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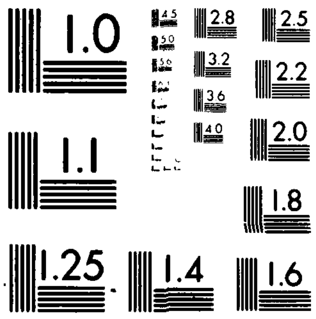

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU

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AERONAUTICAL ANALYTICAL REWORK PROGRAM

INTERIM REPORT

LEVEL II

HELICOPTER TRANSMISSION CONTAMINATION STUDY

AD A088197

SEPTEMBER 1976

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ANALYTICAL REWORK/SERVICE LIFE PROJECT OFFICE

NAVAL AIR DEVELOPMENT CENTER, WARMINSTER, PA 18974

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Aeronautical Analytical Rework Program

⑨ Helicopter Transmission Improvement Study.

Subtask
Helicopter Transmission
Contamination Study

By

J. M. McGrew

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Prepared For

Analytical Rework/Service Life Project Office
Air Vehicle Technology Department
Naval Air Development Center
Warminster, Pa. 18974

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ABSTRACT

A study has been completed which shows that the use of finer filtration than present practice results in a significant improvement in transmission service life. Four candidate filter approaches are identified which potentially offer finer filtration than presently used filters. Recommendations are made for implementation of these concepts in existing Naval helicopters.

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1.0 INTRODUCTION

Helicopter transmissions present difficult filtration problems in that the output shaft runs at relatively low speeds, thus subjecting the bearings and gears to high loads with low surface velocities. This combination of operating conditions means low lubricant film thicknesses in the contact zones. Thus, the bearings and gears in a helicopter transmission are more likely to be susceptible to damage from contaminants in the lubricant than in higher speed, lightly-loaded transmissions. The obvious solution is finer filtration. However, finer filtration alone without consideration of its impact on the operation and maintenance of the helicopter is not sufficient.

Contamination control in helicopter transmissions is attained if and when the contamination level of the lubricant is equal to or less than the contaminant tolerance level of the transmission components. This report describes a study which attempts to define the three factors which determine the transmission contamination level.

1. Amount and nature of contaminant ingressing from internal and external sources
2. Sensitivity of transmission components to contaminants
3. Particle capture capability of the transmission filter.

Four new candidate filter concepts are identified which offer the potential for improved helicopter transmission performance, and recommendations made for implementation of these concepts in existing Naval helicopters.

2.0 HELICOPTER TRANSMISSION CONTAMINANT ENVIRONMENT

Before one can evaluate the effect of contaminants on transmissions, it is important to know what types of contaminants exist in the typical helicopter transmission environment. We first examine this question.

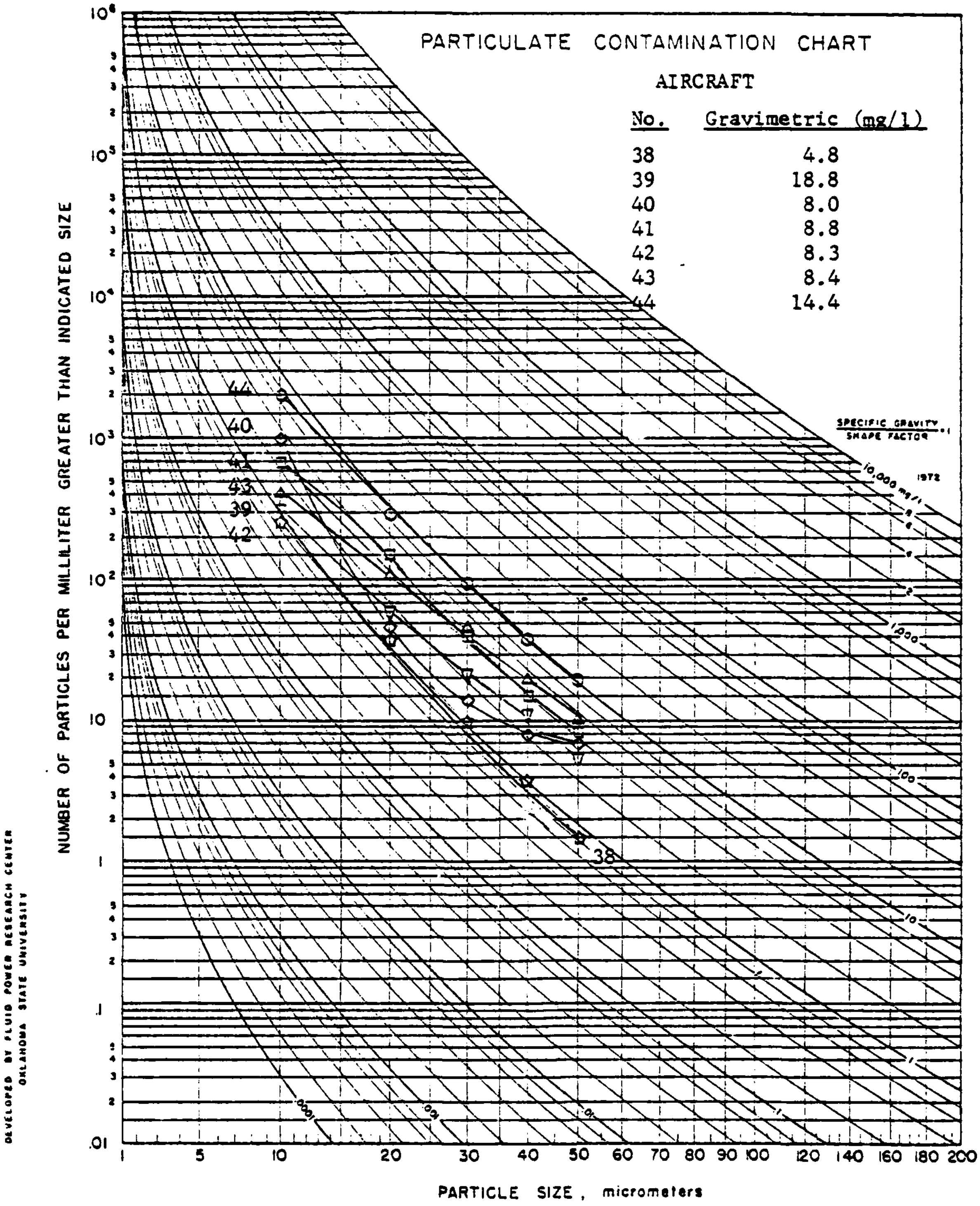
Bensch and Bonner (1) have conducted a survey of the contaminants which exist in typical field hydraulic systems. The objective of their research effort was to collect and analyze hydraulic fluid samples from a variety of field hydraulic systems operating over a wide cross-section of the United States. The compilation of these data provide an overall quantitative and qualitative summary of contaminants which exist in typical systems.

A total of 44 samples were extracted from 11 types of machinery, including 7 aircraft, both fixed-wing types and helicopters. A wide section of the United States was represented in the survey, as samples were taken from as far west as Arizona and as far east as Pennsylvania. Operating environments for the aircraft which were sampled varied from relatively clean during flight to somewhat dusty near the ground. Although this data was taken for hydraulic system evaluation, it is the only systematically accumulated data on the subject and provides a reasonable approximation to the helicopter transmission contaminant environment.

2.1 Particle Count and Gravimetric Analysis

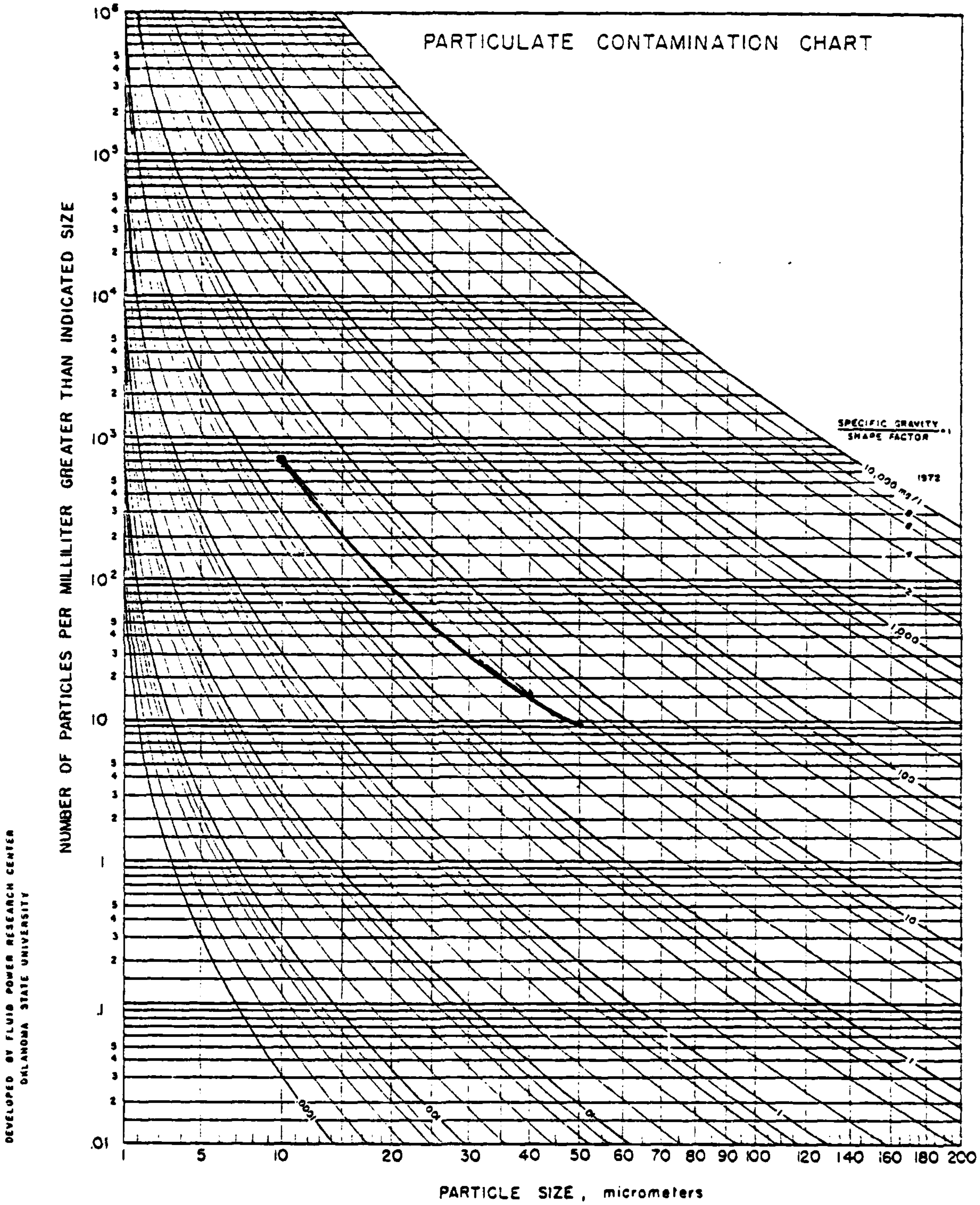
Figure 1 presents the particle counts and measured gravimetric levels for each of the aircraft samples. The data scatter for the 7 samples are relatively large. The calculated average count for aircraft as a class is shown in Figure 2.

Another important and fundamental conclusion can be made by comparing the theoretical gravimetric levels predicted on the Particulate Contamination Charts in Figure 1 with the actual measured values. The theoretical value is obtained by constructing a straight line through a set of particle counts and determining the gravimetric line (curved lines) to which the straight



Average Particle Counts and Gravimetric Levels for Aircraft Samples

Figure 1



Average Particle Count and Gravimetric Level for Aircraft Samples

Figure 2

line is tangent. In most instances, where a straight line accurately represents the particle size distribution, the theoretical gravimetric level is very close to the measured value. Although, for some of the samples, the calculated values read from the Chart are not exactly correct, they do give a relative guide to the contaminantion level of the system, which is of extreme importance in contamination control procedures.

2.2 Chemical Analyses

The results of the chemical analyses are shown in Table 1. Also shown is the average composition of the four samples.

From Table 1, the contaminants in the aircraft environment can be divided into three broad classes.

Class	Average % by Weight
Carbonaceous	48
Silaceous	47
Metallic	5

The carbonaceous material (LOI) accounts for approximately 48 percent of the particulate matter observed in the samples. The carbon material is usually degraded lubricant. Carbon particulates usually start out very small, but soon agglomerate into clumps ranging from 5 to 100 microns in size. Carbonaceous particles are not chemically active, but they usually carry a fairly high electrostatic charge, which helps form clumps and accounts for the tenacity of such carbon particles in clinging to surfaces in the oil flow path.

Carbonaceous particles are most harmful in the following ways:

1. The agglomerated carbon particles are often large enough to block an oil jet which causes a reduction of oil flow to a bearing.

2. The particles can get into a rolling element bearing and cause bridging of the EHD film--which may be only 4 to 10 microinches thick.

TABLE I

TYPICAL CHEMICAL ANALYSES OF FIELD CONTAMINANTS IN AN AIRCRAFT ENVIRONMENT

Percent Content by Weight							
Fe	Cu	Cr	Al	Zn	Sn	SOA[1]	LOI[2]
0.7	ND	ND	3.00	0.50	ND	25.8	70.0
3.1	ND	ND	1.70	0.30	ND	59.9	35.0
5.0	0.70	ND	ND	1.70	ND	47.6	45.0
2.9	0.23	0.13	0.30	0.60	ND	55.8	40.0
Average							
2.92	.23	.03	1.24	.78	ND	47.3	47.5

NOTES:
1. SOA indicates acid insoluble silicates, oxides, and other anions.
2. Loss on ignition (LOI) represents carbons and volatiles.
3. ND represents "none detected".

3. The carbonaceous particles can plate out on heat transfer surfaces causing a perturbation in the normal thermal transfer path--which may lead to a warped metal structural part.

The Silaceous material (SOA) is particulate material such as sand and dust which have been ingested into the system. Sand and dust particles are not normally considered to be chemically active--however, any particle can serve as a nucleation point for helping to form agglomerates.

The chief harm attributable to sand and dust particles lies in their abrasiveness. Fine sand and dust particles--including laterite from Southeast Asia, can be extremely abrasive and thus harmful to any rubbing, rolling, or sliding elements.

Rolling element bearings subjected to sand and dust become pitted and often exhibit high rates of component wear.

Metallic debris is the most chemically active particulate material in the transmission lubrication.

