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DEVELOPMENT OF HIGH FLOW HYDRAULIC SYSTEM FILTERS

final report to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA 35812

CONTRACT NAS8-11642

JULY, 1965

Arthur D. Little, Inc.

DEVELOPMENT OF HIGH FLOW HYDRAULIC SYSTEM FILTERS

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I. SUMMARY

An improved filter has been developed for use in the engine gimbal actuator system of the Saturn S-1C launch vehicle. This filter differs from conventional woven wire cloth elements in that it is fabricated from a medium composed of randomly oriented four- and eight-micron stainless steel fibers. Thus it is able to act as an efficient depth filter rather than a surface collector.

The filter has been designed to remove particles with somewhat greater efficiency than the presently used 325 x 1900 Dutch Twill wire cloth element. Our principal objective, however, has been to achieve a significant increase in solids-holding capacity while maintaining high reliability. On the basis of comparative data obtained in the laboratory it appears that the new element should be capable of holding up to five times as much collected particulate matter as conventional filters before reaching an arbitrary cutoff pressure drop. While the initial pressure drop is somewhat higher than that of conventional elements, the increased solids capacity makes this difference inconsequential.

Removal of collected material by ultrasonic agitation is, of course, less effective with a depth-type filter than with a surface collector. Nevertheless, we have found that with special cleaning techniques, an appreciable portion of the collected material may be removed. Because of the increased capacity of the new element and because of its probable cost advantage over woven wire cloth elements, the necessity and/or desirability of cleaning is questionable.

A serious problem with many depth-type fibrous filter media is their tendency to shed fibers during use, resulting in recontamination of the cleaned fluid. In the present case, such media migration is controlled in part by the long fibers used to form the web and in part by sintering the medium assembly after pleating. Laboratory results indicate negligible fiber migration under varying test conditions.

During the course of our development program over 150 samples of candidate filter media have been evaluated. Among the most promising types of materials investigated were media samples submitted by Brunswick Corporation. These webs represented the first practical commercial attempt to employ randomly oriented small diameter metal fibers in a fluid filter medium. (It is well known that as fiber size decreases, filtration performance improves.) Accordingly, a Brunswick stainless steel fiber web tailored to our particular requirements was selected for use in our filter. Since the process by which Brunswick makes the fiber is a new one, the method of forming a usable filtering web required considerable development. The product included in the new filter elements thus represents the best material available from Brunswick at the present time. Our analysis of the medium indicates some lack of uniformity, however, and there is strong evidence that the small diameter fibers incorporated in the web are not being used to full advantage. Thus there is

room for further improvement in the performance and reliability of the product.

In addition to the Brunswick material, there were other candidate media which were found to have many of the attributes which we were seeking. We were especially interested in the possibility of finding a material whose development was further advanced than the Brunswick web. This would then allow more direct procedures to be used in procurement of standardized finished elements.

One of the other promising candidates came from Bendix Corporation, who now manufacture a line of disposable depth-type filters incorporating fine glass fibers. These are sold under the trade name Microfil. Because Bendix was willing to tailor their material to approach our specific requirements, we arranged (after a number of evaluation steps) to procure full-size cartridges designed to fit the S-1C filter manifold assembly. While these elements have a higher initial pressure drop and lower solids capacity than those incorporating the Brunswick web, filtration efficiency is comparable and true depth collection is achieved. Special techniques are used to control media migration. Thus the Bendix element provides the alternative of a commercially available, low-cost unit having comparable efficiency and perhaps three times the solids-holding capacity of currently used woven wire cloth cartridges.

II. INTRODUCTION

This report summarizes work accomplished under Contract NAS8-11642 on the development of improved high flow hydraulic system filters for use in the thrust control actuators of the S-1C stage of Saturn 5. It was our objective to develop a filter which would constitute an advance in the state-of-the-art with respect to solids removal efficiency, solids capacity, and performance reliability.

The final prototype filter developed under this contract had to be designed for use in the existing filter manifold assembly of the S-1C. Thus, over-all dimensions of the element were fixed (approximately 3¼" diameter x 7" length). Design rating was to be 120 gpm of RP-1 (which is used as the hydraulic fluid) at an operating pressure of 3000 psig.

During recent years there has been a consistent trend toward more stringent requirements for hydraulic system contamination control. In general, improved cleanliness has been sought through the use of filters made from tightly woven screens or sintered metal powders of very small particle size. While substantial improvements in control of particulate contaminants have been achieved by this approach, it is apparent that a point of diminishing returns has been reached. That is, any further efforts devoted to the achievement of high filtration efficiencies through the use of more tightly woven constructions or finer metal powders must result in unreasonably high pressure drop, extremely limited solids capacity, and exorbitant costs.

It was our contention that the logical approach to the objectives of this program involved the use of randomly oriented fibrous structures. It is well known that as fiber size decreases, filtration efficiency increases. Further, by properly designing the properties of a fibrous web, it is possible to achieve both collection in depth and over-all high efficiency.

In the early stages of the program, our prime concern was with the selection of a filter medium having both high efficiency and high capacity for solids. Only after sufficient information was available to permit this selection could the prototype element be designed to accommodate it. Thus our approach has involved the following phases:

A. Study and analysis of the current status of knowledge and practice in fluid filtration and related areas.

B. Procurement and evaluation of samples of candidate media from all possible sources.

C. Selection of the filter medium which most closely approached our performance objectives.

D. Design, construction, and evaluation of prototype filters incorporating the chosen filter medium.

Our efforts and accomplishments in each of these phases are described in the sections of this report which follow.

III. LITERATURE AND INDUSTRY SURVEY

Our initial task under this assignment involved an extensive review of the technical literature in order to establish the state-of-the-art and in order to take maximum advantage of current research. To supplement this effort, we contacted a number of industrial organizations which were active in fluid filtration or related areas. The results of this survey are summarized in the paragraphs which follow.

A. LITERATURE REVIEW

Our search of the technical literature included both U.S. and foreign publications and patents as well as U.S. Government reports in the following general categories:

1. Liquid filtration with special emphasis on hydraulic fluid cleaning techniques

2. Metal fiber technology

3. Sources of small diameter fibers

4. Other related aspects of fluid filtration

Over 200 references were reviewed and approximately 75 were copied and retained for study and future reference. In addition, our Document Services Group performed a continuing review of current publications and presentations so that we might monitor developments as they occurred. A bibliography of some of the more pertinent references is included in Appendix A.

While it is difficult to draw firm conclusions from a review such as this one, our findings are summarized generally below:

a. Most of the recent efforts of the filter industry on hydraulic fluid filtration have been devoted to the use of either sintered metal powders, Dutch Twill woven wire cloth, or both. With such systems, efficiency can only be obtained at the expense of solids capacity. Though some depth-type collection occurs with sintered metal powders, the geometry of packed spheres severely limits the performance obtainable. With a tightly woven wire cloth, efficiency can be obtained by making the pore size sufficiently small. In such a case, however, collection is almost entirely on the surface so that capacity for solids is extremely low.

b. Some work on filters made from randomly oriented metal fiber webs was done at Armour Research Foundation (now Illinois Institute of Technology Research Institute) several years ago. Their efforts resulted in a metal fiber felting process which is capable of producing randomly oriented webs. The webs are subsequently sintered to provide strength. This process is now being used commercially by Huyck Corporation.

c. Other processing techniques have been slow to materialize because of the expense of making metal fibers of suitable size. Patents pertaining to a system of spinning metal fibers from melts are assigned to Marvalaud, Inc., an affiliate of American Viscose Corporation. These techniques have not been used commercially, however, since adequate markets have not materialized.

d. Fram Corporation has licensed a replicating technique for metallizing fibers of various types. This process is just starting to be used in the production of filters, but apparently no commercial sales have yet been made.

e. Brunswick Corporation has started pilot production of their process for making metal fibers and metal fiber webs. These techniques are so new, however, that very little had been done in the field of fluid filtration prior to this contract.

f. Some work has been done on the use of filter aids to permit collection in depth with controlled pore size woven wire cloth media. In those cases where the precoat layer can be formed without danger of system contamination, and where there is no danger of accidental backflow through the filter, this can be an effective method.

g. Fram Corporation has done some work on a phenolic resin-bonded cellulose paper filter which they claim will withstand 3000 psi differential pressures.

h. Considerable effort has been devoted in recent years to the growth of crystalline filaments from metals and from ceramics. These filaments, called "whiskers," possess extremely high tensile strengths (2,000,000 to 3,000,000 psi) and show 3-4% elastic deformation. Pure sapphire whiskers of this type have recently become available from Thermokinetic Fibers, Inc. While the 1-3 micron fiber diameter is of interest as a potential filtering fiber, present costs are prohibitively high ($40-85/gram). In addition in our application, strength must be inherent in the web, not in the fiber. Thus conventional ceramic fibers of similar size would appear to be equally useful and far less expensive.

B. INDUSTRIAL CONTACTS

Our position as an independent contract research organization with no interest in ultimate manufacture of the filters developed under this program has permitted us to obtain the cooperation of many industrial organizations during the course of this work. It is obvious, of course, that the filter industry has been motivated by a desire to keep up with developments as they occur and by a desire to be in a favored position for ultimate manufacture of filter units. While we were fully aware of this motivation, we felt it was in the best interests of NASA to take advantage of new technology in this field wherever it might be located. Accordingly, we took the position that we would work closely with industry whenever such a course was feasible and of potential benefit to our program. We were extremely careful, however, to avoid making any commitments which might have limited our own activity. Thus, we solicited samples of experimental media for evaluation and we welcomed any other contribution which might be made. In addition, we expressed a willingness to discuss the general aspects of our program with industry whenever it appeared that such a discussion might beneficially augment our own efforts.

Listed alphabetically below are the industrial organizations with which we have had some direct contact, either through their expressions of interest in our program or through consideration of their products as candidate filter media.

1. Aeroflex Laboratories, Inc., Plainview, New York
2. Aero-Flow Dynamics, Inc., Corry, Pennsylvania
3. Aircraft Porous Media, Glen Cove, New York
4. Bendix Filter Division, Madison Heights, Michigan
5. Brunswick Corporation, Groton Laboratory, Groton, Massachusetts
6. Continental Copper and Steel Industries, Inc., Caldwell, New Jersey
7. Cuno Engineering Corporation, Meriden, Connecticut
8. Fram Corporation, Providence, Rhode Island
9. Gelman Instrument Company, Ann Arbor, Michigan
10. Greer Hydraulics, Los Angeles, California
11. Huyck Metals, Milford, Connecticut
12. Hydraulic Research and Manufacturing Company, Burbank California
13. Millipore Filter Corporation, Bedford, Massachusetts
14. Pallflex Products Corporation, Putnam, Connecticut
15. Selas Flotronics, Spring House, Pennsylvania
16. Thermokinetic Fibers, Inc., Nutley, New Jersey

IV. MEDIA EVALUATION PROGRAM

A. APPARATUS

1. Laboratory Test Facility

A small-scale laboratory test stand was designed and constructed in order to permit comparative evaluations of candidate filtering materials to be made. The general arrangement of the apparatus is shown schematically in Figure 1. Figure 2 is a photograph of the facility. While the basic system is a simple one allowing either single pass or recirculating operation, we attempted to incorporate sufficient flexibility to permit a variety of operations to be carried out without facility modification. Some of the features of the system are discussed briefly below:

a. Main Flow System

The test fluid (RP-1) could be drawn from one or both of the two epoxy-lined reservoirs by a variable-speed gear pump capable of delivering up to 3 gpm @ 75 psi. The arrangement was such that fuel could be by-passed back to the reservoirs or it could be pumped through the test filter system to the receiving vessel. Through valving changes and the use of quick-disconnect couplings, it was possible to alter the relative position of system components and the mainstream flow pattern in a variety of ways to suit particular needs.

b. Sample Holding Arrangements

The original system was designed to take a 3.5-inch diameter sample filter which was positioned in such a way that 0.05 sq. ft. of area was exposed to the test fluid. The arrangement is shown in Figure 3. In the latter stages of our program when element and module configurations were being investigated, we substituted various housing arrangements for the flat sheet holder.

c. Sampling

Provision was made for withdrawing upstream and downstream samples through unrestricted upstream-facing ports. Millipore bomb sampling equipment was used to retain particulates present within the samples. During most of our filter media screening program we collected particulates which passed the test filter on a 142 mm diameter type DA (0.65 μ pore size) Millipore filter. In this manner, the total amount of material which penetrated the test filter was determined gravimetrically; sampling was therefore not required.

d. Contaminant Injection

Each of the fuel reservoirs was equipped with an efficient

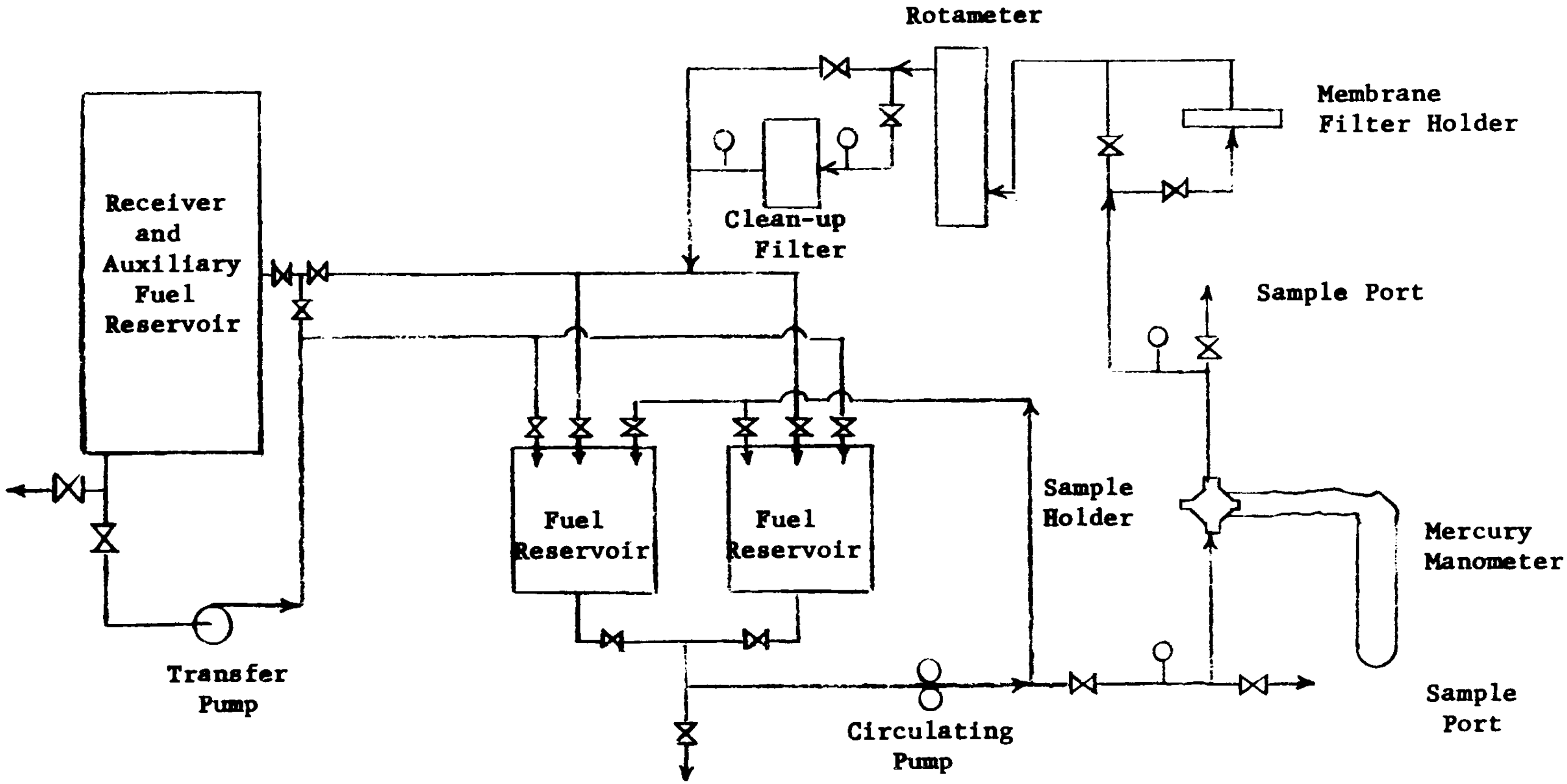

Figure 1

SCHEMATIC FLOW DIAGRAM OF LABORATORY TEST FACILITY

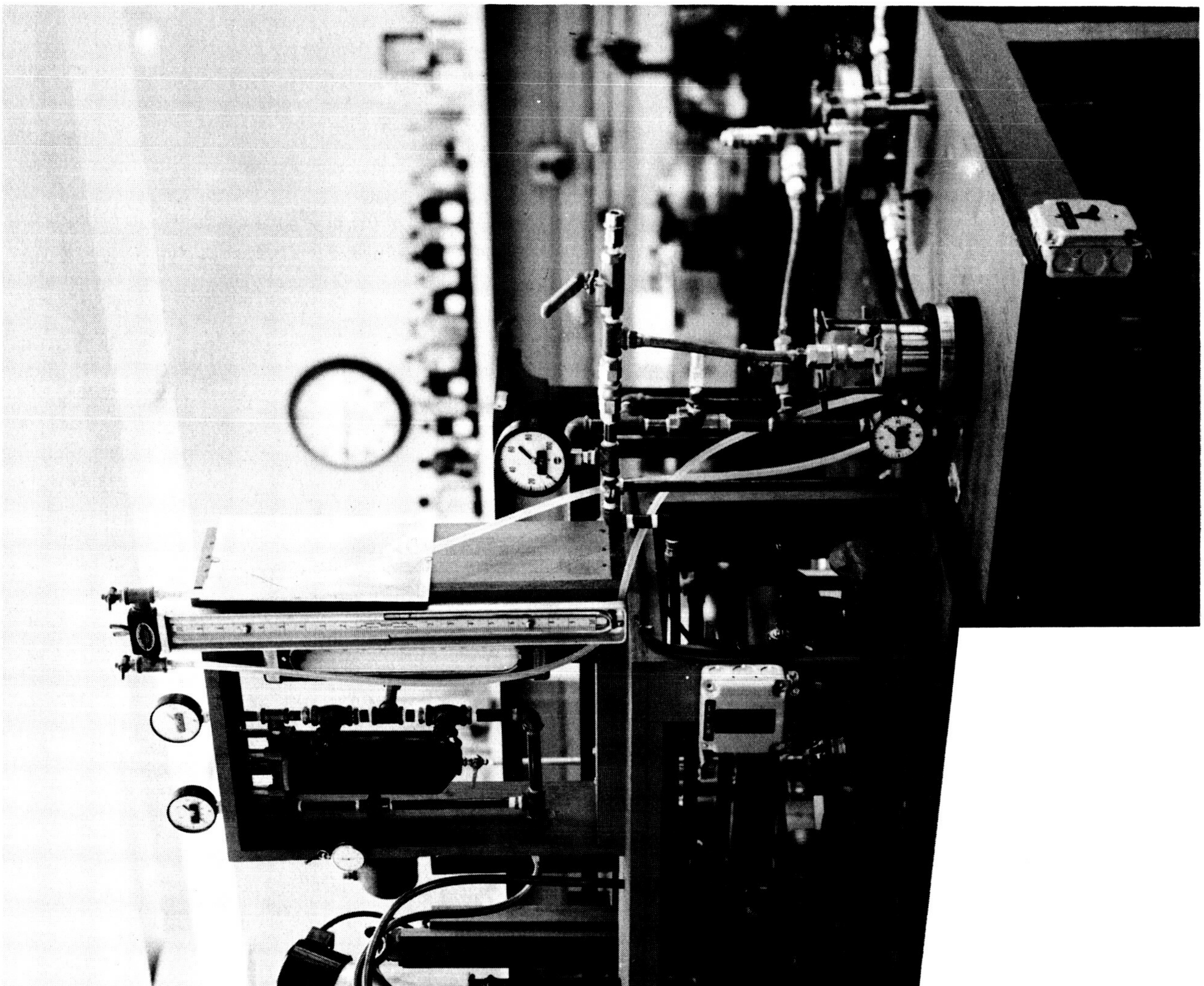

FIGURE 2   LABORATORY TEST FACILITY

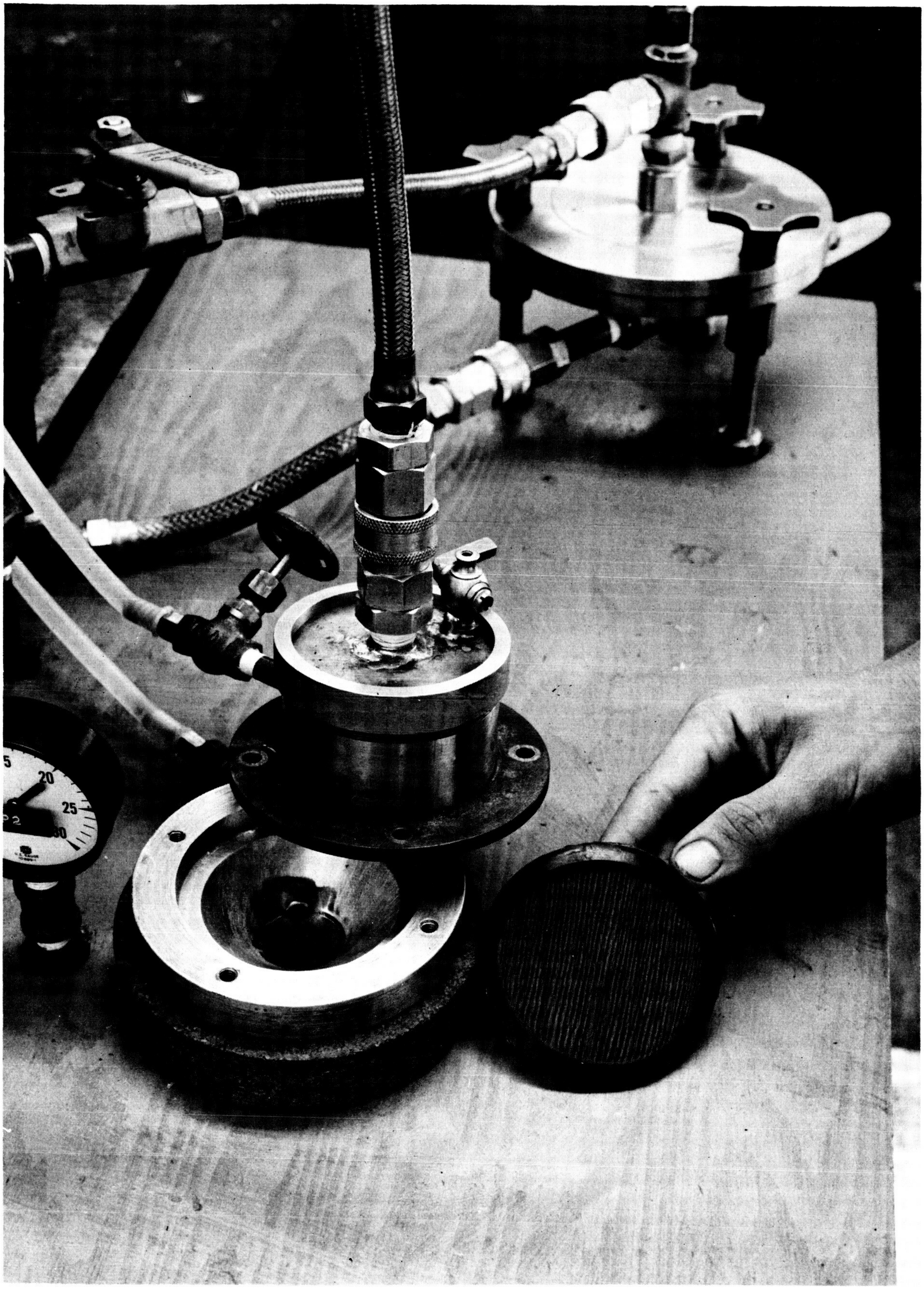

FIGURE 3   SAMPLE MOUNTING SYSTEM

stirrer capable of maintaining particulate contaminants in dispersion. Our procedure involved contaminating a quantity of fuel with a known amount of particulate matter and pumping it directly to the test filter system. While this procedure resulted in direct abrasion of the gear pump, the rate of erosion was so low that no serious difficulty was encountered during the course of the entire program.

