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DEVELOPMENT OF ABRASIVE OIL CONTAMINANT
INDICATOR SYSTEM FOR M35A2 2 1/2 TON TRUCK
AND M151A2 1/4 TON TRUCK ENGINES

David A. Monaghan

Foster-Miller Associates, Incorporated

Prepared for:

Army Tank Automotive Command

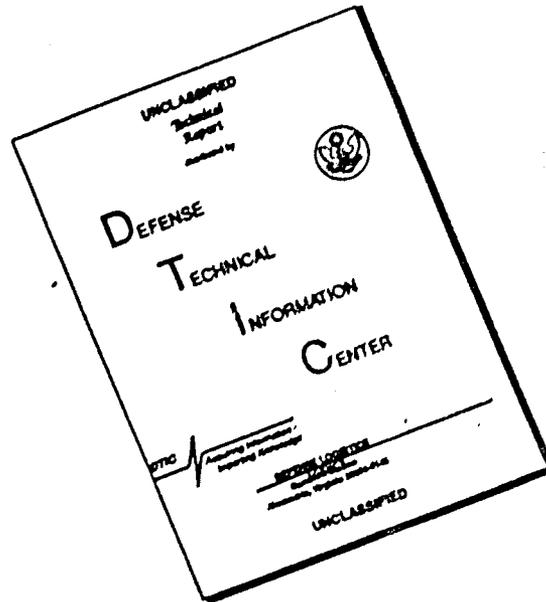
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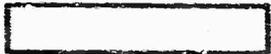
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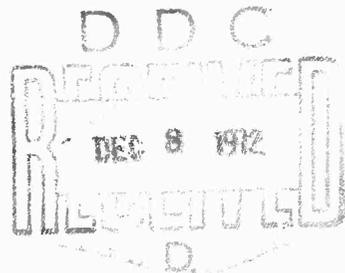
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DEVELOPMENT OF ABRASIVE OIL
CONTAMINANT INDICATOR SYSTEM FOR
M35A2 2 1/2 TON TRUCK AND
M151A2 1/4 TON TRUCK ENGINES



by D. A. Monaghan

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Contract No. DAAE07-71-C-0241

TACOM

PROPULSION SYSTEMS LABORATORY

U.S. ARMY TANK AUTOMOTIVE COMMAND Warren, Michigan

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13. ABSTRACT An investigation was undertaken to develop an abrasive oil contaminant indicator for use on the M35A2 2 1/2 ton and the M151A2 1/4 ton trucks. This included quantitative determination of the characteristics of abrasive lubricant contaminant, the development of a concept to detect and indicate the presence of the abrasive particles, the design, fabrication and testing of a device to implement this concept in a practical manner. The sensor developed employs a thin metallic coating on a non-conducting quartz substrate which is abraded by the action of the abrasive particles in the lubricant. The extent of the wear is indicated by an increase in the electrical resistance of the path due to the reduction in the cross sectional area of the metallic conducting path. Excessive abrasive action actuates a warning light in the cab of the vehicle through an electronic circuit. The warning signal persists until the wear element is changed. The program included extensive investigation of lubricant contamination, experimental determination of the feasibility of the proposed concept, development of prototype sensor and electrical indicator designs, fabrication and testing of the prototype designs, installation of the indicators on military vehicles and cost evaluation of the indicator systems in production quantities.			

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Diagnostic						
Engine Diagnostic						
Lubricant Monitor						
Oil Life Indicator						
Contaminant Monitor						
Abrasive Indicator						

I-B

13. Abstract (cont.)

As required by the contract, 6 complete systems were supplied for the 2 1/2 ton truck and 6 systems for the jeep. These systems included all installation and plumbing hardware required to mount the device in the vehicle. In addition to the sensor systems 20 additional replaceable wear elements were supplied for use in field testing.

I-C

DEVELOPMENT OF ABRASIVE OIL
CONTAMINANT INDICATOR SYSTEM FOR
M55A2 2 1/2 TON TRUCK AND
M151A2 1/4 TON TRUCK ENGINES

Final Technical Report
11629

Contract No. DAAE07-71-C-0241

By
David A. Monaghan

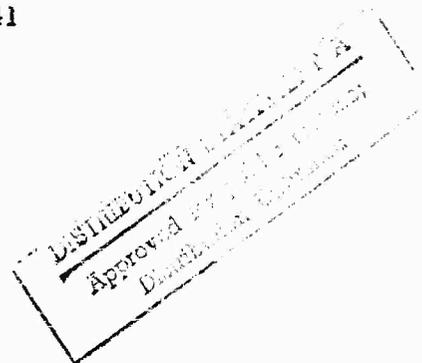
Submitted to

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135 Second Avenue
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31 May 1972

I-D



FOREWORD

This report was prepared by Foster-Miller Associates, Inc. of Waltham, Massachusetts under U. S. Army Contract DAAE97-71-C-0241. Effort on the contract was directed by the U. S. Army Tank Automotive Command, Warren, Michigan. Mr. Daniel F. Ancona was the Contracting Officer's Representative.

This report covers work performed from 24 June 1971 to 31 May 1972. The development effort was performed by the Engineering Studies Division of Foster-Miller Associates, Inc. under the supervision of Mr. Adi R. Guzdar. Mr. David A. Monaghan was the Project Engineer for the program. Valuable technical contributions were made by Dr. Carl R. Peterson and Mr. David Friswell of Foster-Miller Associates.

The author wishes to acknowledge and express his appreciation for the assistance provided by Messrs. Fred Pradko, Donald Sarna, and Daniel F. Ancona of the U. S. Army Tank Automotive Command.

TABLE OF CONTENTS

	<u>Page No.</u>
FOREWORD	i
ABSTRACT	ii
1. Introduction	1
1.1 Objective	1
1.2 Background	2
1.3 Scope of Effort	3
2. Quantitative Problem Definition	6
2.1 Lubricant Degradation and Contamination	6
2.2 Vehicle Specifications and Operating Conditions	19
2.3 Summary of Background Investigation	23
3. Abrasive Oil Contaminant Indicator Concept	27
3.1 Description of Overall Concept	27
3.2 Geometrical Design of Wear Element	27
3.3 Material Selection	28
4. Flow Loop Facility and Test Program	34
4.1 Oil Flow Facility	34
4.2 Test Preparation and Procedures	38
4.3 Detailed Test Program and Results	43
5. Prototype Indicator Design	54
5.1 General Design Considerations	54
5.2 1/4 Ton Truck Sensor Body	55
5.3 2 1/2 Ton Truck Sensor Body	58
5.4 Wear Element Design	58
5.5 Indicator System	62
6. Testing of Prototype Units	64
6.1 Functional Laboratory Evaluation	64
6.2 Environmental Test Program	64
6.3 Vehicular Testing	67
7. Production Cost Estimates	68
8. Conclusions and Recommendations	70
BIBLIOGRAPHY	71

TABLE OF CONTENTS (Cont.)

	<u>Page No.</u>
APPENDIX A - INSTALLATION INSTRUCTIONS - OIL LIFE INDICATOR - 1/4 TON TRUCK	73
APPENDIX B - INSTALLATION INSTRUCTIONS - OIL LIFE INDICATOR - TRUCK	76
APPENDIX C - ESTIMATE OF PARTICLE IMPACTION AND WEAR RATE	78
DISTRIBUTION LIST	90

1. Introduction

This report describes the effort and results of an engineering study of particulate oil contamination and the development, design and testing of a device for indicating the cumulative damage potential of contaminated engine lubricant. The work has been performed under U. S. Army Contract No. DAAE07-71-C-0241 initiated 24 June 1971. This report is the final report summarizing the program effort and significant results.

1.1 Objective

The overall objective of this program is the development of a diagnostic device to provide an indication of cumulative damage potential of contaminated engine lubricant. The device is responsive to accumulated particle concentration (due to metallic, dust and foreign particle ingestion from the environment) through the use of metallic elements exposed to erosive flow and corrosive action of lubricating oil. The same basic device - with minor modifications - is applicable to both the M151A2 1/4 ton truck engine and the M35A2 2 1/2 ton truck engine. Both devices employ bistable electronic circuitry to provide a go/no-go indication to the vehicle operator in the cab.

The program was specifically designed to achieve the following:

- (a) Determine the operating conditions, contamination levels and distributions, and physical limitations pertaining to the abrasive damage indicator.
- (b) Develop sensor and indicator concepts compatible with the above characteristics.

- (c) Construct a test loop to simulate the engine lubrication system.
- (d) Test the sensor under contaminated and clean lubricant conditions to establish feasibility.
- (e) Design, build and install prototype systems on the 1/4 and 2 1/2 ton trucks.
- (f) Complete a preliminary test program to ensure compatibility with vehicles.

1.2 Background

The military employs a great many internal combustion engines of various types in a wide variety of vehicles and applications. Many, if not most applications entail adverse operating conditions and at the same time demand highly reliable service. It is therefore necessary to maintain these engines:

- (a) to assure their availability; and
- (b) to estimate the available running time or "life" before maintenance or replacement is required.

Faced with a declining supply of skilled maintenance personnel and increasingly complex equipment, field maintenance has become increasingly difficult. To counter this the military has turned to the development of "self diagnostic" equipment.

Eventually, self diagnostic capability would be desirable for entire vehicles and progress is being made in this direction. For

the engine itself, it happens that a large majority of field failures can be traced to relatively simple and, if properly identified, easily remedied malfunctions of the fuel, coolant, ignition or lubrication systems. The effort presented in this report has been directed at the development of an indicator which is sensitive to abnormally high levels of particulate contaminant in the lubricating oil and provides warning to the operator in time to permit remedial action before catastrophic failure.

This device is particularly suited to military vehicles because of the wide variety of operating conditions. Under these variable operating conditions, the rate of oil contamination can vary considerably and there is considerable incentive to match the oil and filter change interval to the actual oil condition.

1.3 Scope of Effort

The scope of this program includes the development of a sensor and indicator system to provide warning of excessive particulate contaminant buildup in the engine lubricant of the M151A2 1/4 ton truck engine and the M35A2 2 1/2 ton truck engine. As a result of this program, typical contaminant levels and distributions have been established. The development feasibility has been proven for a device sensitive to particulate contamination. Prototype sensor and indicator systems have been designed and fabricated. The major tasks completed during this program include:

1.3.1 Quantitative Problem Definition

This task provided the background information required for effective design and testing of the contaminant sensor and indicator system.

It included an extensive survey of recent literature to quantify the effect of lubricant contamination on internal

combustion engine wear. The survey included chemical contamination as well as particulate contamination. Typical wear rates were determined as were contaminant particle size distributions and methods of determining lubricant condition.

This effort included contact with persons in the lubrication and filter industries to utilize their practical experience with laboratory and full scale testing.

Specific quantitative information regarding the actual vehicles to be used and their operating conditions was obtained directly from military and civilian personnel closely associated with the equipment and from pertinent military manuals.

This background information is presented in detail in Section 2.

1. 3. 2 Concept Evaluation

This task was directed at developing, refining and evaluating the basic abrasive damage indicator concept originally proposed. Based on the detailed information gathered in the first task, several variations of the abrasive indicator concept were conceived and analyzed. Preliminary testing established feasibility and indicated a preferred design. Section 3 describes the original concept and its refinements.

1. 3. 3 Experimental Facility and Evaluation

Considerable effort was expended to develop a special test facility to simulate the conditions in an internal combustion engine lubrication system and permit the control of critical variables. The test facility was built in the Foster-Miller laboratory.

An extensive test program was run to establish concept feasibility and determine the effect of the variation of several parameters on the performance of the sensor. The details of the test program and the pertinent results are reported in Section 4.

1.3.4 Prototype Indicator Design

Prototype sensor and indicator systems were designed for the jeep and diesel engine based on the results of the flow test program. The design, presented in Section 5, included wear elements, sensor body, mounting hardware and indicator system.

1.3.5 Prototype Testing and Installation

In this task described in Section 6 the prototype devices were subjected to the appropriate environmental and vibration test programs. One of each unit was installed on the appropriate vehicles to insure compatibility and noninterference with the other functions of the vehicle.

1.3.6 Cost Evaluation

Estimates of production cost were made for both the diesel truck version and jeep version of the oil life indicator system in lots of 100 and 1000. These are presented in Section 7 and will facilitate the evaluation of the overall value of the device and its cost effectiveness.

2. Quantitative Problem Definition

An extensive investigation was required to provide the background information required for effective design and testing of the contaminant sensor and indicator system. This investigation provided the quantitative information on the abrasive contaminant of lubricating oil in general and the operating characteristics of the specific vehicles under consideration.

Detailed definition of the problem required investigation of two major areas:

- (a) lubrication degradation and contamination
- (b) specifications of the particular vehicles and their operating conditions

The first area required an extensive literature search in the area of internal combustion engine lubrication and wear. Considerable information was also available from personnel associated with the major oil companies and filter manufacturers.

Details of the vehicle specifications, physical limitations and typical operating conditions were gathered from operators manuals, repair manuals and parts manuals available from the U. S. Army. Also very helpful was the first hand experience and opinions of military and civilian personnel familiar with the day-to-day operation and maintenance of the vehicles being considered.

Details of the problem definition task are presented in the following sections.

2.1 Lubricant Degradation and Contamination

The results of a careful survey of engine lubrication and

wear are presented in this section. Chemical and mechanical contaminants are reviewed first, typical engine wear rates under normal and abnormal operating conditions are discussed followed by a presentation of the methods of monitoring a lubrication system to determine when oil has been exhausted.

2.1.1 Chemical and Mechanical Contaminants

Chemical contaminants normally found in internal combustion engine lubricants are rust, soap, algae, solvents, detergents, acids, bases, salts and the inhibitor and dispersant packages originally added to the oil. These may all be identified by chemical and spectrographic analysis of an oil sample. It has been suggested that acids alone do not promote chemical corrosion, but when acids and peroxides appear simultaneously, corrosive wear increases rapidly. The peroxides seem to react with the metal to form oxides which react with the acids to form salts. It is generally agreed that while the formation of varnish and sludge is a chemical process, gross metal removal is primarily a mechanical wearing process.

Mechanical contaminants form the insoluble content of the oil, made up of minute particles of foreign matter that enter small clearances in bearings and other moving parts. These particles cause the abrasive wear of piston rings, cams, lifters and bearings. The majority of these particles are composed of amorphous carbonaceous matter, silica, alumina, iron and iron oxides. Other metal oxides also appear in various concentrations which depend on the design of the engine, the materials used, and any malfunctions which may be occurring.

This contaminating matter arises from various sources;

- (1) airborne dust which passes first the air filter and then the piston rings,
- (2) hard carbon produced in the combustion chamber,
- (3) metal particles abraded during the wear process which subsequently react with the air and oil chemistry.

Table 7, excerpted from Reference (1)*, shows the results of chemical and particle size analyses of the contents of three types of oil filters. Three centrifugal filters and three metal edge filters were obtained from compression-ignition engines and three paper element type filters from various gasoline engines. The values reported are the average values for each of the three filter-engine combinations. Three of each filter-engine combination were inspected and the average values reported.

2.1.2 Effect of Particulate Contamination on Engine Wear

The effect of abrasive contaminant on I. C. engine life has been extensively investigated by engine and component manufacturers, oil companies and filter manufacturers. (2, 3, 4, 5)

Three basic types of test programs are employed for determining these effects, each with advantages and limitations.

- (1) Accelerated Testing - add high concentrations to the lubricant and the intake air to cause rapid wear. The wear is determined by disassembly of the engine.

* Numbers in parentheses refer to references list in the Bibliography.

TABLE I - ANALYSIS OF MATERIAL TAKEN FROM VARIOUS ENGINE FILTERS (REF 1)

Chemical analysis, percent by weight	Diesel engine centrifugal filter material (mean values)	Diesel engine metal edge filter material (mean values)	Petrol engine paper element filter material (mean values)
Water	nil	nil	0.72
Petroleum ether insolubles	37.30	34.70	39.25
Petroleum ether solubles	62.70	65.30	61.03
Analysis of petroleum ether insolubles:			
Chloroform solubles	4.70	4.60	13.82
Chloroform insolubles	32.60	30.10	25.43
Analysis of chloroform insolubles:			
Carbonaceous matter	24.90	25.70	10.88
Ash	7.70	4.40	14.55
Analysis of ash estimated as:			
Iron oxide (Fe ₂ O ₃)	3.63	1.62	1.71
Alumina (Al ₂ O ₃)	0.49	0.65	0.31
Copper (Cu)	0.35	0.09	trace
Lead oxide (PbO)	0.03	0.04	6.77
Silica (SiO ₂)	0.35	0.11	0.58
Calcium oxide (CaO)	0.07	0.03	trace
Zinc (Zn)	0.51	0.46	nil
Phosphorus (P)	0.29	0.21	0.08
Tin oxide (SnO ₂)	0.06	0.03	0.10
Soluble sulphates (SO ₄)	1.26	0.72	trace
Insolubles			2.19
Particle size analysis, percentage of total number by optical microscope method:			
Less than 2 microns	90.5	88.4	87.1
2-5 microns	9.0	10.8	12.9
Larger than 5 microns	0.5	9.8	

- (2) Field Fleet Testing - Utilize vehicles operating under similar controlled conditions to compare various filtration techniques or lubricant chemistries. Disassembly and comparison of similar components is required.

- (3) Radioactive Tracer Testing - use radioactive tracers in the wearing elements to accurately measure even low wear rates with small quantities of abrasive. The wear may be monitored continuously without dismantling the engine. This technique appears to be the most satisfactory to date.

The results of the various studies seem frequently inconsistent and occasionally contradictory. Depending on the details of the test setup - the engine materials, the lubricant, the filter and the contaminant used - the results can vary considerably. It does appear that several general conclusions may be drawn and indeed are rather widely accepted. These are:

1. The primary contributor to abrasive engine wear is silica.

2. There is a threshold concentration for silica above which wear increases rapidly.

3. There is a particular particle size range which may be considered most critical.

Silica (SiO_2) has long been accepted as a primary contributor to engine wear. A major component of road dust,

it enters the engine in relatively large sizes with the intake air, is partially ground by the piston rings and makes its way to the sump where it remains suspended in the oil. The standardized air fine cleaner test dust used by the filter manufacturers to evaluate their products is almost 70 percent silica as shown in Table II.

Piston ring wear rates with a typical 6 cylinder valve-in-head test engine were on the order of 0.2 to 0.5 mg per hour per ring under normal operating conditions. The addition of standardized air cleaner test dust in a concentration of 0.3 grams per 1000 cubic feet of air increases the wear rate by a factor of 100.⁽³⁾ The results of the experimental study are shown in Figure 1. This concentration is typical of that entering an engine during a dust storm through an efficient paper filter. Calculations indicate that a specific weight of abrasive added to crankcase oil causes about 10 times the wear of an equivalent weight of airborne abrasive, since the major portion of airborne abrasive blows out the exhaust.

In general, a silica concentration in excess of 15 parts per million causes accelerated wear of engine parts. The wear rate is related to the total wear metal content of the lubricating oil. Wear metals include iron, lead, copper, chromium, aluminum, nickel, silver and tin. Typical concentrations of these metals in diesel engine lubricant are:⁽⁷⁾

Iron	< 60 ppm
Lead	< 10 ppm
Copper	< 15 ppm
Chromium	< 10 ppm
Aluminum	< 5 ppm
Nickel	< 1 ppm
Silver	< .1 ppm
Tin	< 1 ppm

TABLE II - CHEMICAL ANALYSES AND PARTICLE SIZE
DISTRIBUTION OF AC FINE TEST DUST

IIa Chemical Analysis of AC Fine Test Dust

	Percent by Weight
SiO ₂	67-69
Fe ₂ O ₃	3-5
Al ₂ O ₃	15-17
CaO	2-4
MgO	0.5-1.5
Total Alkalis	3-5
* Ignition Loss	2-3

IIb Particle Size Distribution of Dust

Size, microns ^a	Percent of Total Weight
0-5	39 ± 2
5-10	18 ± 3
10-20	16 ± 3
20-40	18 ± 3
40-80	9 ± 3

^a 1 micron = 0.000039 in.