Whenever metal particles are generated in a mechanical system, they are highly chemically reactive at two loci, i.e., the displaced particle is highly reactive--as is also the scar left at the site where the metal piece was removed.

Chemically reactive materials seek a chemical partner in order to form a stable compound--or a satisfied complex.

In the transmission system the most reactive material present to react with the metal debris is the lubricant additive package--the anti-oxidants, the anti-foamants, the VIS extenders, etc. Once the metallic debris has reacted with the additive package and has chemically depleted it, the additive package can no longer perform its intended function. This accounts for the increase in acid neutralization number, and viscosity in most lube systems with time.

3.0 FILTRATION PRINCIPLES

Numerous filtration principles have been used in the past to protect machinery. The major types are shown in Table 2.

3.1 Settling

Settling is the oldest and least efficient method for achieving precision filtration. In theory, (Stokes Law) and by using large volume oil systems and a very large baffled oil storage tank with proper oil inlet and outlet plumbing, one could achieve removal of even the fine particulates from transmission oil. In practice, the transmission lube system size--and the size of the oil sump are set by heat transfer requirements rather than filtration criteria.

However, settling tanks should be utilized wherever possible to augment the other more sophisticated filtration methods used to protect the system.

3.2 Static Filters

Two basic mechanisms are generally utilized in static filters.-- Surface filtration and depth filtration.

3.2.1 Surface Filtration

Surface filtration is the process of removing contaminant particles on the single two-dimensional surface of a filter medium. Woven wire cloth is perhaps the best known example of this type filter although edge-type, membrane, and wound-wire filters also fall into this general category. A surface filter is really a sieve, that is, it consists of a number of discrete holes, or pores, through a single layer of material. Particles larger than the pores will be stopped by the media; particles smaller than the pores will pass through. Figure 3 shows a simplified model of a surface-type filter. Because of the uniform distribution of pore sizes in a surface type filter, and because of the sieving action of the filtration mechanisms itself, the surface type filter is the closest to an "absolute filter".

TABLE 2

FILTER PRINCIPLES

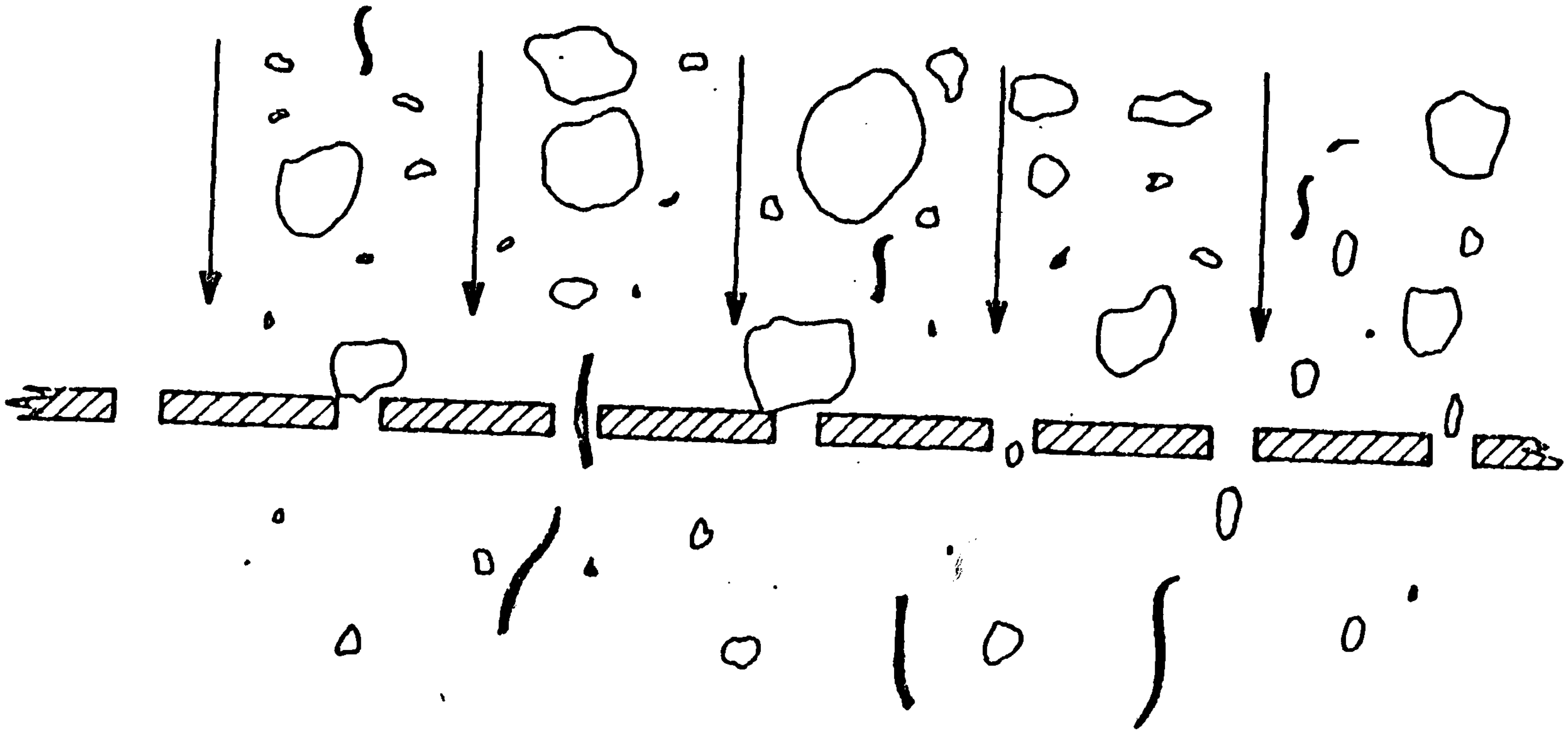
1. Settling

2. Static Filtration (Barrier Filters)
   a) Depth Filters
   b) Surface Filters
   c) Composite Filters (Depth and Surface Type)

3. Cyclonic, Inertial Separation

4. Centrifugal Separation

5. Magnetic Separation



Surface Filtration

FIGURE 3

Since the media is a single layer thick, cleaning is quite easy. Often, a simple back-flush is adequate, although ultrasonic cleaning can be performed to assure the removal of non-spherical particles lodged in the surface weave of the medium.

Surface media are not subject to migration of either the media or the contaminant. Since the medium is usually woven of fine wire, no short fibers exist which can be washed out of the filter. Contaminant migration of particles larger than the filter rating is not possible when the contaminant is resting on the surface of the media.

Surface media do have some drawbacks. Contaminant capacity is related to the surface area of the media. As each pore is blinded by a contaminant particle, that portion of the filter surface is removed from service. In time, as the contaminant load increases, the amount of clean surface area available for filtration becomes less and less and the pressure drop through the filter gets higher and higher until the filter must be removed for cleaning.

Another shortcoming of a surface type filter media is its inability to handle oddly shaped particles. A spherical particle 15 microns in diameter will be stopped on the surface of a 12 micron woven wire cloth, while a spherical particle 10 microns in diameter will penetrate. In the same fashion, a cylindrical particle 15 microns in diameter by 15 microns in length will also be stopped. But, a cylindrical particle 10 microns in diameter by 10, or 100, or 1000 microns in length may pass straight through the media. In other words, a long, thin particle oriented properly in the fluid stream can penetrate the media. Therefore, the contaminant retention effectiveness of a surface filter must be based on a three-dimensional analysis of the contaminant. Surface type filters are not fully effective in removing fibrous contaminants.

3.2.2 Depth Filtration

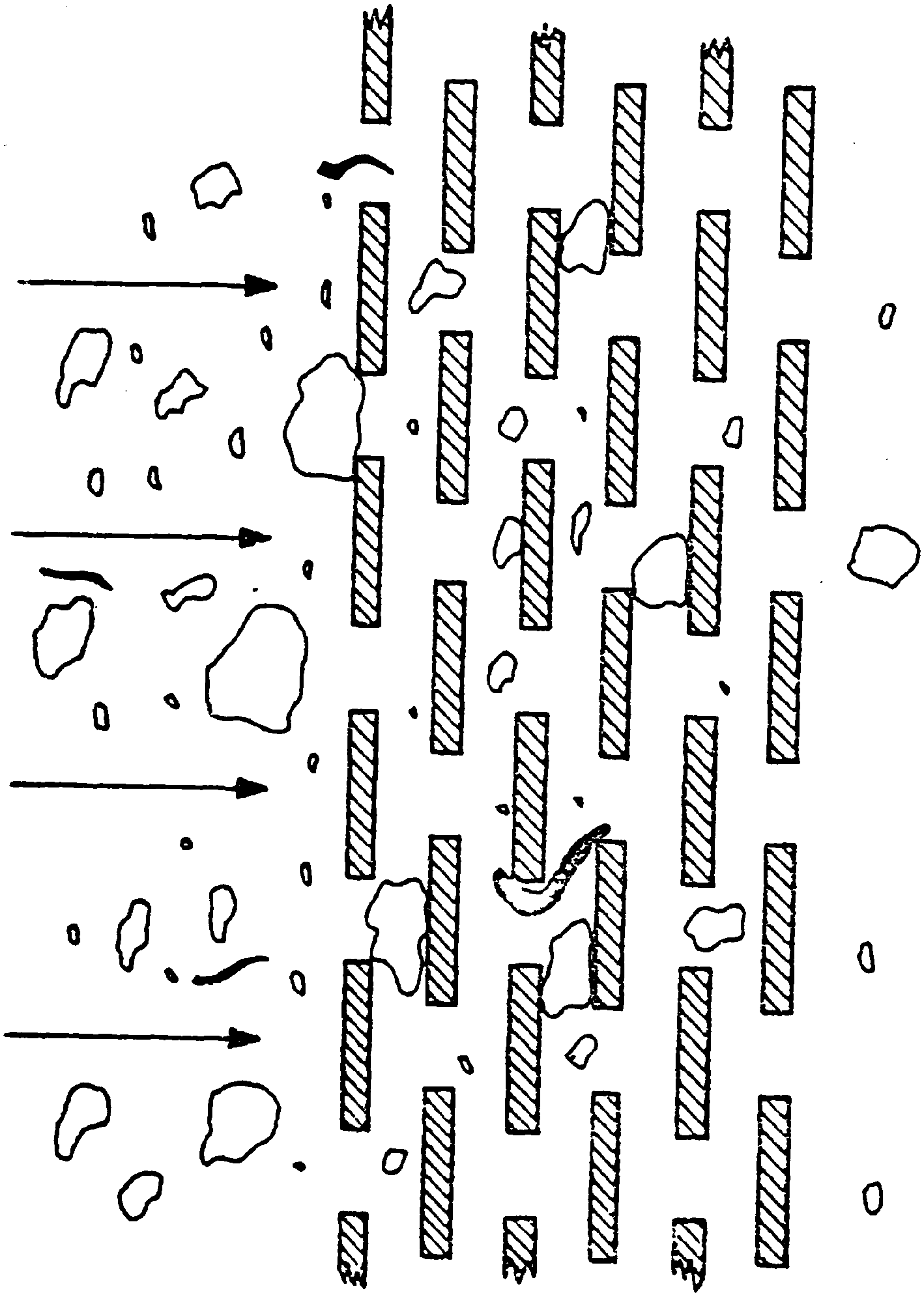
Depth filtration is three-dimensional. Instead of a single layer of filter medium, a depth filter is composed of dozens of layers of porous material so structured as to force a particle to follow a tortuous path into the media. A depth media is a matrix of randomly oriented fibers. This produces a random array of pores of widely varied sizes. Each pore through one layer is blanked off by the constructional material composing the next layer. Figure 4 shows a simplified model of a depth-type filter.

The first layer of media will collect some of the incoming contaminant particles, although a great deal of the entering contaminant will pass on to deeper layers of the media. The particles, attempting to traverse the tortuous path through the media, change direction radically, coming to rest somewhere within the matrix. The particle may be stopped at a small pore, although present theories concerning depth filtration consider silting, sedimentation, and very small surface and electrostatic forces contribute greatly to contaminant removal.

To allow the phenomenon of depth filtration to work, one condition must exist. The external pores must be a great deal larger than the contaminant particle to permit penetration to lower depths of the media. This decrees that some of the contaminant must penetrate the media--not only the very small particles, which follow the flow stream, but also a few of the larger particles, which are pushed through by fluid forces exceeding the media's attractive and retentive abilities.

In depth type filter media, the retention of contaminants at various levels throughout a three-dimensional matrix offers much greater dirt holding capacity than does surface media. However, this increased capacity is achieved at the expense of a somewhat higher initial pressure drop.

Media migration is considered one of the greater drawbacks to the use of depth filters. Since the filter medium often is a web of short fibers or a bed of small granules, it is always possible for some of these particles to break loose from the matrix and be carried downstream. This "shedding" or "washout" phenomenon is most evident in lube systems subjected to rapid variations in pressure and or flow rate.



Depth Filtration

FIGURE 4

3.2.3 Comparison of Surface and Depth Filtration

Although some of the relative advantages and disadvantages of surface and depth type filter media have been described earlier, a more direct comparison may be worthwhile. Table 3 lists some of the broad classifications of common filter media and attempts to define the relative advantages of each. Included are some approximate data relative to micron rating ranges available, temperature range limitations, and a comparison of mechanical features of each of the media.

3.2.4 Composite Filter Media

Some filter manufacturers have developed composite depth/surface filter media. These media combine the characteristics of each filter type and result in filter elements with greater dirt holding capacity and improved filtration efficiency. Composite filter media elements are relatively new and their cost approximates that of top quality wire cloth filter element construction.

3.3 Cyclonic or Inertial Separation

The cyclone is a simple, static, and relatively inexpensive separating device. The cyclone is somewhat analogous to the centrifugal pump in that a cyclone too is very sensitive to design point--it must be designed for a specific fluid flow rate. Any deviation from the design flow rate causes a much greater fall off in cyclone efficiency.

Cyclone design analysis indicated that a cyclone operated at the optimum design point achieves general limits of separation corresponding to 95 percent of 10 micron particles. Below 10 microns, the efficiency drops rapidly (3).