No matter how a contaminant is introduced into a test system, the prime criterion for obtaining meaningful results concerns the degree of dispersion of the particulate matter. Unless particles are broken down to their ultimate size effectively and reproducibly, any measurements of filtration performance are of negligible value.

Our technique for dispersing contaminant involved weighing out the desired amount of material and placing it in a bottle with a small quantity of fuel. The bottle was capped and immersed in an ultrasonically agitated bath for a period of 30 minutes. The contents of the bottle were then carefully washed into the proper quantity of fuel in the reservoir. Microscopic examination of Fine AC Test Dust prepared in this manner indicated essentially total dispersion with no visible agglomerates of particulate matter.

2. Bubble Pressure Testing

A simple system for measuring the bubble pressure of test samples of filter media was set up which included a horizontally mounted sample holder and means for applying air pressure from below. In general, for a porous material with cylindrical pores, the pressure required to force the first dynamic bubbles of air through the medium when it is submerged below the surface of a liquid is related to the size of the largest capillary as shown below:

$$p = \frac{2s}{r}$$

where p = bubble pressure

s = surface tension of the liquid

r = radius of the largest pore

Because most of the materials with which we were concerned were not made up of parallel cylindrical capillaries, the indicated maximum pore size was not necessarily directly related to the size of the largest particle which might penetrate the filter. Nevertheless, we believe that the measurement does have significance, especially when comparing similar materials. We chose to use analytical reagent-grade methyl alcohol as the test fluid for bubble pressure measurement, since this material is readily available and is sufficiently pure to insure constant and reproducible surface tension.

3. DOP Tester

Measurements of the inherent filtration capabilities of various candidate media have been made with a dioctyl phthalate (DOP) smoke penetrometer. This apparatus is a LaMer-Sinclair type aerosol generator arranged and operated in such a way that an essentially monodisperse oil aerosol of 0.3 micron particles is produced. A forward angle light-scattering photometer is used to provide a measurement of the amount of smoke penetration through a filter under test. By proper operation of the system it is possible to read directly the smoke penetration from 100 per cent to as low as 0.001 per cent. (Per cent efficiency is, of course, 100 minus the per cent penetration.)

While this test method was developed for use in evaluating high-efficiency air filters, experience has shown that a direct correlation exists between filtration performance in liquid systems and DOP performance for a wide variety of types of filters. Since it is a rapid and nondestructive method of assessing inherent capabilities, it has been used extensively in our program.

4. High-Pressure Test Facility

In order to evaluate performance characteristics of filter media and filter configurations under conditions simulating ultimate use, it was, of course, necessary to consider operation under high-pressure conditions. Accordingly, a simple high-pressure test stand was set up as shown in Figure 4. This was a low flow rate system which was adaptable to the testing of small samples of filtering materials under use flow conditions or which could be used to investigate structural aspects of cartridges under static or impulse pressure conditions.

B. EVALUATION PROCEDURES

1. Basis for Evaluation

Since it was the principal object of this contract to develop a filter with an appreciably higher capacity for solids (at comparable efficiency) than that currently achieved with woven wire cloth elements, we elected to use typical Dutch Twill screens as our basis for comparative evaluation. Thus the properties of woven wire cloths (particularly the 325 x 1900 material used in the Saturn S-1C filter manifold assembly) were studied in detail in our program in order to define the present state-of-the-art. Potential utility of candidate media was then determined by direct comparison of performance capabilities.

2. Experimental Procedures

For the purpose of comparative evaluation of various filtering materials, we elected to investigate performance on the basis of efficiencies determined by gravimetric methods. In addition, our test methods were such that considerable information about capacity for

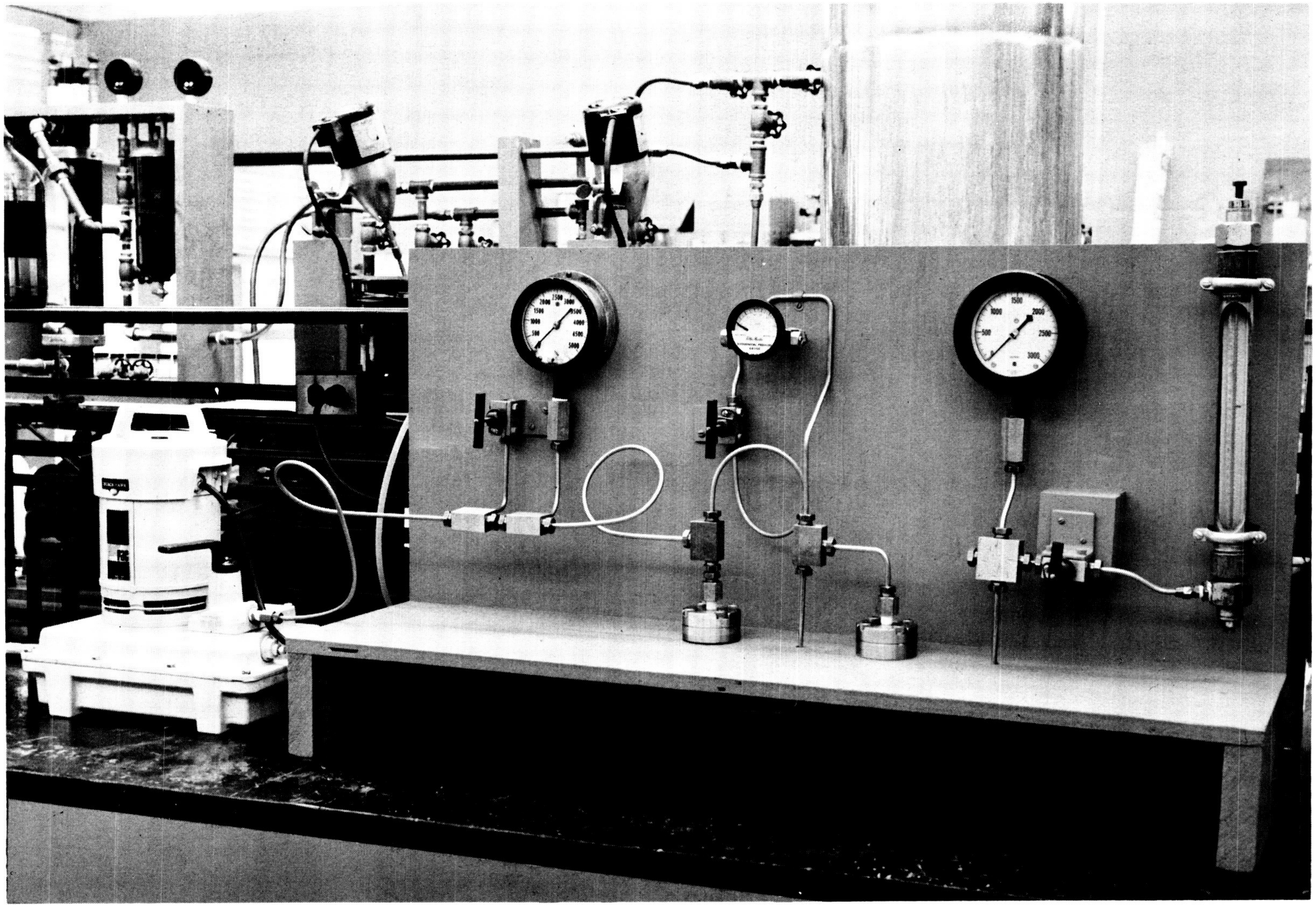

FIGURE 4 HIGH PRESSURE TEST STAND

dispersed solids (i.e., filter life) was also determined. Efficiencies can, of course, be determined through particle size analysis of upstream and downstream samples. Where the performance of candidate materials may vary over a wide range, however, and where a rapid and accurate assessment of performance is required, gravimetric techniques offer a distinct advantage.

In general, our test procedure involved the addition of a carefully measured quantity of predispersed contaminant to a known volume of fuel. After thorough mixing, the contaminated fuel was pumped through the test filter and a Type DA (0.65 μ pore size) Millipore filter in series. Contaminant which penetrated the test specimen was retained on the Millipore.

Initially, a pre-extracted, tared membrane was used. After the residual fuel was extracted with petroleum ether, the increase in filter weight caused by the retained contaminant was used to calculate the test sample efficiency. It was noted, however, that the extractables in the Millipore were somewhat erratic and hard to control in a filter as large as 142 mm in diameter. Accordingly, our procedure was modified so that the membrane was carefully ashed in a muffle furnace and the weight of residual material in the crucible taken as the penetrant.

An arbitrary set of test conditions was used for most of our screening runs, but the effect of several variables has also been investigated. As a reference condition, we selected a flow rate of 10 gpm/ft^2 at a contaminant concentration of 100 mg gal, using Fine AC Test Dust. Each test was normally run for a period of 15 minutes, provided that the capacity of the filter for solids was not exceeded prior to that time. Efficiencies determined in this manner were thus averages which were not necessarily representative of either the initial or the final performance. Nevertheless, the average efficiency determined, the rate of pressure drop build-up, and the total time of the run, provided the means for obtaining a clear and concise measure of comparative performance. In addition, the supplemental information obtained for each candidate filter medium on aerosol penetration, bubble pressure, clean flow pressure drop, and media migration, broadened the scope for comparative evaluation.

3. Filter Media Rating Systems

In attempting to compare the performance of many different filter media, the large amount of data sometimes tends to make interpretation difficult. A simple, uniform method of comparatively rating efficiencies and solids retention capacities is necessary. Ideally, a single rating number would combine terms related to inherent efficiency, solids-holding capacity, and average efficiency during the life of the filter. We have found, however, that it is more straightforward to use two rating numbers, one representing inherent filtration performance and a second representing solids capacity and average efficiency.

The inherent filtration capability of a material determines its initial performance. The manner of testing must be meaningful, rapid, and must not significantly load the medium. For this determination, we have elected to use the dioctyl phthalate (DOP) aerosol penetrometer described in Section IV.A.3.

For filtration of aerosols from gases, using a monodisperse aerosol, a figure of merit, E, may be calculated from the following expression:

$$E = \frac{-100 \log \frac{P}{100}}{\Delta p}$$

where P = per cent of aerosol penetrating through the filter

Δp = initial pressure drop at a given linear velocity

It has been found that E is nearly constant for a given fiber size (i.e., it is essentially independent of variation in thickness or density) and that it increases steadily as fiber size decreases.

While the DOP test method and its related figure of merit were developed for aerosol filter evaluation experience has shown that for a given filter medium, the inherent filtration capability in a gaseous system correlates closely with its performance in a liquid system. Accordingly, the value of E computed from our experimental data has been used as a measure of the inherent capability of a filter medium.

The second characterization of the medium covers the efficiency of solids removal and retention capacity in liquid systems. It is based on results obtained under the standard conditions used in our test facility. Because standard conditions are employed, the capacity of the test medium may be taken as the length of time required to reach a specified pressure drop. The final form of the combination of efficiency and capacity is an arbitrary one which is based upon the requirements of this contract. In the following paragraphs, we present an explanation of the system.

In general, for any given filter type, capacity is gained as efficiency decreases. It is apparent, therefore, that the form of the rating number should be capacity multiplied by efficiency. Although either term could be raised to a power to emphasize its effect, there is no justification for such a complication.

The point at which the capacity of the medium has been reached may be defined in a number of ways. The characteristic curve of pressure drop versus time presents several choices. One possibility is to measure the time at which the second derivative of this curve reaches its maximum.

Although the "knee" in the curve is quite apparent, the inaccuracies from performing a double differentiation on the data militate against this method. A more reasonable system is to note the time at which a specified pressure drop has been reached. By choosing a pressure sufficiently high, the point will always be in the nearly vertical section of the pressure drop-time curve. The higher this pressure drop, the more independent of experimental inaccuracies the time determination will be. For our study, a pressure difference of 30 inches of mercury has been used to represent the capacity of the medium.

The simplest system would be to use the efficiency directly in computing the rating number. Unfortunately, this method gives unsatisfactory results by giving too much emphasis to capacity at the expense of efficiency. In order to eliminate this problem, and in order to relate the rating to the requirements of this contract, we have elected to assign a rating of zero to any medium for which the efficiency is less than an arbitrary cutoff value. In the present case, the efficiency specified by the contract is a minimum of approximately 80% weight removal of particles over 10 μ equivalent diameter. The test contaminant being used contains approximately 60% by weight of material under 10 μ. Accordingly, we have selected a 40% weight efficiency on the AC Fine test dust as a reasonable minimum performance requirement. Media with efficiencies greater than 40% are assigned an efficiency number from zero at 40% efficiency to one at 100% efficiency. Mathematically, the efficiency number, N, is defined as

$$N \equiv \begin{cases} 0, \text{ if Efficiency} \leq 40\% \\ \dfrac{\text{Efficiency}}{60} - \dfrac{2}{3} \qquad \text{if } 40 \leq \text{Efficiency} \leq 100 \end{cases}$$

The performance rating, $\mathcal{R}$, of a particular medium is taken as the product of the efficiency number, N, and the capacity defined above.

We have applied this system to the results obtained in our work. The inaccuracies in the data used in calculating the rating probably limit the reproducibility of the value to about 5 to 10%. Within this limitation, the system appears to provide a useful means of comparing different filtering materials.

C. EVALUATION OF CANDIDATE MEDIA

During the course of this contract we have given consideration to over 150 samples of candidate filter media of widely differing properties. These have included both conventional types of filtering materials and products still in the developmental stage. We have, in general, been guided by NASA's requirement for a filter superior in solids capacity and at least equivalent in efficiency to the presently used 325 x 1900 Dutch Twill wire cloth. Accordingly, we have attempted to document rather thoroughly the performance obtainable with woven wire cloth products so that a firm point of reference might be established.

In this section of the report, we present in summary form the principal results obtained in our comparative evaluation program. As indicated in subsequent sections, however, many other factors were taken into consideration in selecting a filter medium with which to make prototype cartridges. For purposes of clarifying the presentation of a large amount of data, we have separated our results into four categories: conventional filter media; high-efficiency filter media; metal fiber products; and other candidates. Each of these categories is discussed in the paragraphs which follow:

1. Conventional Filter Media

Included in this category are materials which are commercially available and which are commonly used in hydraulic and other fluid filters. Performance results are summarized in Table I; each of the types of materials is described briefly below:

a. 325-Mesh Stainless Steel Screen

This is a conventional square weave wire cloth which is included here as a performance reference. It is obvious from the results presented that it provides for very inefficient removal of dispersed particles unless they are very large, or unless a cake of collected material is first permitted to build up.

b. Dutch Twill Wire Cloth

Four samples of Dutch Twilled media, typical of those used in current hydraulic fluid filters, were evaluated. These are rated approximately as follows:

25 μ absolute, 15 μ nominal, 165 x 1400 mesh
18 μ absolute, 10 μ nominal, 200 x 1400 mesh
15 μ absolute, 7.5 μ nominal, 325 x 1900 mesh
12 μ absolute, 5 μ nominal, 325 x 2300 mesh

The 325 x 1900 cloth was obtained from a local supplier; the other three were provided to us by Fram Corporation. Data for the former sample show an efficiency slightly higher than anticipated, due to the fact that the wire size was smaller than normal (0.0014 warp and .0009 shoot rather than the 0.0014 warp and .0011 shoot used in present elements for the filter manifold assembly). For all of these samples, since collection is primarily on the surface of the cloth, capacity for solids is low.

Three additional samples of currently used Dutch Twill wire cloth were supplied to us by Aircraft Porous Media, Inc. These differed from the others in that they were sintered after weaving, thus reducing the possibility of flaws appearing in the medium during handling.

TABLE I

PERFORMANCE OF CONVENTIONAL TYPES OF FILTER MEDIA

Material	Source	Bubble Pressure in. H_2O	DOP Performance* ΔP mm H_2O	DOP Performance* Aerosol Penetration %	DOP Performance* E	Fluid Filtration Performance Initial ΔP in. Hg	Fluid Filtration Performance Final ΔP in. Hg	Fluid Filtration Performance Run Duration min	Fluid Filtration Performance Solids** Capacity min	Fluid Filtration Performance Efficiency %	R
325 Mesh Screen	Hub Wire	5.1	-	~100	-	<0.03	<0.03	15	-	18	0
Dutch Twill, 165 x 1400, 25 μ abs.	Fram	13.0	-	-	-	0.10	40	4	3.6	51	1
Dutch Twill, 200 x 1400, 18 μ abs.	Fram	14.2	-	-	-	0.24	52	3	2.4	61	1
Dutch Twill, 325 x 1900, 15 μ abs.	Hub Wire	22.4	13	99	0.1	0.3	30	2.25	2.25	73	1
Dutch Twill, 325 x 2300, 12 μ abs.	Fram	24.1	-	-	-	0.33	70	2	1.6	70	1
CH Rigimesh, 15 u absolute	APM	17.7	21	96	0.1	0.45	42	1.75	1.6	68	1
NK3 Space Age Mesh, 18 μ absolute	APM	15.0	6	98	0.1	0.22	32	3.25	3.2	57	1
K3 Space Age Mesh, 18 μ absolute	APM	10.8	4	99	0.1	0.15	34	3.75	3.6	47	0
Sintered SS Powder, 10 μ nominal	Cuno	11.3	150	84	0.05	2.5	43	3.5	3.2	67	1
Sintered SS Powder, 5 μ nominal	Cuno	14.0	196	59	0.1	3.4	33	3.0	2.9	79	2
Z Supramesh, 15 μ absolute	APM	16.0	54	91	0.06	1.3	38	3.5	3.1	79	2
Z/60 Supramesh, 15 μ absolute	APM	-	38	90	0.1	Sample too small for testing					
Paper, 40 μ nominal	Fram	3.2	4	98	0.5	0.06	0.24	15	>15	30	0
Paper, 10 μ nominal	Fram	7.2	43	80	0.2	0.69	47	9	7.7	72	4
Paper, 5 μ nominal	Fram	8.9	80	72	0.2	1.32	44	2.7	2.4	79	2

*0.3 μ Aerosol penetration and pressure drop measured @ linear velocity of 28 ft/min through sample.

**Solids capacity is defined as total running time before reaching ΔP of 30" Hg under standard test conditions of 10 gpm/ft^2 of RP-1 containing 100 mg/gal dispersed AC Fine Test Dust.

Performance is generally comparable to other Dutch Twills.

c. Sintered Stainless Steel Powders

Two samples of sintered stainless steel filter media rated at 10 and 5 microns were procured from Cuno Engineering and evaluated in order to obtain additional references to the present state-of-the-art. Although sintered powdered metals do accomplish some collection of particulates in depth, the effect is a relatively small one as indicated by comparing the rating number for these materials with that of the wire cloths.

d. Combination of Sintered Powders and Wire Cloth

Two samples of APM's Supramesh were also included in our program. These materials consist of a layer of powder metal particles on top of a conventional Dutch Twill wire cloth. The entire assembly has been sintered to form an integral material. As shown by the results in Table I, performance is generally typical of powder metal filters (though the twill backing provides for an absolute particle size cutoff and minimizes media migration).

e. Phenolic Resin Impregnated Papers

Three samples of typical paper filter media were supplied to us by Fram Corporation. These were made from cellulose fibers and were saturated with a phenolic resin. The manufacturer designated them as 40, 10, and 5 micron nominal filter papers. Because of the randomly oriented fibrous structure, particles are collected in depth, resulting in higher rating numbers.

2. High-Efficiency Filter Media

While none of the conventional filtering materials discussed above showed a particularly high efficiency, it was recognized that many commercially available materials have a small pore structure (as in a membrane filter or a fibrous web incorporating submicron fibers) and thus a high inherent filtration efficiency. Although our primary objective was not increased efficiency, many of these materials were encountered and evaluated during the course of our contract. Experimental results have been grouped together for such materials and are presented in Table II.

a. Millipore Type WH

This is a nylon reinforced 0.45 μ pore size membrane filter which accomplishes collection almost entirely upon its surface. Solids capacity is thus necessarily limited, but particle removal is essentially absolute.