* material lost during analysis

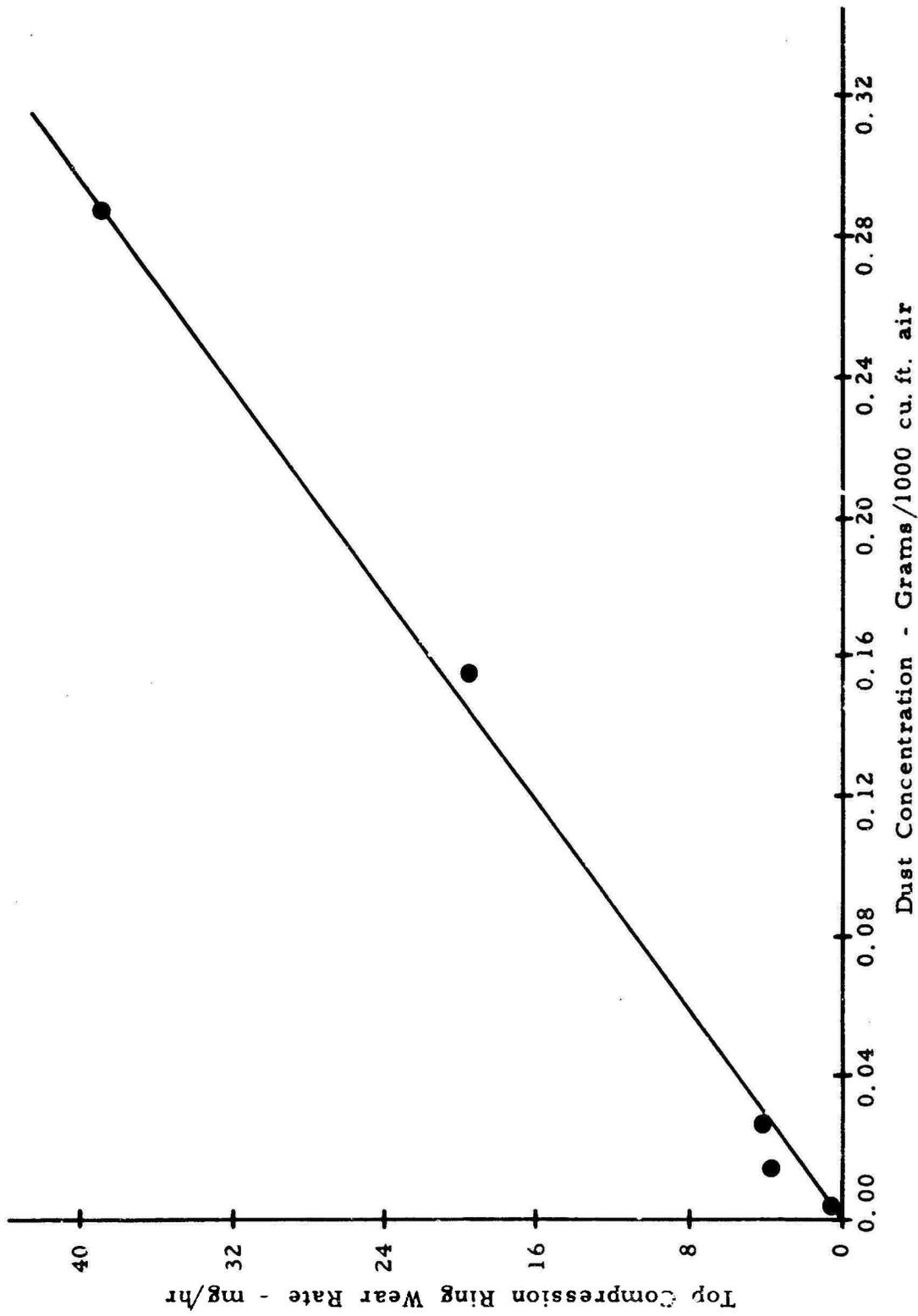


Figure 1 - Effect of Dust Concentration on Top Compression Ring Wear.

From Reference (3)

As the silicon content of the lubricant increases, the total wear metal content increases as shown in Figure 2. From this curve, the detrimental effect of silica is evident. The 15-20 ppm threshold range was reported by Paul Friend⁽⁷⁾ of Mobil Oil to apply to automatic transmissions and gearboxes as well as I. C. engines. Similar phenomena are reported for railroad diesel engines which ingest braking sand through the intake manifold. The threshold at which wear increases rapidly is 20 ppm for this application.⁽⁸⁾

The size of the silica particles strongly influences the rate of abrasive wear. The variation in wear rate with abrasive particle size has been studied in considerable depth.^(3, 5) Watson, et. al.⁽³⁾ established relative wear rates for various particle size fractions of the standard test dust in the lubricating oil. The results of the wear after 30 minutes of operation are presented in Figure 3a. Maximum wear is indicated for test dust particles of 21.5 micron diameter. This result is similar to similar tests in which the dust was airborne as shown in Figure 3b.

This data is presented in tabular form for the wetted and airborne contaminant in Table III and IV.

Other papers report higher wear rates in the 5-10 micron range than in the 10-20 micron range⁽⁵⁾ but this is traceable to different piston ring and bearing materials.

In general particle sizes less than 5 microns do not cause significant wear. Particles of diameters greater than 20 micron are easily trapped by oil filters and therefore are not available for abrasive action. The most critical range of particle size lies between 5 and 20 microns.

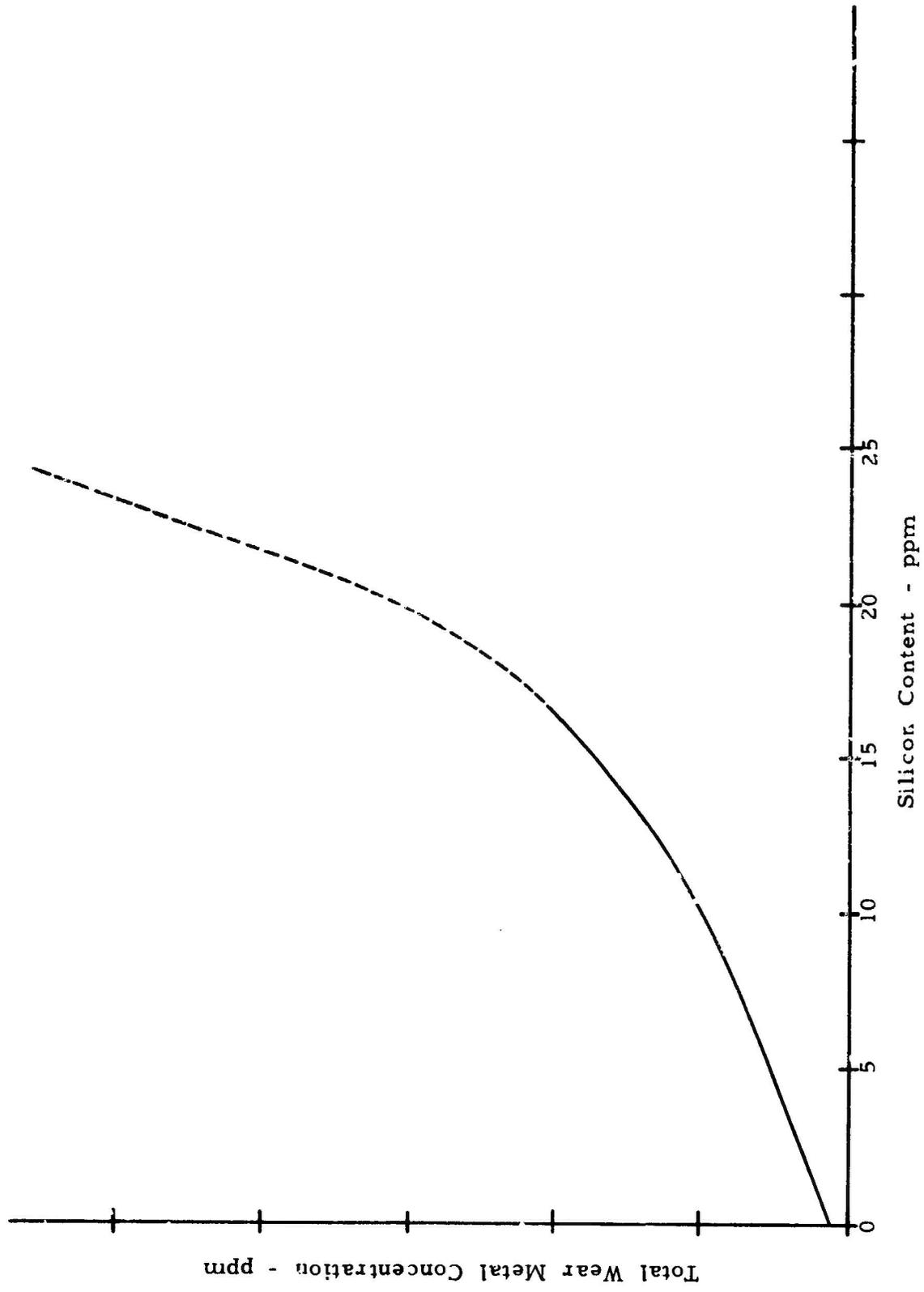


Figure 2 - Effect of Silicon Concentration on Wear Metals in Lubricant
from Reference 7

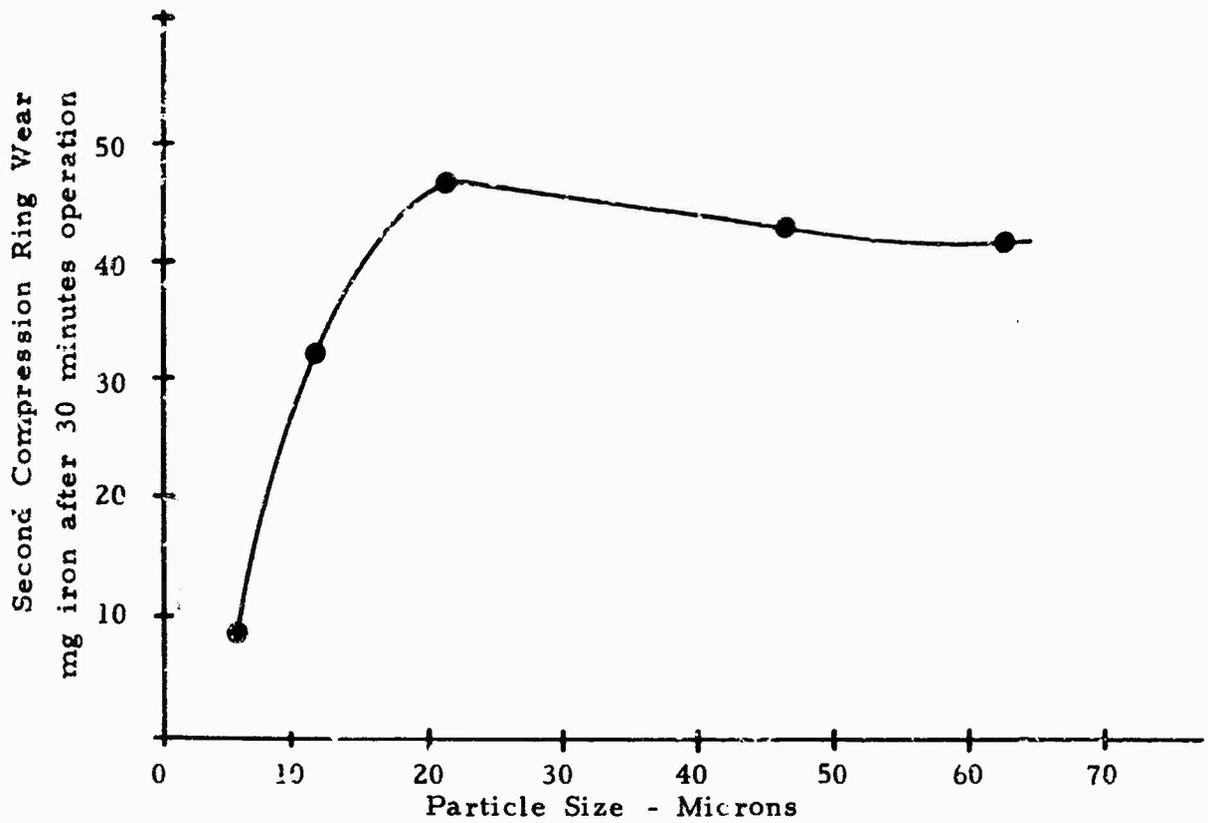


Figure 3a - Effect of Dust Particle Size on Second Compression Ring Wear (Ref. 3)

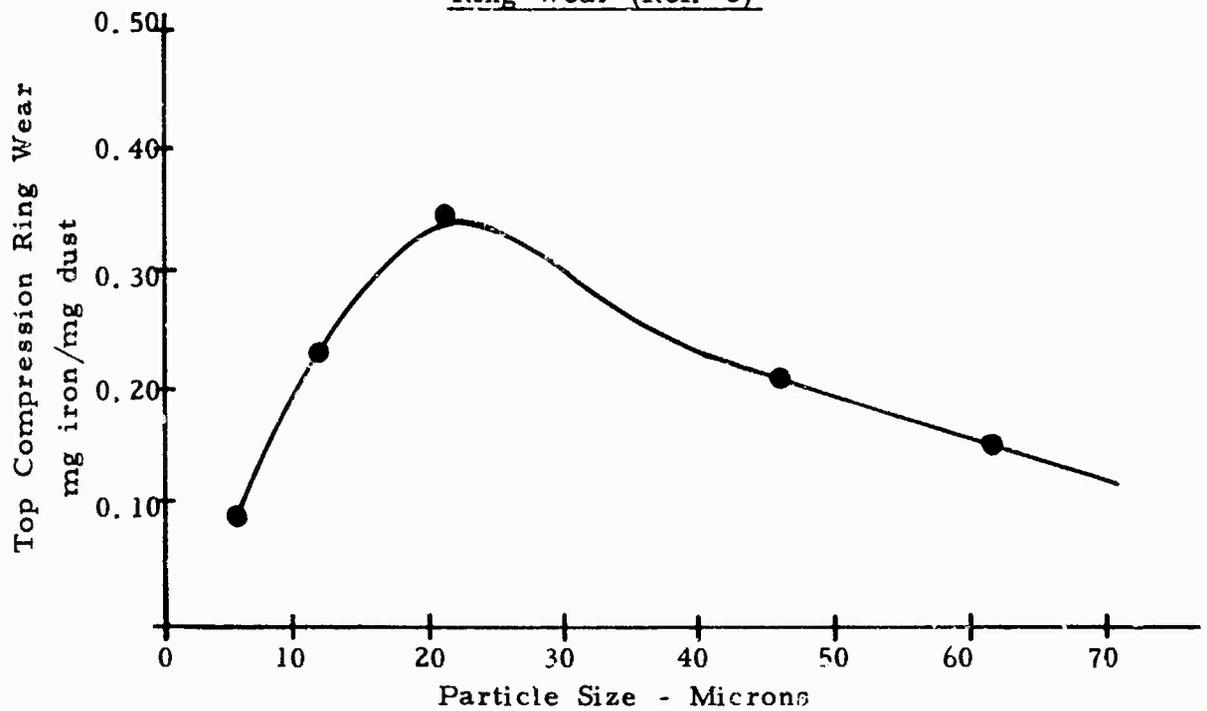


Figure 3b - Effect of Dust Particle Size on Top Compression Ring Wear (Ref. 3)

TABLE III - EFFECT OF ADDING ROAD DUST TO CRANKCASE OIL (3)

Engine Speed: 2500 rpm
 Engine Load: 45 bhp

Two grams road dust added to crankcase oil						
Nominal Classification Size, microns	Diameter of Mean Weight - % Particle, microns	Second Compression Ring Wear, mg Iron				
		0 Min	15 Min	30 Min	60 Min	
0-5	5.7	0	4.5	9.0	15.3	
5-10	12.5	0	17.2	32.7	--	
10-20	21.5	0	26.2	45.6	65.6	
20-40	46.0	0	26.8	43.0	62.8	
40-80	62.0	0	27.2	41.0	58.4	

TABLE IV - EFFECT OF DUST PARTICLE SIZE (3)

Engine speed: 2500 rpm
 Engine load: 45 bhp

Abrasive added to air induction system				
Nominal Classification Size, microns	Diameter of Mean Weight - % Particle, microns	Diameter of Largest Particle Observed, microns	Top Compression Ring Wear, mg iron per mg dust	
0-5	5.7	8	0.09	
5-10	12.5	22	0.23	
10-20	21.5	51	0.33	
20-40	46.0	84	0.21	
40-80	62.0	161	0.15	

2.2 Vehicle Specifications and Operating Conditions

The details of the multifuel engine and jeep engine lubrication systems and normal operating conditions were required to provide the background for the design and testing of the oil abrasive content sensors. These details were gathered from the appropriate military manuals and military personnel. The information on the multifuel engine lubrication system was found primarily in the "Trouble Shooting Manual, LDS-465-1 Multifuel Engine"⁽⁹⁾ published by Continental Aviation and Engineering Corporation. The jeep lubrication system was described in army Manual TM9-2805-213-34. Information excerpted from these sources is presented in the following sections.

2.2.1 Lubrication System - Multifuel Engine⁽⁹⁾

The multifuel engine incorporates a full-pressure lubrication system. The design of the oil pan, in conjunction with a scavenger pump system, ensures a continuous supply of oil to the pressure pump.

Filtration of the oil is accomplished by two replaceable-element-type filters. A coolant jacketed oil cooler is provided to perform two functions. The first is to transfer heat from the coolant to the lubricating oil to speed the warmup of the lubricating oil during starts. The second is to maintain the lubricating oil temperatures at an acceptable level during normal operation.

Schematics of the multifuel engine lubrication system as obtained from References 9 and 10 are reproduced directly in Figures 4 and 5. Detailed specifications of the lubrication system are presented in Table V.

2.2.2 Lubrication System - 1/4 Ton Truck Engine

Positive, full-pressure lubrication is provided

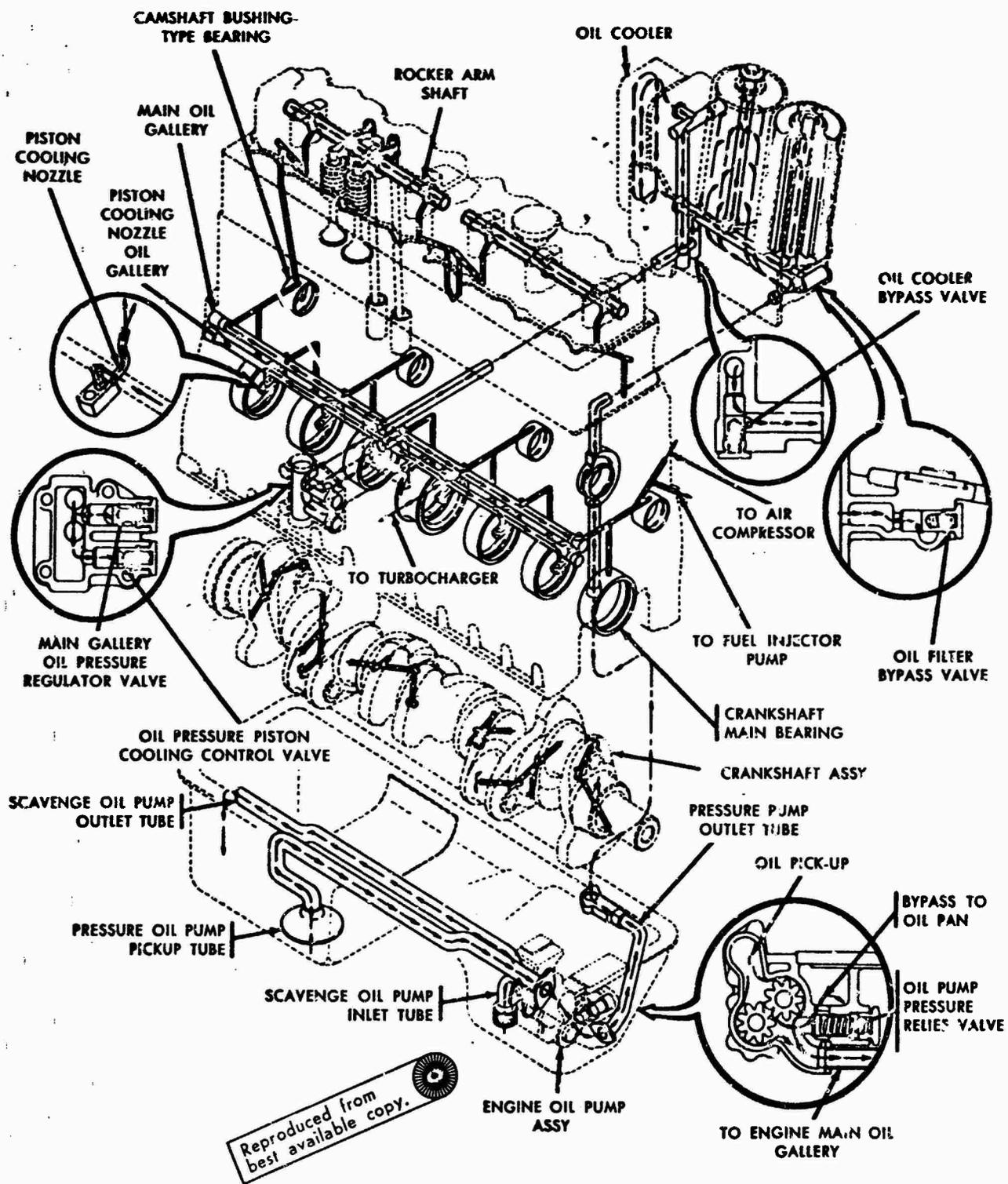


Figure 4 - M35A2 Engine Lubrication System Diagram (Ref 9)