3.4 Centrifugal Filter

Centrifugal filters remove dirt and oil degradation products from the lubricant by subjecting the dirt laden lubricant to high centrifugal forces as it flows through the centrifuge. The centrifugal forces are induced by rotating

Filter Type	Nominal Micron Range Available	Temp Range (°F)	Ability For Absolute Cut-Off	Filter Ability		Clean-ability	Pressure Drop per Unit Area	Dirt Holding Capacity
				Part-icles	Fibers			
Surface Media								
Woven Wire Mesh	2 and above	Cryogenic to +1000	Fair	Good	Poor	Fair	Low	Poor
Sintered Wire Mesh	2 and above	Cryogenic to +1000	Fair	Good	Poor	Fair	Low	Poor
Wound Wire Mesh	2 and above	Cryogenic to +1000	Good	Good	Good	Fair	Low	Good
Membrane	0.1 to 12	Ambient to 260	Good	Good	Good	Nil	High	Poor
Depth Media								
Pressed Paper	5 to 100	Ambient to 275	Poor	Poor	Fair	Nil	Med.	Fair
Felted Synthetic Fibers	5 to 100	Ambient to 400*	Poor	Fair	Good	Nil	Med.	Good
Felted Metallic Fibers	5 to 100	Cryogenic to +1000	Fair	Fair	Good	Fair	Med.	Good
Woven Synthetic Fibers	2 to 100	Ambient to 400*	Fair	Fair	Good	Fair	Good	Fair
Woven Glass Fibers	5 to 100	-100 to +1000	Poor	Good	Good	Poor	Med.	Good
Sintered Porous Metal	2 to 60	Cryogenic to +1000	Fair	Good	Good	Fair	High	Fair

*Recent developments in synthetic fiber technology and in high temperature adhesives have raised operating temperatures of some advanced types of filter elements to over 400°F. until recently nonmetallic media was limited to 275°F.

After Reference 2

Common Filter Media

TABLE 3

the centrifuge at speeds high enough to produce force fields stronger than 1500 G. The "G" forces move the dirt across the lubricant flow and deposit it in a special dirt retainer located along the periphery of the outer wall of the rotating centrifuge or overboard the dirt to a secondary collecting sump.

The properly designed centrifuge will remove from the lubricant stream anything that has a different mass or specific gravity than the lubricant. Thus, a centrifuge can be designed to remove air entrained within the lubricant--the air, being lighter than the lubricant, will collect around the centrifuge shaft and can be vented overboard or back to the engine gearbox--and, at the same time, the centrifuge will remove matter with a higher specific gravity from the lubricant and deposit it in the peripheral dirt retainer.

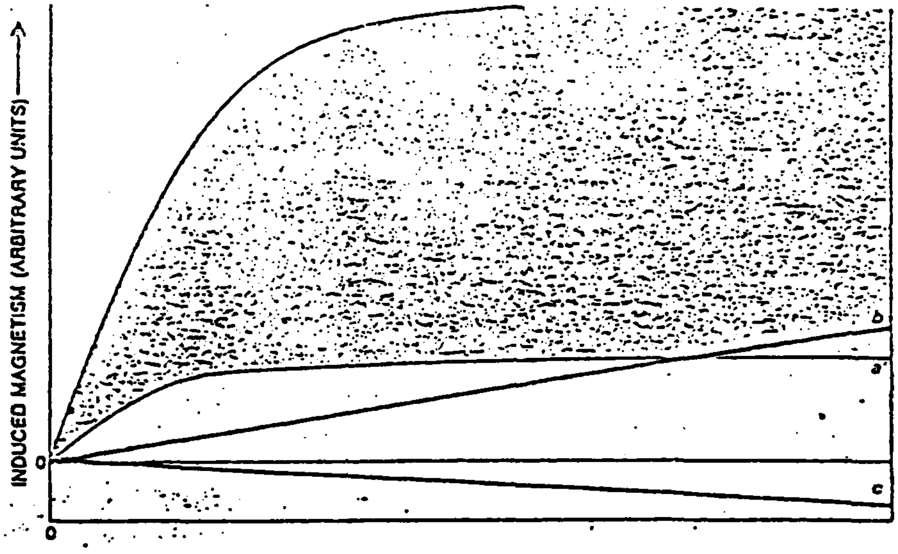
The centrifugal oil filter in a recirculating lube system can be rated at the equivalent of 1 micron absolute.

3.5 Magnetic Filters

A magnetic field can also be used to filter particulates. The physical phenomena governing magnetic separation fall into two groups. How do various substances behave when they are exposed to a magnetic field? How are the magnetic forces exerted? In the first group, consider a graph that plots the response of various classes of substances to increasingly strong magnetization. Such a graph displays three different kinds of magnetic behavior.

3.5.1 Ferromagnetic Materials

Strongly magnetic materials members of the ferromagnetic group, are easily magnetized by a relatively weak magnetic field, and so the slope of their magnetization curve is steep at the beginning. (That is why a bar magnet, which does not have a strong magnetic field, can attract ferromagnetic materials.) As the strength of the magnetic field increased, all the individual domains--regions with paired north and south magnetic poles--in a ferromagnetic material become aligned;



THREE RESPONSES are evident when the magnetization of a material is plotted as a function of the applied magnetic field. Ferromagnetic materials (a) show an immediate steep curve; some respond more strongly than others (darkened area) but all eventually "saturate", as the flattening curves show. Paramagnetic materials(b) show a much shallower response, but they rarely saturate; in a strong field their magnetization can exceed that of a weakly ferromagnetic material. Diamagnetic materials(c) are of no industrial importance. On exposure to a field such a material shows a slight but opposite magnetization.

Figure 5

magnetization "saturates" the material. Thereafter the slope of the curve remains relatively flat regardless of any further increase in the strength of the magnetic field. The saturation level, that is, the field strength beyond which no further magnetization takes place, depends on the iron content of the material. For example, pure iron is saturated at a magnetization of some 220 electromagnetic units per cubic centimeter in an applied field of several hundred guass.

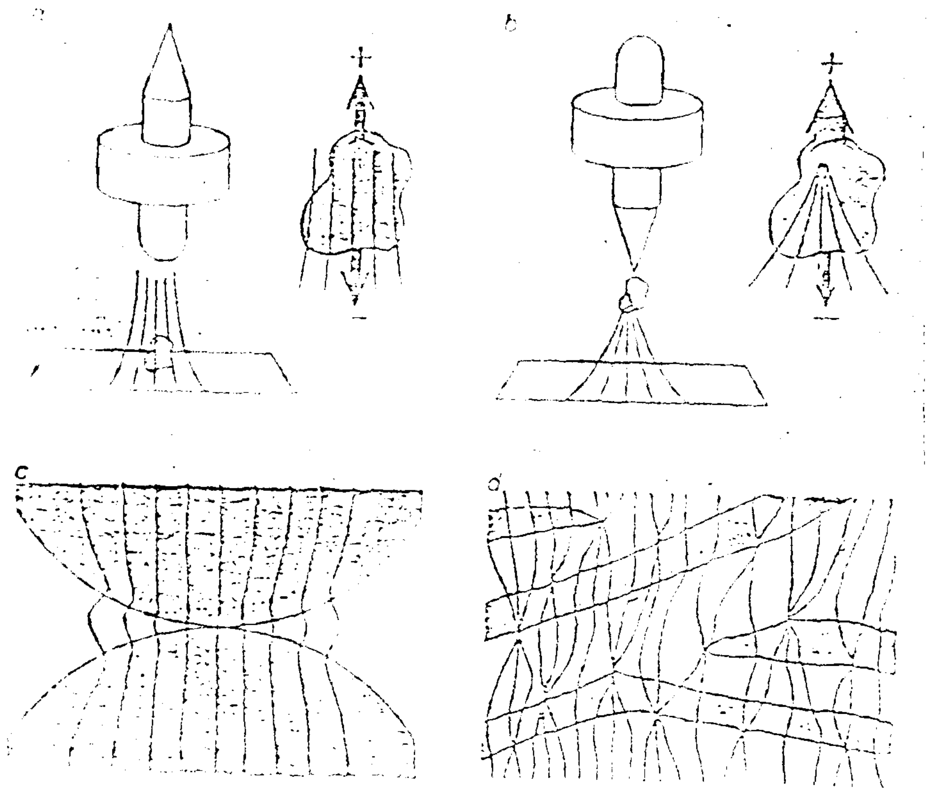
3.5.2 Paramagnetic Materials

Weakly magnetic materials, members of the paramagnetic group, are far less susceptible to an applied magnetic field than ferromagnetic materials. At low field strengths their magnetization curve on the graph remains well below the ferromagnetic curve and its slope is much shallower. A paramagnetic material, however, rarely becomes saturated, and so its degree of magnetization continues to increase as the applied field gets stronger. This means that even though a bar magnet will not attract a paramagnetic material, such materials may become more highly magnetized in a sufficiently strong field than dilute ferromagnetic materials.

3.5.3 Diamagnetic Materials

A third type of behavior in a magnetic field is displayed by materials that become magnetized in a direction opposite to that of the applied field. These are diamagnetic materials, and their curve on the graph is shallow and negative. For the purposes of this discussion diamagnetism is a small effect with no practical importance.

On the second heading -- how magnetic forces are exerted on materials in an applied field -- it is useful to think of each magnetized particle as acting temporarily as if it were itself a small bar magnet, with a north pole at one end and a south pole at the other. In magnetically "hard" materials,



MAGNETIC-FIELD GRADIENT is needed if an appreciable force is to be exerted on a fine particle. Flux lines (color) around the blunt pole of a magnet (a) are essentially uniform with respect to the particle below the pole; the magnetic forces acting on the two poles of the particle (enlarged at right), being equal and opposite, cancel out. Flux lines around the sharp pole (b) are divergent with respect to the particle; the resulting high gradient exerts a strong force on the particle (enlarged at right). Stacked iron balls (c) represent one extreme in making a high-gradient matrix. They conduct the flux well (color), but their field is almost uniform. Steel wool (d) represents the other extreme. As the pinched flux lines show, gradients are high, but steel wool, being mostly void, is very hard to [illegible]

Figure [illegible]

the parallel alignment of the dipoles is in fact not temporary but permanent, and a magnet made of such a material is called a permanent magnet. The alignment in magnetically "soft" materials is impermanent; it is induced only while a magnetic field is applied, and it becomes random when the field is absent.

When a uniform magnetic field is applied to a magnetized particle, the forces acting on the two poles of the particle will be equal and opposite. The forces therefore cancel each other, and the resulting net force is zero. Only if the applied field differs in intensity at the two extremities of the particle will a net magnetic force act on the particle. This is to say that the applied field must have a gradient, a spatial variation that is appreciable in terms of the dimensions of the magnetized particle. Anyone who has tried to remove iron filings from a horseshoe magnet is familiar with this effect. The lines of force extending from the poles of the magnet diverge in such a way that the density of the magnetic flux (the intensity of the field) increases with nearness to either pole and the minimum spatial variation in the flux is at the sharp edges of the pole. It is the higher gradient of the magnetic field at the sharp edges that makes the iron filings preferentially collect there. In short, the net force exerted on a magnetized particle by a magnetic field is proportional to three quantities: the intensity of the magnetization the field has induced in the particle, the volume of the particle and the gradient of the field, that is, the difference between the intensity of the field at one end of the particle and the intensity at the other.

These principles have been used by S. G. Frantz Company, Inc., in their FerroFilter which uses either a permanent or electromagnet for separation of ferromagnetic particles. Sala Magnetics Corporation Inc., has under development a high gradient magnetic filter but does not yet offer a commercial unit.

4.0 SENSITIVITY OF HELICOPTER TRANSMISSIONS TO CONTAMINANTS

The subject of contamination effects on hydraulic system components have been examined repeatedly, and the results widely reported, (4-19). Similar studies on transmission system components have not been as intensive or widespread. Examination of the relationship between particle size, concentration and transmission reliability is best begun by comparing particle size and lubricant film thickness existing in the components of the transmission. As may be seen in Table 4, the film thickness in these components is considerably below the filter capability of currently used filters. Thus one would expect that improvement in transmission reliability could be achieved by going to finer filtration. We now examine the existing field and experimental data to support this contention.

TABLE 4

TYPICAL HELICOPTER COMPONENT FILM THICKNESS
State of the Art Filter Capability = 10 - 40 micrometers

	Film Thickness Micrometers
Rolling Element Bearings	0.1-1
Gears	0.1-1
Seals	0.05-.5

4.1 Failure Analysis Data

Boeing Vertol Company conducted a survey (20) of helicopter transmission data.

The failure data presented by Boeing was compiled from four sources: the CH-46 and CH-47 data consists of transmission overhaul reports; the CH-3 data was derived from report SER 50547, STUDY OF HELICOPTER TRANSMISSION SYSTEMS DEVELOPMENT TESTING, Final Report, dated 5 June 1968; the UH-1 data was reduced from USAAVLABS Technical Report 70-66, MODE OF FAILURE INVESTIGATIONS OF HELICOPTER TRANSMISSIONS, dated January 1971.

Table 5 is based on data from nine transmissions and presents percentages of failures occurring by component and by failure modes.

It is important to note that the two components which fail most frequently are the ones which are most sensitive to contaminants.

If the removals are classified by the failure mode, then debris/corrosion is the dominant mode observed. These results tend to confirm the sensitivity of transmission performance to contaminants in the lubricant.

4.2 Transmission Tests

The number of transmission field tests is very limited. Hughes Helicopter conducted two 100-hour test programs (21) on upgraded OH-6A transmissions, one using a 46-micron filter and one using a 3-micron filter. These tests were conducted at a maximum of 317 horsepower at an input rpm of 6000 as compared to the current OH-6A rating of 270 horsepower. In addition, the power spectrum was more stringent than the OH-6A requirements. The results of these tests showed that the transmission with the 3-micron filter demonstrated superior wear characteristics compared to the transmission tested with the standard filter. The analysis of the oil used with the 3-micron filter showed far lower iron content, lower total acid values, and no signs of silica content. The chip detectors from the transmission with the 3-micron filter also exhibited far less accumulation of metal particles compared with the chip detectors from the transmission using the standard filter.

Both transmissions incorporated improvements including among others, improved gear surface finish, improved securing of roller bearing races and reduction of preload on all tapered roller bearings.

The inspection of the transmissions after the two 100-hour tests, at the high power spectrum, showed no deterioration or potential failure of these units. It was concluded that incorporation of the 3-micron filter, by itself, would result in significant improvement in transmission service life.

