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STUDY OF AVIATION-FUEL FILTER/SEPARATORS

Annual Summary Report
May 1967
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by

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ABSTRACT

An annual review is presented of a research program concerned with studying the filter/separator phenomena. The study consisted of reviewing published information, determining physical properties of jet fuels, performing electrokinetic experiments, and studying the coalescence of drops on single fibers and in packed fiber beds. This included designing small-scale experimental equipment and developing analytical procedures.

The literature search revealed little new information about the coalescence of emulsions in fiber beds. Much disagreement still exists about the mechanism of coalescence. Also, no accepted theory exists on the mechanism of the coalescence of micron-size droplets in the passage of an emulsion through a fiber bed.

An exploratory study was made of the generation of streaming current by JP-5 fuel flowing through fiber beds. The sign and magnitude of the current is dependent upon the type of fiber, fuel conductivity, type of fuel additives, and the physical property of the fiber bed. A small amount of free water in the fuel always causes a considerable increase in current generation.

A photographic technique was used to measure the coalesence and water droplet growth rates on various types of single fibers placed in a flowing JP-5-water emulsion. The drops appeared to grow by acquiring free water from the main stream rather than from the surface of the fiber. Water droplets on glass fibers have the fastest initial growth rate followed by Teflon, nylon, then Dacron. Droplets having a diameter greater than 500 microns were observed on glass fibers, while the maximum sizes for Teflon and Dacron were, respectively, 75 and 60 microns. On the nylon fiber there were considerable droplet chain formations.

Coalescence studies with glass fibers showed that for a specific fiber diameter there appears to be an optimum bed thickness for obtaining complete coalescence and a reasonably low pressure drop. Little difference was found between treated and untreated glass fiber beds. In the study, treated glass fiber beds were studied having a thickness range of 1/16 to 1/4 in. and a bed density range of 6 to 14 lb/cu ft. Flow velocities ranged from 2 to 6 ft/min.

Successful coalescence of free water from jet fuel was achieved with 1/2-in.-thick Teflon, nylon and Dacron fibrous beds. The overall performance of these beds as emulsion coalescers was considerably less than the coalescence performance observed in beds made up of glass fiber beds. However, work with the plastic fiber beds was limited almost entirely to 1/2-in.-thick beds. Effects of bed density were not determined.

Studies showed that cotton is an excellent media for coalescing free water from jet fuel. The coalescence performance of a 1/2-in., 14.0 lb/cu ft bed is comparable to the optimum fiber glass bed determined in this program. The swelling of the cotton fibers did not produce an excessive pressure drop.

STUDY OF AVIATION FUEL FILTER/SEPARATORS*

I. INTRODUCTION

This research program is concerned with studying filter/separator (F/S) phenomena. Its objective is to develop a fundamental and basic understanding of the operation of F/S and of the influence of pertinent physical and chemical factors upon its operation. Specifically, the goal is to determine the interrelationship of these factors so that the exceptional combinations that result in F/S failure can be minimized.

Actually, the F/S phenomena can be divided into three different phases, or operational conditions: (1) the filtration of solid contamination, (2) the coalescence and removal of emulsified water, and (3) the combination of the filtration and coalescence operations. The work described in this report pertains primarily to the coalescence and removal of emulsified water.

The course of this program consisted of a review of published information and an experimental research program. The experimental program was designed to determine the data that are useful not only to explain results in this report but also to be helpful in future work. The first part of the work consisted of determining the physical properties of jet fuels that contained various amounts of fuel additive. These properties were mainly interfacial tension and electrical fuel conductivity measurements. Work was also done on determining the electrical charge generation nature of fuel flowing through various types of fiber beds.

The main work described in this report was concerned with the coalescence of free water from additive-free jet fuel with the use of various types of fiber beds. This work consisted of developing the necessary analytical procedures, designing and constructing a coalescer cell in a fuel-flowing system, and developing a system for generating a standard fuel water emulsion. The coalescence study was done mainly with the use of fiber beds; however, some work was done on drop coalescence on single fibers.

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II. LITERATURE SEARCH

A search was made of published information on the coalescence of dispersions or drops and especially the coalescence of dispersions in fiber beds or F/S. The purpose of the search was to obtain information about the most recent theories or experiments on this subject. The knowledge was then used to better define the various problems of F/S and also to develop our experimental program.

Because F/S phenomena are not well defined and because F/S operation is complex, the literature search had to cover many branches of physics and chemistry. F/S operation is complex because of the large number of components, such as solid and liquid contaminants, fiber beds, fuel and fuel additives. Actually, a good literature search correlating all these branches of physics and chemistry to F/S phenomena has never been made. Furthermore, considerable interest in this area has been evidenced in the literature during the past three years, as indicated by the large number of publications.

For the search, the literature was divided into six groups:

(1) Properties of emulsions
(2) Surface wetting
(3) Coalescence of drops (not in fiber beds)
(4) Coalescence in fiber beds
(5) Static electricity in petroleum fuel
(6) Fuel contamination.

Most of the literature was obtained by reviewing journals on colloids, surfactants, fuels, physical chemistry, chemical engineering, petroleum, aircraft engineering, and fluid handling. A fairly complete survey was also made of the U.S. patents.

Results of the survey are given in the Appendix. This listing is not complete; however, it does cover most of the important references found in the survey. Reprints of most of the listed articles were obtained, and the bibliographies in these articles were checked for useful references. This was especially true of publications concerned with the coalescence of dispersions in fiber beds.

Before discussing any of the literature, it is necessary to point out that this research program is concerned primarily with studying F/S phenomena. It is mainly an experimental program, and the efforts devoted to the literature survey were very limited. Hence the literature review in this report is very brief and is concerned almost entirely with the coalescence of dispersion in fiber beds.

In addition, it would take a tremendous effort to review the information listed in the six categories in the Appendix and to apply them to F/S phenomena. The net result of such an effort would undoubtedly be the same as that found in a British survey (ref. III-20) on industrial problems related to the formation and coalescence of dispersions. After reviewing the literature, they concluded that it is very difficult to propose research programs that would both contribute directly to the solution of industrial problems and at the same time form the basis of a coherent advance of knowledge in this field. This is especially true for F/S phenomena.

A. The Coalescence of Drops

One of the methods used to investigate F/S phenomena consists of studying the coalescence of two drops. There is considerable theoretical and experimental literature on the subject; most of it has been published within the past ten years. A review of this work shows that it is very difficult to apply the results to a kinetic system containing micron-size droplets that are coalescing in fiber beds. In general, the coalescence of two drops at an interface can be considered to take place in at least two stages. First, the liquid must drain from the region separating the drops that are to coalesce. After this film is reduced to a certain critical thickness, it ruptures so that coalescence can occur. This rupturing can be called the second stage. Hence the speed of coalescence is affected by the forces impelling the drops together, the drainage resistance of the film between the drops, and the ultimate strength of this film at its critical thickness.

Much of the literature is devoted to studying the interface between the drops and the numerous variables and additives that affect its behavior. However, most of it is directed towards studying cloud formation or the numerous industrial problems concerned with emulsion stability. Very little of the work has been concerned with F/S phenomena.

B. Coalescence in Fiber Beds

After reviewing the literature, it can be concluded that no accepted theory exists on the mechanism of the coalescence of micron-size droplets in the passage of an emulsion through a fibrous bed. Sareen (ref. IV-29) has listed observed generalizations that have been accepted in various publication. However, he stated that experiments can be devised and carried out such that nearly all of the generalizations are either confirmed or denied. This is also evident in the conflicting conclusions on observations that can be found in the literature. For several years the Russians (ref. IV-32, IV-33) have claimed that the best material for a fiber coalescer should have a certain average hydrophilicity. It should be sufficiently high that the droplets will adhere to the fibers and sufficiently low that self-cleaning of the filter can take place. Sareen (ref. IV-29) indicated that fiber wettability is not the most important factor for successful coalescence. Farrow (ref. IV-10) stated that the fiber surface should be hydrophobic. In the patent literature claims have been made for successful coalescence using a wide variety of different types of fibers. Hence it appears that there is not even a general agreement on the type of surface that forms the best coalescer.

Several mechanisms have been proposed for explaining the coalescence of micron-size droplets in fiber beds. Sareen (ref. IV-29) has listed and described inertial impaction, direct fiber interception, Brownian movement, electrostatic movement, and rupture in capillaries as some of the mechanisms causing coalescence. Bartle (ref. IV-2) has described pore catchment, flow path intersections, and impingement as the mechanisms. Others have presented theories concerned with preferential wetting (ref. IV-26) and separation by membranes (ref. IV-21).

An attempt to correlate all of the known coalescence theories with generalizations such as flow rates, physical properties of the fiber bed, interfacial tension, and the effects of numerous additives would quickly lead to confusion. During the operation of fuel F/S, certain generalizations such as the effects of low interfacial tension have been observed; however, none of these have been placed in military specification (ref 5). Recently, military specifications (ref. VII-5 and 6) have been established for measuring fuel cleanliness relative to its freedom from surfactant materials. A modified CRC water separometer is used. This is a small volume apparatus in which a water-fuel emulsion is prepared and metered through a cell containing a standardized fiberglass coalescer. The effluent is analyzed for entrained water by light transmission, and coalescing efficiency is expressed in terms of a water separation index, modified (WSIM). Although the WSIM is designed primarily to detect the presence of surfactants in jet fuels and although surfactants generally lower the interfacial tension (IFT) of fuels, it is surprising that often the two cannot be correlated. Field surveys (ref. VI-5) have shown often there is no correlation between WSIM and IFT, and based upon this extensive survey. there is insufficient data for setting limits on the IFT of jet fuels.

Based upon this literature survey, it appears that many types of proposed research programs concerned with F/S phenomena can be justified. These may range from basic studies devoted to investigating interfaces or droplet-coalescing models to observing overall results obtained in coalescing emulsions in fiber beds. The course taken in this program is described in Section V.

C. Fuel Contamination

Although this program is concerned mainly with studying coalescence in F/S, it is also concerned with studying the filtration of solid contaminants from jet fuel. A brief literature survey was conducted on this subject and the results are listed in the Appendix (Section VI).

The main observation noted in this survey is that recently no one has really defined or determined what solid contaminants are found in fuel systems. There is no doubt that the contaminants vary in different parts of the country, in different military fuel systems, and according to various fuel loading practices. However, during recent years very little work has been done in this field. It is true that recently considerable research has been done on biological contamination of jet fuel; however, this is a special type of contaminant that is not being considered in this review. A recent survey (ref. VI-7) of eight Air Force bases indicated the virtual absence of any viable microorganisms in the fuel phase. It is believed that improvements in fuel-handling procedures and the use of anti-icing additives have contributed significantly to this lack of serious microbial contamination.

As far as known, the last significant survey (ref. VI-2) was done over 15 years ago by the Armour Research Foundation for the Air Force. Results of this four-year study had a major influence on establishing the use of coarse AC dust as a standard contaminant in military specification (ref. VII-7). Since that period, fuel-handling procedures and military aircraft have changed considerably, and it is doubtful whether the same conditions exist. What is needed is a recent survey in which the contaminants are better defined. The Russians appear to be doing considerable work in this area (ref. VI-4, 10,12,13,14).

Considerable work is also being done in the United States on high- and low-temperature fuel stability; however, work on normal contaminants found in fuel seems to be lacking. Part of this lack of interest is due to the general belief that present F/S are good dirt filters, and all fuel used in military aircraft is clean. Also, the use of fuel monitors has guaranteed that no contaminated fuel can reach the fuel tank of an aircraft.

However, work at IITRI (ref. VII-8 and 9) has shown that these fuel monitors are not good dirt filters. There is also a question about the red oxide contaminant used in MIL-F-8901A for evaluating F/S. This contaminant has a particle-size distribution in which 47.7% of particles are less than 0.25 μ. However, during the evaluation of F/S an AA millipore filter with a pore size opening of 0.80 μ is used to analyze the fuel (ref. VII-10). This procedure does not appear to be reasonable.

In conclusion, it can be said that the problem of filtering solid contaminates from jet fuel is not clear, and it requires much more study. This very brief review also indicates that before an experimental program is set up, not only the open literature but also the analytical techniques used in the evaluation of F/S should be reviewed.

D. U.S. Patent Review

A fairly comprehensive search was made of all U.S. patents concerned with the coalescence of liquid droplets by fibers, granular material, or screen-type media. The survey was divided into two parts (1) the coalescence of water drops from liquid hydrocarbon fuels with the use of fiber-containing cartridges and (2) droplet coalescence in equipment or systems other than fiber-containing cartridges. The following types of patents were not included:

(1) Removal of water from dry cleaning solvents
(2) Removal of oil from water used for stream generation
(3) Removal of mists from gas streams.

The purpose of the survey was to learn as much as possible about the operation, construction, and design of coalescers. The information will be used in conjunction with studies of the mechanism of coalescence and in the evaluation of performance data obtained from commercial and laboratory coalescers.

1. Cartridge-Type Coalescers

Although the performance data found in the patents are almost nil, the patents do furnish some information concerning construction and operation. Most of the patents are concerned with describing the mechanical features of the filter-coalescer cartridges. Information such as fuel flow rates and filter capacities is usually not provided. However, by carefully reading the numerous patents concerned with coalescer cartridges, it is possible to give a description of a classification that includes most of the commercial or patented coalescer elements. This group is mainly concerned with inside-out flow elements.

A review of the U.S. patents listed in Table 1 revealed that over 90% of the coalescer elements use treated fiberglass as the coalescing medium. Phenolformaldehyde is the main resin used to bind the glass fibers into a fixed matrix. However, other resins such as melamines or silicone resins are mentioned in a few patents. Also, soft unspun or unbonded glass fibers are sometimes used as coalescing media.

a. General F/S Characteristics

In general, the patented filter-coalescer elements can be described as having three sections. These sections can be of various geometric forms or shapes, and they can be interconnected by many different methods.

The first section is the filtering section, and its main purpose is to remove solid contaminants rather than free water. It is quite often composed of coated coarse (5- to 20-μ diameter) glass fibers with a density of 6 to 10 lb/ft^3. The layer thickness can be 1/2 in. or more, and the pore diameter is approximately 25 to 30 μ. In some patents, the contaminant holding capacity of the filtering section is increased by using grooves, slots, ribs, or rings at the inlet side of the filtering layer to result in more uniform filtering.

The second section is the coalescing fiberglass layer. It can be from 1/32 to 1/2 in. thick, and it is composed of glass fibers with diameters ranging from 1 to 7 μ. The density of the coalescer layer can be from 6 to 12 lb/ft^3, and the pore diameter can range from 1 to 3 μ. It is difficult to generalize on the coalescer layer because of the wide variation in physical construction. Often, mixtures of fibers or a combination of different layers of fine and coarse fibers are used to form this section. Also, soft unspun fiber is used, in addition to phenolic bonded fiber.

The third section is the separator section of the coalescing units. Its purpose is to collect and to lead off the large coalesced water droplets. Often, this section consists simply of a woven cotton sock that fits around the outside surface of the cartridge. In some elements, the separator consists of a thick coarse fiberglass layer that is followed by the cotton sock. Other elements use a fourth stage consisting of a hydrophobic pleated paper or a Monel screen. The May patent, U.S. 3,085,690, uses a 240 to 260-mesh (59 to 65 μ) Teflon-coated screen cage that slides down over a coalescer cartridge. In most patents, the separator section has a minimum pore opening of 20 to 30 μ.