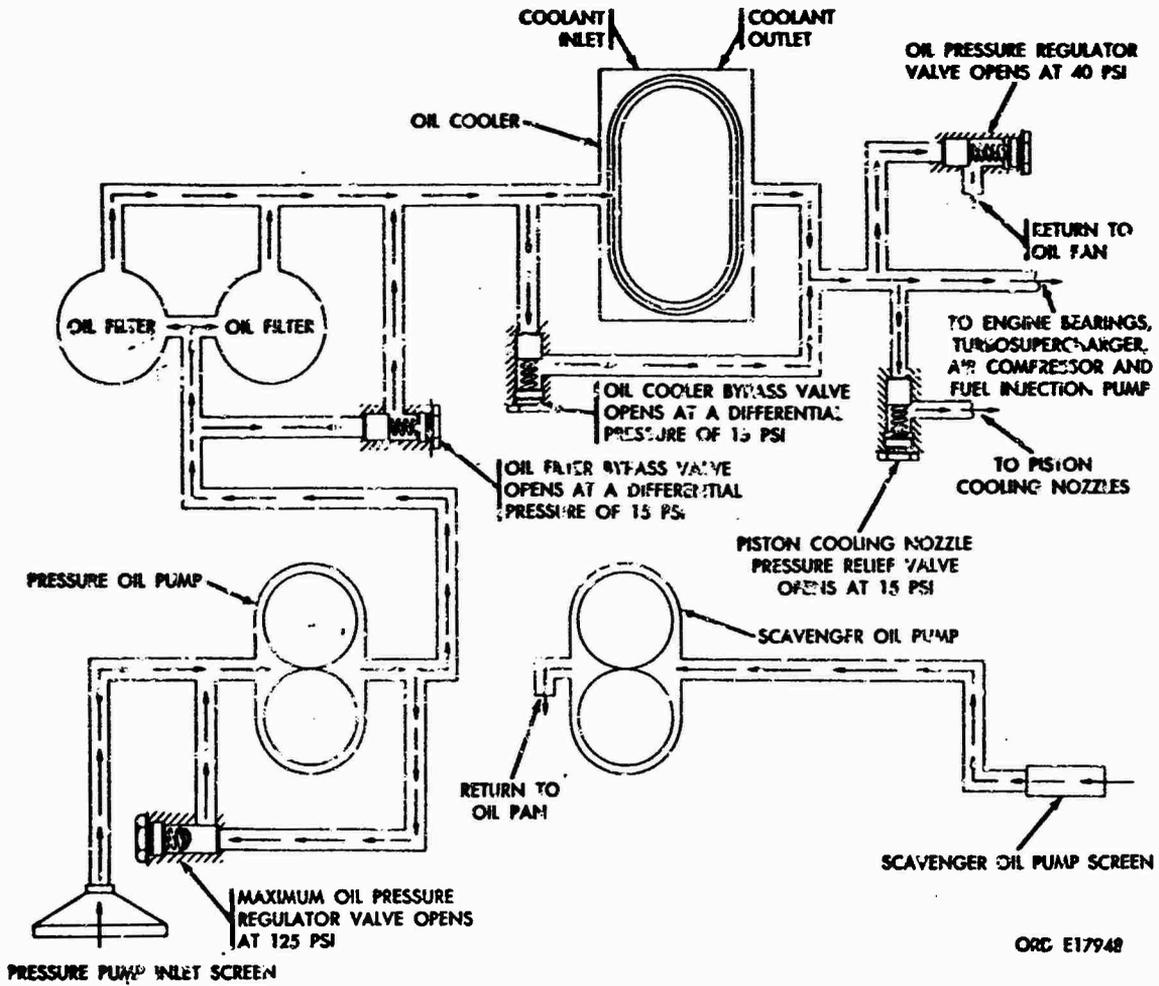


Figure 5 - M35A2 Diesel Engine Oil Flow Circuit Diagram. (Ref 10)

TABLE V - M55A2 LUBRICATION SYSTEM

Lubrication Oil Specification

+32° to +120° F	OE 30 (MIL-L-2104)
-10° to + 40° F	OE 10 (MIL-L-2104)
-65° to + 0° F	OES (MIL-L-10295)

Normal Oil Pressure

at idle speed	10 psi min
at operating speed	50-65 psi at 2800 RPM (measured in crankcase main gallery)

Oil Pump

Type	Gear pump with internal pressure relief at 125 psi
Capacity	22 gpm at 2800 RPM
Oil Filter	full flow replaceable cartridge type
Oil Capacity	22 quart total

Oil Passage

approx. 3/4" diameter

by a gear-type oil pump. A spring-loaded relief valve in the pump limits the maximum pressure in the system. The oil is picked up from the sump and is pumped through a short passage in the block to the full flow filter. The filter also has a relief to permit bypassing if the element becomes clogged. From the filter, oil flows to the center main bearing, camshaft, and the rest of the engine, as shown in Figure 6 which is reproduced directly from Reference 11.

The specifications for the lubrication system are presented in Table VI.

4.3 Summary of Background Investigation

Based on the investigation of internal combustion engine lubricant contamination the following conclusions may be drawn.

- (1) Silica is the primary contributor to abrasive engine wear.
- (2) Wear increases rapidly as the concentration of Silica rises above a threshold of 15-20 ppm.
- (3) The 5-20 micron range is the critical abrasive particle size.
- (4) Standard air cleaner test dust provides a suitable contaminant for the concept evaluation testing.

The lubrication system specifications for the 1/4 ton and 2 1/2 ton trucks are summarized in Table V and Table VI. The oil pump flow rates for both systems were considered adequate to permit sampling of a small portion of flow from the pump in parallel with the engine lubrication system. Parallel sampling for the

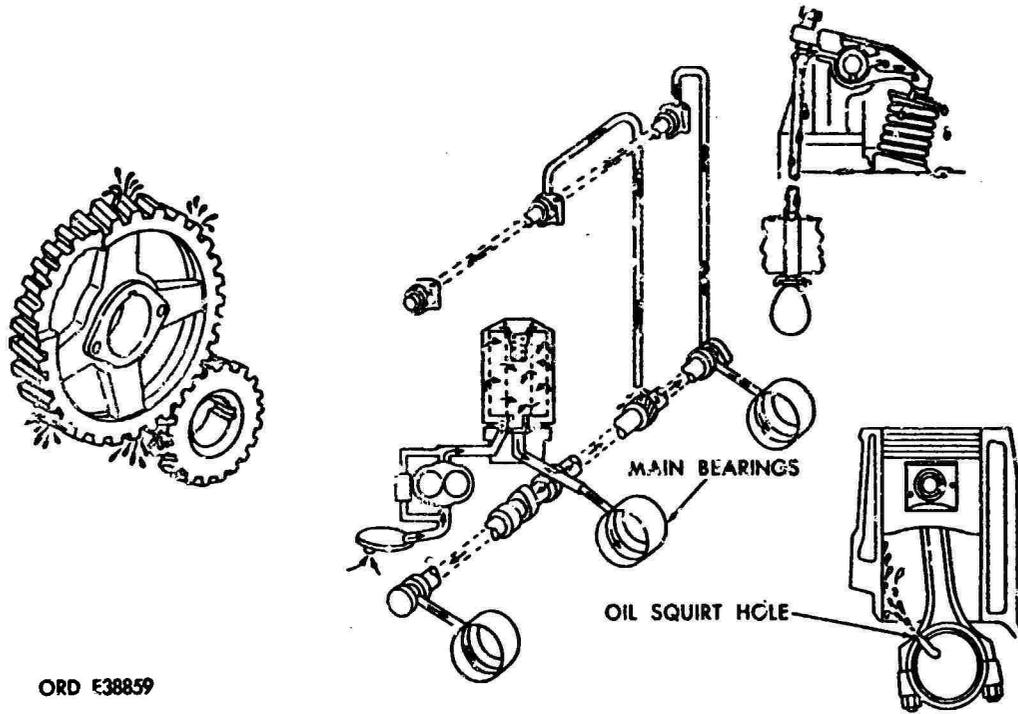


Figure 6 - M151A Jeep Engine Lubrication System
- Oil Flow Diagram - Ref (11)

TABLE VI - M151A1 - LUBRICATION SYSTEM

Lubrication Oil Specifications

32° - 120° F	OE 30 (MIL-L-2104)
-10° - 40° F	OE 10 (MIL-L-2104)
-65° - 0° F	OES (MIL-L-10295)

Normal Oil Pressure

at idle - 15-30 psi	full pressure lube. system
at operating - 35 - 45 psi	

Oil Pump

Type	Gear with integral pressure relief valve
Capacity	6.3 gpm at 4000 RPM
Oil Filter	full flow disposable cannister
Oil Capacity	5 quart sump

Oil Passages

approx. 7/16" diameter

prototype sensor systems insured the availability of pressure sufficient to produce oil velocities capable of causing a significant rate of abrasive wear. Placing the sensor in series with the lubrication system would have reduced the pressure drop available for accelerating the oil to a small fraction of the system pressure and thus not permitted the velocities required to produce the abrasive wear.

For the ultimate system either parallel sampling or a full flow series approach may be employed with appropriate modification of the pump characteristic.

3. Abrasive Oil Contaminant Indicator Concept

3.1 Description of Overall Concept

The abrasive oil contaminant indicator employs a thin metallic element which is inserted in a convenient location in an oil line and erodes under the abrasive action of the solid particles suspended in the lubricant flow. The erosion rate is influenced by the particle size, material, shape and velocity, and the total erosion is related to running time.

The parameters which result in erosion of the element are similar to those affecting engine wear. With proper design the element can provide an analog of the engine wear and indicate when contaminated oil is producing excessive wear.

The wear is sensed in this concept by an increase in the electrical resistance of the element caused by the decrease in the cross sectional area of the conducting path. An electronic circuit senses resistance increases above a threshold and activates a warning indicator light.

3.2 Geometrical Design of Wear Element

To achieve wear of the metallic path, impact of particles against the wear element is required. Calculations based on impaction efficiency theory, described in references 12 and 13, indicate that for the particles of interest in this study a wire with radius less than 4 mils would be required to produce even a 0.2 percent per hour change in cross sectional area. Smaller wire diameters are not feasible because of strength requirements, so sharp edge wear has been employed.

Conducting paths must be deposited at the edge of non-conducting substrate materials. The substrate supplies the mechanical

support for the extremely thin metallic path required to sense wear due to particle impact.

Various configurations such as cylinders, rectangular prisms and sharp edges were envisioned as shown in Figure 7. In order to maximize the wear rate, high velocity is required immediately adjacent to the wear surface. This will minimize the boundary layer thickness and increase the fluid shear at the wear surface.

The flow patterns around the three favored geometries are shown in Figure 7. For the cylindrical case, the fluid velocity ideally varies from zero at the stagnation points shown to twice free-stream velocity at the upper and lower sections. For the square cross section the velocity varies from zero at the stagnation points to theoretically infinite velocity at the corners. For the sharp edge the velocity is approximately equal to the freestream value.

Based on flow velocity and manufacturing considerations a rectangular prism geometry was selected with the conducting path along one edge only rather than across the entire surface. The configuration selected is shown in Figure 8.

Calculations presented in Appendix C indicate relatively low impaction efficiency even for the rectangular prism, consequently low wear rates were anticipated. The element configuration must result in significant resistance changes due to this wear. Thus an extremely small cross sectional area of the conducting path is required. The paths employed in the test program were narrow, since impaction occurs only at the very edge, and thin to minimize the cross sectional area.

3.3 Material Selection

Having selected a promising geometry for the wear element, suitable materials are required for both the substrate and the

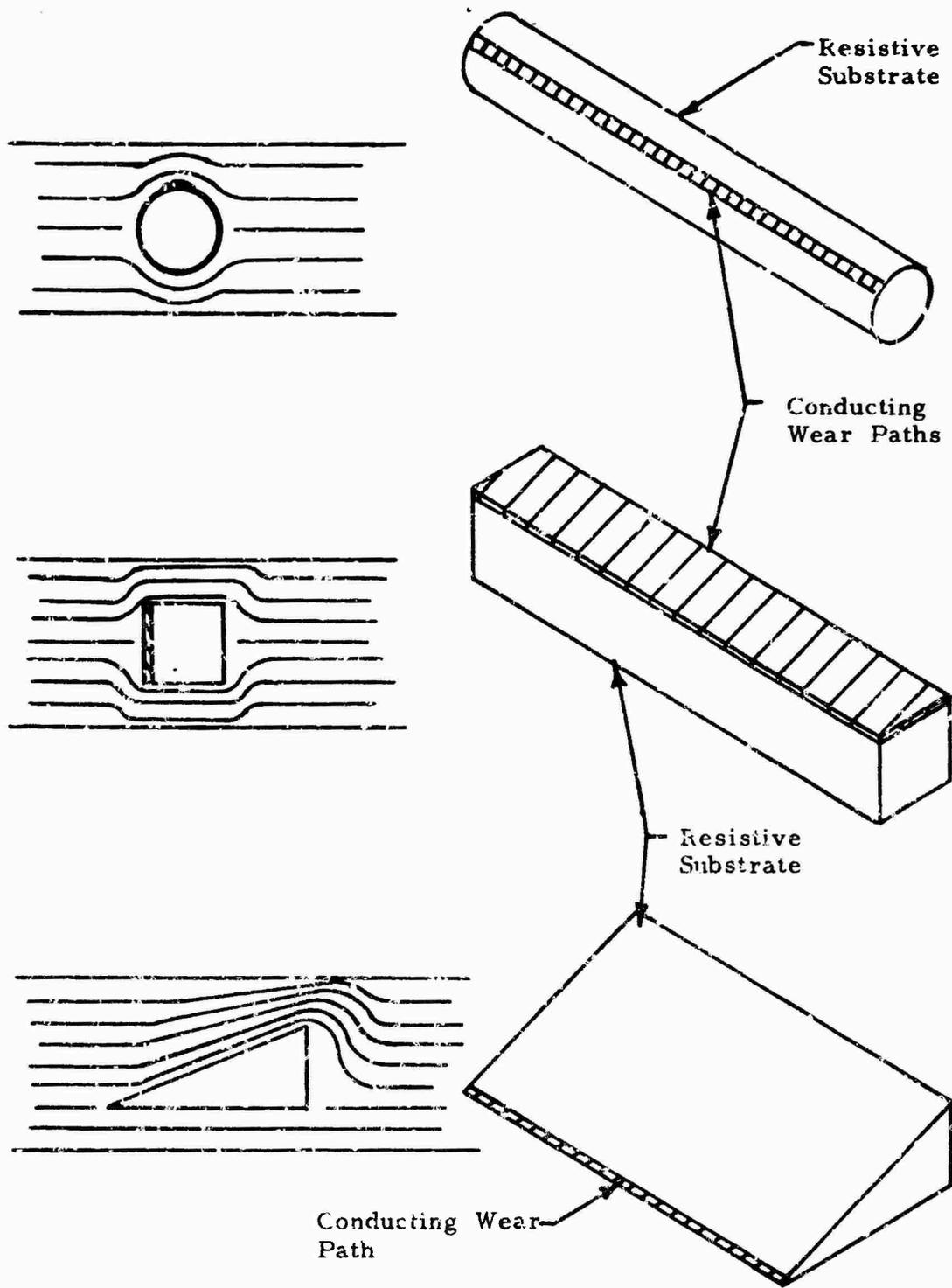


Figure 7 - Potential Wear Element Configurations

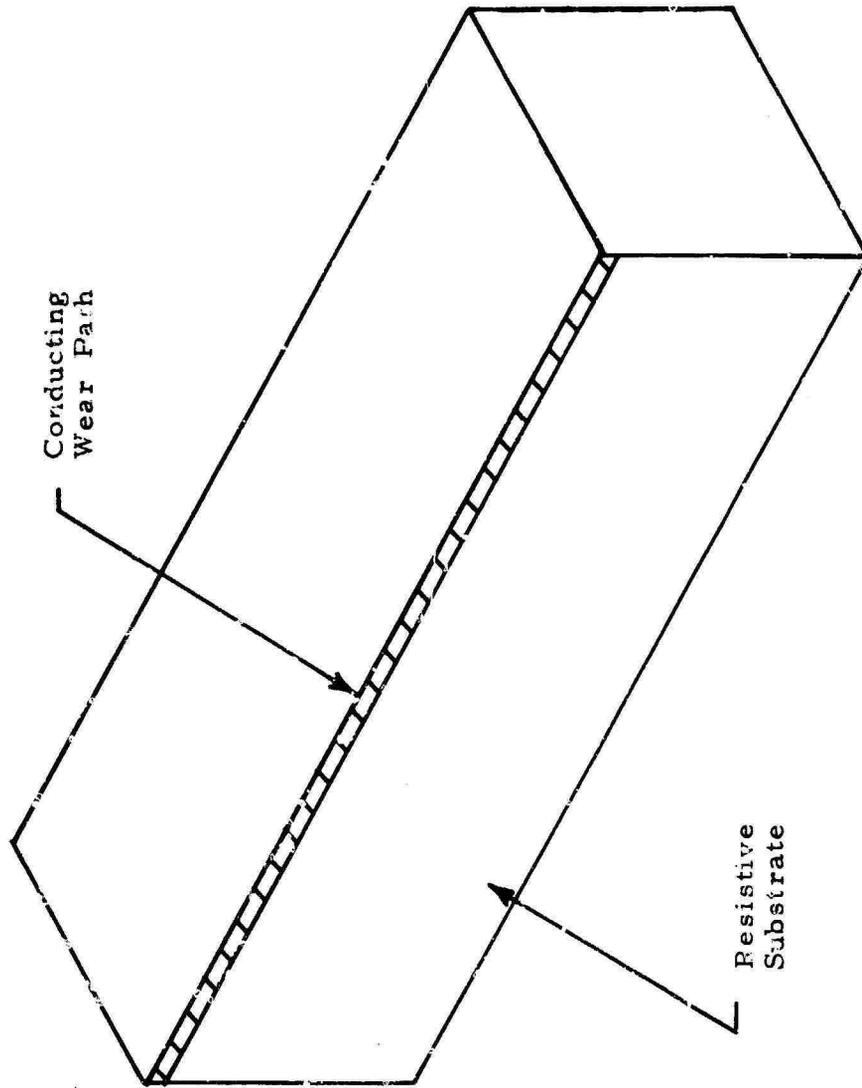


Figure 8 - Sketch of Wear Element Concept

conducting path. Also required is a process for intimately bonding the path to the substrate material.

The following sections discuss the considerations in the selection of the materials and the bonding process.

3. 3. 1 Conducting Path

The properties required of a conducting path material may be summarized as:

- (a) electrically conducting
- (b) abradable
- (c) readily available at low cost
- (d) chemically stable (non-corrosive)

Most metals satisfy the first three requirements in varying degrees and the nobler metals satisfy the latter as well. There was considerable question regarding the desired hardness characteristics. It is obvious that an extremely hard material will abrade at an extremely low rate and probably not be satisfactory. On the other hand, a soft material may tend to smear under the action of the hard particles rather than be removed. The most satisfactory material would fall between these extreme cases.

In order to compare the performance of several possible materials, a test loop was built and a test program run. The conducting materials tested included nickel, chromium, silver and gold. Based on the tests described in Section 4, gold was selected as the most satisfactory path material.

3.3.2 Substrate Materials

Substrate materials must be:

- (a) electrically nonconductive
- (b) compatible with the conducting path material and bonding process
- (c) easily fabricated in the desired shape
- (d) dense with fine grain structure to yield a smooth surface
- (e) compatible with the lubricating medium

In addition to the above characteristics, the substrate materials must possess suitable abrasion characteristics. An easily abradable substrate will permit more rapid removal of the conducting path material as the substrate itself is worn. An extremely hard substrate will reduce the conducting path removal rate by resisting the abrasive action and providing support for the weaker path material.

Several substrate materials were tested during the experimental program described in Section 4. These include delrin, high density alumina, quartz and flint glass.

Bonding Process

In order to produce suitable wear elements it was necessary to choose a process that would intimately bond the conducting material to the substrate in such a way that chipping, peeling or flaking would not occur.

Among the processes considered were vacuum deposition, mechanical sputtering and a photo resistive process which involves mechanical sputtering followed by a photo-etching process.