TABLE 5

After Reference 20

TRANSMISSION FAILURE ANALYSIS (20)

a) By Component

Part	% of Total
Bearings	45.9
Gears	23.3
Retention and Mounting	15.3
Structure	5.0
Shafts	3.9
Lube System	3.3
Clutches	3.2

b) By Component Failure Mode

1.	Debris/Corrosion	30.5
2.	Pitted/Spalled	20.8
3.	Wear	15.5
4.	Fracture	6.5
5.	Broken	6.0
6.	Scuffing	3.3
7.	Cracked	3.0
8.	Chipped	3.0
9.	Fretting	2.9
10.	Bent	2.7
11.	Flaking	2.1
12.	Tracking	1.6

However, continued testing of the filter under a later program (22) showed that the filter did not have consistent life. Figure 7 shows the system pressure versus test time using the 3-micron filter. As noted in this figure, the initial pressure drop across the filter was 5 psi which is within the 7.5 psi maximum specified drawing requirements. At 100 hours, the delta pressure increased to approximately 8 psi. However, after 120 hours the delta pressure versus time increased at a high rate until a 42 psi pressure drop was recorded at the 148th hour of testing. Testing was terminated when the downstream pressure dropped to 25 psi. Changing the pump bypass pressure from 57 to 80 psi did not show any substantial increase of filter life. At the 153rd hour of testing, a new filter was installed which completed over 38 hours before the test was stopped due to excessive delta pressure.

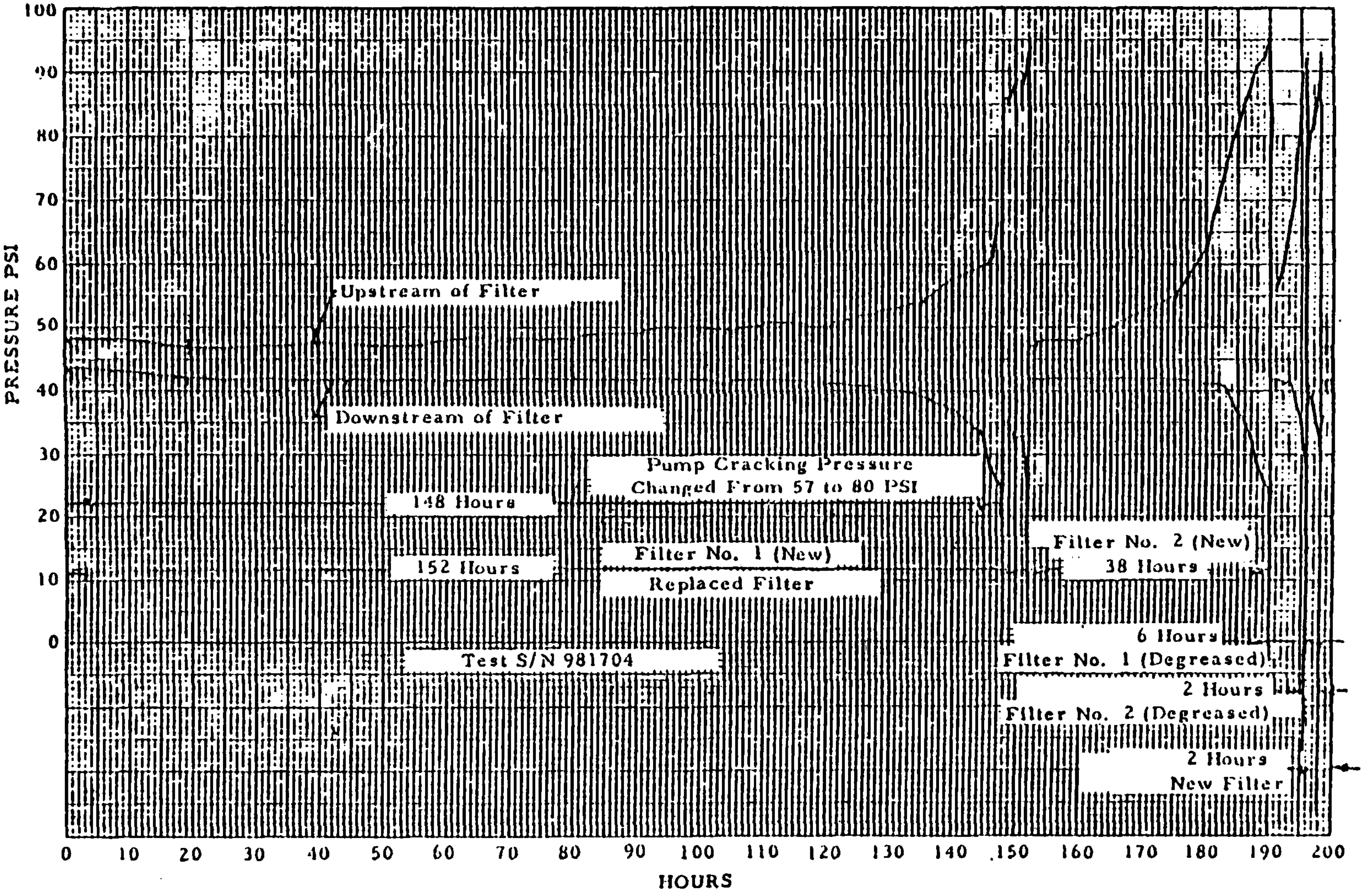
An investigation of this premature clogging resulted in the following consensus:

a) The 3-micron filter was satisfactory for only 150 hours of service life.

b) The specification control drawing should show a 15 micron absolute rating but with a specification for a transmission filter element to filter discrete particle efficiency of at least 95 percent of particles having 5 micron size with additional data to ensure desired performance.

c) For a filter service life of 300 hours, the filter size must be increased to provide at least double the original dirt holding capacity.

Since fine filtration is recommended to meet the low film thickness of the low speed gear stages, the type of filter element is important. Figure 8 shows the efficiency of various filter ratings and types to remove various particle sizes. From this curve it can be seen that a 15 micron absolute wire mesh element cannot stop any discrete particle smaller than 11 micron. However, a disposable filter having a 15-micron absolute rating can stop 99 percent of particles 5 micron or larger while a 5 micron absolute rating



System Pressure Versus Time
3-Micron Static Filter

Figure 7

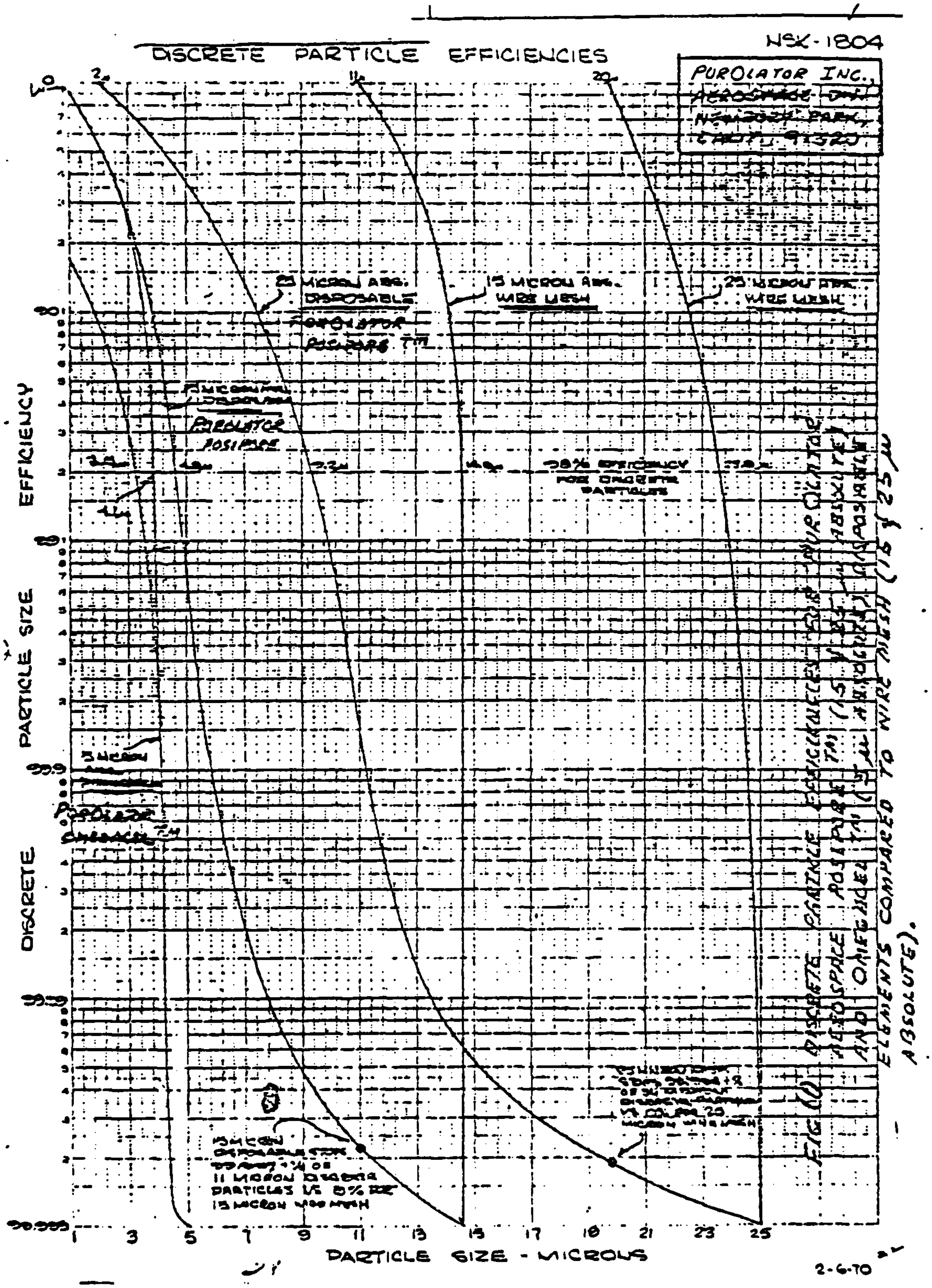


FIG (1) DISCRETE PARTICLE EFFICIENCIES FOR PUROLATOR AEROSPACE POSIPORE TM (15 & 25 μ ABSOLUTE) AND ORIFICHEL TM (5 μ ABSOLUTE) ELEMENTS COMPARED TO WIRE MESH (15 & 25 μ ABSOLUTE).

Figure 8

filter can stop 99 percent of the particles of 4 micron. A disposable type filter element of the same rating shows exceptional improvement overall compared to a wire mesh filter. However, the net gain of a 3 to 5 micron versus a 15 micron absolute rated filter is questionable in a transmission system. The one percent of particles that can pass through the filter element from 5 to 15 micron range should have a small effect on the wear life of the transmission system.

4.3 Ball Bearing Sensitivity

The Naval Air Engineering Center (23), has been conducting bench testing of oil wetted components. The objective of their study is to monitor both the component surface condition and the respective generated wear particle characteristics and parameters. Correlation can then be drawn between component condition and particle characteristic/parameter trends.

Possibly the most significant finding to result from this program has been the full realization of what a truly clean lubrication system can mean in extending the life of operating components. Ultra clean lubrication systems, utilized in ball bearing bench testing, have consistently resulted in the extension of bearing operational life in excess of 40 times their calculated expected life. This life extension dramatically illustrates the major influence oil particulate contaminants exert on the wear rate of a lubricated component.

A viable method of artifically inducing failure was experimentally determined to be the introduction of a Vickers hardness indent onto the inner bearing race. This artificial dent was used to simulate debris dents. Seven out of the twelve ball bearings run to failure, failed at the Vickers indentation. Although failure was induced, the bearings still exhibited lives in excess of six times the Lundberg-Palmgren computed L_{10} life.

Several bearings under test were periodically disassembled to monitor surface wear progression. These dismantled bearings exhibited a new break-in period upon reassembly, as reflected in the respective wear particle analysis. Spectrometric analysis utilizing a military certified atomic emission spectrometer was extremely ineffective in predicting ball bearing bench failures.

4.4 Cylindrical Roller Bearing Sensitivity

Naval Air Engineering Center has also conducted roller bearing bench testings. Preliminary findings, include:

a) Although artifically dented exactly as the ball bearing, none of the fourteen roller bearings on test exhibited a failure at the Vickers indentation.

b) Only a slight life improvement was exhibited by the roller bearings over the Lundberg-Palmgren L_{10} life in the clean oil system.

c) Spectrometric analysis utilizing a military certified atomic emission spectrometer was extremely ineffective in predicting roller bearing failures.

4.5 Tapered Roller Bearing Wear

Fitzsimmons and Clevenger (24) have conducted an evaluation of three contaminant parameters and their influence on tapered roller bearing wear; namely, (a) concentration level in the lubricant, (b) size, and (c) hardness. In addition, other variables that came to light as the test program progressed such as (1) effect of time, (2) effect of change in the particles (shape and size), (3) effect of continued introduction of new contaminant into the lubricant, and (4) effect of types of lubricants and lubricant viscosity were also studied.

The major conclusions of this study were:

a) There is a linear relationship between tapered roller bearing wear and the amount of contaminant in the lubricant. The proportionality of this linear relationship varies, depending upon the particle size and hardness of the contaminant and the lubricant.

b) Tapered roller bearings will continue to wear as long as the particle size of the contaminant in the lubricant is greater than the lubricant film thickness between the bearing surfaces.

c) Significant tapered roller bearing wear can only occur if the contaminant particle hardness is equal to or greater than that of the bearing material.

5.0 CANDIDATE FILTER DESIGNS

The previous sections have attempted to document the helicopter transmission contamination environment, the known filter principles, and the sensitivity of transmission components to contaminants. We now discuss several new candidate filter designs which would represent possible improvements on the present technology.

