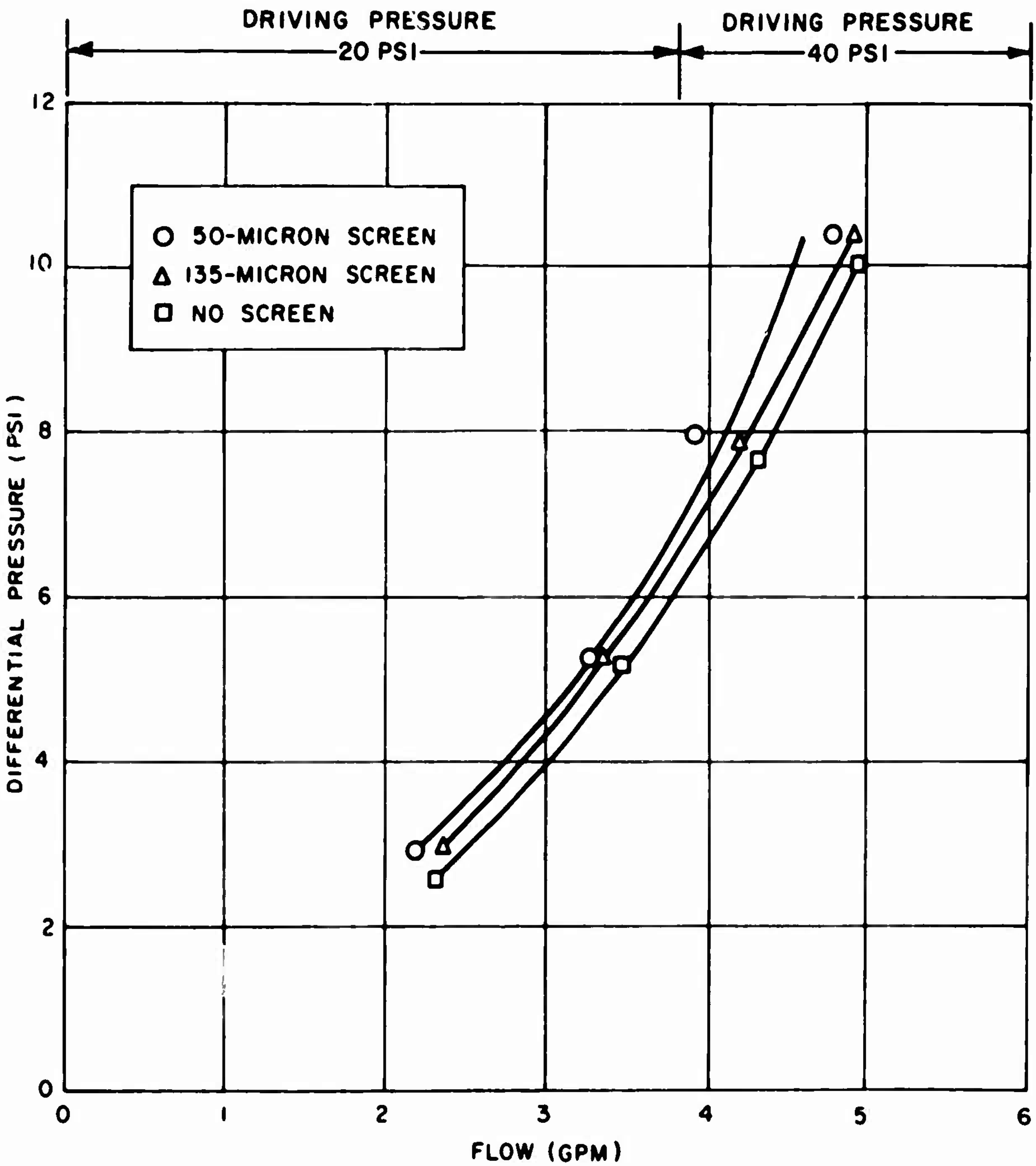

Figure 14. Flow vs. Differential Pressure, Different Screens 140°F.