Mechanical sputtering onto a masked surface was selected for the initial elements because of the molecular nature of the bond and the relatively low cost in small quantities. Uniformity between samples is difficult to control with sputtering because of variations in the masking process. Sputtering time may be adjusted for small batches to compensate for the masking variations. The sputtering process proved quite satisfactory for the wear elements for our test program and prototype sensors.

For larger quantities the photo resistive process is recommended. The photo resistive process involves uniform sputtering of one face of the element and then selective removal of portions of the sputtered layer using a photo etch process. Higher set up costs would be offset in large quantities and the quality and uniformity of the conducting path is expected to be superior.

4. Flow Loop Facility and Test Program

A flow loop was designed and built to simulate the flow of lubricant - both clean and contaminated - in internal combustion engines. The flow loop and test program were developed to:

- (a) determine concept feasibility
- (b) select wear path material
- (c) select substrate material
- (d) optimize flow geometry.

A description of the flow facility, the test program and the pertinent program results are presented in the following sections.

4.1 Oil Flow Facility

The flow loop is designed to simulate the flow of lubricant in an internal combustion engine. Since the tests include oil that is heavily contaminated with abrasive particles, careful selection of the test loop components was required. It was necessary to insure that the components were not destroyed by the abrasive and also that the abrasive particles were not unnecessarily degraded by the action of the pump.

In order to permit testing over a wide range of operating conditions it is necessary to independently vary the oil flow rate, pressure and temperature. In addition to varying the parameters it was important to maintain close control over them as well.

The facility employed is shown schematically in Figure 9 and photographically in Figure 10.

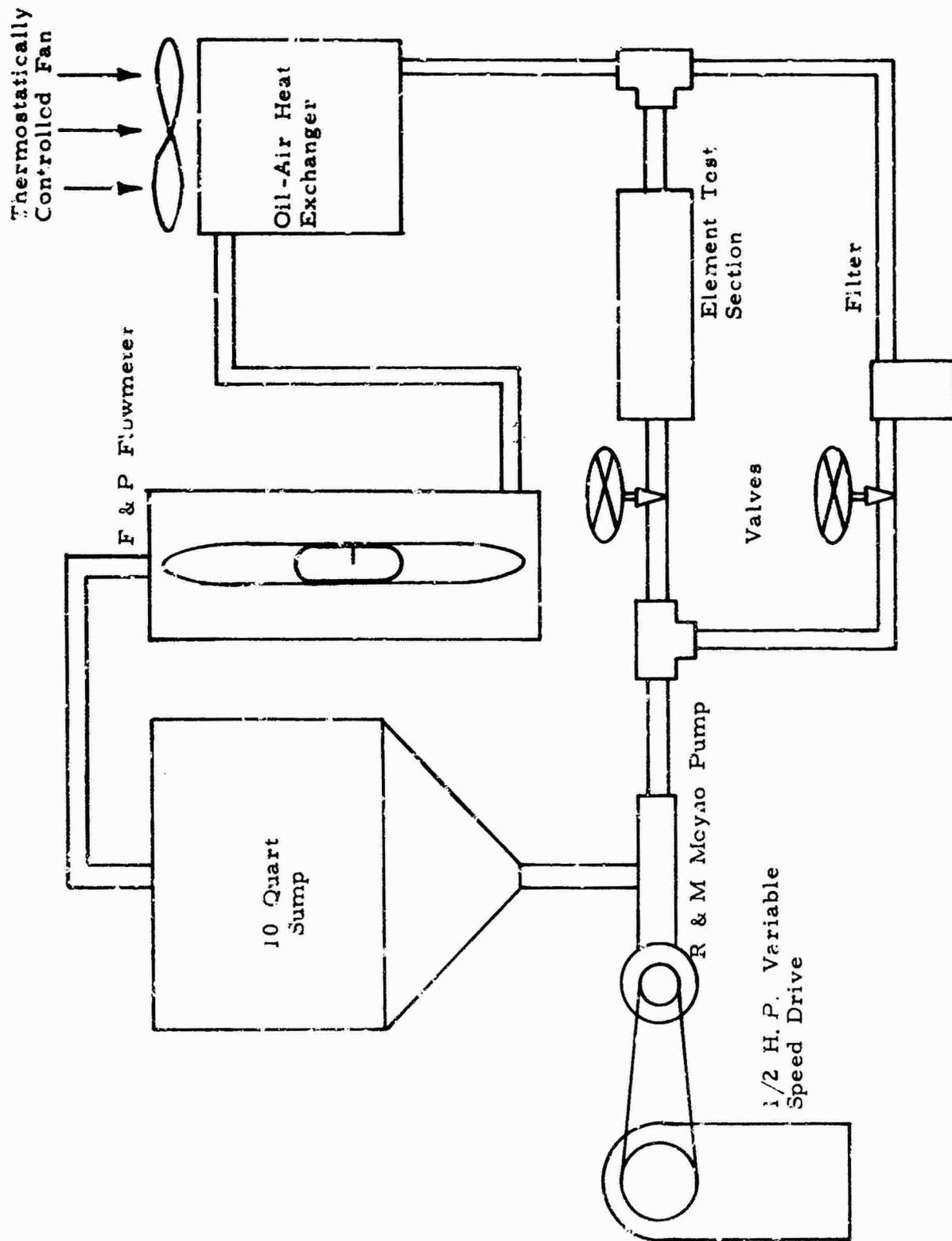


Figure 9 - Schematic of Oil Flow Test Facility

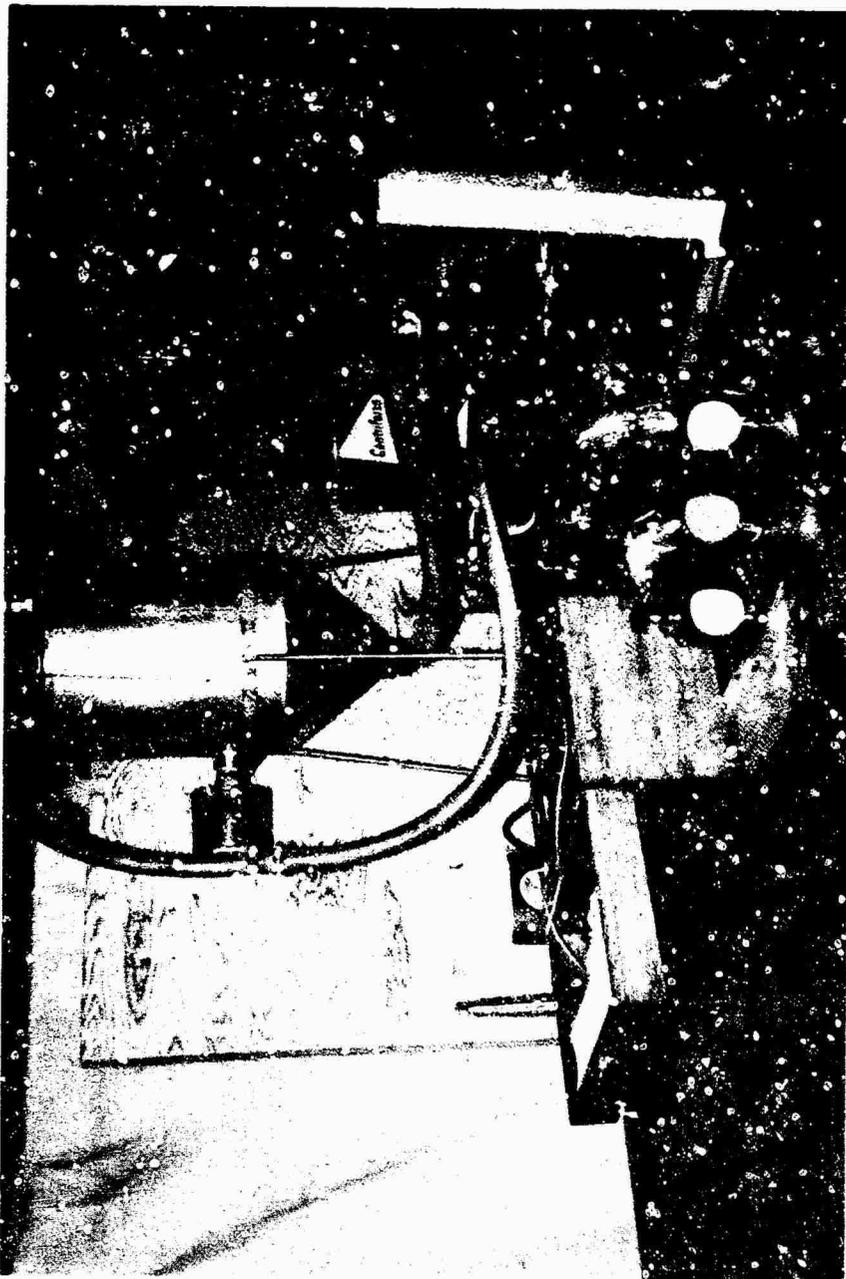


Figure 10 - Laboratory Oil Flow Facility

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The heart of the system is a Robbins and Myers Moyno pump Model 2L3 with a capacity of up to 6 gallons per minute. The Moyno is a positive displacement pump which employs a steel rotor and a rubber stator to push fluids at a uniform discharge rate without pulses. The unique design permits the pumping of solid particles with a minimum of degradation to the pump or the particles.

In operation, a Moyno pump may be compared to a precision screw conveyor. As the rotor turns within the stator, cavities are formed which progress toward the discharge end of the pump carrying the material being handled.

The Moyno Pump is driven by a Dayton 1/2 HP Adjustable Speed Drive Unit through pulleys and a timing belt which provide a 6.65 to 1.0 speed reduction throughout the operating range of 705 to 4230 RPM. Flow rates up to 6.0 gpm were achieved at pressures ranging from zero to 55 psi.

From the pump the flow passes through one of two parallel paths to the element test section. One of the paths is direct while the other includes a standard military throwaway canister type automotive oil filter. Two valves determine the oil flow path. For contaminated flow tests the filter is excluded from the loop. For periodic filtering of the contaminant from the lubricant or for control tests with clean oil, the valve positions are changed and all flow passes through the filter.

In the wear element test section, several elements were installed in series in the lubricant flow and exposed to the abrasive action of the stream. Electrical connections permitted monitoring of the electrical resistance of the elements during operation. From the test section the flow passes through a Fischer and Porter flow-meter of 10 gpm capacity and then through an Astrodyne oil-air heat exchanger equipped with a thermostatically controlled fan.

A custom built 10 quart stainless steel sump accepts flow from the heat exchanger and provides a slight positive pressure at the inlet to the pump. The sump is designed to minimize the settling out of the abrasive particles during operation. The conical shape directs the solid particles into the pump inlet and the jet of return oil is directed so as to scour the side walls. The sump is wrapped with heating tapes and insulated to provide temperature control of the oil. An Alien Bradley temperature controller activates either the heating tapes or the cooling fan when the sump temperature is not within the allowable range.

The loop was designed to minimize the degradation and sedimentation of the particulate contaminant during operation. Sampling valves have been included to permit periodic evaluation of the lubricant and the contaminant.

The oil used in the test loop was Valvoline in both 10W and 30W ranges. It conforms to the military specifications for vehicular applications.

4.2 Test Preparation and Procedures

Prior to the full scale test program, preliminary tests were run to evaluate the performance of the test loop. During this period the behavior of the lubricant, the abrasive contaminant and the test loop components were monitored to provide an indication of expected behavior.

During these preliminary tests, chemical analyses and particle analyses were employed to monitor the degradation of the particles and the wear of system components. Analysts, Incorporated of Linden, N. J. provided chemical and particle size analysis of the oil samples forwarded to them throughout the preliminary test program. These analyses indicated that the degradation of system components

was negligible during typical testing periods. The only wear metal to increase in concentration during testing was copper. This copper was traceable to the tubing lines and did not affect the performance of the test facility or of the abrasive indicators because of its softness.

The particle size analyses remained virtually identical in the 5-10 micron and 10-25 micron ranges during typical testing periods. Operating periods as long as 24 hours produced particle count changes of less than 5 percent in these ranges. In the larger particle size ranges (i. e. greater than 25 micron) the number of particles increased by as much as a factor of three in a 24 hour period. Since this increase was not accompanied by a similar increase in wear metal concentrations it was attributed to wear of the rubber pump stator - the only component likely to produce non-metallic particles. The total volume of these particles was small and did not affect pump performance during the entire test program.

Wear tests using simple element geometries were performed to verify the conclusions of the particle size analysis. A series of carefully controlled experiments established the "effective abrasive life" of the contaminant under a wide variety of flow and temperature conditions.

To determine the "effective abrasive life" a wear sensor was inserted in the fluid stream and the resistance monitored. The equivalent of 15 ppm of abrasive was added to the lubricant and the resultant wear monitored through electrical resistance changes. Typically the rate of wear decreased after a few hours. The addition of fresh abrasive to the lubricant invariably reproduced the initial wear rate.

The effects of maintaining fresh contaminant in the lubricant is demonstrated graphically in Figure 11 and 12. Figure 11 shows the increase in wear path resistance over a 26 hour period for

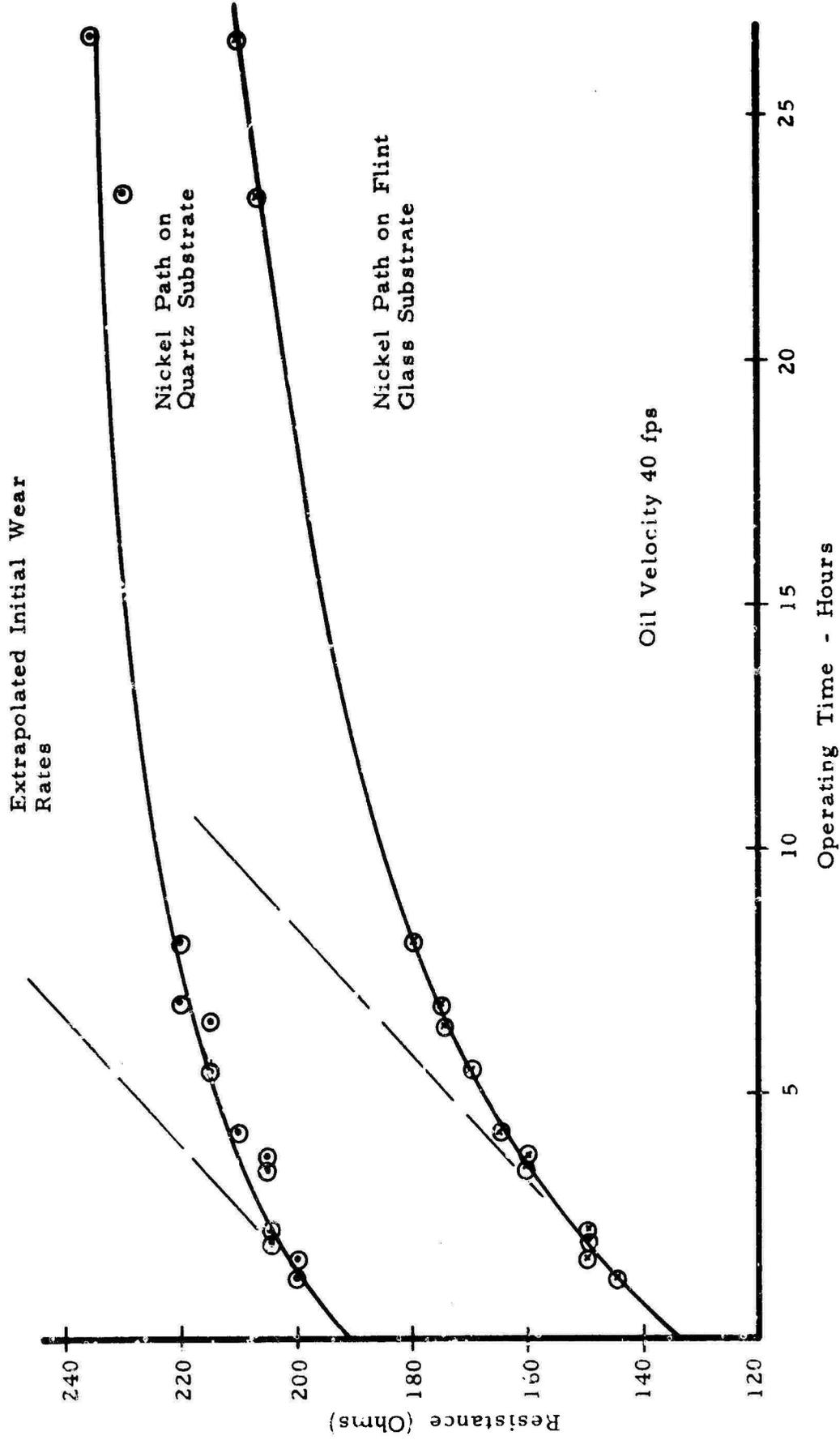


Figure 11 Abrasive Wear Characteristics - No Abrasive Contaminant Renewal

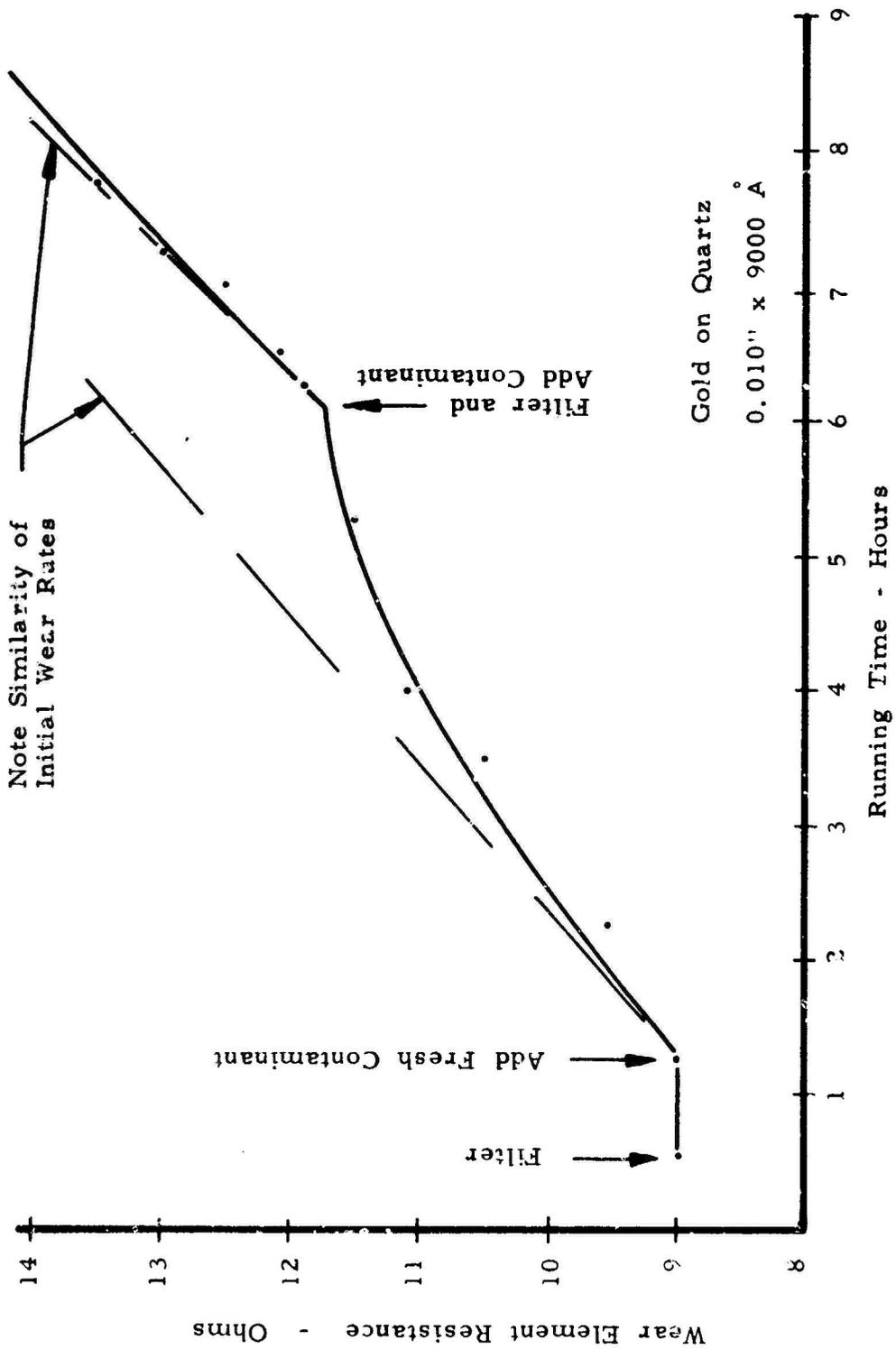


Figure 12 Typical Wear Characteristics of Element

two types of elements with fresh contaminant added only at the beginning of the period. The decay in wear rate during the test period is evident. For both elements the increase in resistance during the first four hours of operation was approximately equal to the total increase in resistance realized during the subsequent 22 hours.