5.1 Ultrafine Static Filter

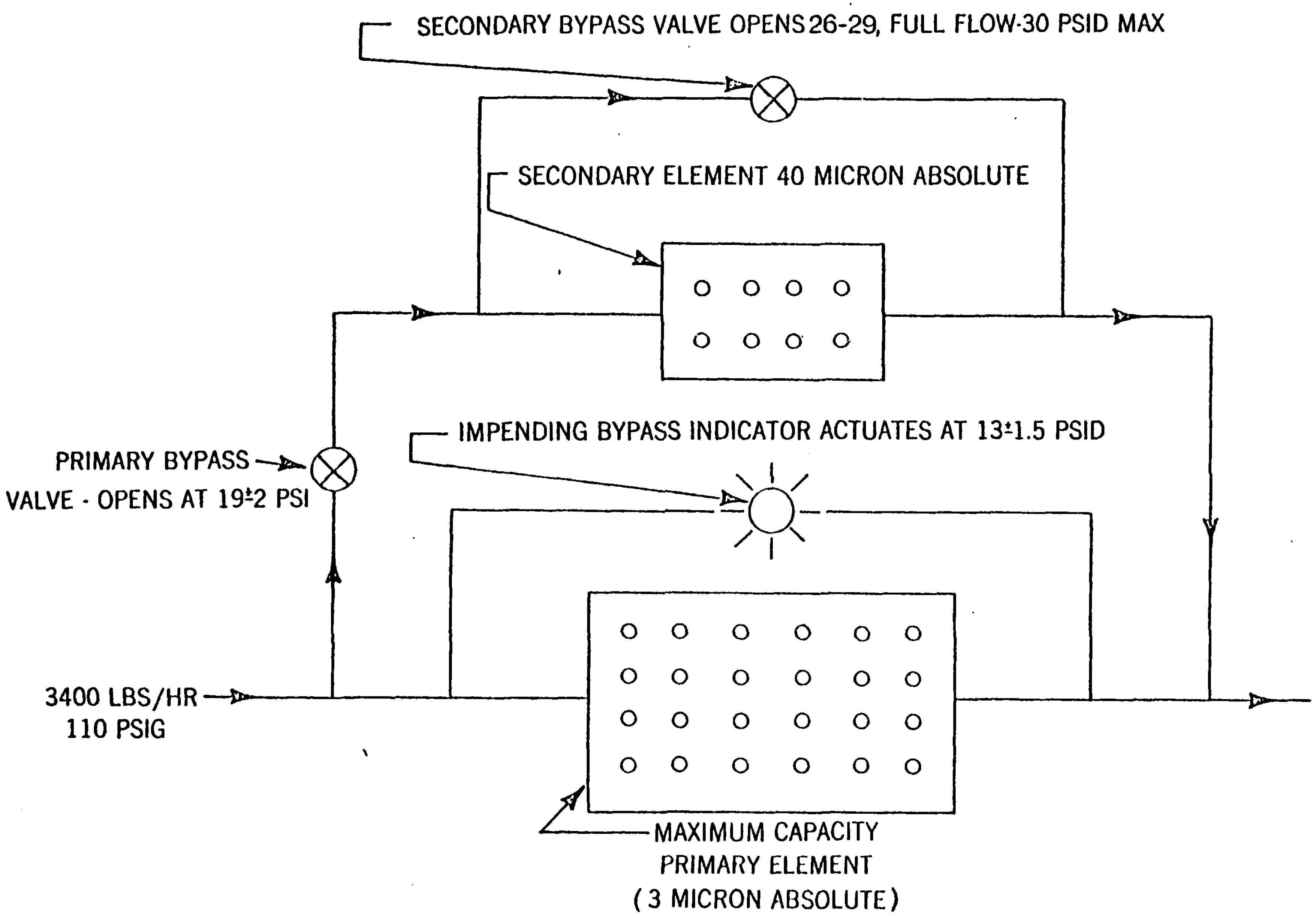
The trend in static filter application in new helicopter transmission designs is toward finer filtration. For example, the T-700 engine developed for the UTTAS helicopter is to be equipped with three (3) micron filters (26).

On helicopter transmissions in the current Navy inventory, the trend is also toward finer filtration. The H-2 helicopter formerly used a 41 nominal, 81 absolute filter and is now equipped with a 20 nominal, 40 absolute filter.

Several ultrafine filters are on the market rated at 3 microns. Units by Aircraft Porous Media, Inc. and Purolator, Aerospace Division are available commercially. Typical of this type of filter, is that developed for the T53 Gas Turbine. A similar design is to be used on the T-700 engine developed for the UTTAS helicopter.

This candidate filter design incorporates the following features as shown in Figure 9.

1. A primary element optimized for maximum dirt capacity.
2. An impending bypass warning indicator for this primary element that indicates at excessive differential pressure. A bimetallic thermal latch to avoid false indications due to cold oil, and also has to be non-resettable unless the element is changed.



NEW FILTER DESIGN REQUIREMENTS SCHEMATIC

Figure 9

3. A bypass valve across the primary element which opens at a preset pressure.

4. A small cleanable 40-micron absolute secondary element in the primary bypass line for use in the event that the indicator warning is not heeded within a few hours.

5. A bypass valve around this secondary element that opens at a total filter differential at the maximum allowable pressure.

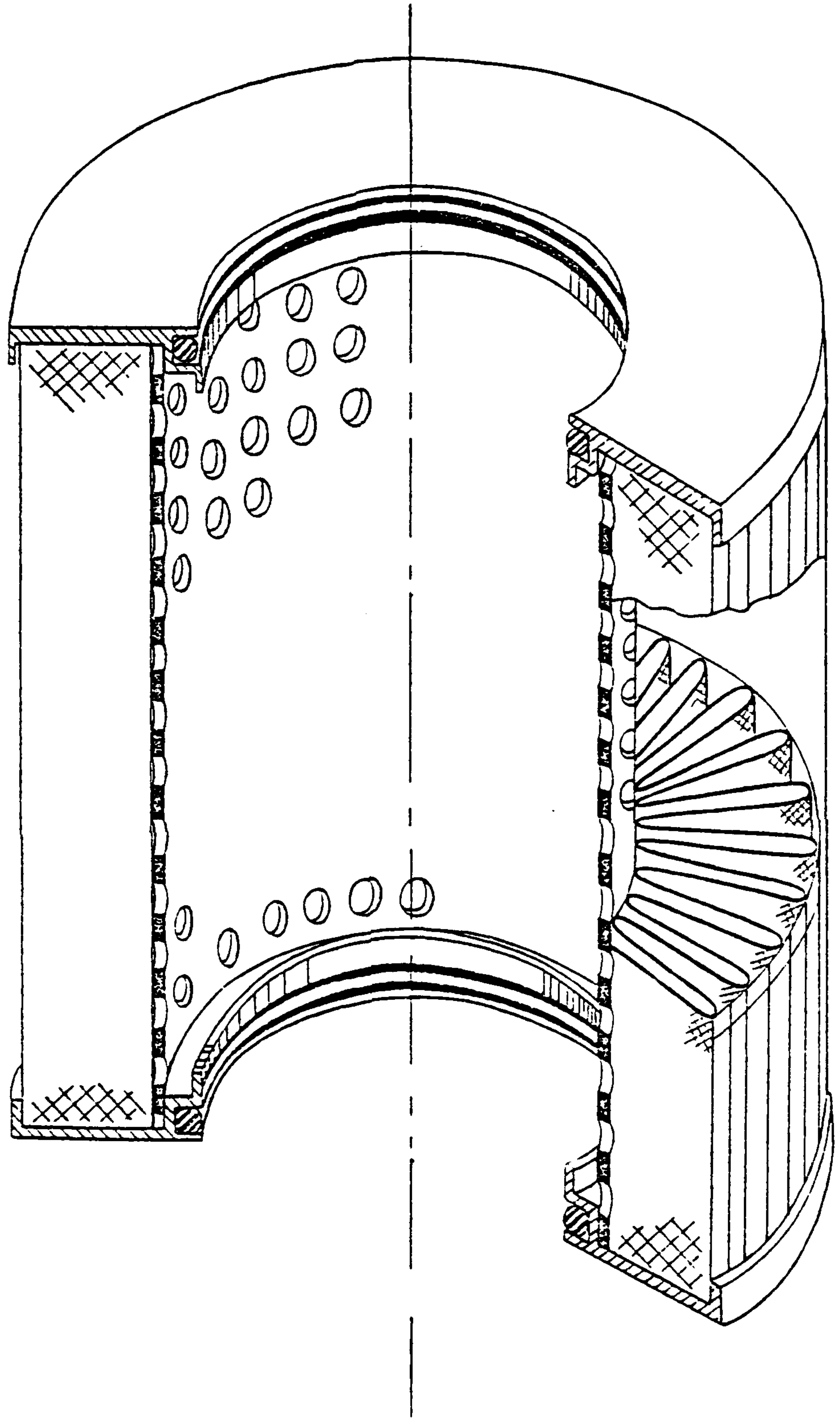
5.1.1 Primary Element Design

Figure 8 shows the primary element which is made of a disposable ultra-fine inorganic filter paper. Advantages of this construction include.

1. High flow capability
2. High dirt capacity
3. High strength and stability from -100°F to 400°F
4. Compatibility with all presently used hydraulic, lubricating, and fuel fluids (liquid and gaseous)
5. A most favorable economic relationship of cost, reliability, wear elimination and maintenance.

The configuration is the familiar cylindrical outline, with the media in the accordian pleated form, supported by a perforated tube, and sealed to metal end caps with epoxy resin. To maintain the three-micron absolute integrity, identical "O" ring seals are provided at the inner diameter of each end cap.

The element is slipped over the standpipe-like structure extending from the filter cover effecting an "O" ring seal when pressed on fully. The standpipe-like structure is actually a housing for the secondary element and bypass valving (see Figure 9). With the element thus positioned, the act of screwing the cover into the filter body automatically installs the element into position, sealed at both its ends by "O" rings. In reverse,



PRIMARY FILTER ELEMENT

Figure 10

unscrewing the cover carries out the disposable element on the "standpipe" exposed for easy removal.

5.1.2 Secondary (Metal) Element and Bypass Valving

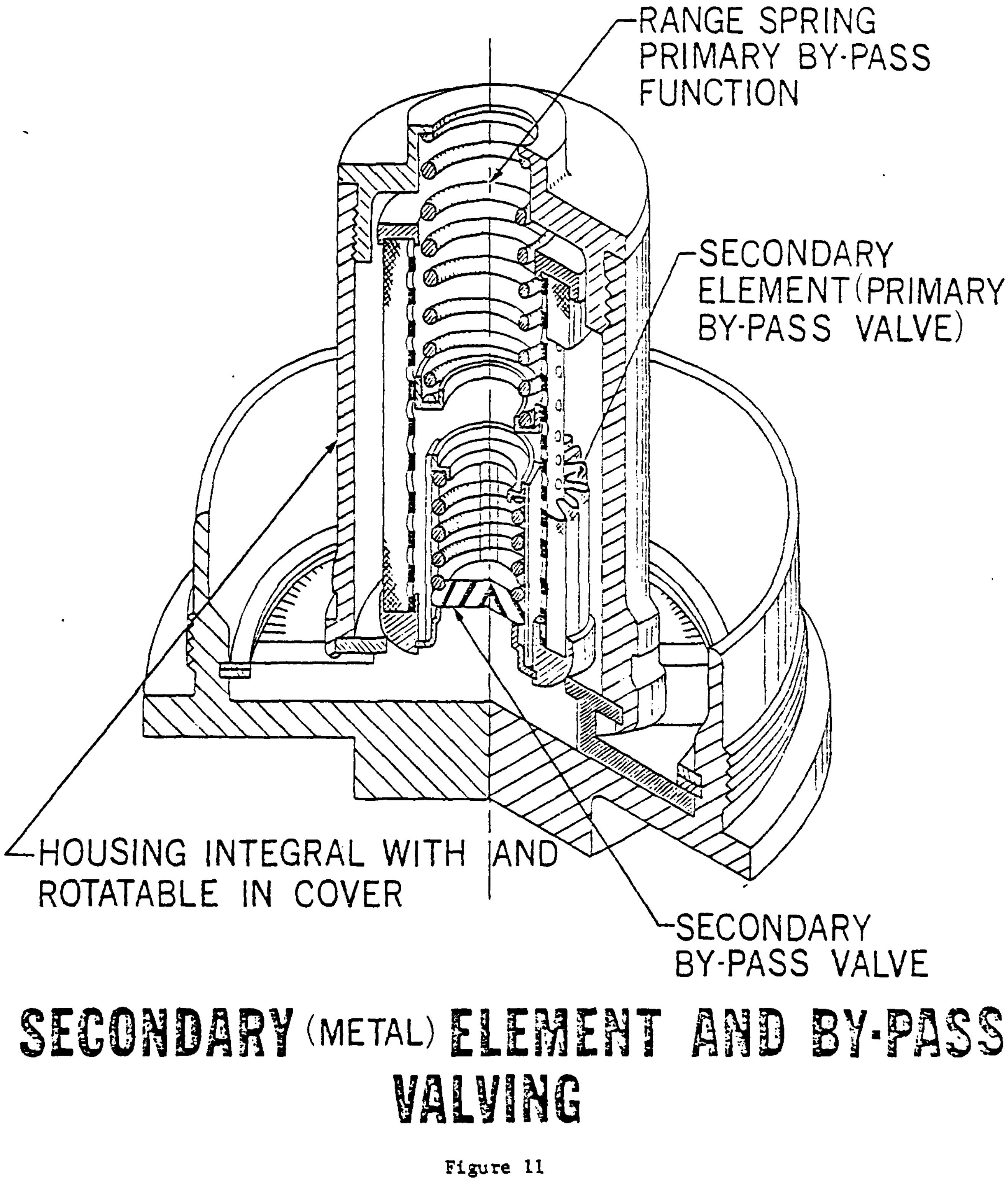
In providing the specified secondary element, plus the two bypass valving functions, the candidate design eliminates any need for field adjustments. As shown in Figure 11, the secondary element bypass valve is a spring loaded face seal type with a flat lapped seat, permanently integral with the element, and located within the element support core.

The metal element is a 40-micron absolute, 17-micron nominal, sintered stainless steel woven wire mesh, pleated for extended area, the pleated mesh being nickel brazed to the end pieces. One end of the element has a spherical nose shape which, by spring force, functions as the primary relief valve poppet. The secondary element being thus movable, by virtue of its being also a valve poppet, the necessary housing requirements were met in such a way as to provide these other features:

1. Foot extensions of the housing enabling the entire unit to be integral with the filter cover. To install the primary element, it is slid over the housing to the point where the "O" ring snaps in place. By screwing the cover into the filter housing, the primary element is automatically positioned. Unscrewing the cover also carries out the primary element for ease of removal.
2. The valve seat forms one end of the valve housing, and the other end is a threaded plug which provides primary relief valve spring loading, and also allows removal of the metal element for cleaning.

5.2 Inertial Filter

Inertial filters are used extensively in industrial processes but have not found application in the automotive or aerospace industries. Figures 12 - 15 show a commercially available inertial filter.



SECONDARY (METAL) ELEMENT AND BY-PASS VALVING

Figure 11

The oil enters through the inlet tube to a swirl cup. The oil is directed out of the swirl cup into the swirl chamber through the louvers cut in the sides of the cup. The oil swirling in the swirl chamber, by centrifugal force, starts the separation process by forcing the heavier impurities such as water, dirt, metal particles, etc., to the outside of the chamber where they move outwardly and downwardly from the flowing oil as a result of gravitational and inertial forces.