Table 1

U.S. PATENTS CONCERNED WITH FILTRATION OF WATER FROM LIQUID FUELS

Patent No.	Date Issued	Date Filed	Title	Patentee	Assigner	Coalescing Material
1,624,832	April 12, 1927	April 12, 1926	Gasoline Filter	W. C. Glover		Cotton batting
2,556,722	June 12, 1951	Oct. 25, 1946	Removal of Water Haze from Immersible Liquids	The Atlantic Ref. Co.	A. B. Hershberger	Miscellaneous fibers coated with silicon halide
2,638,221	May 12, 1953	Jan. 14, 1952	Fuel Filter and Demulsifier		W. A. Carroll	Fiber glass, excelsior
2,656,929	Oct. 27, 1953	Nov. 22, 1947	Dehydrator Cartridge	Bowser, Inc.	R. L. Dolan	Creased paper wadding
2,657,808	Nov. 3, 1953	Oct. 12, 1950	Water Separator	Bowser, Inc.	P. A. Mankin	Fiber glass
2,701,062	Feb. 1, 1955	Jan. 25, 1952	Coalescer	Fram Corp.	J. W. Robinson	Soft, unspun glass fiber
2,707,563	May 3, 1955	May 29, 1948	Filter	Bendix Aviation Corp.	W. Kasten and G. C. Ericke	Fiber glass
2,725,986	Dec. 6, 1955	Aug. 25, 1950	Water Fuel Separator	Bowser, Inc.	H. E. Marvel	Treated fiber glass
2,739,713	Mar. 27, 1956	Oct. 12, 1953	Cartridge for Removing Free Water, etc.	Fram Corp.	J. W. Robinson	Treated fiber glass
2,757,803	Aug. 7, 1956	Jan. 4, 1954	Apparatus for Separating Immisicible Liquids	Fram Corp.	J. W. Robinson and M. R. Souders	Paper and fiber glass
2,766,890	Oct. 16, 1956	July 8, 1949	Fluid Purifier	Bendix Aviation Corp.	W. Kasten	Fiber glass
2,800,232	July 23, 1957	Dec. 9, 1953	Separator for Liquids	Bowser, Inc.	H. E. Marvel	Treated fiber glass
2,864,505	Dec. 16, 1958	Sept. 7, 1956	Vertical 2-stage Demulsifier	Bendix Aviation Corp.	W. Kasten	Treated fiber glass
2,872,043	Feb. 3, 1959	June 6, 1956	Water Separator	Fram. Corp.	J. N. Fitgerald and O. C. Redman	Treated fiber glass
2,883,345	April 21, 1959	Jan. 28, 1954	Emulsion Breaker	Bowser, Inc.	J. A. Taylor and G. Topol	Treated paper or treated fiber glass
2,911,101	Nov. 3, 1959	Aug. 19, 1955	Filters	Richmond Eng. Co.	J. W. Robinson	Treated glass fiber
2,919,030	Dec. 29, 1959	Jan. 20, 1956	Filter-Dehydrator	Bowser, Inc.	M. G. Grant and G. J. Topol	Treated glass fiber
2,953,249	Sept. 20, 1960	Mar. 1, 1955	Filter and Dehydrator	Bowser, Inc.	G. J. Topol and L. R. Baranowski	Treated glass fiber
2,959,289	Nov. 8, 1960	Apr. 4, 1956	Filter and Dehydrator	Briggs Filtration Co.	D. M. Figert and M. G. Grant	Treated fiber glass
2,960,234	Nov. 15, 1960	Sept. 5, 1958	Water Separator Cartridges	Fram Corp.	A. R. Fredrickson	Treated fiber glass
2,961,097	Nov. 22, 1960	Jan. 27, 1959	Liquid Separator with Water Flow Controller	U.S. Government	M. G. Grant	Treated fiber glass

Table 1 (Cont.)

Patent No.	Date Issued	Date Filed	Title	Patentee	Assigner	Coalescing Material
2,984,361	May 16, 1961	Mar. 11, 1957	Separator for Liquids	Bowser, Inc.	H. E. Marvel	Treated glass fiber
3,016,345	Jan. 9, 1962	May 14, 1958	Hydrocarbon Filtration	Permanent Filter Corp.	H. A. Price	Unbonded glass fiber
3,019,904	Feb. 6, 1962	Aug. 14, 1959	Aviation Fuel Filter	E. B. Stecher		Teflon fibers
3,027,009	Mar. 27, 1962	Jan. 28, 1959	Filtration Equipment	Permanent Filter Corp.	H. A. Price	Unbonded glass fibers
3,044,957	July 17, 1962	June 1, 1959	Porous Separator Media	Fram Corp.	L. A. Dow and R. D. Parsons	Glass fibers, treated paper
3,048,275	Aug. 7, 1962	Aug. 13, 1957	Filter-Water Separator	Bowser, Inc.	R. T. Headrick	Fiber glass
3,049,240	Aug. 14, 1962	July 20, 1959	Filtration Equipment	Permanent Filter Corp.	F. A. Smith	Unbonded glass fibers
3,061,107	Oct. 30, 1962	Mar. 16, 1959	Filter Cartridge and Method of Making the Same	L. W. Taylor		Treated glass fibers
3,085,690	April 16, 1963	Mar. 2, 1959	Water Separator	C. H. May		
3,115,459	Dec. 24, 1963	May 25, 1961	Filter	Ametek, Inc.	R. C. Giesse	Polyethylene-coated fibers, treated glass fibers
3,144,407	Aug. 11, 1964	July 10, 1961	Separator for Immiscible Fluids	Fram Corp.	C. Olmos	Treated paper
3,165,470	Jan. 12, 1965	Nov. 2, 1959	Liquid Coalescing and Separating Apparatus	Ametek, Inc.	R. C. Giesse	Polyethylene-coated fibers, treated glass fibers
3,170,873	Feb. 23, 1965	July 7, 1958	Water Filter Separator	Briggs Filtration Corp.	C. H. May	Treated fiber glass
3,186,551	June 1, 1965	April 11, 1960	Jet Fuel Filtering, Emulsion Breaking and Drying Device	Faudi Feinbau G. m.b.H.	A. Dornauf	Treated glass fibers
3,187,895	June 8, 1965	Jan. 23, 1963	Fuel-Water Separator	Pall Corp.	D. B. Pall	Paper using glass cellulose and redwood fibers
3,209,916	Oct. 5, 1965	Oct. 4, 1961	Filter Construction	Briggs Filtration Corp.	C. H. May	Treated fiber glass
3,210,229	Oct. 5, 1965	June 30, 1961	Liquid Fuel Filters	Bowser, Inc.	E. C. Snyder	Treated glass fibers

Table 1 (Cont.)

Patent No.	Date Issued	Date Filed	Title	Patentee	Assigner	Coalescing Material
3,214,368	Oct. 26, 1965	June 12, 1963	Method and Apparatus for Treating Immisicible Liquids	Rellunit Inter., France	J. Muller	Plastic grooved rings
3,223,240	Dec. 14, 1965	Dec. 19, 1961	Filter Cartridge for Separator	Rellunit Inter., France	J. Muller	Treated stacked paper rings
3,223,244	Dec. 14, 1965	Mar. 1, 1955	Filter and Dehydrator	Bowser, Inc.	G. Topul and L. Baranowski	Treated fiber glass
3,228,527	Jan. 11, 1966	Mar. 5, 1962	Water Separating Fuel Filter	Maremont Corp.	R. W. McPherson	Treated fiber glass
3,229,817	Jan. 18, 1966	May 31, 1962	Assembly for Separating Immisicible Fluids	Pall Corp.	D. B. Pall	Miscellaneous fibers
3,256,997	June 21, 1966	Sept. 30, 1963	Apparatus for Separating Immersible Liquids	Pall Corp.	D. B. Pall and S. Krakaver	Glass, nylon, Dacron, cellulose, asbestos, Teflon, etc.
3,262,572	July 26, 1966	May 27, 1963	Separator-Filter	Purolator Products, Inc.	C. A. Cook	Paper
3,268,442	Aug. 23, 1966	May 8, 1964	Process for Separating Immisicible Liquids	Pall Corp.	D. B. Pall and others	Diatomaceous earth and fiber glass

b. Coalescence Theories

Although almost all patents concerned with coalescence do not discuss the theory of operation, a few do present such information. These few patents are all concerned with glass fiber coalescer beds with 1μ to 3μ diameter fibers in beds with a density range of 6 to 12 lb/ft^3. The following is a brief summary of these patents.

U.S. 3,256,997. The mechanism by which coalescence occurs is not entirely clear and has yet to be fully established. There are two possibilities. One is that the coalescer passages are hydrophobic, and the other is that they are hydrophilic. In either case, coalescence can occur by the following mechanism.

Since the suspended droplets are too large to pass through the coalescer passages, they tend to collect at their entrances. As the fuel flows through the passage, the droplets tend to consolidate or coalesce to form large droplets. As the droplets grow, they offer increasing resistance to the entry of suspending fluid into the passages. At some point, determined by surface tension and the diameter of the passages, the pressure of the suspending liquid against the droplets overcomes the interfacial tension between the fuel and the droplets. Since the droplets tend to maintain their spherical configurations, compressing them and forcing them through the coalescer passages results in their emerging on the other side as large coalesced droplets. A droplet that is smaller than the opening can pass into the opening, but it may become trapped in any passage on the other side. Oversized droplets passing through probably clean off any such droplets clinging to the walls and absorbing these as well.

U.S. 3,061,107. Water has an affinity for the surface of individual glass fibers, and it collects and forms small droplets. These small droplets unite and form larger droplets at the intersection of two or more fibers. After being forced to the outer surface of the filtering element, the large droplets of water drop from the filtering cartridge by gravity.

U.S. 3,016,345 and 3,027,009. The Permanent Filter Corporation has a group of patents based on destroying the electrical charge on water droplets. It is theorized that tiny water droplets are held in a suspended state in the fuel by electrostatic charges. Their tendency to stay dispersed is increased by similar droplet charges that inhibit coalescence. These charges must be neutralized in order to promote drop growth or coalescence. It has been found that the electrical charges can be removed or neutralized by passing the fluid through a metallic grounded matrix. The particles or drops become charge-free and are rendered into a coalescible condition.

It has been found that charge-neutralizing can be facilitated if the hydrocarbon is first passed through a fabric woven of synthetic fibers such as Nylon, Dacron, or Orlon. Such fibers have the property of increasing the static electrical charges on the droplets. Apparently increasing these charges results in a more effective neutralization of the charges by the porous metallic matrix.

The neutralized water droplets are coalesced in a glass fiber bed, whose pore diameter is approximately equal to the diameter of the smallest droplets.

2. General Coalescence Patents

The patents concerned with droplet coalescence in granular or fibrous media but not in cartridge-type filters are listed in Table 2. These patents are more numerous than those dealing with cartridge coalescers; however, they are not very informative.

Table 2 shows that many different types of media have been patented for use as coalescers of emulsified liquids. It is very difficult to evaluate the effectiveness of these coalescers since the patents furnish little or no performance data. Practically all the patents furnish no information relating to fluid velocities, bed densities, emulsion concentrations, or coalescer efficiencies. Most of the patents are concerned with the coalescence of water-in-oil emulsions with the use of glass fiber or excelsior beds. However, recent patents have revealed new types of media that may have some value as emulsified fuel coalescers. This material consists of polyolefin fibers or precipitated polymers. It would be of interest to evaluate some of them in the laboratory.

Table 2

U.S. PATENTS ON COALESCENCE OF IMMISICIBLE LIQUIDS

Patent No.	Date Issued	Title	Emulsion	Coalescing Material
994,377	June 6, 1911	Separating and Collecting One Liquid Suspended in Another	Oil in water; water in oil	Cotton cloth
995,402	June 13, 1911	Apparatus for Separating Water from Oils	Water in oil	Metal screen
1,015,662	Jan. 23, 1912	Purifying Device for Hydrocarbon-Fuel Gasoline	Water in gasoline	Felt
1,019,161	Mar. 5, 1912	Strainer and Water Separator for Gasoline Supply	Water in gasoline	Metal screen
1,081,030	Dec. 9, 1913	Water-Separating Filter for Gasoline	Water in gasoline	Fine-mesh wire gauge
1,106,352	Aug. 4, 1914	Gasoline and Water Separator	Water in gasoline	Fine-mesh wire gauge
1,121,994	Dec. 22, 1914	Method of Water Purification	Oil in water	Sawdust, pumice, peat
1,242,784	Oct. 9, 1917	Method for Separating Mixtures of Liquids	Water in oil	Infusorial earth
1,304,124	May 20, 1919	Method and Apparatus for Dehydrating Emulsions	Water in oil	Linen cloth, wire cloth
1,455,136	May 15, 1923	Oil Separator	Oil in water	Terrycloth
1,480,091	Jan. 8, 1924	Dehydration	Water in oil	Sand
1,501,877	July 15, 1924	Process for De-emulsifying Liquids	Oil in water	Diatomaceous earth
1,547,712	July 28, 1925	Process for De-emulsifying Liquids	Oil in water	Fibrous material; organic and inorganic
1,573,389	Feb. 16, 1926	Method and Apparatus for Breaking Emulsions	Water in oil	Cotton, filter aid
1,596,585	Aug. 17, 1926	Process for Breaking Water in Oil Emulsions	Water in oil	Iron or zinc shavings
1,596,586	Aug. 17, 1926	Process for Treating Water in Oil Emulsions	Water in oil	Sand
1,649,103	Nov. 15, 1927	Apparatus for Treating Emulsified Oil	Water in oil	Foraminated plates
1,650,514	Nov. 22, 1927	Process of Dehydrating Oil	Water in oil	Crushed rock
1,710,154	Apr. 23, 1929	Apparatus for Treating Emulsified Oil	Water in oil	Orifices
1,887,774	Nov. 15, 1932	Method of Treating Emulsions	Water in oil	Crushed quartz
1,911,797	May 30, 1933	Method of Breaking Emulsions	Water in oil	Iron sulfide
1,911,840	May 30, 1933	Apparatus for Treating Emulsions	Water in oil	Quartz, iron sulfide
1,947,709	Feb. 20, 1934	Wetted System Separator and Method	Water in oil	Glass wool
2,018,302	Oct. 22, 1935	Continuous Process Contact Dehydration	Water in oil	Quartz
2,176,806	Oct. 17, 1939	Apparatus for Contacting Immisicible Liquids	Water in oil	Sand
2,214,248	Sept. 10, 1940	Emulsion Breaker	Oil in water	Corrugated plates

Table 2 (Cont.)

Patent No.	Date Issued	Title	Emulsion	Coalescing Material
2,270,411	Jan. 20, 1942	Process for Desalting Petroleum	Water in oil	Quartz
2,270,412	Jan. 20, 1942	Process for Dehydrating Oils	Water in oil	Quartz
2,359,386	Oct. 3, 1944	Fluid Separator Apparatus	Water in gasoline	Porous metal
2,454,605	Nov. 23, 1948	Desalting Crude Oil	Water in oil	Glass fibers
2,494,392	Jan. 10, 1950	Process and Apparatus for Treating Emulsions	Water in oil	Glass fibers
2,522,378	Sept. 12, 1950	Resolving Water and Oil Emulsions	Water in oil	Glass fibers
2,548,568	Apr. 10, 1951	Water Separator	Water in gasoline	Excelsior
2,555,607	June 5, 1951	Separation of Immisicible Liquids	Water in oil	Glass fibers
2,601,904	July 1, 1952	Method and Apparatus for Treating Crude Oil Emulsions from Oil Wells	Water in oil	Excelsior
2,609,932	Sept. 9, 1952	Fluid Purifying Device	Water from gasoline	Fiber glass, cotton
2,611,490	Sept. 23, 1952	Apparatus for Separating Immisicible Liquids	Water in hydrocarbons	Fiber glass
2,626,709	Jan. 27, 1953	Liquid Separator	Water in hydrocarbons	Fiber glass
2,742,156	Apr. 17, 1956	Fluid Purifying Separators	Water from gasoline	Excelsior
2,758,720	Aug. 14, 1956	Separation of Emulsions by Filtration	Water in oil	Screens coated with Teflon, fibers, etc.
2,781,909	Feb. 14, 1957	Diesel Oil Separator	Water from oil	Excelsior
2,858,027	Mar. 15, 1957	Liquid Dispersion Separating Device	Immisicible liquids	Excelsior, fiber glass
2,924,336	Feb. 9, 1960	Liquid Dispersion Separating Device	Immisicible liquids	Excelsior, fiber glass
2,937,977	May 24, 1960	Filter and Vacuum Dehydrator	Water from oil	Fiber glass
3,014,861	Dec. 26, 1961	Treatment of Immisicible Liquid	Immisicible liquids	Coke, glass, Teflon, polyethylene, etc.
3,035,701	May 22, 1962	Filter and Separator for Demulsified Oil in Water Mixture	Water in oil	Excelsior
3,085,068	Apr. 9, 1963	Method of Resolving Emulsions	Water in oil	Mineral wool
3,179,603	Apr. 20, 1965	Breaking Emulsions	Immisicible liquids	Polyolefin particles
3,195,295	July 20, 1965	Immisicible Fluids Separator	Water in oil	Felt, metal, wool, etc.
3,208,596	Sept. 28, 1965	Lubricating Oil Clarifier and Coalescer	Water in oil	Sintered metal
3,215,619	Nov. 2, 1965	Process for Removal of Entrained Moisture from Hydrocarbons	Water in hydrocarbons	Carboxymethylcellulose on sand
3,215,623	Nov. 2, 1965	Removal of Immisicible Liquid Contaminants from Fluids	Oil in water	Precipitated polymer

Table 2 (Cont.)