Figure 12 contrasts the effect of periodic filtration of the oil and renewal of the contaminant on the wear characteristics using another type of element. The magnitude of the resistance level of the elements of Figures 11 and 12 varies widely but the trends are quite similar. In Figure 12 the decrease in wear rate after only a few hours of operation and the return to this wear rate upon renewal of the contaminant point out the necessity for frequent renewal.

These results indicate that the "effective abrasive life" of the contaminant may be only a few hours. Since particle counts do not indicate major size degradation of the particles over a few hours, the reduced abrasive action must be attributed to smoothing of the rough edges and rounding of the particles.

In an internal combustion engine, abrasive particles are continuously ingested with the incoming air and collected by the lubricant. Fresh abrasive particles are continuously being added to the system. Only when the oil filter is bypassed do the same particles pass repeatedly through the system.

To simulate this condition in our test program, the lubricant is filtered completely every two hours and fresh contaminant added in the appropriate amount. This procedure produced a lubricant with contaminant concentration and abrasive characteristics that remain constant with time.

The limited test program did not permit testing a wide range of contaminant types and concentrations. AC Air Filter Test Dust with chemical composition and particle size distribution as shown in Table II provided an inexpensive, widely accepted contaminant, typical of that found in service. The concentration used in all tests was 15 ppm of contaminant by weight. Since only 60 percent of the test dust is silica, this provides a 9 ppm silica content. Although somewhat lower than the 15-20 ppm threshold level commonly accepted, this level did produce measurable wear of the test elements. The lower concentration was chosen to provide a conservative indication of the maximum sensitivity of the device. It is a simple matter to reduce the sensitivity of the wear elements and sense only higher abrasive concentrations.

4.3 Detailed Test Program and Results

An experimental program was developed to evaluate the feasibility of the proposed abrasive damage indicator concept and determine wear element and sensor designs which are sensitive to lubricant contaminant. The scope of this program was too limited to produce sensor elements which are "calibrated" in terms of typical operating hours and contaminant levels. Rather, sensor element designs have been developed which definitely prove the feasibility of monitoring the abrasive action of particulate contaminant in lubricating oil with relatively simple and inexpensive sensor elements.

The test program required several stages of development to include consideration of all aspects of the design. The overall program is outlined in Table VII. The details of each test sequence are discussed in the following sections in sufficient depth to indicate the rationale for the selection of the subsequent modification.

TABLE VII ABRASIVE WEAR TEST PROGRAM OUTLINE AND RESULTS

Series	Wear Element Geometry	Conducting Path Geometry and Material	Velocity at Wear Path	Length of Test	Result	Comments
I	Thin cylinders (5 mil wire) stretched across flow	Silver Gold	65	57 hrs. 57 hrs. 57 hrs. 57 hrs.	{ Virtual examination produced no evidence of wear	Simple cylindrical geometry does not appear likely to produce wear under reasonable flow conditions and contaminant concentrations
II	High density alumina rectangular prism 5/16 x 5/16 x 1" with wear mat'l along one edge only (see Figure 13)	0.30" wide Nickel strip 1000 Å 3000 Å 7000 Å 10000 Å	40, 80 fps	20 hrs. 1 hr. 4 hrs.	Resistance increase 2000 Ω - 2400 Ω Resistance increased 5000 Ω - 5800 Ω Resistance showed no change	The rough surface characteristic of the alumina lead to unpredictable resistance values. Also high initial wear rates until conducting material is worn off the high spots - then wear stops. Need smooth substrate.
III	Glass prisms - { Quartz (hard) Flint glass (soft) }	0.30 x 1000 Å Nickel strip	{ 65 40	26 hrs. 12 hrs.	Resistance increase 45 percent No measurable change	Both quartz and glass elements behave similarly. All wear occurs within 0.10" of edge. Narrower conducting strip is warranted to increase sensitivity. Substrate hardness is not apparently important.
IV	Quartz Prisms	0.10 x 3000 Å Nickel strip 0.10 x 6000 Å Chromium strip	40 40	6 hrs. 6 hrs.	No measurable resistance change, but visible wear No measurable or visible wear whatsoever	40 fps appears to be minimum velocity required to produce wear with these elements and conducting path materials. Chromium is too hard; nickel appears marginal. Softer material should be considered. Narrower strip is good!
V	Quartz Prisms	0.10 x 9000 Å x 5/16" Gold Strip 0.10 x 9000 Å x 1/16" Gold Strip	37 37	8 hrs. 32 hrs. 12 hrs. 24 hours	7.8 Ω - 11.5 Ω increase 7.8 Ω - 85 Ω increase 1.4 Ω - 3.1 Ω increase - 4.2 Ω	Gold is quite sensitive to the contaminant at reasonable velocities. The 5/16" long strip provides more satisfactory resistance levels and continuous change throughout life of element.

The results of the experimental investigation are summarized:

- (a) the conducting wear path material requires support from an electrically nonconducting substrate
- (b) glass substrates provide acceptable wear resistance and surface finish
- (c) significant abrasive wear occurs only at the extreme edge, therefore maximum sensitivity requires narrow path width
- (d) gold conducting paths provide a satisfactory combination of corrosion resistance and wear
- (e) to achieve desired sensitivity the entire length of path providing the resistance must be exposed to the abrasive action of the oil.

The decision process and the resulting wear element design are discussed in the following sections.

4.3.1 Wire Abrasive Sensors

Preliminary calculations of impact efficiency, presented in Appendix C indicate that a wire diameter less than five mils is required to produce resistance changes of 0.04 percent per hour. Wire of this diameter is not available commercially and not practical for manufacture. This is particularly true for the low strengths associated with the soft metals required for abrasion sensitivity. The wire could not supply the strength required to resist the forces produced by the following oil.

In order to provide a rough check on the validity of this assertion, wear elements were fabricated from five mil wires of gold, silver and several soft metal alloys. The five mil wire was the finest available in the desired materials.

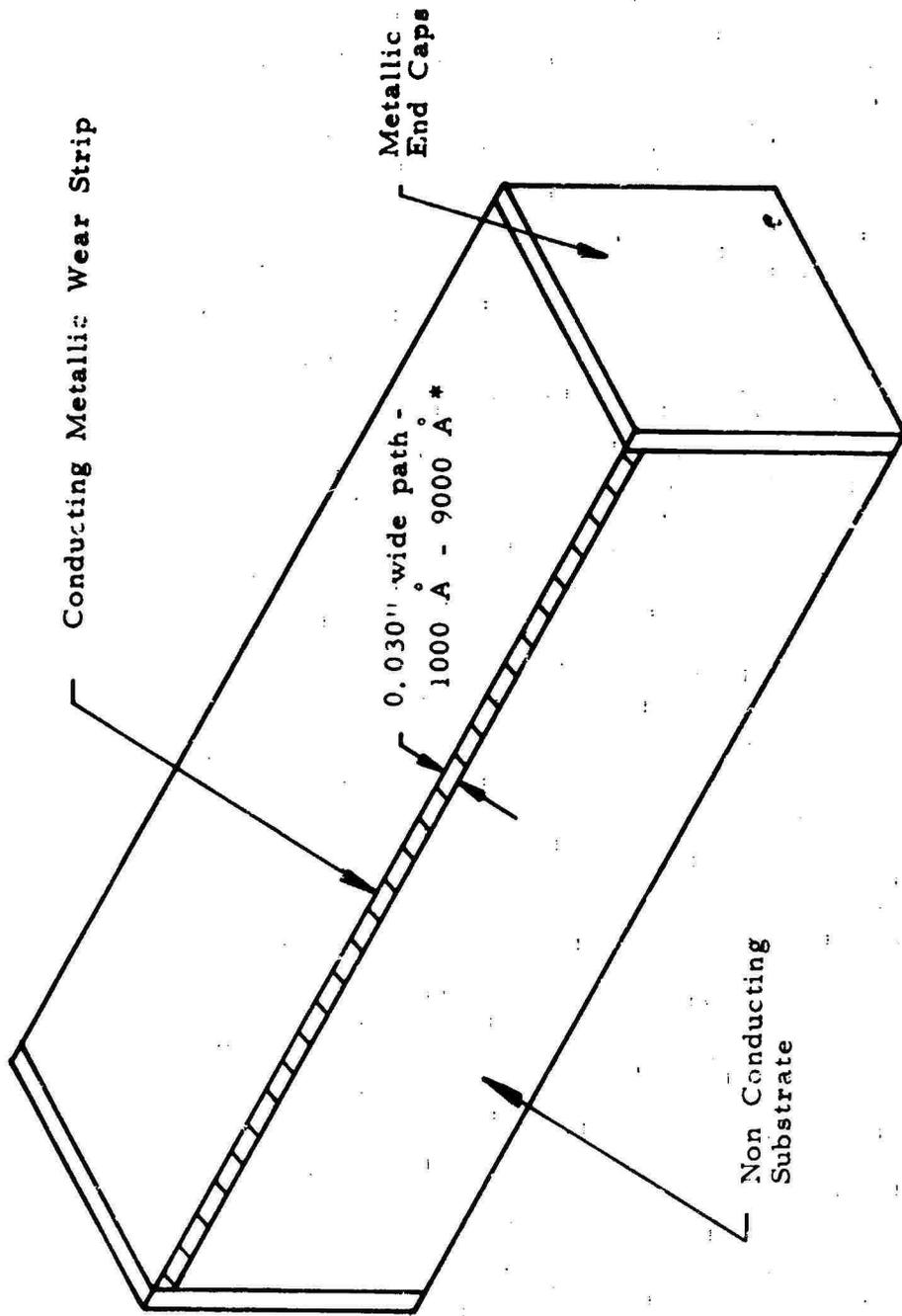
The wire elements were suspended across the lubricant flow and subjected to heavily contaminant fluid at velocities typical of those attainable in I. C. engine lubrication systems.

Despite the heavily contaminated fluid and the high flow velocity, no abrasive wear was detected visually or by resistance measurements, even after the equivalent of 3000 miles of high speed operation. This series of tests, employing fine wires from a range of soft materials, verified the theoretical prediction that wires suspended across the flow are not sufficiently sensitive to abrasion to detect the presence of abrasive particles.

4.3.2 Rectangular Alumina Substrates

To provide a substrate to support the conducting path, rectangular prisms were ground from high density alumina. A .030" wide nickel conducting path was deposited along one edge. Metallic end caps were bonded to the ends of these elements with doped epoxy to provide attachment points for electrical measurements. A sketch of the initial rectangular elements is shown in Figure 13.

The elements tested in the oil flow loop included several wear path thicknesses. Results obtained were extremely unpredictable. Frequently, wear rates - as measured by resistance changes - were initially high and decreased sharply after a short period of testing. Careful examination of the surface characteristics provided an explanation of the inconsistent behavior. The high density alumina provided a surface which is extremely



* $1 \text{ \AA} = 10^{-8} \text{ cm}$

Figure 13 Initial Wear Element Configuration

rough relative to the thickness of the conducting path. Variations in the surface finish between specimens, produced significantly variable initial resistance levels for supposedly identical pieces. The rough surface characteristics result in wear rates which are high initially but decay rapidly as the "high spots" are easily abraded, leaving the remaining conducting material in the valleys, inaccessible to the abrasive particles. These tests indicated the need for an extremely smooth surface on the wear element.

4.3.5 Glass Substrates

Glass was tested as a substrate material because of its low cost and extremely smooth surface characteristics when ground and polished. Both quartz and flint glass were tested to provide a comparison of the behavior of hard and soft substrate materials.

Nickel was sputtered along one edge .030" wide and 1000 Å (10^{-5} cm.) thick. A range of velocities were tested to determine the velocity required to produce reliable wear characteristics.

These tests indicated that the wear threshold velocity for the nickel-glass elements is on the order of 40 feet per second. At this velocity there was visual indication of abrasive action but no significant increase in the resistance level. At velocities above 40 feet per second the wear is clearly evidenced by increased resistance as shown in Figure 11. There was no significant difference between the behavior of the quartz and flint glass substrate materials.

Microscopic examination of the abraded elements indicated that the wear of the conducting path was not uniform across the full .030" width of the nickel strip but rather

concentrated in a band approximately .007" wide at the edge of the substrate. To increase the sensitivity of the elements, the width of the conducting strip was reduced to .010" for subsequent tests.

4.3.4 Quartz Substrates - Narrow Wear Paths

Narrow conducting paths, .010" wide, were sputtered onto quartz substrates. Both nickel and chromium were tried as wear path materials to evaluate the effect of wear path hardness on abrasion characteristics for a given substrate material.

The chromium on quartz elements showed no wear whatsoever. Chromium is apparently sufficiently hard to completely resist the abrasive action of the contaminant. The nickel on quartz elements did show visible indication of wear although the increase in resistance was not as great as desired. This trend indicates that softer conducting wear path materials are desirable.

The reduction in wear path width seemed adequate with the nickel, indicating abrasive action across the entire path width. Since the ends of the element are not exposed to the fluid flow, wear is concentrated at the center of the path length. To increase the sensitivity, wear must take place along the entire high resistance portion of the conducting path. To this end the wear path geometry was altered so that virtually all path resistance was contributed by the portion of length exposed to abrasive action.

4.3.5 Quartz Substrates - Gold Paths

Gold was selected as a conducting path material because of its relative softness and its resistance to corrosive action. To check the effect of a reduction in conducting path length on sensitivity, two modified wear path geometries were tested. They are shown in Figure 14. Calculations based on the area and length of the conducting path indicate that the wide portions provide only 30 percent of the total electrical resistance. Virtually all the measurable

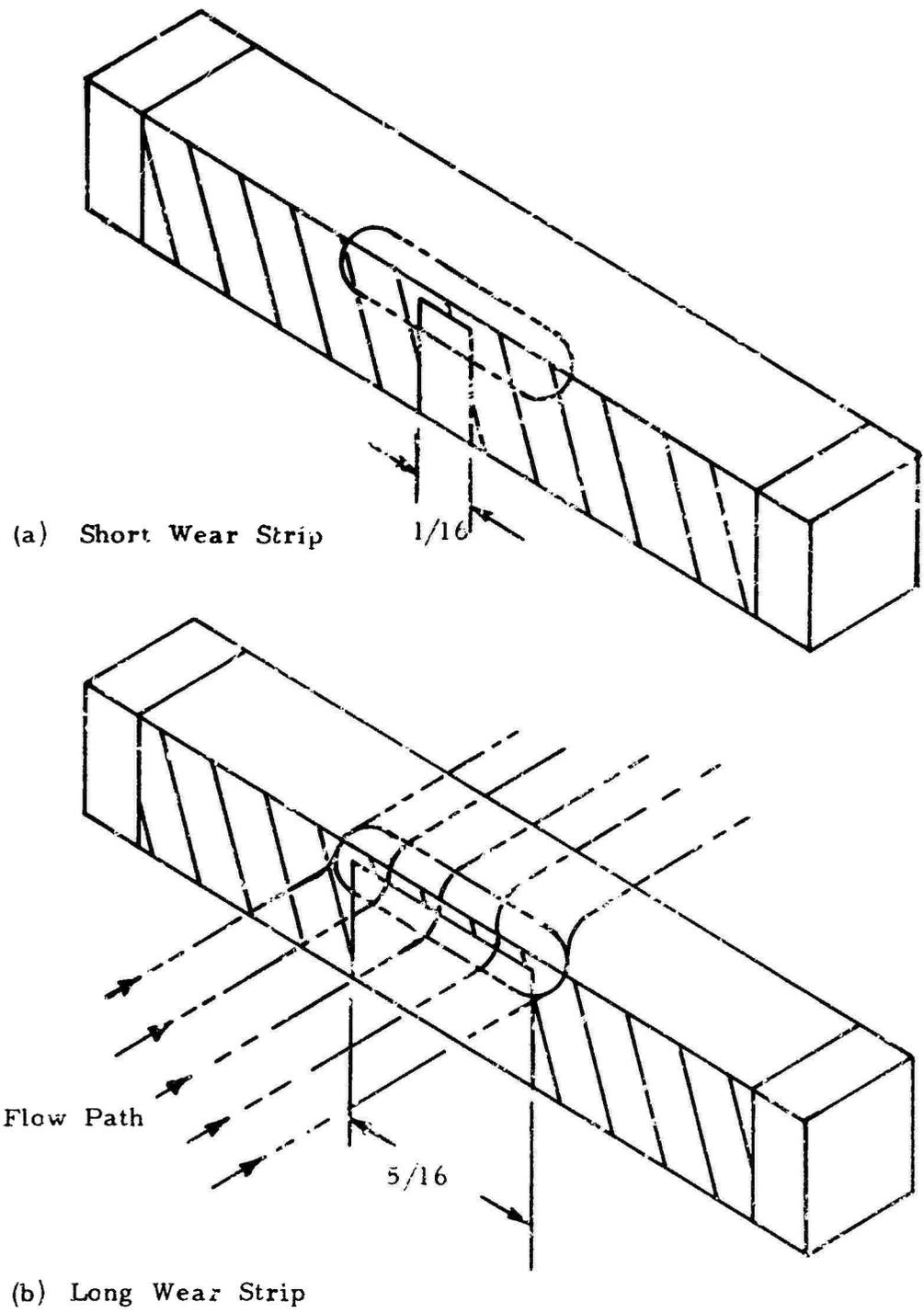


Figure 14 Modified Wear Path Geometries

resistance of the path is attributable to the narrow strip in the center. Consequently an increase in the resistance of the narrow strip significantly affects the overall resistance of the conducting path. If the narrow portion of the wear path extended beyond the fluid boundaries as in the previous configurations, an increase in the resistance at the center would produce a smaller percentage change in the total resistance. Figure 15 indicates how the abrasive wear is localized at the most sensitive portion of the conducting strip.

The tests produced extremely promising results. The gold strip exhibited significant wear at a flow velocity past the wear path of 40 feet per second. Wear was concentrated at the center and the modified path geometry amplified the effect of the resistance change at the narrow strip.

Based on these tests the maximum sensitivity is achieved when the narrow strip extends to the edges of the flow path but does not extend beyond the flow. Sensitivity is reduced if the narrow strip does not cover the full width of the flow stream.

A typical wear characteristic for this preferred element design is presented on Figure 16. Note the relatively uniform wear rate and the absence of any measurable wear during the extended filtration period.