TABLE II

PERFORMANCE OF SPECIAL HIGH-EFFICIENCY FILTER MEDIA

Material	Source	Bubble Pressure in. H_2O	DOP Performance* ΔP mm H_2O	Aerosol Penetration %	E	Fluid Filtration Performance Initial ΔP in. Hg	Final ΔP in. Hg	Run Duration min	Solids** Capacity min	Efficiency %	R
Millipore WH	Millipore	350***	1120	0.000	>0.4	36	72	2.7	-	~100	-
Type E Glass	Gelman	22.6	97	0.034	3.6	2.7	26	5.6	6.1	99.3	6
Versapor 6429	Gelman	35.6	385	0.000	>1.3	8.1	45	5	3.8	99.3	4
Glass Asbestos Paper	ADL	9.4	84	0.80	2.5	2.1	42	8	7.3	97	7
Glass Rayon Vinyon Paper (GRV)	ADL	9.2	29	7	4.0	0.6	23	11	~12	93	10
13044-46-1	APM	>180	>3700	0.000	<0.14	-	-	-	-	-	-
13044-46-2	APM	21	362	0.12	0.8	9.8	41	3.5	2.75	98.3	3
13044-46-3	APM	13	69	15	1.2	2.2	43	5	3.8	94.6	3
13044-46-4	APM	-	1260	0.20	0.2	-	-	-	-	-	-
13044-46-5	APM	38	1040	0.008	0.4	-	-	-	-	-	-
13044-46-6	APM	47.5	745	0.042	0.5	-	-	-	-	-	-
13044-46-7	APM	28.5	242	0.020	1.5	5.6	42	3.5	2.9	99.1	3
13044-46-8	APM	11.1	160	0.03	2.2	5.7	Medium broke during testing				

*0.3 μ Aerosol penetration and pressure drop measured @ linear velocity of 28 ft/min through sample.

**Solids capacity is defined as total running time before reaching ΔP of 30" Hg under standard test conditions of 10 gpm/ft^2 of RP-1 containing 100 mg/gal dispersed AC Fine Test Dust.

***Based on data from manufacturer.

b. Gelman Type E

This is a high-efficiency, resin-bonded glass fiber filter medium containing submicron fibers. Its efficiency was found to be high and its capacity relatively high due to its depth filtration characteristics.

c. Gelman Versapor 6429

This is a glass fiber paper (made from submicron fibers) which has been impregnated with an epoxy resin. The manufacturer rates it at 1.2 micron pore size. It shows collection efficiency similar to the Type E (from which it is probably produced) but solids capacity is lower.

d. Glass Asbestos (GA) Paper

This is a high-efficiency air filter medium incorporating submicron asbestos fibers. It also shows a high efficiency in a liquid system and relatively high solids capacity.

e. Glass-Rayon-Vinyon (GRV) Paper

This is another air filter medium of somewhat lower efficiency than the GA filter. It is considerably stronger, however, and still incorporates sufficient submicron fiber to provide efficient filtration in depth.

f. APM High-Efficiency Media

APM manufactures a line of depth-type collectors which incorporate fine fibers to achieve high collection efficiencies. Of the eight materials supplied to us by APM, the first three in Table II are media which represent commercially available filters; the other five are classed as experimental. It may be seen from the DOP penetration results that the inherent efficiency of these materials is generally high. This is obtained, however, at the expense of resistance to flow as indicated by pressure drop measurements. Because of the high ΔP, only four of the eight samples were run on the laboratory test facility. The rating number, $\mathcal{R}$, was found to be about 3, indicating depth collection, but less than some of those mentioned above.

3. Metal Fiber Products

Three types of randomly oriented webs made from metallic filaments have been considered. These materials are made by widely differing processes and, as shown in Table III, their performance also is quite varied.

a. Metallic Depth Media

Fram Corporation's Metallic Depth Media (MDM) is made by

TABLE III

PERFORMANCE OF METAL FIBER FILTER MEDIA

Material	Source	Bubble Pressure in. H_2O	DOP Performance* ΔP mm H_2O	DOP Performance* Aerosol Penetration %	DOP Performance* E	Fluid Filtration Performance Initial ΔP in. Hg	Fluid Filtration Performance Final ΔP in. Hg	Fluid Filtration Performance Run Duration min	Fluid Filtration Performance Solids** Capacity min	Fluid Filtration Performance Efficiency %	R
MDM, 10 μ nominal	Fram	10.1	16	82	0.6	0.3	40	15	13.7	72	7
MDM, 2 μ nominal	Fram	21	93	54	0.3	1.4	39	7	6	86	5
Feltmetal, 20% density, 1/64" thick	Huyck	5.7	5	94	0.6	0.2	39	10	8.8	68	4
Feltmetal, 40% density, 1/64" thick	Huyck	11	106	70	0.2	1.3	51	4.5	3.5	78	2
Feltmetal, 40% density, 1/32" thick	Huyck	14.4	120	63	0.2	3.0	42	3.5	3.1	84	2
Feltmetal, 40% density, 1/16" thick	Huyck	20.5	348	18	0.3	11.1	47	2.25	1.7	92	2
Feltmetal, 60% density, 1/64" thick	Huyck	24	345	30	0.2	11.7	46	0.9	0.6	85	1
13182-1-7, 100% 15 μ fiber	Brunswick	1.9	2	93	1.2	0.1	0.1	15	>15	20	0
13182-1-9, 100% 15 μ fiber	Brunswick	2.4	2	92	1.2	0.1	0.1	15	>15	25	0
13182-1-6, 50% 15 μ; 50% 8 μ fiber	Brunswick	4.4	4	94	0.9	0.1	0.5	15	>15	44	>1
13044-32-1, 100% 8 μ fiber	Brunswick	10	13	84	0.6	0.2	40	15	13.7	74	8
13182-1-8, 100% 5 μ; Rando Webber	Brunswick	10.7	13	78	0.8	0.3	43	13	11.4	80	8
13182-1-5, 100% 5 μ; Rando Webber	Brunswick	9.1	10	82	0.9	0.2	39	15	13.9	79	9
13182-1-2, 50% 8 μ; 50% 4 μ fiber	Brunswick	6.9	7	90	0.6	0.2	2.4	15	>15	61	>6
13182-1-11, 50% 8 μ; 50% 4 μ fiber	Brunswick	8.5	2	90	2.0	0.3	38	15	13.9	79	9
13182-1-1, 25% 8 μ; 75% 4 μ fiber	Brunswick	9.3	14	77	0.8	0.3	46	15	13.5	77	8
13182-1-3, 25% 8 μ; 75% 4 μ fiber	Brunswick	11.4	29	53	1.0	0.5	44	15	13.1	88	10
13182-1-4, 100% 4 μ fiber	Brunswick	9.2	12	76	1.0	0.2	29	15	15.2	80	10
13182-1-10, 100% 4 μ fiber	Brunswick	11.1	18	63	1.1	0.3	39	15	13.9	80	9
13182-1-12, 100% 4 μ fiber	Brunswick	6.6	8	83	0.9	0.2	38	13	12.1	79	8

*0.3 μ Aerosol penetration and pressure drop measured @ linear velocity of 28 ft/min through sample.

**Solids capacity is defined as total running time before reaching ΔP of 30" Hg under standard test conditions of 10 gpm/ft^2 of RP-1 containing 100 mg/gal dispersed AC Fine Test Dust.

replicating the structure of a non-metallic fibrous web in metal and subsequently sintering it. The process is capable of yielding a web which is as uniform as the original structure (which might be made on a paper machine or, as in the case of the samples supplied to us by Fram, on an air-laying machine such as a Rando Webber). Fiber size is limited, however, since the structure is replicated by building up a metal layer on the surface of the original fibers. Thus, the replicated fibers must be considerably larger than the originals. Our data indicate depth-type collection and significantly better performance than woven wire cloth filters.

b. Feltmetal

The Huyck Corporation products, called Feltmetal, are made by a felting and sintering process in a wide range of densities and thicknesses. Our results indicate some improvement in performance over conventional hydraulic fluid filter media, but the differences are relatively small. At the present time, the fiber size used in Huyck products is limited to a minimum of about 15 microns. Thus performance capabilities are inherently limited. The materials are highly uniform, however, due to the wet felting process used during manufacture.

c. Brunswick Metal Fiber Webs

During the course of this contract, a large number of samples of metal fiber webs have been received from Brunswick Corporation. Since the fibermaking process was new, techniques for forming candidate filter media were necessarily developmental. Consequently, many samples fell far short of expectations.

During the last half of our program, however, Brunswick succeeded in making fibers as small as 4 microns in quantities sufficient for our needs. The results presented in Table III are arranged to show performance of typical webs having fiber sizes varying from 15 down to 4 microns in diameter. With the exception of the two samples made from five-micron fibers, all of these webs were made on standard textile carding equipment, and were creped in a Bird-Walton Compactor after formation. (The five-micron webs were made on a Rando Webber from relatively short fibers.) While there are some difficulties inherent in a carding process which limit the uniformity obtainable (and which prevent full utilization of small fiber capabilities), the potentialities of the process are clearly evident from the results shown in Table III.

4. Other Candidates

Three other types of filter media have also been considered in our program. Since these did not fall logically into any of the prior categories, results have been grouped together and are presented in Table IV.

TABLE IV

PERFORMANCE OF OTHER CANDIDATE FILTER MEDIA

Material	Source	Bubble Pressure in. H_2O	DOP Performance*			Fluid Filtration Performance					
			ΔP mm H_2O	Aerosol Penetration %	E	Initial ΔP in. Hg	Final ΔP in. Hg	Run Duration min	Solids** Capacity min	Efficiency %	R
Microfil, 5 µ nominal	Bendix	>12	290	6	0.4	5.4	32	4	3.5	99	3
Microfil, 10 µ nominal	Bendix	10	70	9	1.5	1.6	34	4.3	4.3	94	4
Microfil, 15 µ nominal	Bendix	7	-	-	-	1.3	35	8	7.8	68	4
Microfil, 20-40 µ nominal	Bendix	6.5	30	87	0.2	0.7	51	7.9	7.5	68	3
Microfil, 25 µ nominal	Bendix	6	-	-	-	0.6	38	7.5	7.4	63	3
Microfil, 40+ µ nominal	Bendix	5	18	92	0.2	0.4	43	9	8.6	~50	1
Microfil, Tailored Element	Bendix	15	55	70	0.3	1.6	38	6.5	6.1	76	4
P639-H308	H&V	2.5	10	32	5.0	0.15	0.8	15	>15	66	>6
P639-H308, Hot Pressed @ 100 psi	H&V	7.2	24	12	3.9	0.4	34	12	11.5	84	8
P639-H308, Hot Pressed @ 200 psi	H&V	7.2	41	1.9	4.2	0.6	35	7	6.6	87	5
TV20A40	Pallflex	7.0	-	-	-	2.1	43	1.75	1.3	89	1
TZ120D50	Pallflex	5.2	10	87	1.2	0.15	2.2	7.5	7.1	54	2

*0.3 µ Aerosol penetration and pressure drop measured @ linear velocity of 28 ft/min through sample.

**Solids capacity is defined as total running time before reaching ΔP of 30" Hg under standard test conditions of 10 gpm/ft^2 of RP-1 containing 100 mg/gal dispersed AC Fine Test Dust.

a. Bendix Microfil

Bendix Filter Division manufactures a line of filters which incorporate fine glass fibers in a randomly oriented depth-type configuration and which are sold under the generic name, Microfil. Because the nature of the material used is such that controlled performance is achieved in the process of element manufacture, it was not possible for Bendix to supply us with flat sheet samples of Microfil media. Instead, a series of special cartridges was made up and submitted to us for evaluation. These cartridges were designed to cover a range of performance capabilities generally conforming to our requirements.

Six elements were initially supplied for evaluation. Since it was found that our efficiency target of 80% was not closely approached and since fiber migration was found to be appreciable (see Section IV.E.), an additional candidate element was subsequently submitted. This element was tailored to our efficiency requirements and had additional provisions for migration control. Evaluation results indicate depth-type collection though pressure drop is higher and solids-holding capacity is lower than some of the other promising candidates.

b. Hollingsworth & Vose Co. (H&V)

H&V is a paper manufacturing company with considerable experience in the production of filtering materials. In addition, they have a Rando Webber production line for manufacturing air-laid randomly oriented fibrous webs. The P639-H308 material is a Vinyon-bonded air-laid web containing small diameter asbestos fibers. While its efficiency was found to be only moderate, capacity as indicated by pressure drop rise was high. As received, the material is thick and rather fluffy. With proper pressing conditions, however, the efficiency may be increased while still maintaining relatively high capacity. Even after pressing, the material is relatively thick so that the area obtainable within a given cartridge envelope would be limited. In addition, fiber migration was severe due to the short asbestos fibers used.

c. Pallflex Products Corporation

Pallflex makes a number of porous materials using glass cloth, fine glass fiber, and Teflon. Since some of these materials have inherently high filtration efficiency, samples of representative materials were obtained for evaluation. Examination of these materials revealed that the fine fiber content was present in a thin layer on the top surface. As a result, particle collection occurs primarily on the surface so that capacity is low.

D. EFFECTS OF WEB STRUCTURE AND FIBER SIZE

1. Experimental Handsheets

Results presented in Section C above clearly indicate the superiority of depth-type collectors and the beneficial effects which can be achieved with small diameter fibers. It has been demonstrated that greatly increased solids capacities and much higher filtration efficiencies can be obtained with many of our candidate media than with conventional woven wire cloths or sintered metal powders.

In order to demonstrate in a carefully controlled manner the effects of fiber size, fiber concentration and web weight, three different series of wet-formed handsheets have been made in the laboratory and evaluated as candidate filter media. All of the sheets made have been based on the glass-rayon-Vinyon (GRV) formulation previously discussed, which is a commercially available air filtration medium.

The GRV material consists of equal parts of chopped rayon and Vinyon fibers with about 20 per cent of 3/4-micron glass fibers. It is made on standard papermaking equipment and is bonded together by the thermoplastic Vinyon fibers which soften and partially fuse as the web is dried on the machine. Because of the short fiber lengths used and because of the method used to bond the web together, strength is on the low side for a liquid filtration application and migration of the fibers under certain flow conditions is evident. Nevertheless, it seemed worthwhile to investigate the effects of variations in formulation using this type of medium because of the ease of making a large number of similar sheets with widely varying performance.

Three different series of handsheets were designed to show:

a. The effect of increasing web weight using the same fiber composition for all sheets (Series S-1). In this series, 20% of the fiber mix was 3/4-micron glass fiber.

b. The effect of increasing the concentration of fine glass fiber (Series S-2). In this series, the concentration of 3/4-micron glass fiber was varied from 0-30 per cent by weight.

c. The effect of the size of the fibers used to obtain filtration performance (Series S-3). In this series, five different sheets were made which incorporated 20 per cent glass fiber with sizes varying from 3 to 0.5 micron.

The results of this laboratory program are presented in Table V and Table VI. Table V summarizes performance as indicated by the rating numbers E and $\mathcal{R}$, while Table VI presents actual experimental data.

In Figure 5, we show graphically what happens to average filtration efficiency and to $\mathcal{R}$ as the content of 3/4-micron glass fiber is increased. While the exact position of some points must be estimated, the results are clearly evident:

(1) Over-all efficiency increases continuously with increasing

TABLE V

DESCRIPTION OF EXPERIMENTAL HANDSHEETS

Number	Weight % Glass Fiber	Glass Fiber Diameter, μ	Sheet Weight gram/ft²	E	R
S2-1	0	-	9.2	<1	0
S2-2	5	3/4	9.8	1.8	>1
S2-3	10	3/4	9.6	2.5	>8
S2-4	15	3/4	10.9	2.8	-
S2-5	20	3/4	11.6	3.4	10
S2-6	25	3/4	12.6	3.3	10
S2-7	30	3/4	13.2	3.6	8
S3-1	20	3	11.4	1.2	0
S3-2	20	2	11.2	1.8	>3
S3-3	20	1	11.2	2.3	>5
S3-4	20	3/4	11.3	3.4	9
S3-5	20	1/2	10.9	3.8	8
S1-1	20	3/4	6.3	3.3	-
S1-2	20	3/4	9.9	3.4	7
S1-3	20	3/4	10.4	3.5	7
S1-4	20	3/4	12.8	3.4	8
S1-5	20	3/4	18.1	3.5	8

TABLE VI

SUMMARY OF RESULTS FOR EXPERIMENTAL HANDSHEETS

Material	Approx. Min. Fiber Dia. microns	Bubble Pressure in. H_2O	DOP Performance* ΔP mm H_2O	Aerosol Penetration %	E	Fluid Filtration Performance Initial ΔP in. Hg	Final ΔP in. Hg	Run Duration min	Solids** Capacity min	Efficiency %	R
S3-1	3	3.9	2	91	1.2	0.10	0.15	15	>15	32	0
S3-2	2	5.5	6	74	1.8	0.15	0.38	15	>15	53	> 3
S3-3	1	6.1	12	54	2.3	0.2	(~6.8)	15	>15	60	> 5
S3-4	3/4	6.75	27	13	3.4	0.5	41.8	11.5	10.2	91	9
S3-5	1/2	7.0	55	0.78	3.8	1.5	38.5	9.5	8.5	97	8
S2-1	15	2.7	2	97	< 1	< 0.1	< 0.1	15	>15	22	0
S2-2	3/4	4.0	4	82	1.8	0.06	0.2	15	>15	45	> 1
S2-3	3/4	4.1	10	57	2.5	0.15	8.4	15	>15	70	8
S2-4	3/4	6.1	18	32	2.8	0.4	-	-	-	81	-
S2-5	3/4	8.5	28	11	3.4	0.6	37.6	13	12.2	90	10
S2-6	3/4	9.1	46	3	3.3	0.8	27.2	10.25	10.6	94	10
S2-7	3/4	12.1	58	0.83	3.6	1.0	-	10	9.1	95	8
S1-1	3/4	-	14	34	3.3	-	-	-	-	84	-
S1-2	3/4	7.75	23	17	3.4	0.4	43	10	8.8	86	7
S1-3	3/4	7.4	30	9	3.5	0.6	43	10	9.0	89	7
S1-4	3/4	7.4	29	10	3.4	0.6	40	10	9.3	89	8
S1-5	3/4	7.6	40	4	3.5	0.9	34	10	9.7	88	8

*0.3 μ Aerosol penetration and pressure drop measured @ linear velocity of 28 ft/min through sample.

**Solids capacity is defined as total running time before reaching ΔP of 30" Hg under standard test conditions of 10 gpm/ft^2 of RP-1 containing 100 mg/gal dispersed AC Fine Test Dust.

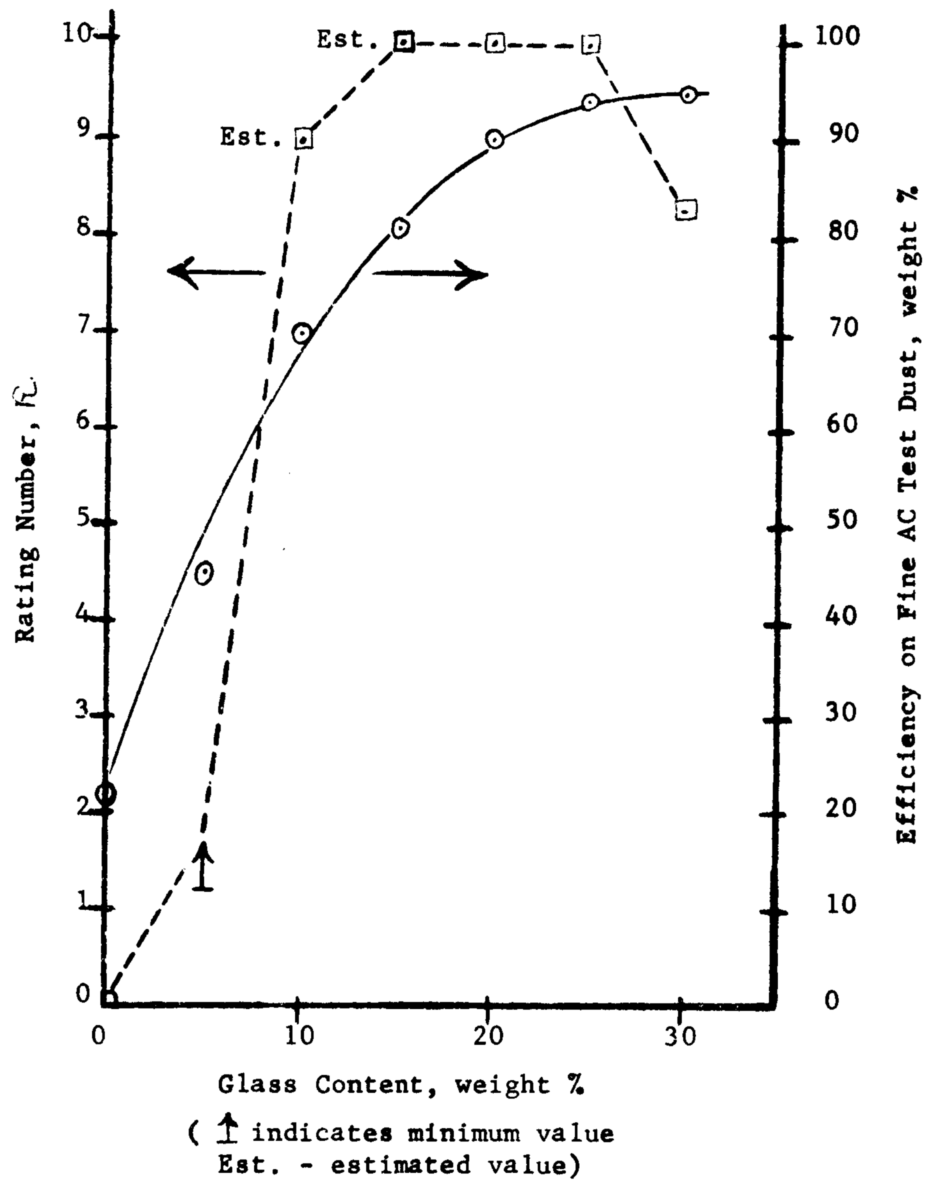

Figure 5

EFFECT OF FINE GLASS FIBER CONTENT ON EFFICIENCY AND RATING NUMBER R small fiber concentration.

(2) An examination of the variation in $\mathcal{R}$ indicates that optimum performance is achieved (for this type of formulation and under these test conditions) at a fine fiber concentration of about 20%. Increasing the proportion of fine fiber above this concentration merely results in increased surface collection and thus lower solids capacity.

In like manner, we may examine the effect of fiber size on filtration efficiency and on $\mathcal{R}$ as shown in Figure 6. Again, we note that efficiency increases steadily as fiber size decreases. In this case, however, $\mathcal{R}$ shows less tendency to peak. While a slight decrease in $\mathcal{R}$ was found for the minimum fiber size investigated, experimental errors are such that this may not be significant.