Patent No.	Date Issued	Title	Emulsion	Coalescing Material
3,222,413	Dec. 7, 1965	Emulsion Control in Hydrocarbon Purification	Immisicible liquids	Polyolefin fibers
3,231,091	Jan. 25, 1966	Separator	Oil in water	Wire screen
3,239,452	Mar. 8, 1966	Coalescence Process Using Polyolefin Fiber	Acid haze from hydrocarbons	Polyolefin fibers
3,249,229	May 3, 1966	Fuel Storage and Dispensing System	Water in fuel	Fiber glass
3,249,438	May 3, 1966	Combination Filter and Separator Unit	Water in oil	Fiber glass
3,256,988	June 21, 1966	Coalescing Filter	Oil in hydrocarbons	Sintered stainless steel
3,293,165	Dec. 20, 1966	Separation Process for Resolving Water and Oil Suspension	Water in fuel	Coated granules

III. PHYSICAL PROPERTIES OF JET FUELS

Before or during the study of the mechanism of droplet coalescence, it is necessary to measure the physical properties of the fuel used. These measurements are then used to explain the behavior of the coalescing system. For example, a low interfacial tension may mean poor coalescence of water from fuel; however, this result is not a hard and fast rule. Most of the major changes in the physical properties of fuel are caused by the presence of additives or impurities. Because of these changes, many studies have been devoted to investigating the effects of these additives. As yet, a good explanation of their behavior in a fuel system has not been presented.

The purpose of this work is to measure the effects of additives upon two properties of JP-4 and JP-5 fuels. One property is interfacial tension, and the other is the electrical resistance of the fuel. Fuel conductivity is the reciprocal of the fuel resistance. Some effects of interfacial tension upon droplet coalescence are known; however, little is known about the effects of fuel conductivity upon the coalescence mechanism.

During the course of the program, other fuel properties such as the WSIM (water separation index, modified) will be determined. All these data will be used in the analysis of data obtained in coalescence studies, which will be described in future reports.

A. Interfacial Tension

Interfacial tensions of various fuel-surfactant systems were measured by the procedure of ASTM D971-50. The results of the measurements, shown in Figures 1 and 2, show widespread effects of the additives. These results are in general agreement with the limited amount of data in the open literature. However, the illustrated results do not always correlate with the limited amount of published coalescence data. It has been reported that as little as 1 ppm of sodium sulfonate ruins a F/S coalescing system. Although many additives affect the interfacial tension more than sodium sulfonate, they have much less effect on the coalescing operation. Na-Sul EDS affects the interfacial tension much more than sodium sulfonate, yet it has less effect on water coalescence. However, Na-Sul EDS is a fuel additive that, when present at concentrations of 50 to 60 ppm, often has a harmful effect on water coalescence.

Interfacial tension was measured by using the ASTM procedure. No studies were made on the effects of aging time, temperature, or additive combinations. The effects of water contamination and pH values upon the interfacial tension could also be determined. However, this is beyond the scope of this program.

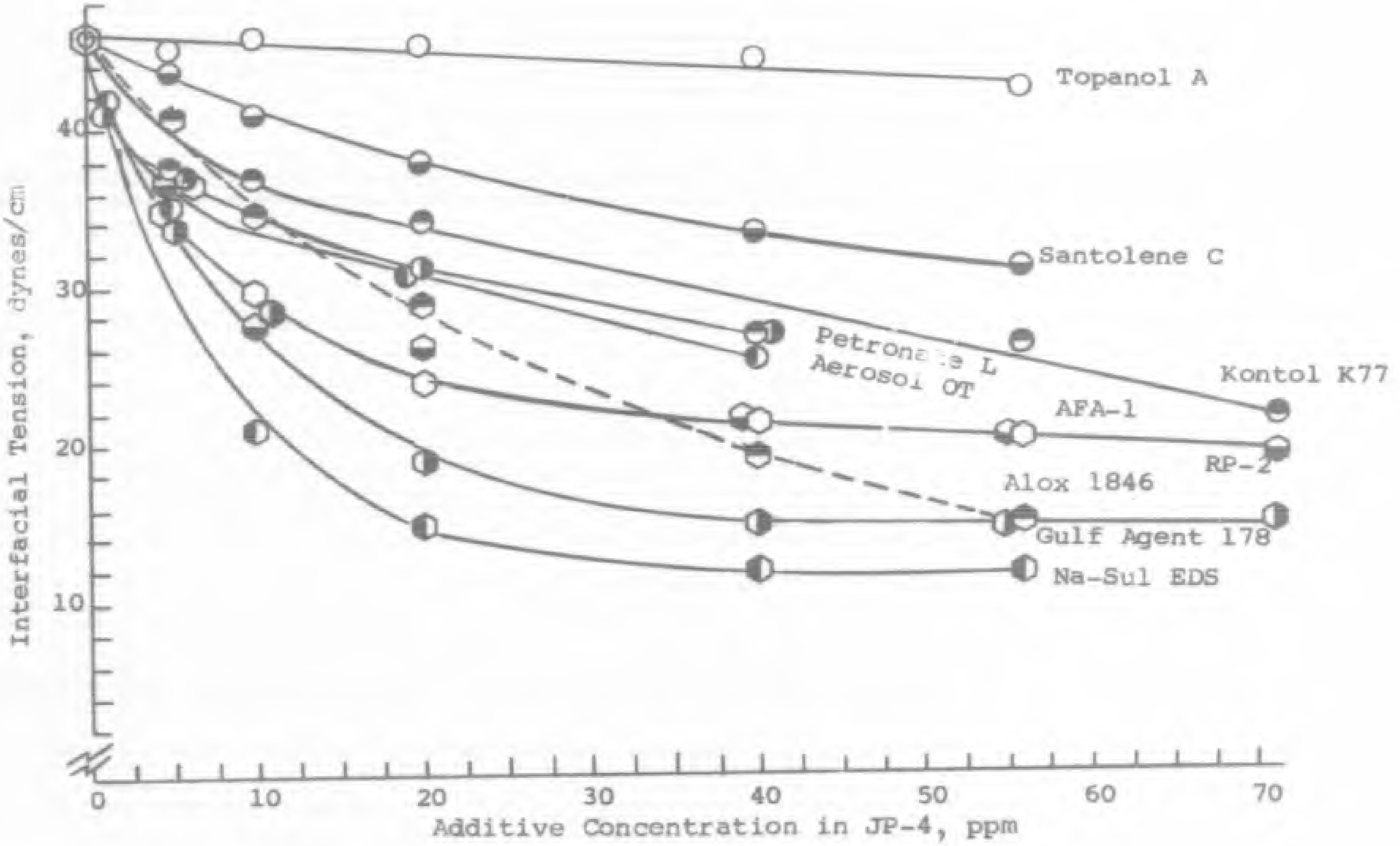


Figure 1

INTERFACIAL TENSION VERSUS ADDITIVE CONCENTRATION IN JP-4 AT 77°F

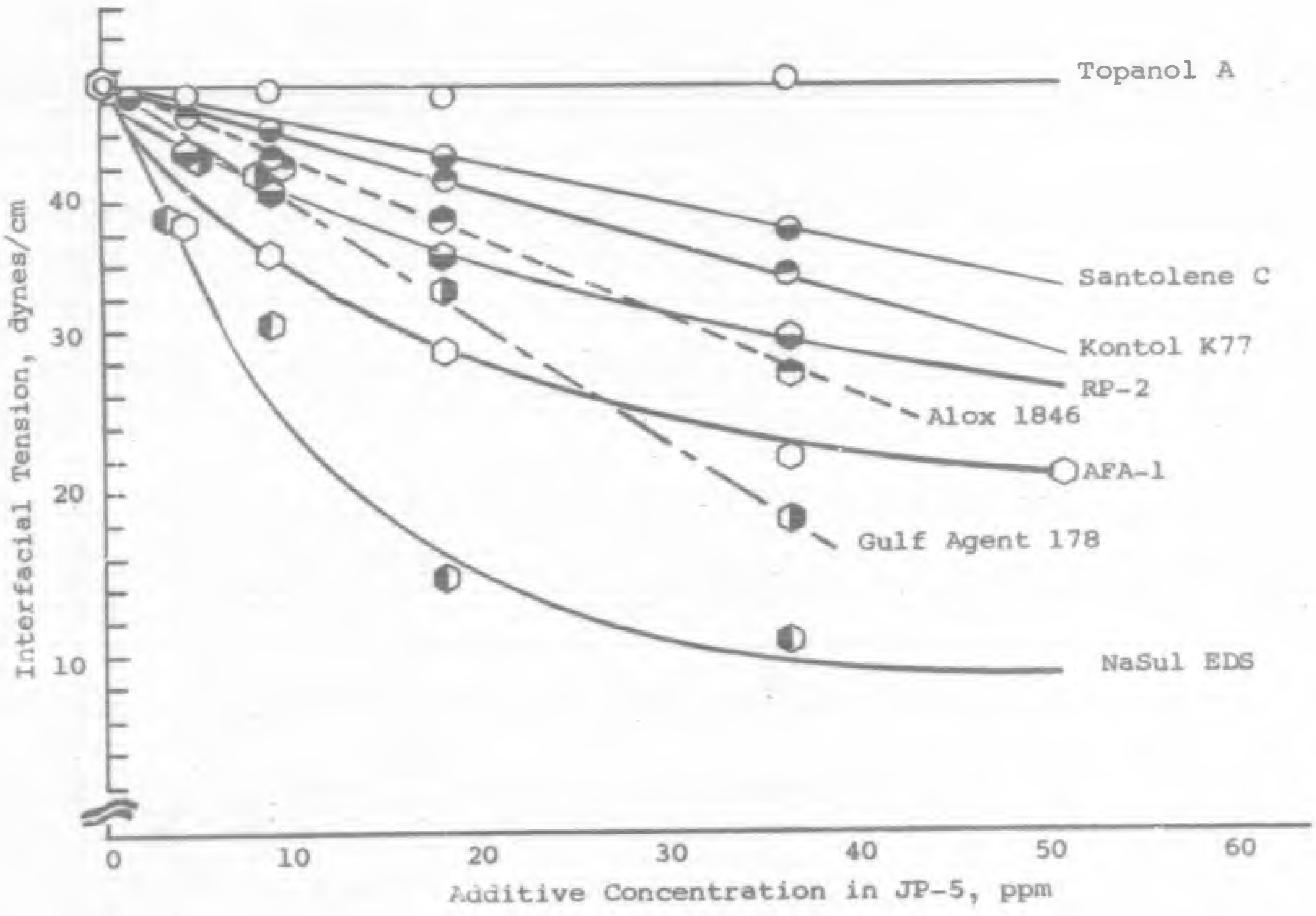


Figure 2

INTERFACIAL TENSION VERSUS ADDITIVE CONCENTRATION IN JP-5 AT 76°F

Much can be written about the interfacial tension effects of fuel additives. However, this information alone is not enough to explain the failure of certain F/S operations. More related information about other properties of the fuel system is needed.

B. Electrical Conductance

A fuel property that has received considerable attention in the literature during the past few years is electrical conductivity. However, almost all of the information has been correlated with the electrical hazards association with fuel handling. Essentially none of it has been associated with the effect of electrical conductivity upon the operation of a fuel-water coalescer. There are reasons to believe that fuel conductivity may affect the coalescence mechanism. Hence, equipment was set up to measure this property.

The measurement of the true electrical conductivity of fuel has always been classified as a difficult determination. Factors such as extremely high resistivities and polarization effects at the electrodes make true reproducible results very difficult.

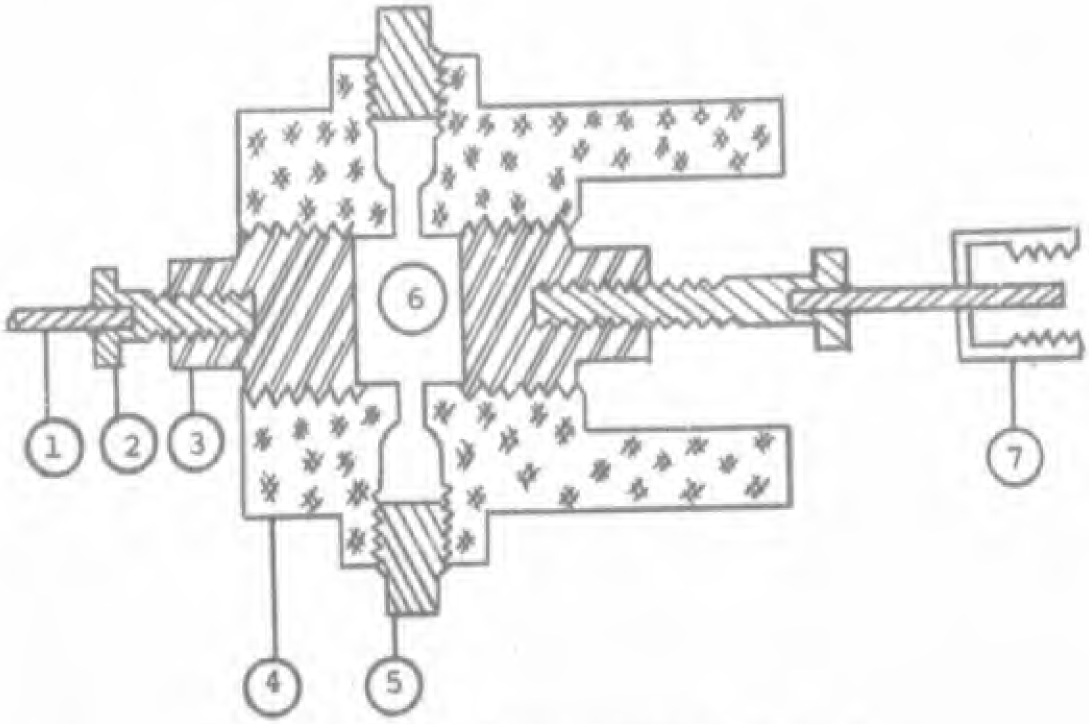
1. Equipment and Procedure

The Teflon cell and the electrical system used for making electrical resistivity measurements are shown in Figures 3 and 4. During the determination, plus and minus voltages of 50 and 100 volts, respectively, were applied across the cell. In each of the determinations, a Victoreen Fentometer was used to measure the current. The following equation was used to calculate the specific resistivity:

$$r = C \frac{E}{I} \tag{1}$$

r = specific resistivity, ohm-cm
E = applied voltage to the cell, volts
I = measured current, amp
C = cell constant (2.0 for this cell)

During the measurement of fuel resistivity it was observed that most of the four determinations made on each sample checked rather closely. However, as the additive concentration reached a maximum (50 to 70 ppm), the results began to scatter. Some additives such as RP-2 were more difficult to characterize than others.