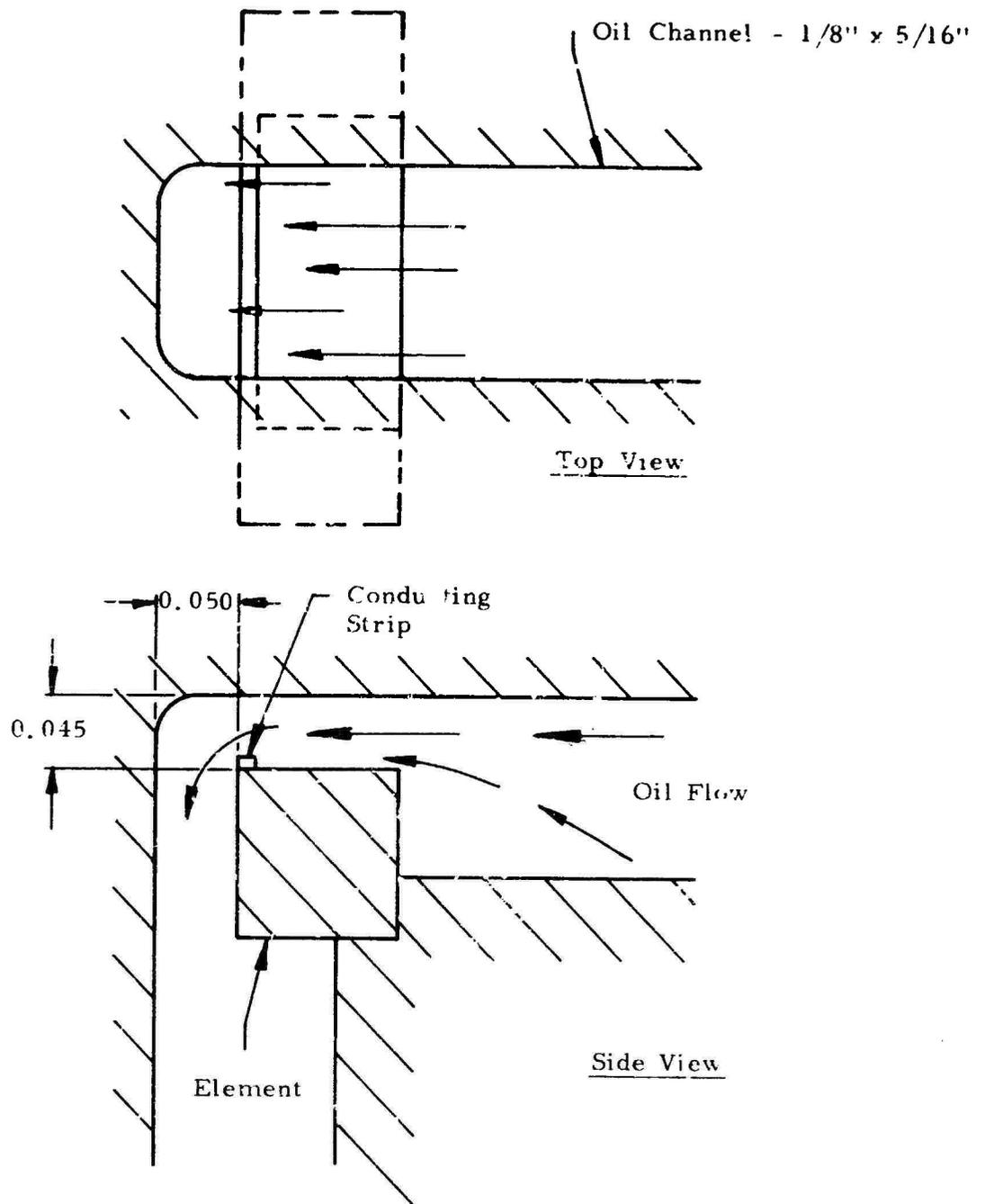


Figure 15 Oil Flow at Wear Element

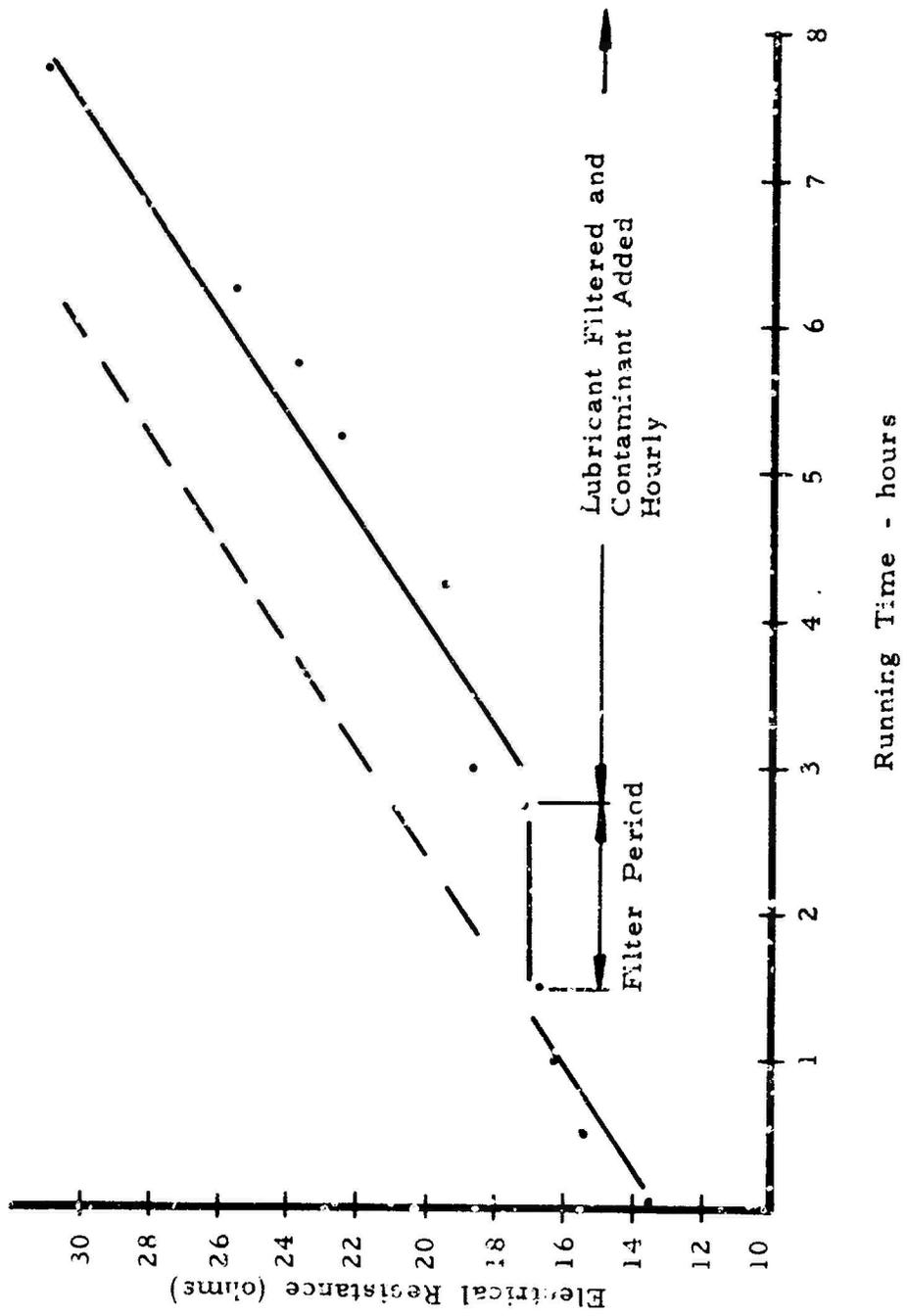


Figure 16 Wear Characteristic of Preferred Element Configuration

5. Prototype Indicator Design

Based on the positive results of the experimental program, prototypes of an abrasive oil contaminant indicator were designed and fabricated. Two completely different sensor bodies are required to meet the requirements of the 1/4 ton and 2 1/2 ton trucks. These bodies house wear elements that are identical. The electronics in the vehicles which process the signal from the wear element and provide the warning signal are also identical for both applications.

The following sections discuss the general design considerations, the particulars of the design of the sensor body for both the 1/4 ton and 2 1/2 ton trucks, the specifications of the wear elements and the design details of the electronic circuit.

5.1 General Design Considerations

The test program indicated a minimum threshold velocity is required to produce reliable abrasive wear and that the rate increased as the velocity increased above this threshold level. The increase in wear rate is effectively an increase in the sensitivity of the device and therefore is desirable.

To provide the maximum velocity, both sensor bodies are designed to sample the lubricant flow from the main stream at the highest pressure available. This occurs upstream of the filter and therefore includes unfiltered oil. The sampled oil is directed past the wear surface of the element and back to the sump with restrictions necessary to provide identical flow velocities past the wear elements and therefore similar sensitivities for the two applications. Thus the primary function of the sensor body is to direct a small flow of the unfiltered lubricant from the main stream, past the wear element, and back to the oil sump. The sensor body must also provide access to the element for changes, provide the electrical signal to the electronics and minimize the possibility of an external oil leak.

It must be stressed that the sensor bodies presented herein, with their external oil lines, are for concept evaluation purposes and testing only. If an abrasive oil contaminant indicator is adopted for general use, the elements will be mounted directly into oil passages in the engine block or the filter housing.

5.2 1/4 Ton Truck Sensor Body

Photographs of the disassembled sensor body for the 1/4 ton truck application are presented in Figure 17. The body is mounted between the standard cartridge filter and the engine on the oil filter adapter as shown in Figure 18. The long hollow bolt clamps the sensor to the adapter but permits rotation to facilitate positioning of the oil return line. Oil enters the filter from the engine through the off center hole in the sensor. At this point, a small portion of the oil bypasses the filter, washes past the wear element, and returns directly to the sump through the line from the side of the sensor body. The balance of the oil returns from the filter to the engine through the hollow "bolt" which also serves to mount the oil filter.

The sensor body is easily disassembled on the vehicle to provide access to the wear element for required changes as shown in Figure 19. Sealing between the sensor and the adapter as well as between the parts of the sensor is effectively accomplished with O-rings.

The 37 to 42 psi pressure available from the pump on the 1/4 ton truck is more than adequate to provide oil velocities on the order of 40 feet per second. A .113" diameter orifice in the return line restricts the flow rate to 1.5 gallons per minute, less than 25 percent of the total pump output. This flow rate could be reduced by employing still smaller passages in the sensor.

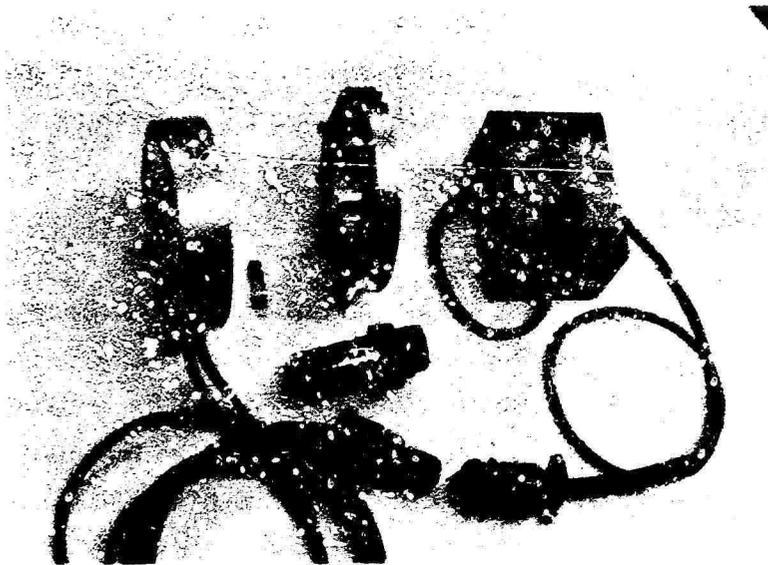


Figure 18 Sensor Installed on 1/4 Ton Truck

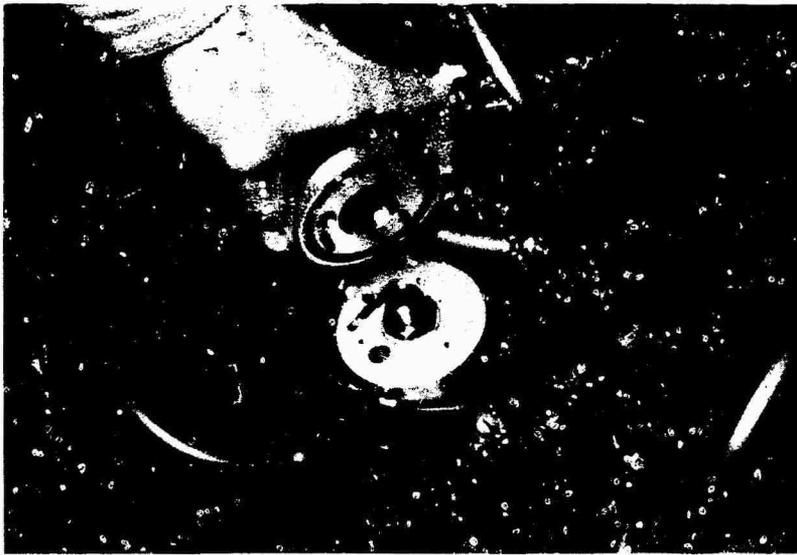


Figure 19 Sensor Disassembled on 1/4 Ton Truck
For Wear Element Change

Electrical signals are carried to the indicator box in the cab through 16 gage stranded wire conductors. Epoxy is used to bond the lead into the element and seal effectively against external oil leakage.

5.3 2 1/2 Ton Truck Sensor Body

The 2 1/2 ton truck sensor body is shown disassembled in Figure 20. The short pipe nipple screws directly into an existing hole in the oil filter housing assembly, mounts as shown in Figure 21, and bypasses a small portion of the unfiltered oil from upstream of the filters. This nipple provides both the passage for the oil and the mounting for the sensor. The 125 psi oil pressure available at this location will produce excessively high oil velocity at the wear element if the element provides the only restriction to flow. A 0.125" diameter orifice located in the return line has been sized to provide the same 40 feet per second fluid velocity past the element as achieved in the 1/4 ton truck sensor. Since the critical passage dimensions are identical in the two applications the total flow is the same, 1.5 gallons per minute.

The sensor body provides easy access to the wear element through a removable cover sealed by a Vellumoid gasket as shown in Figure 22. The electrical signal is transmitted by the two conductor lead, potted in epoxy, through the side of the device.

5.4 Wear Element Design

The details of the wear element design are presented in Figure 23. Identical elements are employed in the 1/4 ton and 2 1/2 ton truck systems.

Rectangular quartz prisms, ground and polished on two sides, are used as the substrate. A molecular layer of tin is sputtered directly to the substrate to improve the adhesion of the 9000 Å gold layer forming the conducting path. The length of

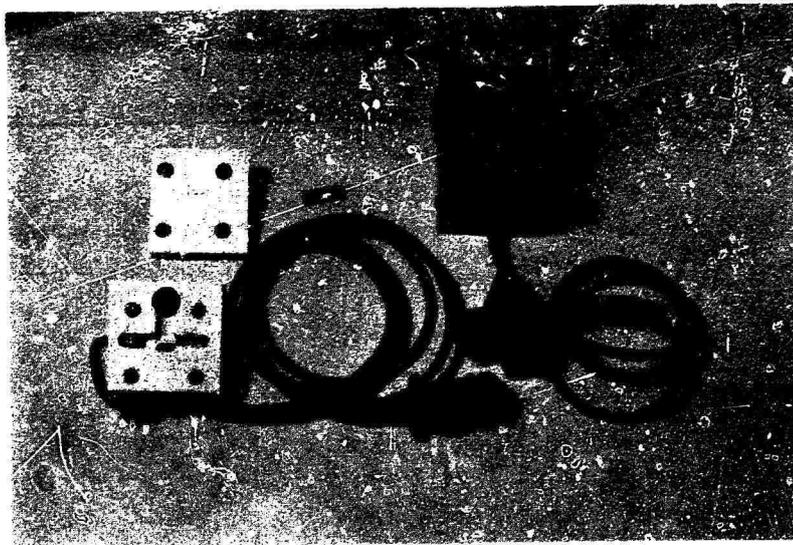


Figure 20 Disassembled 2 1/2 Ton Truck Sensor

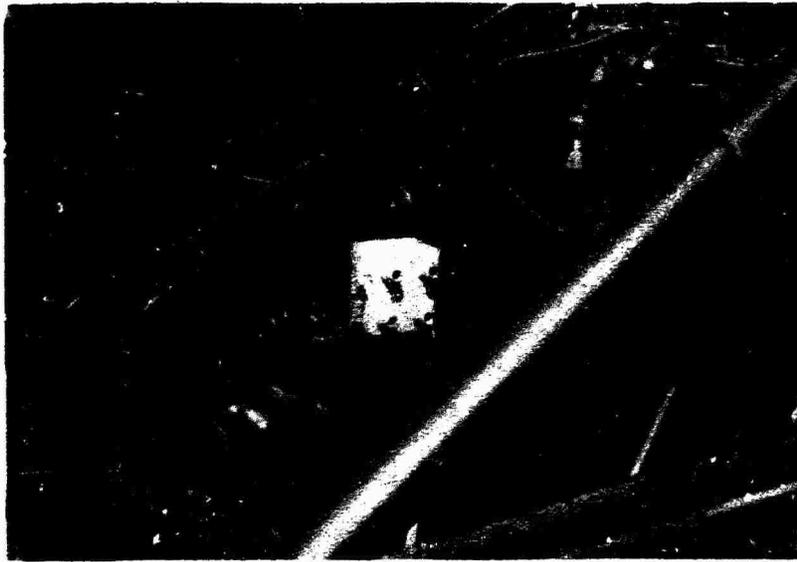


Figure 21 2 1/2 Ton Truck Sensor Installed on Vehicle



Figure 22 Sensor Disassembled for Wear Element Change

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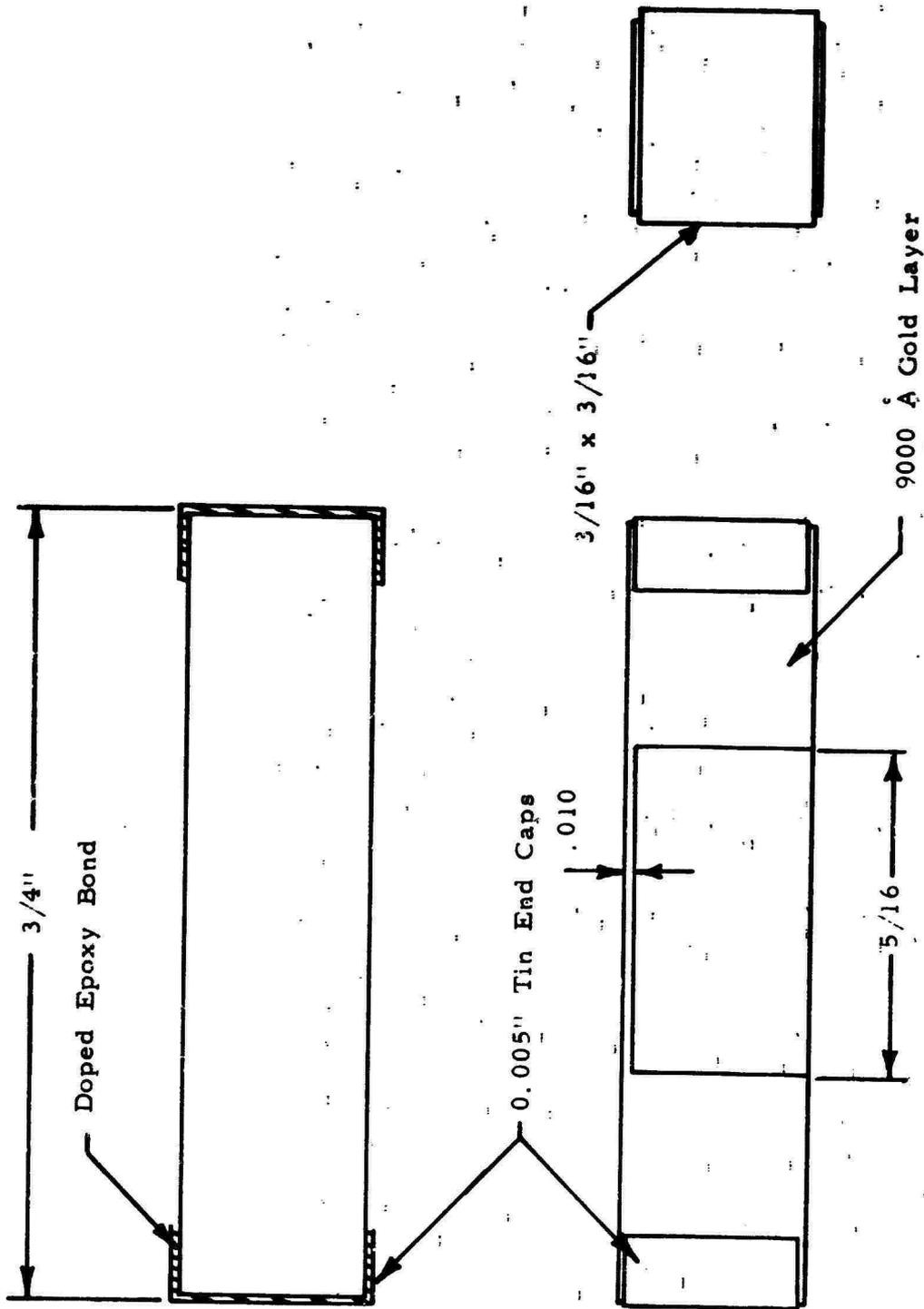


Figure 23 - Quartz Prism Wear Element

sputtering time is adjusted to yield path resistance, end to end, of eight ohms.

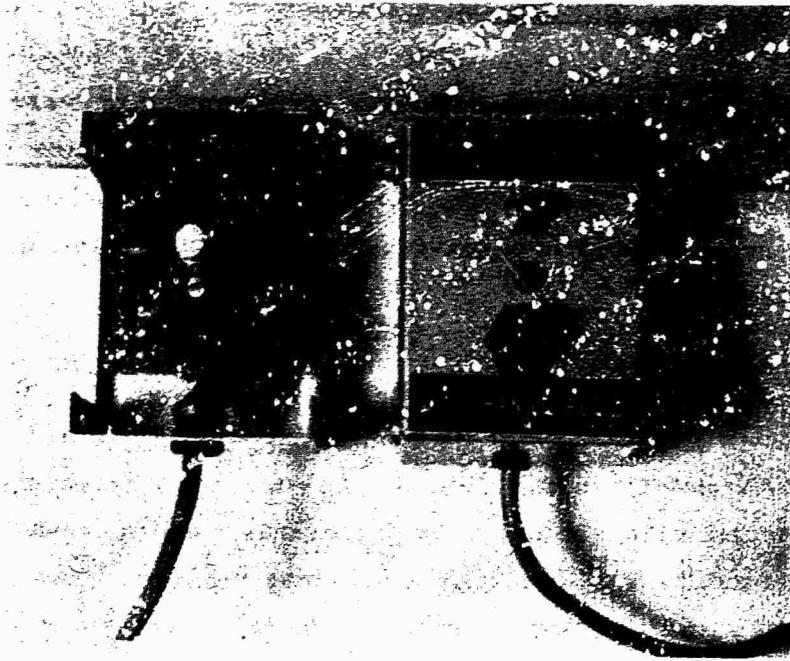
End caps of .005" tin sheet provide electrical contacts at either end of the element that will provide reliable resistance readings. These end caps are bonded to the substrate using a heavily doped epoxy which insures low resistance electrical contact with the gold. The end caps overlap the conducting gold path to provide good contact and offer protection against mechanical damage.