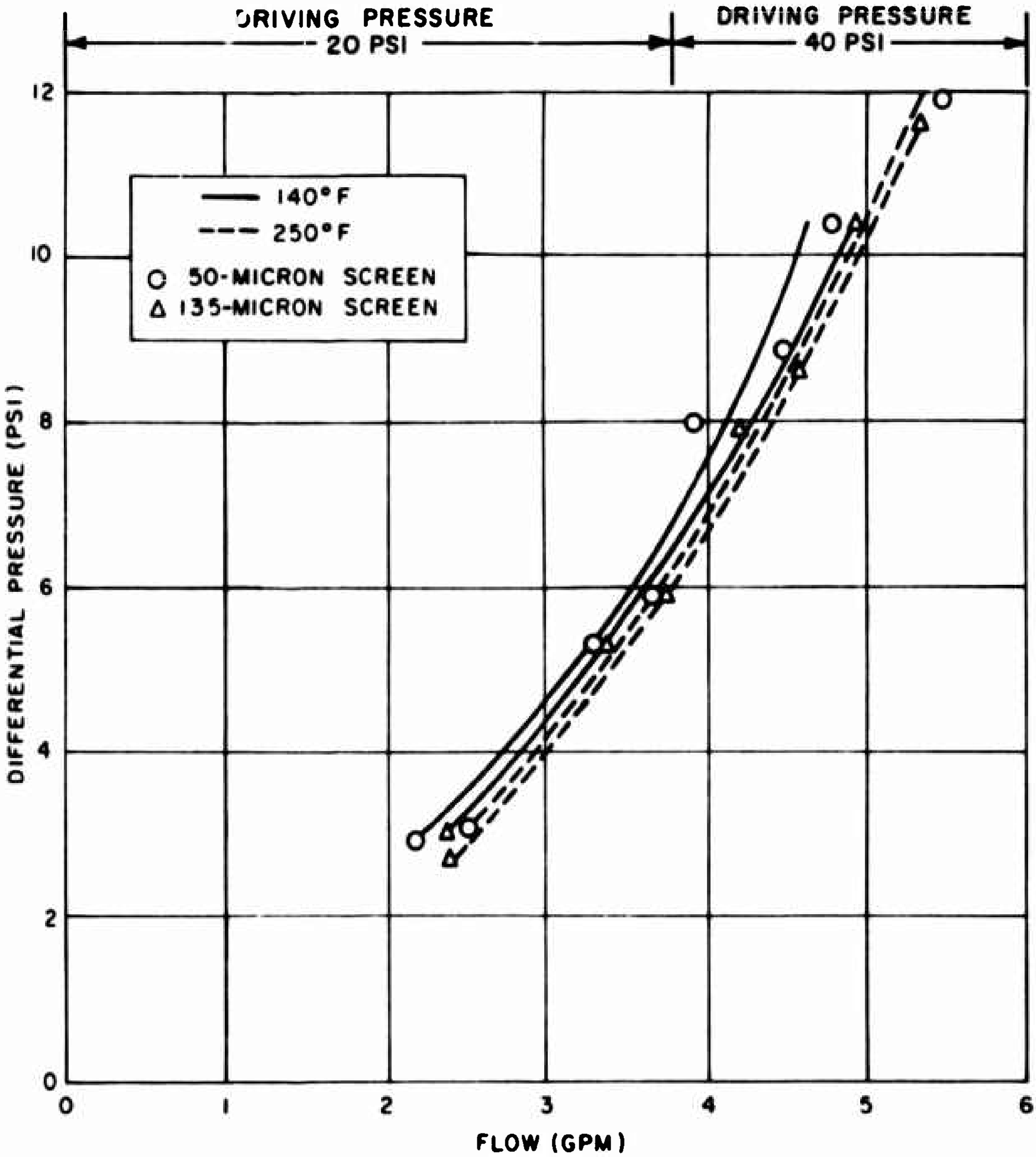

Figure 15. Flow vs. Differential Pressure, Effect of Temperature.

TABLE III. PARTICLE REMOVAL EFFICIENCY – UNSIZED IRON FILINGS

Weight of Filings Added (gm)	Weight Remaining Upstream (gm)	Weight in Detector (gm)	Efficiency (%)	Flow Rate (gpm)
2.00	1.48	.42	81	3.2*
2.00	.60	1.03	74	3.2*
2.00	.62	1.01	73	3.2*
2.00	1.06	.84	89	3.2*
2.00	.74	.96	76	4.5**
2.00	.99	1.01	100	4.5**

*Driving pressure, 20 psi
**Driving pressure, 40 psi

in the sump and was lost in each determination because the oil had to be diluted with petroleum ether prior to filtering. Further, smaller quantities of iron particles were used, and the inaccuracies involved in rinsing the small quantities of particles from the sump would be nearly as great as the inaccuracy involved in ignoring them. As noted before, removal of the particles from the tank was usually incomplete, and the high and low efficiency calculations resulted. The 50-micron filter screen was used in the sensor for this test series. A single 3.2-gpm flow rate was used. The test results are shown in Table IV.

