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DECONTAMINATION OF HYDRAULIC FLUIDS AND DYNAMIC HOSE STUDY

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FOREWORD

This Technical Document Report was prepared by the Fluid Power and Controls Laboratory of the School of Mechanical Engineering, Oklahoma State University of Agriculture and Applied Science. The work was initiated by the Research and Technology Division, Wright-Patterson Air Force Base, Ohio, and accomplished under contract AF 33(657)-9958, Supplemental Agreement No. 2.

This contract with Oklahoma State University was initiated under RTD Vehicle and Maintenance Branch and is titled "Decontamination of Hydraulic Fluids and Dynamic Hose Study." It was accomplished under the technical monitorship of Theodore C. Ning, SEG (SEMSM), Air Force Project Engineer, under the general technical guidance of W. J. Short, Chief, Vehicle and Maintenance Branch. The work on the project was divided into separate areas, whereby the responsibility for each area was assigned to different members working under the direction of Dr. E. C. Fitch, Project Director; R. E. Reed, Project Advisor; R. E. Bose, Project Leader. The individual work assignments were as follows:

Field Sample Collection -- R. E. Bose
Field Sample Analysis -- D. Fincher and M. L. Rogers
Hydroclone Support Studies -- W. T. Wittmer
Filtration Comparison Tests -- J. E. Bose
Hydroclone Verification and Qualification -- W. R. Lynn
General Design Criteria -- B. J. Roberts and J. A. Jones
Dynamic Hose Study -- J. W. Webb, R. Stuntz, and H. Basrai

This report covers work conducted from January 1964 to January 1965 under contract AF 33(657)-9958, Supplemental Agreement No. 2.

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ABSTRACT

This report includes a description of the installation of the prototype hydroclone on standard hydraulic test stands as a means of upgrading the decontamination capabilities in USAF ground support equipment. The acquisition of hydraulic fluid samples from the field installations and the laboratory tests of these samples are discussed along with a comprehensive technical comment on the results of the various analyses. A comparison of filtration performance of the hydroclone and the final filter presently being used on the hydraulic test stands is presented. Studies on field test units are presented herein which were conducted to determine the maintainability, compatibility endurance limits, reliability, and service life of the hydroclone and its critical components. A recommended test procedure is presented for the verification of hydroclone performance and the establishment of qualification requirements for quantity production. General design criteria curves for optimum hydroclones are given which can be used to design a hydroclone, using MIL-F-5606 hydraulic fluid, to separate specific sizes and densities of various contaminants found in USAF ground support equipment. A unique method for the dynamic testing of high pressure hose assemblies and the cleaning of new hose assemblies is presented along with the contaminant generating characteristics of high pressure hoses constructed of various materials.

This report has been reviewed and is approved:

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SECTION I

INTRODUCTION

The research conducted under Supplemental Agreement No. 2 of contract AF 33(657)-9958 had the objectives of determining (1) the suitability and capability of a hydroclone of optimum configuration on a hydraulic ground cart and (2) the contaminant generating characteristics of two commercial high pressure hose materials used on hydraulic ground carts. The results of the initial hydroclone contract at Oklahoma State University indicated that a highly desirable decontamination device was offered by a hydroclone of optimum configuration. These results were derived from an extensive laboratory program on the basic parameters associated with vortical separators. Since the laboratory program could not reveal the performance of the hydroclone when applied to a system with service contaminant, an extensive field test program was deemed necessary. Furthermore, a field test program was needed to insure that a hydroclone was compatible with base level systems and that the vortical field effects on the fluid were not detrimental. In order to extend and supplement the parameter studies completed on the initial contract for a 30 gpm hydroclone, a comprehensive parameter study was conducted to obtain a general design criteria for a family of hydroclones with different flow rates, pressure drops, and dirt holding capacities.

In order to implement this field program, a Test Plan was established and approved whereby field studies were schduled at Edwards AFB, California, and Tinker AFB, Oklahoma. This program involved the installation of a hydroclone kit at each Base and monitoring the hydroclone performance capabilities by the collection and evaluation of fluid samples. The hydroclone kits consisted of the prototype hydroclone developed during the first year of the contract and associated sample valves, hose fittings, and mounting brackets. The development of field sampling techniques were required as well as the verification of fluid sample analysis techniques.

The laboratory program consisted of performing a new series of parameter studies using hydroclones ranging in size from 0.75 to 1.50 in. in diameter and flow rates from 5 to 30 gpm. This laboratory phase required the verification of the optimality of the 30 gpm prototype hydroclone and a comprehensive experimental extension of the optimum configuration for various flow rates. This program represented a major part of the work of Supplemental Agreement No. 2 of contract 33 (657)-9958.

The test program to determine the contaminant generating characteristics of high pressure hose assemblies required the establishment of techniques whereby the results would be acceptable to all parties concerned. The proposed technique for obtaining quantitative information on the generation rate of contaminant from hose materials was by pulsing a liquid-filled hose sample. It was assumed that the subjection of materials to such dynamic conditions would be comparable to the conditions experienced in field operations. The complete test facilities were designed and constructed which necessitated a

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major analytic and experimental effort. The dynamic hose test facility consisted of an electro-hydraulic servo valve controlled by a signal generator which operated matched hydraulic cylinders that created the pressure pulses. The evaluation of the generated contaminant was made in the Oklahoma State University clean room. Both gravimetric and microscopic evaluations were performed on fluid samples obtained from static and dynamic tests. The static tests gave the amount of built-in contaminant and the dynamic tests gave the amount of generated contaminant.

The studies reported herein represent the work performed from January 3, 1964, through January 3, 1965. The hydroclone field program involved approximately nine months of work, and the hose study extended over the entire contract period.

SECTION II

HYDROCLONE FIELD INSTALLATIONS

A. INTRODUCTION

The prototype hydroclones designed and constructed under contract No. AF 33(657)-9968 were installed at two Air Force Bases to determine the suitability of a hydroclone of optimum configuration for the decontamination capabilities of standard hydraulic test stands. The application of hydroclones to ground service carts requires special consideration from an operation point of view in order to verify the compatibility of the hydroclone with the rest of the system and to establish the unit's general reliability. The prototype hydroclone required an extensive field test program to demonstrate its practical significance and such a field program had to be comprehensive in nature and conducted under actual operating conditions. For example, the hydroclone had to be extensively tested by using service-generated contaminants rather than conventional laboratory-type contaminant (AC test dust).

The prototype hydroclones which were designed for optimum performance at a flow rate of 30 gpm were installed on hydraulic test stands that were theoretically capable of delivering the required flow rates. The hydroclones were installed so that operation of the hydraulic test stands was not hindered during normal flushing use at the particular Air Force Bases.

B. INSTALLATION

Hydraulic test stands at Tinker AFB, Oklahoma and Edwards AFB, California were designated as the Air Force Bases where the prototype hydroclones were to be installed. The test stand used at Tinker AFB was a portable gasoline engine driven hydraulic test stand, Type MJ-1, designed to deliver 30 gpm flow at 3000 psi pressure. The hydraulic test stand is used by the Air Force for ground checking and maintenance of aircraft hydraulic systems. The stand can be used to flush or fill the hydraulic system independent of the aircraft pumps using filtered hydraulic fluid. The test stand used at Edwards AFB was a portable gasoline engine driven hydraulic test stand, Type MJ-2, designed to deliver 30 gpm at 3000 psi pressure.

The hydroclones that were installed on the hydraulic test stands were included in a kit which contained the necessary plumbing for the mounting of the hydroclone on the particular hydraulic test stands. The prototype hydroclone kits were composed of the hydroclone proper, sample valves upstream and downstream of the hydroclone, a mounting bracket, two five foot lengths of size 16 high pressure hose assemblies, replacement seals, and the necessary tools to install the unit on the test stand.

The hydroclone was mounted on the side opposite the control panel at the rear of the test stand and accessible to the high pressure flow line of the hydraulic test stand. (See Figures 1 and 2.) The high pressure hose "A" that normally was connected to the inlet of the high pressure filter was reconnected to the inlet of the hydroclone. The high pressure

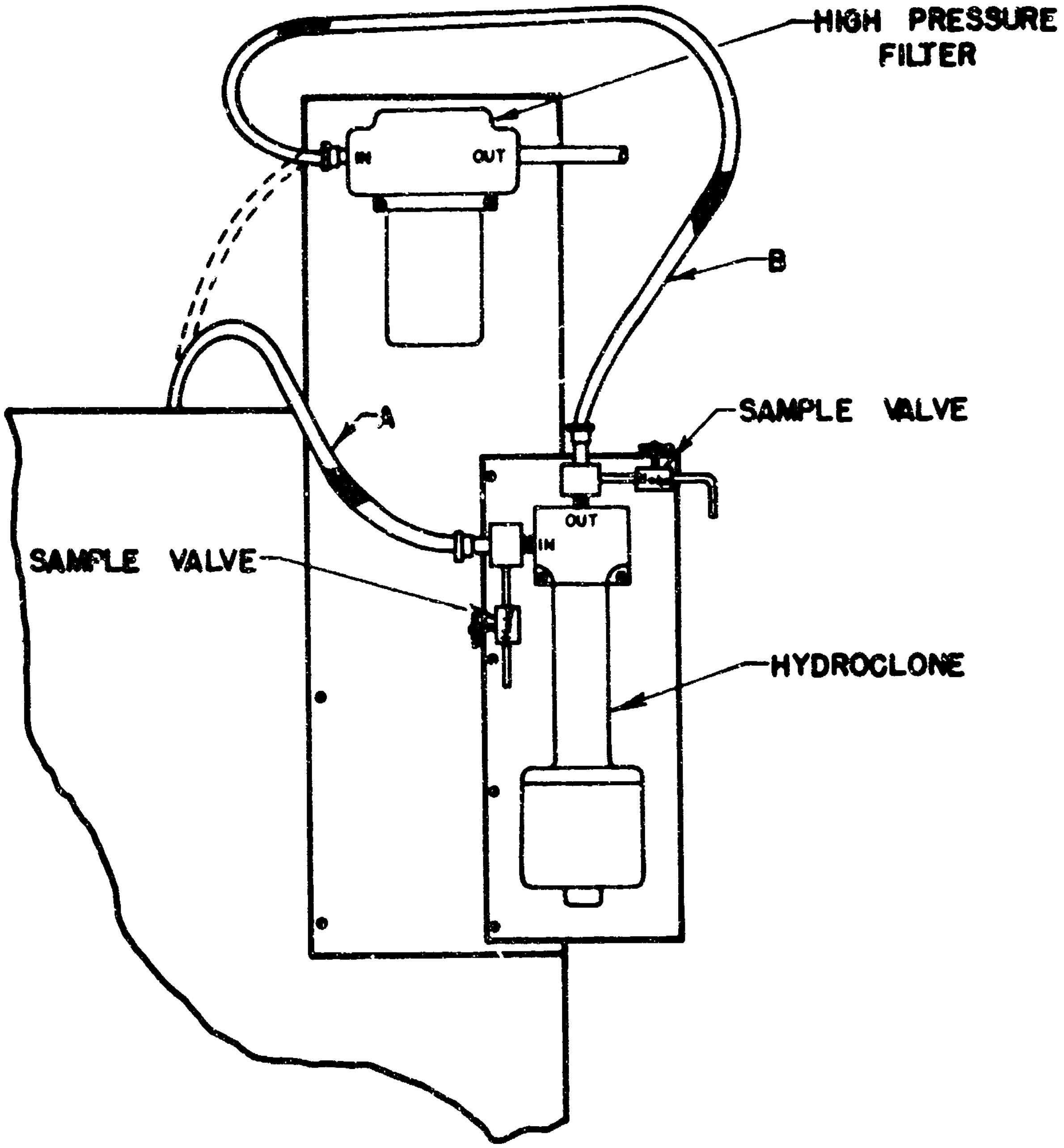

Figure 1. Installation of the Prototype Hydroclone Kit at Tinker Air Force Base, Oklahoma.

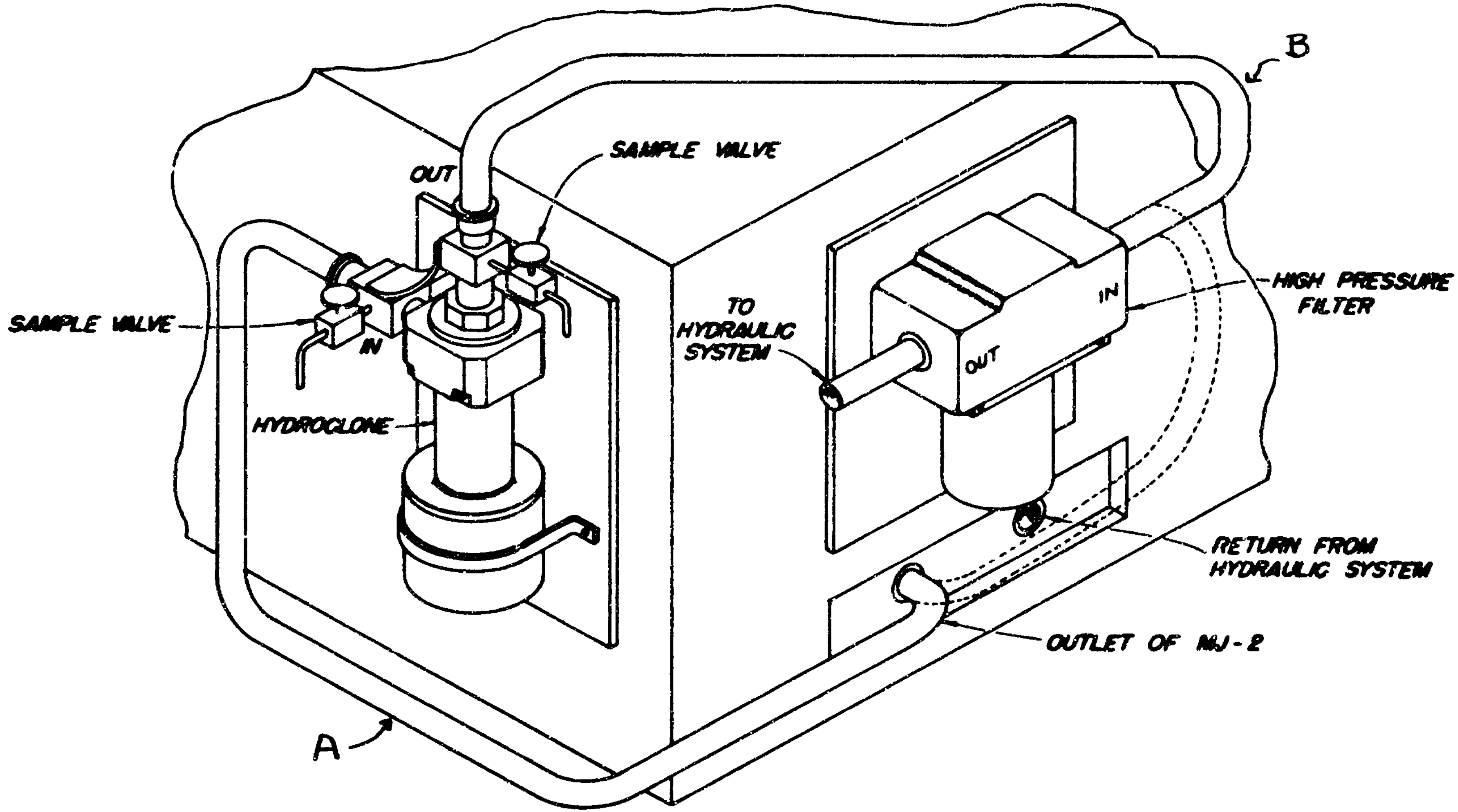

Figure 2. Installation of the Prototype Hydroclone Kit at Edwards Air Force Base, California.

"B" provided in the hydroclone kit was connected between the outlet of the hydroclone and the inlet to the high pressure filter. During the test periods, the hydraulic fluid was pumped from the hydraulic test stand reservoir by the low pressure boost pump through a 10 micron low pressure filter. (See Figure 3.) The fluid from the low pressure filter continued through the high pressure pump, a high pressure 10 micron filter, and the flow control valve. The fluid then passed from the flow control valve through the hydroclone, high pressure final filter, and then to the aircraft. The hydraulic fluid from the aircraft was pumped through the suction return inlet to the reservoir. During the sample collection periods, the high pressure hose, normally connected to the aircraft, was disengaged and connected to the low pressure return line.

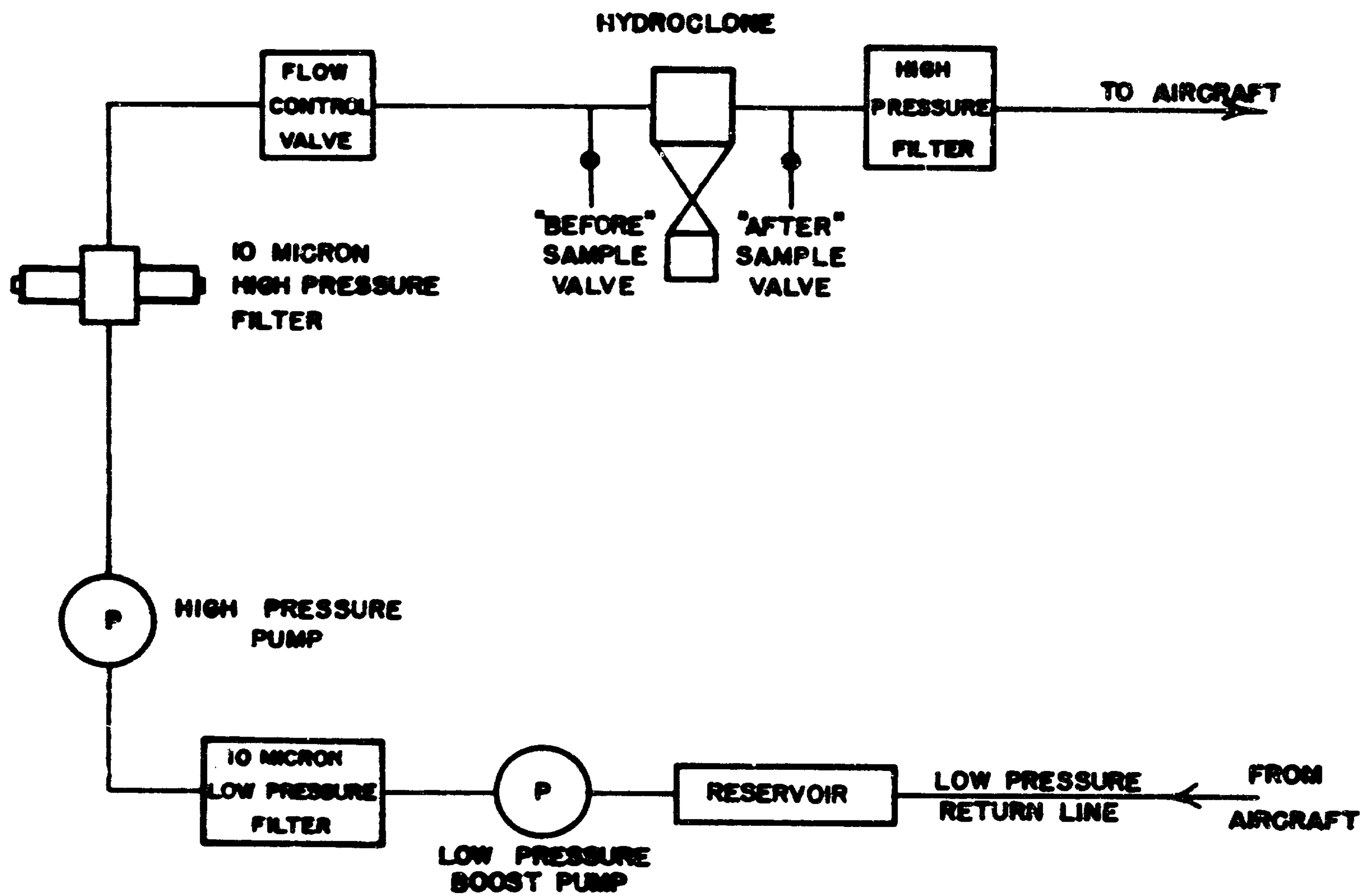

Figure 3. Flow Schematic of Hydraulic Test Stand

SECTION III

FIELD SAMPLE COLLECTION

A. INTRODUCTION

The determination of the hydroclone's performance based on laboratory analysis was quite extensive as evidenced by the final technical report RTD-TDR-63-4262 prepared under contract No. AF 33(657)-9958 by Oklahoma State University. However, the hydroclone's performance from field tests was needed to fully evaluate the hydroclone's capabilities under actual operating conditions. In order to evaluate an experimental unit of this type at various Air Force Bases, it was necessary to determine the amount of contaminant per unit volume of fluid, the number and size of the contaminant, and the type of contaminant that is prevalent in the system. Therefore, samples of fluid were acquired before the fluid entered the hydroclone and after the fluid left the hydroclone to determine the efficiency of the experimental unit. These samples of fluid were also used to determine the size, number, and amount of contaminant present before and after the fluid passed through the filtering unit.