The swirl chamber contains several metal alloy slugs, which are composed of magnesium, aluminum, tin and zinc; these are provided to neutralize acids and molecular water by corrosive action. Gums, resins and sulphur are catalyzed by these slugs and other metal surfaces contained in the rectifier. The oil, having passed through the swirl chamber, passes into the partitional area and is directed to the center of the unit where it rises upward into the stand cup and returns to the engine through the return pipe. It is in this controlled flow path that other contaminants are separated. To better visualize what happens in the controlled flow path, we illustrate by showing the spiral path in a straight line. (See Figure 15) Particles having a higher specific weight than oil such as large abrasives and globular water are removed by sedimentation aided by centrifugal force from the swirl chamber and by inertial force as the oil changes its direction of flow from downward to lateral. As the oil progresses toward the stand cup, the purest oil (lightest substance) rises to the top and sedimentation separates heavier than oil contaminants which settle into the sedimentation area out of the flow path of the oil and finally into the sump area. Other contaminants including both small abrasive and nonabrasive contaminants such as carbon are removed by electrostatic attraction to the metal of the rectifier as a result of their having been ionized in the circulating oil since ionization naturally occurs in the engine. Others of these contaminants flocculate together and build up in size sufficient to settle downward or to be coalesced and cohered to the surface areas of the rectifier. To assist the electrostatic attraction and the coalescence to the attraction area of the rectifier (partition walls), the oil flows in a channel having perforated and corregated the walls, and in the resultant parabolic flow and

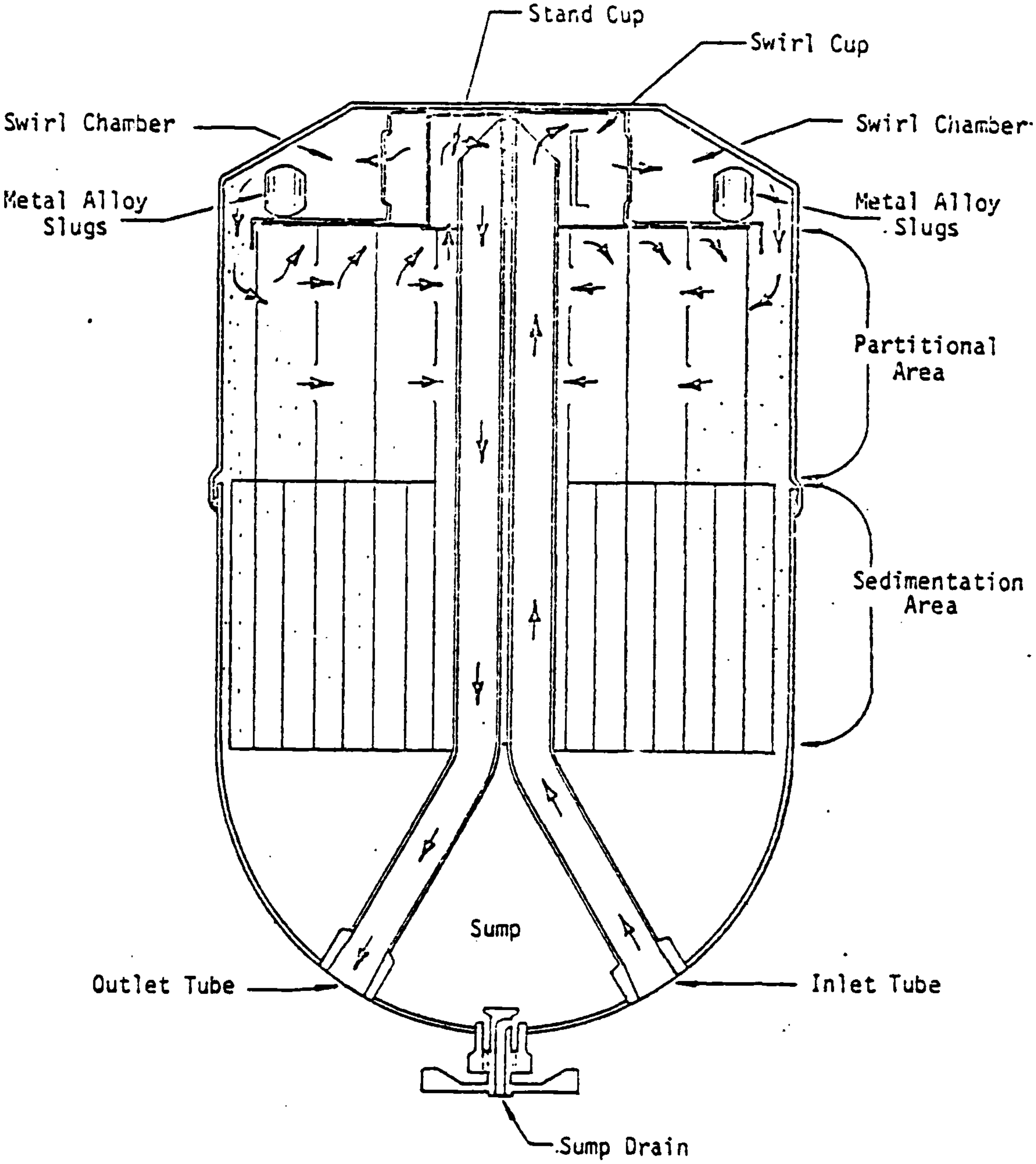
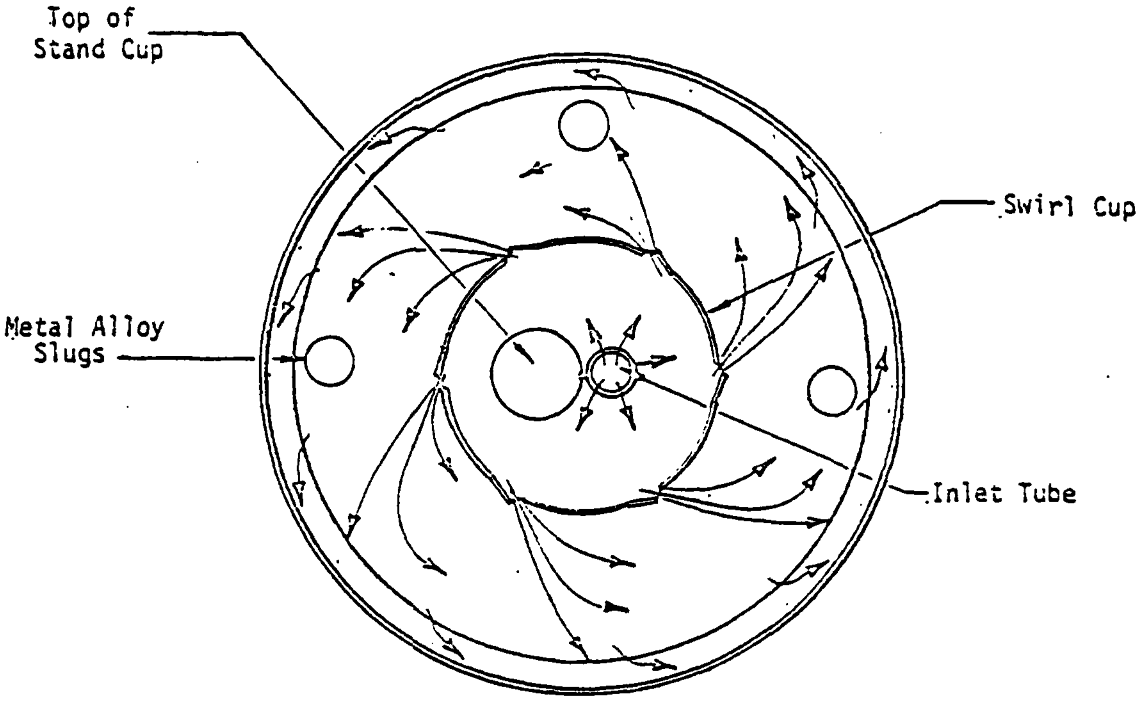

Stand Cup
Swirl Cup
Swirl Chamber
Swirl Chamber
Metal Alloy Slugs
Metal Alloy Slugs
Partitional Area
Sedimentation Area
Sump
Outlet Tube
Inlet Tube
Sump Drain

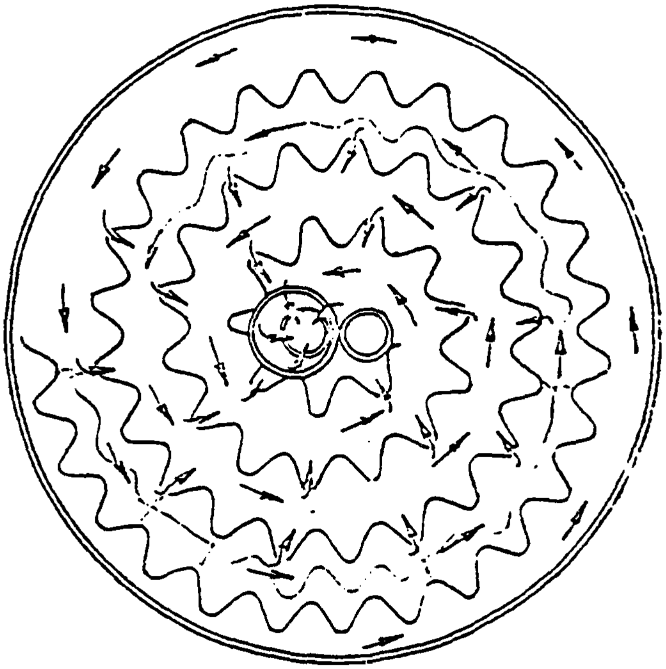
Figure 12



SWIRL CHAMBER

Swirl Chamber showing fluid being directed from the swirl cup into the swirl chamber. The swirling oil generates a centrifugal force action which starts the sepapration process.

Figure 13



PARTITIONAL AREA AND SEDIMENTATION AREA

Partitional Area showing the controlled flow path of the oil. (Immediately below the partitional area, the Sedimentation area is made of double corrugations separated by metal dividers forming a honeycombed section. Each opening contains an independent column of stagnant fluid.)

Figure 14

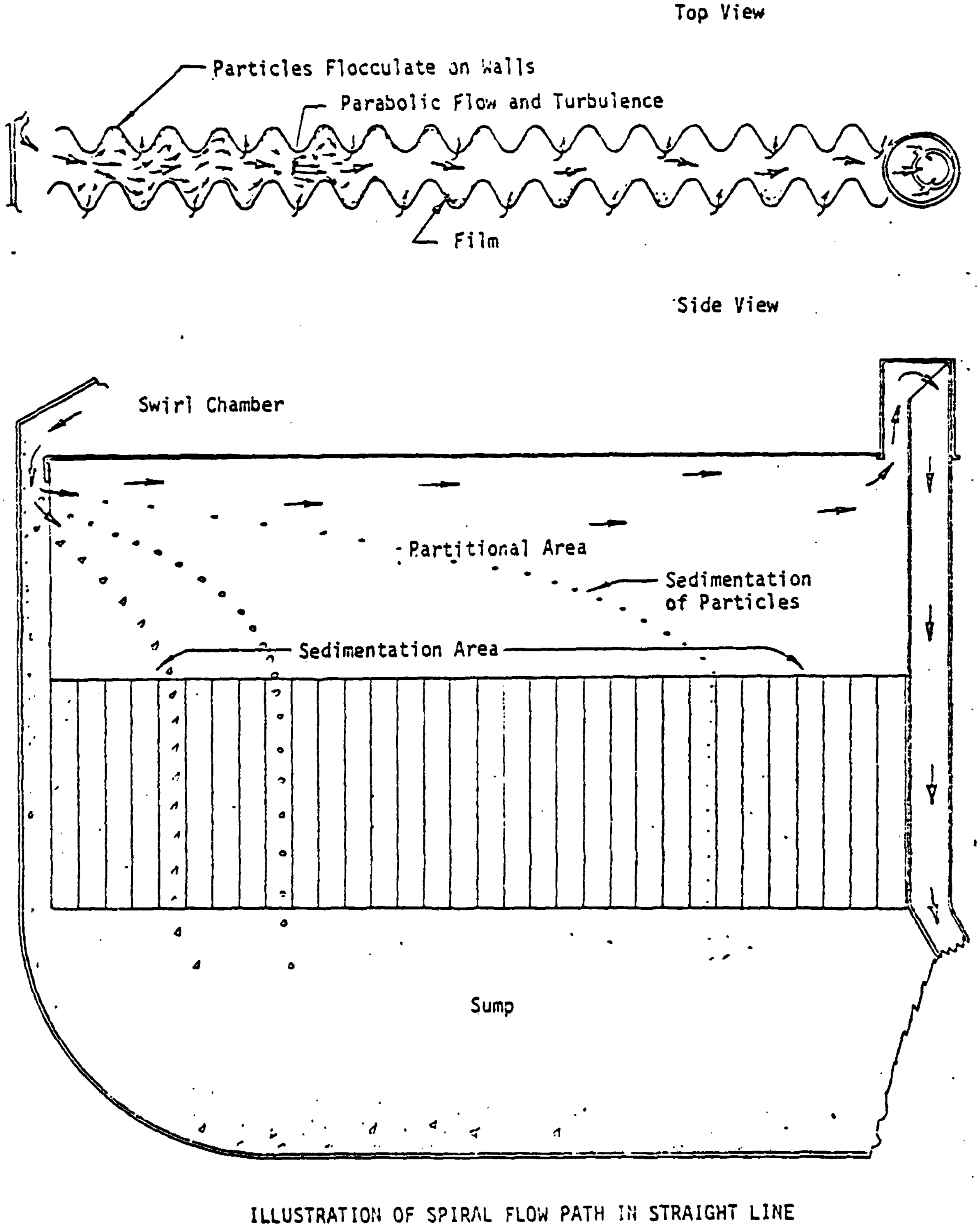


ILLUSTRATION OF SPIRAL FLOW PATH IN STRAIGHT LINE
(As if spiral were uncoiled)

Figure 15

turbulence which is assisted by the cross jet flow streams created by the perforations in the partitions, the particles are directed sufficiently close to the partition walls for this electrostatic attraction and coalescence to take place. The particles naturally flocculate on the walls of the partition and finally coalesce into a film heavy enough to slide down the partition into the sedimentation area and finally into the sump.

A particle in the controlled flow stream within the rectifier can be compared to a piece of debris floating on a small stream or creek. It will either sink or by reaction to the turbulence generated in the flowing stream, be shoved to one bank or the other. The particle in the rectifier will immediately settle out or be directed to one side of the partition or the other to be separated by electrostatic attraction or cohesion.