5.5 Indicator System

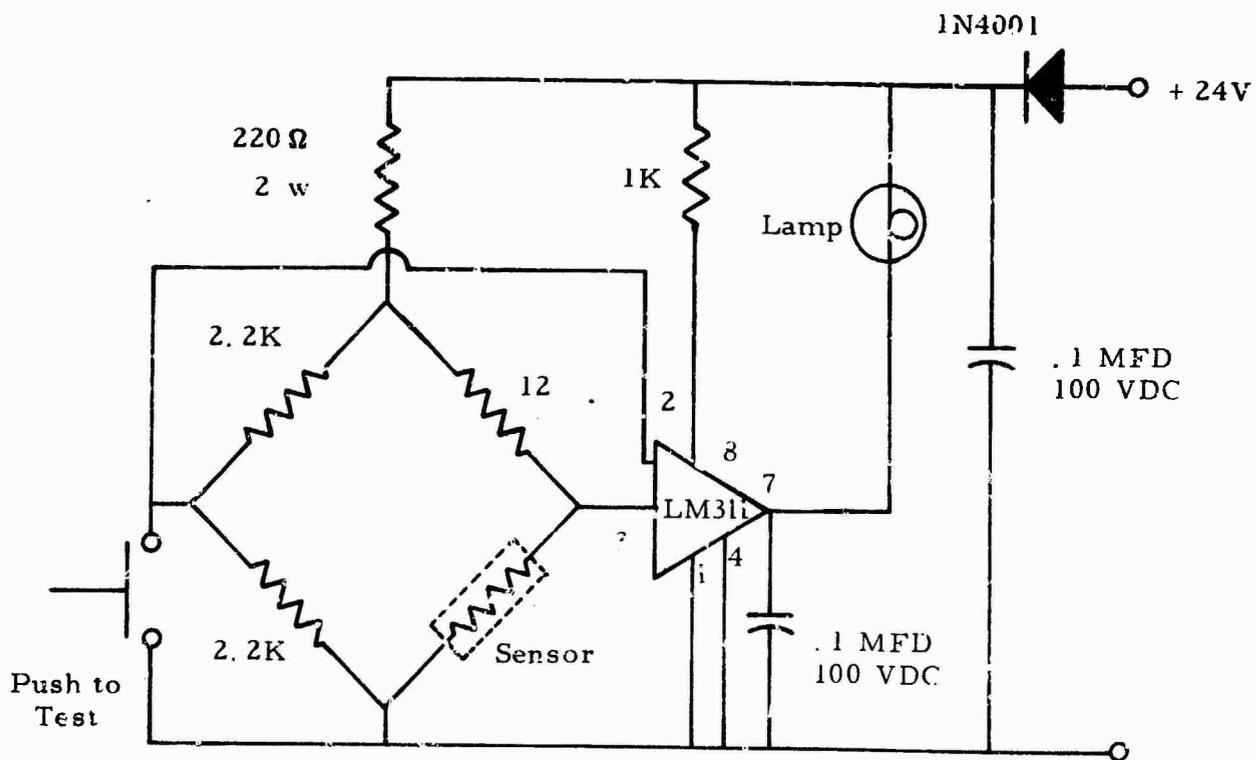
The indicator box and a diagram of the electronic circuit are shown in Figure 24.

The electronics employs a bridge circuit connected to a high gain, high common mode rejection comparator. This produces a signal which is sensitive to a wear element resistance change of 0.01 percent, stable over a wide range of temperatures and input voltages.

The careful application of low precision electronic components has kept the cost of the indicator box to a minimum. The connectors are the single largest cost item.



(a) Indicator Light Box



(b) Electrical Schematic of Electronic Circuit

Figure 24 - Indicator System for Oil Life Indicator

6. Testing of Prototype Units

The abrasive damage indicator prototype units were subjected to rigorous testing to assure reliable operation under the adverse conditions of military use. The test program included functional evaluation in the laboratory, environmental testing and limited vehicular testing.

6.1 Functional Laboratory Evaluation

Before installation on the vehicles one each of the prototype units were subjected to preliminary testing under the easily controlled conditions of the laboratory test facility. The tests assured leak tightness and electrical continuity under a wide variety of operating temperatures and pressures.

Of particular interest were the epoxy seals on the electrical leads and their behavior under the action of high temperature lubricating oil at high pressure. This preliminary evaluation indicated satisfactory behavior.

6.2 Environmental Test Program

Environmental tests were conducted on the sensor prototypes and the indicator system in the Foster-Miller Laboratory and the Acton Environmental Testing Laboratories in Acton, Mass. Tests felt most critical were run both with and without oil in the sensor.

6.2.1 High Temperature Testing

The sensor and indicator were soaked for several hours at 165°F in a small high temperature chamber in the Foster-Miller Laboratory. Temperature sensitivity of the elements and the electronics was less than 2 percent of the resistance measured.

Simulation of a worn element triggered the indicator circuit throughout the temperature range.

6.2.2 Low Temperature Testing

The sensor and indicator system were cooled to -65 °F by soaking in a mixture of dry ice and acetone. Again the device functioned adequately with temperature sensitivity not measurable with our instrumentation. No temperature compensation will be required to produce satisfactory operation over the full range of temperatures.

6.2.3 Vibration Testing

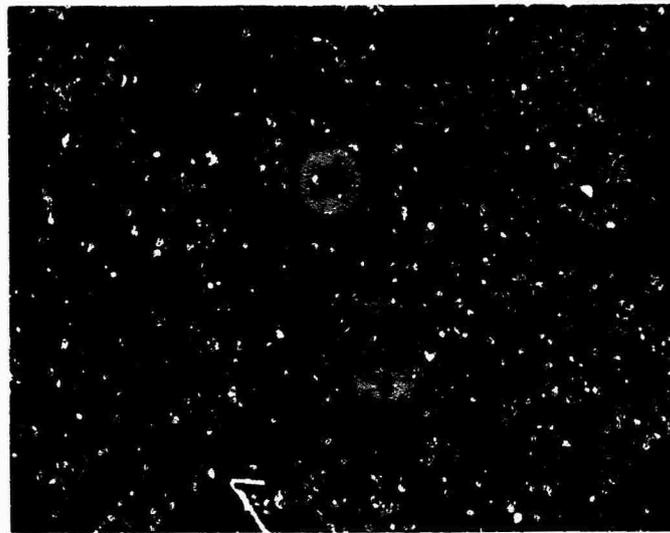
The indicator systems were mounted on a shaker table and subjected to vibration at frequencies from 5-500 cps at a constant load of 2-1/2 "g's". A photograph of both sensor units and their indicator boxes mounted on the shaker table is shown in Figure 25.

The devices performed satisfactorily throughout the entire frequency range with no false signals indicating malfunctions in the sensor or electronic package.

The frequency range and "g" loading is as per MIL-STD-810B for equipment of this type installed on ground vehicles.

6.2.4 Shock Testing

Both sensor designs and their indicators were mounted on a shock table and subjected to loads of 20 "g's" for 18 milliseconds in three directions. This represents the normal shock test for equipment installed in ground vehicles. Operation of the



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Figure 25 Oil Life Indicator Systems Mounted for Vibration Tests

devices was normal after being subject to 3 shocks in each place. A 75 "g", 11 millisecond shock, considered to represent collision conditions produced no adverse effects.

6.3 Vehicular Testing

The appropriate sensors and indicators were installed on the M35A2 2 1/2 ton truck and the M151A2 1/4 ton truck supplied by USATACCM. The sensor on the jeep is installed beneath the oil filter cartridge on the filter housing. On the diesel truck, the sensor may be screwed directly into an existing tapped hole in the oil filter housing. Photographs of the installations are presented in Figure 18 and Figure 21. For both vehicles, the indicator box is mounted in the cab of the vehicle beneath the dashboard. Detailed installation instructions are presented for each vehicle in Appendix A and B.

The vehicular testing was limited to observing no malfunction during 20 miles of driving under the limited range of operating conditions to be encountered on the local highways. The destructive nature of the abrasive prohibited simulation of operation with heavily contaminated lubricant.

Operation of the abrasive damage indicator systems for both vehicles was as anticipated under normal driving conditions.

7. Production Cost Estimates

The final prototype units as supplied to USATACOM cost \$105.92 and \$73.42 each for the 1/4 ton truck and 2 1/2 ton truck engine respectively. These costs are in quantities of 6 and are exclusive of the wear elements. The breakdown of cost is as follows:

	<u>Jeep</u>	<u>Truck</u>
(a) Electrical System Components	21.42	21.42
(b) Plumbing Lines and Fittings	6.00	10.50
(c) Machined Parts for Sensor	73.50	36.50
(d) Assembly and Testing	<u>5.00</u>	<u>5.00</u>
	\$105.92	\$73.42

Estimated costs for the devices in a quantity of 100 is as follows:

	<u>Jeep</u>	<u>Truck</u>
(a) Electrical System	14.25	14.25
(b) Plumbing	5.60	8.80
(c) Machined Parts	10.80	7.10
(d) Assembly and Testing	<u>3.00</u>	<u>3.00</u>
	\$33.65	\$33.15

The above costs indicate major savings in the cost of the machined parts. No major design changes have been considered since quantities even up to 1000 are not sufficient to warrant redesign for stamping or die casting. The major manufacturing method is tape controlled milling. The above costs include the cost of the tape. Cost in the ultimate application would be less than shown above due to modification of existing castings.

Estimated costs for the devices in a quantity of 1000 are as follows. These costs reflect additional savings due to quantity discounts on purchased parts, economies of handling and amortization of the control tape cost over the additional units.

	<u>Jeep</u>	<u>Truck</u>
(a) Electrical System	9.46	9.46
(b) Plumbing	2.10	5.00
(c) Machined Parts	5.40	3.55
(d) Assembly and Testing	<u>1.50</u>	<u>1.50</u>
	\$18.46	\$19.01

The wear elements are identical for both the jeep and the diesel truck application. Their cost is \$15.00 each in small quantities for which the sputtering process is employed. For larger quantities and for increased uniformity a photo etch process is recommended. Estimates of the costs for both processes are as follows:

	100	1000	10,000
Mechanical sputtering	13.00	6.00	2 - 3.00
Photo Etching Process	6.00 - 8.00*	3.00 - 4.00	.50 - 2.00

* Plus \$1200 engineering cost to optimize the process.

The low unit cost for the large quantities using the photo etching process reflects considerable automation. In these quantities the material and process costs are small compared to the cost of handling of the pieces. One wear element for a wide range of applications will permit economies of automation and thus minimize the cost of the wear elements.

8. Conclusions and Recommendations

An abrasive contaminant indicator has been developed which is sensitive to contaminant of the type and concentration felt to be critical in internal combustion engine lubrication systems. The wear element responds to the abrasive content of the oil over a period of time by an increase in electrical resistance of a conducting strip. An electrical circuit triggers a warning light when the abrasive action exceeds predetermined limits. These sensors have been applied to the lubrication systems on the M35A2 2 1/2 ton truck and the M151A 1/4 ton truck.

The feasibility of the abrasive damage indicator concept has been established. The testing of the prototype sensor elements in the laboratory and the preliminary vehicular testing were not sufficient to produce calibrated versions of the abrasive damage indicators.

Prior to extensive field testing a more detailed laboratory investigation to optimize the wear element design is required. This program should:

- (a) optimize wear element production techniques to insure repeatability and minimize cost
- (b) determine the variation in wear element performance under identical conditions
- (c) determine the effect of variation in operating conditions - velocity, temperature, viscosity, contaminant type and level, dead storage - on the performance of the wear element.

Having completed this investigation a full scale test program should be undertaken involving installation on a number of vehicles under typical operating conditions.

BIBLIOGRAPHY

1. A. T. Weare, "A Standard Contaminant for Oil Filter Testing" Proceeding Instn. Mech. Eng. Vol. 176, No. 10, 1962.
2. J. E. McClelland, S. M. Billell, "Filter Life versus Engine Wear", SAE No. 650866.
3. C. E. Watson, F. J. Hanly, and R. W. Burchell, "Abrasive Wear of Piston Rings," Paper presented at SAE Annual Meeting, Detroit, January 1955.
4. K. A. Frassa and A. B. Sarkis, "Diesel Engine Condition Through Oil Analysis," SAE No. 680759, Presented at SAE National Fuels and Lubricants Meeting, Tulsa, Oklahoma, October, 1968.
5. G. E. Thomas, R. M. Culbert, "Ingested Dust, Filters, and Diesel Engine Ring Wear," SAE No. 680536 Presented at West Coast Meeting, San Francisco, August, 1968.
6. H. Halliwell, "Radiotracers Reveal Engine Wear During Detergent Oil Study," SAE Transactions Vol. 68, 1960.
7. Paul Friend - Mobil Oil Corp. Technical Services, Personal Communication, 3 August 1971.
8. Dick Fein - Texaco Oil Company - Personal Communication 20 July 1971.
9. "Trouble Shooting Manual - LDS-465-1 Multifuel Engine" Continental Aviation and Engineering Corporation, Detroit, June 1968.
10. "Field and Depot Maintenance for Engine, Diesel: Turbosuper charged, Fuel Injected, Water Cooled, 6 Cylinder, Assembly - 2815-897-5061" Dept. of the Army TM9-2815-204-35, February 1964.
11. "Field Maintenance Manual - Engine Assembly (2805-678-1820) and Clutch," Dept. of the Army, TM9-2805-213-34, January, 1963.
12. Guzdar, A. R. et al., "Development of an Improved Water Separator for use in Aircraft having an Air Cycle Refrigeration System," Foster-Miller Associates, Technical Report AFFDL-TR-69-13, May 1969.
13. Richardson, E. G. (Ed), "Aerodynamic Capture of Particles," Pergamon Press, London, 1960.

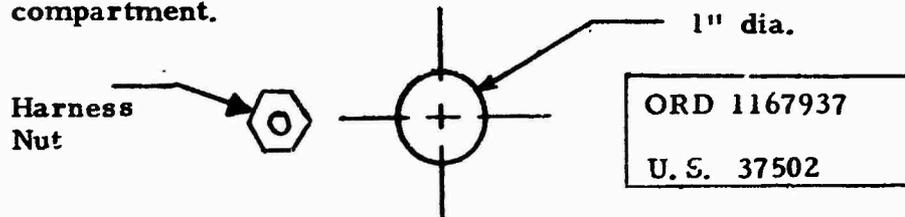
14. Guzdar, A.R., op. cit.
15. Strauss, W., "Industrial Gas Cleaning", Pergamon Press, London, 1966.
16. Langmuir, I., and Blodgett, K. B., "A Mathematical Investigation of Water Droplet Trajectories", Army Air Force Technical Report No. 5418 (1946).
17. Langmuir, I., "The Production of Rain by a Chain Reaction in Cumulus Clouds at Temperatures above Freezing", Journal of Meteor., Vol. 5, No. 5, p. 175.
18. Pearcey, T., and Hill, G. W., "A Theoretical Estimate of the Collection Efficiencies of Small Droplets", Quart. J. Roy. Meteorol. Soc., Vol. 83, No. 355, p. 77, 1957.
19. Herne, H., "The Classical Computations of the Aerodynamic Capture of Particles by Spheres".
20. Rabinowicz, E., "Friction and Wear of Materials," John Wiley and Sons, 1965.
21. Wong, J. B. and Johnstone, H. F., "University of Illinois Engineering Experiment Station Technical Report No. 11, (1953).

APPENDIX A

INSTALLATION INSTRUCTIONS - OIL LIFE INDICATOR - 1/4 TON TRUCK

1. Remove oil filter and filter nut in center of oil filter housing. Place element housing on filter housing and secure with adapter bolt (short end up). Do not tighten adapter bolt and be sure "O" ring is properly located between filter housing and element housing.
2. Assemble special bulkhead fitting to short leg of oil return tube and hand tighten only. Remove front wheel from passenger side of vehicle. Rotate element housing to position elbow fitting at approximately 11 o'clock position and insert long leg of oil return tube into elbow so that oil return tube hangs down toward oil pan.
3. From inside passenger wheelwell, position oil return tube and bulkhead fitting on oil pan and mark location of 4 mounting holes. Drill four 7/64" mounting holes as marked and one 3/8" dia. hole in center of the 4 mounting holes. Use heavily greased magnetized drill bit to prevent metal chips from entering oil pan.
4. Mount special bulkhead fitting and cork gasket on oil pan and secure with 4 sheet metal screws and lock washers supplied.
5. Insert oil return tube into bulkhead fitting and then into element housing. Position element housing for best tube routing and tighten element housing adapter bolt. Tighten oil return tube fittings and replace front wheel.

6. Run wires and connector neatly up to horn and inside harness retaining straps. Run packer connector thru grommet along with windshield washer hose. Replace oil filter.
7. Remove 4 slotted head screws on instrument panel and pull panel forward. Disconnect speedometer cable behind panel for more working room.
8. Remove back from indicator light box, and secure to dashboard using the two screws already in dash. Secure indicator light box to back cover.
9. Drill or punch 1" dia. hole in firewall between vehicle identification tag and harness nut as seen from engine compartment.



10. Route indicator light cable under dashboard and over the hole in firewall. Push connector thru hole and connect to make end from element housing. Insert grommet in hole.
11. Disconnect wire from "BAT-GEN" gauge and plug in the adapter tee to the gauge. Plug in both sensor wire and original wire into adapter tee.
12. Replace speedometer cable and attach instrument panel back to dashboard.

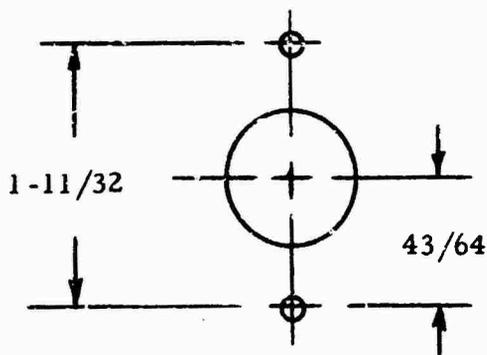
INSTRUCTIONS FOR REPLACING SENSOR ELEMENT

1. Remove oil filter. Remove 3 socket head capscrews on element housing and lift off top of housing.
2. Carefully remove sensing element by pushing it against spring and lifting up. Observe the location of the stripe on the element and notice that it faces toward the adapter bolt and is near the top surface of the housing.
3. Replace the element with a new one and install in exactly the same position as the old one. For check purposes, a red dot on the element should line up with a red dot on the housing next to the element chamber.
4. Be sure "O" ring seal is still in element cover and replace element cover with the 3 capscrews. Replace oil filter and tighten.

APPENDIX B

INSTALLATION INSTRUCTIONS - OIL LIFE INDICATOR - TRUCK

1. Remove $3/8$ NPT pipe plug from oil filter housing and install element housing assembly. Tighten assembly and stop when elbow tube fitting is on right side and pointing down at approximately 45° .
2. On opposite side of block, remove 1" NPT pipe plug located just above oil pan and install oil return plug as supplied. Tighten elbow in plug until it points straight down.
3. Connect steel oil tube between element housing and oil return plug. Oil tube is routed under oil pan. End of tube having the 45° bend connects to element housing. Attach tube support brackets and secure to nearest oil pan bolt. (Some additional bending or modification may be necessary.)
4. To the left of the steering column drill a $3/4$ " dia. hole and two $5/32$ " dia. holes as shown below.



5. Remove back of indicator light box and secure to dashboard just to the left of the instrument panel using the 2 available screws. Secure indicator box to its back.
6. Route indicator box cable down and under dash box and mount male cable connector in drilled holes using two 6-32 screws and nuts.

7. Route cable from element housing neatly toward firewall and tape where necessary. Connect cable at bulkhead and bring free lead from connector along top of firewall to large grommet located to the left of the valve cover. Push wire thru grommet into cab of truck.
8. Remove the 4 screws holding the instrument panel and pull the panel forward. Splice the packer connector tee wire into the "BAT-GEN" wire and plug in the wire coming through the grommet.
9. Replace instrument panel and secure any loose wires with tape or clamps.