The evaluation of fluid samples that are representative of the system under investigation was performed under pseudo-clean atmosphere so that the results of the tests would be meaningful. Perhaps the most important requirement was the cleanliness needed in the washing and packaging of sample containers that were transported to the field installation site and used in the collection of the fluid samples. Groups of sample bottles cannot be absolutely contaminant free but they can be cleaned to a specified known level and this "tare" or remaining contaminant can be subtracted from the number and size of particles found in the field samples after evaluation. This specified level of known size must be below the absolute rating of the experimental unit undergoing field tests. The sample containers must be sealed after the cleaning so that contaminant from the surrounding environment cannot enter the container when transported to the field installations.

The equipment used for the extraction of the fluid from the system to the sample containers was designed to minimize contaminant retaining orifices that would reduce flow as a result of "silting" and consequent filtering of the fluid that is being collected. The sample valves used to direct the fluid from the main flow line to the sample container were located at points where homogeneous solutions of fluid and contaminant were representative of the system's contaminant level. The introduction of contaminant into the sample bottles was minimized by washing down all components that came into contact with the sample containers during the collection period. The valves were flushed before taking a fluid sample and not adjusted throughout the collection period.

B. FIELD SAMPLE COLLECTION

1. Fluid Sample Container Cleaning and Packaging

The containers chosen for field sample collections were 500 ml glass screw cap bottles. The glass bottles were chosen for several reasons:

glass bottles were easier to clean to a specified low contaminant level, and approximately 500 ml of fluid was needed to perform the various tests on the fluid sample. The various tests performed on each sample were: viscosity reading, gravimetric analysis, particle count, and a microscopic examination of the contaminant in the fluid sample. The viscosity readings were needed to determine the effect of vortical fields produced in the hydroclone upon the viscosity. Particle counts of the upstream and downstream samples were used for the determination of the units separation efficiency while the gravimetric analysis determined the weight of contaminant before and after the fluid passes through the hydroclone. A microscopic examination of the contaminant collected on a filtrate pad was needed to determine the different types of materials found in the system such as metallic and fibrous particles. A 500 ml sample of fluid gave a sufficient amount of fluid for all the tests needed to evaluate the hydroclone performance in the field program.

The 500 ml screw cap bottles were the type with the small neck in order to expose the smallest area to external contaminant. The bottles and their caps were ultrasonically cleaned in a detergent solution to remove any residue and contaminant present in the bottle. The bottles and caps were rinsed with hot water to remove the detergent and set upon a rack to drain. They were then transported to the clean room where sub-micron filtered alcohol was used to flush any water that might be present in the bottles. The bottles and caps were then flushed with sub-micron filtered petroleum ether, Type F, to remove any contaminant. A four-inch square of polyethylene film 4 mils thick washed in sub-micron filtered petroleum ether was placed over each bottle neck and fastened with several rubber bands and the caps immediately screwed on tight. A small amount of petroleum ether was left in each bottle to provide vapor so that contaminant from the air would tend to be repelled when coming near the neck of the bottle. Nine sample bottles prepared in this manner were taken on each sample collection trip. Four samples upstream of the hydroclone were taken and four samples downstream of the hydroclone were taken while the ninth sample bottle was used for the determination of the contaminant level of a system that did not have a hydroclone.

2. Sample Collection Equipment

The equipment used for the sample collections consisted of the sample bottles described above and the sample valves located before and after the hydroclone unit. The sample valves were composed of three items: 1) A round-nosed probe extending into the main fluid stream located in the center of the main line, 2) a 1/8-in. ball valve for regulation of flow from the main line into the sample bottle, and 3) a 1/8-in. seamless tube sharpened at one end to direct the fluid from the sample valve into the sample bottle. Orifices were placed in the sharpened exterior probes so that the ball valves could be fully opened, thus eliminating the crescent-shaped orifice that results when the ball valve is slightly opened. (See Figure 4.) When high pressure systems are sampled and flow is directed through a slit or a small annular opening, flow will decrease due to "silting" and filter the fluid as the sample is collected. If the system is relatively dirty, flow will even cease because of the contaminant

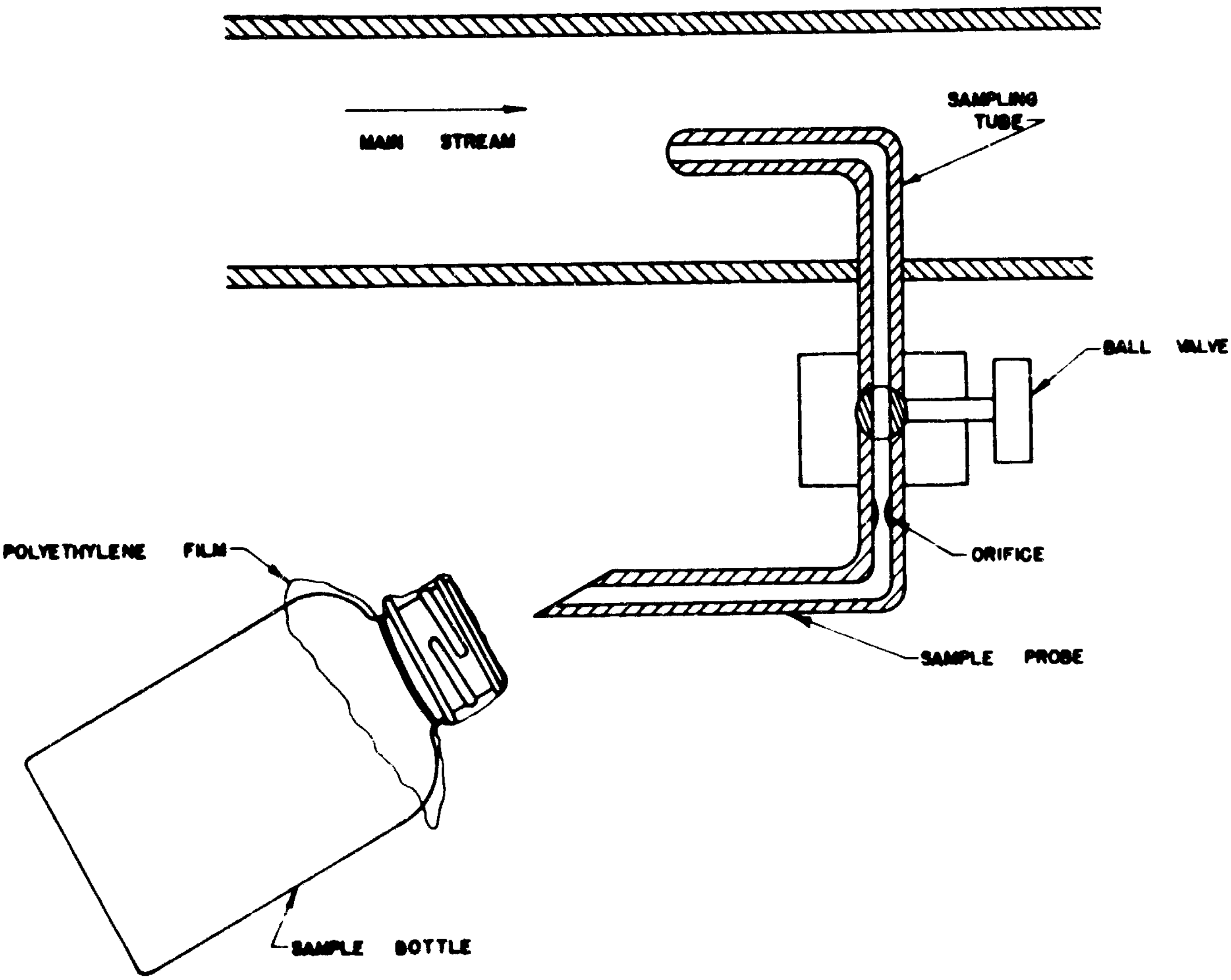

Figure 4. Field Fluid Sampling Apparatus.

blocking the opening. However, the systems that were sampled in the hydroclone field tests were relatively clean and at a pressure of 450 psi or lower, thus "silting" was not considered a problem in these tests. The pressure of 450 psi was the drop across the unit at maximum flow while the fluid was being circulated through the test stand during the sample collection period.

The collection of the fluid samples using the above described equipment is briefly given below:

(a) The high pressure hose normally connected to the aircraft during flushing operations was connected to the suction return line of the hydraulic test stand.
(b) Fluid was pumped through the hydroclone at 5 gpm and a sample taken upstream of the hydroclone after the sample valve had been washed with a sub-micron filtered solvent and thoroughly flushed by draining a pint of fluid without adjusting the valve.
(c) The flow control valve was then fully opened allowing maximum flow through the hydroclone and opening both sample valves.
(d) Samples upstream and downstream were taken simultaneously until the required number of samples, four upstream and four downstream, were collected.

Since the flow rates normally used for flushing operations were between 5 and 10 gpm, the first sample collected upstream of the hydroclone at a 5 gpm flow rate would represent a system that did not have a hydroclone.

C. EVALUATION OF SAMPLING EQUIPMENT

The equipment used for the collection of fluid samples from the field installation where the prototype hydroclones were being field tested is satisfactory for both field and laboratory results.

The method of sealing the sample bottles with a polyethylene film to keep out airborne contaminant gave very good results over the previous method of open sample bottles that were used in earlier field sample collection trips. Extreme care is not required when transportation to remote areas and relatively dirty environments are encountered. Perhaps the only "bad point" of this method is that although the probe that punctures the film covering of the bottle is washed with a sub-micron filtered solvent, it is still possible that contaminant from the air will stick to the probe and enter the bottle when the samples are taken.

SECTION IV

FLUID SAMPLE ANALYSIS

A. INTRODUCTION

Three methods of analysis were performed on the fluid samples that were collected in the prototype hydroclone field tests so that a comprehensive evaluation of the experimental unit would be accomplished. The three methods of evaluation were: 1) a gravimetric analysis of the fluid's contaminant, 2) a particle size distribution of the contaminant present, and 3) a microscopic examination of the contaminant. A comprehensive evaluation of the samples was necessary in order to determine the weight, number, size, and type of particles, since the hydroclone's theory of operation is based on the fact that the density of the particles must be greater than the density of the hydraulic fluid if an effective separation is to occur. The establishment of the separation characteristics for a wide range of particle densities such as iron, bronze, cotton, paper, and other service contaminants was needed to fully evaluate the performance of a hydroclone on a standard hydraulic test stand.

A gravimetric analysis of the fluid's contaminant before and after it flowed through the hydroclone was needed to determine the separation characteristics for service-generated contaminant. A particle count on the fluid upstream and downstream of the hydroclone was needed to determine the efficiency of the unit under field conditions and the distribution of service-generated contaminant. A microscopic examination of the fluid's contaminant was performed to determine the types of service-generated contaminant found in the fluid samples and to give some insight or correlation between the gravimetric results and particle counts of the upstream and downstream fluid samples.

B. TEST PROCEDURE

1. Gravimetric Analysis

The determination of the weight of contaminant per unit volume or gravimetric analysis was performed in the Fluid Power and Controls Laboratory's clean room located in the Mechanical Engineering Laboratory. All equipment used in the analysis of these samples was cleaned in an ultrasonic tank using a standard solvent and rinsed with hot water before being rinsed with sub-micronic filtered standard solvent. The following procedure was used for determining the gravimetric analysis of the fluid samples that were taken from the prototype hydroclone during the field test program:

(a) A filter pad was placed in a glass petri dish and heated in a vacuum oven to remove moisture.
(b) The pad was then placed on an analytic balance and weighed.
(c) The pad was placed on a vacuum filter press and a measured volume of the fluid sample was filtered.
(d) A standard sub-micron filtered solvent (petroleum ether) was used to wash down the periphery of the pad and the walls of the filter press funnel.

(e) The pad was removed to a vacuum oven and heated to evaporate all moisture.

(f) The pad was then weighed again.

The amount of contaminant per unit volume was then determined by subtracting the initial and tare weight from the final weight.

2. Particle Count

The number and size of contaminant in the fluid samples were determined by the use of an HIAC Automatic Particle Counter. The fluid sample bottles could be attached directly to the particle counter thus minimizing the error due to airborne contaminant. The path of the fluid sample was purged with sub-micron filtered solvent before each sample was evaluated on the counter. The particle count registers were calibrated at 6, 11, 15, and 20 microns prior to each group of samples to be tested. Air pressure was applied to the samples and regulated to control the flow through the counter. Three sets of counts for each fluid sample were made and the average of these counts was recorded as the number of particles per unit volume of fluid.

3. Microscopic Examination

The microscopic examination to determine the separation characteristics of particles such as iron, bronze, cotton, paper, and other service contaminants was conducted in the clean room of the Fluid Power and Controls Laboratory. The filtrate pad was scanned using a 100 power magnification on the microscope and recording the largest particles found in the various categories of materials.

C. RESULTS OF ANALYSIS

1. Gravimetric Analysis Results

The results of the analysis obtained from the field samples taken at Edwards AFB are most encouraging from the standpoint of using hydroclones for upgrading the decontamination capabilities of the hydraulic system in USAF ground support equipment. Even with the low flow rates that were used for flushing the various systems of the aircraft, the hydroclone was able to reduce the contaminant to a constant level and maintain this level throughout the test program. The gravimetric results from the tests conducted at Edwards AFB in order of which they were obtained are as follows:

Sample	Upstream Mg/L	Downstream Mg/L	Difference Mg/L
1	31.6	10.6	21.0
2	33.9	10.9	23.0
3	15.2	12.5	2.7
4	11.7	11.2	0.5
5	8.6	8.6	0
6	12.3	11.2	1.1
7	7.9	11.0	-3.1
8	10.2	10.2	0

The negative difference shown for fluid sample number 7 can be attributed to either an error in the analysis procedure or the fact that the sample bottle was not clean prior to the fluid sample. The tests were conducted at 24.8 gpm which was the maximum flow rate that could be achieved from the hydraulic stand and were taken by connecting the outlet of the high pressure filter to the return line of the hydraulic test stand. Therefore, the samples were collected by circulating the fluid within the hydraulic test stand proper and this accounts for the fluctuating readings as the fluid samples were taken. In effect, the flushing of the test stand reservoir and system was being accomplished as the fluid samples were taken. It would almost be impossible to collect fluid samples during flushing operations of an aircraft because of the intermittent flows that are used. The tests indicate that the hydroclone will reduce and maintain the contaminant level of the fluid below 11.2 mg/l at 24.8 gpm. Based upon laboratory studies, it has been verified that a significant reduction in the contaminant level would be achieved if the flow rate was 30 gpm which must be obtained for optimum separation efficiency with the prototype hydroclone.

The results of the analysis of the field fluid samples obtained at Tinker AFB, Oklahoma were not as good as the results obtained at Edwards AFB. The microscopic analysis of the samples from Tinker AFB showed a tremendous number of small particles below 5 microns that were olive green in color and would not settle out in the fluid. The majority of the field fluid samples was taken after the hydraulic test stand had been completely overhauled. Consequently, since Tinker AFB maintenance personnel mainly use the Sprague hydraulic test stand Model 1127-100 which is capable of delivering 20 gpm maximum flow, the hydroclone was not subjected to many hours of operation. In fact, in the last two months of the testing program, only 6 hours of operation were recorded; and a large percentage of those was recorded by OSU personnel acquiring fluid samples. A partial list of the gravimetric analysis results from the tests conducted at Tinker AFB in the time order that they were obtained is as follows:

Sample	Upstream Mg/L	Downstream Mg/L	Difference Mg/L
1	32.8	24.5	8.3
2	33.0	20.5	12.5
3	12.5	13.1	-0.6
4	12.1	13.5	-1.4
5	11.8	10.0	1.8
6	10.6	7.7	2.9
7	10.7	14.[illegible]	-3.3

The results that are shown above were taken over a period of 60 days with only 6 hours of actual operating time on the hydraulic test stand. The gravimetric analysis of the samples shows that the contaminant level of the hydraulic test stand was reduced from 33.0 mg/l to around 10.7 mg/l and maintained at this level. The negative difference readings of the upstream and downstream samples can be attributed to test procedure errors or "dirty" sample bottles, but the results do show the contaminant level of the hydraulic test stand.

The gravimetric analysis of the samples obtained from Tinker AFB and Edwards AFB shows that hydroclones will reduce the contaminant level of a hydraulic system to a certain level and maintain this level. This reduced constant contaminant level depends upon the percentages of the various types of contaminants that are present in the system.