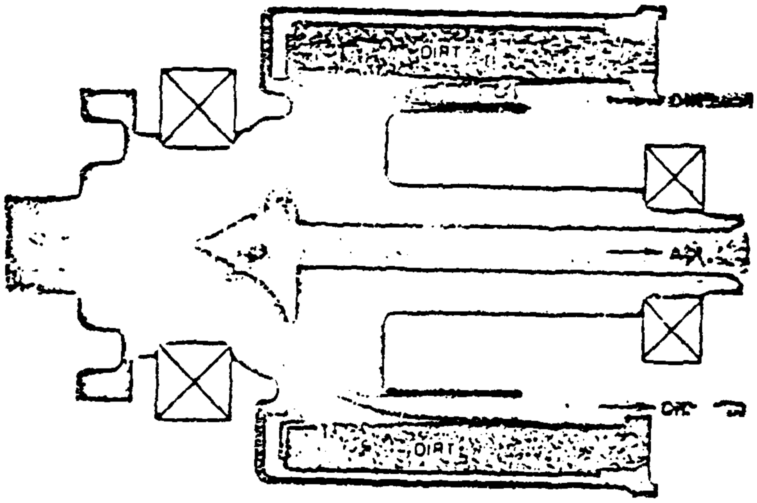
The removal of the sump oil and the replacement of fresh oil to the main oil reservoir is the only servicing the unit requires and institutes the principle of the gradual oil change.

5.3 Centrifugal Filter

It is possible to enhance the inertial separation principle by subjecting the dirt laden lubricant to high inertial forces as it flows through a centrifuge.

A centrifuge removes particulate matter from fluid by centrifugal force as shown in Figure 16, entering fluid is accelerated to high speed rotation within a canister. The centrifugal force created by such rotation drives the dense particles in the fluid to the outer diameter of the canister where they are caught and held. The cleaned fluid is returned to the oil tank deaerator for removal of the remaining entrained air and for cooling.

The contaminated oil and entrained air enter the centrifuge shaft axially from the inlet cavity and begin to rotate in a cavity in the centrifuge shaft. A spinner in the inlet aids in the separation of some of the entrained air, which passes axially through the bore in the shaft to the air outlet port in the cover. The centrifuge is not intended to replace the deaerator contained in the engine oil tank. The oil collected at the periphery of the cavity in the



Internal Flow in MAIC Centrifuge
(Cross-Sectional Simplified Drawing
Showing Flow Path)

Figure 16

centrifuge shaft is pumped from the shaft through a series of radial holes leading to the centrifuge canister. This pumping imparts a tangential velocity to the oil, which creates the centrifugal forces required to remove contaminants from the oil. As the oil passes through the annular passage in the canister, the dirt migrates from the oil into the dirt-retaining basket, where it collects and is retained.

The cleaned oil, leaving the centrifuge basket, flows to a sump in the bottom of the centrifuge housing. A positive displacement internal gear type scavenge pump removes the oil and excess air from the sump and delivers it through system piping to the oil tank.

A poppet type by-pass valve is contained in the centrifuge housing to maintain oil flow around the centrifuge in the event oil flow into the unit exceeds the capacity of the centrifuge or in the event of centrifuge failure. The valve is preset to by-pass full flow when the inlet pressure to the centrifuge is a present valve above the discharge pressure.

Advantages calimed for the centrifugal filter include:

1. The centrifugal filter, when applied to a recirculating oil system, removes all of the particulate matter that is more dense than the lubricant itself. Thus it removes particles down to the colloidal range.

2. The centrifugal filter does not cause a pressure drop in the system--it usually produces a net rise in system pressure. (Pressure rise can be slight or substantial depending on the design of the unit.)

3. The centrifugal oil filter can be designed to do an effective job of deaerating of engine lubricant--lubricating oil that has been deaerated can be shown to have better heat transfer characteristics and higher film strength.

When a static filter screens dirt out of a system and holds it--and if the dirt trapped in the filter is chemically active, the lube system has a built-in <u>reaction</u> <u>vessel</u>. This is the exposure of the chemically active "dirt" particles to the recirculating lubricant and accelerating the degradation rate of the remaining lubricant in the system.

A centrifuge pulls particulate matter out of the lubricant and either overboards it, or stores the "dirt" in a peripheral retainer that presents relatively little surface area to the recirculating lubricant--thus, oil degradation rate is reduced by several orders of magnitude. Consequently, lube systems protected by centrifugal filters show very little change in acid neutralization number or viscosity with time.

The disadvantages of the centrifugal filters include:

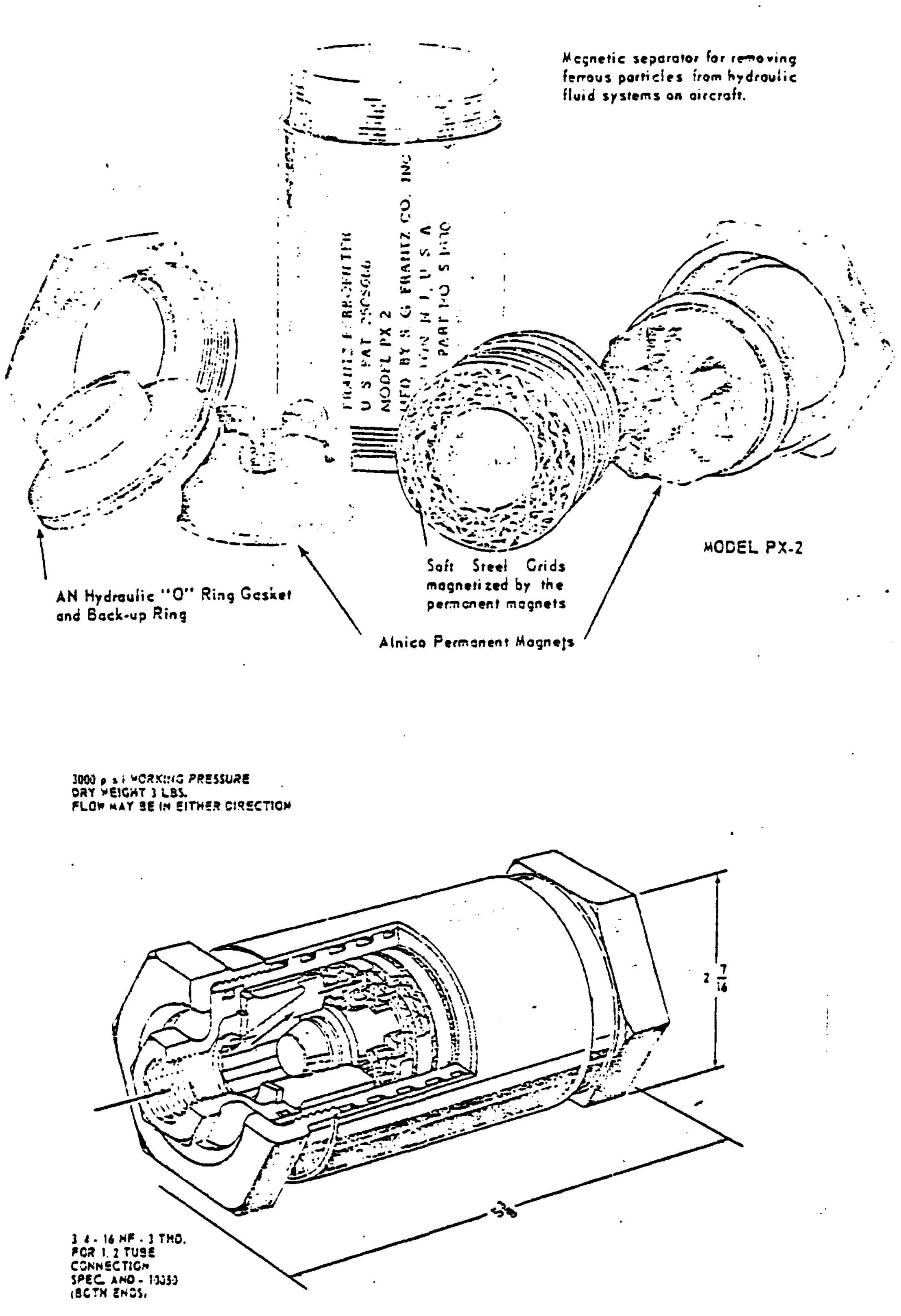
1. They require an external power source and
2. They are more expensive than a static filter.

5.4 Magnetic Filter

The survey revealed only one vendor (S. G. Frantz Co., Inc.) who offers a commercially available unit. A unit designed for an aircraft application is called the FerroFilter and is shown in Figure 17. The separating matrix is a stack of carbon steel or stainless steel grids magnetized by permanent magnets. The grid edges divide and redivide the stream so that all particles must pass through a succession of strongly convergent magnetic fields. The particles are attracted to the grid edges, where the magnetic force converges. Advantages claimed by the manufacturer include:

- Removal of ferromagnetic contaminants;
- No element replacement - grids are virtually indestructible under normal use; there are no disposable parts;
- Durability - service life is virtually unlimited, with little or no maintenance; there are no moving parts to wear out;
- Full flow, low pressure drop - FerroFilters are designed for installation in the full flow, not in a by-pass;
- Simple, compact, accessible - FerroFilters fit easily into pipelines or can be bolted directly to equipment without piping, yet all parts are readily accessible for cleaning.

S. G. Frantz Company, Inc. also manufactures electromagnetic separators. However, the electromagnetic filter is not available in a size envelope suitable for a helicopter transmission application. Sala Magnetics Inc. has a magnetic filter under development but so far has not offered the unit on a commercial basis.


Magnetic separator for removing ferrous particles from hydraulic fluid systems on aircraft.

Candidate Magnetic Filter

Figure 17

6.0 CONCLUSIONS

The available helicopter transmission experience indicates that incorporation of finer filtration (3 micron) results in a significant improvement in transmission service life. However, if proper clean-up procedures are not employed, finer filters are subject to premature plugging. Specific findings include:

- Existing failure analyses data indicates that bearings and gears are the two transmission components which fail most frequently.
- The lubricant film thickness common to bearings and gears in helicopter transmissions are much below the capture capability of currently used filters.
- Debris/corrosion is the dominant failure mode of all transmission components.
- Bench tests of individual components such as ball, cylindrical and tapered roller bearings indicate improved fatigue and wear life with finer filtration.

Four candidate filter concepts have been identified which potentially offer finer filtration than presently used filters. These are:

Filter Type		Potential Vendors
Ultrafine Static	-	Aircraft Porous Media, Inc. Purolator, California
Inertial Filter	-	Dynatek Industries, Inc.
Centrifugal Filter	-	Pure Carbon, MAIC Division
Magnetic Filter	- -	S. G. Frantz Co., Inc. Sala Magnetics, Inc.

All but two of the potential vendors have offered to supply candidate filters in the recommended program described in the next section.

7.0 RECOMMENDATIONS

This study has shown that the use of filters with smaller particle size capture capability results in a significant improvement in transmission service life. Four candidate filter concepts have been identified which potentially offer finer filtration capability than presently used filters. However, before any of these candidate filters are retrofitted in existing transmissions the following steps are recommended.

7.1 Determination of Helicopter Transmission Contaminant Ingression

Although the contaminant environment common to helicopter transmissions was discussed earlier in the report (Section 2.0), there is no well documented evaluation of contaminant ingression in helicopter transmissions. It is therefore recommended that the rate of ingression and nature of contaminants in helicopter transmissions be determined. Much information is already available through the SOAP Program. However, it is important to also obtain particle density and particle distribution counts in conjunction with the SOAP samples.

To conduct this study it is suggested that a specific transmission be selected; e.g., CH53. Working at the squadron level, lubricant samples should be taken at the same time the SOAP samples are taken. The additional samples would be used to obtain the particle density and distribution counts. The additional information coupled with the SOAP analysis will provide a measure of ingression rate as a function of time. It is estimated that data accumulated on approximately twenty-five transmissions over a six month period would give a statistically significant sample.

7.2 Determination of Filter Capture Capability

It is recommended that the candidate filters' capture capability be evaluated using the new multi-pass performance test.*

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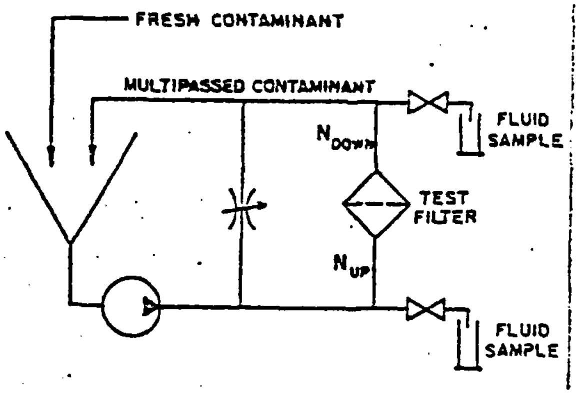
*ANSI Standard B93.31 - 1973.

Basically, the test consists of placing the test filter in a circulating system where rated flow can be maintained. (See Figure 18) ISO approved contaminant "air cleaner fine test dust" is continuously added to the test system in a precisely controlled manner. The particle size distribution upstream and downstream of the test filter are measured to provide a realistic evaluation of separation performance. The filtration (Beta) ratio calculated from the test data is an accurate reflection of separation capability of the filter and is defined as:

> "The number of particles greater than size μ in the influent fluid to the number of particles greater than the same size μ in the effluent fluid."

The higher the Beta ratio, the greater the filter's capability to capture particles. For Beta equals two, half of the particles greater than a given size are captured; and a Beta of one means the filter cannot remove any particles above the designated size.



Multi-Pass Performance Test

Figure 18

7.3 Determination of Transmission Contamination Sensitivity

It is proposed that the transmission contamination sensitivity be determined in two ways, through field test and through bench tests.

7.3.1 Field Tests

The sample transmission selected for the ingression rate determination (Section 7.1) would also form the data base for the determination of component contamination sensitivity. The transmissions selected would subsequently be followed through rework. Preferably, a portion of them should also undergo an analytical rework inspection. Knowledge of the MTBR and the condition of the components at rework would provide an indication of the sensitivity of the components, bearings, seals, gears, etc. to the level of contamination in the transmission.