SENSOR ELEMENT REPLACEMENT INSTRUCTIONS

1. Remove 4 screws on sensor housing cover and remove cover and gasket.
2. Remove element by pushing it against spring and lifting up. Observe the location of the stripe on the element and notice that it faces away from the elbow fitting and is near the top surface of the housing.
3. Replace the element with a new one and install in exactly the same position as the old one. For check purposes, a red dot on the element should line up with a red dot on the housing next to the element chamber.
4. Replace the gasket, cover and 4 screws. Tighten securely.

APPENDIX C

ESTIMATE OF PARTICLE IMPACTION AND WEAR RATE

The rate of wear produced by particles impacting a surface is dependent on two phenomenon - the rate of particle impact and the amount of material removed per particle impact. The mechanism of particle impact is well understood and the theories have been applied extensively to the capture of particles by fibrous filters, screens and liquid scrubbers. The wear, or amount of material removed by each impacting particle is more difficult to quantify. There is no satisfactory theory for determining the amount of material removed. There is not even sufficient knowledge to compute the force pushing the particle against the target surface after impact. In fact, very limited theories indicate that the particle may be lifted away from the target.

In the following paragraphs the basic phenomena of impaction and wear will be presented as they apply to a wire placed across a flow stream. Existing theory is presented for the calculation of impaction efficiencies and simple models have been proposed for estimating the wear. Based on these approximations, order of magnitude estimates of wear rates have been made and conclusions drawn regarding more favorable target geometries.

C.1 Particle Impact (Ref 14)

Particles are transported close to a target by the fluid stream where upon one or more of a number of short-range mechanisms act to accomplish the actual impaction. The importance of these short-range forces varies with the size and velocity of the particle; the size of the target and the presence of electrostatic, gravitational or thermal attractive or repulsive forces.

C.1.1 Collection Mechanisms

The basic short-range mechanisms affecting impaction are inertial impaction, interception, diffusion, and electrostatic forces.

a. Inertial Impaction

In the flow past an obstacle placed normal to the fluid stream, the streamlines spread around the body, as shown in Figure C-1a. The particles having inertia cannot follow the streamlines and some of them impact the obstacle. The mechanism of inertial impaction assumes that the particles have mass but no size.

b. Interception

In this case the particles are assumed to have size but no mass. The particles follow the streamlines around the body. If the streamline on which the particle lies approaches closer than $d/2$ to the target, as shown in Figure C-1b, the particle will touch the target.

The interception mechanism becomes most effective when the ratio of the particle diameter to the target diameter is close to unity.

c. Diffusion

Very small particles, in the submicron size range are rarely collected by impaction or interception. The particles follow the streamlines around the body. However, superimposed on this streamline path is a random, zigzag motion of the particles, called Brownian motion, which is caused by irregular bombardment by gas molecules. This Brownian motion results in some deposition

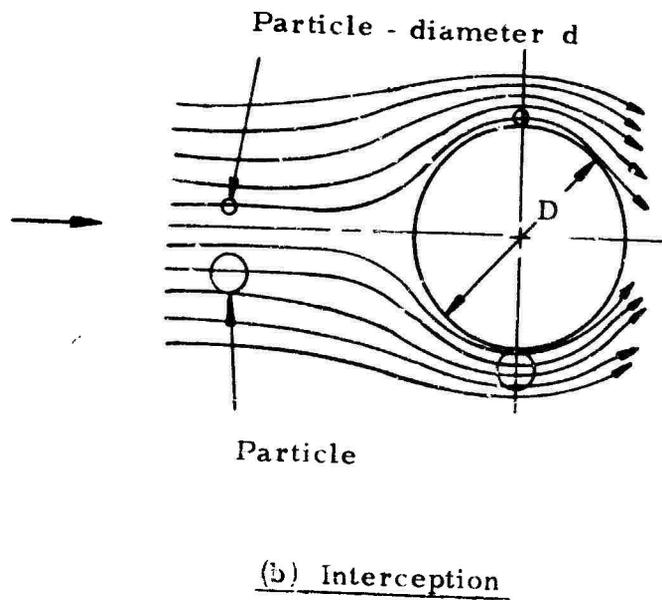
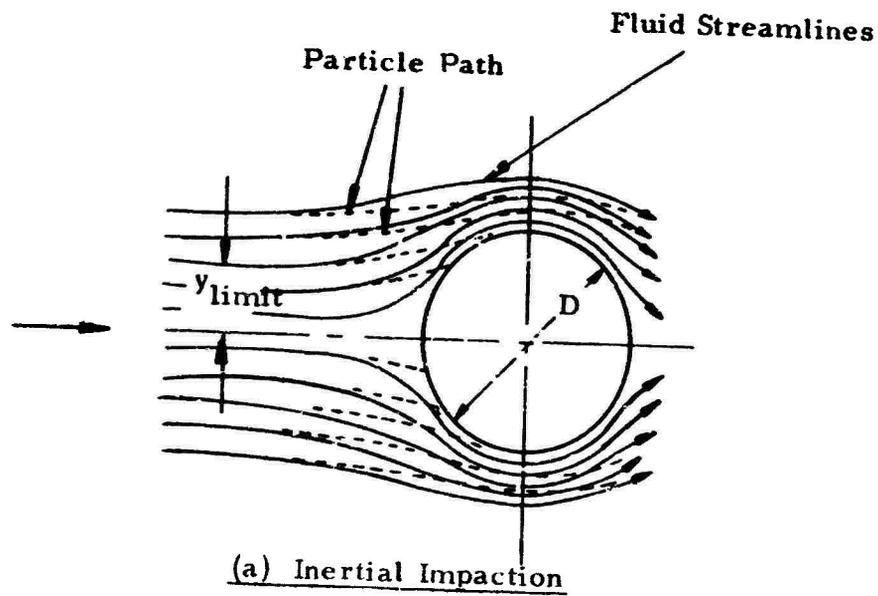


Figure C-1 Particle Impact

of particles on the collector surface, as the particle, following the fluid streamlines, passes close to the target. This is called diffusion.

d. Electronic Forces

Static, dynamic, and induced electronic forces between particles and the target can result in collection. These forces are relatively weak in a liquid except for surface-active fine emulsions.

C.1.2 The Predominant Collection Mechanisms

From these four basic types, it was determined that inertial impaction and interception would be the two predominant mechanisms for the particle and target size range, and for the flow velocities of interest.

The theory of capture by inertial impaction and interception is described in the following paragraphs.

a. Inertial Impaction

The inertial impaction process is described in terms of an inertial impaction efficiency, η_I defined as the fraction of particles which can be collected from a normal cross-sectional area of the gas stream equal to the frontal or projected area of the target. If the particles are uniformly distributed in the gas stream, it is seen from Figure C-1a that this same η_I can be expressed in terms of the limiting trajectory of the particle which will just touch the target. Thus,

$$\eta_I = \frac{y_{\text{limit}}}{D/2} \quad \text{for a cylinder} \quad (\text{C-1})$$

and

$$\eta_I = \left(\frac{y_{\text{limit}}}{D/2} \right)^2 \quad \text{for a sphere} \quad (\text{C-2})$$

Various investigators over the last twenty years have devoted considerable analytical effort to determine this limiting trajectory and consequently the impaction efficiency. The basic Navier-Stokes equations are nonlinear and cannot be solved analytically in closed form for flow around a single collector, such as a cylinder or a sphere. The relative velocity between the particle and the fluid being low, and the particle diameter small, Stokes law has been utilized to calculate the drag force on the particle. Under these conditions, the equations of motion of the smaller particle may be written down explicitly in terms of the fluid flow pattern around the larger sphere. After these equations are reduced conventionally to dimensionless form, the equations of motion are shown⁽¹⁵⁾ to depend upon two characteristic dimensionless groups, i.e., the inertial impaction parameter Ψ , and the Reynolds number of the target Re_D . These are defined as

$$\Psi = \frac{C (\rho_p - \rho_f) d^2 V_a}{18 \mu D} \quad (C-3)$$

and

$$Re_D = \frac{\rho_f V_a D}{\mu} \quad (C-4)$$

where

C = the Cunningham correction factor for molecular mean free path (1.00 in the present case)

ρ_p, ρ_f = the densities of the particle and the fluid

V_a = the relative upstream velocity of the undisturbed fluid with respect to a stationary target

μ = the viscosity of the fluid

d, D = the particle and target diameters

The equations of motion have been solved by making various approximations depending on the Reynolds number, Re_D , past the collector. The classical methods^(16,17) have considered purely potential and purely viscous flows. Iteration formulae have been developed⁽¹⁷⁾ for predicting flows of intermediate Reynolds numbers. A differential analyzer was utilized by Langmuir and Blodgett⁽¹⁶⁾, and digital computers by Fonda and Herne⁽¹⁹⁾, Percy and Hill⁽¹⁸⁾. Fonda and Herne have solved the complete equations without making approximations and their results compare very well with the earlier solutions obtained by Langmuir and Blodgett^(16,17).

Figure C-2 shows the variation of the inertial impaction efficiency, η_I , with the inertial impaction parameter, ψ , for cylinders. Theoretical curves for both viscous (low Re_D) and potential (high Re_D) flows have been provided, and experimental data shown for comparison.

The curves show that a high value of η_I is associated with a high value of ψ . This means that for a given particle size d , and for given fluid properties, a high relative velocity V_a or a small collector diameter D is required to obtain a high impaction efficiency.

For the range of parameters of interest in the present study the inertial impaction efficiency may be determined from Equations (C-3) and (C-4) and Figure C-2.

$$\text{Let: } (\rho_p - \rho_f) = 10^{-4} \text{ lb sec}^2/\text{in}^4$$

$$d = 10\mu = 0.4 \times 10^{-3} \text{ inches}$$

$$D = 5 \text{ mils} = 5 \times 10^{-3} \text{ inches}$$

$$V_f = 40 \text{ fps}$$

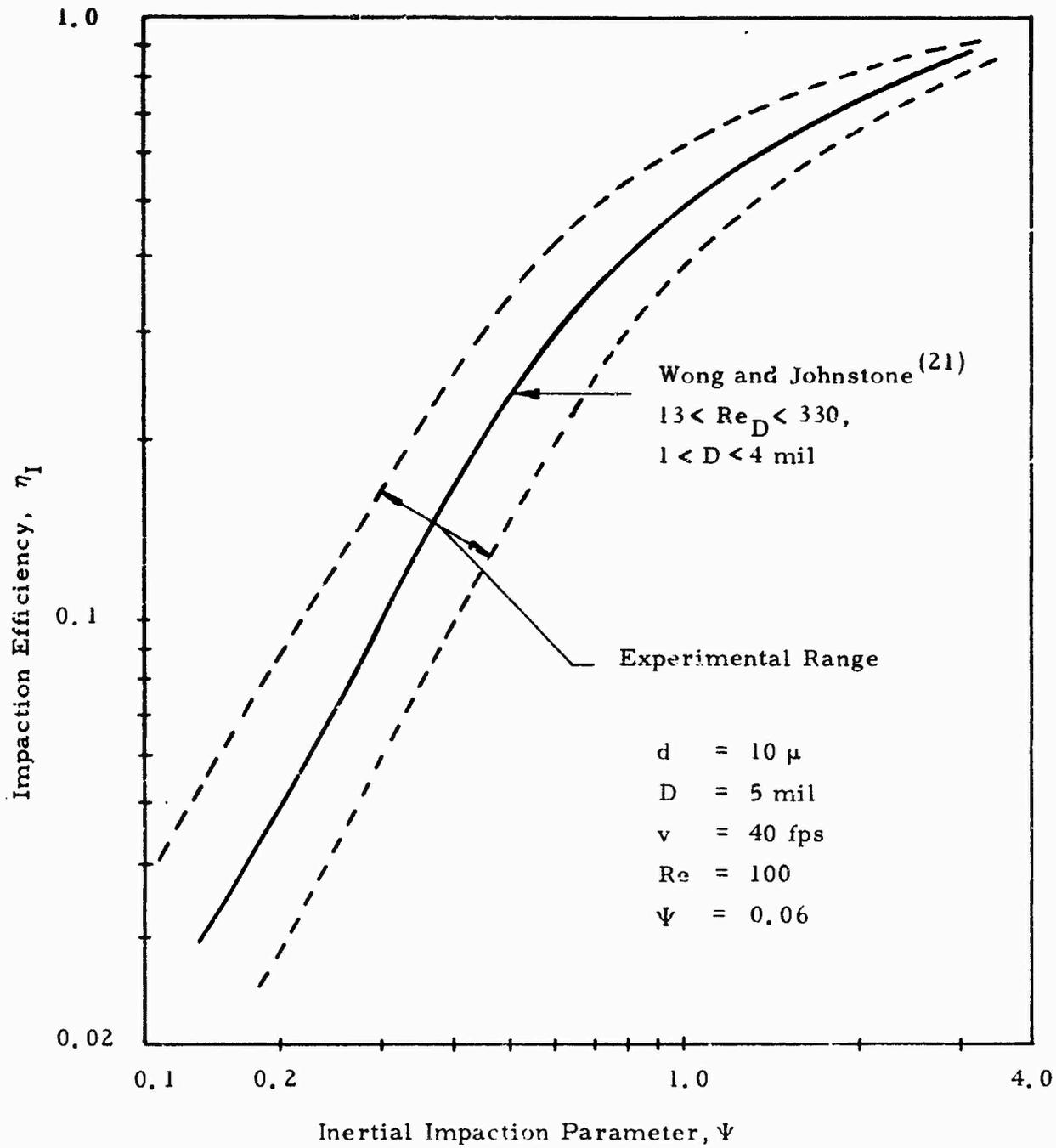


Figure C-2 Inertial Impact Efficiency versus Inertial Impact Parameter Ψ for a Cylindrical Target

$$\mu = .21 \times 10^{-3} \frac{\text{lb sec}}{\text{ft}^2}$$

$$C = 1.0$$

From Equation C-4, $Re = 100$

from (C-3), $\psi = 0.06$

and from Figure C-2, $\eta < 1.0$ percent.

b. Interception

The impaction efficiency for interception is easily estimated. Reference to Figure C-1b indicates that the stream-line carrying the particle must pass within one particle radius of the cylindrical target for contact to occur. Thus only the particles in the very center of the flow will impact the target. The efficiency of interception as an impact phenomena may be expressed⁽¹⁵⁾ as:

$$\eta_{\text{Int}} = 1 + \frac{d}{D} - \frac{1}{1 + d/D} \approx 2 \frac{d}{D} \text{ if } d \ll D$$

For a given particle size the interception efficiency is improved by decreasing the target diameter.

For the parameters of interest in the present study

$$\eta_{\text{Int}} \approx 2 \frac{d}{D} = 2 \frac{0.4 \times 10^{-3} \text{ in}}{5 \times 10^{-3} \text{ in}} = 16 \text{ percent}$$

The combined impaction efficiency therefore may be determined⁽¹⁵⁾.

$$\eta_{\text{imp} + \text{int}} \approx 1 - (1 - \eta_{\text{imp}}) (1 - \eta_{\text{int}}) \approx 16 \text{ percent}$$

C.2 Material Removal Rate

In order to establish order of magnitude estimates of material removal rates due to particle impact it is necessary to establish an "abrasive energy" for a given particle. Assume that abrasive energy is either:

- (a) inertial energy

$$\begin{aligned} E_I &= 1/2 MV^2 \\ &= 1/2 \left(\frac{\pi d^3}{6} \right) \rho_p V^2 \\ &\approx 1 \times 10^{-9} \text{ in lbs} \end{aligned}$$

for the particle sizes and velocities of interest, or,

- (b) the product of drag force times sliding distance

$$\begin{aligned} E_D &\leq 3 \pi \mu d V D \\ &10 \times 10^{-9} \text{ in lbs} \end{aligned}$$

It appears therefore that an upper limit on particle abrasive energy is 10^{-8} inch pounds (or 10^{-2} dyne cm in more convenient units).

Since gold has a hardness of 60 kg/mm^2 , the maximum volume of material removed by one particle is: (Ref. 20).

$$\Delta V = \frac{k E_D}{p} = .3 \times 10^{-14} \text{ cm}^3$$

where

k = abrasive constant = 2×10^{-3}

E_D = abrasive energy (calculated above)

p = hardness of material = 60 kg/mm^2

To establish wear rate estimates the total number of impacting particles must be determined.

From Figure C-3

$$N = C \bar{V} \eta L D t$$

where

C = concentration of particles

V = velocity of flow

η = impaction efficiency

LD = projectial area of wire

t = time

Also from Figure C-3 the change in area of the target may be estimated

$$\begin{aligned} \frac{\Delta A}{A} &= \frac{N \Delta V}{L A} \\ &= \frac{C \bar{V} \eta L D t (\Delta V)}{L \pi D^2 / 4} \end{aligned}$$

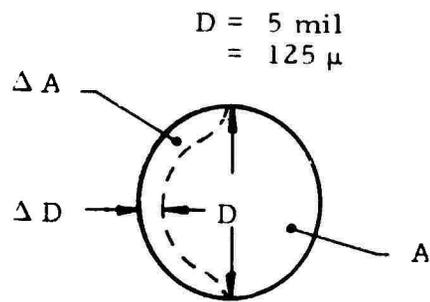
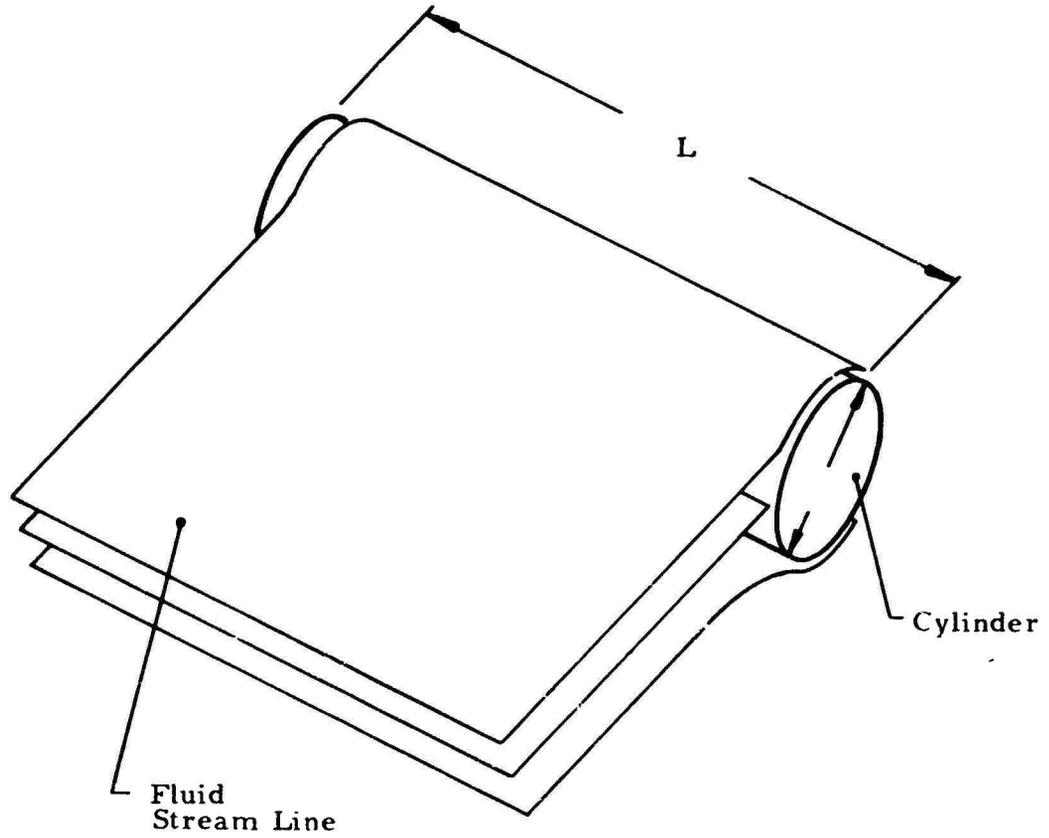


Figure C-3 Detail of Target Wear

$$\frac{\Delta A}{A} / \text{hr} = 4 \times 10^{-3}$$

e. g. 0.04 percent change/hour.

To calculate the wear rate at the surface we assume that all wear occurs uniformly on the front side of the target

$$\therefore \Delta D = \frac{\Delta A}{D} \approx 4000 \text{ \AA}/\text{hour}$$

This is a very upper limit for wear. If, as is more likely $E_I = 10^{-9}$ in lbs then

$$\frac{\Delta A}{A} = 0.004 \text{ in 1 hour}$$

and
$$\Delta D = 400 \text{ \AA}/\text{hour}$$

These calculations predict extremely low wear rates for cylindrical targets of practical dimensions. They point out the necessity of a conducting path with a cross sectional area of the same order as the wear rate. For this reason conducting wear paths supported by a non conducting substrate material were considered.