Series S-1, in which web weight was varied, shows only a slight effect. Thus we may conclude that once a certain minimum thickness is obtained, further increases in weight (without significant changes in density) cannot be justified on the basis of performance (though, of course, strength and handling requirements may make such increases necessary).

2. Effect of Support Screens

Since many of the promising candidate media were relatively weak materials, it was of interest and importance to study means for providing mechanical strength. The simplest technique for providing additional support is to use woven wire screens on both sides of the medium in a sandwich construction. Such an arrangement would thus provide protection for both normal flow and for back-flow pulses.

In order to determine if such a sandwich construction would affect the performance of a depth-type filter medium, a sample of a Brunswick 5-micron fiber web (Sample 13182-1-8) was mounted and evaluated with 100-mesh stainless steel screen on both sides. Previous tests yielded values of 80% and 8 for the efficiency and rating, respectively. With screen in place on both faces, these values were found to be identical. The coarse supporting screen thus has no apparent effect on the performance of a medium with the characteristics desired in the present application.

An additional question concerning the use of screens pertained to a possible method of controlling migration of fibers from the filter medium. (The effectiveness of a Dutch Twill woven wire cloth in this capacity is discussed in Section E below.) Such a method would be of questionable utility, however, if the retained fibers plugged the twill. To resolve this point, 325 x 1900 twill was used as a backing screen for a sample of GRV paper, which had been found to have serious migration problems. Typical performance results for this material are 95%

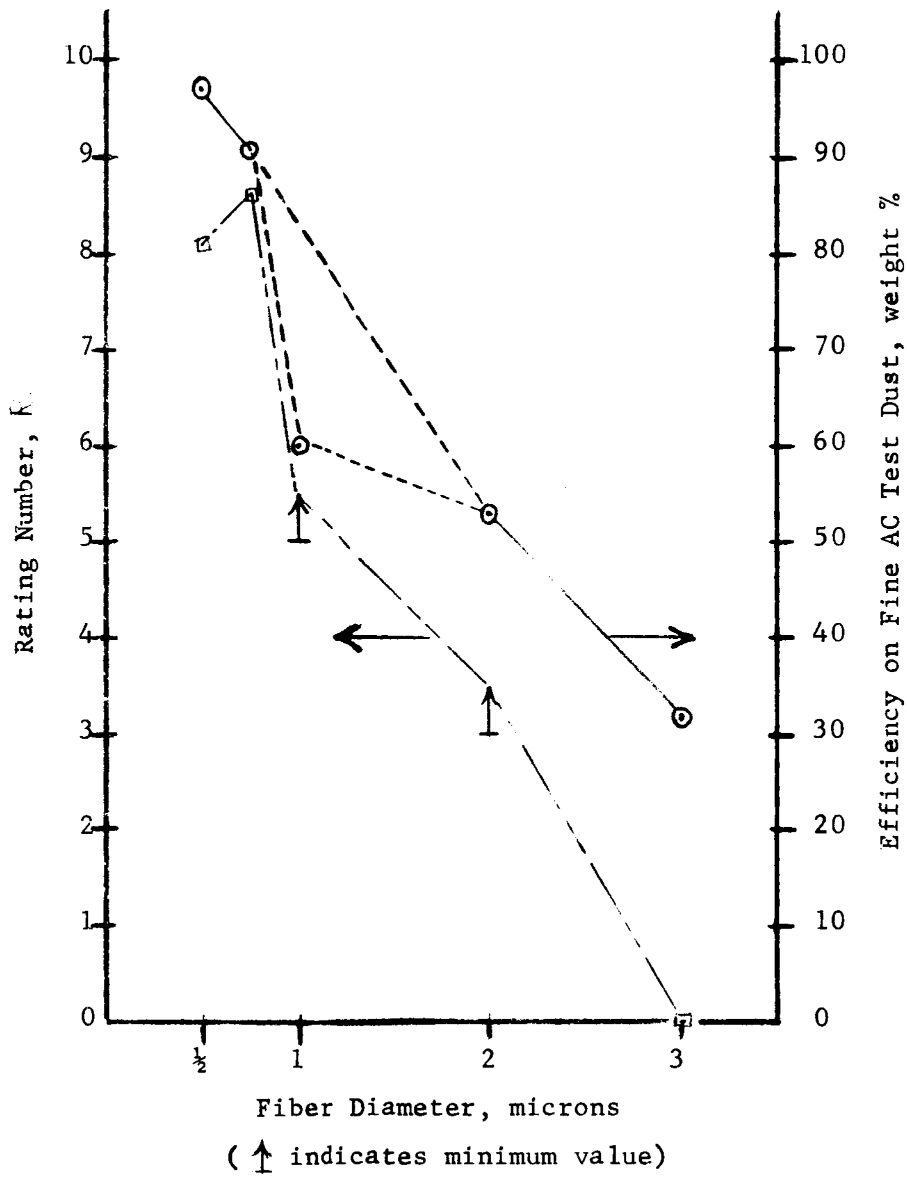

Figure 6

EFFECT OF MINIMUM FIBER SIZE ON EFFICIENCY AND RATING NUMBER R efficiency and a rating of 8. With the twill screen backing, these values were 95% and 9. It therefore appears that fibers retained by the twill do not wedge in the pores of the screen but are held flat on the surface. Thus no deleterious effects are evident.

E. MEDIA MIGRATION AND METHODS OF CONTROL

In most of our screening program for candidate media, we did not attempt to differentiate between particles passing the test medium and particles of the filter medium dislodged by the fluid flow. It is well known, however, that fuel contamination by migration of the filter medium is particularly troublesome with fibrous filters. In order to assess the magnitude of the problem and the effectiveness of alternative methods of control, we devised a test method using our high-pressure test stand. The arrangement was such that a Millipore filter was positioned immediately downstream of the test specimen (in a separate filter holder). Any fibers which were dislodged from the test medium were collected on the surface of the Millipore and were subsequently counted under the microscope.

Our test procedure involved subjecting each sample to a specified program of 20 pressure pulses (0-3000 psi) followed by two minutes of steady flow at a rate of about 55 gpm/ft^2 (using MIL-H-5606 hydraulic fluid). Total flow through the sample for an entire test program was about 2500 ml (or 25 times that used in ARP-598). Fiber counts were made for the entire Millipore filter area using a binocular microscope at 40X or 60X magnification.

Results of the migration study are summarized in Table VII for a number of candidate media. While none of the experimental materials achieves the integrity of a woven wire cloth, we can make the following statements:

1. Cellulosic and mineral fiber media such as the APM, Fram, and initially supplied Bendix products show appreciable migration.

2. Huyck Feltmetal and Fram MDM show relatively low migration since they are sintered products.

3. The long fiber length used in most of the Brunswick samples results in low migration rates. (Brunswick sample 12746-4-7 included in Table VII was made on a Rando Webber from relatively short fibers.)

4. Sintering significantly reduces migration from the Brunswick samples.

5. The differences noted between initial and subsequent tests reflect the rapid removal of loosely held fibers. Since no attempt was made to preclean the media, this suggests means

TABLE VII

SUMMARY OF FIBER MIGRATION RESULTS

Material	Source	Filter Rating, R	ΔP* psid	Fiber Migration Data: Total Fiber Count, Initial Test	Total Fiber Count, Subsequent Tests (Ave)	Approximate Fibers per 100 cc Test Fluid, Initial Test	Approximate Fibers per 100 cc Test Fluid, Subsequent Tests (Ave
Dutch Twill, 325 x 1900	-	1	15	0	0	0	0
Feltmetal, 20%, 1/64" thick	Huyck	~4	8	19	14	0.8	0.6
13044-46-3 Paper	APM	3	79	80	58	3	2
Paper, 10 μ nominal	Fram	4	36	148	145	6	6
MDM, 10 μ nominal	Fram	~8	19	14	11	0.8	0.4
MDM, 2 μ nominal	Fram	5	90	13	11	0.5	0.4
12746-4-7	Brunswick	>6	4	155	35	6	1.4
12746-4-7 (S)	Brunswick	-	4	11	9	0.4	0.4
12746-7 + 325 x 1900 Dutch Twill	Brunswick	-	21	13	5	0.5	0.2
13182-1-1	Brunswick	8	12	5	8	0.2	0.3
13182-1-1 (S)	Brunswick	-	10	10	2	0.4	0.1
13182-1-2	Brunswick	>6	8	24	12	1	0.5
13182-1-3	Brunswick	10	20	22	9	0.9	0.4
13182-1-3 (S)	Brunswick	-	21	11	6	0.4	0.2
13182-1-4	Brunswick	10	6	15	10	0.6	0.4
13182-1-4 (S)	Brunswick	-	8	14	3	0.6	0.1
13182-1-5	Brunswick	9	7	25	10	1	0.4
13182-1-6	Brunswick	>1	6	9	8	0.4	0.3
13182-1-8	Brunswick	8	10	30	22	1	0.9
13182-1-8 (S)	Brunswick	-	7	8	11	0.3	0.4
13182-1-10	Brunswick	9	48	42	17	2	0.7
13182-1-10 (S)	Brunswick	-	41	12	7	2	0.3
13182-1-11	Brunswick	9	9	16	7	0.6	0.3
13182-1-12	Brunswick	8	5	23	10	0.9	0.4
GRV Paper	ADL	8	32	37	27	2	1
GRV Paper + 325x1900 Dutch Twill	ADL	8	56	8	8	0.3	0.3
Microfil 10	Bendix	4	-	45	31	2	1
Microfil 20-40	Bendix	3	-	50	17	2	0.7
Microfil, Tailored Element	Bendix	4	-	7	5	0.3	0.2

*At 50 gpm/ft^2 - 3000 psi using MIL-H-5606 Hydraulic Fluid
(S)Sintered at ADL

by which total fiber migration may be partially controlled.

6. For those materials which have an appreciable tendency to migrate, a significant reduction in fiber count can be achieved by using a Dutch Twill backing. (This method of control was also used by Bendix in the tailored element.)

F. ULTRASONIC CLEANING OF CONTAMINATED MEDIA

An important aspect of performance for any filter element is the ease and degree of completeness with which collected contaminant can be removed. In order to investigate cleanability, our laboratory ultrasonic bath was equipped with a small centrifugal pump and a membrane filter holder in a simple recirculating system. Observation of actual cleaning in the system indicated that contaminant was removed with somewhat greater efficiency when the bath was not agitated mechanically. Accordingly, a sequential timing arrangement was set up in which the pump operated for only about 20 seconds in every minute. Our cleaning procedure thus involved immersion of the test specimen in the bath containing water and an anionic surfactant for varying periods, during which time it was continously vibrated ultrasonically. Loosened dirt was removed from the bath during the pumping cycles.

The ease and thoroughness of contaminant removal for typical candidate media is shown graphically in Figures 7 and 8. In these plots we have shown pressure drop rise as a function of time (under our standard test conditions) for the initial run and a second run after cleaning. Results are generally as would be predicted. That is, a surface-collecting material such as a Dutch Twill screen may easily be cleaned essentially to its original condition. The depth-type collectors, however, retain a portion of the originally collected particulates, resulting in a capacity decrease for the second run.

The possibility of improving the cleaning action for depth-type media was subsequently investigated using a modified technique. In this procedure, the sample was liberally coated with a nonionic surfactant (Tween 80) before placing it in the cleaning bath which contained only water. After one hour of ultrasonic agitation, the sample was rinsed, dried, and retested.

It was found that cleaning action was significantly enhanced by the use of this method. In many cases, performance obtained after cleaning appeared to be entirely equivalent to that of the original material. Data for initial performance and retesting are shown in Table VIII for a number of materials.

For the flat Brunswick samples, there appears to be a decrease in efficiency after multiple cleanings. This may be due in part to the fact that the web was not sintered after fabrication. Thus the fibers may have been shifting and rearranging during each cleaning cycle. The sintered MDM sample shows more conventional performance in that the efficiency

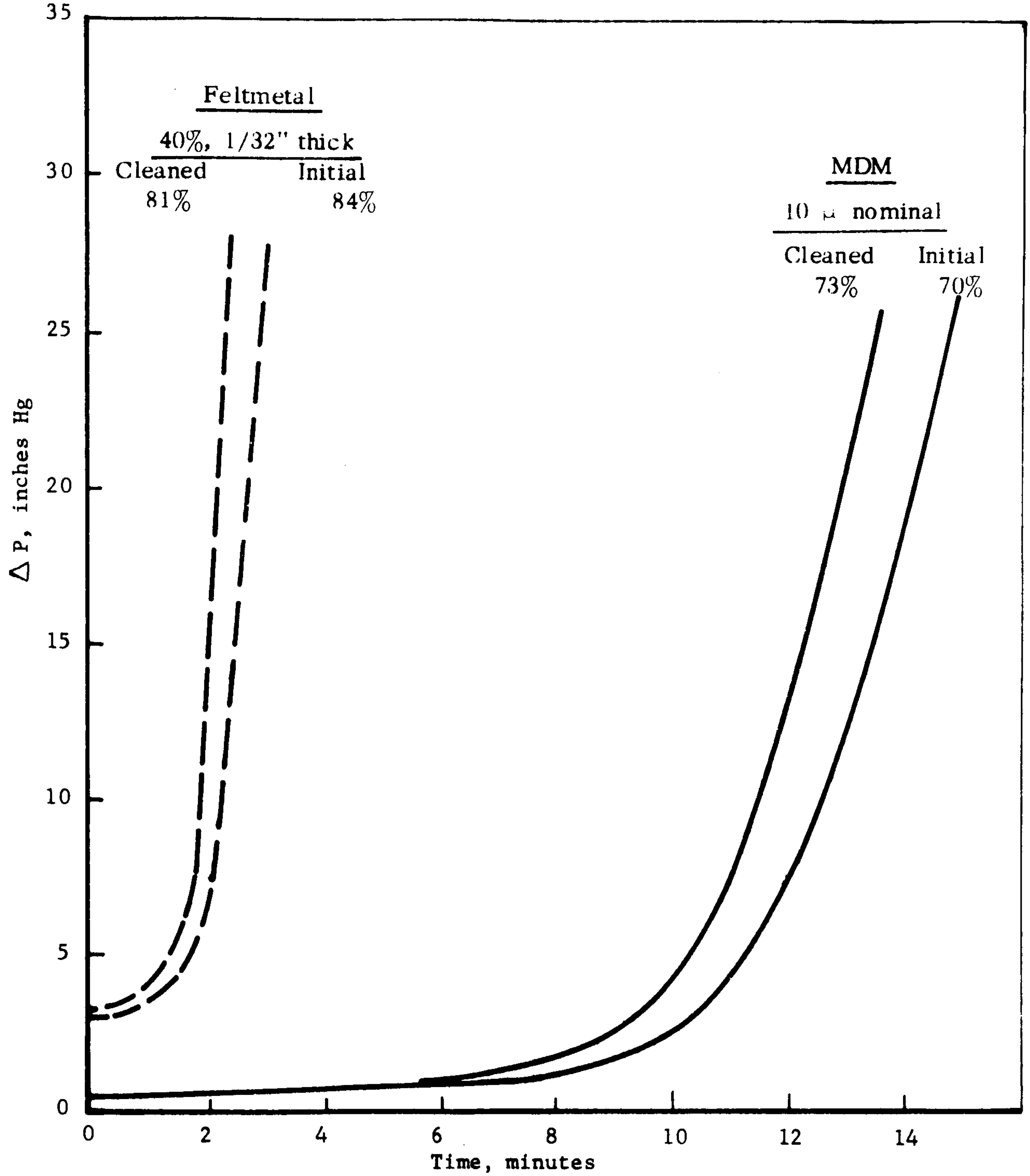

Figure 7

PRESSURE DROP AS A FUNCTION OF TIME FOR TWO MEDIA TESTED AS RECEIVED AND CLEANED AFTER INITIAL RUN
(10 gpm/ft^2 RP-1, 100 mg/gal Fine AC Test Dust)

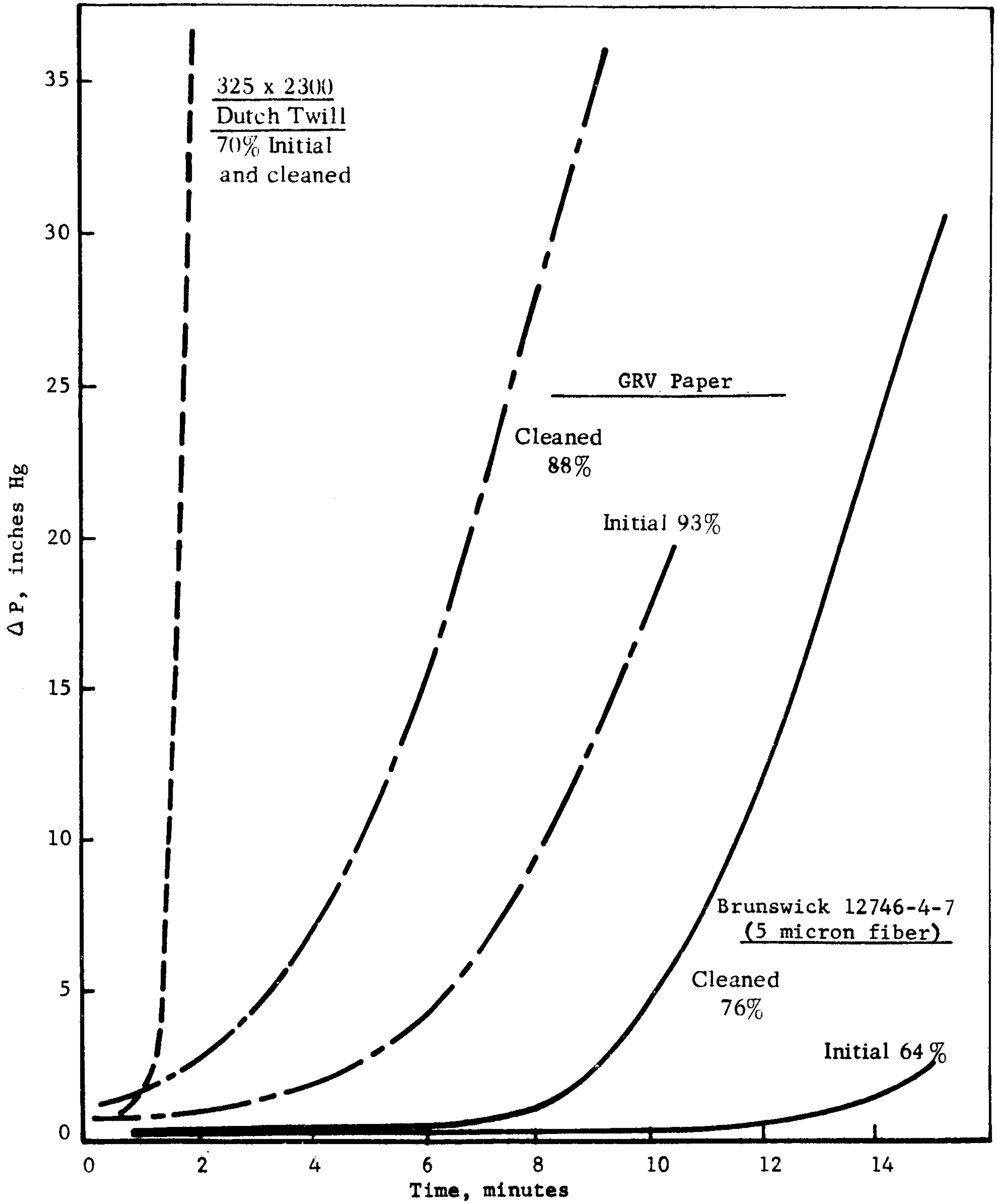

Figure 8

PRESSURE DROP AS A FUNCTION OF TIME FOR THREE MEDIA TESTED AS RECEIVED AND CLEANED AFTER INITIAL RUN
(10 gpm/ft^2 RP-1, 100 mg/gal Fine AC Test Dust)

TABLE VIII

SUMMARY OF RESULTS FOR CLEANED MEDIA

Material	No. Times Cleaned	Run Duration (min.)	Pressure Drop, in. Hg Initial	5 min.	10 min.	Final	Efficiency	Solids* Capacity min	R
Brunswick 13182-1-3	0	15	0.5	1.4	11.8	44	88	13.1	10
	1	14	0.6	1.4	11.8	39	85	12.8	10
Brunswick 13182-1-10	0	15	0.3	0.6	4.4	39	80	13.9	9
	1	14	0.4	0.6	5.9	42	78	12.9	8
	2	15	0.3	0.6	2.8	31	81	14.8	10
	3	15	0.3	0.6	2.3	35	78	14.5	9
	4	15	0.3	0.5	1.7	26	79	15.5	10
	5	15	0.3	0.4	1.0	16	73	17	9
Brunswick 8 μ web pleated and sintered	0	13.5	0.7	0.8	1.2	26	57	13.7	4
	1	15	0.5	0.6	1.0	17	60	~16.6	~5
Fram 10 μ MDM	0	15	0.4	0.8	4.8	40	72	13.8	7
	1	15	0.4	0.8	5.0	47	73	13.4	7
	2	15	0.4	0.9	6.3	4	79	13.2	8
	3	15	0.4	0.9	9.3	50	80	12.8	8
Bendix Microfil 15	0	8	1.3	4.2	-	35	68	7.8	4
	1	8.5	1.4	5.0	-	43	65	8.1	3
	2	8.0	1.8	6.4	-	33	67	7.9	4

*Solids capacity is defined as total running time before reaching ΔP of 30" Hg under standard test conditions of 10 gpm/ft^2 of RP-1 containing 100 mg/gal dispersed AC Fine Test Dust.

increases while capacity decreases as more of the fine particles are retained within the fibrous structure.

Pleated samples (as exemplified by the Bendix elements) also exhibit good cleanability using this technique. A single sample of pleated and sintered Brunswick material (which contained no small fibers) actually showed both a higher efficiency and a longer life after cleaning.

It should be noted that while these results are encouraging, they are not based on conditions which are entirely representative of those found in the field. Our test procedures were such that a run was terminated after pressure differentials reached approximately 20 psi whereas in the field such differentials might well exceed 100 psi. In the latter case, it is likely that collected contaminants might be held more tightly within the filter structure, thus making removal more difficult.