TABLE IV. PARTICLE REMOVAL EFFICIENCY—SIZED IRON PARTICLES

Size Range (Microns)	Quantity Added (gm)	Quantity Collected (gm)	Removal Efficiency (%)
44 to 73	.200	.111	55.6
	.100	.110	110.0
	.200	.174	87.0
	.100	.102	102.0
	.200	.171	85.5
			Average 88.0
73 to 149	.100	.099	99.0
	.200	.175	87.5
	.300	.229	76.2
	.100	.096	96.0
	.200	.143	71.5
	.300	.236	78.5
	.200	.147	73.5
	.300	.254	84.7
			Average 83.4
149 to 177	.100	.079	79.0
	.200	.188	93.9
	.300	.270	90.0
	.100	.095	95.0
	.200	.184	92.0
	.300	.280	93.3
			Average 90.5
177 to 297	.100	.098	98.0
	.200	.152	76.0
	.100	.104	104.0
	.200	.189	94.5
			Average 93.1

The overall average removal efficiency is 87.9 percent, with the smaller particle size ranges having a somewhat lower efficiency and the larger ranges having a higher efficiency, as indicated.

TESTS WITH SIZED MAGNETIC AND NONMAGNETIC PARTICLES

Iron and lead filings were separated into four size ranges by sieving the filings. It was originally intended to achieve particle sizes by a settling technique, but it was found that the particles could not be properly separated from the oil through which they were settled. This made it difficult to place the particles in the monitor capacitor. The following size separations were used:

1. 44 to 73 microns
2. 73 to 145 microns
3. 145 to 177 microns
4. 177 to 297 microns

At least three tests were made with each of the different size ranges, with iron as the magnetic particles and lead as the nonmagnetic particles. During a test run, a known weight of particulate material was allowed to settle into the annulus of the monitor capacitor, which was filled with MIL-L-7808 oil. The reference capacitor was also filled with MIL-L-7808 oil, but no particulate matter was placed in it. Both totalizer meter and difference meter readings were taken after each addition of particles. The results of the totalizer readings are shown in Figures 16 through 19.

The result obtained with lead particles is roughly one-half of that obtained for an equivalent amount of iron particles in the same size range. This results from the higher density of lead and not from a difference in the magnetic properties. A given weight of lead displaces only about one-half as much oil as the same weight of iron.

The linearity of results within a given run is fair, but the between-runs reproducibility can be as high as 15 scale units. This could result in an error of 80 milligrams of iron. The source of the error seems to lie in the way in which the particles settle in the annulus and in nonuniformity of the coating on the inner plate of the capacitor.

The between-runs reproducibility may not have as detrimental an effect on the actual operation of the unit as it would appear since the change in difference reading between two sampling times is the main indicator of system condition. Since the slopes of the weight versus scale reading plots are very nearly the same, the difference scale readings are also very nearly the same between the same two weight points on different curves. If a system generates 14 milligrams of iron per hour under normal running conditions, a doubling of the rate to 28 milligrams per hour at initial failure would be detected if the sampling time was 1 hour. In a system holding 14 quarts of oil, a change from 1 ppm of iron per hour to 2 ppm of iron per hour should be detected in the 1-hour sampling period. The iron particles must be in excess of the filter screening opening size.