2. Results of Particle Counts

The separation efficiency of the prototype hydroclone as determined by using the particle counts from the field samples gave no indication of the hydroclone performance. Gravimetric data and corresponding particle count data from several of the samples taken at Tinker AFB and Edwards AFB are as follows:

Gravimetric Analysis, Mg/L

	Before	After	Microns	Before	After
(1)	31.6	10.6	6	3523	7636
			11	1117	3020
			15	103	262
			20	47	121
(2)	12.3	11.6	6	1591	2514
			11	194	603
			15	52	138
			20	16	33

The gravimetric analysis of these samples clearly indicated that excellent separation occurred whereas the particle count increased for the specific micron sizes. A microscopic examination of the fluid samples indicated the presence of water in the hydraulic fluid. The results of laboratory research performed at Oklahoma State University have shown that particle counts are much higher when water is present in the hydraulic fluid. Similar results have been achieved by the NASA group at Oklahoma State University in their study of sampling techniques and also by manufacturing representatives of the HIAC Particle Counter. Furthermore, it has been shown that water present in the hydraulic fluid and forced through the hydroclone is finely divided into many smaller particles thus displaying more particles downstream than upstream. The presence of water will not appear in the gravimetric weight since the pads are heated in a vacuum oven in the process of determining the gravimetric analysis. In future tests where the particle count of the fluid samples is needed, the samples will be placed in a heated environment at a predetermined temperature and with a vacuum applied to the fluid sample to boil off any water that is present in the hydraulic fluid. Particle size distribution curves for laboratory and field samples are given in Figure 5.

3. Microscopic Analysis Results

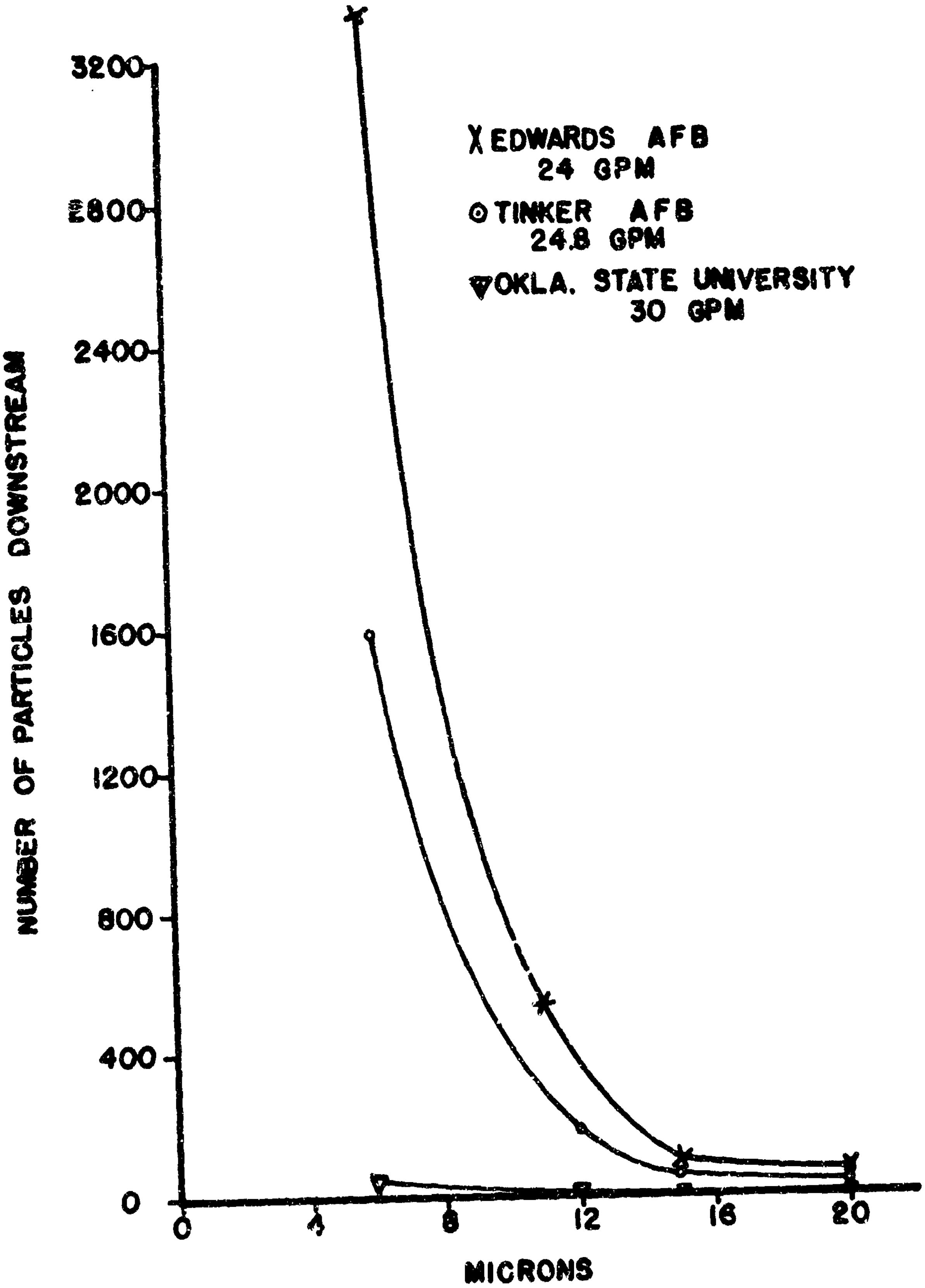

Figure 5. Particle Size Distribution Curves.

An examination of the filtrate pads from the field samples showed that essentially all large particles were fibers of cotton and paper. A complete list of the largest particles of various materials found in the fluid samples is given in Table 1.

TABLE 1

LARGEST PARTICLE SIZES IN FIELD SAMPLES, MICRONS

	Tinker AFB		Edwards AFB	
	Up	Down	Up	Down
Iron	none observed above 5 microns			
Bronze	200	----	----	----
Paper	500, 300, 500 400, 200, 100 200, 200, 500	300, 300 100, 100	300, 100 200, 200	600, 200
Fiber (a) Plastic	200, 200, 150 200, 100, 100 50	25, 300, 50 75, 50	500, 200, 300 200, 100	600, 100, 200 100, 100, 300 100, 200, 100 50
(b) Cotton	none observed above 5 microns			
Carbon	25, 25	50, 100, 30 50	200	----
Aluminum	50, 50	100, 50, 25 100	150	----

SECTION V

FILTRATION COMPARISON TESTS

A. INTRODUCTION

A test program to compare the filtration characteristics of the Oklahoma State University hydroclone prototype and a conventional filter conforming to Air Force Specification MIL-F-27656 was an integral part of the current contract. To help understand the difficulty in making such a comparison, an outline of the comparable characteristics of the hydroclone and filter is presented in Table 2.

TABLE 2

COMPARABLE UNIT CHARACTERISTICS

Characteristic	Filter	Hydroclone
1. Dirt Holding Capacities	Limited by unit size	Large
2. Micron Rating	Absolute or nominal	Nominal-dependent on contaminant density
3. Cleanability	Not at air base level	Cleaned anywhere
4. Reliability	Plugs by nature of its function	Non-plugging
5. Flow-Pressure Relationship	Low initial pressure drop, increases with loading	High initial pressure drop, constant with loading
6. Compatibility	Variable flow rate	Requires constant flow rate for optimum separation
7. Cost	High initial, expensive maintenance	Low initial, maintenance negligible
8. Maintenance	Short interval, routine change of elements	Long interval, routine cleaning of collection chamber
9. Size	Low ratio of dirt capacity to unit size	High ratio of dirt capacity to unit size

An examination of this table indicates that no general comparison can be made since the hydroclone principle of filtration varies considerably from that of a conventional filter. A close study of this table clearly indicates that if the factors influencing the selection of a filtration unit are limitless dirt holding capacity, low initial cost, excellent cleanability, removal or normal contaminants generated with a hydraulic system (iron, copper, brass, etc.), then the hydroclone theory of filtration will provide a very excellent means of filtration. On the other hand, if the selection is to be based on the absolute separation of low density particles such as cotton and paper fibers then a filter conforming to Air Force Specification MIL-F-27656 provides an excellent means of filtration. However, associated with this filter are the ever present problems of reconditioning (recleaning, bubble point, packaging, etc.) and short interval routine changing of filter elements.

With these thoughts in mind, a comparison test program was designed to supplement the facts presented in Table 2 which was compatible with standard filtration evaluation tests set up by various government organizations. One of these standard tests is the Air Force Specification MIL-F-27656 which is the qualification procedure for an absolute 5 micron hydraulic filtration unit.

B. COMPARISON TEST PROCEDURE

Before an extensive efficiency study could be made, a test procedure had to be designed to assure realistic and repeatable results. The test program conducted was patterned after the hydroclone performance test program. The hydroclone test program was basically one of determining the contaminant removal efficiency of the unit by sampling both upstream and downstream of the hydroclone when subjected to a system loaded with artificial contaminants. All efficiency tests were made in the following order:

1. Before any test was started, the hydraulic fluid was circulated through control filters until a steady state value of particle count background had been obtained.
2. Once the background of the system had been reduced to this level, the unit to be tested was placed in the test section.
3. The test temperature of the hydraulic fluid was set and maintained at 100 ± 2°F.
4. Viscosity of the oil was determined and was within the acceptable range as required by Air Force Specification.
5. Iso-kinetic samplers were then placed directly upstream and downstream of the filter element.
6. Artificial contaminant was then mixed into a slurry by applying ultrasonic vibration to the oil and contaminant mixture.
7. This slurry was then mixed with three gallons of prefiltered hydraulic oil and placed in the injection chamber which had been previously cleaned and flushed with prefiltered hydraulic oil.
8. The injection time was then set for 10 minutes.
9. Hydraulic fluid was circulated (30 gpm) through the test element and 500 ml fluid samples were taken both upstream and downstream of the filter element before contaminant injection was started. After the contaminant injection was in progress, fluid samples were then taken simultaneously from both upstream and downstream samplers of the test unit at 2 minute intervals for 10 minutes and then every 5 minutes for 20 minutes.

C. COMPARISON TESTS

Tests were performed on both units using contaminants specified in Air Force Specification MIL-F-27656. These contaminants were standardized coarse air cleaner (AC) test dust and carbonyl iron E. The following tests were performed on the hydroclone and filter element:

Test No. 1

This test consisted of mixing 10 grams of carbonyl iron E in a slurry mixture and injecting this amount upstream of the filter element during a 10-minute injection period. The results of this test are given in Table 3.

Test No. 2

Test No. 2 consisted of placing the prototype hydroclone in the test section of the hydraulic stand and subjecting it to the same contaminant mixture as specified in Test No. 1. The results of this test are given in Table 4.

TABLE 3

Origin of Sample - Filter Conforming to Air Force Specification MIL-F-27656 - Contaminant Carbonyl Iron E

PARTICLE COUNT ANALYSIS (HIAC)

Particle Diameter (Microns)	Particles Above Specified Diameter		
	Upstream Avg.	Downstream Avg.	Efficiency
3 minutes			
6	9,148	530	94.2%
10	395	61	84.6%
15	16	2	87.5%
20	12	1	91.7%
6 minutes			
6	16,949	356	97.9%
10	1,385	92	93.3%
15	36	1	96.7%
20	20	0	100 %
9 minutes			
6	15,602	0	100 %
10	1,199	0	100 %
15	21	0	100 %
20	11	0	100 %

GRAVIMETRIC ANALYSIS

	Upstream	Downstream
Test No. 1	12.6 mg/l	10.6 mg/l
Test No. 2	30.6 mg/l	12.2 mg/l

TABLE 4

Origin of Sample - Prototype Hydroclone - Contaminant, Carbonyl Iron E

PARTICLE COUNT ANALYSIS

Particle Diameter (Microns)	Particles Above Specified Diameter		
	Upstream Avg.	Downstream Avg.	Efficiency
6	7,861	573	92.7%
10	300	0	100 %
15	5	0	100 %
20	2	0	100 %
6	16,188	41	99.7%
10	1,199	0	100 %
15	21	0	100 %
20	11	0	100 %
6	12,481	97	99.7%
10	851	0	100 %
15	17	0	100 %
20	8	0	100 %

GRAVIMETRIC ANALYSIS

Upstream	Downstream
19.6 mg/l	7.3 mg/l

Test No. 3

Test No. 3 consisted of mixing 20 grams of standardized coarse air cleaner (AC) test dust in a mixture of MIL-F-5606 hydraulic oil and injecting this amount of contaminant upstream of the filter element during a 10-minute injection period. The prototype hydroclone was then checked in the same manner. The results of these two tests are given in Table 5.

TABLE 5

GRAVIMETRIC ANALYSIS

Origin of Sample - Filter Conforming to Air Force Specification MIL-F-27656 - Contaminant AC Coarse Test Dust

Upstream	Downstream
21.7 mg/l	14.2 mg/l
30.6 mg/l	12.2 mg/l

Origin of Sample - Prototype Hydroclone - Contaminant, AC Coarse Test Dust

Upstream	Downstream
22.2 mg/l	9.2 mg/l

D. RESULTS AND CONCLUSIONS

In this section representative data from both filtration units show excellent results with both contaminants used. These results will be discussed in this section of the report.

Test No. 1 consisted of injecting 10 grams of carbonyl iron E during a 10-minute period upstream of the filter unit. The particle count efficiency of this test is given in Table 3. A close examination of these results shows that the efficiency drops in the 10 and 15 micron sizes. This decrease in efficiency of the filter unit in the 10 micron and 15 micron range can be attributed to the lower number of particles being counted in these size ranges. The somewhat higher efficiency at the 6 micron range may be attributed to the higher number of 6 micron particles available in the artificial contaminant. With this high number of particles being injected, errors due to sample preparation and bottle cleanliness are minimized. The somewhat unexpected lower efficiency in the 10 micron, 15 micron and 20 micron ranges may be attributed to the lower number of particles being counted in both the upstream and downstream samples. To make a more exact study, a higher number of particles in these size ranges should be added to the standard contaminants in order to minimize errors due to residual contaminants in sampling equipment.

Examination of the efficiency results given in Table 3 for the three periods of sampling indicate an increase in efficiency of the filter unit as it collects contaminant. This is understandable in that the filter is gradually becoming more efficient as the contaminant builds up around the filter element.

Results using the prototype hydroclone with carbonyl iron E as contaminant (see Table 4) show that the efficiency of this unit is as good a filtration unit as the filter with which it was compared. The efficiency of the hydroclone remains constant with respect to time under the conditions as set forth in the test procedure.

Gravimetric results of both units using carbonyl iron E as a contaminant clearly show that the hydroclone is the better filtration unit. Gravimetric results are the result of passing the contaminant through the filtration unit only once and do not represent the filtration unit's capacity as a function of time. The downstream analysis of the hydroclone was 7.3 mg/l as compared with 10.6 mg/l and 12.2 mg/l for the filter. Similar results have been obtained in the field testing program, which was part of this contractural agreement. The hydroclone theory of operation is based on the ability of the unit to separate particles whose density is greater than the fluid in which they are entrained. Carbonyl iron E, which was used for this test, is such a contaminant and verifies the results of the field and laboratory data. Some question may arise since the efficiency of both units is comparable, but the gravimetric results are not comparable. This can best be explained by careful consideration of the hydroclone theory of operation. Although the absolute efficiency of the hydroclone unit may only be 5 microns, any smaller particle whose density is greater than that of the fluid will have a certain effective separating efficiency. It is, therefore, safe to assume that particles less than 5 microns have a significant separating efficiency with the hydroclone. Also, if the contaminant used has a number of particles of smaller size than the unit is rated, a somewhat higher gravimetric result will occur on the filter. This higher figure may be attributed to the large number of particles smaller than the absolute rating of the unit. Such was the case with the filter tested. Gravimetric results given in Table 3 indicate that, as the concentration of contaminant upstream is increased from 12.6 mg/l to 30.6 mg/l, the downstream gravimetric analysis increases from 10.6 mg/l to 12.2 mg/l for the filter.

Gravimetric results using standardized coarse (AC) test dust are presented in Table 5. The downstream analysis of the hydroclone was 9.2 mg/l as compared with 14.2 mg/l and 12.2 mg/l for the filter unit. However, the downstream gravimetric results did not increase with an increase in upstream concentration as with the carbonyl iron E contaminant. This may be attributed to the size distribution of the (AC) coarse test dust.

SECTION VI

LABORATORY AND FIELD SUPPORT STUDIES

A. INTRODUCTION

The laboratory and field support studies that were performed in conjunction with the field testing of the prototype hydroclone were: 1) hydroclone compatibility with the standard hydraulic test stand systems; 2) hydroclone vortex field effects on the hydraulic fluid used in the system; 3) the determination of the endurance limits, reliability, and service life of the critical hydroclone components; and 4) the verification of the maintainability of the hydroclone.

The introduction of new equipment into a system that is presently used for flushing aircraft systems always raises the question of whether the new equipment is compatible with the system that it is installed upon. To be compatible, the new equipment must be able to perform its designed function and not interfere with the normal procedures and operations of the hydraulic test stand.

Because of the large centrifugal forces and high shear stresses applied to the fluid as it passes through the hydroclone, a study was conducted to determine whether the hydroclone vortex field would have an effect on the hydraulic fluid used in the test stands. A long range record of the viscosity was needed from the field test program to determine if any changes in the viscosity of the hydraulic fluid occurs as a result of introducing the hydroclone in the hydraulic test stand system.

The erosive action of contaminant entrained in the hydraulic fluid upon the critical components of the hydroclone could result in the damaging of the components and considerably reduce the separation efficiency of the hydroclone. The critical components that are susceptible to erosive action in the hydroclone are: 1) the inlet or vortex ring, 2) the cone liner, and 3) the overflow nozzle. A field study was necessary to determine what effect service contaminant had upon the critical components.

The determination of the maintainability of the hydroclone from field tests was mainly a task of observing the unit under test conditions and a periodic inspection of the hydroclone components throughout the test program to determine wear characteristics.

B. LABORATORY AND FIELD SUPPORT TEST PROCEDURES

1. Hydroclone Compatibility

The determination of the compatibility of the hydroclone with the standard hydraulic test stand system consisted of observing the hydroclone during flushing operations and discussions with personnel who use the hydraulic test stands for various purposes such as flushing aircraft hydraulic systems, filling the systems with micronically filtered hydraulic fluid, and providing a source of hydraulic pressure for testing hydraulic systems and components.

2. Hydroclone Vortex Field Effects

Each group of fluid samples taken at Edwards AFB and Tinker AFB was analyzed at the Oklahoma State University Fluid Power and Controls Laboratory to determine the viscosity of the hydraulic fluid. A Brookfield Synchro-Lectric Viscometer was used to determine the viscosity of the groups of samples from the field installations.

3. Endurance Limits, Reliability, and Service Life of Hydroclone Critical Components

The test procedure for evaluating the endurance limits, reliability, and service life of the hydroclone critical components consisted of a periodic inspection of the inlet ring or nozzle, cone liner, and overflow nozzle. The prototype hydroclone located at Tinker AFB was chosen since it was relatively near the research laboratory and could be returned after an examination of its critical components.

4. Hydroclone Maintainability

Observations of the prototype hydroclone were used for the verification tests of the hydroclone's maintainability. A periodic examination of the hydroclone seals and the amount of contaminant in the collection chamber was the main part of the test procedure.

C. RESULTS AND CONCLUSIONS

1. Hydroclone Compatibility

In order for a hydroclone to be compatible with a hydraulic test stand, the flow rate used in the various operations that the test stand performs must be equal to the flow rate for which the hydroclone is designed. The flow rates used at Tinker AFB and Edwards AFB for flushing procedures were only 1/6 to 1/3 of the flow rate for which the hydroclone was designed. The theoretical maximum flow rate of the hydraulic test stand is 30 gpm at a pressure of 3000 psi. However, the systems of the aircraft are approximately 5 to 10 gpm, depending on the aircraft; and flow rates of the same magnitude are used in the flushing operations.