Nevertheless, on the basis of these experiments, we conclude that while it may never be possible to equal a surface collector in cleanability, proper processing techniques should permit depth-type fibrous filters to be reused a number of times. It follows that the greatly increased solids capacity inherent in a depth collector obviates the need for perfect cleaning prior to reuse of the element.

G. EFFECT OF TEST CONDITIONS ON FILTER PERFORMANCE

1. Effect of Contaminant

In our contract, minimum filter performance is specified in terms of particle size distribution data for upstream and downstream samples. These data are based on actual counts of particulate contamination found in the field and thus they relate to state-of-the-art performance of currently used filters.

If we attempt to incorporate these data in a set of test conditions which can be used in the laboratory, however, serious problems arise. The field-collected data acknowledge the presence of no particles smaller than 10 microns. Thus the implication is that the contaminant to be removed is a very coarse one. Consequently, the task of the filter could be interpreted to be an easily achieved one since no small particles would be present to contribute to plugging.

In actual fact, of course, any contamination found in the field will include large numbers of particles smaller than 10 microns. These, in turn, will have a marked effect upon filter performance--an effect which, in most cases, will be more pronounced than that of the larger particles. In the paragraphs which follow, we describe a brief experimental program which was designed to indicate clearly the magnitude of these effects.

In our media screening program, we used AC Fine Air Cleaner Test

Dust as a standard contaminant. Although this material does not have the particle size distribution specified in the contract, we chose it because of its availability, its known particle size, and its general use as a test contaminant. It was recognized at the outset that the collection efficiencies and capacities observed with this contaminant would be lower than for the coarse material specified. To demonstrate the effect of particle size on efficiency and capacity, a series of determinations were made using five different related contaminants and two filter media. Except for the contaminants, test conditions were the standard ones used in our evaluation program. Results of these tests are summarized in Table IX and Figures 9 and 10.

The contaminants used in this program were all derived from natural Arizona Road Dust so that properties other than particle size are essentially constant. In addition to the two test dusts which are commercially available (AC Fine and AC Coarse), three fractions with much narrower size distributions were prepared. These are identified as "fine," "medium," and "coarse." While accurate size distributions for these fractions have not been made, we estimate average particle sizes at about 2, 10, and 30 microns, respectively. The "coarse" fraction bears the closest resemblance to the contaminant specified in the contract.

The effect of contaminant size on efficiency was quite pronounced in a test series using filter medium S2-3a. This material was a glass-rayon-Vinyon paper made up in our laboratories; it was essentially the same as medium S2-3 used in the experimental handsheet work (see Section IV.D.2). As may be seen in Table IX, the efficiency of removal of the larger contaminants was very high, while the smaller particles penetrated more easily. The pronounced difference in the pressure drop-time curves in Figure 9 may be attributed to the plugging of the medium by the retained contaminant. Note, however, that the "fine" fraction penetrates to such an extent that pressure drop increases very slowly.

The efficiency of the GRV paper is so high that differences in observed efficiency are quite small. Differences in capacity, however, as seen in Figure 10 are very striking. The plugging effect of small particles is demonstrated by an increasingly rapid rate of pressure drop increase for runs with the fine fraction and the AC test dusts. While the reason for the crossing of the curves for the AC Coarse and the "medium" fraction runs is not readily apparent, it seems likely that it is due to differences in the proportion of small particles in the two contaminants.

Our original recognition of the increased efficiency and capacity for larger contaminants has been demonstrated. More important, however, is the dramatic effect of very small particles on filter performance. While all of the mechanisms involved in fine particle filtration have not been established, it is evident that particle size distribution of the contaminant is a prime variable. In view of these results, a contaminant of the type specified in the contract would present little challenge to a filter, since it contains no particles smaller than 10 microns. It thus seems improper to consider qualifying a filter on such a basis.

TABLE IX

SUMMARY OF EXPERIMENTAL RESULTS
WITH FIVE DIFFERENT CONTAMINANTS

Medium	Contaminant	Run Duration minutes	ΔP @ 5 minutes inches Hg	Final ΔP inches Hg	Efficiency weight %
GRV Paper	"Coarse"	32	0.8	6.6	98.1
GRV Paper	AC Coarse	15	1.0	13.2	97.4
GRV Paper	"Medium"	32	2.4	25.2	99.4
GRV Paper	AC Fine	11	2.8	23	93
GRV Paper	"Fine"	8	6.4	22.6	96.4
GRV Paper	"Fine"	8	7.0	23.4	96.8
S2-3a	"Coarse"	15	0.3	1.7	97
S2-3a	AC Coarse	15	0.3	5.1	93.6
S2-3a	"Medium"	15	0.9	8.0	96.8
S2-3a	AC Fine	14	0.7	41	82.4
S2-3a	"Fine"	15	0.7	3.0	59

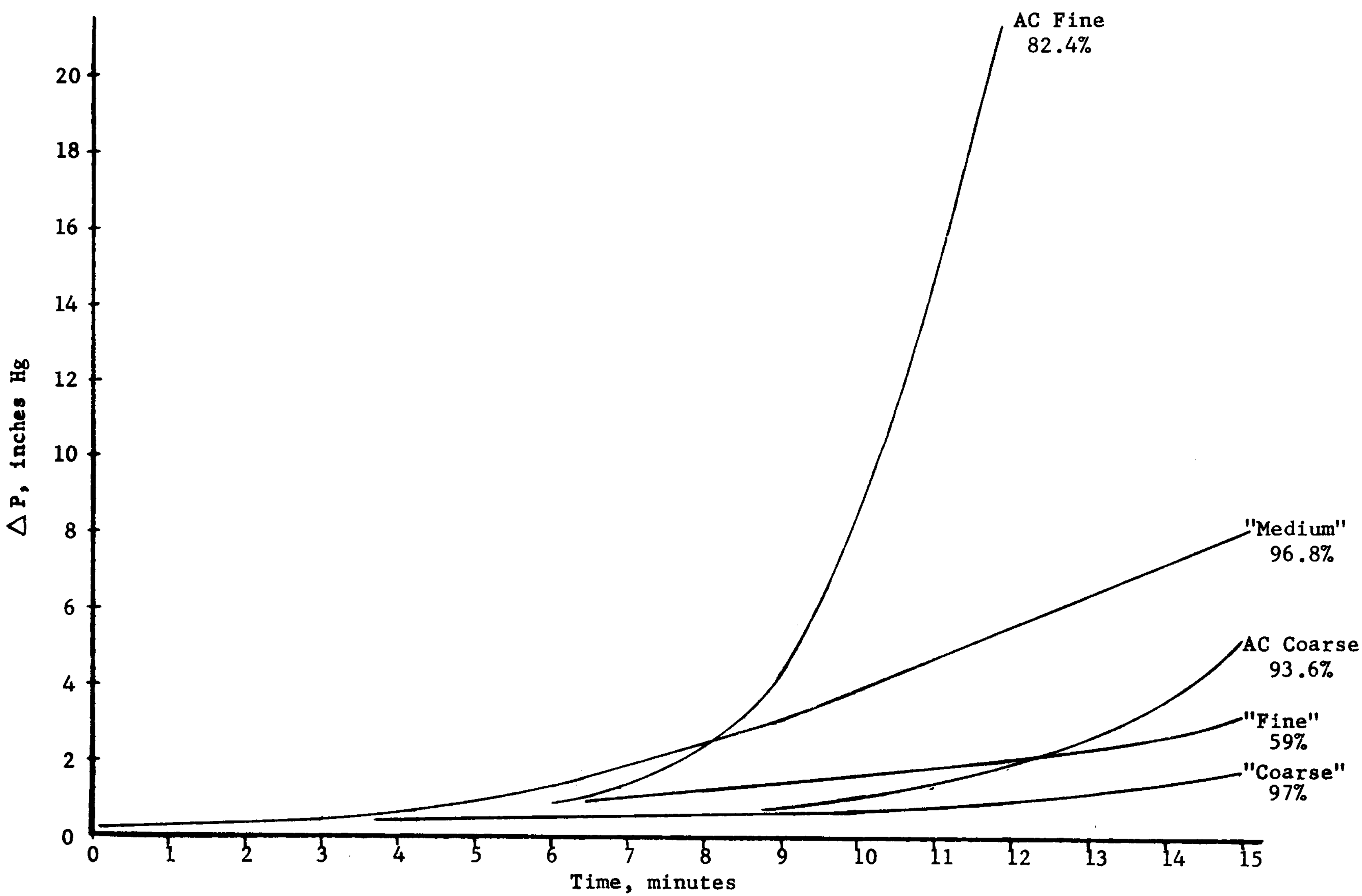

Figure 9

PRESSURE DROP AS A FUNCTION OF TIME FOR MEDIUM S2-3a WITH FIVE DIFFERENT CONTAMINANTS
(10 gpm/ft^2 RP-1, 100 mg/gal contaminant)

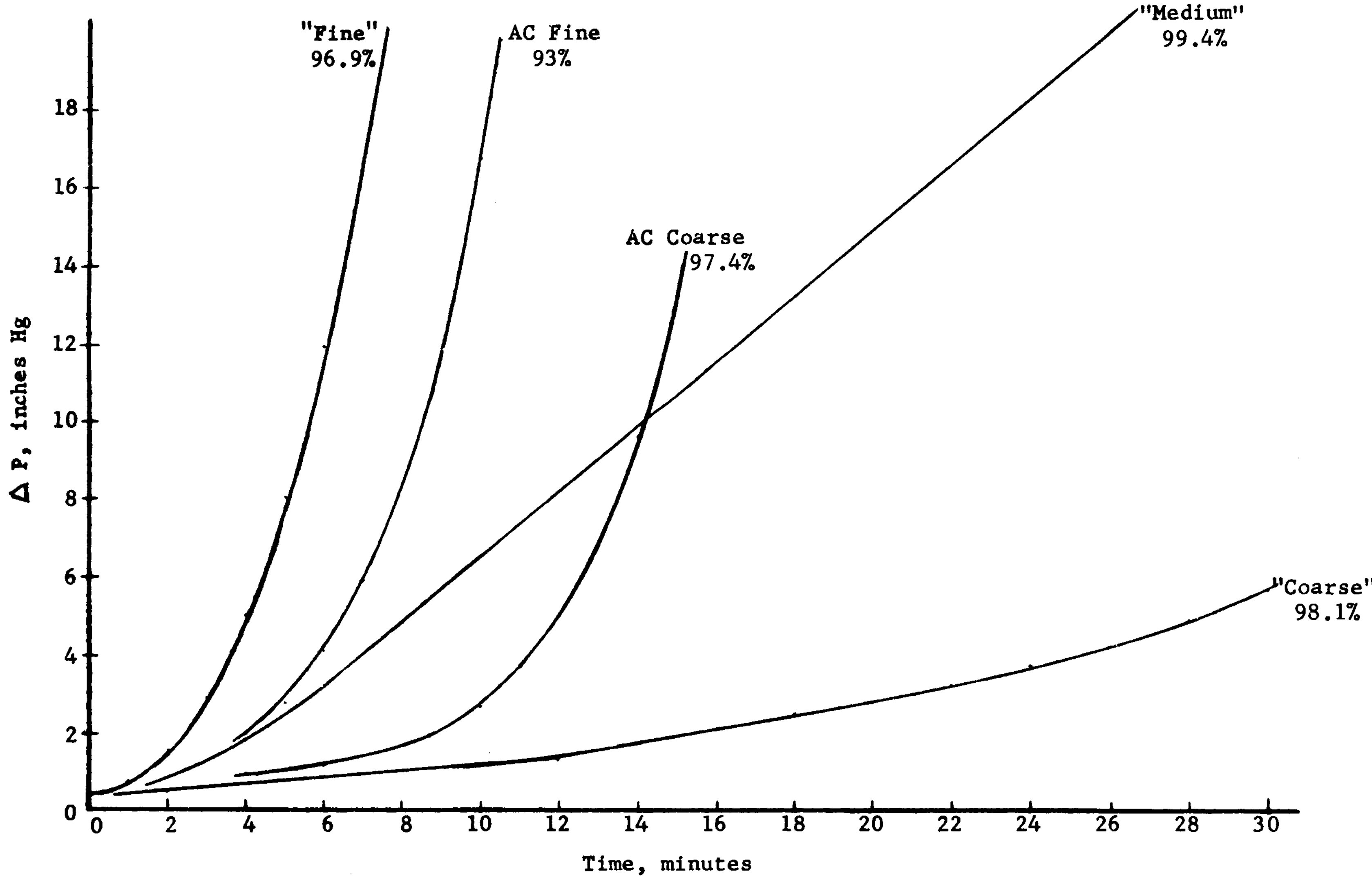

Figure 10

PRESSURE DROP AS A FUNCTION OF TIME FOR GRV PAPER WITH FIVE DIFFERENT CONTAMINANTS
(10 gpm/ft^2 RP-1, 100 mg/gal contaminant)

2. Effect of Contaminant Concentration

Since the contaminant concentration selected for our comparative evaluation testing (100 mg Fine AC Test Dust/gal) was not necessarily typical of actual use conditions, a series of runs was made in which concentration was varied. For this series we elected to use the GRV paper medium since it exhibits high efficiency and depth collection characteristics. Results are presented in Table X. It may be seen that at lower solids concentrations average efficiency drops somewhat. The change is relatively small, however, and may be due in part to experimental error. Pressure drop build-up data for three runs at 10 gpm/ft^2 and at 100, 50, and 25 mg/gal of Fine AC Test Dust are plotted in Figure 11 in terms of the amount of dirt added to the system. The data are so consistent that a single curve can be drawn for all three runs. Thus it seems safe to conclude that changes in solids concentration in the range of 25 to 100 mg/gal have only a minimal effect upon filtration performance.

3. Effect of Flow Rate

It was also recognized in the early stages of our contract that the specific flow rate of 10 gpm/ft^2 used in our standard test procedure was appreciably lower than that which would be encountered in the final filter element. Accordingly, data were taken for two candidate media and for 325 x 1900 Dutch Twill to show the effect of increasing flow to a rate comparable with that expected in a cartridge.

When testing at 35 gpm/ft^2, we found that the contaminant level had to be reduced to 50 mg/gal, one-half the concentration used with the larger area, in order to keep the rate of pressure drop build-up within manageable bounds. Results for the three filter media are shown in Figure 12. The curves are smoothed from two separate runs, except in the case of the Brunswick web, which is a single determination. Efficiencies are given for each determination.

Viewed graphically, the results are in general agreement with those obtained at lower flow rates. Their similarity, however, is more obvious if a slightly different method of presentation is used. If we consider the amount of contaminant which penetrates the filter rather than that which is retained, we obtain the following table:

TABLE XI

COMPARISON OF RESULTS FOR HIGH AND LOW FLOW RATE TESTS

Material	High Flow Rate Penetration (%)	High Flow Rate Time to 40 psid (min)	Low Flow Rate Penetration (%)	Low Flow Rate Time to 30" ΔP (min)
13182-1-8 (Brunswick)	27	8.1	20	11.4
GRV Paper	12	5.0	7	9.5
325 x 1900 Twill	46	1.1	27	2.2

TABLE X

EFFECT OF TEST CONDITIONS ON PERFORMANCE OF GRV PAPER

Flow Rate gpm/ft^2	Test Contaminant	Contaminant Concentration mg/gal	Run Duration min	Pressure Drop inches of Mercury				Efficiency Weight %
				Initial	5 min	10 min	Final	
10	Fine AC Dust	100	11	0.58	2.7	16.7	22.8	93
10	Fine AC Dust	100	5	0.60	3.2	--	--	94
10	Fine AC Dust	50	10	0.58	1.1	3.2	--	90
10	Fine AC Dust	25	20	0.58	0.8	1.1	3.2	89

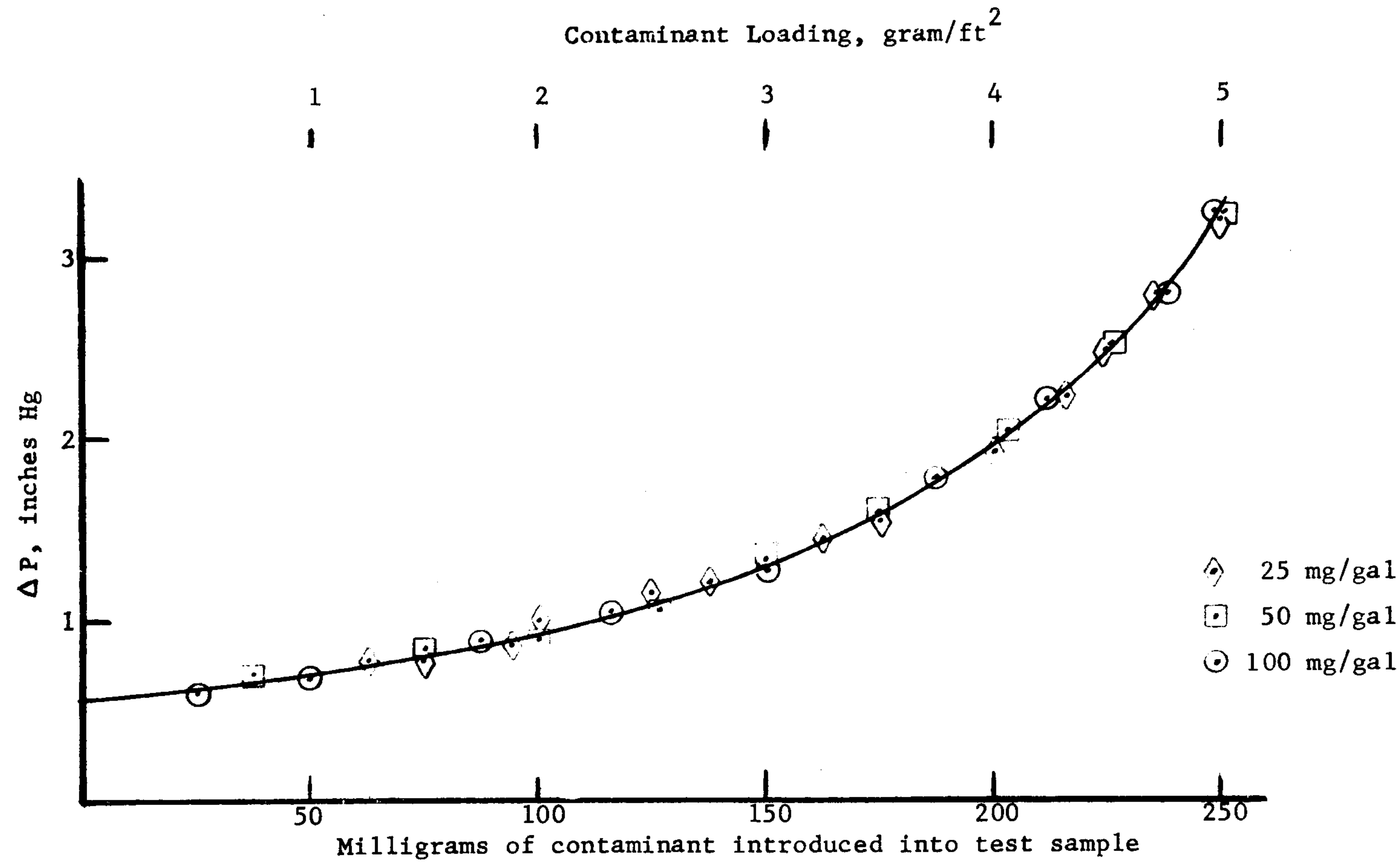

Figure 11

PRESSURE DROP OF GLASS-RAYON-VINYON PAPER AS A FUNCTION OF CONTAMINANT LOADING
(Data from 3 different runs @ 25, 50, and 100 mg/gal Fine AC Dust)

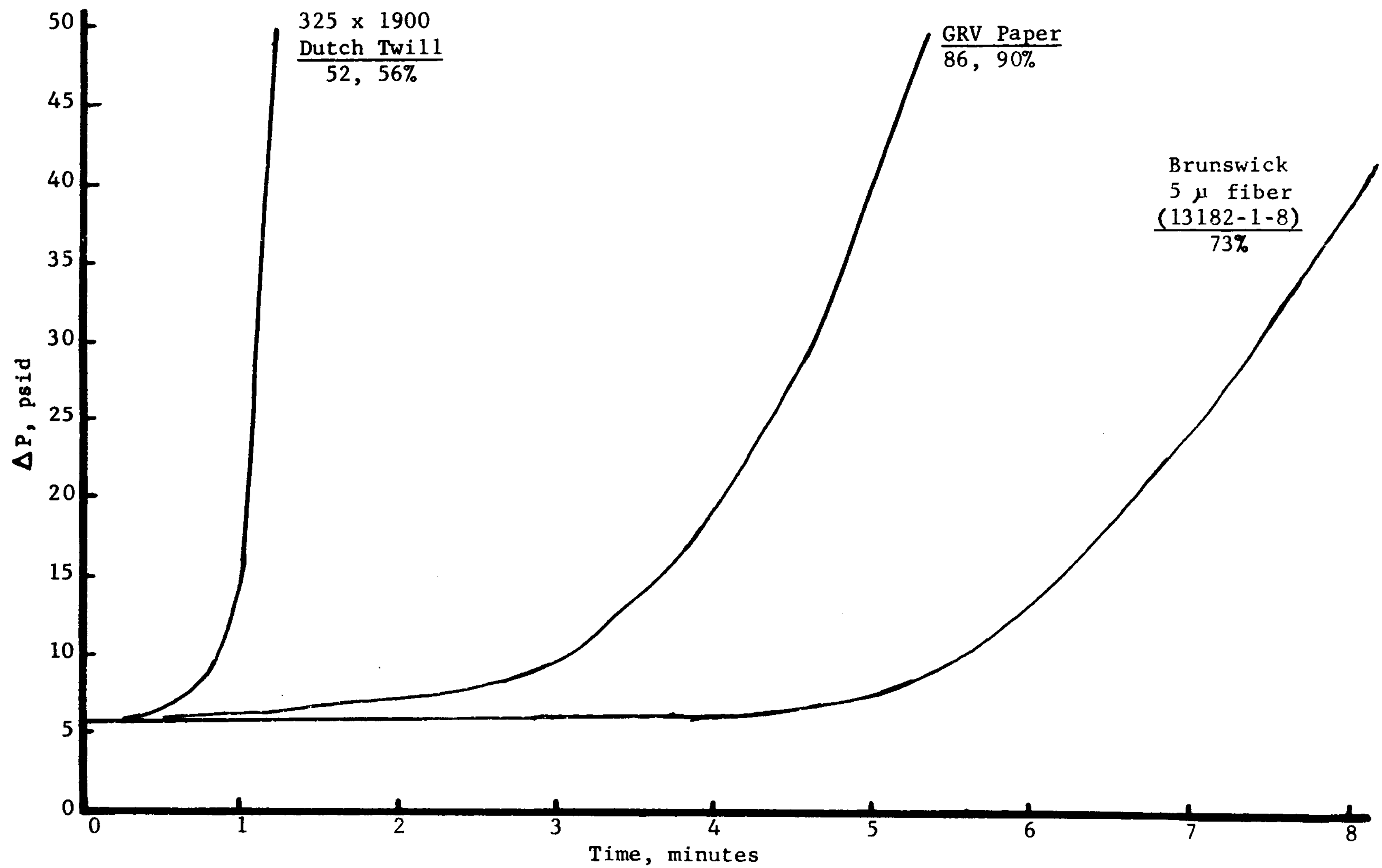

Figure 12

PRESSURE DROP AS A FUNCTION OF TIME FOR THREE MEDIA UNDER HIGH FLOW CONDITIONS
(35 gpm/ft^2 RP-1, 50 mg/gal Fine AC Test Dust)

In the low flow case, the specific flow rate was 10 gpm/ft^2 and the nominal loading rate was 1.0 gram/min ft^2. In the high flow test, these values were 35 gpm/ft^2 and 1.76 gram/min ft^2. Use of the time to 40 psid as a measure of capacity in the latter test is merely a matter of convenience. If we use the Dutch Twill as a standard for both capacity and penetration, the other materials may be compared on a percentage basis. The metal fiber web thus shows only about 2/3 the penetration of the twill, the exact values being 60% and 74% for high and low flow conditions, respectively. The GRV paper shows about 26% as much penetration as the twill under either test condition. The capacity is similarly from 5 to 7 times as great for the Brunswick material and about 4 times as great for the paper.