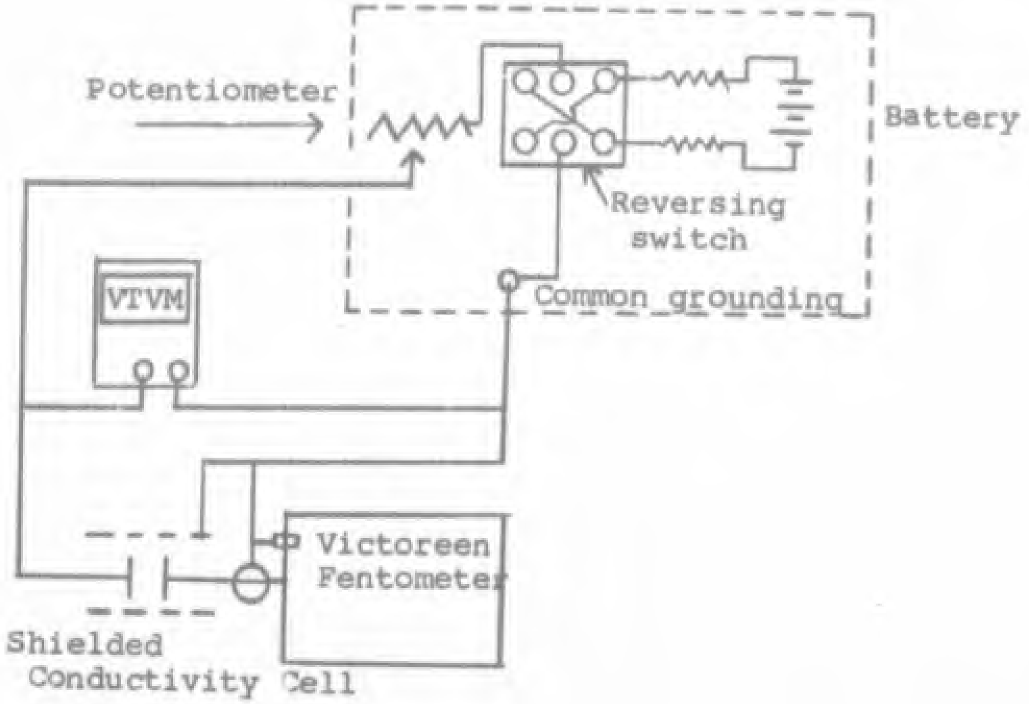


Scale - Approximately 1 to 1

1	Brass rod
2	Brass bolt 1/4-20
3	Stainless steel pipe plug 1/2
4	Teflon body machined, drilled, tapped
5	Steel pipe plug 1/8-27
6	Chamber hold c.a. 5 ml
7	Amphenol connector to Fentometer

Figure 3

CELL FOR MEASURING FUEL CONDUCTIVITY



2 Meg ohm resistors on battery leads.
Battery, 300 volt Everready #493 (NEDA 722).
Potentiometer, limiting voltage output 0-120 volts d.c.
Switch, positive or negative voltage.
VTVM, Knight, vacuum tube voltmeter.
Victoreen Fentometer, Electrometer, Model 4768, 115 volt, 60 cycle, by The Victoreen Instrument Company, Cleveland, Ohio.
Victoreen used to measure current has an input polarity switch positive or negative reverses panel meter.
Five high meg. resistors 10^8, 10^9, 10^{10}, 10^{11} and 10^{12} gives 3 x 10-15 3 x 10^{-7} amperes full scale current accuracy 1% for 10^8, 10^9 and 10^{10} resistors
2% for 10^{11} and 10^{12} resistors.

Figure 4

CONDUCTIVITY SCHEMATIC DIAGRAM

2. Results

Results of the work (Figures 5, 6 and 7) show that the fuel resistance varies widely with the type of additive and the additive concentration. In fact, the base resistance of the referee fuel (with no additives) varies considerably from drum to drum. This variation is evident in Figure 6.

A comparison of the observed data and known coalescence data reveals some interesting correlations. Sodium sulfonate, which affects coalescence considerably more than most of the additives, also has the greatest effect on fuel resistance, especially at a low additive concentration (1 to 5 ppm). Na-Sul EDS, which also affects coalescence but not quite as much as sodium sulfonate, also has a large effect on the fuel resistance. However, this effect is less than that with the sodium sulfonate and opposite to the interfacial tension effects. Na-Sul EDS affected interfacial tension much more than sodium sulfonate.

An interesting observation was the negligible effect that the anti-icing additive has on fuel resistivity. This is shown in Table 3, in which the reproducibility of the measurements is also shown.

Table 3

EFFECTS OF ANTI-ICING ADDITIVE
ON ELECTRICAL RESISTIVITY OF JP-5 FUEL

Temperature: 75°F

Additive: 99.6% methyl cellulsolve
0.4 vol. % glycerine

Voltage used: ±50 and ±100 volts

Additive, ppm by vol.	Resistivity, ohm-cm x 10^{-14} range	average
0	1.6 to 1.8	1.7
200	1.3 to 1.3	1.3
400	1.1 to 1.2	1.2
600	1.3 to 1.6	1.4
800	1.2 to 1.4	1.3
1000	1.2 to 2.1	1.6
1200	1.2 to 2.0	1.6
1600	1.3 to 2.1	1.6

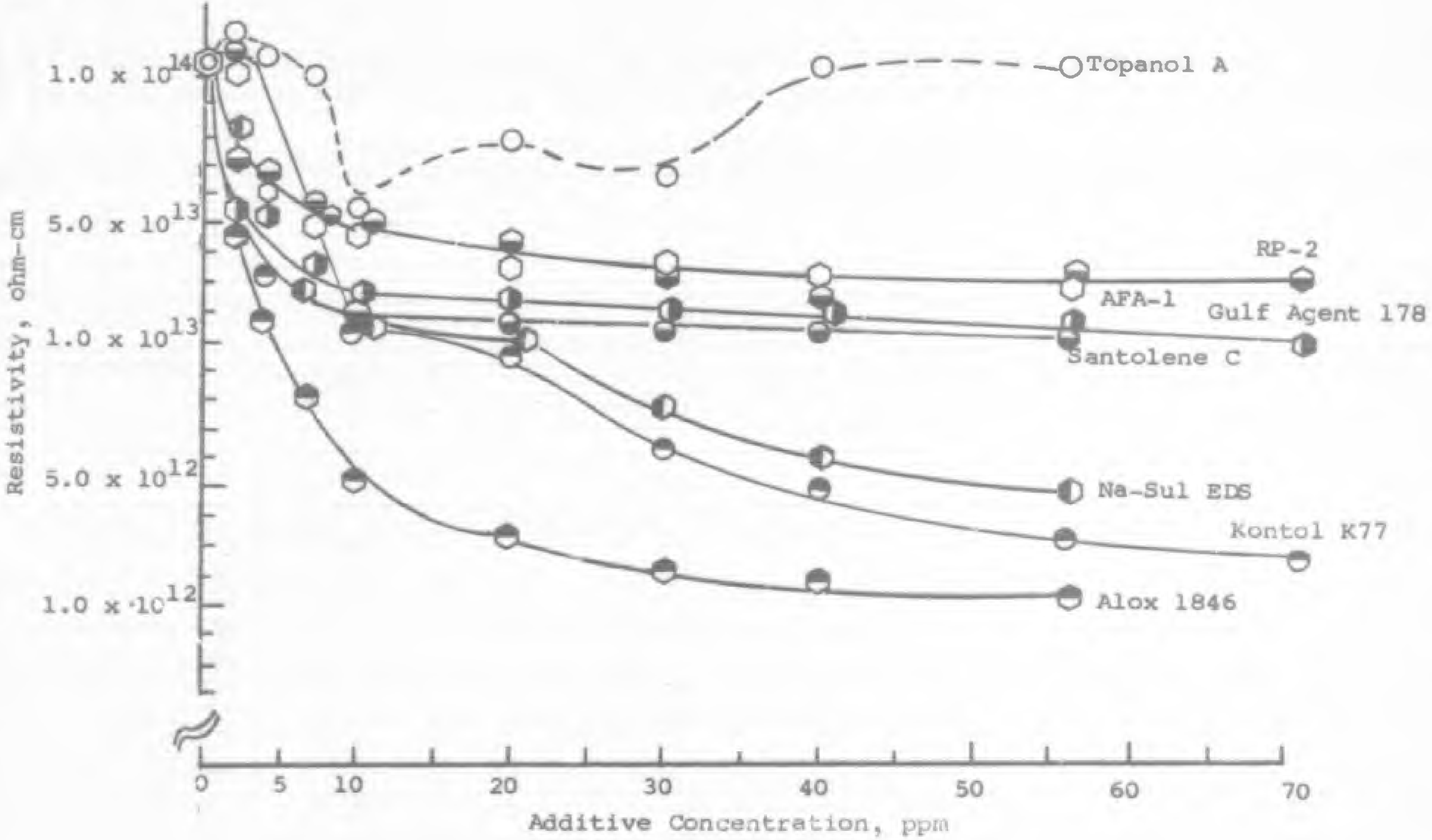


Figure 5

EFFECT OF ADDITIVES ON ELECTRICAL RESISTIVITY OF JP-4 FUELS

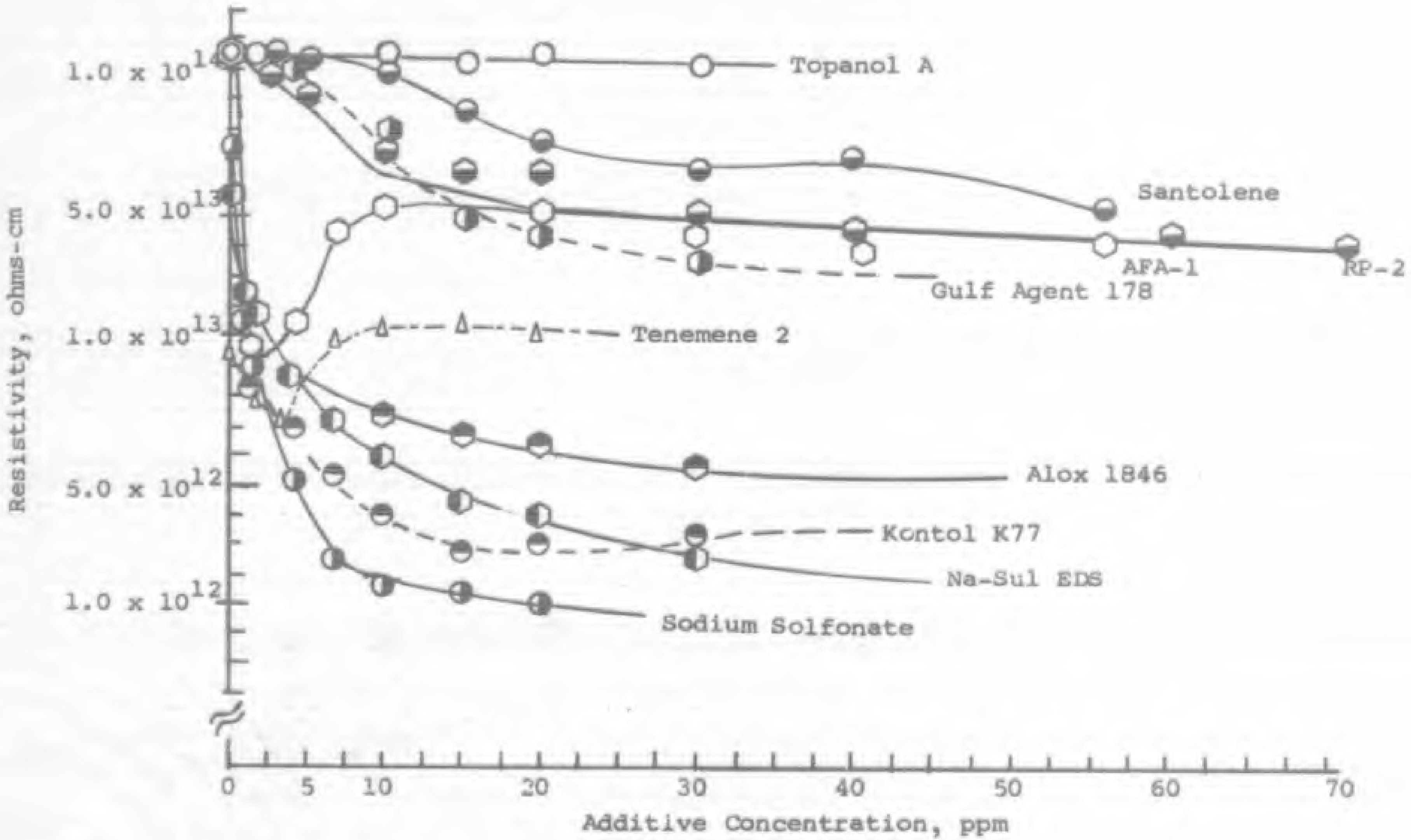


Figure 6

EFFECTS OF ADDITIVES ON ELECTRICAL RESISTIVITY OF JP-5 FUEL

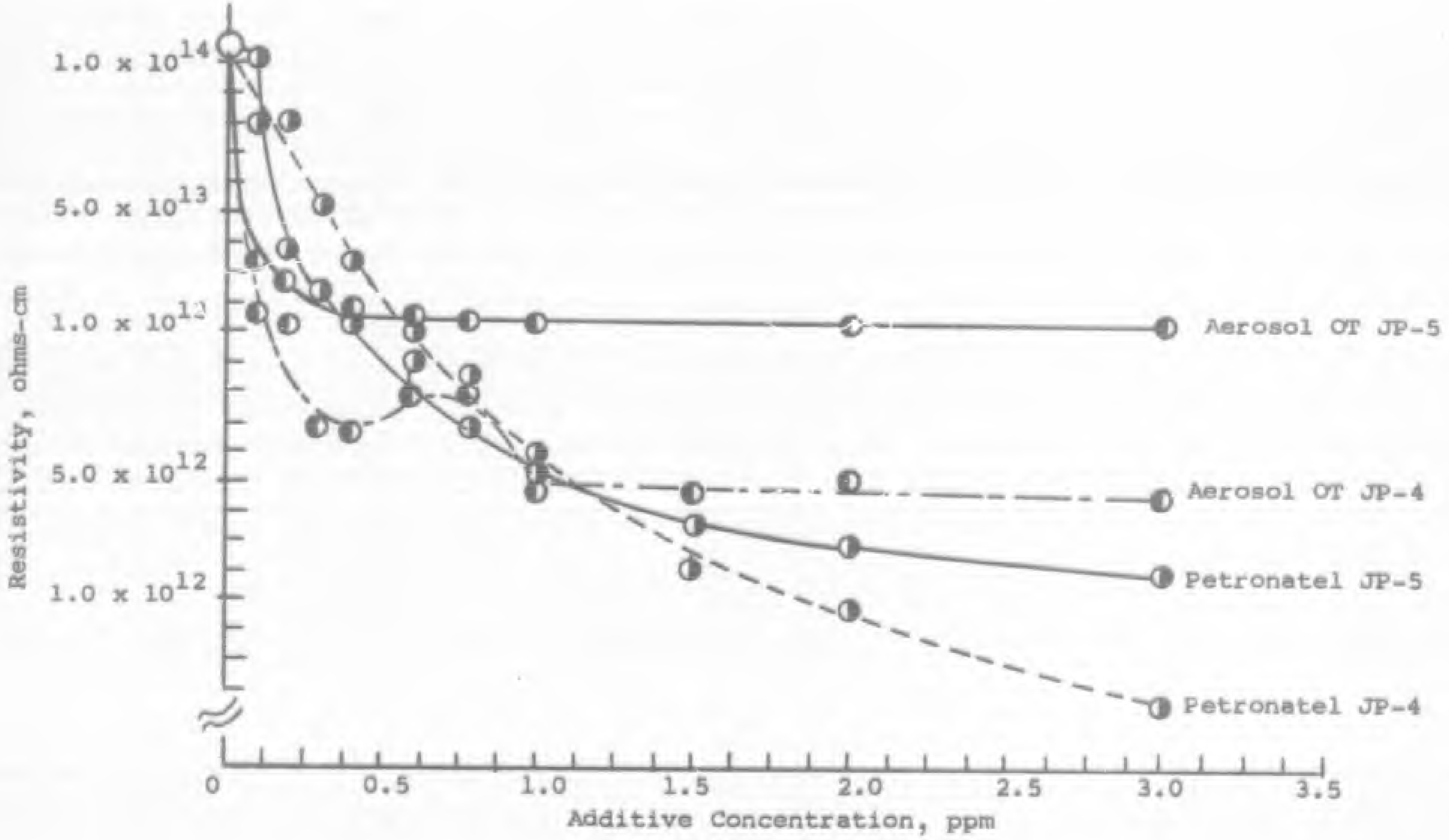


Figure 7

EFFECT OF ADDITIVES ON ELECTRICAL RESISTIVITY

It is expected that the observed resistivity data will aid considerably in interpreting data obtained in coalescence experiments in which fuels containing additives are used.