Maintenance personnel at Tinker AFB and Edwards AFB indicated that if a hydroclone was designed at a flow rate of 15 gpm it could be used quite extensively in the flushing operations.

2. Hydroclone Vortex Field Effects

The flow rates used in the flushing operations of the aircraft systems produced pressure drops of only 10 to 50 psi at the corresponding flow rates of 5 to 10 gpm. The viscosity readings from the different sampling trips varied from one trip to another indicating that the hydraulic fluid was being mixed as a result of flushing various aricrafts and adding new oil to replenish leakage that occurred. The pressure drops that were encountered during the field tests of the hydroclone were not of a large magnitude that would affect the viscosity. Research laboratory tests of pressure drops of several hundred times the magnitude as those encountered in the field tests have been performed with no indication of viscosity changes.

3. <u>Endurance Limits, Reliability, and Service Life of Hydroclone Critical Components</u>

The periodic examination of the critical hydroclone components (inlet nozzle or ring, cone liner, and overflow nozzle) revealed that the erosive action of the entrained contaminant of the fluid at the low flow rates did not have any damaging effect on the components. The anodized surface of the inlet ring and overflow nozzle was not scored by the action of the contaminant against the hydroclone surfaces. With flow rates of only 5 to 10 gpm and corresponding pressure drops of 10 to 50 psi, the forces exerted on the particles to propel them to the walls for removal to the collection chamber were of a very small magnitude; and the resulting erosive action was trivial.

4. <u>Hydroclone Maintainability</u>

A periodic examination of the contents of the collection chamber revealed a small amount of contaminant had been removed in the field tests. This can be attributed to the fact that a low flow rate was normally used; and the separation efficiency of the hydroclone was not optimum. Also, the hydroclone was located in a test circuit that contained two filters with a 10-micron rating and a filter whose absolute separation was below 5 microns. Therefore, the hydroclone was handicapped in respect to collecting a large amount of contaminant.

SECTION VII

HYDROCLONE VERIFICATION AND QUALIFICATION TEST PROCEDURE

A. INTRODUCTION

Several methods of evaluation of a hydroclone's performance have been used at Oklahoma State University both in field and research laboratory installations. The qualification requirement for a hydroclone is that its flow rate and pressure drop at a specific fluid viscosity are within the limits set by a given specification. In addition, the particles from an artificially injected contaminant (less than or equal to the absolute rating of the hydroclone for that contaminant) must not appear downstream of the hydroclone. Therefore, a system that is to be used for the verification of hydroclone performance for quantity-produced units must be able to regulate the flow, background particle size, and temperature and have some method of determining the size of particles found downstream of the hydroclone. A filtering system upstream of the contaminant injector must be able to remove all particles greater than or equal to the rating of the hydroclone. Several methods that can be used to determine the size of particles downstream of the hydroclone are: 1) in-line particle counter such as a HIAC Automatic Particle Counter used at Oklahoma State University; 2) "Bomb Sampling Kit" manufactured by Millipore; and 3) sample valves and sealed sample containers such as used in the field sample collection of this hydroclone testing program. Figure 6 shows the three types of apparatus used for fluid sample evaluation. The in-line automatic particle counters give a complete closed system which eliminates error due to environmental conditions and must be considered as one of the better methods of evaluation. The "Bomb Sampler Kit" is an in-line sampler that uses a special sealed packaged filtrate pad and a by-pass system to collect the contaminant. A microscopic examination of the filtrate pad is used to determine the size of particles passed by the unit. The method used in the field sample collection program consists of samplers mounted on the downstream side of the hydroclone and bottles cleaned and packaged in a clean room. This method is not recommended if a clean room is not available since extreme cleanliness must be exercised in the washing and packaging of the sample containers and the background contaminant level of the sample bottles must be known. The fluid samples collected by this method can be counted on an automatic particle counter or can be filtered through a filtrate pad and the contaminant counted under a microscope.

B. TEST STAND REQUIREMENTS

The requirements of a test stand to evaluate a hydroclone's performance are:

1. A high pressure pump large enough to supply the flow rate for the particular hydroclone to be tested;
2. A flow control valve to regulate the fluid to the hydroclone within ± [illegible]% of the rated flow of the hydroclone;
3. A high pressure filter with an absolute rating less than the absolute rating of the hydroclone;

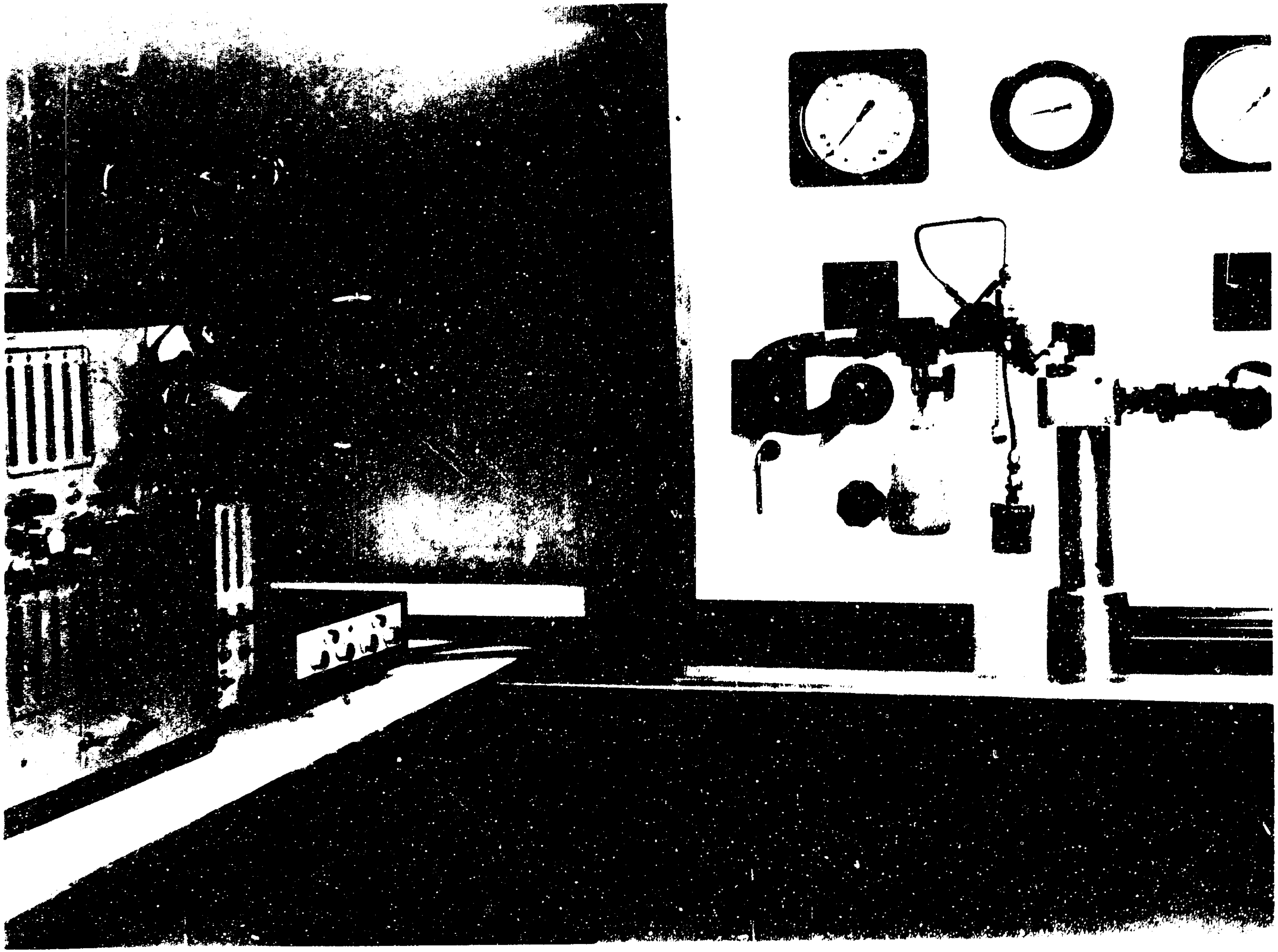

Figure 6. Apparatus for Collection and Evaluation of Fluid Samples.

4. A method of temperature control to maintain the fluid upstream of the hydroclone at ± 2°F of the specified temperature for the test;
5. A differential pressure measurement instrument across the hydroclone with an accuracy of 1% of the pressure drop across the hydroclone;
6. A system to inject a contaminant slurry into the main system downstream of the high pressure filter. The injection system reservoir should have a capacity of 10 gallons and a continuous method of stirring the mixture of fluid and contaminant at a rate of 12 revolutions per minute;
7. A flow meter;
8. A method of determining the largest injected artificial particle found downstream of the sample such as an in-line particle counter, in-line sampler, or a combination of sample valve and sealed fluid containers.

A flow schematic of a test stand using these components is shown in Figure 7. All three of the methods for the determination of the largest injected particle described in this section have been used at Oklahoma State University in conjunction with a test stand of this type and the results are comparable.

C. TEST PROCEDURE

The recommended test procedure using the above test equipment is as follows:

1. Mix 5 grams of artificial contaminant with 1 quart of test fluid to form a slurry.
2. Pour the above slurry into the 10 gallon injection reservoir and add prefiltered fluid that has an absolute rating smaller than the hydroclone until the reservoir is filled.
3. Start the motor of the injection reservoir stirring mechanism and operate 15 minutes before injection.
4. Start the injection pump and regulate the flow to the main system at 1 gpm.
5. Adjust the flow control valve until the flow through the hydroclone is [illegible]% of the rated flow of the hydroclone.
6. Adjust the temperature controller to ± 2°F of the test temperature.
7. Record the differential pressure which must be within the upper limit set by the designer.
8. If steps 5, 6, and 7 are satisfied, then proceed to step 9. If steps 5, 6, and 7 are not satisfied, the hydroclone must be examined to determine the cause of malfunction.
9. Evaluate the downstream fluid by one of the three methods given below:
   (a) in-line counter - No particle larger than the absolute rating of the hydroclone should appear on the display register.
   (b) in-line sampler - A microscopic examination of the filter pad using the ARP 598 method should reveal no particles larger than the absolute rating of the hydroclone.
   (c) sample valve and sample containers - Evaluate the sample with the use of an automatic particle counter and/or a microscopic examination of the filter pad of the fluid sample. The tare of the sample bottles must be subtracted from the count recorded by the counters or the ARP 598 count procedure.

The procedure for the operation of the in-line counters and in-line samplers is provided by the manufacturers of their products.

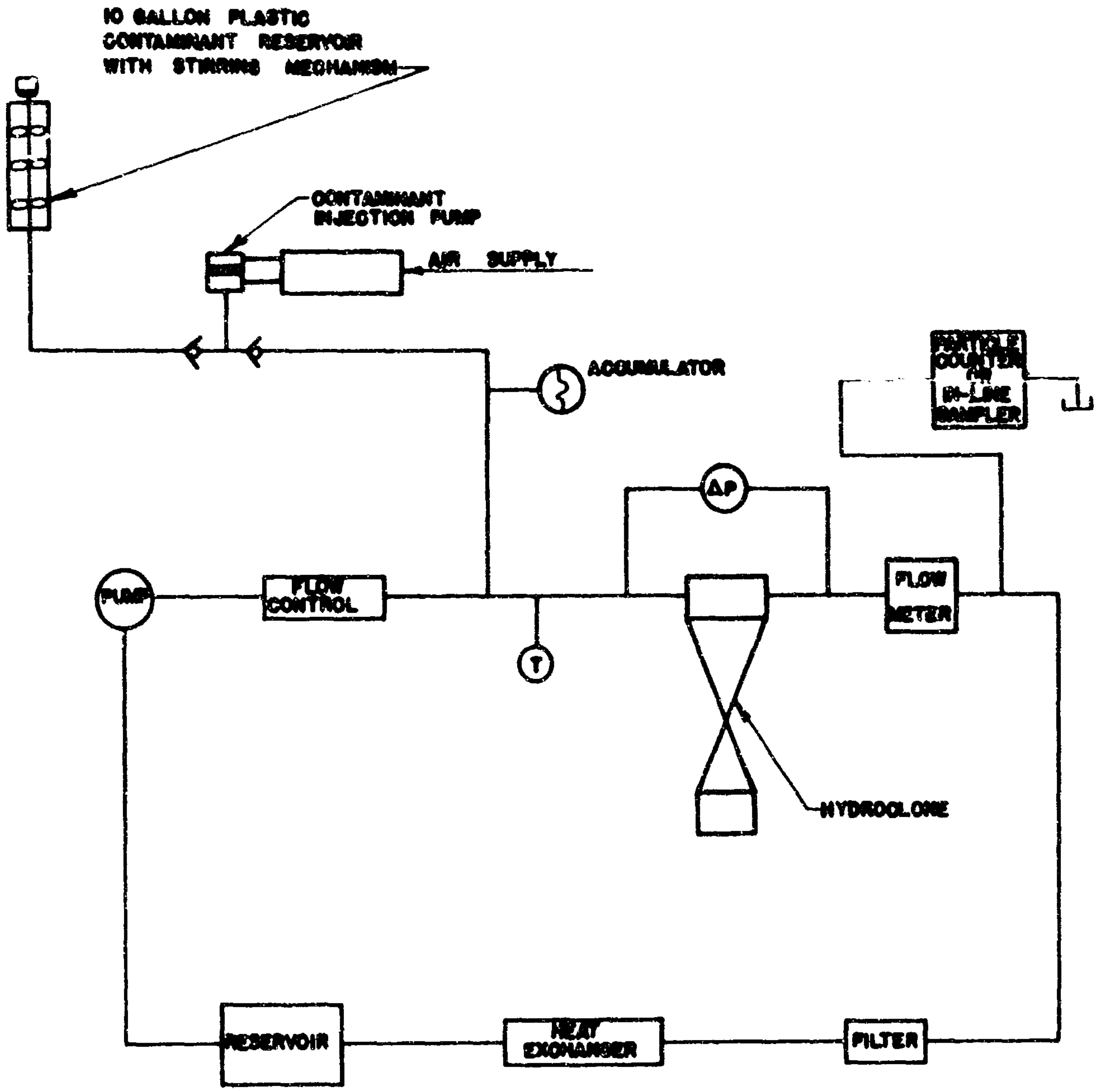

Figure 7. Proposed Test Flow Circuit.

D. EVALUATION OF TEST PROCEDURE

The above test procedure and the three different methods of evaluation were used at Oklahoma State University in the hydroclone evaluation test program. The results of all three methods were comparable and particles equal to or larger than the absolute rating of a particular hydroclone were not found downstream of the hydroclone.

SECTION VIII

GENERAL DESIGN CRITERIA

A. INTRODUCTION

During the period from 27 December 1962 to 27 December 1963, a 1.375 in. prototype hydroclone (a 1.375 in. hydroclone means that the hydroclone has a cone diameter of 1.375 in.) rated at 30 gpm was developed at Oklahoma State University. This hydroclone resulted from extensive experimental work performed under contract AF 33(657)-9958. This program consisted of a comprehensive study of both separation efficiency and pressure drop criteria. As an extension of this work, under contract AF 33(657)-9958 No. 2, a general design criteria was to be developed for a family of hydroclones using MIL-F-5606 hydraulic fluid. These hydroclones were to be designed to operate effectively in the range of flow rates from 5 to 30 gpm.

Since it had previously taken one year to develop one hydroclone, the problem was how to develop several hydroclones in the same length of time. It was decided that the wealth of information obtained from the previous year's work should be used if at all possible. One way to do this would be to use the 1.375 in. hydroclone as a basis for the design of the family of hydroclones. To use the 1.375 in. hydroclone as a basis for design, it had to be determined if the general configuration of this hydroclone would still be optimum for smaller cones. That is, would the relationships established between the major cone diameter and other critical parameters for the 1.375 in. hydroclone be the same for smaller hydroclones.

To determine this, a small hydroclone with the prototype hydroclone configuration was built and tested. These tests were conducted on the hydraulic test stand, using injected AC Test Dust as the contaminant to be separated. Critical parameters such as inlet diameter and overflow diameter were investigated. Once the hydroclone configuration was determined, future work then consisted of building several hydroclones and testing them. The tests themselves consisted of circulating contaminated MIL-F-5606 through the test hydroclones and determining efficiencies at several flow rates.

In this section, "efficiency" will be used to describe the hydroclone performance in the range above a specified particle size. This is calculated by taking the difference between the upstream and downstream counts at a specified micron setting and then dividing this value by the upstream count. This efficiency expresses what percent of the particles above a specified diameter is being separated from the fluid.

B. TEST EQUIPMENT

Most of the equipment necessary to carry out the hydroclone tests was already available at Oklahoma State University. A brief description of this equipment follows:

1. Power Test Stand

Circulation of fluid through the hydroclone is provided by a power stand (see Figure 8) which consists of a pump, a reservoir, flow metering equipment, a control panel, and a mount for the test hydroclone. The reservoir is an elevated tank with a capacity of 120 gallons and was designed to have all return lines located below fluid level to reduce aeration. Fluid from the reservoir is gravity-fed to the circulation pump which has a capacity of 30 gpm at 2000 psi. The pump is a positive displacement-type gear pump and was selected because its constant delivery characteristic provides a stable, easily regulated flow of fluid into the system. The pump incorporates pressure-compensated wear plates which reduce the side clearance of the housing and hence reduce slippage flow. The pump is driven by a 40 horsepower, three phase, 1767 rpm electric motor.

From the pump, fluid flows through a pilot-operated pressure relief valve which can be remotely adjusted on the instrument panel. A solenoid-operated, 3-way flow diverting valve receives the fluid from the relief valve and diverts the fluid from the test section to the reservoir in the event a leak or failure downstream should occur. In the de-energized position of the solenoid valve, fluid flows into a diverting valve and back to the reservoir; whereas in the energized position, fluid flows into the test section through a flow control valve. The flow control valve passes some of the total stream into the test section, depending on the requirements of the test, while the remaining fluid is returned to the reservoir. As previously mentioned, 30 gpm are available from the pump; hence, the flow control valve governs a flow range of 0 - 30 gpm through the test section--the operating range of the MJ-1 hydraulic cart for which the prototype hydroclone was optimized.

The test section of the power stand consists of a panel which provides a mounting for the test hydroclones, pressure gauges upstream and downstream of the unit, a temperature indicator, and taps for collecting discrete or continuous fluid samples. The fluid which leaves the test section encounters a back pressure valve. This valve, a standard ball valve, is used to maintain a high enough back pressure on the hydroclone to prevent flashing of the fluid. A heat exchanger is placed in the return line of the system to cool the hydraulic fluid so that over-heating, and consequent possible fractionation, of the oil is avoided. A hydraulic gear motor, installed in the return line, monitors the flow rates. The fluid is filtered prior to termination in the reservoir to remove contaminant from the hydraulic system so this contaminant will not interfere with succeeding tests. The filter has a nominal separation rating of 1/2 microns.