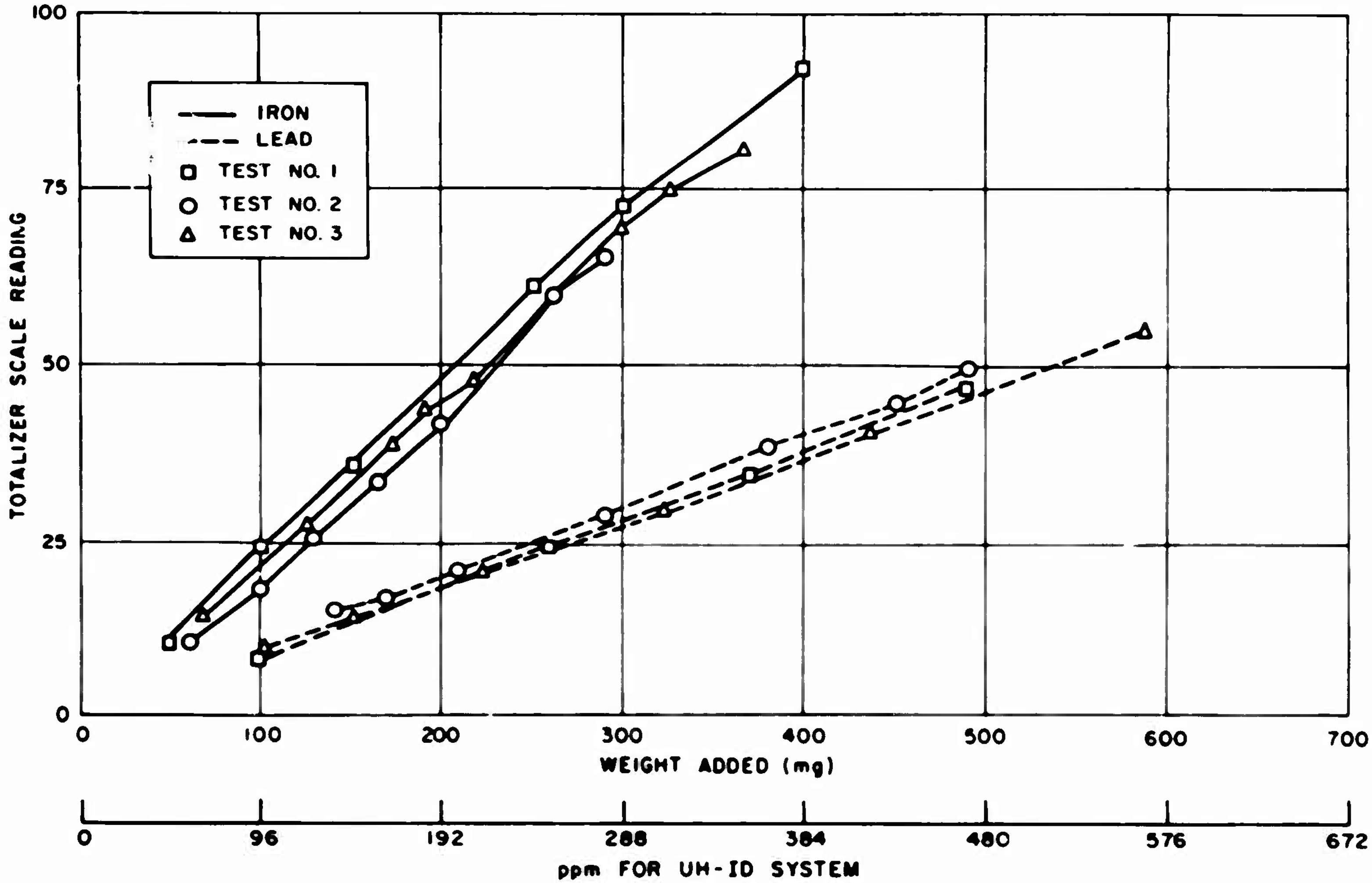

Figure 16. Totalizer Reading vs. Weight Added - 44 to 73 Microns.