IV. ELECTROKINETICS

Because the often unpredictable failure of the coalescing operation cannot be explained by the decrease in the interfacial tension of the fuel, it is necessary to look for and measure other parameters in the system. Recently (ref. VII-1), efforts have been made to measure the contact angles and the work of adhesion of water droplets to various types of surfaces. However, all these studies were made under static conditions, and it is difficult to extrapolate them to a kinetic condition in which the droplet sizes are much smaller.

In the present study, an electrokinetic technique offers a ready and sensitive method for determining changes at a fiber surface. It consists of measuring the streaming current in a fiber bed through which a fuel flows. The measured streaming current is very sensitive to the nature of the fiber surface, the adsorbed surface materials on the fiber, the nature of the fuel, and the additive or contaminants in the fuel. With the use of the physical constants in the system, a theoretical potential (zeta potential) that exists on the surface of the fiber can be calculated with the use of derived equations.

A. Experimental Procedure

The cell used in the study consisted of a Lucite cylinder that contains the fiber bed and the electrodes. Figure 8 is a schematic drawing. The bed diameter is 3.80 cm, and the bed thickness is 0.5 cm. The electrodes consisted of circular brass plates made from perforated metal with 11/64-in. holes with 1/4-in. centers (43% openings).

During the experiments the fuel was allowed to recirculate through the ungrounded cell by using the setup shown in Figure 9. All of the system except the test cell was grounded.

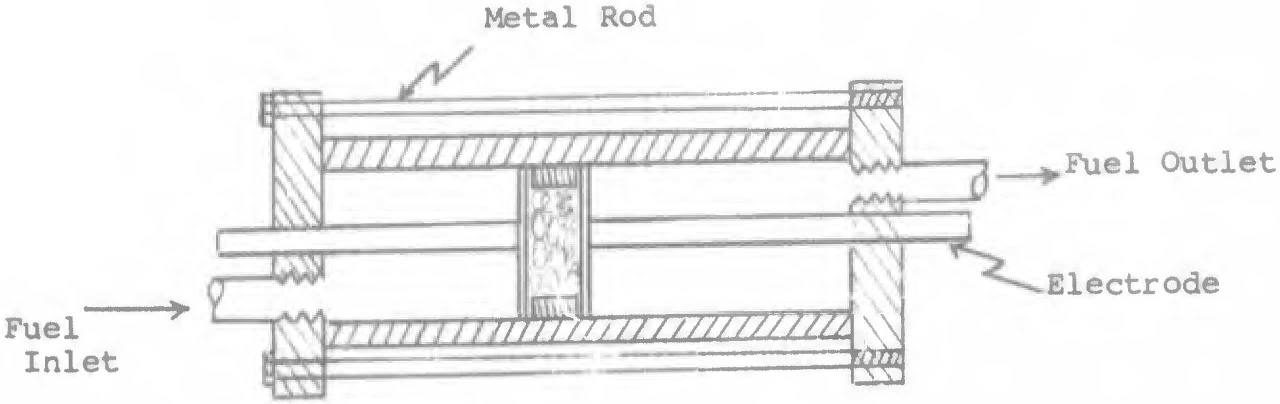
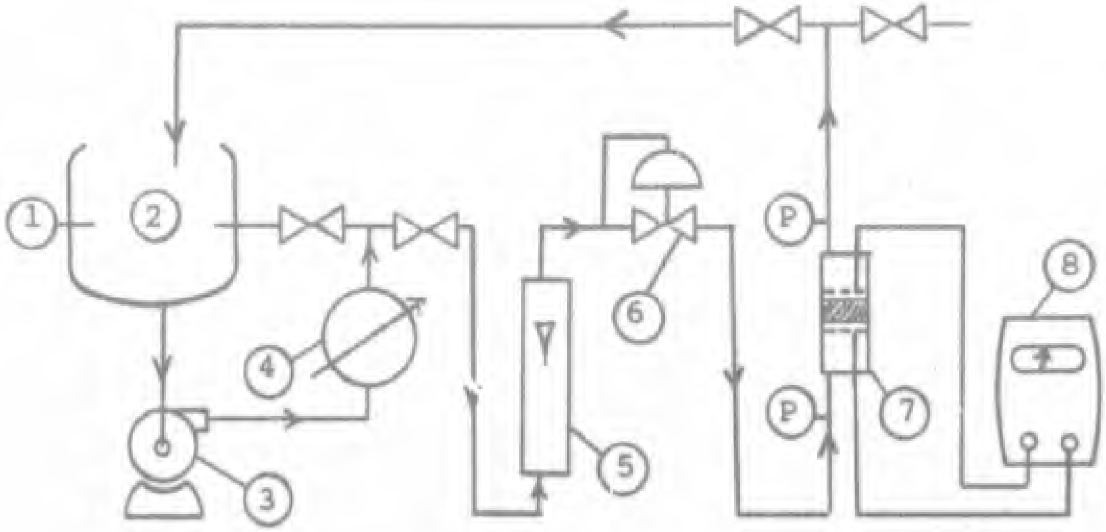


Figure 8

CELL USED IN ELECTROKINETIC EXPERIMENTS

The experimental study consisted of two main phases. One was concerned with flowing additive free JP-5 fuel through various types of fiber beds. This fuel conformed to military specifications (MIL-J-5624F Amend. 2 April 1964). The other consisted of flowing JP-5 fuel containing various additives through glass fiber beds. A small amount of work was also done on the contaminants in a plugged F/S element.



① Thermometer.

② 20 liter plastic tank with cover.

③ Centrifugal pump.

④ Cooling condenser.

⑤ Rotameter.

⑥ Control valve.

⑦ Fibers in coalescence cell.

⑧ Victoreen Electrometer.

Figure 9

EXPERIMENTAL SETUP FOR ELECTROKINETIC EXPERIMENT

B. Theoretical Considerations

A theoretical explanation of the concept of charging of a fiber bed by flowing fuel is concerned with the double layer theory, which has been developed mainly for explaining the behavior of aqueous systems; it has, however, been applied to hydrocarbon systems.

A fiber bed or a solid surface in contact with a liquid containing polar materials acquires an electrical charge by various mechanisms; the most important of these is the yielding of mobile ions of one sign to the liquid and the adsorption from the liquid of cations or anions with a specific affinity for the solid. Excess charges of opposite sign accumulate as a diffused ionic layer of "gegenions" (the Gouy-Chapman layer) in the liquid adjacent to the solid and are distributed in accordance with the Poisson-Boltzman equation. This mobile charge leads to the electrokinetic phenomenn that can be used to measure the difference in potential between the surface of the solid and the bulk liquid. The quantity so measured is known as the zeta potential.

The classical equation (ref. VII-2, VII-3) for calculating the zeta potential by using the streaming current generated by a fluid flowing through a fiber bed is:

$$\frac{I \eta L}{pD} = \frac{A \zeta}{8\pi} (1 - \alpha c) \tag{1}$$

where

I = current
η = fluid viscosity
L = fiber-bed depth
P = pressure drop across fiber bed
D = fluid dielectric constant
A = cross-sectional area of bed
ζ = zeta potential
α = volumetric density of fiber
c = fiber concentration
π = constant.

In the experimental cell containing JP-5 fuel at 75°F, the following relation can be derived from Equation 1:

$$\zeta = \frac{I}{p} \quad \frac{.343 \times 10^9}{(1 - \alpha c)} \tag{2}$$

where

I = current, amp
p = pressure drop, psi
α = fiber, volumetric density, cm^3/g
c = fiber concentration, g/cm^3
ζ = zeta potential, millivolts.

C. Experimental Results and Discussion

Before presenting any data or discussions, it is necessary to point out that the present study is of an exploratory nature. Because of the difficulties in obtaining true current measurements, reproducing experiments, and determining the effects of many variables, it is very difficult to make definitive conclusions. There is little literature on this subject, and often during experimentation, the results change unexpectedly. These facts are evident in the following discussions.

1. Different Types of Fibers

Results of the experiments done with JP-5 fuel flowing through various types of fiber beds are tabulated in Table 4. These results are interesting since they indicate that the data follow a triboelectric series. Also, the magnitude of the currents is measureable. These experiments were reproducible; however, the use of a different fuel showed different results. The data in Table 4 were obtained by using fuel with a conductivity of 1×10^{-13} mhos cm^{-1}. When JP-5 fuel with a conductivity of 1.7×10^{-14} mhos cm^{-1} was used, the current generated was in the range of only 10^{-10} to 10^{-11} amp. This is a very low, unstable range since a slight increase in fuel flow rate, temperature, or fiber bed thickness may result in a changing of the current sign. The change in current sign was often unpredictable, and the system was undoubtedly affected by unknown variables or contaminants. This observation was not unexpected since it is known (ref. VII-4) that the production of static electricity by hydrocarbons appears to depend upon the electrical conductivity of the liquid. It also appears that the use of hydrocarbon fuels with a conductivity of 10^{-13} mhos cm^{-1} will result in maximum static electricity production (ref. VII-4). The use of fuel with a conductivity of 10^{-14} mhos cm^{-1} may result in a hundredfold decrease in the generation of static electricity. These magnitudes are the same as those observed in the present experiments.

During the course of this study, no equipment was available for determining fuel conductivity. Hence there was some confusion when it was observed that the use of new fuel results in practically zero current production. In a search for an explanation of the results, a Teflon cell was constructed, and measurements were made of the conductivities of fuel taken from five different 50 gal drums. The procedure and equipment for obtaining the conductivities are given in Section III. Results of the measurements are given in Table 5.

Table 4

CURRENT GENERATION BY FLOW OF JP-5 FUEL THROUGH VARIOUS TYPES OF FIBER BEDS

Temperature:	80 to 85°F
Bed depth:	0.50 cm
Bed diameter:	3.80 cm
Fuel resistivity:	1.0×10^{-13} ohms-cm

Fiber	Bed Density, lb/cu ft	Pressure Drop, psi	Flow Rate,* ft/min	Current Generation, amp		Run Time, min
				Start	End	
Treated fiber glass	1.31	0.5 to 2.0	1.3 to 2.6	$+2.3 \times 10^{-9}$	$+2.4 \times 10^{-9}$	20
Treated fiber glass	2.70	1.0 to 2.0	1.6 to 2.6	$+3.4 \times 10^{-9}$	$+3.6 \times 10^{-9}$	10
Treated fiber glass	4.00	1.0 to 1.5	1.4 to 1.6	$+5.6 \times 10^{-9}$	$+5.7 \times 10^{-9}$	10
Untreated fiber glass	2.40	1.0 to 3.0	2.1 to 3.6	-1.1×10^{-9}	-3.0×10^{-9}	30
Untreated fiber glass	6.27	1.0 to 3.0	1.4 to 3.4	-1.2×10^{-9}	-6.0×10^{-9}	30
Teflon	43.1	1.0 to 3.0	1.4 to 2.8	$+1.7 \times 10^{-9}$	$+1.6 \times 10^{-9}$	10
Teflon	67.1	1.0 to 3.0	1.1 to 2.1	$+2.6 \times 10^{-9}$	$+6.2 \times 10^{-9}$	20
African Asbestos	16.6	1.0	1.4	-2.7×10^{-10}	-8.0×10^{-9}	45
Dacron	13.9	0.5 to 3.0	1.1 to 2.8	-1.4×10^{-7}	-1.0×10^{-8}	50
Nylon	25.7	1.0 to 3.0	1.1 to 2.6	$+2.0 \times 10^{-8}$	$+2.5 \times 10^{-8}$	20
Rayon	17.6	1.0	1.4	$+8.1 \times 10^{-9}$	$+1.0 \times 10^{-8}$	43

*Flow through the perforated metal (43% openings) electrodes.

Table 5

VARIATION OF FUEL RESISTANCE IN JP-5 FUEL

Drum	Fuel Resistivity, ohms-cm x 10^{-13}
1	1.0
2	6.0
3	6.4
4	3.8
5	4.0

Table 5 shows that there is an appreciable variation in the resistivity of the fuel. These drums were all obtained in the same fuel shipment, and the fuel contained no known additives.

The data in Table 4 show that an increase in fiber-bed density always results in an increase in current. This is reasonable, since an increase in fiber-bed density means that more surface is available for current generation. However, the flow data show that the double layer theory (Equation 1) does not explain many of the observed phenomena. For example, an increase in flow rate generally did not result in an increase in current. Also, the theory does not explain the change in sign of the current. The magnitude of the zeta potential at the surface of the fiber varied from 0 to 4 mv. Voltages greater than ±300 volts were observed across the bed. This was the maximum value that could be measured by the instrument.

2. Effects of Additives

The effects of additives on current generation by fuel flowing through a treated fiber glass bed are summarized in Table 6.

General observations are as follows:

(1) The sign of the generated current was generally positive. This is the sign that was observed for additive-free fuel flowing through this type of fiber bed. Sulfonated additives such as Petronate HL and Na-Sul EDS in the presence of a small amount of water (20 to 30 ppm) generally resulted in negative current. These particular additives are bad actors in filter/coalescers. Also, there is no doubt that the sign of the current can be dependent upon a

Table 6

EFFECTS OF ADDITIVES ON CURRENT GENERATION BY FUEL FLOWING THROUGH TREATED GLASS FIBER BEDS

Fuel flow rate: 1.1 ft/min
Bed density: 5.5 lb/cu ft
Temperature: 76°F
Fuel conductivities: 1.5 x 10^{-14} mhos/cm.