2. Flow Meter

The flow rate of fluid through a hydroclone has a significant effect on the hydroclone's performance. The flow meter incorporated in each hydroclone test system digitally displays the fluid flow rate in the power stand test section and enables the operator to adjust the flow control valve to a specified level. This unit contains a fixed displacement hydraulic motor with a gear mounted on its shaft. A magnetic pickup generates a pulse every time a gear tooth passes it. These pulses are amplified and transmitted through a gating

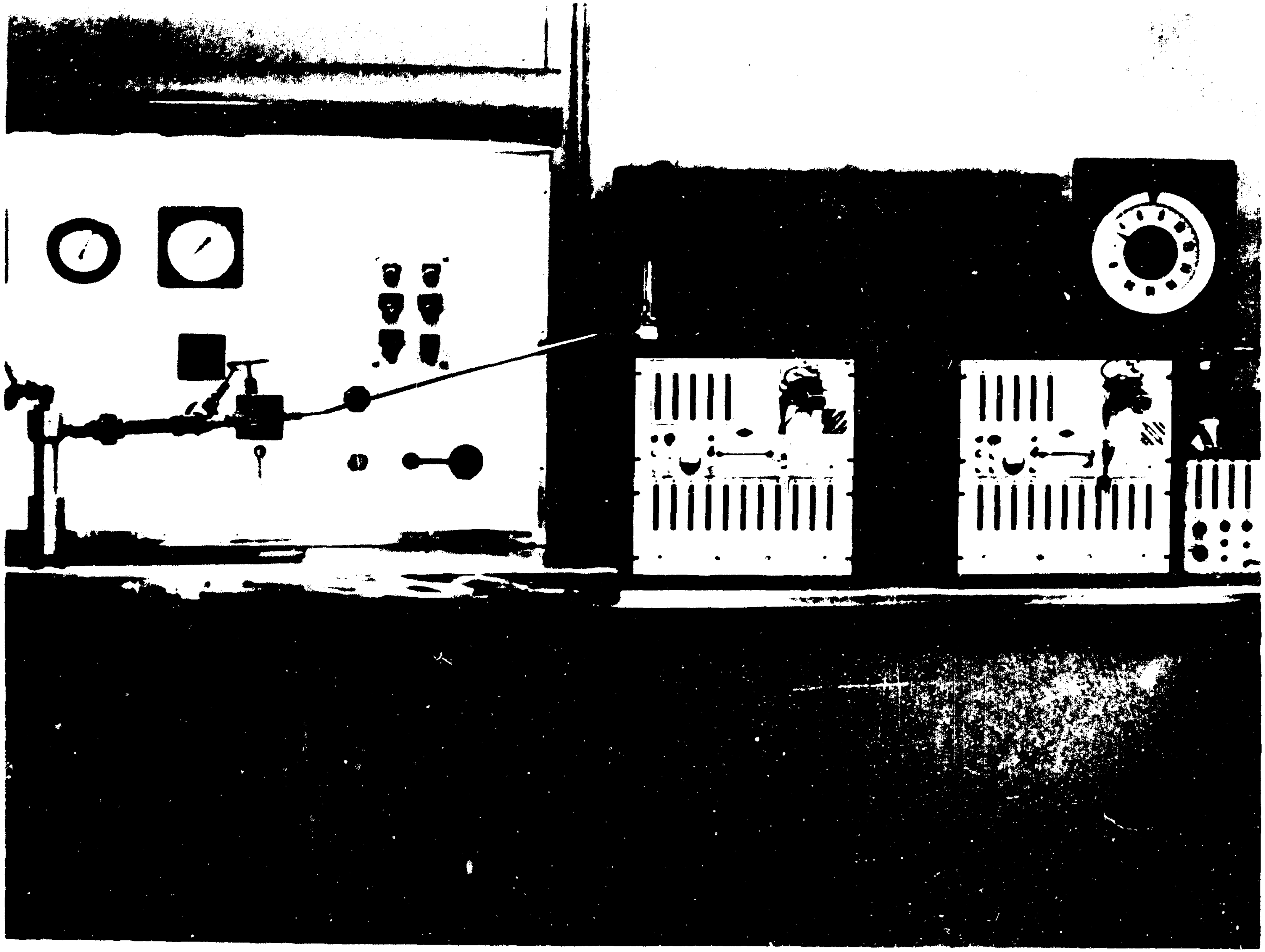

Figure 8. Hydraulic Power Stand.

circuit of an electronic pulse counter, and the cumulative pulses are displayed by the counter. The flow meter was calibrated against a precision turbine meter in June, 1964.

3. Contaminant Evaluation Stand

The HIAC Automatic Particle Counter was chosen for a number of reasons. First, the operation of the HIAC is extremely simple and easily mastered. Second, the HIAC is very well suited to the techniques of laboratory analysis. Third, this counter is considerably faster than optical methods. Fourth, the counter is completely subjective; it is free from operator bias. Fifth, the HIAC performs particle discrimination by use of a photoelectric cell, thus eliminating the need for mixing the sample with other fluid having questionable contaminant levels and interactive effects. A picture of the HIAC Particle Counter is shown in Figure 9.

During the operation of the HIAC Particle Counter, the fluid specimen is forced through a sampling tube into a fluid passage by the pressure in the main system. This fluid passage is designed so that any foreign particles in the fluid must pass single file by a counting window. A parallel light beam is focused to penetrate this window and the fluid, and finally impinges on a phototube inside the unit. The resulting phototube output is constant unless a particle passes the window and interrupts a portion of the light beam. Any interruption causes a change in the output signal by an amount proportional to the size of the particle.

The output signal is directed to a chopper section where it is either sensed or rejected, depending upon whether its amplitude exceeds the value for which the sensitivity adjustment has been set. The signals sensed by the chopper section are amplified to operate a trigger, which provides the proper pulse to operate an electronic counter. The particle counts registered by the electronic counters in conjunction with a measured amount of sample fluid provide information on the number of particles per unit volume.

4. Temperature Controller

Fluid temperature is maintained within 1°F of a set point with a Minneapolis-Honeywell 3-Mode Automatic Temperature Controller. The final control element of this system is a motorized water valve which regulates water flow to a heat exchanger connected in the hydraulic circuit of the power stands. The controlling device was calibrated by the manufacturer, and its performance was checked at the time of its installation approximately 1 June 1963.

5. Injection Stand

The injection stand is used to inject contaminant into the hydraulic test system at a controlled rate. The contaminant used for the hydroclone tests is standardized AC Fine Test Dust. The distribution of particle sizes in this test dust is shown on the next page:

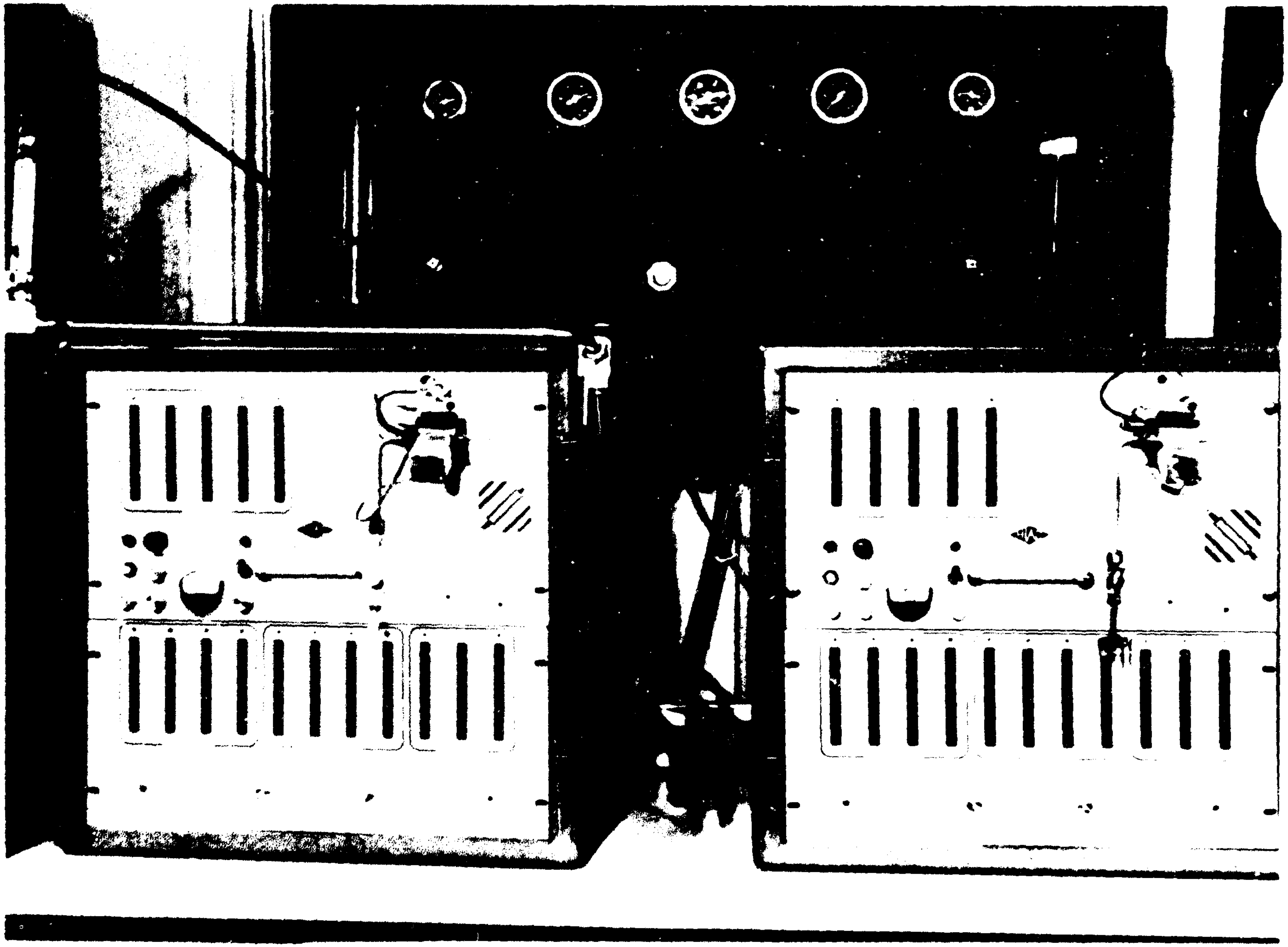

Figure 9. HIAC Automatic Particle Counters.

Size (Microns)	Percentage by Weight
0 - 5	39 ± 2%
5 - 10	13 ± 3%
10 - 20	16 ± 3%
20 - 40	18 ± 3%
40 - 80	9 ± 3%

The particles to be injected are mixed with hydraulic oil of the same type used in the test stand hydraulic system to form a thin slurry. Mixing is accomplished in a small reservoir which is equipped with a motor-driven agitator. The uniformly distributed slurry is injected continuously into the test unit section of the power stand while contamination separation data are being taken.

The injection of the slurry is accomplished by means of an air-oil intensifier. This intensifier has a rated capacity of 2 gpm. It will inject fluid into system pressures as high as 5000 psi when operating with a 100 psi air supply.

C. TEST PROCEDURE

To initiate the test program, a 0.75 in. hydroclone was constructed with the same configuration at the 1.375 in. hydroclone. That is, the ratios of D_c/D_o, D_c/D_i, D_c/D_u and the cone angle were the same for both hydroclones.

The parts actually constructed were the overflow nozzle, the inlet ring, and the cone. The vortex finder and the inlet ring were machined from aluminum. The cone was constructed by casting a polyester resin with an aluminum powder base over an aluminum mandrel. The aluminum powder base polyester resin is much easier to machine than the raw polyester resin. The inner coatings of these cones do not have aluminum powder mixed with it because the resin without the aluminum powder is much harder and wears longer. The aluminum mandrels have a polished surface which provides a smooth finish for the cast cone.

The hydroclone housings did not have to be constructed. Two special hydroclone housings were available that could be disassembled and the parameters changed easily. With these two test hydroclone housings, tests could be conducted on hydroclones with diameters ranging from 0.75 in. to 1.5 in.

These three parts, (the overflow nozzle, inlet ring, and cone), represent the components that must be changed to investigate certain parameters. Previous investigations at Oklahoma State University showed that a cone agle of 10° was best for the size hydroclones under investigation. The investigations also showed that a D_u of approximately 1/8 D_c was best. That left two parameters D_i and D_o to be checked on the 0.75 in. hydroclone. This test procedure was as follows:

1. The assembled test hydroclone was placed on the hydraulic test stand. The test stand was started and the fluid was allowed to circulate through the hydroclone until the test temperature of 120°F was reached.

2. A measured amount of AC test dust was added to the fluid in the contaminant slurry reservoir. The stirring motor was started to achieve and maintain a homogeneous mixture.
3. The flow through the hydroclone was regulated to a specified rate and the contaminant injection pump was started.
4. After sufficient time to allow steady conditions of flow, upstream and downstream bottle samples were taken from the sample probes on the test stand. The pressure drop was recorded.
5. The test was stopped. The parameter under investigation was changed and steps 1 through 4 were repeated.
6. Later, the bottle samples were evaluated for particle counts on the automatic particle counters.

These efficiency tests confirmed that the 1.375 hydroclone configuration was optimum. The relations were $D_i = D_c$ and $D_o = D_c$. Since the 1.375 in. and 0.75 in. hydroclones were to have the same configuration, it could be safely assumed that all intermediate hydroclones should be of this same configuration.

Once the configuration of the hydroclones to be tested was determined, the work consisted of building several hydroclones and testing them. Six hydroclones were built; the sizes were 0.75 in., 0.875 in., 1.0 in., 1.125 in., 1.25 in., and 1.5 in. hydroclone.

The test procedure was as follows:

1. The assembled test hydroclone was placed on the hydraulic test stand. The test stand was started and the fluid was allowed to circulate through the hydroclone until the test temperature of 120°F was reached.
2. A measured amount of AC test dust was added to the fluid in the contaminant slurry reservoir. The stirring motor was started to achieve and maintain a homogeneous mixture.
3. The injection pump was started and the flow rate was set to 5 gpm. After steady state conditions were established, upstream and downstream bottle samples were taken from the sample probes on the test stand.
4. The flow rate was increased to 10 gpm and more bottle samples were taken. The test was continued in this manner up to 30 gpm.
5. The bottle samples were evaluated on the automatic particle counters.

When the efficiency tests were completed, considerable data had been obtained. These tests had provided information on separation efficiency and pressure drop at various flow rates for each hydroclone tested. This information is shown in graphical form in Figure 10 and 11. Figure 10 is a plot of constant K for Q versus D_c. This graph has great utility since it allows selection of a hydroclone to operate at a certain flow rate for absolute separation of any contaminant of any specified size above 6 micron. A condition on the type of contaminant is that it must have a specific gravity greater than that of MIL-F-5606.

Figure 10 is to be used in conjunction with the equation

$$D_p = K \sqrt{\frac{\mu}{\rho_s - \rho_l}}$$

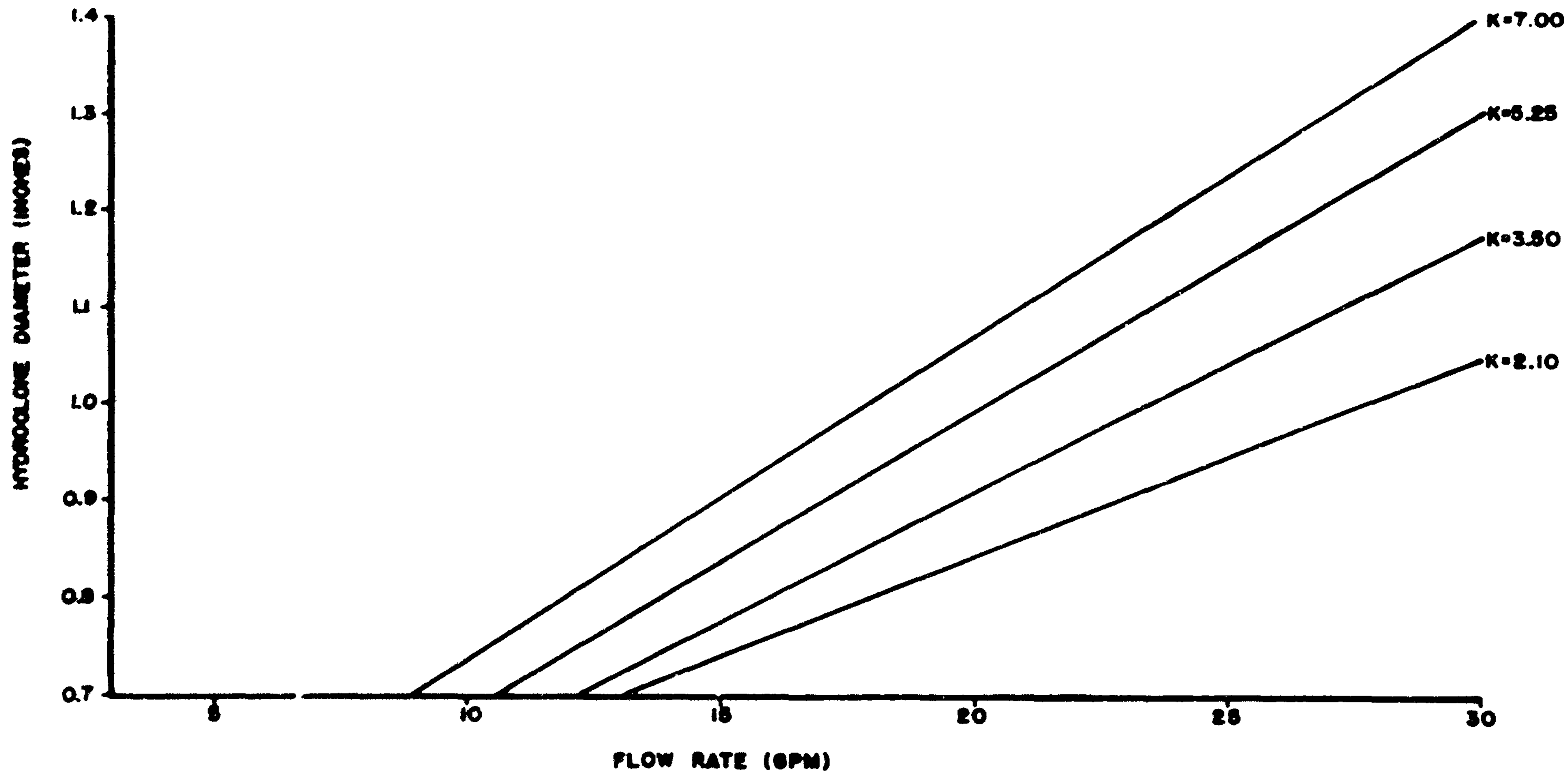

Figure 10. Design Criteria Curves.