Because of the consistency of these results, we feel justified in using our standard test conditions to obtain comparative performance evaluations on various media. The increase in penetration with increasing flow rate is to be expected. The most significant point, however, is that the performance of both surface and depth collectors vary in the same manner. Thus the decision to use 325 x 1900 Dutch Twill as a reference standard appears to be a reasonable one.

V. SELECTION AND PROCUREMENT OF MEDIUM FOR FINAL ELEMENTS

A. FINAL CANDIDATES

On the basis of results obtained in the media evaluation program described in Section IV, it was necessary to select the material to be used in the prototype filters required as end items under this contract. While many of the candidates could be immediately eliminated from consideration on the basis of one or more performance inadequacies, at least four types of materials showed sufficient promise to merit final consideration. Performance characteristics of each final candidate and factors affecting final selection are discussed in the paragraphs which follow:

1. GRV-Type Paper

A paper type of material incorporating fine glass fibers has a number of unique advantages. Since such a material is made on standard papermaking equipment, highly uniform and reproducible formation can be achieved. In addition, precise control of filtration performance can routinely be accomplished by continuously varying the amount of glass fiber in the web according to requirements indicated by a DOP aerosol penetrometer used as a quality control monitor.

As indicated in Figure 13a, performance of a GRV-type material tailored to provide about 80% efficiency under our standard test conditions shows a far greater capacity for solids than the 325 x 1900 Dutch Twill with which it is compared. Further, we can expect that the same sort of relationship would exist for full-size cartridges.

On the other hand, these materials are relatively fragile and would require special measures to provide for adequate strength and ruggedness in a cartridge. In addition, as with any short-fibered paper, media migration is a serious problem which would have to be controlled by means of a downstream barrier. A final factor militating against use of this material is the temperature limitation imposed by the Vinyon fiber. At the maximum temperature of 165 F specified for this filter, some softening of the Vinyon will occur. Thus it would be difficult to ensure integrity under all possible conditions of use.

2. Fram MDM

As shown in Figure 13b, the sample of 10-micron nominal MDM supplied by Fram Corporation also shows performance far superior to the woven wire cloth. While efficiency of this sample is marginal, it seems likely that the medium could be tailored to achieve most of our objectives. In spite of the fact that fiber size is presumably limited by the nature of the replicating process, and in spite of some visible non-uniformity in the samples, we feel that this material could be successfully incorporated in a full-size element.

Figure 13a

GRV Handsheet S2-3a
82% efficiency, R = 9

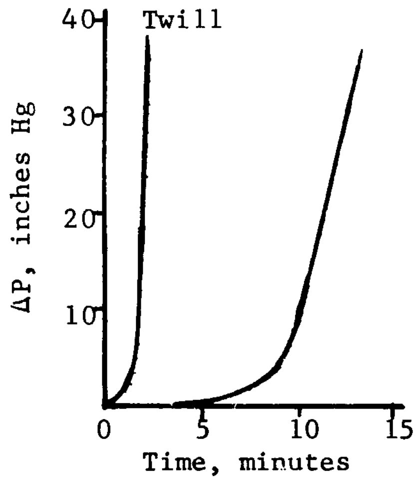

Figure 13b

Fram MDM, 10 μ nominal
72% efficiency, R = 7

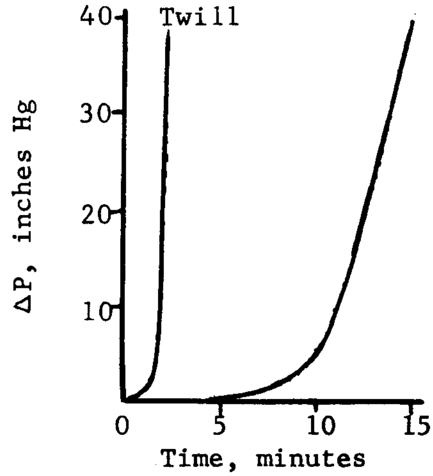

Figure 13c

Brunswick 13182-1-11
79% efficiency, R = 9

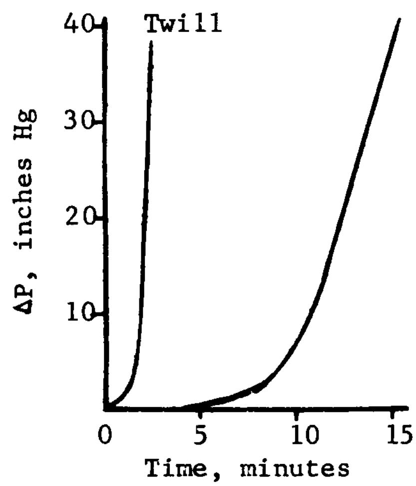

Figure 13d

Bendix Microfil, Tailored Element
76% efficiency, R = 4

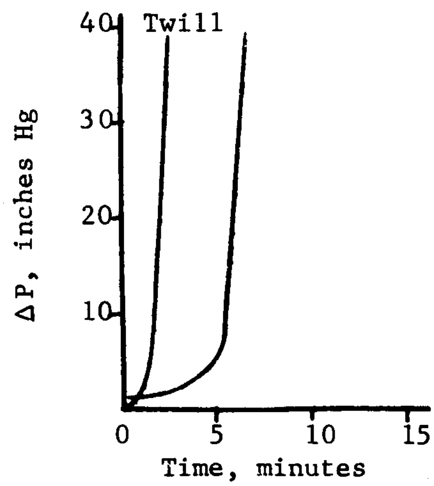

Figure 13

PERFORMANCE COMPARISON OF FINAL CANDIDATES AND DUTCH TWILL
(325 x 1900, 73% efficiency, R = 1)

3. Brunswick Metal Fiber Webs

Performance of a typical Brunswick sample made from 4- and 8-micron fibers is compared graphically to 325 x 1900 Dutch Twill in Figure 13c. It may be seen that solids capacity is comparable to the MDM, but efficiency is higher due to the presence of small fibers. Some inconsistencies in results were found for various Brunswick samples indicating difficulties in achieving adequate uniformity. We suspect that due to this lack of homogeneity throughout each sample, the full utilization of small fiber capabilities was not being consistently realized. Nevertheless, a high level of performance was found for most fine fiber samples submitted. Further, media migration appeared to be adequately controlled by the long fiber length used and by sintering the web after formation. As a result of its consistently high level of performance, therefore, the Brunswick material was selected for use in the prototype filter elements.

4. Bendix Microfil

Although initial Microfil elements supplied by Bendix failed to meet our requirements, the specially tailored element which was subsequently submitted made a closer approach. Performance of this element is shown graphically in Figure 13d. It may be seen that solids capacity is appreciably lower than that of the other three final candidates. Since media migration had been adequately controlled, however, and since full-size cartridges could be readily manufactured at low cost (probable cost, less than $75/cartridge), four full-size elements were ordered for further investigation and evaluation.

B. FINAL FILTER MEDIUM

Brunswick Corporation had available only a limited quantity of four-micron fiber for incorporation into the web required for our filter elements. Since the quality obtainable in a continuous length of the material was unknown, we requested that all of the available fiber be converted into our medium.

Costs were established at:

$30.00 per pound for 8-micron fiber
$47.50 per pound for 4-micron fiber
$25.00 per pound for processing

Our finished web was to weigh about 2.5 oz/ft^2 so that media costs (for 50% 4-micron, 50% 8-micron fiber) were in the range of $10.00/ft^2. This is about one-third the cost of small pore size woven wire cloth filter media.

Two lengths of material approximately 27 feet long by 10 inches wide were received from Brunswick. Each of these pieces was carefully examined and evaluated with respect to aerosol filtration capability using our DOP test apparatus. In addition, selected samples were removed from the web for evaluation in our laboratory filter test facility.

In general, we found this material to be satisfactory. Its capabilities were not quite as impressive as the best samples which we had previously evaluated, but performance appeared adequate. Filtration efficiency varied within the material but was generally as high or higher than our minimum requirement. Capacity for solids was slightly lower than we had hoped for, but still appeared to be many times greater than that of a typical woven wire cloth.

The only significant problem with the material was uniformity. Certain areas of the webs were found to be relatively high in aerosol penetration. In addition, one section of one piece had a number of holes and tears which made that area unsuitable for use in a filter element.

Because of the lack of uniformity, we carefully "mapped" the available web areas, including their flaws and showing their variations in performance. On the basis of these maps, we selected a total of six lengths from which full elements or modules could be fabricated. These lengths were sequentially rated so that the media which appeared to promise the best filtration performance could be incorporated in the final end items; those with somewhat poorer performance were used in module and prototype evaluation.

VI. ELEMENT DESIGN CONSIDERATIONS

A. ALTERNATIVE CONFIGURATIONS

As we approached the point of designing filter elements, we considered a variety of possible configurations and calculated the area of filter medium obtainable with each. These calculations were done assuming a housing of approximately the size used in the present filter manifold assembly. In general, we gave consideration to two different types of configuration--pleated structures and stacked discs.

The expanded area obtainable through pleating is, of course, dependent upon the physical properties of the filter medium. Pleat frequency is dependent upon the thickness of the material being folded and pleat depth is influenced by strength and toughness. Thus a wide range of available areas may be considered for use within a given available volume.

For preliminary purposes, we estimated that with a Brunswick web sandwiched between two stainless steel screens, a pleat frequency of 10 per inch (based upon the inside perimeter of the element) was realistic. As indicated in the calculations in Appendix B, we determined that filter area is maximized when the pleat depth is equal to approximately ¼ of the outer diameter of the cartridge (or in our case, approximately 0.75-inch). It should be noted, however, that while this calculation indicates the maximum pleated area which can be included within a given volume (at a specific pleat frequency), it does not guarantee full utilization of the area. Thus it was apparent that collapse of individual pleats under the differential pressures to be encountered in use was a possibility that required consideration.

An alternative to a pleated structure is a small-scale variant of the rotary disc pressure filter used in chemical processing applications. In this configuration, two annular pieces of medium are sealed together around the outer edge and held apart by a spacer. The filter is then composed of a stack of such segments. Fluid flows from outside the disc into the space between the pieces of medium and then into the central collection channel. Although the disc-type element is more expensive to construct, it does provide increased area under many circumstances. Elements of this type are commercially produced at present.

Modifications of the basic disc element have been considered as means of introducing additional area into the available space. Although more costly to make, the special use envisioned could justify such expense. The basis for these modifications is that the channel dimensions assumed are necessary only at the points of maximum flow. The central collecting channel, for example, must have its full diameter only at the exit from the element. Its diameter may be zero at the capped end of the element because there is no liquid entering the channel at that point. Ideally, the diameter of the channel would change in such a way that at any position in the channel the apparent linear velocity would be the same. Similar considerations apply to the outer diameter of the element and the clearance between the housing and the element. Two types of such modified disc elements have been considered in the calculations. The first is an element in which only the outer diameter changes. The second example assumes both a tapered outer diameter and a tapered internal channel. This latter configuration provides definite advantages in terms of usable area, but construction of the doubly tapered element would be very costly.

In Table XII, we present a summary of our element area calculations. Sketches of the configurations and the methods of calculation are included in Appendix B.

TABLE XII

SUMMARY OF ELEMENT AREA CALCULATIONS

Configuration	Calculated Area in^2	Estimated Usable Area in^2
Plain Cylinder	70	70
Presently used Dutch Twill Pleated Element	710	565
Maximized Brunswick Pleated Element	566	525
Simple Disc	480	450
Tapered Disc	550	515
Doubly Tapered Disc	606	575

The calculated areas are based on the outer surface of the filter medium according to the assumptions given in Appendix B. It is obvious that in any real filter there will be areas unavailable due to end and edge seals, creases and bends in the medium, and supports for the medium. To provide some estimate of the area lost in this manner, we have taken the total length of seals and creases and assumed that the area 1/32 of an inch to either side of such lines is unusable. Subtracting this area from the calculated area then gives an estimated usable area for the particular configuration. No deductions have been made, however, for end seal and support losses.

B. OTHER FACTORS AFFECTING DESIGN

While the disc-type element was recognized as a possible design (especially if serious variations in the performance of the filter medium had been found), the simplicity of a pleated structure was much more attractive. Accordingly, our efforts were concentrated on this approach. Initial evaluation of factors affecting design was to be accomplished with a series of small cartridge modules having all dimensions except length comparable to full-size elements. Among the points which required clarification and study before the final element design could be completed were the following:

1. Pleat Depth

While calculations had indicated how maximum area could be obtained, we needed to establish that this depth was usable in actual practice.

2. Pleat Frequency

The number of pleats which could be formed and effectively used in an element of fixed size had to be established experimentally.

3. Seam Joint

Since the filter medium must be joined to close the cylinder after pleating, consideration was given to welding techniques as well as the use of structural adhesives.

4. Sintering

It was our intention to sinter the pleated assembly to control migration; effects upon performance still required investigation.

5. End Seals

Possible methods of joining the filter medium to end caps included brazing or the use of structural adhesives.

6. Design of Components

Since the strength and ruggedness of the cartridge is determined by the end caps and center tube, these components had to be carefully designed after the dimensions of the pleated structure were established. In addition, the bottom cap required a spring member to provide approximately 1000 lb. axial load when the cartridge was installed in the housing. The design of this latter feature would also be influenced by the arrangement of other cartridge components.

VII. MODULE CONSTRUCTION AND EVALUATION

A. SUPPLEMENTAL APPARATUS

1. Pleating Equipment

In order to permit a rapid and thorough assessment of the effect of variations in pleating configurations, we arranged to rent a pleating machine from Chandler Machine Company, Ayer, Massachusetts. This equipment was set up in our laboratory and permitted us to realize considerable economies in both time and expense.

2. Sintering Furnaces

Two laboratory-size tube furnaces equipped with dry gaseous hydrogen inerting systems were used for experimental sintering of metal fiber webs. While these units had sufficient capacity for preliminary investigations, larger equipment was required for prototype modules and full-size elements. Accordingly, arrangements were made to sinter larger filter assemblies at New England Metallurgical Corporation, Boston, Mass.

3. High Flow Test Facility

Because of the high costs and relatively limited need, we elected not to construct full-scale flow testing facilities. In order to obtain information on clean flow pressure drop of modules and cartridges, however, we made arrangements to rent from Butler Aviation a commercial jet aircraft refuelling truck as a test stand. This arrangement provided us with a large source of filtered kerosene-type fuel, a 600 gpm pump, and necessary metering and control facilities.

B. DESCRIPTION OF MODULES

A total of four cartridge modules were prepared using the Brunswick web sandwiched between 80-mesh stainless steel screens as the filter medium. These elements were about 1.25 inches long but were otherwise comparable to proposed final elements. It was our object to use these modules to resolve the design questions posed in Section VI. Accordingly, the modules differed in pleat frequency, seam joining system, end sealing system, and sintering. Pleat depth was arbitrarily set at 0.75-inch for this series, since it had been established that this would provide for maximum area of the medium. Figure 14 is a photograph of one of the modules and an adapter used in flow testing.

C. PERFORMANCE OF MODULES

Modules were evaluated for bubble pressure, DOP penetration, clean flow pressure drop, filtration efficiency and solids capacity at varying flow rates, media migration, cleanability, and differential pressure capability. Evaluative results are summarized in Table XIII. Some

FIGURE 14 FILTER MODULE AND ADAPTER

TABLE XIII

RESULTS OF MODULE EVALUATION

Test Specimen	Bubble Pressure in H_2O	DOP Penetration %	ΔP @ Rated Flow #/in^2	Test Flow Condition gpm/ft^2	Solids Conc. mg/gal	Efficiency %	Time to 30" ΔP min	R @ 10 gpm/ft^2	Remarks
325 x 1900 Dutch Twill	19	100	-	10	100	73	2.2	1	Flat sheet
325 x 1900 Dutch Twill	19	100	-	35	50	54	1.0	-	Flat sheet
Brunswick Web #13182-1-8	10.7	78	-	10	100	80	11.4	8	Flat sheet
Brunswick Web #13182-1-8	10.7	78	-	35	50	73	5.8	-	Flat sheet
Brunswick Web from cartridge stock	11.6	78	-	10	100	83	9.4	7	Flat sheet
Module 19LC 10 pleats/inch	9	53	2.5	10	100	-	8.4	-	
Module 19LC	9	53	2.5	10	100	83	7.7	6	After cleaning
Module 19LC	9	53	2.5	29	50	77	5.2	-	
Module 19L 11 pleats/inch	-	66	3	-	-	-	-	-	
Module 19RC 10.5 pleats/inch	10	65	2.5	10	100	87	8.3	6	Negligible fiber migration
Module 19RC	10	65	2.5	29	50	67	5.4	-	
Module 19RC	10	65	2.5	29	50	68	5.5	-	After cleaning

previously reported data on flat sheets are included to show correlations.

We encountered considerable difficulty in demonstrating on a laboratory scale a 3000 psi differential pressure capability. This was due not to any fault of the cartridge, but rather to limitations imposed by our test equipment. We made several attempts to load cartridge modules with particulates to an extent sufficient to demonstrate adequate structural integrity, using our high-pressure test stand. Unfortunately, the pumping capacity of this facility was so low that solids capacity was extremely high. Even if virtually all available sites were filled with collected contaminant, the flow rate was so low during loading that the collected cake was still porous. As a result, maximum pressure obtainable in this manner was limited to about 850 psid.

An additional attempt was made to show adequate structural integrity by covering the entire upstream side of a filter module with a plastisol. It was recognized that this was not an entirely realistic test condition, since the load was being applied to the upstream protective screen rather than to the fibrous web. Nevertheless, it seemed worthwhile to investigate this approach also. During the subsequent testing of this element the plastisol ruptured at about 2000 psid, necessitating termination of the experiment short of demonstrating full differential pressure capability.

In other respects, performance of pleated cartridges was satisfactory. On the basis of clean flow pressure drop measurements (using the aircraft refuelling vehicle), we concluded that a pleat frequency of about 10.5 pleats/inch (based upon inside perimeter) was optimum for our system. Fully sintered modules having this pleat frequency were found to behave in a manner entirely analogous to that obtained with flat sheets. Solids capacity was reduced slightly due to the pleated configuration and, as expected, clean flow pressure drop was somewhat higher than for a flat sheet. Efficiency was generally higher than 325 x 1900 Dutch Twill wire cloth and fiber migration was adequately controlled by the use of long fibers and by sintering operation. On small-scale tests, the element configurations appeared to be cleanable, using the techniques previously described.

VIII. PROTOTYPE ELEMENT CONSTRUCTION AND EVALUATION

A. DESIGN CONCLUSIONS

On the basis of the module evaluation program as well as some additional laboratory experimentation, the following design conclusions were drawn with respect to full-scale prototype elements.

1. Pleated Structure

Pleat depth was set at 0.75-inch and pleat frequency at 10.5 per inch. This corresponds to 54 pleats per cartridge or a total input area of about four square feet.

In order to insure adequate space for fluid flow between individual pleats and in order to preclude the possibility of pleat collapse under high differential pressures, we elected to incorporate separators within the downstream structure. While the separation function is carried out in part by the screens used in the sandwich construction, this procedure provides a degree of insurance. A very open 18-mesh, 9-mil wire, stainless steel screen was selected for use as the separator material.

2. Seam Joint

We elected to use a fusion weld technique at the pleat seam since this provided for a neat joint with minimal surface area loss. Electron beam welding was briefly investigated and found to be more difficult to control than simpler conventional welding methods.

3. End Cap Seal

Preliminary experimentation indicated that it was extremely difficult to control the flow of a brazing alloy up into the fibrous medium structure. Thus it was difficult both to effect an adequate seal and to maintain unplugged filter area within the pleated assembly. Because of these problems and because the particular application for which this filter was intended did not require high-temperature capability, we investigated the use of filled epoxy resin systems. It was found that by using a resin with the proper viscosity characteristics, adequate wetting of the pleated assembly could be achieved without significant amounts of resin penetration through wicking and capillary action. Strength of a joint properly sealed with an epoxy resin was adequate.

4. Component Design

With the dimensions of the pleated assembly fixed, it was possible to proceed with the design details of the center tube and end caps required for the prototype cartridges. The center tube was designed to provide the required support for the pleated structure. It consisted of a heavy walled 304 stainless steel tube perforated to permit adequate fluid flow. End caps were also made of 304 stainless steel and were based in part upon the design of the presently used wire cloth element. Because of the relatively deep pleat used, a special method of providing spring pressure for axial loading of the cartridge was required. The design included a series of four stainless steel lock washers stacked and retained in a cavity in the bottom end cap. It was found that the restoring force of the compressed lock washers was sufficient to provide the required axial loading.