Additive	Current nanoamps						
	Additive Concentration, ppm by wt						20-30 ppm Water Added
	0	1	3	5	7	10	
			JP-5 Fuel				
RP-2	-0.17	+0.10	+1.7	+3.1	+3.7	+4.4	+36.0
Petronate Hl	-0.10	-3.6	-5.5[a]	-9.0[b]	-14.3	-18.5	-52.0
Sanolene C	+1.25	+0.85	+0.82	+0.83	+0.83	+0.84	+8.0
Topanol A	+0.25	+0.26	+0.28	+0.29	+0.30	+0.01	+0.65
Alox 1846	-0.04	-0.10	+0.25	+0.30	+0.69	+0.92	+2.9
Tenemene II	+0.12	+0.14	+0.29	+0.40	+0.52	+0.72	+1.5
Na-Sul EDS	+0.6	+3.3	+7.9	+11.5	+14.0	+19.4	+11.0
			JP-4 Fuel				
RP-2	+1.2	+6.1	+0.74	+1.1	+1.3	+1.7	+1.4
Petronate HL	+3.5	+12.0	+19.0	+22.0	+23.0	+83.0	-12.0
Sanolene C	+1.7	+1.6	+1.7	+1.8	+1.8	+1.9	+2.8
Na-Sul EDS	-0.05	+0.74	+2.1	+3.4	+4.6	+4.8	-13.3

[a] 2 ppm.

[b] 4 ppm.

time element. The current values given in Table 4 represent equilibrium values that were attained after 3 to 20 min. Most of the currents were positive, and the sign did not change. However, other experiments showed that sometimes the sign can change without any known reason. This is especially true with the sulfonates. One definite observation that could always be repeated is that negative current in the presence of sulfonates never changed to positive current.

(2) An additive of 20 to 30 ppm of free water to the fuel resulted in a considerable increase in the current generating rate. Also, the presence of sulfonated materials caused much more current generation than the presence of other additives.

(3) Additives that have a great effect on fuel conductivity also have a great effect on streaming current generation. An increase in additive concentration generally results in an increase in current generation. This observation pertains to the particular fuel used in this experiment.

3. F/S Contaminant

The AEL Laboratory sent IIT Research Institute a plugged F/S element that they had obtained from a Naval fuel-supply station. During an evaluation in their laboratory, AEL observed that the element had a very high pressure drop. They sent the element to IITRI, where the reasons why the element had failed in the coalescing evaluation were evaluated.

Inspection of the element revealed that it was an inside-out flow element from Filters Incorporated. It was constructed in three sections. The first was an inner, ribbed, coarse, bonded-glass, dirt-filter section; the second was a thick, bonded, fine-glass coalescer layer; the third was a 1/2-in.-thick bonded coarse-glass separator layer. A cotton sock surrounded the third layer. A cross section through the element showed that the filter layer was not plugged but contained a considerable amount of oily brown dirt. The coalescer layer was completely plugged with a hard, dense cake of a resinous deposit. The third layer was very clean and contained no sign of contamination.

An infrared analysis of a toluene extract of the coalescer-layer contaminant revealed that it was an asphaltic type of material. It was a typical hydrocarbon found in nature. A concentrate of the liquid portion of the contaminant has the physical property of crude petroleum oil. Based on these observations, it is very probable that the element was used with jet fuel that had been pumped through a contaminated pipe line.

A further study of the coalescer-layer contaminant revealed that it contained a considerable amount of very fine clay-like dirt. It is very remarkable that none of the contaminant went past the coalescer layer and into the separator layer.

A study of the extracted liquid contaminant showed that it had almost no effect on the fuel interfacial tension. However, it did have an appreciable effect on the fuel conductivity. Electrokinetic experiments showed that 2 ppm of the contaminant in JP-5 fuel caused a 100% increase in the current-generating property of the fuel flowing through a glass-fiber bed. Also, the experiment revealed that a coated glass-fiber surface has a great affinity for the contaminant; this result was evidenced by the extremely rapid change in the current-generating rate. The current-generating rate was not reduced by replacing the fuel with fresh fuel containing no contaminant.

Although the above experiments revealed some information about the behavior of the contaminant in the fuel system, more experimentation is needed to determine its effect on coalescence. This study will be made in the next phase of this program.

4. Summary

An exploratory study was made of the generation of streaming current by JP-5 fuel flowing through the fiber beds. The study showed that, in general, reproducible experiments can be made if the type of additives and fibers, fuel conductivity, and the physical properties of the fiber bed are taken into consideration. With additive-free fuel, some fibers generate positive current and others generate negative current. Also, certain additives such as sulfonates generally cause negative currents, and others cause positive currents. The presence of a small amount of free water always causes a considerable increase in current generation.

Although the present electrokinetic technique offers a ready and sensitive method of determining changes in a fuel-filtering system, it still needs considerable study. In order to obtain a reasonable explanation of some of the observed phenomena, it is necessary to study the effects of numerous variables such as time or aging, fuel conductivity and composition, fiber diameter and forms, additives and their combinations, and system variables such as velocities, temperature, and bed density. Such a study is well beyond the scope of this program.

V. COALESCENCE STUDY

The main experimental work in this phase of the program consisted of coalescing fuel-water emulsions on single fibers and in packed fiber beds. However, before this work was started it was necessary to develop or design equipment or analytical procedures for the coalescence experiments. This consisted of first assembling equipment for producing a standard fuel-water emulsion with a known droplet size distribution. An analytical procedure was then developed that made possible a quick accurate determination of free water in fuel. The final preparation for the coalescence experiments consists of constructing a coalescer cell for supporting the packed fiber beds and also a small glass cell for supporting individual fibers. Procedures and results of this work are described in the following sections.

A. Standard Emulsion

Before performing meaningful coalescence experiments, it is necessary to have a system for generating an emulsion that simulates those found in actual fuel supply systems. This emulsion will be used for coalescence experiments, electrokinetic studies, investigations of droplet adhesion to various types of fibers, and development of various coalescing and filtering systems.

The system used for preparing the emulsion is shown in Figure 10.

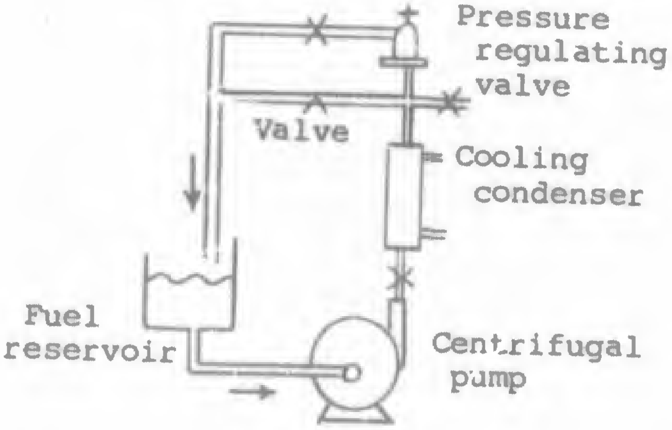


Figure 10

SYSTEM FOR FORMING A FUEL-WATER EMULSION

Photomicrographic equipment that was set up consists of a Zeiss microscope with a Leitz camera attachment. A Polaroid pack was used to obtain photographs of the emulsion. Other auxiliary equipment used was a Multiblitz microflash unit and a special photographic cell for viewing and photographing the emulsions. Summaries of the various phases of this work are given below.

After the jet-fuel circulating system had been set up, the microscope and the auxiliary equipment were placed on a table near the equipment. Various closed sample cells were investigated to select a photographic cell system that would allow a satisfactory photograph of the emulsion. Various lighting arrangements, such as dark-field illumination, phase-contrast illumination, and transmitted light, were tested in relation to the cell system to achieve the best results. The best combination was used to obtain the first set of photomicrographs for particle-size measurements.

1. Photographic Cell System

Initial efforts were directed toward the use of a well-type slide. The emulsion sample was pipetted into the well and observed or photographed as soon as possible. The disadvantages of this method were settling of larger emulsion droplets, adsorption of droplets on glass surfaces, coalescence of droplets, and prolonged manipulation between photographs. The disadvantages far outweighed the advantage of ease of sample-handling.

In a flowing system, the emulsion was pumped through the photographic cell. Attempts were made to photograph the emulsion at reduced speeds. A constant flow for repeated successful photographs was not obtained, and streaks of droplets were obtained. A bypass was then incorporated so that flow would be continuous when flow through the cell was stopped and a picture taken. After taking the picture, the valve was opened and flow resumed through the cell to purge it and to make it ready for the next sample.

Several cell designs were evaluated. The cells were made of Lucite or brass with optical glass discs of various thicknesses to enclose depths of jet fuel emulsion from 0.5 to 10 mm. Each design had a basic fault relative to the flow pattern of the emulsion or to the illumination of the system. The cell design selected for the initial photomicrographs was a square Pyrex tube necked down into a cylindrical tube and connected into the flow system. A disadvantage of this cell is the optical limitation for use with magnifications higher than 100x. However, a 100x magnification is satisfactory for the current work.

2. Illumination

In the determination of the lighting arrangement most suited for photomicrographs of fuel-water emulsions, transmitted light, dark-field illumination, and phase-contrast illumination were used. The dark-field illumination was very good for visual observation of the emulsion. In the photomicrographs, however, the water droplet could not be distinguished from the particulate matter, especially for those particles smaller than 2.0 μ or at high magnifications. Phase-contrast illumination did not have a decided advantage in the viewing or taking of photomicrographs. The use of transmitted light with appropriate filters appeared best and was used for taking the photomicrographs.

To increase the light intensity for photography without interfering with the illumination for visual observation, a Multiblitz microflash unit was used as a photographic light source. The rated flash duration of 0.002 sec could stop the settling motion of the large water droplets when flow was momentarily stopped for exposure.

3. Photomicrographs

By using transmitted light, a microflash unit, a photographic sample cell, and a 10x objective with a 10x eyepiece, a series of photographs was taken of the circulating jet fuel with the addition of various increments of water and surfactant. A Karl Fischer analysis of the jet fuel showed an initial concentration of 160 ppm of free water. A measured amount of water was added to the jet fuel and circulated to establish equilibrium. The flow through the cell was stopped, the photograph taken, and the flow resumed. A series of pictures was taken at approximately 3-min intervals for each increment of water added. Upon addition of 990 ppm of water, 10 ppm of sulfonate surfactant was added, and the resultant emulsion was photographed. Another 20 ppm of surfactant was added, and the emulsion was again photographed. After continuous circulation for 30 min, the jet fuel-990 ppm water-30 ppm surfactant emulsion was again photographed.

4. Results

The droplets in the photographs were measured and counted. The results show that the emulsions are a typical representation of the type found in large-scale fuel systems. In such systems, the droplets range from 1 to 5 μ. The average results are shown in Table 7. No significant results were obtained on comparing photographs taken with each addition of water. The photographic sequence did not indicate any trends. The trend found is shown in Table 7.

Table 7

AVERAGE SIZE DISTRIBUTION OF WATER DROPLETS IN WATER-JP-5 EMULSION AT 76°F

Free Water, ppm	Sulfonate, ppm	% Less Than Stated Size				
		1.0μ	2.9μ	4.8μ	6.7μ	8.6μ
160		56.7	90.4	98.4	99.4	100
243		58.4	88.5	98.1	99.6	100
409		60.0	87.8	98.4	99.4	100
658		48.9	76.0	92.6	98.0	100
990		42.6	70.8	85.6	91.6	100
990	10	48.6	76.4	90.0	97.4	100
990	30	51.5	79.5	95.6	99.8	100
990 (30 min)	30	54.9	89.2	99.1	100	-

Addition of water to the fuel-water emulsion resulted in an increase in number of particles less than 1.0 μ and a decrease the greater the quantity of water. The use of sulfonate additive resulted again in a gradual increase in number of particles below 1.0 μ. The overall results showed that from a centrifugal pump, 40% or more of the particles are below 1.0 μ, 70% or more are below 2.9 μ, 85% or more are below 4.8 μ, and 91% or more are below 6.7 μ.

B. Analytical Procedures

Before the coalescing operation can be evaluated, it is necessary to have an analytical method for accurately determining the free water in the effluent fuel stream. Many analytical methods have been developed or suggested; however, all of them have some drawbacks. Undoubtedly, the most widely accepted method is the use of the Karl Fischer analysis for total water. This method has been used in military specifications for many years. However, various publications have indicated that this method does not have sufficient reliability to be considered a standard for rating F/S. The ASTM manual states that the method has a repeatability of 11 ppm for free water determinations in fuel. This value is considerably more than the 5 ppm cited in F/S specifications as the maximum allowable excess of effluent water content above the saturation value. Reasons for the inaccuracies in the Karl Fischer method are:

(1) Failure to obtain reliable water saturation values of the fuel

(2) Change in water saturation values due to additive removal or usage

(3) Loss of free (and dissolved) water during sampling (nonhomogeniety, surface effects, etc.)

(4) Errors due to the titrations

(5) Failure to determine the true sample temperature.

These sources of error can be minimized by careful handling of the fuel sample and also by consistent titration procedures. In general, an average of three samples is required to determine the actual amount of free water in the fuel. Thus, this method is time-consuming and not well suited for tests in which many quick determinations should be made. However, this method is fairly reliable, and because better methods have not been developed, it is still the standard method in military specifications.

Other methods that have had some success are the use of light transmission or reflectance. However, these methods have some serious drawbacks; they are very sensitive to dirt as well as to free water. They are sensitive to variations in the color of the dirt and also dirt agglomeration. Even in a system in which there is no dirt, the readings can be in error because of the variations in the particle size of the water drops. This variation can be overcome by using a constant-temperature emulsifier; however, this requires special equipment.

1. AEL Pads

Recently, a "Free Water in Fuel Detector" was developed by the Naval Aeronautical Engine Laboratory. This method consists of flowing a fuel sample through a cellulose pad or disc that has been coated with sodium fluorescein. When the exposed pad is viewed under ultraviolet light, the free water in the fuel causes the pad to fluoresce. The amount of fluorescence is proportional to the amount of free water in the fuel and can be estimated by comparing the samples with a set of printed standards that also fluoresce under ultraviolet light.

This method appeared to furnish a quick means for accurately determining free water in fuel, and considerable efforts were spent in evaluating it. This evaluation consisted of developing methods for preparing and analyzing the pads for evaluating them in a 50-gpm test loop. The test loop was set up to evaluate a single F/S element and military effluent testers such as the Bendix go-no-go gauges. During this study, the amount of free water in the fuel was determined by four different methods:

(1) AEL detector pads

(2) Karl Fischer analysis

(3) Material balances

(4) IITRI water pads.

The fourth method has recently been developed at IIT Research Institute and is described in Section VB2.

Because of the nature of this report, little data from the above study are given. However, based on the work, the following conclusions and observations were made:

(1) If used correctly, the detector pads can be used to estimate a small amount (less than 15 ppm) of free water in fuel.

(2) The fuel-sampling time should be in the approximate range of 30 to 45 sec. A slow rate results in high readings, and a fast rate results in low readings.

(3) By using the specified amount of sample, the detector pad will not be affected by 0 to 1 ppm of free water. This free water can be detected by using twice the amount of fuel sample.

(4) The detector pads are affected by dissolved additives such as RP-2 and Santolene C but not by the standard anti-icing agent.

(5) The accuracy of the pads is 1 to 2 ppm at the lower range of the standard scale and 3 to 5 ppm at the upper range.

(6) The free water range in which the detector pads can be used is approximately 0 to 10 ppm. It is very possible that this range could be extended considerably by using a smaller or a diluted sample; however, this procedure was not evaluated.

(7) The present printed standards are questionable, and they should be recalibrated.

The last observation, perhaps the most important one made, is based on considerable work done in this and other programs. The true relation between the actual free water present and the detector pad readings (Figure 11) shows that the pads have approximately 50% of the value specified by the printed standard pads. In other work at IITRI, it was determined that the relationship shown in Figure 11 applies to JP-4 and gasoline. This particular calibration pertains to the emulsion used in the 50-gpm test loop. It is believed that the emulsion is typical of the type found in large-scale fuel systems. It is estimated the droplet size in the emulsion varied from 1 to 20 μ.

On the basis of this brief summary of the evaluation of the detector pads, it is apparent that they cannot be used to evaluate a small-scale laboratory coalescer. The usage range is very small, the required sample flow rate is too great, and additives may affect the pad readings.