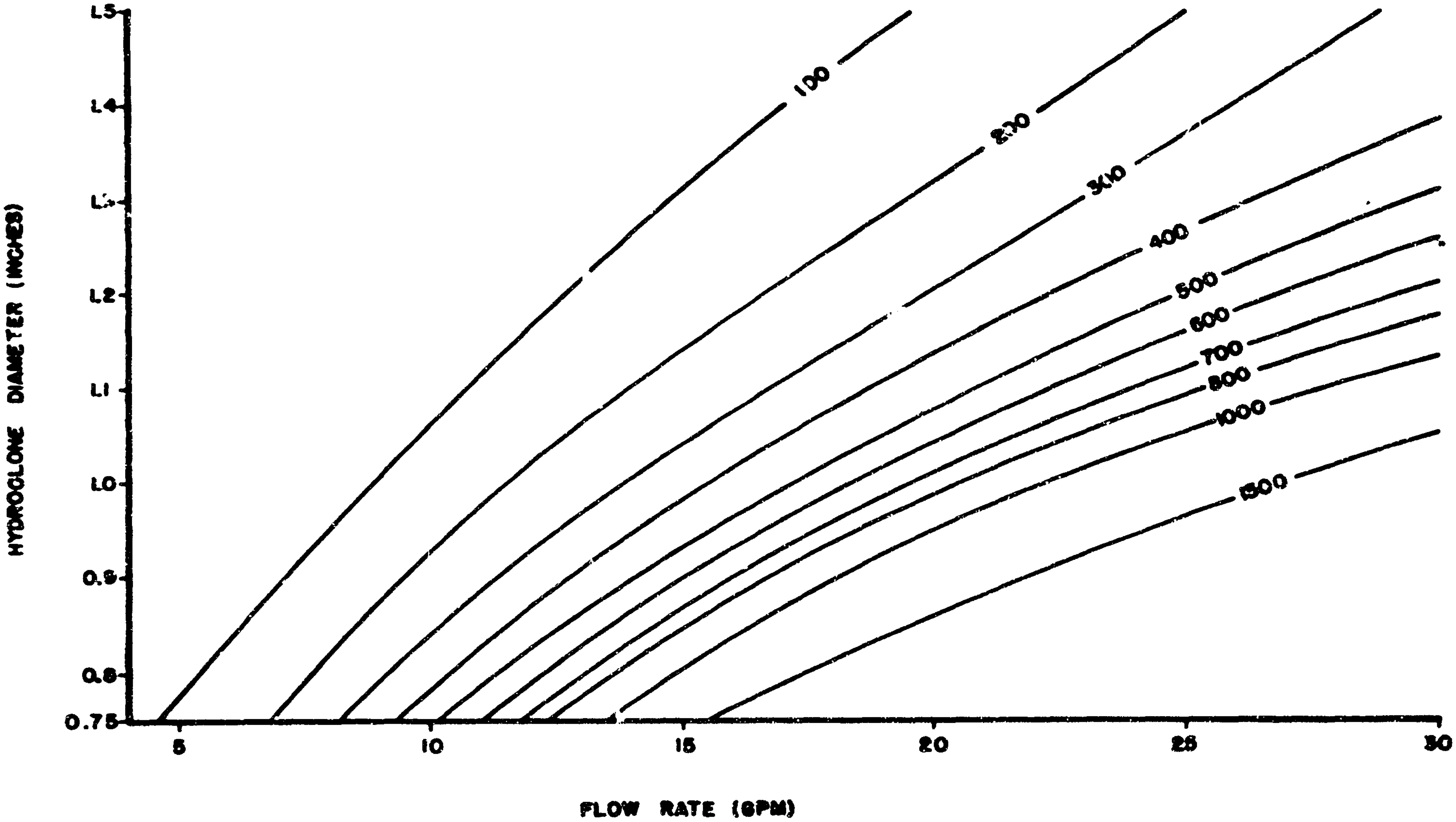

Figure 11. Pressure Drop Curves for Design Criteria.

Where D_p = the smallest particle to be absolutely separated (in microns)

μ = viscosity of the fluid (in centipoises)

ρ_s = specific gravity of the solid to be separated

ρ_1 = specific gravity of the fluid

As an example of how to use the graph, suppose that it is desired to separate all 6 microns and larger iron particles from MIL-F-5606 and that the system normally operates at 30 gpm.

For MIL-F-5606 at 120°F μ = 10 centipoises

For iron ρ_s = 7.87

For MIL-F-5606 ρ_1 = .855

calculating K

$$K = D_p \sqrt{\frac{\rho_s - \rho_1}{\mu}}$$

$$= 6\mu \sqrt{\frac{7.87 - .855}{10}}$$

$$= 5.03$$

From the graph at 30 gpm and K = 5.03, it can be seen that a 1.30 in. hydroclone will be needed. From Figure 11 the pressure drop is seen to be approximately 500 psi.

D. RESULTS AND CONCLUSIONS

A general design criteria has been established for hydroclones in the range of flows from 5 to 30 gpm. By knowing the size and density of the particle to be absolutely separated and the flow rate at which the hydroclone is to operate, the critical dimensions of the hydroclone can be determined. The power requirements for this hydroclone can also be determined. A physical dimension table for the hydroclone relating the design curves with conventional filters of comparable size is given below:

Physical Dimension Table

$$K = D_p \sqrt{\frac{\rho_s - \rho_1}{\mu}}$$

D_c = f (Q, K) from Figure 10

$D_i = \frac{1}{4} D_c$

$D_o = \frac{1}{4} D_c$

D_u = 1/8 D_c

φ = 10°

List of Symbols

D_c = major cone diameter, inches

D_i = diameter of inlet nozzle, inches

D_o = diameter of overflow nozzle, inches

D_u = diameter of underflow, inches

φ = included cone angle, degrees

SECTION IX

DYNAMIC HOSE STUDY

A. INTRODUCTION

Contract AF 33(657)-9958 No. 2 required Oklahoma State University to design and fabricate appropriate test facilities and to perform dynamic generation tests. Analytical design procedures were used to develop a test stand that would transmit an actual transient pressure wave to the hose being tested. Equipment was purchased and the stand was constructed in the Fluid Power Controls Laboratory. Also, it was required to procure commercial hose assemblies and install them on a standard hydraulic test stand at Tinker AFB for a deterioration phase study. Comparable polytetrafluoroethylene-lined and rubber-lined hoses were procured, installed, and periodically tested by project personnel.

Further, the contract stated that static tests on these hoses were to be conducted to determine the original cleanliness level (built-in contamination). These tests were performed on the hoses as they were received from the manufacturer. The particle generation characteristics of the hoses under transient pressure condition were to be determined by using the dynamic test facility. The hoses were subjected to low pressure static and dynamic tests before they were put into field service. High pressure tests were performed after some deterioration had taken place. It was required that periodic dynamic tests would be performed in the laboratory on the field deteriorated hose assemblies. One polytetrafluoroethylene-lined hose and one rubber-lined hose were immediately started on the deterioration phase of the study while the other two hoses were dynamically tested at low pressure in the laboratory. Two series of high pressure dynamic tests were performed on the first set of hoses and one on the second set.

B. THE DYNAMIC HOSE FACILITY DESIGN

To take advantage of all previous experimentation in this field of study, an intensive literature survey was conducted. This investigation provided valuable background data, although it was discovered that the concept of dynamic contaminant generation had not been previously examined.

1. Analytical Considerations

The concept of particle generation due to transient pressure pulsations was evolved from several other methods for fatigue testing of hydraulic hoses. This method of pressure pulsation was thought to involve the worst possible field application that a hose would incur. The following analytical considerations assisted in defining the mode of pulsation needed to develop the test stand.

The hydraulic natural frequency of the test system can be derived by construction of its analogous mechanical system. Figure 12 shows a schematic of the hydraulic test system and its mechanical analogy.

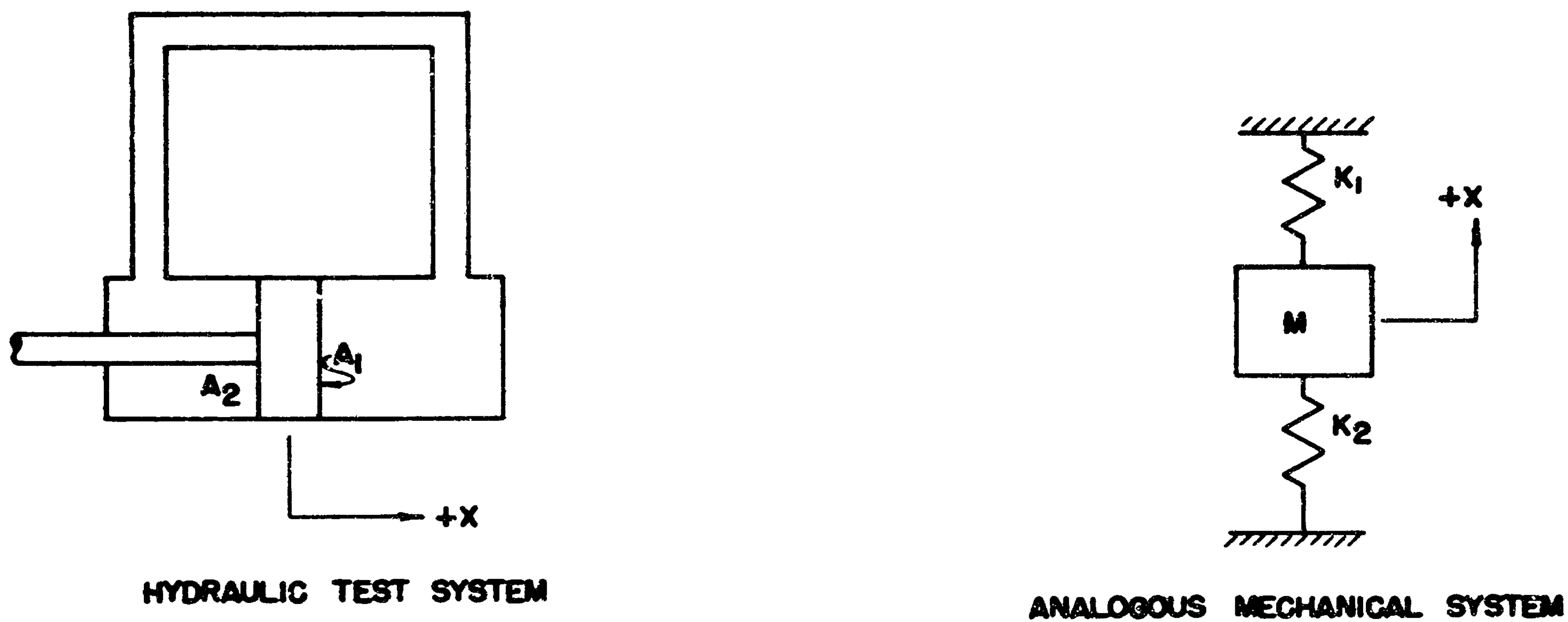

Figure 12. Hydraulic System Analogy.

The natural frequency of the mechanical system is

$$f_m = \frac{1}{2\pi}\left[\frac{K_1 + K_2}{M_s}\right]^{\frac{1}{2}} \quad (9.1)$$

where K_1 and K_2 = mechanical spring constants,

M_s = mass of mechanical system.

In the hydraulic system, the hydraulic spring constants, due to the compressibility of the fluid, can be expressed as follows:

$$K_1' = \frac{A_1^2 \beta}{V_1} \quad (9.2)$$

and

$$K_2' = \frac{A_2^2 \beta}{V_2} \quad (9.3)$$

Substituting these values of K_1' and K_2' into Equation 9.1, we can express the natural frequency of the hydraulic system as follows:

$$f_h = \frac{1}{2\pi}\left[\frac{\beta}{M}\left(\frac{A_1^2}{V_1} + \frac{A_2^2}{V_2}\right)\right]^{\frac{1}{2}} \quad (9.4)$$

where β = bulk modulus of fluid,
M = mass of piston and enclosed fluid,
V_1 = volume of fluid displaced for positive stroke,
V_2 = volume of fluid displaced for negative stroke,
A_1 = large area of cylinder,
A_2 = small area of cylinder.

If the hydraulic system shown in Figure 12 were excited by a sinusoidal oscillation at this frequency, hydraulic resonance would occur and could result in large fluid oscillations. These oscillations, depending upon the inherent damping of the system, could result in serious damage to the system components.

The variables in Equation 9.4 are explicitly defined once the system parameters are specified. Therefore, a dynamic test facility that would be capable of producing pressure pulsations in the frequency range specified by Equation 9.4 might be advantageous.

Since the hydraulic hose was the component tested, it was also helpful to try to determine the natural frequency of just the hydraulic hose. From the solution of a well-known wave equation, the fundamental natural frequency of a hydraulic hose can be determined. This frequency equation, derived by Den Hartog (6), is as follows:

$$f_h = \frac{1}{2L}\left[\frac{E}{\rho}\right]^{\frac{1}{2}} \quad (9.5)$$

where E = modulus of elasticity of the hose,
ρ = density of the hydraulic hose,
L = length of hydraulic hose.

The disadvantage of Equation 9.5 is that the natural frequency of the hose cannot be explicitly determined for a certain type of hose. All the values in the expression 9.5 can be readily obtained for a hydraulic hose expect its modulus of elasticity. A true modulus of elasticity for a hydraulic hose does not exist. Most high pressure hoses are made of several layers of rubber, nylon, teflon, or other materials, with a high pressure shell of steel wire braid on the outside. Due to the complexity of such a hose, an exact modulus of elasticity is unobtainable. At the present time, the only applicable use of Equation 9.5 to finding the natural frequency of a hydraulic hose is to define an effective modulus of elasticity. This effective modulus of elasticity for the hydraulic hose was calculated with the aid of Lames' (3) equation for thick-walled cylinders:

$$E_h = \frac{P_i d^2}{E} \frac{2 - \mu}{D^2 - d^2} \qquad (9.6)$$

where E_h = hoop strain on the outer surface of the hose,
P_i = internal pressure,
d = inside diameter of hose,
D = outside diameter of hose,
E = modulus of elasticity,
μ = Poisson's ratio of the hose.

By solving Equation 9.6 for E and determining E_h and μ from experimental hose data, the value of the modulus of elasticity of the hose was determined. The value of E_h was determined by relating the strain to the change in diameter of the hose under pressure by the following relationship:

$$E_h = \frac{D_f - D_i}{D_i} \qquad (9.7)$$

where D_f = final diameter of hose at system pressure,
D_i = initial diameter at zero pressure.

The hoop strain was then determined from Equation 9.7 by measuring D_f and D_i from experimental hose tests. Likewise, Poisson's ratio was calculated with the aid of experimental hose tests from the following equation:

$$\mu = -\frac{E_h}{E_a} \qquad (9.8)$$

where E_a = axial strain.

When the values obtained from Equations 9.7 and 9.8 were substituted into Equation 9.6, the effective modulus of elasticity for a one-inch high pressure teflon hose at 1000 psi was found to be 9×10^{8} psi. This value was only approximate since large errors could have resulted due to the experimental determination of the hoop strain and Poisson's ratio. Although an accurate value of the modulus of elasticity of the hose could not be determined by this method, an important result was generated from this approach. When the hoop strain was calculated for various pressures, it was found that the strain was not a linear function of pressure. Therefore, the modulus of elasticity of the hose was not constant but varied nonlinearly with pressure. This is particularly interesting when reference to Equation 9.5 shows that the natural frequency of a hydraulic hose must depend upon the pressure of the hydraulic system. This phenomenon can be explained if the hose itself is analyzed from a standpoint of its construction. As mentioned previously, the structure of most high pressure hydraulic hoses is quite complex, consisting of several inner layers of rubber or teflon with a steel wire braid on the outside. At low pressure, the bulk of the system pressure is absorbed by the inner core of the hose. As the pressure is increased, the inner core is completely compressed; and the hose approaches a thick-wall cylinder of steel wire braid. Therefore, at low pressures, the modulus of elasticity of the hose is approximately equal to the modulus of elasticity of the inner core. But as the pressure increases, the modulus of elasticity of the hose approaches the elasticity of the steel wire braid.

The magnitude of the increase in natural frequency due to this change in modulus of elasticity of the hose with system pressure depends upon the compliance characteristics of the system. In some systems where high pressure steel wire braid is used, the increase in natural frequency for a large pressure rise could be quite significant.

It is obvious from this discussion that a comprehensive analytical solution to the problem of calculating the natural frequencies of hydraulic hoses was not possible. Certain analytical approaches to help facilitate the design of the dynamic hose stand were possible, and they will be presented in the following pages of this chapter.

The pressure response and the pressure overshoot of the dynamic test stand depended upon the compliance characteristics of the system. Therefore, in the complete analysis of the dynamic test stand that follows, all possible accumulator effects were considered to accurately determine their effect on system pressure response. Reference to the dynamic test system shown in Figure 13 will aid the reader in this analysis.

Since the dynamic test stand consists of a test system and a power system, the analytical analysis of each system will be presented separately. Considering the test system first, we have the following relationship:

$$Q_1 = Q_2 + Q_a + Q_b + Q_c - Q_L \qquad (9.9)$$

where Q_1 = flow into front side of cylinder,

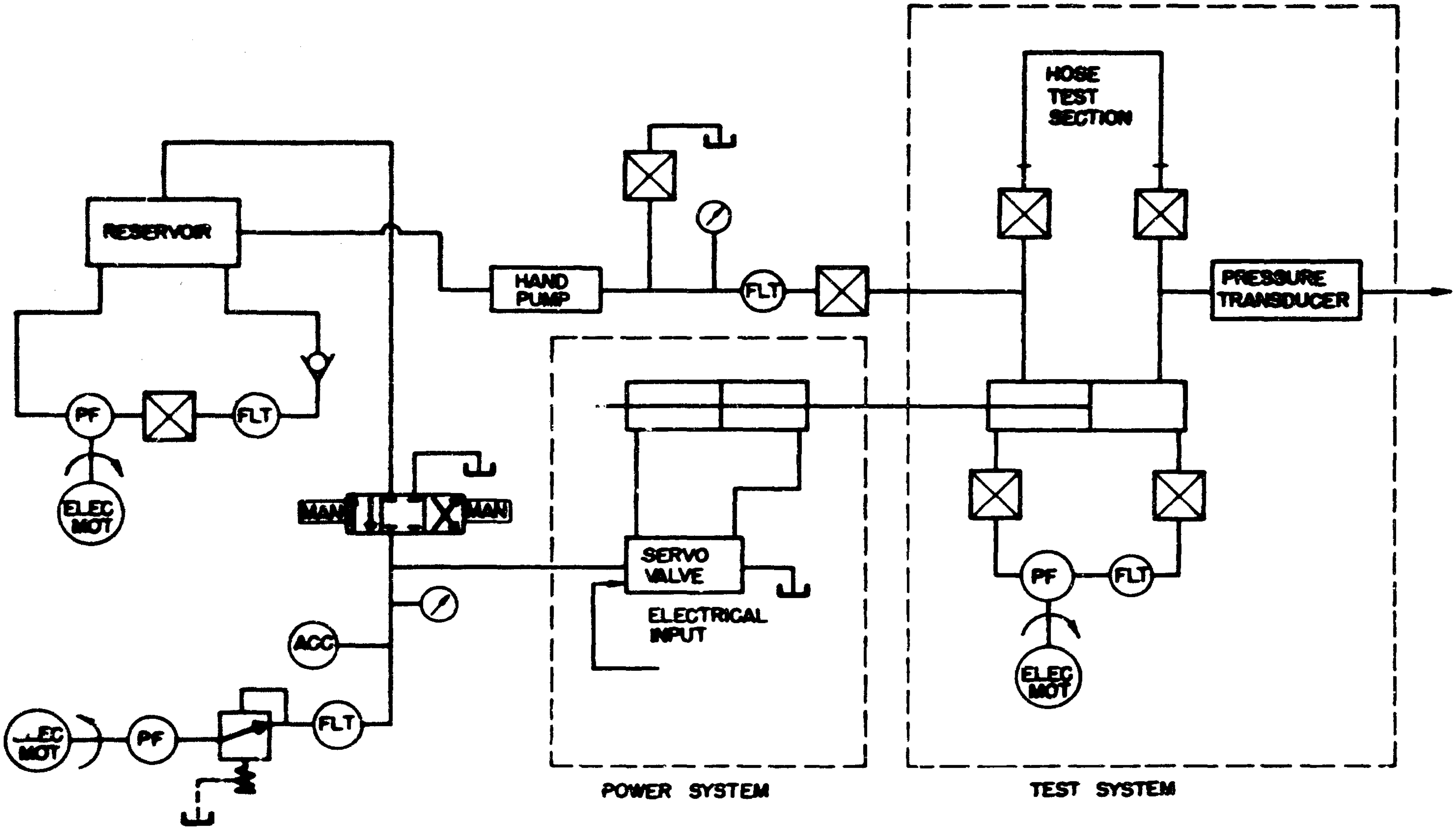

Figure 13. Flow Schematic for Dynamic Hose Study.