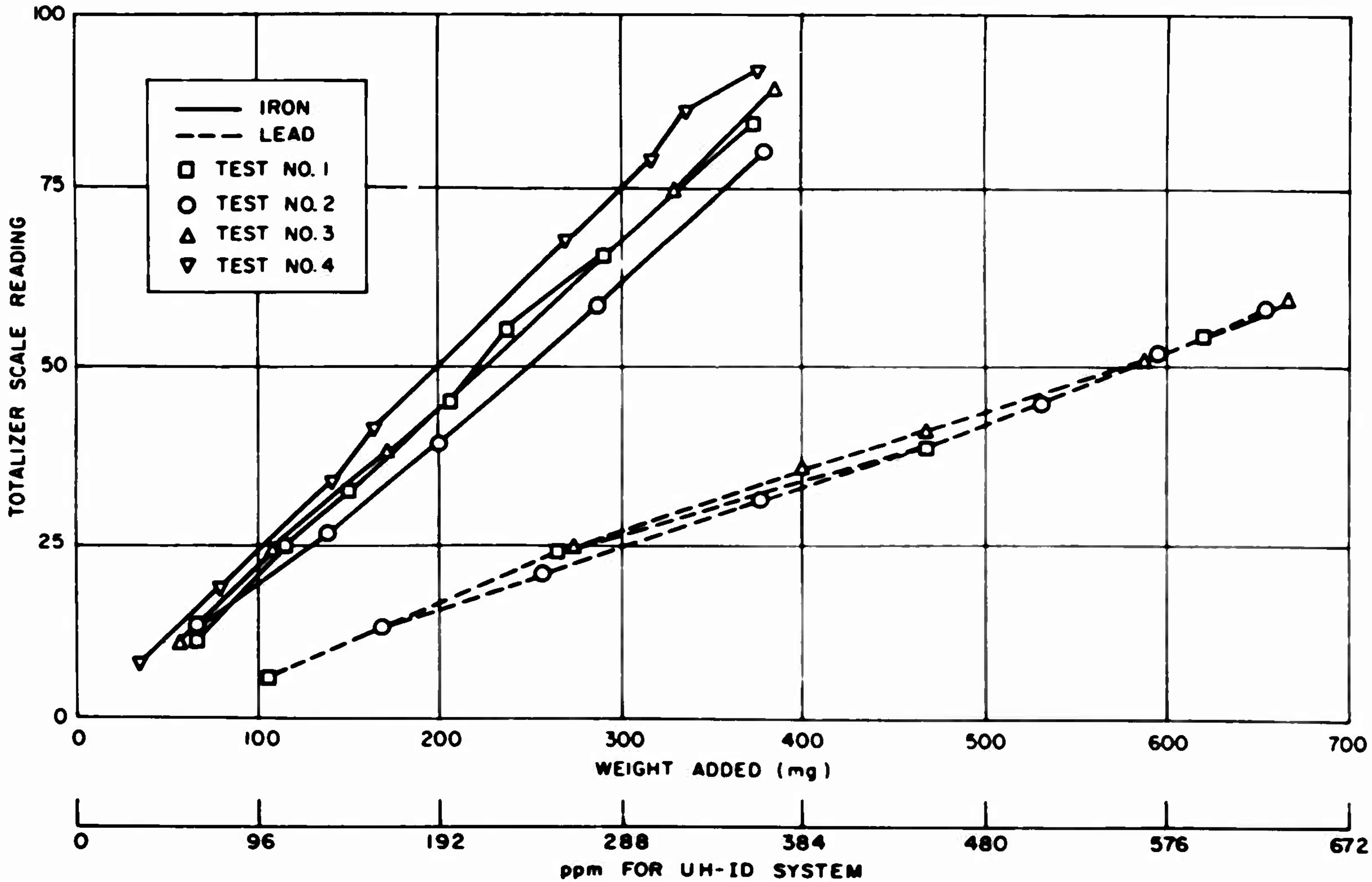

Figure 17. Totalizer Reading vs. Weight Added - 73 to 145 Microns.