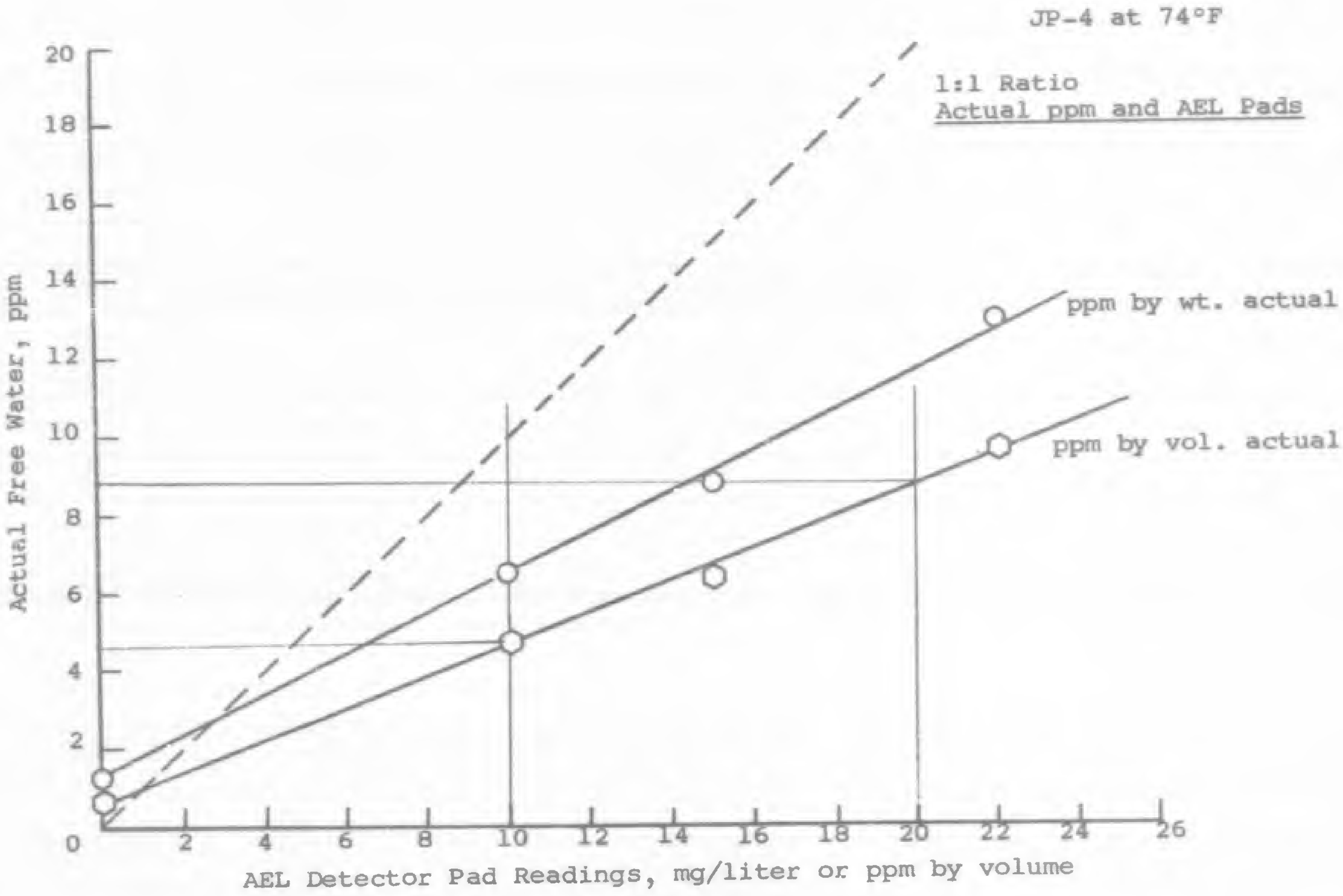


Figure 11

COMPARISON OF DETECTOR PAD READINGS WITH ACTUAL FREE WATER PRESENT

2. IITRI Free Water Pads

During the course of various programs concerned with the study of fuel purification, considerable thought was devoted to developing a quick, simple, and accurate method for determining free water in jet fuel. As a result of work that was begun before the start of this program, such a method was developed. However, it was not proven feasible until it was applied to evaluating coalescence experiments in this program. The abbreviated description that is given in this report does not indicate the extent of the research effort that was directed to the development of this method.

The basis of this method is the adsorption of free water by preconditioned cellulose pads. If cellulose pads similar to the AEL detector pads (without the dye) are suspended in fuel stored over water, the pads will adsorb water until an equilibrium value is reached. This operation could take more than 1 week. However, based upon the temperature, the pads will attain a certain moisture content. If a fuel sample containing free water is passed through the cellulose, the pads will adsorb only the free water. The free water can be determined by cutting up the pad and titrating the free water in methanol. This method has been proven to be much more accurate than the conventional Karl Fischer method for determining free water in jet fuel. However, it is not simple, since constant-weight preconditioned saturated pads and also the Karl Fischer equipment are required.

A major improvement in the pad method was attained when it was determined that the moisture in the pad could be determined with a Hart Moisture Meter (ref. VII-11). This simple instrument consists of a battery-operated electrical circuit for determining the electrical resistance of the paper pad. The procedure consists of clamping the pad in the instrument (at 125 psi) and, after adjusting the circuit, reading the resistance values from a meter. Experiments using the Karl Fischer method and the Hart Moisture Meter showed that a linear correlation exists between the Hart readings and the moisture in the pads. A correlation for JP-4 is shown in Figure 12. If a set of constant-weight pads with a weight different than the value shown in Figure 12 is used, another line, parallel to the one shown in Figure 12, is obtained.

The present procedure for using the IITRI pads to determine the free water in fuel is as follows. A water-saturated pad stored in fuel is first evaluated in the Hart Moisture Meter. After passing a measured amount of sample fuel through the pad, the pad is evaluated again in the Hart instrument. The difference between the two readings is multiplied by a constant to determine the amount of free water in the fuel. It is not

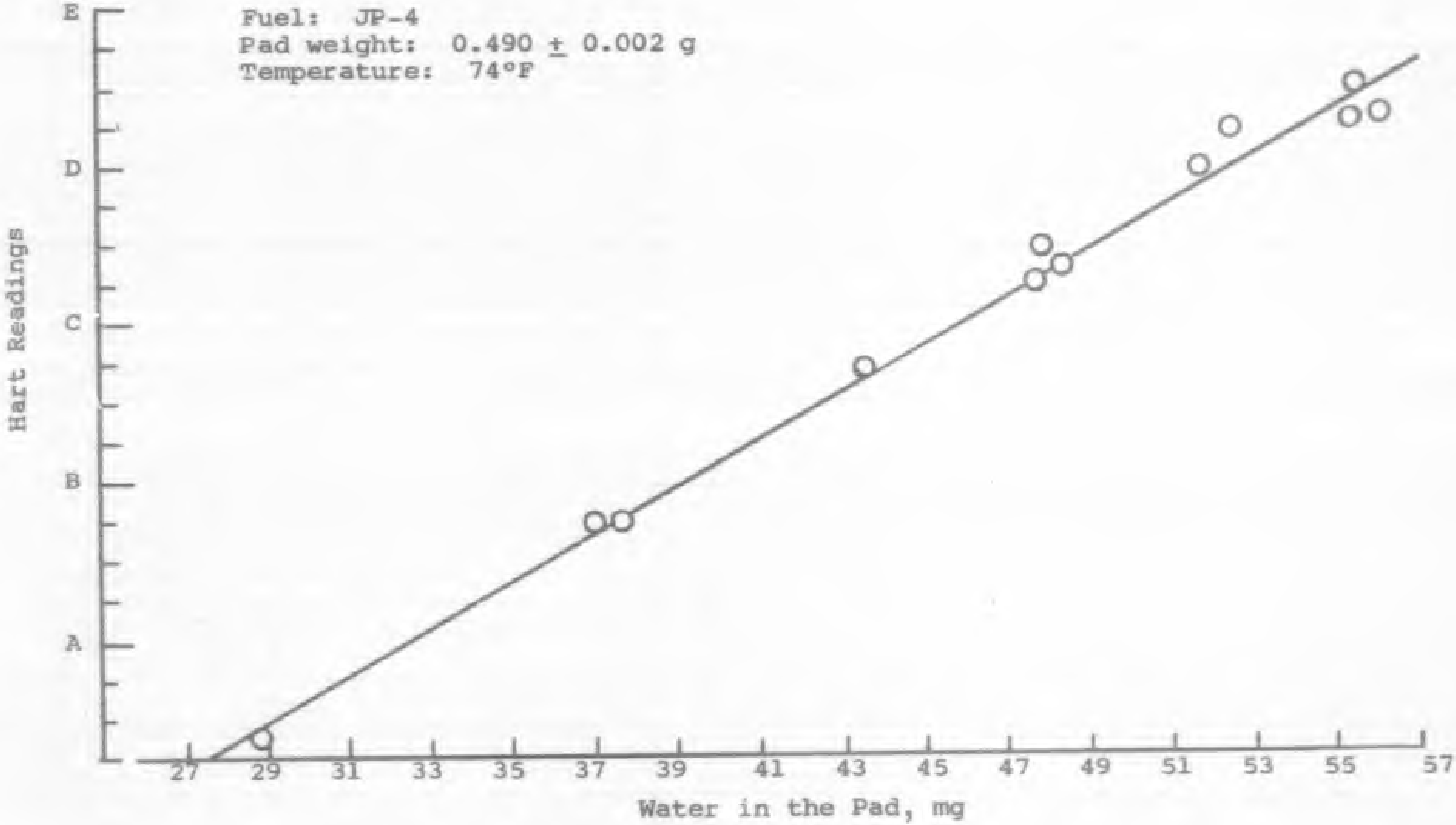


Figure 12

CORRELATION BETWEEN HART READINGS AND PAD MOISTURE necessary that the moisture in the original pad be in equilibrium with the water-saturated fuel. As long as the moisture in the pad is equal to or greater than the equilibrium saturation value, these pads can be used in this method.

After it was determined that the IITRI pad method was an excellent method for determining free water in fuel, it became apparent that a pad preparation problem still existed. Many methods for preparing the conditioned pads were tried; however, only one proved to be of practical value. This method consists of first preparing a fuel-water emulsion with a predetermined amount of free water. A weighed amount of pads is then placed in the emulsion, and the system is hand-shaken until the fuel is clear. The pads can be checked with the Hart Meter to determine whether they have adsorbed enough water.

C. Coalescence Equipment

This equipment was of two different types: one for single-fiber studies and the other for coalescence in packed beds. These are described below.

1. Coalescer Cell System

After a quick analytical method for determining free water in jet fuel had been developed, studies of fiber bed coalescence were begun. The method consisted of first completing a cell that could be easily disassembled and into which any combinations of fiber glass layers could be placed. The cell shown in Figures 13, 14, and 15 is composed mainly of a Lucite cylinder into which various sizes of Lucite cylinders are inserted. These inserts determine the bed depth, and they also seal and support the bed. Aluminum adaptors attached to each end of the main Lucite cylinder serve as transition pieces to provide uniform fuel flow to and from the coalescer fiber bed. O-rings are used to seal the aluminum adaptors against the main Lucite cylinders. Means are provided to remove accumulated air and coalesced water. Figure 13 is a schematic of the system. The separator is a 7-in.-long vertical Lucite tube with a 3-in. outside diameter.

2. Coalescence on a Single Fiber

A series of experiments were performed in which emulsified water in JP-5 fuel was made to coalesce on various types of single fibers. The coalescer unit consisted of a 1/4-in.-I.D. Lucite tube that had part of its wall cut out. Selected single fibers were cemented at right angles to the longitidinal axis

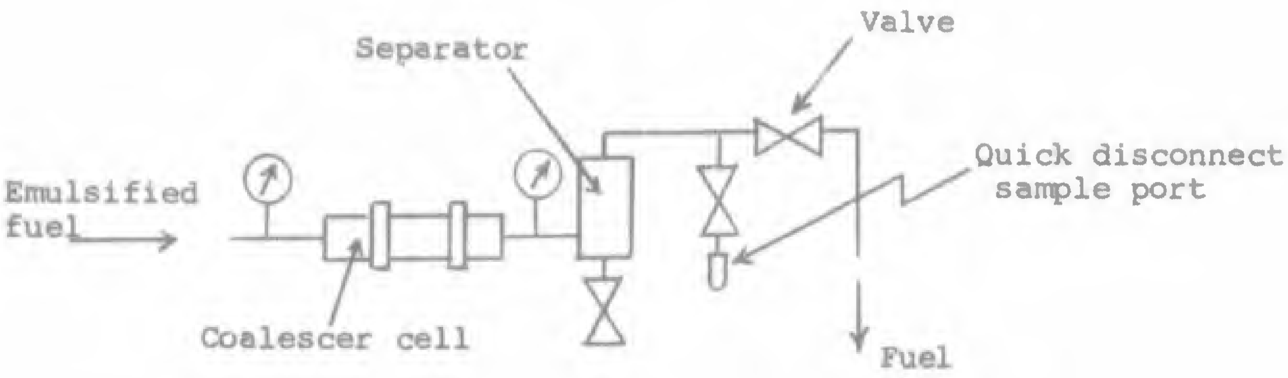


Figure 13

SCHEMATIC OF COALESCER CELL SYSTEM

of the tube, and the cut-out wall section was replaced with a glass cover slip used for microscopic slides. The single fibers were suspended 1/2 to 1 mm below the cover slip. The coalescer cell is illustrated in Figure 15. Focusing of the microscope on the fiber and on the flowing emulsion was then possible.

The photomicrographic setup was similar to that described in Section IVA. Also, the equipment used for preparation of the JP-5 emulsion is the same as that described in this section.

D. Results and Discussion of Coalescence Experiments

Summaries of the work done on the coalescence of water droplets in packed beds and upon single fibers are given in the following paragraphs.

1. Coalescence on Single Fibers

Before presenting and discussing the experimental results, we should point out the differences between coalescence in a fiber bed and on a single fiber.