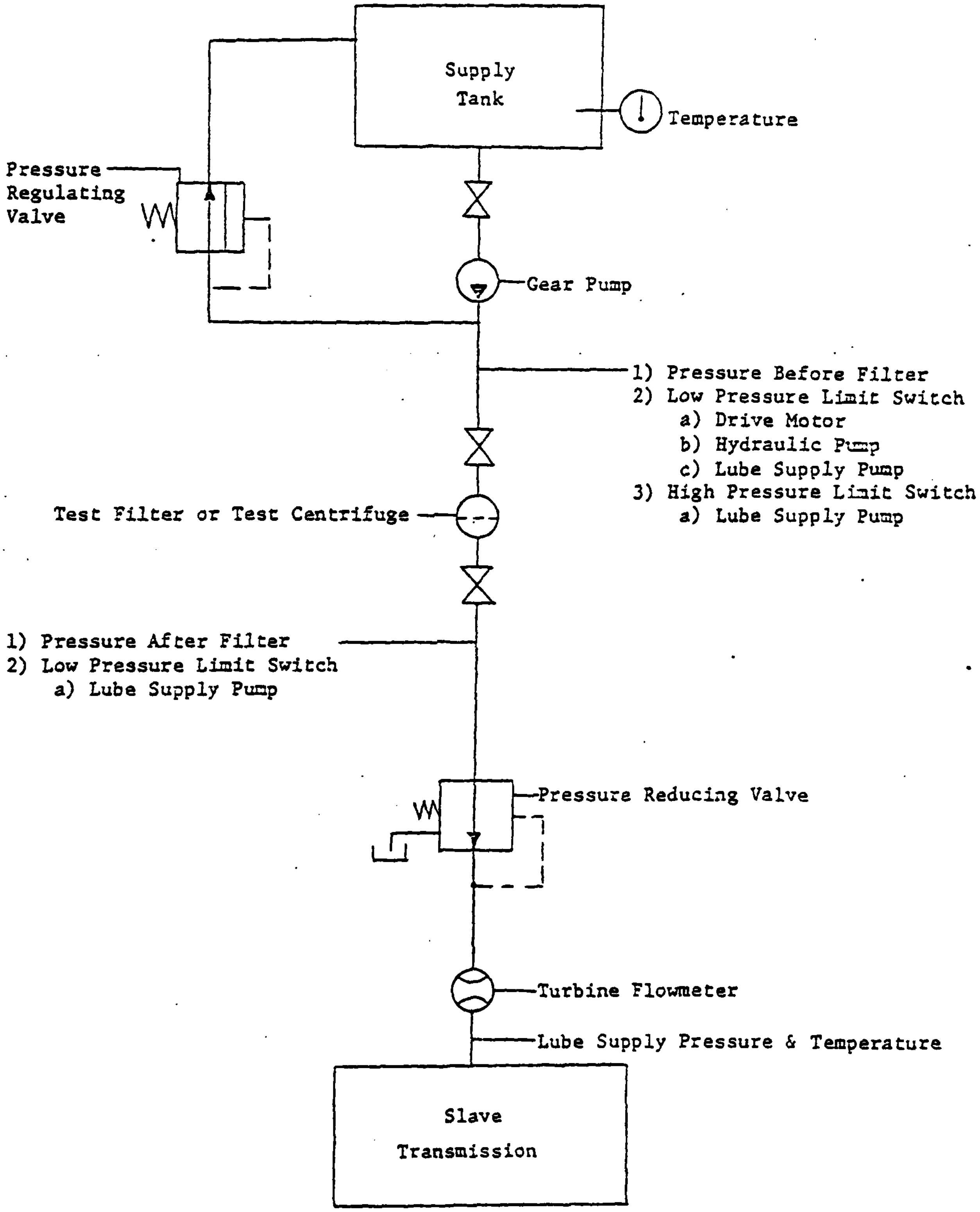
7.3.2 Bench Tests

It is proposed to test the candidate filters on the slave transmission at Sikorsky Division of United Technologies Inc. Although the available slave transmission has its own internal lube system, we are suggesting that it be modified to allow for external mounting of the test filters, contaminant injection, and sampling points.

Proposed Lubricant Supply System

Figure 19 shows the proposed lubricant supply system. Oil would be pumped from an external supply tank through the test filters and then into the slave transmission.

The sampling location is shown in Figure 20 which is at the discharge of the slave transmission. It is proposed to use an Isolog Model M-4KT sampling system.



Proposed Lubricant Supply System

Figure 19

Proposed Contaminant Injection

The contaminant injection system is shown in Figure 21. The test contaminant to be used is summarized below:

Contaminant	Amount
Stainless Steel Particles ($< 40\mu$)	1 Part
AC Arizona Coarse Test Dust	10 Parts
MAIC Carbon Test Dust	80 Parts

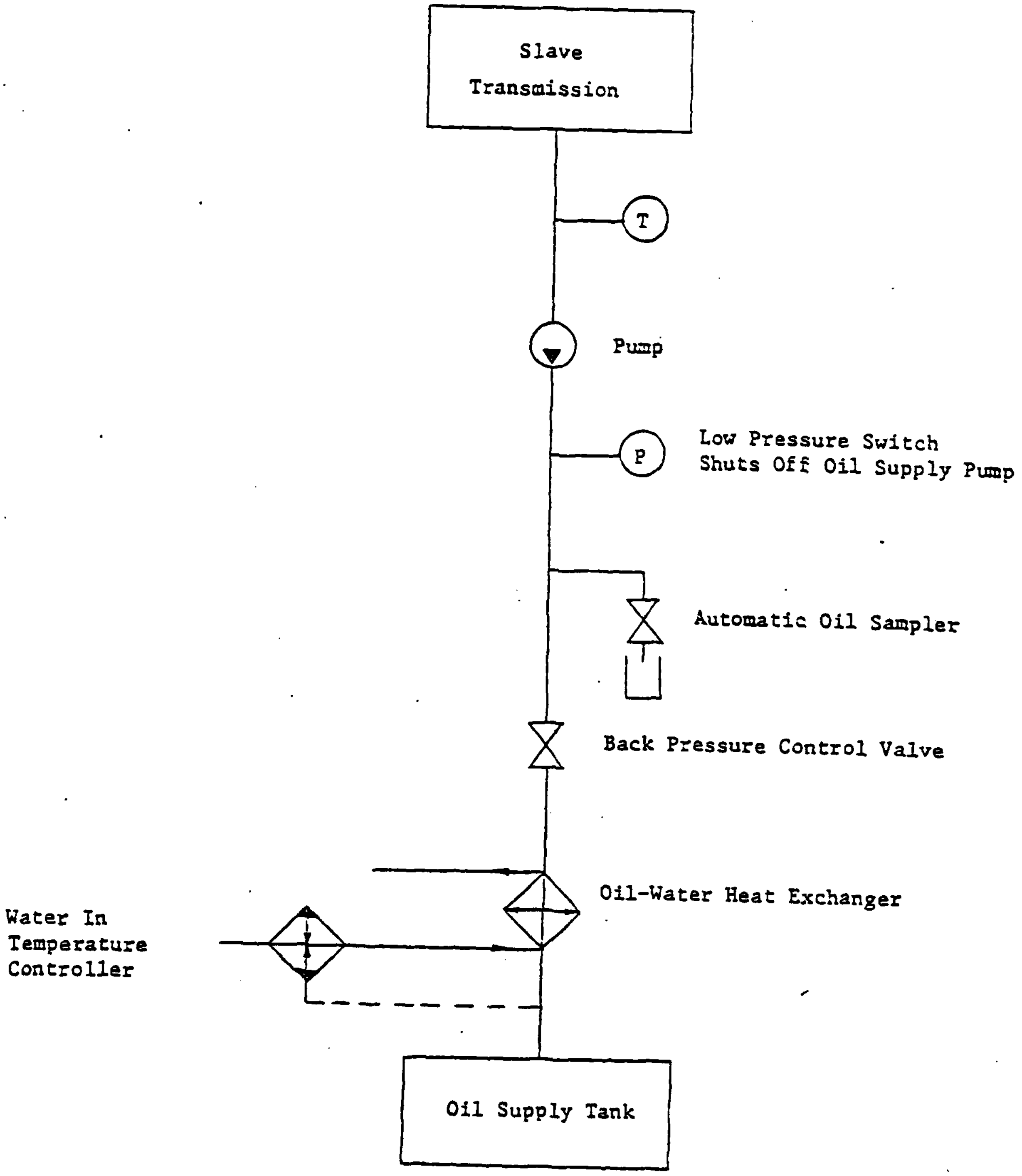
This test contaminant, developed by MAIC, is intended to simulate the composition of engine oil system dirt which we feel will be similar to transmission dirt. This contaminant will be used only if the slave transmission does not generate sufficient debris in the planned test period.

Proposed Transmission Tests

The test filters would then be tested in the transmission lube system described earlier. Prior to starting testing, the system should be cleaned up using a large capacity fine static filter; e.g., Hilco type. This clean-up procedure should be run until samples show that the contaminant level has been reduced to a minimum. This clean-up cycle should be conducted prior to the test of each filter.

The transmission tests should be conducted using the system shown in Figure 19. It is intended to run each filter for a 500 hour test period. Filter flow, temperature, and pressure drop should be measured as a function of time.

If the test transmission itself does not generate enough debris in 500 hours, test contaminant should be introduced in the system using the device shown in Figure 21.



Oil Sample System

Figure 20

Contaminant Level Assessment

Contamination level relates to the amount of contaminant per unit volume of lubricant. This level varies from point to point in a system, depending on the location of contaminant ingression and removal points. The level also varies from one time to another due to changes in machine operation and environment.

To assess the value of the contamination level, the two following measurements should be made:

- Cumulative particle size distribution - the number of particles per millilitre of fluid greater than each particle size.
- Gravimetric level - the weight of the contaminant in milligrams per litre of fluid.

To obtain and report an accurate measurement, the following standards should be followed:

- "Clean" sample containers per ANSI Standard B93.20-1972.
- An acceptable fluid sampling technique - ANSI Standard B93.19-1972.
- An approved gravimetric level technique - SAE Standard ARP 785.
- An approved automatic particle counter calibration procedure - ANSI Standard B93.28-1973.
- An accepted format for reporting contamination levels - ANSI Standard B93.20-1973.

The samples should be taken using the system shown in Figure 20 and described earlier.

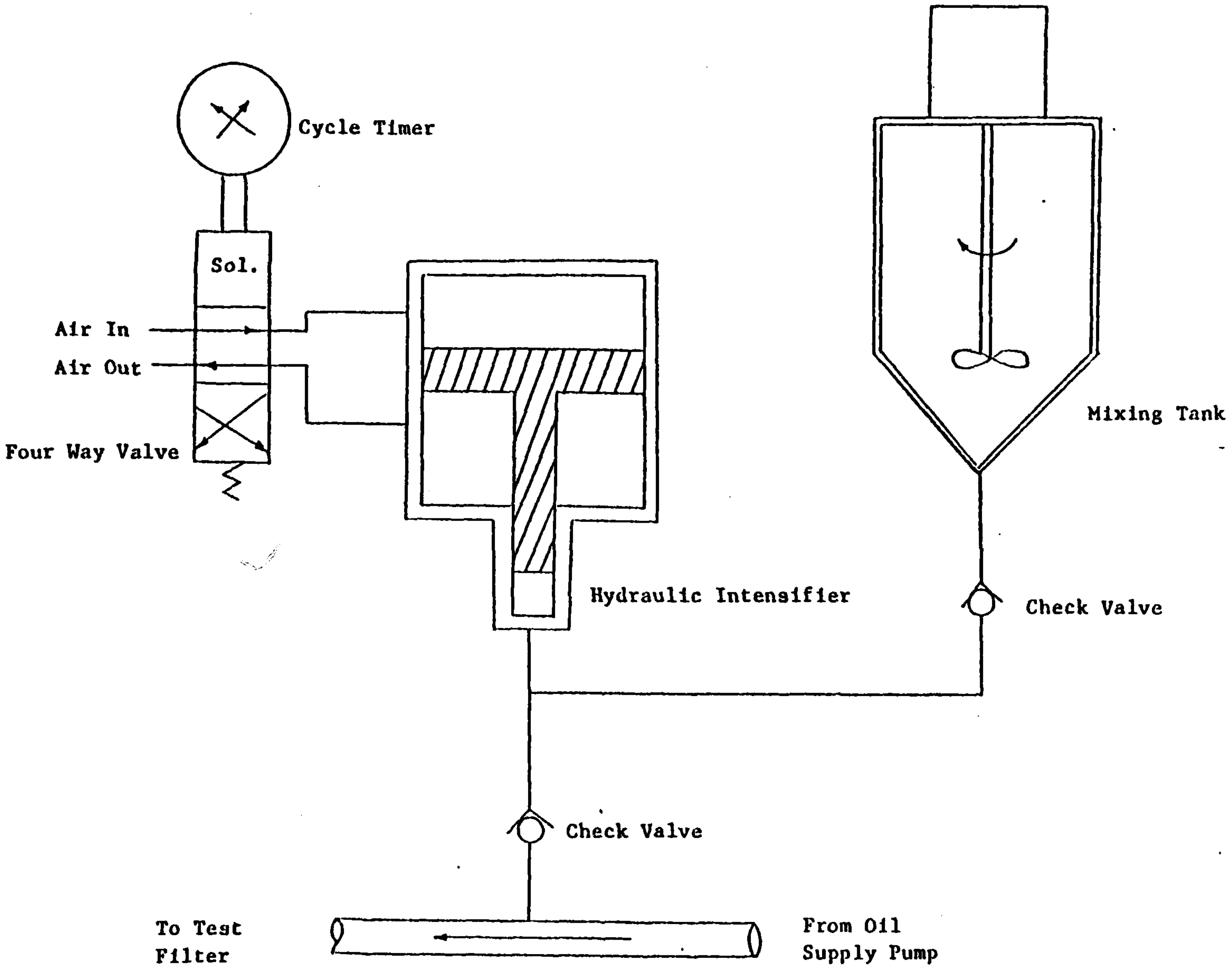
Filter Performance Analysis

It is suggested that the performance of each filter tested be evaluated in terms of the following parameters:

1. Flow
2. Pressure drop
3. Capacity - life
4. Separation performance in terms of Beta ratio
5. Cost
6. Weight
7. Volume
8. Ease of installation and removal

The above parameters define the filter performance.

This information, coupled with data on transmission contaminant ingression and component contaminant sensitivity, will provide the data base which will permit the rational selection of filtration level for optimum transmission life. Once the filtration level is determined, then the necessary filter specifications and rework cleanliness requirements could also be established.



Proposed Contaminant Injection System

Figure 21

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