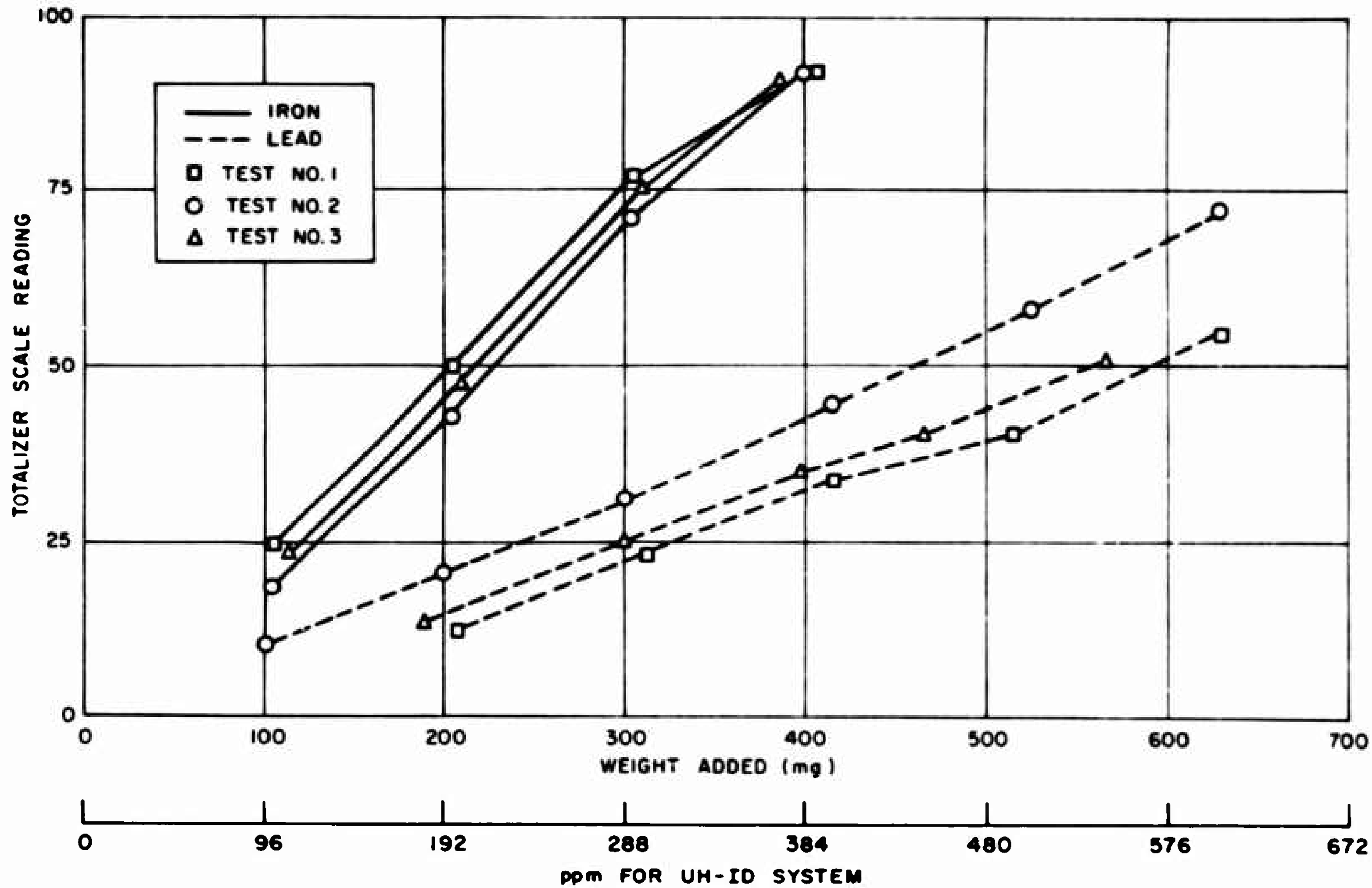

Figure 18. Totalizer Reading vs. Weight Added - 145 to 177 Microns.