Drawings of the cartridge components are included in Appendix C.

B. ASSEMBLY OF PROTOTYPE ELEMENTS

A total of five full-size prototype elements were assembled. Figure 15 is a photograph of two prototype elements and Figure 16 shows a section of another. The first three units were used to resolve problems encountered during the assembly operation and to evaluate performance. The last two were supplied to Marshall Space Flight Center as the required end items.

Because of a number of difficulties encountered during the construction of these elements, some rather specialized techniques had to be developed to insure adequate performance of the finished units. Some of these problem areas are discussed briefly below; procedures followed during assembly are outlined in Appendix D.

1. Uniformity of Pleat Height

Considerable difficulty was experienced in attempting to maintain a uniform pleat height during an entire pleating run. This appeared to be due in part to the nature of the pleating machine and in part to the inherent toughness of the sandwich construction we were attempting to pleat. The problem was largely overcome by arranging to maintain a fixed tension on the web fed to the pleater, and by maintaining considerable back pressure on the material as it emerged from the folding zone.

2. Reducing Pleated Assembly to Proper Size

The nature of the Brunswick web and the pleating arrangements were such that it was necessary to cut the assembly to the proper size after pleating. This was accomplished by compressing the pleats in a special steel jig and, after rough cutting, grinding the compressed structure to the exact size required. Careful cleaning of the medium was then required to remove debris from the grinding operation.

3. Seam Welding

It was found that successful welding of the seam in full-size cartridges was difficult to accomplish in a dependable manner. In several cases after an entire cartridge was assembled, bubble pressure

FIGURE 15 PROTOTYPE FILTERS

FIGURE 16 SECTION OF PROTOTYPE ELEMENT

measurements revealed severe leakage along the seam. Accordingly, we elected to cover the weld routinely with a filled epoxy resin as a precautionary measure.

4. Sintering

Difficulties were also encountered due to differential expansion of clamping systems during sintering. The arrangement was such that the pleated medium, complete with separators, was positioned on the center tube and the entire assembly was sintered. It was necessary, however, to hold the assembly together to prevent sagging of components at sintering temperatures. If the unit was clamped too tightly, the structure was distorted as a result of thermal expansion. Thus a very carefully balanced clamping pressure was required.

5. Alignment

Because the filter was to be used in a high-pressure system, both dimensions of components and alignment were extremely critical. In order to preclude the possibility of elements which would not fit the housing, each end of each cartridge was sealed and cured separately. Alignment was checked at each step by actually testing the fit within the filter housing.

6. End Seal Leaks

Some difficulty was encountered in attempting to effect an adequate seal of the medium to the end caps using the filled epoxy resin. While leaks could be plugged after assembly, it was preferable to prevent their occurrence. Accordingly, the resin was generously applied to both the cap and the medium. After the two components were brought into contact, excess resin was carefully removed.

C. EVALUATION OF PROTOTYPE ELEMENTS

We did not have available all of the equipment which would be required to accomplish full-scale testing and qualification of prototype elements. Further, it did not seem logical or economical for us to acquire such equipment since the elements were to be subjected to thorough testing at Huntsville after delivery. We fully realized, however, NASA's desire to expend qualification testing effort only if a high level of performance could be assured.

Accordingly, we carried out a limited program (for both ADL and Bendix elements) in which we attempted to conduct sufficient evaluation and testing here to assure ourselves that the elements would achieve NASA's objectives and would merit full-scale testing at Huntsville.

Because the medium used in the elements had been rather thoroughly evaluated in both flat sheets and in modules, and because the sections of medium used in the final two prototype filters were those with superior performance, we anticipated no major problems.

Accordingly, all of the Bendix and ADL cartridges were screened for integrity and inherent filtration ability through bubble pressure and aerosol penetration measurements. In addition, individual elements of both types were subjected to clean flow pressure drop measurements with kerosene-type fuels and with air; one ADL element was loaded with particulates to investigate differential pressure capability; and an ADL element was subjected to vibration testing (sinusoidal sweep and resonance tests).

Performance and disposition of prototype elements are summarized in Table XIV. Specific aspects of our evaluation program are briefly discussed in the paragraphs below:

1. Bubble Pressure Tests

Bubble pressure was found to be low for all of the ADL cartridges when initially tested after assembly. This was apparently due in part to discontinuities within the filter medium and in part to difficulties in obtaining adequate penetration of the epoxy sealing system used in cartridge assembly. The final two elements were made with the better sections of the Brunswick web so that problems were less severe. Some spot patching with less viscous epoxy was required, however, to permit attaining bubble pressures comparable to those obtained with flat sheets.

2. DOP Performance

The measurements of aerosol penetration confirm the over-all integrity of the elements (with the possible exception of Bendix #1 which shows a higher smoke penetration than any of the others) and show the improved capabilities of ADL #4 and ADL #5. It should be noted, however, that the penetration values shown in Table XIV are considerably lower than those previously reported for flat sheets or modules. This is because the elements incorporate a much larger surface area and thus the linear velocity through the medium is much lower. This permits more diffusional collection of particles to occur resulting in lower penetration.

3. Clean Flow Tests

Considerably fewer data have been obtained on clean flow pressure drop than we had planned. While the aircraft refuelling vehicle was equipped with a pump capable of delivering 600 gpm, it was found in practice that capacity fell off rapidly as pressure drop through the test system increased. As a result, we were limited to a maximum flow of 80-90 gpm when the housing and necessary adapter connections were incorporated in the pumping loop. In addition, flow control at very low rates was erratic so that performance over a wide range of flow could not be determined. A further complication arose when employees of Butler Aviation went out on strike. While all normal operations were being carried out by supervisory personnel, it became increasingly difficult to make adequate arrangements for our flow tests.

TABLE XIV

SUMMARY OF PROTOTYPE ELEMENT EVALUATION

Source and Element No.	Bubble Pressure in. H_2O	DOP Performance @ 85 lpm		Other Tests and Remarks
		ΔP mm H_2O	Aerosol Penetration %	
ADL #1	End seal leak	2	28	Flow tested, 2.7 psid @ 80 gpm A-1 Turbofuel; loaded with solids to 1200 psid.
ADL #2	End seal leak	2	30	Vibration tested; no evidence of subsequent migration.
ADL #3	Seam leak	2	32	Flow tested, 3 psid @ 90 gpm A-1 Turbofuel.
ADL #4	8.5	2	24	Submitted to MSFC.
ADL #5	8.5	2	25	Submitted to MSFC.
Bendix #1	12.5	6	44	
Bendix #2	10.4	6	32	Flow tested at Bendix, 7.5 psid @ 90 gpm 12 psid @ 120 gpm JP-5.
Bendix #3	14.5	6	24	Submitted to MSFC.
Bendix #4	10.4	6	24	Submitted to MSFC.

Because of these problems, we were able to obtain only limited data on two of our cartridges (as shown in Table XIV) and none on the Bendix elements. Fortunately, however, Bendix had taken some data (using JP-5) on one of their units before shipping it to us, so that a limited basis of comparison exists. In addition, in order to show a direct comparison, we measured resistance to flow in an air system for both Bendix and ADL cartridges. These data are plotted in Figure 17.

4. Differential Pressure Capability

An attempt was made to demonstrate differential pressure capability of ADL element #1 by loading it with a fine iron oxide in our low flow test equipment. Because of limitations in the equipment (as discussed in Section VII.C), we were able to attain only 1200 psid. No evidence of structural failure was apparent after this test, however.

5. Vibration Testing

Facilities were rented from Acton Laboratories, Inc. in order to permit a limited amount of vibration testing on ADL element #2. The test program included a sinusoidal sweep test in which the frequency range from 20 to 2000 cps was scanned in a ten-minute logarithmic sweep along two major axes of the element (which was installed in the housing) at the following input vibration levels:

20-250 cps @ 9.4 g's peak
250-500 cps @ 0.0029 inches D.A. displacement
500-2000 cps @ 37.5 g's peak

Following the sweep tests, the element was subjected to five minutes of vibration at the major resonant frequencies observed. Input vibration levels were maintained at half of those used in the sweep tests.

At the completion of vibration testing, the fluid in the housing was filtered through a Millipore filter in order to check for the presence of any fibers which might have been dislodged from the filter medium. In addition, small quantities of fuel were pumped through the element and were also filtered through a second Millipore filter as a further check on potential migration. No metal fibers were observed on either filter.

Bubble pressure after vibration testing was found to be unchanged. DOP penetration was found to be somewhat higher, but this may have been due in part to the presence of residual traces of fuel within the element (which have been observed in the past to cause high smoke penetration readings).

6. General Comments

In general, we feel that the evaluation results obtained on the ADL elements are in line with our expectations. Clean flow pressure drop is higher than for presently used elements, but because of the inherently

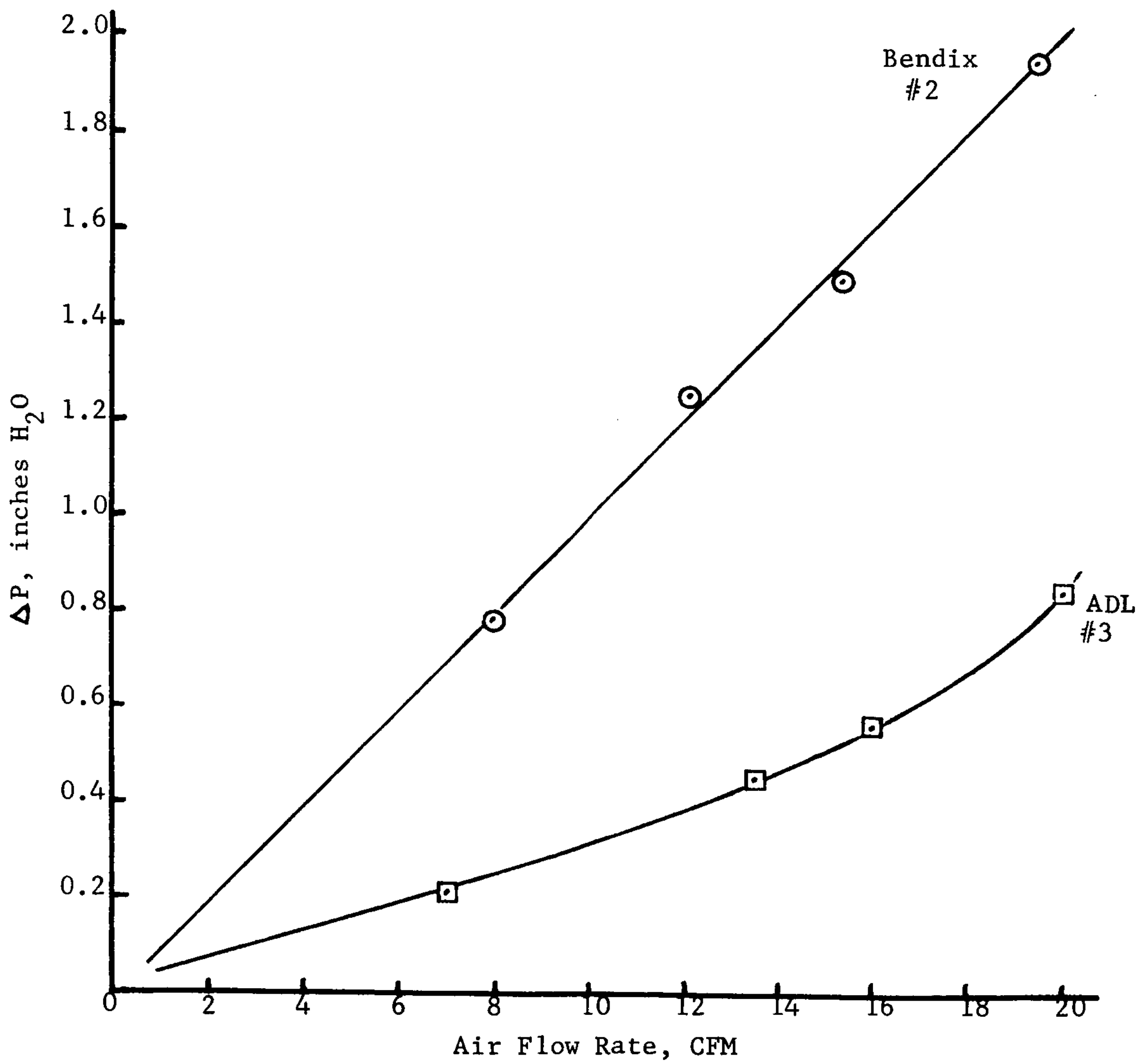

Figure 17

AIR FLOW-PRESSURE DROP CURVES
FOR ADL AND BENDIX ELEMENTS

high solids-holding capacity, initial pressure drop has very little significance. Accordingly, we recommend that these elements be subjected to full evaluation at Marshall Space Flight Center.

The Bendix elements show a higher resistance to flow than was anticipated but again, because of their depth filtration capabilities, this may not be significant. On the basis of the limited data available we can predict somewhat higher collection efficiency and higher solids capacity for the Bendix elements than for conventional woven wire cloth filters. While the efficiency-capacity relationships for the ADL cartridges appear to be superior, the Microfil units have the advantage of being commercially available at low cost. Accordingly, two of these elements have also been supplied to Marshall Space Flight Center for consideration and evaluation.

APPENDIX A

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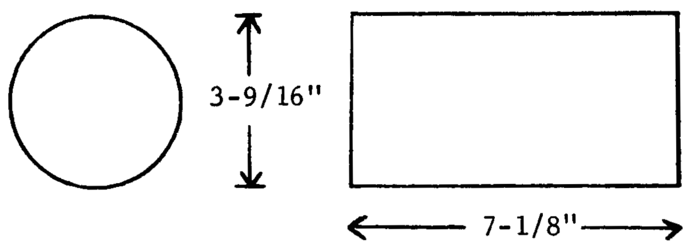
APPENDIX B

CALCULATION OF ELEMENT AREA FOR VARIOUS CONFIGURATIONS

ASSUMPTIONS

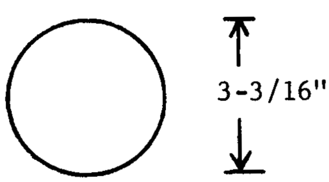
The filter cavity is of the following size and shape:



The filter element must clear the sides of the cavity by 3/16 inch; this may be less in areas of lower flow. The exit port of 1¼ inch diameter is on center at one end. The unusable area of an element is proportional to the length of seams and creases.

CALCULATIONS

Cylindrical Element



$A_F = 7\text{-}1/8 \times \pi \times 3\text{-}3/16 = \underline{71.5 \text{ in}^2}$

$a_u \propto 0$ because cylinder could be formed as a unit rather than from rolled flat stock.

Actual Area
~70 in^2

Presently Used Dutch Twill Pleated Element

Assume 161 pleats of depth 0.31"

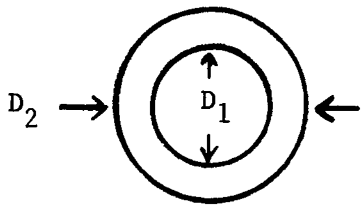
$A_F = 161 \times 2 \times 0.31 \times 7\text{-}1/8 = \underline{710 \text{ in}^2}$

$a_u \propto 161 \times 2 \times 7\text{-}1/8 = 2290$

Assuming that the unusable area along each pleat is 1/16" wide, $a_u = 143 \text{ in}^2$.

Actual Area
~565 in^2

Maximum Area Possible for Pleated Cylinder



Pleat depth = $z = \dfrac{D_2 - D_1}{2}$

Pleat frequency = f

Element length = L

$$A_F = \pi D_1 f \times 2z \times L = 2\pi fL\left[(D_2 - 2z)z\right]$$

$$\frac{dA_F}{dz} = 2\pi fL\left[(D_2 - 2z) + z(-2)\right]$$

Thus, for maximum area, $\underline{z = \dfrac{D_2}{4}}$

Assuming now that the width of the unusable portion is u, we obtain that

$$A_F' = 2\pi fL(D_2 - 2z)z - 2\pi(D_2 - 2z)fLu$$

$$= 2\pi fL\left[(D_2 - 2z)(z - u)\right]$$

$$\frac{dA_F'}{dz} = 2\pi fL\left[(D_2 - 2z) + (z - u)(-2)\right]$$

Thus, for maximum area, $\underline{z = \dfrac{D_2}{4} + \dfrac{u}{2}}$

For typical Brunswick material, let

f = 10 pleats/inch and u = 1/16" as before,

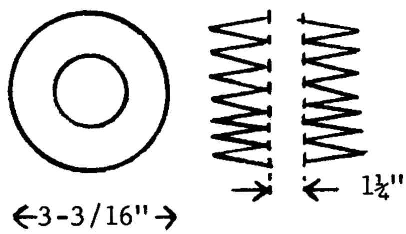
$$A_F = 2\pi(10)(7\text{-}1/8)\left[(3.188 - 1.594)(0.797)\right] = \underline{566 \text{ in}^2}$$

$$A_F' = 2\pi(10)(7\text{-}1/8)\left[(3.188 - 1.656)(0.828 - 0.062)\right] = \underline{525 \text{ in}^2}$$

Disc Types

Assume that we can get 5 discs/inch; use area projected onto plane perpendicular to axis

a) Standard cylindrical system



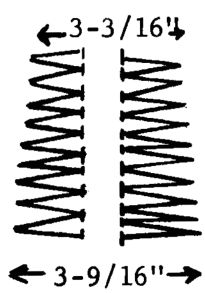
$$A_F = 7\text{-}1/8 \times 5 \times 2 \times \pi \left(\frac{3\text{-}3/16 + 1\frac{1}{4}}{2}\right)\left(\frac{3\text{-}3/16 - 1\frac{1}{4}}{2}\right)$$
$$= 480 \text{ in}^2$$

a_u $\quad 7\text{-}1/8 \times 5 \times \pi\,(3\text{-}3/16 + 1\frac{1}{4}) = 498$

using the 1/16" width assumption,
$a_u = 31 \text{ in}^2$

Actual Area $\sim 450 \text{ in}^2$

b) Tapered outer edge; linearly decrease clearance from 3/16" at high velocity entrance end to 0 clearance at capped end.



Middle disc has OD of 3-3/8"

$$A_F = 7\text{-}1/8 \times 5 \times 2 \times \pi \left(\frac{3\text{-}3/8 + 1\frac{1}{4}}{2}\right)\left(\frac{3\text{-}3/8 \times 1\frac{1}{4}}{2}\right)$$
$$= 550 \text{ in}^2$$

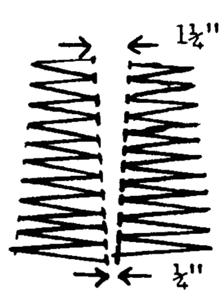
a_u $\quad 7\text{-}1/8 \times 5 \times \pi\,(3\text{-}3/8 + 1\frac{1}{4}) = 520$

using 1/16" width assumption, $a_u = 33 \text{ in}^2$

Actual Area $\sim 515 \text{ in}^2$

c) Doubly tapered; OD as above; ID 1¼" at exit, ¼" at far end

Middle disc has OD = 3-3/8"
ID = 3/4"



$$A_F = 7\text{-}1/8 \times 5 \times 2 \times \pi \left(\frac{3\text{-}3/8 + 3/4}{2}\right)\left(\frac{3\text{-}3/8 - 3/4}{2}\right)$$
$$= 606 \text{ in}^2$$

a_u $\quad 7\text{-}1/8 \times 5 \times \pi\,(3\text{-}3/8 + 3/4) = 463$

using 1/16" width assumption, $a_u = 29 \text{ in}^2$

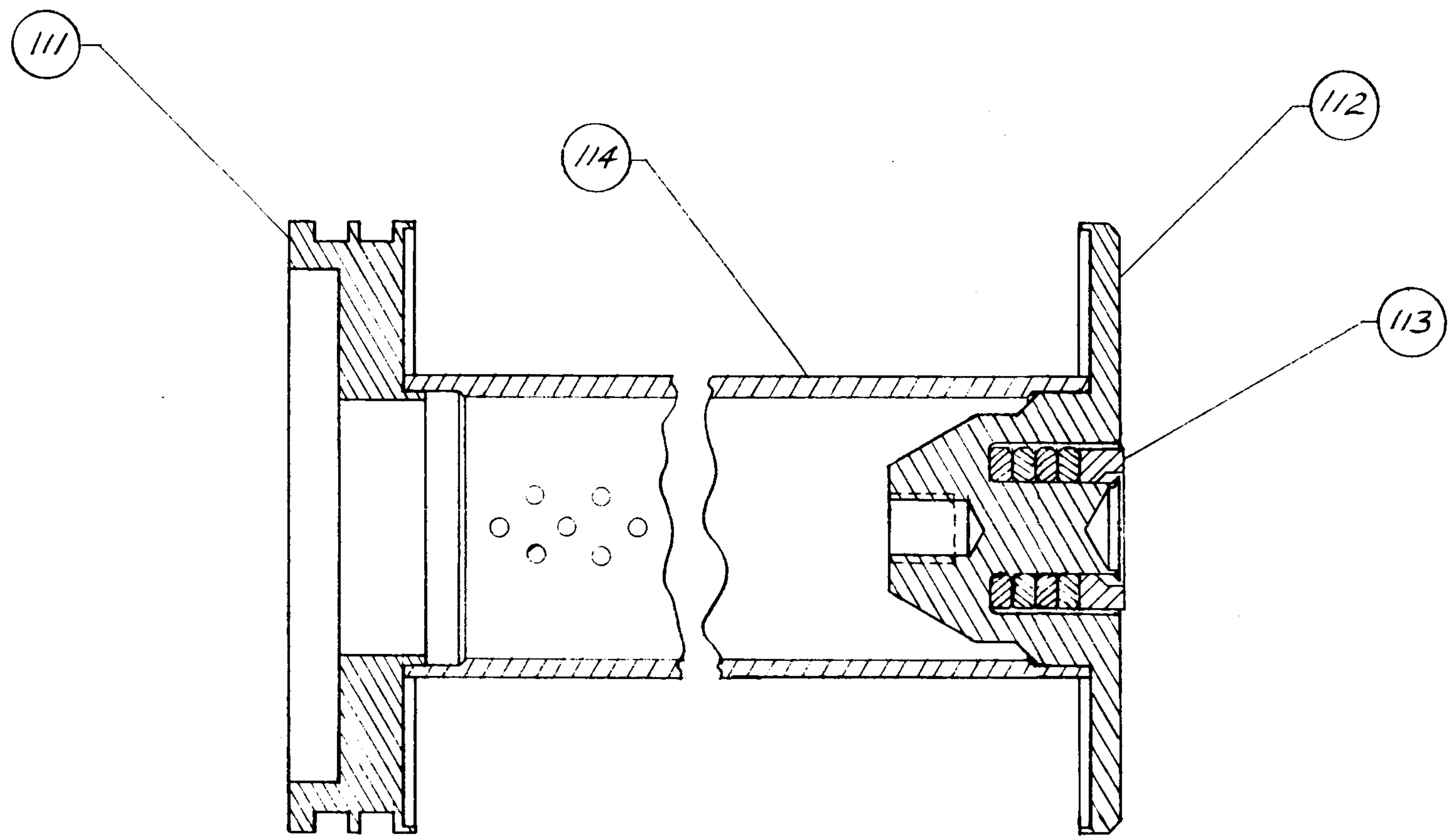
Actual Area $\sim 575 \text{ in}^2$

APPENDIX C

DRAWINGS OF ELEMENT COMPONENTS

Number	Title
66516-110	Element Support Assembly
66516-111	Fitting Seal End
66516-112	End Cap
66516-113	Retainer
66516-114	Support Tube

REVISIONS			
SYM	DESCRIPTION	DATE	APPROVAL



REV.