Q_2 = flow into back side of cylinder,

Q_a = accumulator flow,

Q_h = hose accumulator flow,

Q_c = compressible flow,

Q_L = leakage flow.

Substituting the system parameter relationships for these different flow rates into Equation 9.9, we have the following differential equation:

$$\left[A_1 - A_2\right] \frac{dx}{dt} = \left[C_a + C_h + C_c\right] \frac{dp}{dt} \tag{9.10}$$

where C_a = accumulator compressibility term,

C_h = hydraulic hose compressibility constant,

C_c = fluid compressibility constant.

The leakage flow rate, Q_L, has been neglected since its value is small compared to the other flow rates. The different system compliance terms used in the differential Equation 9.10 are defined as follows:

$$C_a = \frac{\left(V_T - V_c\right)^2}{P_1 V_T} \tag{9.11}$$

$$C_h = \frac{AL}{E} \tag{9.12}$$

and

$$C_c = \frac{V}{\beta} \tag{9.13}$$

where V_T = total volume of accumulator,

V_c = accumulator oil volume,

V = volume of fluid under compression,

P_1 = air precharge pressure of accumulator,

A = area of hydraulic hose.

The accumulator compliance term, C_a, shown in the expression above, is for a hydro-pneumatic accumulator. If a spring-piston accumulator had been used in this analysis, the compliance term would be

$$C_{ap} = \frac{A_c^2}{K_s} \tag{9.14}$$

where A_c = area of piston,

K_s = spring constant.

The more common hydro-pneumatic accumulator will be used in this analysis.

Writing Equation 9.10 in LaPlace form and solving for the pressure, we have

$$P(s) = \frac{\bar{A}}{C_a + C_h + C_c} \cdot X(s) \qquad (9.15)$$

where $\bar{A} = A_1 - A_2$.

Since the input $X(s)$ imposed on the test system by the servo-controlled power cylinder is sinusoidal, we can let

$$X(t) = X_o \sin Wt. \qquad (9.16)$$

Taking the LaPlace transform of the input, we have

$$X(s) = \frac{X_o W}{S^2 + W^2} \qquad (9.17)$$

where W = driving frequency of the servo valve,

X_o = maximum amplitude of sinusoidal input,

S = LaPlace operator.

Substituting Equation 9.17 into Equation 9.15, we obtain

$$P(s) = \frac{\bar{A}X_o}{C_a + C_h + C_c} \frac{W}{S^2 + W^2} \qquad (9.18)$$

Taking the inverse of Equation 9.18 and evaluating the initial conditions, we obtain the pressure in the test system as a function of time:

$$P(t) = P_o \sin Wt + P_s \qquad (9.19)$$

where P_s = initial pressure of test system,

P_o = overshoot pressure of test system.

From Equation 9.19, we can see that the pressure pulsations in the test system are oscillatory with an amplitude of P_o. The value of the overshoot pressure P_o can be obtained from Equation 9.18. The value is

$$P_o = \frac{\bar{A}X_o}{C_a + C_h + C_c} \qquad (9.20)$$

Therefore, the pressure pulsations in the test system consisted of an oscillatory pressure superimposed on a constant precharge pressure.

In order to be able to accurately control the overshoot pressure, we will further analyze the oscillation amplitude of Equation 9.20. From the power system, assuming constant pressure drop across the servo valve during its complete cycle, we have the following relationship for the maximum stroke:

$$X_o = \frac{Q}{2A_p f} \qquad (9.21)$$

where Q = average flow rate of servo valve over $\frac{1}{2}$ cycle,

A_p = area of servomotor,

f = frequency of servo valve.

Combining expressions 9.11, 9.12, 9.13, 9.20, and 9.21, we have the following result for the overshoot pressure:

$$P_o = \frac{\frac{\bar{A}Q}{2}}{2A_p f \left[\frac{\left(V_T - V_c\right)^2}{P_1 V_T} + \frac{AL}{E} + \frac{V}{\beta} \right]} \qquad (9.22)$$

For positive stroke, the servomotor moving toward the right, the accumulator volume V_c can be expressed as follows:

$$V_c = \frac{Q\bar{A}}{2A_p f} \qquad (9.23)$$

Substituting Equation 9.23 into 9.22 and expanding, we have the final result for the overshoot pressure as follows:

$$P_o = \frac{\bar{A}Q}{\left[\frac{4A_p^2 f^2 V_T^2 - 4A_p f V_T Q\bar{A} + Q^2\bar{A}^2}{2P_1 V_T A_p f} + \frac{2AA_p Lf}{E} + \frac{2A_p fV}{\beta} \right]} \qquad (9.24)$$

It can be shown that the first term in the denominator of Equation 9.24 is considerably larger than the other two. Therefore, if a hydro-pneumatic accumulator were used in the system, the compliance terms for the fluid and the hose could be neglected. Eliminating these terms from Equation 9.24, we have the overshoot pressure expressed as a function of only the hydro-pneumatic accumulator characteristics:

$$P_o = \frac{P_1 V_T Q\bar{A}}{\left[2A_p f V_T^2 - 2V_T Q\bar{A} + \frac{Q^2\bar{A}^2}{2A_p f} \right]} \qquad (9.25)$$

Equation 9.25 expresses the overshoot pressure for any given set of system parameters. Since Equation 9.25 is time invariant, the overshoot pressure will be a constant for any set of system values.

It is now desired to analyze Equation 9.25 with respect to flow rate in order to determine if a hydro-pneumatic accumulator will provide a sufficient overshoot pressure. For the pressure pulsation testing of the hydraulic hoses, a minimum of 50 psi overshoot pressure was desired.

In order to obtain the largest value of P_o for a certain flow rate and frequency, it can be seen from Equation 9.25 that P_1 and $\bar{A}$ should be as large as possible while V_T and A_p should be as small as possible. Therefore, selecting the smallest standard accumulator and actuator with the largest recommended air precharge value, the minimum servo valve flow rate capacity can be calculated from Equation 9.25. The values used for this calculation were:

$$V_1 = 1.5 \text{ in}^3$$

$$P_1 = 1000 \text{ psi}$$

$$\bar{A} = .30 \text{ in}^2$$

$$A_p = 1.459 \text{ in}^2$$

$$f = 100 \text{ cps}$$

When these values were substituted into Equation 9.25, it was found that a servo valve flow rate of 100 gpm was needed to produce 50 psi overshoot in the test system. Since this was obviously not feasible, it was concluded that a hydro-pneumatic accumulator could not be used to control the pressure pulsations in the test system. A similar analysis was performed using a spring-piston accumulator. Although the flow requirements of the servo valve were less demanding, they were still of such magnitude that it would not be feasible for a study of this type.

Therefore, in order to obtain the desired pressure pulsations, it was necessary to consider only the compliance characteristics of the hydraulic hose and the fluid. Deleting the accumulator from the test system, the resulting expression for the overshoot pressure is

$$P_o = \frac{\bar{A}Q}{2A_p f\left[\frac{AL}{E} + \frac{V}{\beta}\right]} \qquad (9.26)$$

Substituting this expression into Equation 9.19, we have the resulting equation relating the pressure in the test system as a function of time.

$$P(t) = \frac{\bar{A}Q}{2A_p f\left[\frac{AL}{E} + \frac{V}{\beta}\right]} \sin Wt + P_s \qquad (9.27)$$

where $\bar{A} = A_1 - A_2 \text{ in}^2$,

Q = average flow rate, in^3/sec,

A_p = area of servomotor, in^2,

f = frequency of servo valve, cps,

A = area of hydraulic hose, in^2,

L = length of hydraulic hose, in.,

E = modulus of elasticity, lb/in^2,

V = volume of fluid under compression, in^3,

β = bulk modulus of fluid, lb/in^2,

P_s = initial precharge pressure, lb/in^2.

This equation was used throughout this study to control the pressure pulsations imposed on the hydraulic test hoses at various frequencies. Also, from experimental pressure readings in the test circuit, Equation 9.26 can be arranged as follows to determine an exact value for the modulus of elasticity of the hydraulic hoses:

$$E = \frac{AL}{\left[\frac{\bar{A}Q}{2A_p f P_o} - \frac{V}{\beta}\right]} \qquad (9.28)$$

Since all the values in Equation 9.28 are known from the system parameters except P_o--and it can be obtained experimentally--then a value for the modulus of elasticity can be calculated. Notice also, in Equation 9.28, that the modulus of elasticity of the hose is a function of pressure as mentioned earlier. Therefore, substituting Equation 9.28 into Equation 9.5, an exact relationship can be obtained for the fundamental natural frequency of a hydraulic hose.

2. Design of the Test Stand

A dynamic test facility was built in accordance with the analytical development presented. This test stand has a flow capacity of 10 gpm with operating pressures up to 2000 psi.

The dynamic hose test stand consisted of two systems--a power system and a test system (Figure 13). The power system consisted of high frequency servo valve driven by an electronic oscillator. The oscillator was used in conjunction with a null balance circuit to drive the servo valve at the desired frequency (Figure 14). The servo valve drove a linear servomotor which in turn provided power to an auxiliary test system. The auxiliary test system was connected to the power system through two hydraulic cylinders.

The test system consisted of a single-rod end hydraulic cylinder equipped with special cast iron piston rings to insure low-stiction operation at high frequencies. The output ports of the hydraulic cylinder were connected directly to the hydraulic hose to be tested.

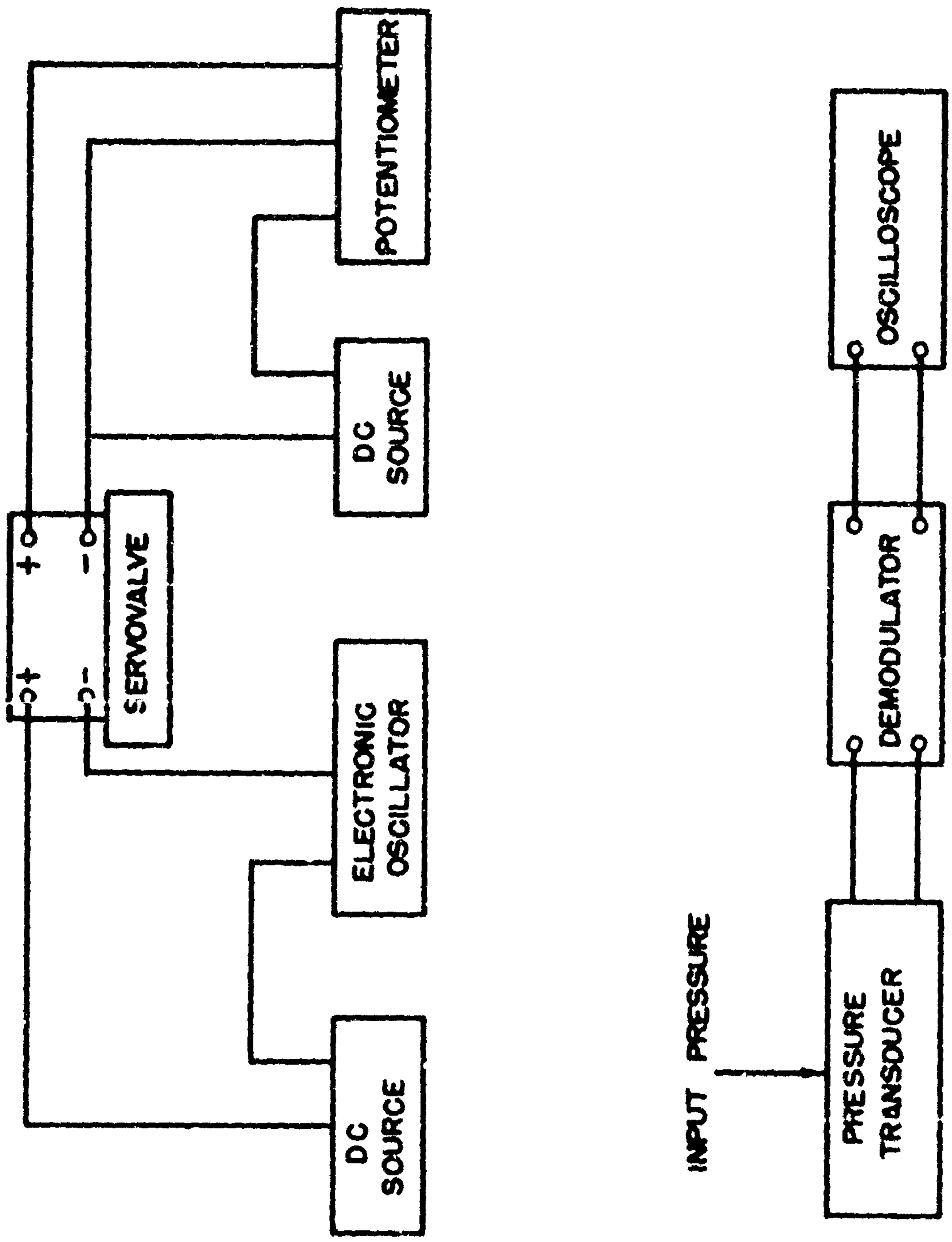

Figure 14. Electronic Schematic for Dynamic Hose Study.

The instrumentation in the test system consisted of a variable-reluctance pressure transducer. The pressure transducer was used to record the pressure transients imposed upon the hydraulic test hose by the single-rod end cylinder. The output of the pressure transducer was modulated with a high frequency carrier wave. The output of the modulator was then displayed on a cathode-ray oscilloscope (Figure 15).

The operation of the dynamic test facility depended upon the operation of two separate systems. As the frequency of the servo valve was adjusted by the electronic oscillator, the servomotor responded under pressure to this frequency. The oscillatory output of the servomotor was transmitted to the hydraulic cylinder of the auxiliary test system. Because of the single-rod end cylinder used in the test system, the pressure within the test system varied sinusoidally with time. The amplitude of this sinusoidal pressure pulsation depended upon the frequency and flow rate of the servo valve and also upon the total compliance of the test system. Since the compliance of the system was constant for a certain hose, the amplitude, within flow and frequency range of the servo valve, could be simulated.

The reason for designing the dynamic test facility to involve two different systems was twofold. First, in order to detect the most minute contamination generated by the hydraulic hose, it was essential for the system in which the test hoses were to be operating to be as clean as possible. If just the power system were used alone, a large amount of fluid would have to be filtered in order to obtain the initial stringent contamination level needed to perform the hose tests. Since the test system itself only contained a small volume of fluid, the problem of background filtration was greatly simplified. Second, the use of an auxiliary test system would provide the opportunity to study the deterioration of hydraulic hoses by investigation with other fluids. Also, the simplicity in the design of the test system greatly reduced the possibility of generating contamination from other components.

In order to establish the contaminant generation characteristics of hydraulic hoses, a comprehensive test procedure first had to be adapted. Since the particle size of the contaminant generated might be quite small, the test procedure contained stringent cleanliness requirements. Also, careful consideration was given to find the generation characteristics of all the components in the test system itself. Since this study only involved the particle generation of hoses, the contaminant generated by the other system components was separated from the particle generation of the hose. As mentioned previously, the test system was purposely designed to minimize over-all system contaminant generation.

Particle generation in the test system, due to the ball valves and the pressure transducer, was very small compared to the contaminant generated due to the hoses and the hydraulic cylinder. The exact amount of contaminant generated by the hydraulic cylinder was not known; but, because of the continual metal-to-metal contact that exists within a cylinder throughout its stroke, it must be considered to be of significant magnitude in regard to the contamination generation of the hydraulic hose. Therefore, this contamination generation due to the hydraulic cylinder was analyzed in order to determine what corrective measures, if any, needed to be taken into account in the testing procedure.

Assuming the hydraulic cylinder to be a contaminant generator, it was necessary to prove whether the contaminant generated by the cylinder presented a problem as far as detecting the actual contaminant generated by the hose. The maximum stroke of the cylinder in the test system was given by Equation 9.21 and will be rewritten here as follows:

$$X_o = \frac{Q}{2A_p f} \qquad (9.21)$$

Multiplying Equation 9.21 by A_1, we obtain the maximum volume of fluid displaced by the cylinder for a positive stroke.

$$V_{max} = \frac{QA_1}{2fA_p} \text{ (positive stroke)} \qquad (9.29)$$

Likewise, the maximum volume displaced for a negative stroke is:

$$V_{max} = \frac{Q}{2f} \text{ (negative stroke)} \qquad (9.30)$$

since $A_p = A_2$ in the dynamic test stand. Only the positive stroke is considered since the volume displaced will be larger than for the negative stroke. For the test system shown in Figure 15, the following values exist:

$$A_1 = 1.766 \text{ in}^2$$

$$A_2 = A_p = 1.459 \text{ in}^2$$

$$Q_{max} = 10 \text{ pgm}$$

$$f_{min} = 100 \text{ cps.}$$

When these values are substituted into Equation 9.29, the maximum volume of fluid displaced during a test was

$$V_{max} = \frac{\frac{10 \text{ gal}}{\text{min}} \times \frac{1 \text{ min}}{60 \text{ sec}} \times \frac{231 \text{ in}^3}{\text{gal}}}{(2) \quad (100 \text{ cps})} \frac{(1.766)}{(1.459)}$$

$$V_{max} = \underline{.25 \text{ in}^3}$$

Since all the contaminant generated by the cylinder was produced within a stroke less than 1/4 in. and the total volume displaced was only .25

in^3, the contaminant generated within the cylinder can never reach the hose test section. This is a good conclusion since the oscillating fluid flow involves amplitudes of only .25 in^3. Since the pressure reversal and flow oscillations occurred in such a short volume, it was assumed that the contaminant generated by the hose was not affected by contamination generated in the rest of the system. Likewise, the particles generated in the hose section remained in this section throughout the hose test due to this small oscillatory flow.