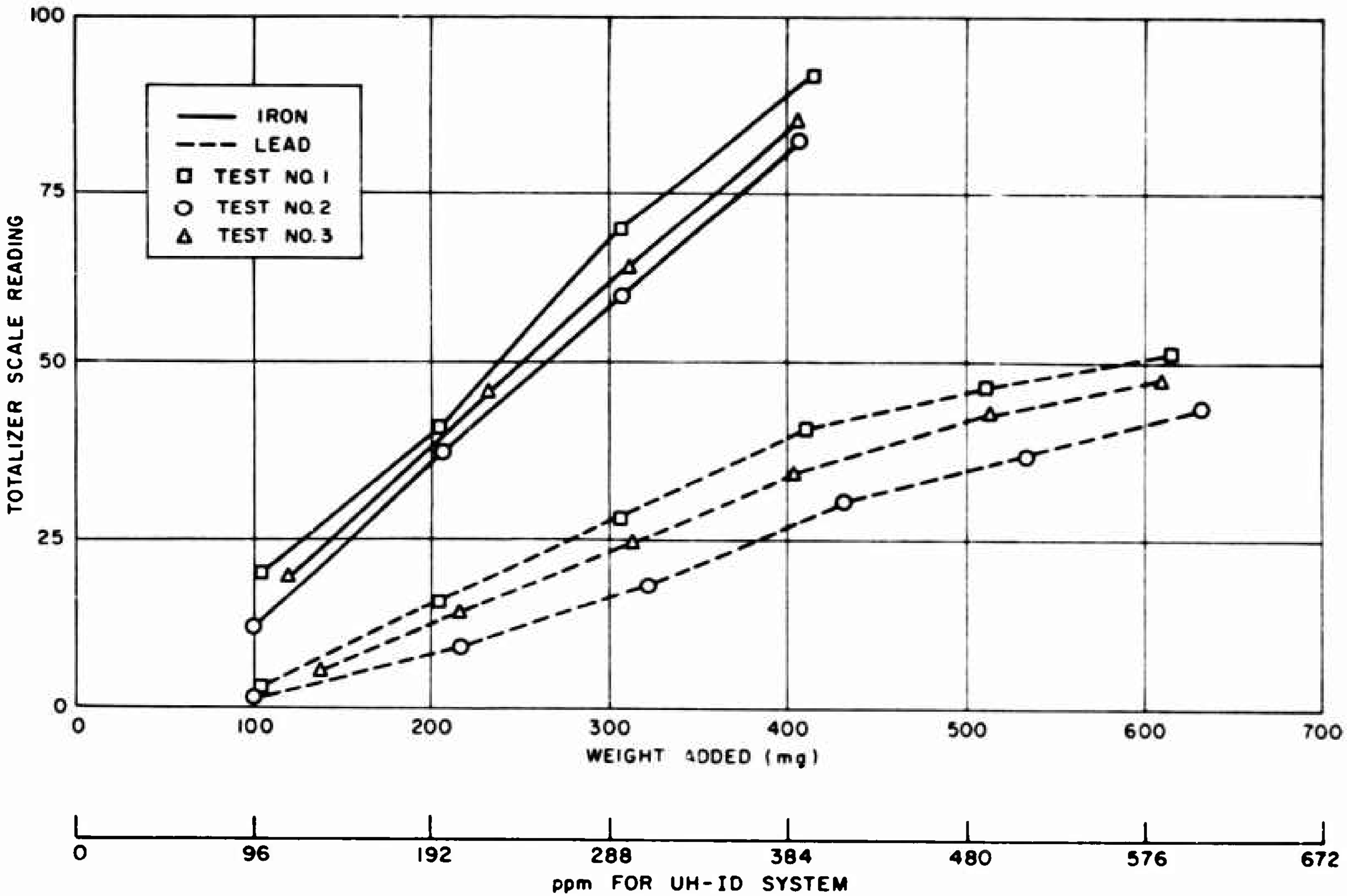

Figure 19. Totalizer Reading vs. Weight Added - 177 to 297 Microns.

The iron content in ppm for any system may be calculated from the following:

$$\frac{\text{Milligrams of Iron Collected}}{.9463\ (\text{System Oil Volume in Quarts})} = \text{ppm of Iron}$$

The comparison of difference scale readings as opposed to the actual differences in totalizer scale readings is given in Tables V through XII. The error, or difference between the two scales, is such that the difference between a scale reading of 4 for a rate of 14 milligrams per hour and a scale reading of 8 for 24 milligrams per hour could be read as less than a doubling of the rate, if a 1-hour sample period is used. The sampling period should be increased to 2 hours in order to read such differences. Increasing the sampling period is preferable to increasing the sensitivity of the monitor, since an increase in sensitivity would reduce the amount of metal collected for a scale reading of 100 on the totalizer, and more frequent servicing would be required. It should be noted that, at the present sensitivity setting of the monitor, assuming a generation rate of 14 milligrams per hour of particles in excess of 44 microns, servicing should be required about every 20 to 24 hours.

TEMPERATURE SENSITIVITY TESTS

The object in using a reference capacitor of exactly the same dimensions as the monitor capacitor was to allow the capacitance bridge to compensate for any changes in the dielectric constant of the oil or dimensions of the capacitors which might be induced by water in the oil or by changes in temperature. While this appeared to be a logical approach and was successful during the breadboard stage, in which standard capacitors replaced the actual monitor and reference capacitors, a specialized problem arose when the real capacitors were substituted. The small but real capacitances between the monitor and reference capacitors and ground, and the likewise small cable capacitances and ground, produced an unbalanced situation in which most of the extraneous capacitance appeared across the monitor capacitor. The capacitance of the monitor was quite small, so the effect was considerable. When the test unit, containing a small amount of iron particles, was heated in an oven from 72°F to 161°F, the reading of the totalizer scale changed from 27 to 63. Subsequent cooling to 72°F returned the reading to 27.

The problem can be minimized or eliminated by shifting the bridge driving signal to the other connecting points of the bridge and using the present signal input points for the bridge output. The bridge will require slight modifications for rebalancing, once the change is made.

VIBRATION TESTS

The in-line unit was subjected to a vibration environment on a standard vibration test fixture. The tests were conducted over a frequency range of 5 to 3600 Hz using a sweep rate of one octave per minute. An acceleration of 10g was achieved at 15 Hz. Below 15 Hz, the acceleration was limited by the double-amplitude displacement of 1 inch. From 10 Hz to 15 Hz, the acceleration increased from 5g to 10g.

TABLE V. COMPARISON OF SCALE READINGS

44-to-73-Micron Iron Particles

Totalizer Scale Actual Difference	Difference Scale Indicated Difference	Error
10	10	0
8	6	-2
8	6	-2
8	7	-1
18	18	0
5	5	0
14	14	0
14	15	+1
11	11	0
5	4	-1
4	4	0
21	22	+1
6	5	-1
6	4	-2
10	8	-2
14	15	+1
12	12.5	+0.5
25	25	0
Average Error Without Regard to Sign		0.8

TABLE VI. COMPARISON OF SCALE READINGS

73-to-145 Micron Iron Particles

Totalizer Actual Difference	Difference Scale Indicated Difference	Error
11	12	+1
13	13	0
8	9	+1
13	12	-1
10	7	-3
10	7	-3
19	13	-6
12	12	0
14	15	+1
13	13	0
17	17	0
21	17	-4
7	7.5	+0.5
11	13	+2
15	15	0
8	8	0
26	25	-1
11	8	-3
7	2.5	-4.5
6	8	+2
11	11	0
13	12	-1
14	12	-2
36	34	-2
15	10	-5
Average Error Without Regard to Sign		1.7

TABLE VII. COMPARISON OF SCALE READINGS

145-to-177-Micron Iron Particles

Totalizer Scale Actual Difference	Difference Scale Indicated Difference	Error
24	26	+2
26	28	+2
27	28	+1
15	15	0
18	18	0
25	29	+4
28	28	0
21	20	-1
Mean Error Without Regard to Sign		1.25