ITEM	REQD	PART NO.	DESCRIPTION	MATL	MATL SPEC	UNIT WT	NEXT ASSY	USED ON

LIST OF MATERIAL

APPLICATION

UNLESS OTHERWISE SPECIFIED

TOLERANCES ON
FRACTIONS DECIMALS ANGLES

MATERIALS

HEAT TREATMENT

FINAL PROTECTIVE FINISH

ORIGINAL ISSUE DATE
DWN DKA DATE 5/12/65
CHKD DATE
APPD DATE

SUBMITTED

A. D. LITTLE, INC.

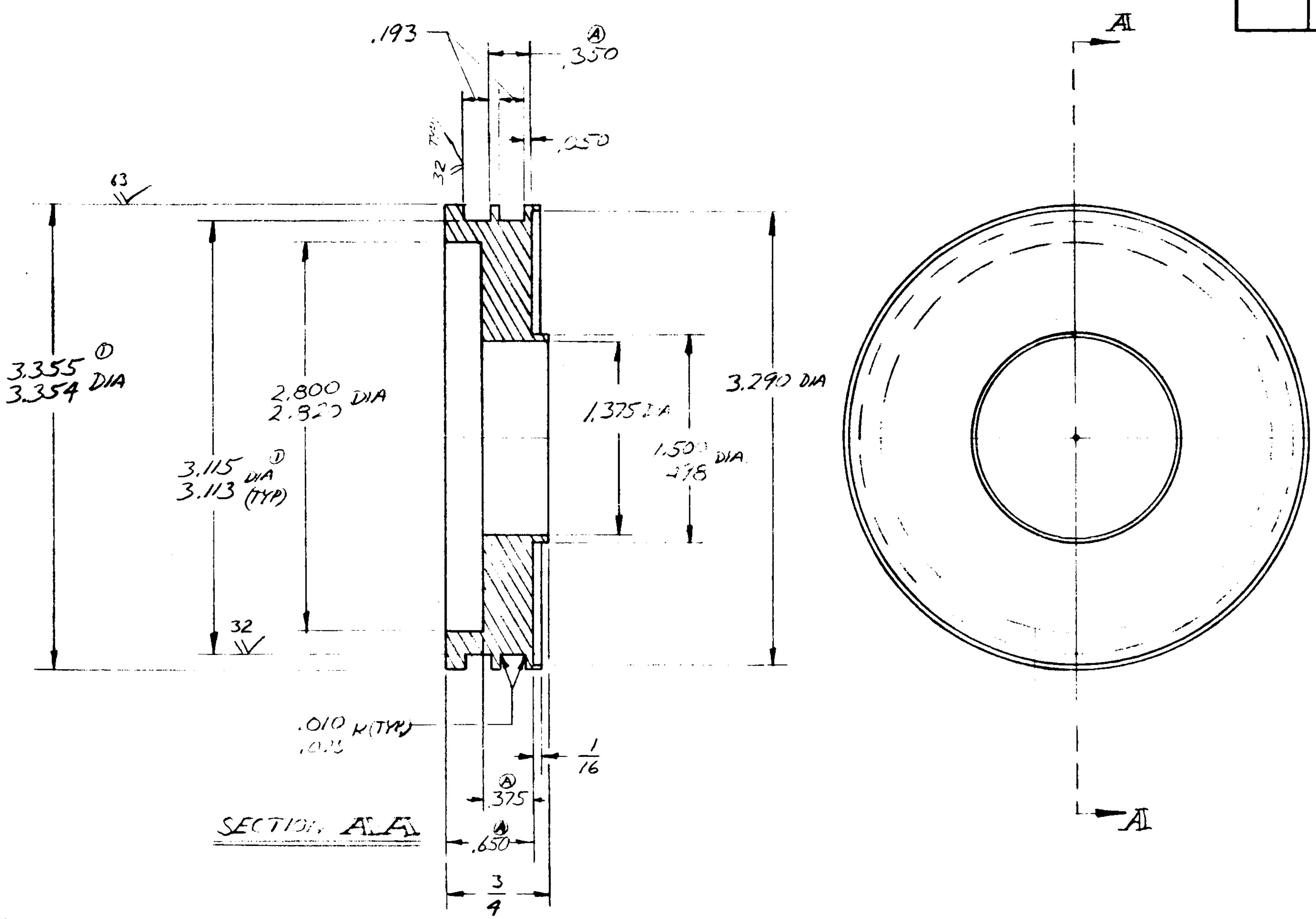
ELEMENT SUPPORT ASSEMBLY

Arthur D. Little, Inc.
CAMBRIDGE 40, MASSACHUSETTS

DWG SIZE B 66516-110

SCALE FULL UNIT WT. CODE 75629 SHEET OF

REVISIONS			
SYM	DESCRIPTION	DATE	APPROVAL
A	MODIFIED .375 DIM FROM .345, ADDED .650 DIM, CHANGED 'O' RING GROOVE LOCATION	5/28/65	



NOTES:

1. 3.355/3.354 DIA. & 3.115/3.113 DIA CONCENTRIC .003 T.I.R.
2. ALL OTHER DIA. CONCENTRIC .005 T.I.R.
3. BREAK CORNERS .005/.010

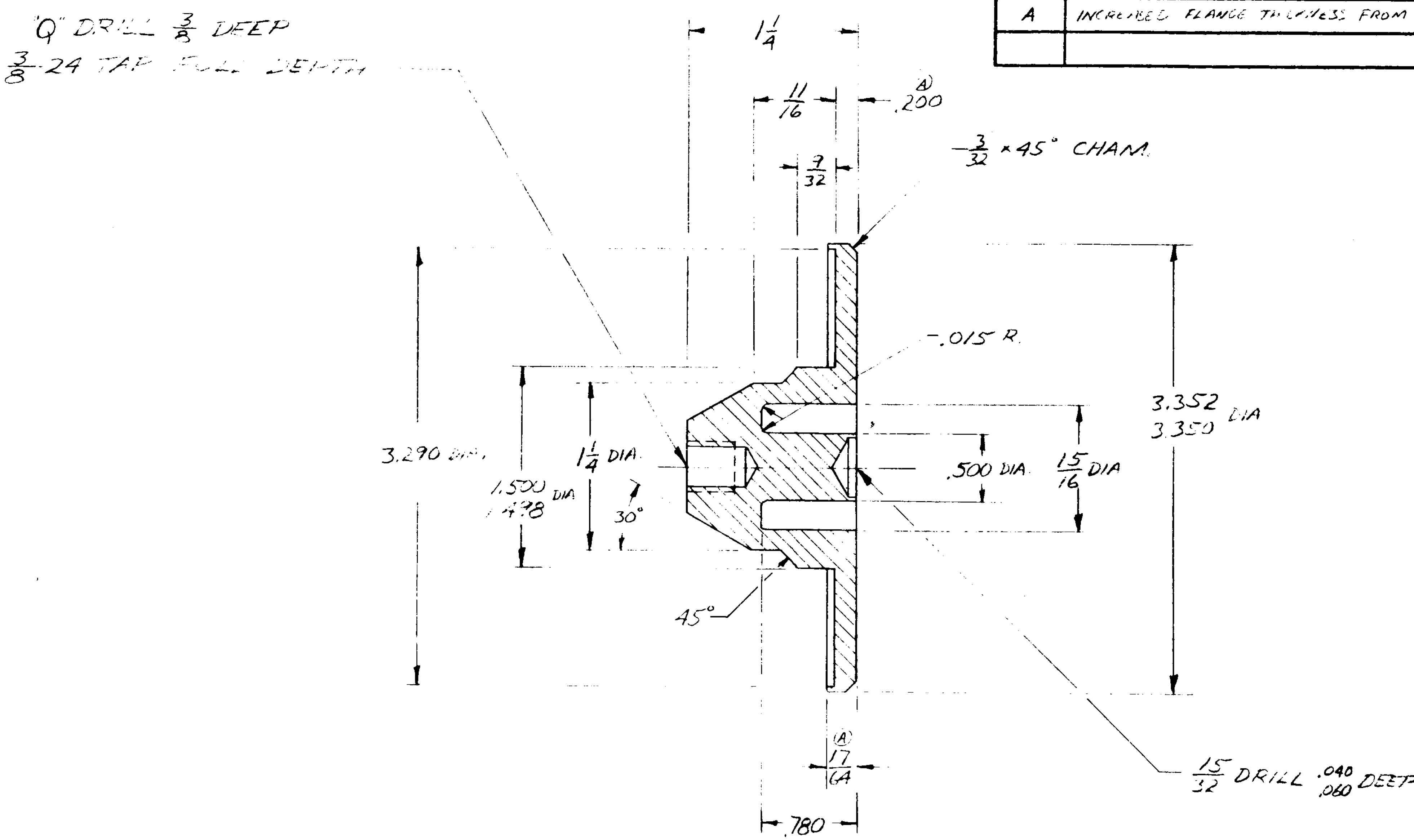
ITEM	REQD	PART NO.	DESCRIPTION	MATL	MATL SPEC	UNIT WT	NEXT ASSY	USED ON
			LIST OF MATERIAL				APPLICATION	

UNLESS OTHERWISE SPECIFIED TOLERANCES ON FRACTIONS ± 1/64 · DECIMALS ±.005 · ANGLES ±1°	ORIGINAL ISSUE DATE DWN D... DATE 5/12/65 CHKD DATE APPD DATE	FITTING SEAL END	**Arthur D. Little, Inc.** CAMBRIDGE 40, MASSACHUSETTS
MATERIALS TYPE 303 STAINLESS SS	SUBMITTED A. D. LITTLE, INC.		DWG SIZE B · 66516-111
HEAT TREATMENT		SCALE FULL · UNIT WT.	CODE 75629 · SHEET OF
FINAL PROTECTIVE FINISH PASSIVATE			

REVISIONS

SYM	DESCRIPTION	DATE	APPROVAL
A	INCREASED FLANGE THICKNESS FROM .160 TO .200	5/28/65	

REV.



NOTES:
1. ALL DIA. CONCENTRIC .005 T.I.R.
2. BREAK .005 / .010
3. INTERNAL .005

ITEM	REQD	PART NO.	DESCRIPTION	MATL	MATL SPEC	UNIT WT	NEXT ASSY	USED ON

LIST OF MATERIAL — APPLICATION

UNLESS OTHERWISE SPECIFIED
TOLERANCES ON
FRACTIONS ± 1/64 — DECIMALS ± .005 — ANGLES ± 2°

MATERIALS: TYPE 303 STAINLESS
HEAT TREATMENT
FINAL PROTECTIVE FINISH: PASSIVATE

ORIGINAL ISSUE DATE
DWN — DATE 5/12/65
CHKD — DATE
APPD — DATE
SUBMITTED
A. D. LITTLE, INC.

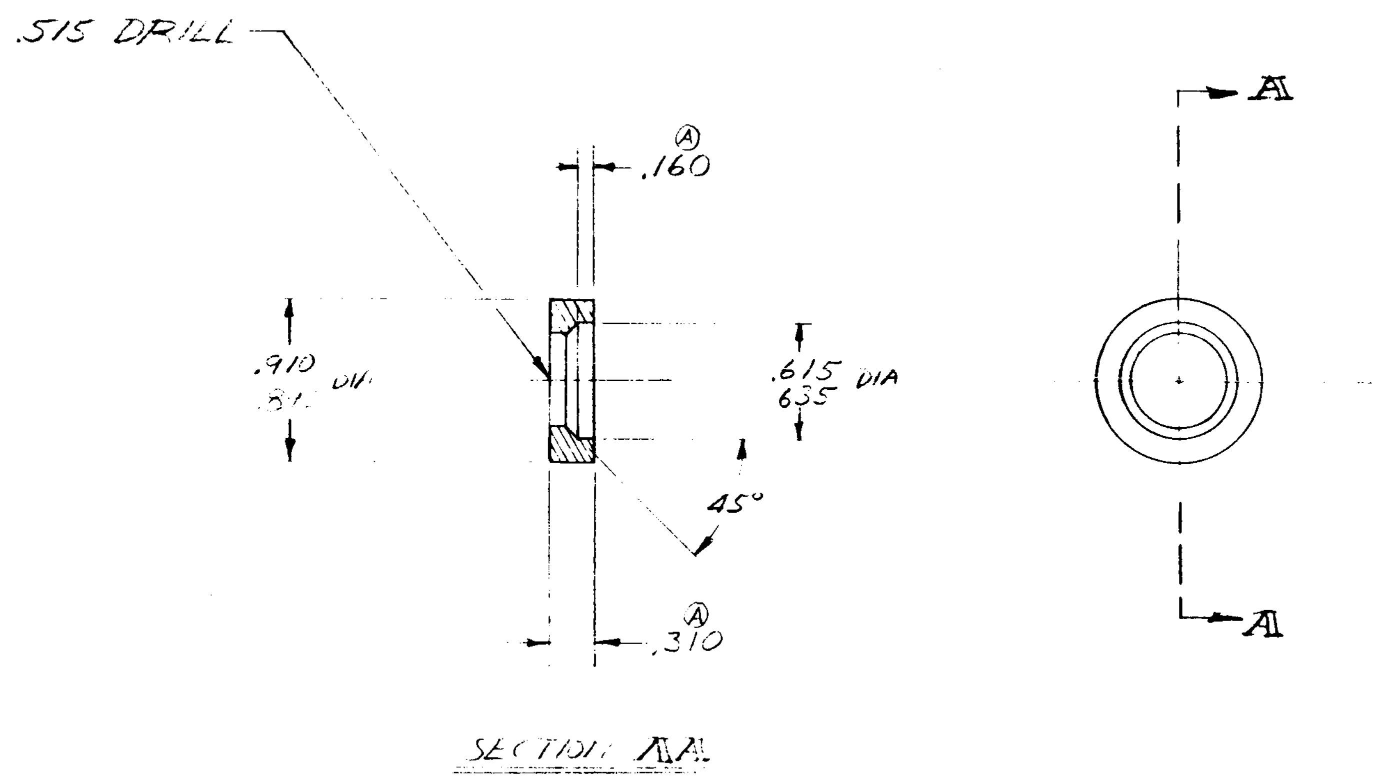
END CAP

SCALE FULL — UNIT WT.

Arthur D. Little, Inc.
CAMBRIDGE 40, MASSACHUSETTS

DWG SIZE B — 66516-112
CODE 75629 — SHEET OF

REVISIONS			
SYM	DESCRIPTION	DATE	APPROVAL
A	INCREASED THICKNESS FROM .250 TO .310, C BORE FROM .100	6/3/65	



NOTES
1. BREAK CORNERS .005 .010

ITEM	REQD	PART NO.	DESCRIPTION	MATL	MATL SPEC	UNIT WT	NEXT ASSY	USED ON

LIST OF MATERIAL — APPLICATION

UNLESS OTHERWISE SPECIFIED
TOLERANCES ON
FRACTIONS ± 1/64 — DECIMALS — ANGLES ± 1°
MATERIALS: TYPE 303 STAINLESS
HEAT TREATMENT
FINAL PROTECTIVE FINISH: PASSIVATE

ORIGINAL ISSUE DATE
DWN DAK DATE 5/12/65
CHKD DATE
APPD DATE
SUBMITTED
A. D. LITTLE, INC.

RETAINER

SCALE FULL — UNIT WT.

Arthur D. Little, Inc.
CAMBRIDGE 40, MASSACHUSETTS

DWG SIZE B — 66516-113
CODE 75629 — SHEET OF

BY DLK DATE 4/23/6_

APPROVED ____ DATE ____

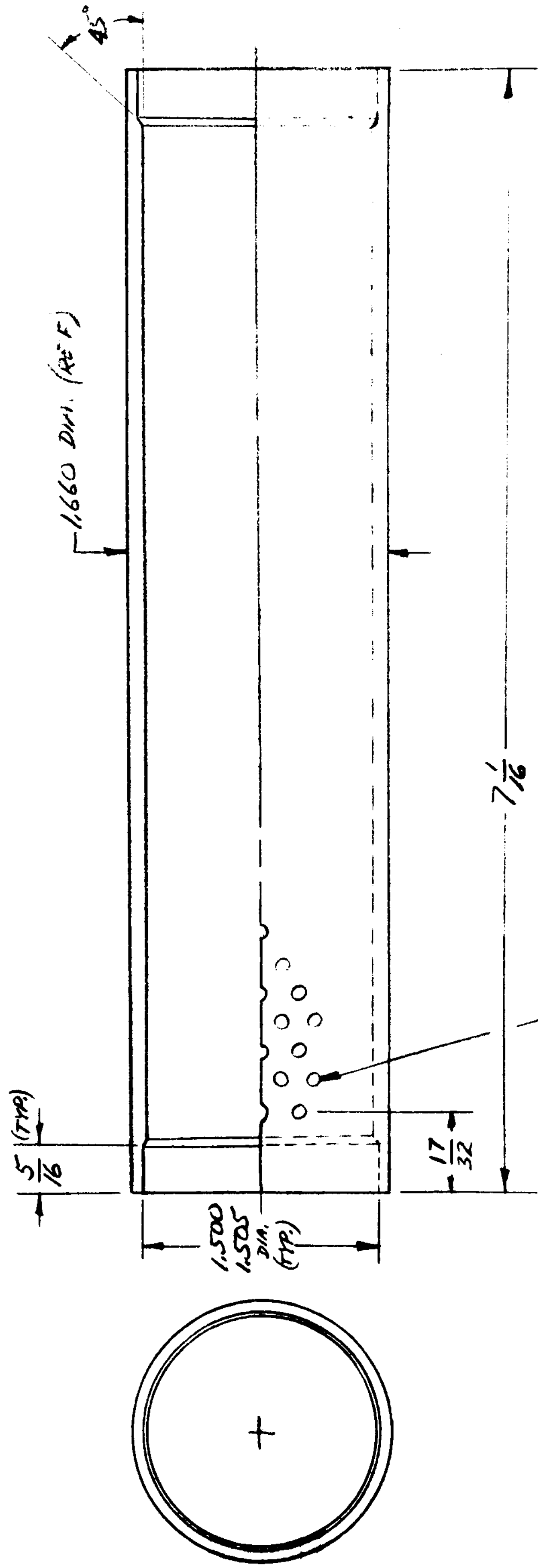
CLIENT NASA

ARTHUR D. LITTLE, INC.
CAMBRIDGE, MASS.

SHEET NO. ____ OF ____

SKETCH NO. ____

CASE NO. 66516



MAKE FROM TYPE 304 STAINLESS TUBING
1.660 OD x .109 WALL

3/32 DIA HOLES ON 3/8" CENTERS IN ROWS 10° APART
ALTERNATE ROWS OFFSET 3/16"

SUPPORT TUBE

66516-114

REMOVE ALL BURRS

APPENDIX D

PROCEDURES USED IN ASSEMBLING FILTER ELEMENTS

The outline below indicates the step-by-step procedures followed in the assembly of full-scale filter elements.

1. Prepare the filter mat and stainless steel screen (80 x 80 mesh-5.5 mil diameter wire-Type 304) for pleating by cutting into 8-inch wide, 7-foot long strips and sandwiching the filter mat between the screens.

2. Pleat the screen-mat-screen assembly on suitable commercial pleating equipment.

3. Compress the pleated structure in a 4-sided metal jig which is 7-1/16 inches wide (the length of the filter medium needed), 3/4-inch high (pleat height) and long enough ($\sim$9 inches) to accommodate the uncompressed pleated structure.

4. Rough cut the pleated structure and grind to the exact dimension required (7-1/16 inches).

5. Remove from jig and cut to the desired fifty-four pleats.

6. Clean in an ultrasonic bath using a solvent for degreasing and a detergent system for particle removal.

7. Clamp the structure together along the pleat axis and fusion weld.

8. Cut wire separators (18 x 18 Type 304 stainless steel wire screen-9 mil diameter wire) into 7-1/16 inches long, ½-inch wide strips and install in the inner pleat structure.

9. Loosely clamp the pleated structure around the center tube using a 5 mil molybdenum sheet between the filter structure and the hose-type stainless steel clamps to prevent subsequent welding of the clamps to the filter.

10. Sinter the clamped unit in a dry hydrogen atmosphere @ 2050 F for 30 minutes and cool rapidly in the same atmosphere.

11. Remove clamps and molybdenum sheet without contaminating the structure.

12. Affix the filter structure (including center tube) to the bottom end cap by applying a liberal coating of a filled

epoxy (3M Company's EC-2214) to both end cap and filter unit, assembling them together using a suitable clamping arrangement. Test alignment in the filter housing, remove and cure for approximately one hour at 250 F.

13. Affix the top end cap in a similar fashion.

14. Apply filled epoxy resin to welded seam area and cure for approximately one hour @ 250 F.

15. Check bubble point of finished unit and patch any leaks with Shell Oil Co. epoxy system--Epon 830 and curing agent U.