Another problem that must be considered in order to accurately monitor all the contaminant generated by the hose is that of particle migration. The above paragraph showed that the particles generated within the hydraulic cylinder were not propelled into the hose section due to oscillatory flow, but what about the migration of particles out the end of the hose when a test is completed? This migration can be calculated using Stoke's equation. Assuming that the particles generated are spherical, it can be shown that the drag force is equal to the submerged weight of the particle. In this case, the terminal fall velocity of the particle from Stoke's equation is

$$V = \frac{d^2 w}{18\mu} \qquad (9.31)$$

where d = diameter of particle,

μ = dynamic viscosity of fluid,

w = difference between the specific weight of the fluid and the particle.

Using the standard AC test contaminant with a diameter of 100 microns in MIL-F-5606 fluid, the terminal fall velocity calculated from Equation 9.31 is .03 in/sec. Therefore, if the main ball valves are closed immediately after a test, the contamination migration through the ends of the hose can be neglected.

Based on the preceding reasoning, it was assumed in this study that any particles trapped in the hose section during a test were generated entirely from the hose itself.

3. Test Specimens

Four, 10-foot hose assemblies were purchased. Two had polytetrafluoroethylene interliners and conformed to MIL-H-[illegible]A-1[illegible]. The other two hoses were similar but had rubber interliners. Upon receipt the hoses were labeled T1 and T2, and R1 and R2 for the polytetrafluoroethylene lined hoses and rubber hoses, respectively. Set 1 consisted of hoses T1 and R1, while set 2 consisted of hoses T2 and R2.

4. Testing Program

(a) Static Tests

As each hose was received from the manufacturer, it was statically tested to determine its initial cleanliness (i.e. the contaminant which it would introduce into a system operating at a constant low pressure). The procedure was developed after a study of industrial procedures. The procedure used to perform the test is summarized as follows:

(1) Each end fitting of the hose assembly was subjected to the ultrasonic cleaner.
(2) Eight hundred ml of triple-filtered MIL-F-5606 was admitted to the hose.
(3) The hose was bent a specified number of times and emptied.
(4) The hose was rinsed twice with triple-filtered petroleum ether.
(5) All the fluid which had been drained from the hose was analyzed gravimetrically and microscopically.

To determine the probability of error caused by chemical attack of the rubber interliners by the petroleum ether, a segment of an interliner was soaked in petroleum ether for 10 min. and examined before and after microscopically. No puffing, pitting, or other surface damage was observed.

(b) Dynamic Tests

Hoses were dynamically tested on the dynamic test stand to measure the contamination which could be "milked" from the pores of the interliner and also the contamination generated by the interliner itself. These tests were run on new and deteriorated hoses and were run at both high and low pressures. The procedure used to perform these tests is briefly summarized as follows:

(1) The hose was washed three times with triple-filtered petroleum ether.
(2) The hose was filled with triple-filtered MIL-F-5606.
(3) A 500 ml background sample was drained from the hose, and the hose was refilled with triple-filtered MIL-F-5606.
(4) The hose was mounted on the test stand and the test performed.
(5) After the test period, the hose was removed from the stand and a 500 ml sample taken.
(6) The sample was analyzed gravimetrically and microscopically with corrections made for any background error.

There was no migration of contaminant in the hose due to the small amplitude of oscillation of a particle in the hose. The sampling technique used eliminated the possibility of sampling contaminant generated by the ball valves. A stainless steel jumper pipe was used instead of a hose on the stand to prove the sampling procedure.

The gravimetric difference of the background sample was subtracted from the weight of the generated contaminant insuring that only the weight of the contaminant was measured and all procedural errors were compensated for. Therefore, the procedure provided an accurate means of measuring the amount of contaminant generated under known transient pressure conditions.

The deterioration phase of the testing was formulated to examine the secondary generation characteristics and reloading characteristics of the hoses. Over a period of six and one-half months only 30 hours of service time were recorded while the hoses were mounted on hydraulic test stands at Tinker AFB.

C. RESULTS

	T1	R1	T2	R2
Built-in Contaminant, mg/l (from static tests)	26.81	3.07	0.85	0.39
Particle Generation New Hoses, mg/l (from low pressure dynamic tests)	-	-	8.66	7.76
Largest interliner particle, microns	-	-	200	200
Particle Generation Deteriorated Hoses (from high pressure dynamic tests)				
Series # 1				
Gravimetric, mg/l				
First Test	137.58	130.0	4.22	0
Last Test	8.52	5.12	0	-
Microscopic, micron				
First Test	900	1000		
Last Test	150	120		
Series # 2				
Gravimetric, mg/l				
First Test	11.14	3.40		
Last Test	0.58	0.78		
Microscopic, micron				
First Test	150	200		
Last Test	30	200		

Figure 15 shows the plot of the gravimetric analysis results for the high pressure dynamic tests of hoses R1 and T1 in Series #1. It can be seen that hose R1 approached a higher level of cleanliness more readily than did hose T1. This is reasonable since hose T1 had a more porous interliner and had seen longer service than had hose R1. Figure 16 shows the microscopic evaluation of the same series of tests. The curves show that the largest particle "milked" from each hose was roughly the same size for each corresponding pair of cleanings. The curves plot into straight lines on log-log paper.

D. CONCLUSIONS

It can be concluded that the cleaning process used by the manufacturer was not adequate to protect closely toleranced hydraulic systems in either the case of polytetrafluoroethylene or rubber-lined hoses. While the rubber hose could be cleaned more quickly from a gravimetric (volume generated) standpoint, it required the same number of cleanings as did the

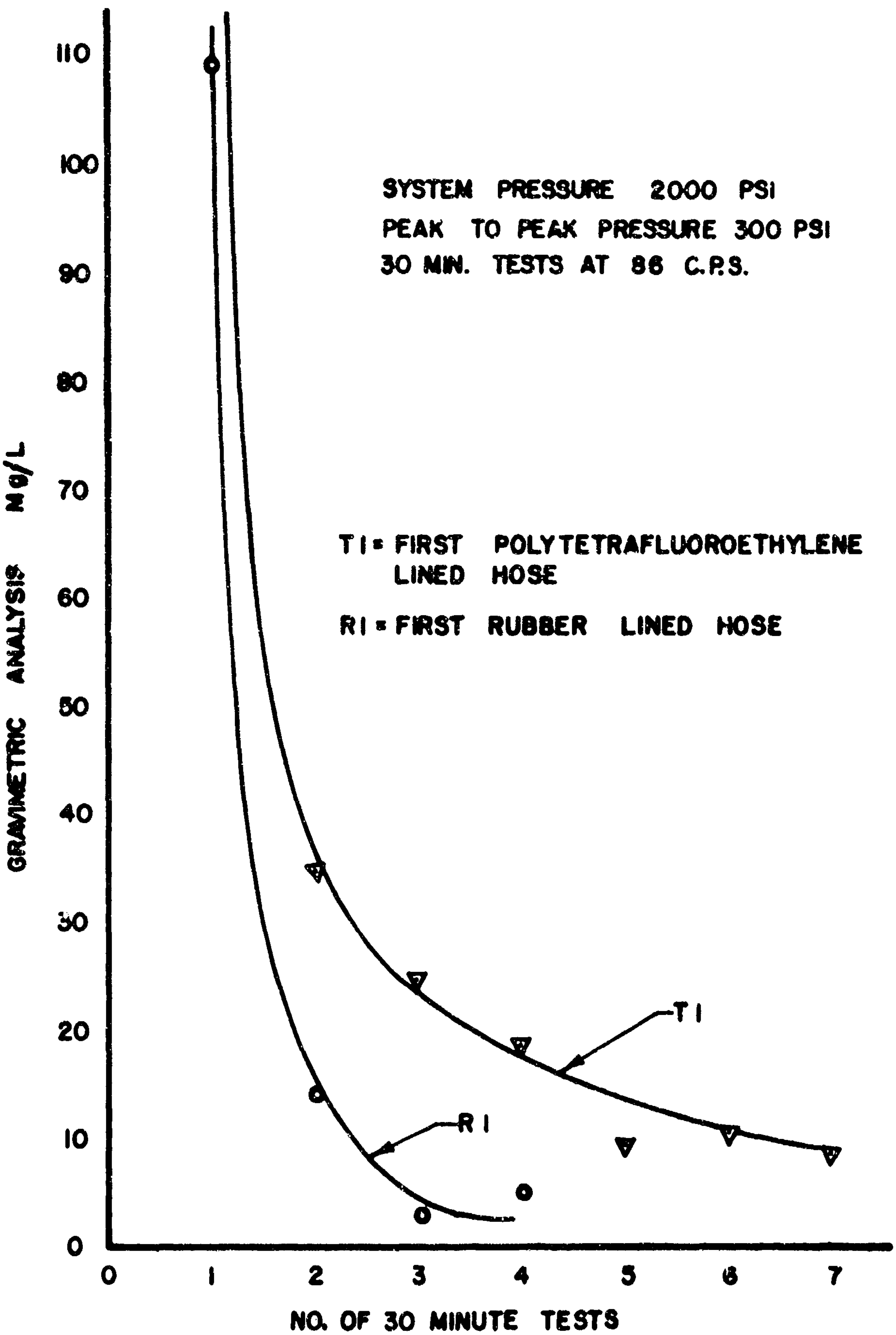

Figure 15. Gravimetric Analysis of Fluid From Hoses Used in the Dynamic Hose Study.

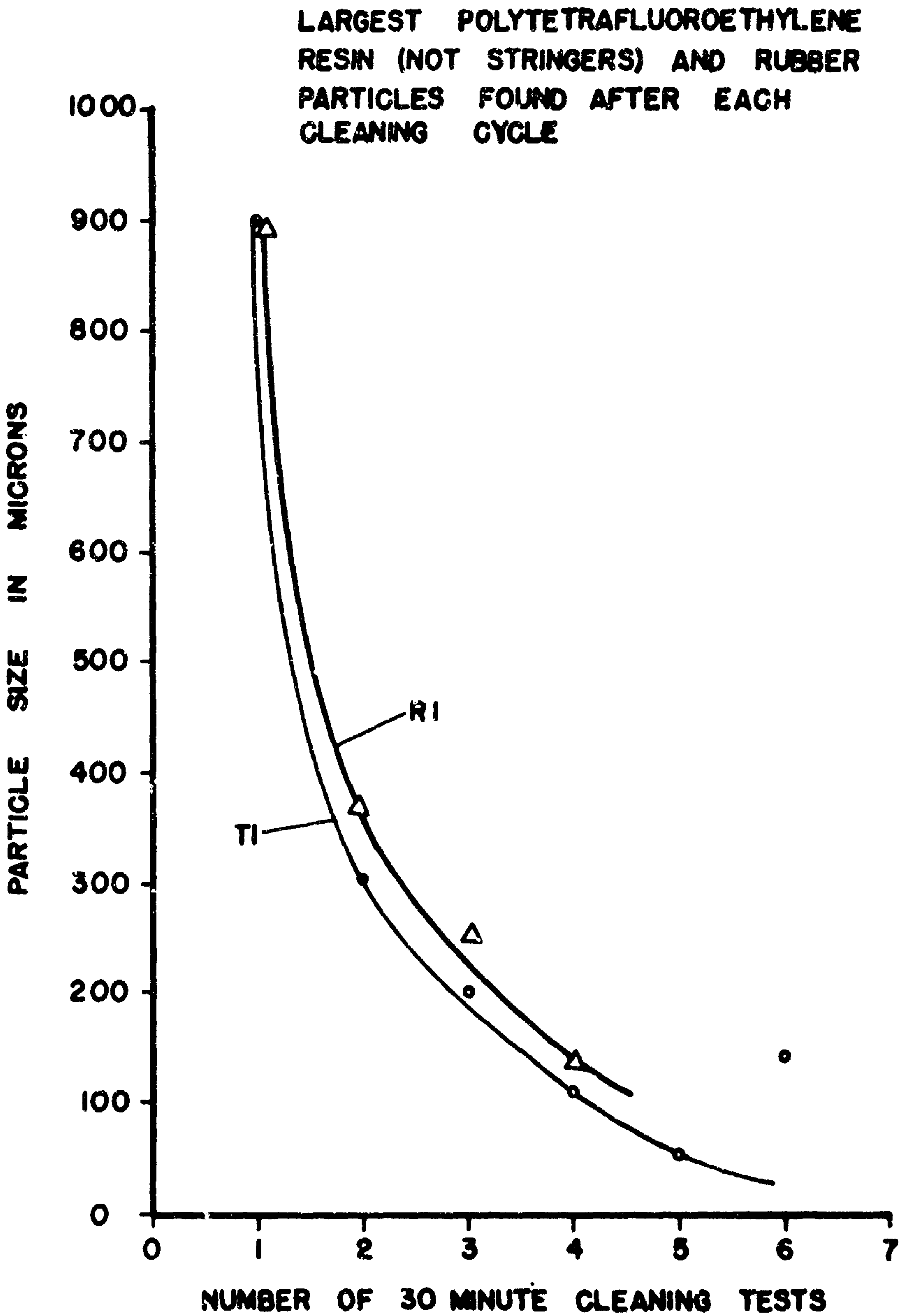

Figure 16. Largest Particle Found in Test Hoses After Each Cleaning Test.

polytetrafluoroethylene-lined hose to establish a small particle size generation characteristic.

While both types of hoses were found to reload after deterioration to a certain extent, it was indicated that a hose which had been cleaned by dynamic pressure pulsation would generate far fewer and far smaller particles than one cleaned by conventional methods. Microscopic studies showed dirt and metallic particles, as well as particles of the interliner material in the test samples, indicating that particle generation and pore extrusion were present as mechanisms of contaminant production. Samples from hoses which had undergone several cleanings showed only traces of interliner material, indicating that once a hose has been dynamically cleaned, a higher energy level is required to "milk" more particles from the interliner.

E. RECOMMENDATIONS

Several phases of this investigation seem applicable to further study. The existing test stand could be modified to produce a larger peak-to-peak pulse at a higher frequency; and, thereby, a more extreme test could be conducted. This could be implemented by redesign of the power system to provide 3000 psi supply pressure, which would increase the peak-to-peak pressure and improve the frequency response using the existing servo-valve. If a larger servo-valve were purchased, a higher peak-to-peak pressure output could be obtained at 2000 psi supply pressure if the valve had a sufficient frequency response.

The optimum energy level which could be used most economically and efficiently to clean a hose to a specified level of cleanliness should be determined. Also, the natural frequency of the hose cannot be strictly defined analytically so an empirical study of this will be helpful in determining the optimum energy level for cleaning.

A microscopic examination of the interliner surfaces could be conducted at various stages of deterioration and cleaning. A modification of production techniques could possibly lead to an initially cleaner hose. Hydraulic system components other than hoses could be tested with transient pressure pulsations.

SECTION X

RESULTS AND CONCLUSIONS

The research conducted under the supplemental agreement No. 2 of contract AF 33(657)-9958 has successfully achieved the objectives outlined in the Work Statement. The laboratory and field test program on the prototype hydroclone has conclusively shown that an optimum designed hydroclone will reduce the contaminant level of a field hydraulic system below that which can be achieved by conventional filtration methods and more importantly maintain this reduced level during flushing operations. Quantitative results from field samples clearly indicate that gravimetric contamination levels are reduced by two-thirds over existing low micron filtration on current hydraulic stands. Furthermore, the utility of the hydroclone for removing important wear particles such as iron, bronze, etc., is incomparable. From a contaminant capacity standpoint, the hydroclone has no rivals. The field tests have demonstrated that the maintainability of the hydroclone is compatible with base level operations throughout the Air Force.

An important aspect was discovered during the field test program concerning flow rate requirements for flushing operations. The 30 gpm flow rate for which the prototype hydroclone was designed is not appropriate for current flushing procedures. A considerable effort was made to establish exactly what flow rates are currently being used in flushing operations. Based on a survey by project personnel, it was found that 15 gpm was compatible with aircraft systems in general. Therefore, the flow rating of the prototype hydroclone tested under this contract did not meet the flushing requirements of field Air Force Maintenance personnel. As a result, the determination of the service life, reliability, and endurance limits of critical components of the hydroclone were limited because of the low flow rates used in the field. It is strongly recommended that a reappraisal of the needs of the Air Force be conducted and a 15 gpm hydroclone be designed and field tested.

The design criteria curves developed during the current contract have established the general physical dimensions for optimum performance of hydroclones with respect to separation efficiency and pressure drop. These curves will be invaluable for developing hydroclones more compatible with field operations. Furthermore, the design curves can be utilized in the design of hydroclones needed for parallel operations where pressure drop requirements are stringent. It has been shown from the hydroclone studies that with the proper selection of materials the service life of the hydroclone should outlast the test stand upon which it is installed.

An extensive laboratory program was conducted to compare the characteristics and performance of the hydroclone with that of a conventional filter conforming to MIL-F-27656A (USAF). This program has revealed the inherent features of each filtration unit and has verified the information obtained from the field study. It has been conclusively shown by the test results that the hydroclone can reduce the contamination level of the system to a degree far exceeding a conventional filter. This can be explained by the fact that the hydroclone exhibits an effective separation efficiency for contaminants below the micron rating of conventional filters. Although this separation efficiency may not be 100 percent at the micron rating of the conventional filters, the effectiveness of the hydroclone at low micron sizes produces a low contaminant level in fluid systems.

The dynamic hose study pursued during this contract has resulted in the development of a unique and effective technique for the cleaning of high pressure hose assemblies as well as other components of a system. The pulsating fluid concept has been shown to "milk out" the contaminant from interstices of the component. This cleaning method gives clean components that would normally slough contaminant in operating systems. Furthermore, the dynamic method developed gave a remarkable means of obtaining quantitative comparisons between material used in the fabrication of high pressure hose assemblies. The employment of dynamic tests such as the one used in this investigation offers great promise for achieving ultra-clean components in the future and is worthy of future study and investigation.

APPENDIX I

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13. ABSTRACT

This report includes a description of the installation of the prototype hydroclone on standard hydraulic test stands as a means of upgrading the decontamination capabilities in USAF ground support equipment. The acquisition of hydraulic fluid samples from the field installations and the laboratory tests of these samples are discussed along with a comprehensive technical comment on the results of the various analyses. A comparison of filtration performance of the hydroclone and the final filter presently being used on the hydraulic test stands is presented. Studies on field test units are presented herein which were conducted to determine the maintainability, compatibility endurance limits, reliability, and service life of the hydroclone and its critical components. A recommended test procedure is presented for the verification of hydroclone performance and the establishment of qualification requirements for quantity production. General design criteria curves for optimum hydroclones are given which can be used to design a hydroclone, using MIL-F-5606 hydraulic fluid, to separate specific sizes and densities of various contaminants found in USAF ground support equipment. A unique method for the dynamic testing

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of high pressure hose assemblies and the cleaning of new hose assemblies is presented along with the contaminant generating characteristics of high pressure hoses constructed of various materials. (U)