TABLE VIII. COMPARISON OF SCALE READINGS

177-to-297-Micron Iron Particles

Totalizer Scale Actual Difference	Difference Scale Indicated Difference	Error
20	23	+1
21	25	+4
29	29	0
22	22	0
12	13	+1
26	27	+1
22	25	+3
23	22	-1
Mean Error Without Regard to Sign		1.38

TABLE IX. COMPARISON OF SCALE READINGS

44-to-73 Micron Lead Particles

Totalizer Scale Actual Difference	Difference Scale Indicated Difference	Error
9	9	0
5	5	0
7	8	+1
9	10	+1
11	12	+1
14	13	-1
15	14	-1
2	4	+2
4	4	0
8	8	0
10	10	0
6	6	0
8	9	+1
17	18	+1
10	9	-1
12	10	-2
26	25	-1
8	5	-3
Average Error Without Regard to Sign		0.9

TABLE X. COMPARISON OF SCALE READINGS

73-to-145 Microns Lead Particles

Totalizer Scale Actual Difference	Difference Scale Indicated Difference	Error
12.5	15	+2.5
7.5	8	+0.5
11	12	+1
14	14	0
6	4	-2
18	17	-1
6	9	+3
17	18	+1
17	20	+3
14	15	+1
13	14	+1
5	5	0
6	7.5	+1.5
18	19	+1
11	12	+1
6	6	0
10	12	+2
8	7	-1
11	12	+1
Average Error Without Regard to Sign		1.2

TABLE XI. COMPARISON OF SCALE READINGS

145-to-177 Micron Lead Particles

Totalizer Scale Actual Difference	Difference Scale Indicated Difference	Error
10	10	0
10	11	+1
11	10	-1
14	14	0
13	14	+1
14	14	0
10	12	+2
2	2	0
10	10	0
11	11	0
11	13	+2
7	6	-1
14	14	0
9	11	+2
Mean Error Without Regard to Sign		.72

TABLE XII. COMPARISON OF SCALE READINGS

177-to-297 Micron Lead Particles

Totalizer Scale Actual Difference	Difference Scale Indicated Difference	Error
2	2	0
7	7	0
9	9	0
13	14	+1
6	7	+1
7	7	0
8	10	+2
3	3	0
13	12	-1
12	14	+2
14	17	+3
5	5	0
5	5	0
12	12	0
Mean Error Without Regard to Sign		.715

Prior to the test, iron filings in the 44-to-73-micron size range were deposited in the monitoring capacitor until a scale reading of 53 on the totalizer scale was achieved. After subjecting the monitor to the vibration program with the axis of vibration along the vertical axis of the monitor, the reading was unchanged, and the difference scale showed a reading of zero. The monitor was then tilted to an angle of 45 degrees to the vertical axis of the monitor. The totalizer scale reading changed to 84 after vibration, and the difference scale showed a reading of 32. While vertical vibration showed no change in the monitor readings, the vibration at 45 degrees caused a shift in the debris which gave a higher reading. The higher reading was traced to unevenness in the coating in the top part of the monitor capacitor. When the shift in debris occurred, the debris rose on one side of the capacitor as far as the uneven area, and the capacitance change was magnified.

CONCLUSIONS

The principle of the metallic debris monitor based on a changing area capacitor is essentially sound. While the bridge circuitry must be modified to compensate for temperature effects, and better uniformity in capacitor coating is required, the unit will show changes in the rate of deposition (hence generation rate) of metallic particles. The particulate materials can be magnetic or nonmagnetic and ~~will~~ be detected as long as the dielectric properties of the annular space are altered.

The prototype unit weight, including the electrical unit, is 10.5 pounds. The weight of the sensing unit alone is 2.9 pounds. The current required for the prototype is approximately 1.0 amperes for the 28 vdc circuit and .05 ampere for the 115 vac circuits. For operation from an aircraft 28 vdc source only, the current requirement should not exceed 1.5 amperes.

The prototype unit should cause approximately 40 psi drop at the 12 gpm flow in UH-1D main gear box. Since the output pressure of the oil pump must be regulated downward by more than 40 psi, sufficient pressure is available to sustain the oil flow.

RECOMMENDATIONS

The in-line metallic debris monitor should be tested on a running transmission in order to prove that the increase in rate of generation of metallic debris, signalling the point of incipient failure, can be detected. The tests should be conducted after the bridge circuitry has been modified to compensate for temperature changes in the oil. An automatic sample period timer should be installed.