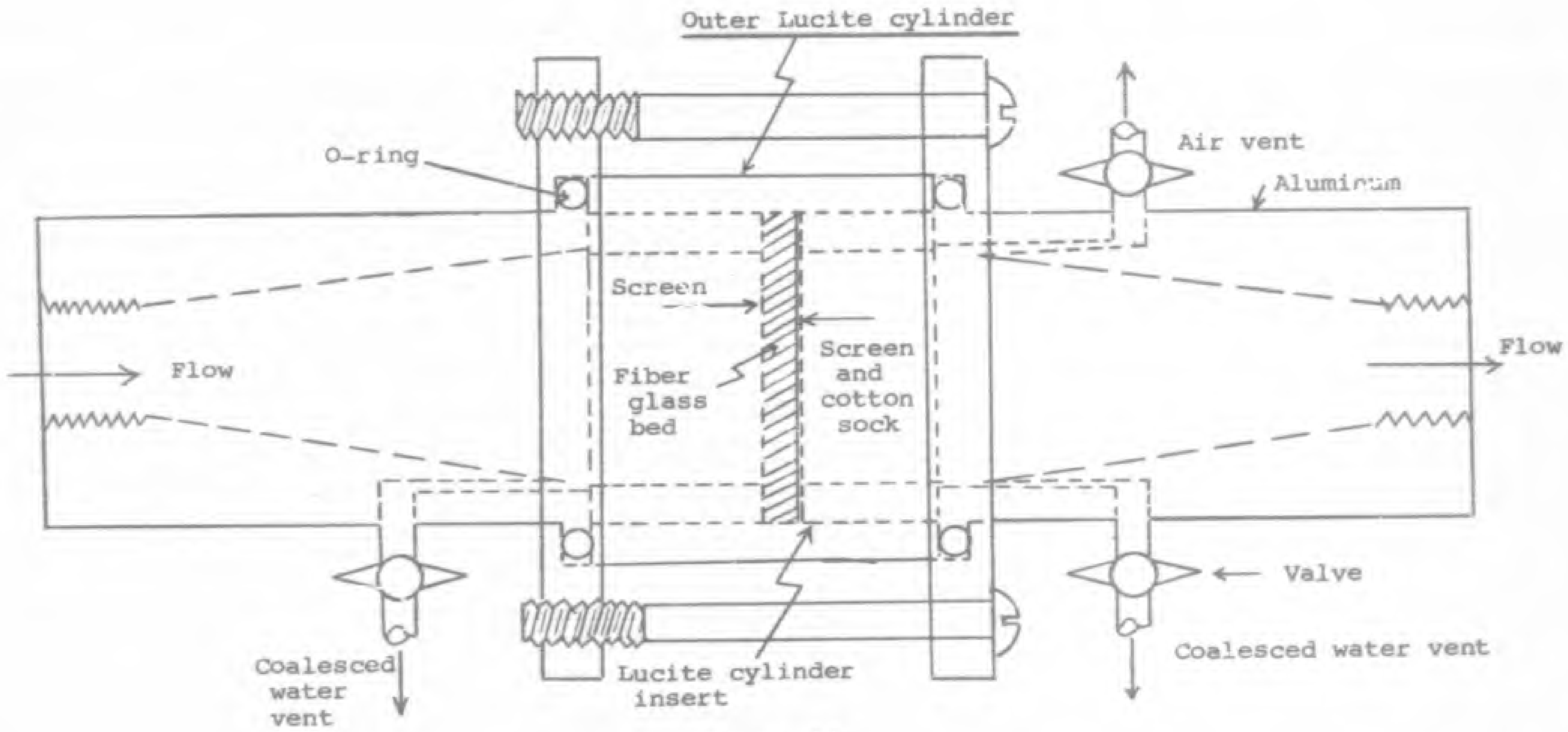


Figure 14

EXPERIMENTAL COALESCER CELL
(Scale = 1:1)

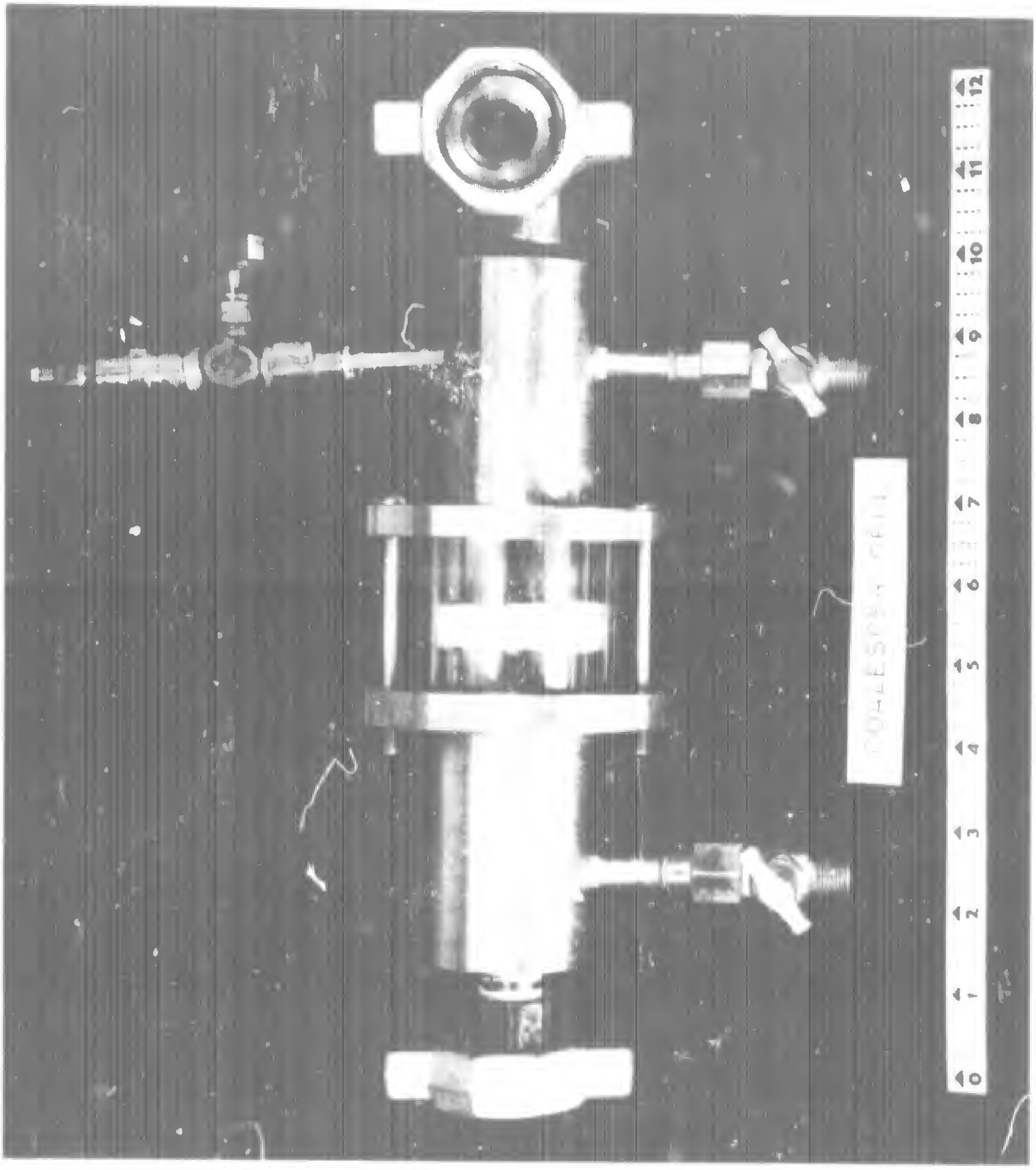


Figure 15
PHOTOGRAPH OF COALESCER CELL

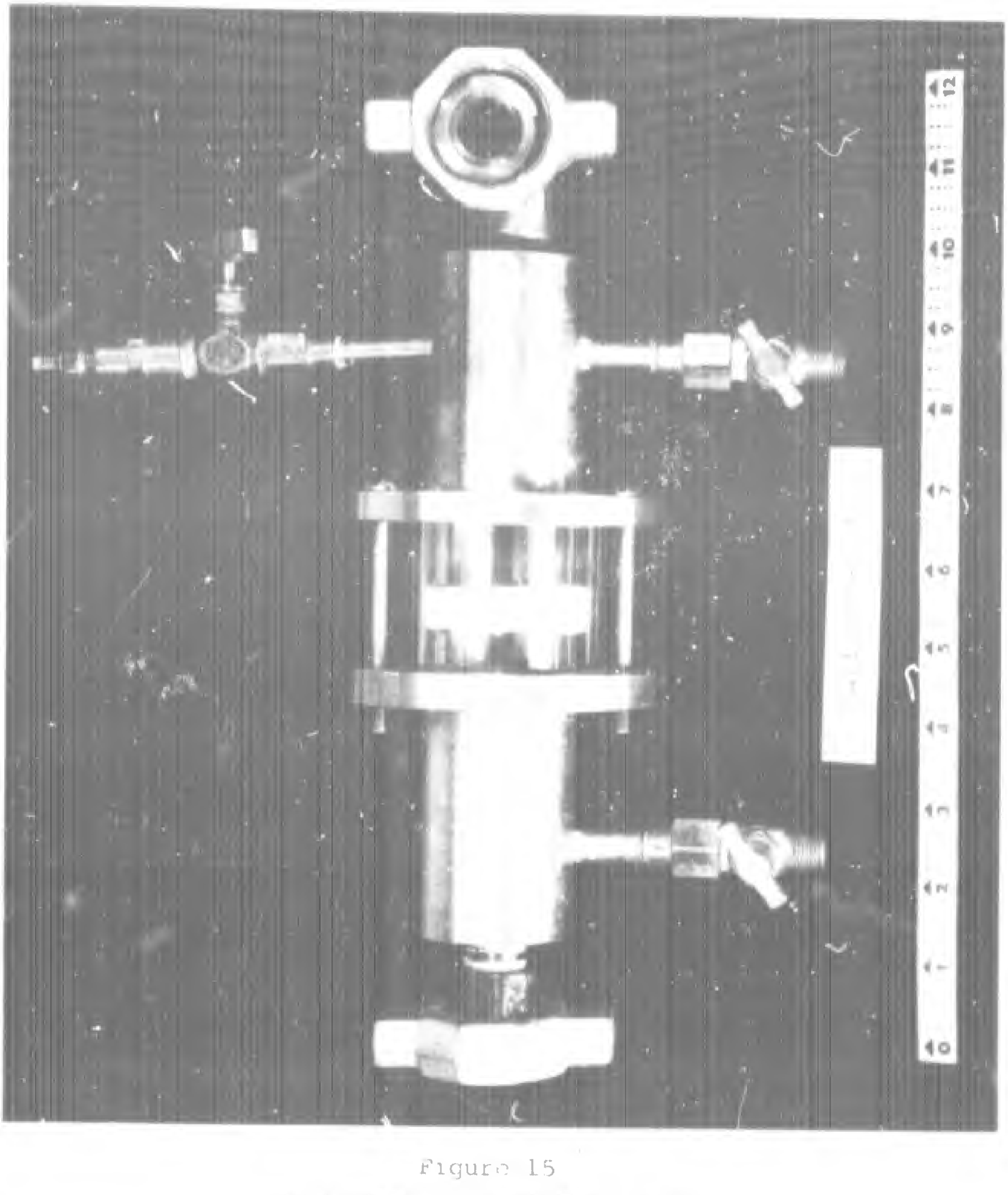


Figure 15
PHOTOGRAPH OF COALESCER CELL

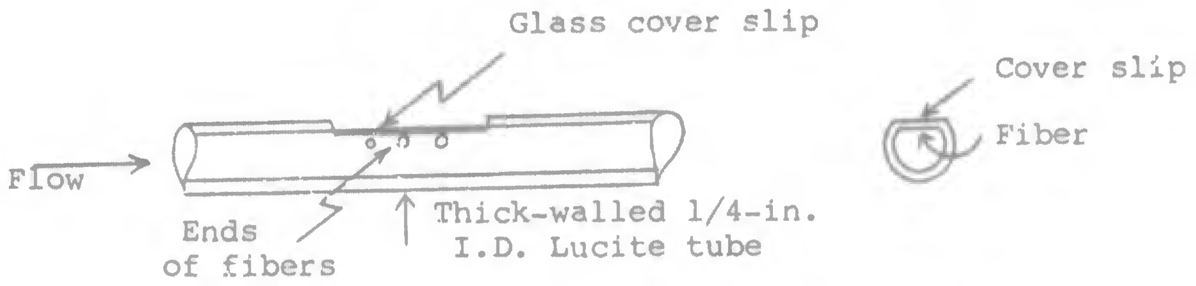


Figure 16

COALESCER CELL FOR SINGLE-FIBER STUDIES

(1) In a packed bed there is considerable turbulence because of the presence of other fibers, which are spread in all directions. There are practically no streamlines.

(2) In single-fiber experiments, there are streamlines, and there is no pressure drop.

(3) There is a buildup of pressure in a fiber bed because of water loading during coalescence. This is not the case with single fibers; however, as the drops grow on single fibers, they do tend to influence the rate of coalescence.

In this study, all the experiments were made with JP-5 emulsions with a free water content of 500 and 1000 ppm. During the early phases of the work, the drop growth rate with the 500-ppm emulsion was too slow, thus most of the experiments were made with the 1000-ppm emulsion. Results of the photographic work are shown in Figures 17 through 26. Curves that show measured droplet growth rates are shown in Figures 27 through 29.

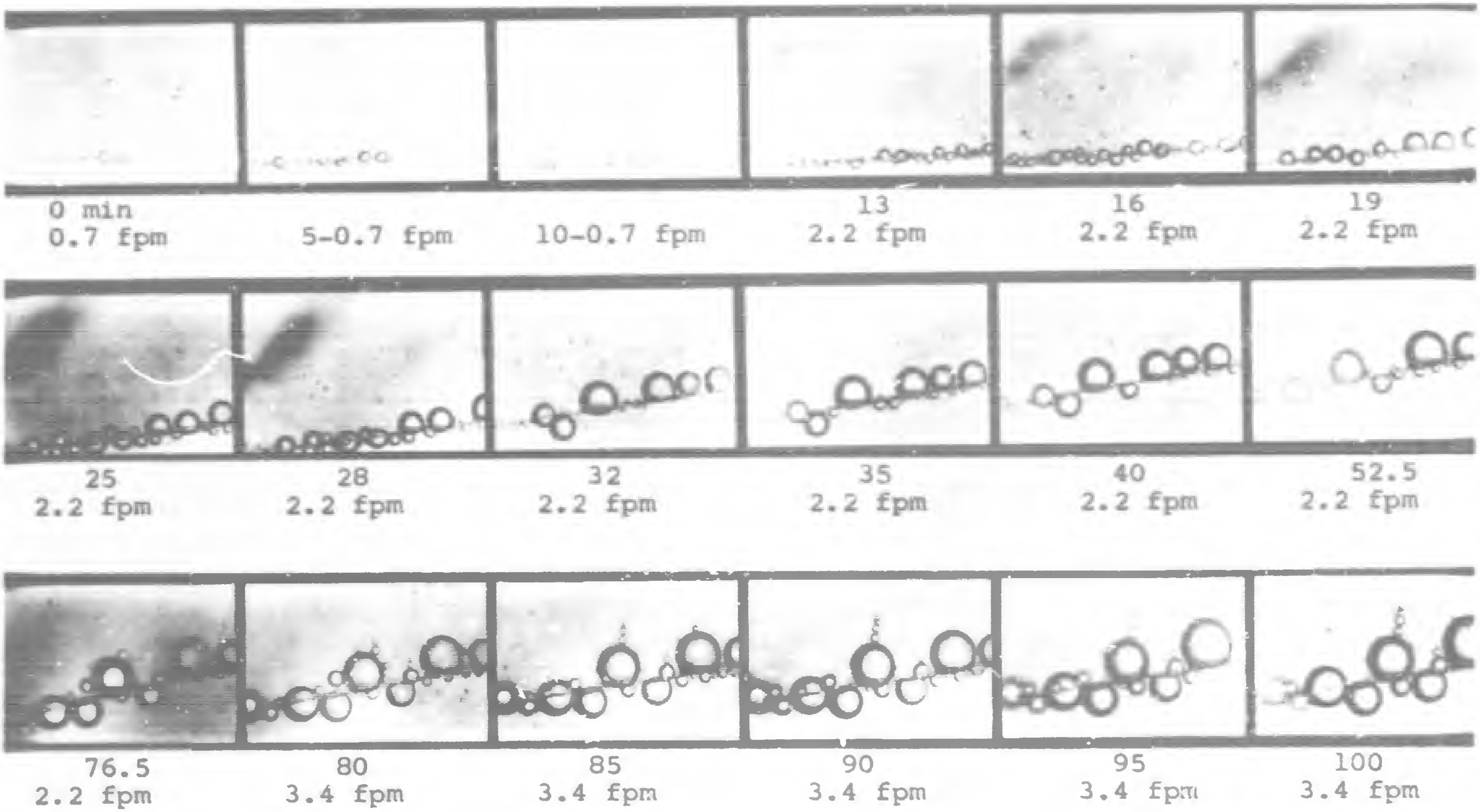


Figure 17

EFFECT OF VELOCITY ON DROP COALESCENCE ON A TREATED FIBERGLASS FIBER

Fiber diameter, 5-6 microns
Emulsion, JP-5-water (1000 ppm)
Local velocity, 0.7 to 3.4 fpm
Film No. 9
Flow direction, page bottom to top

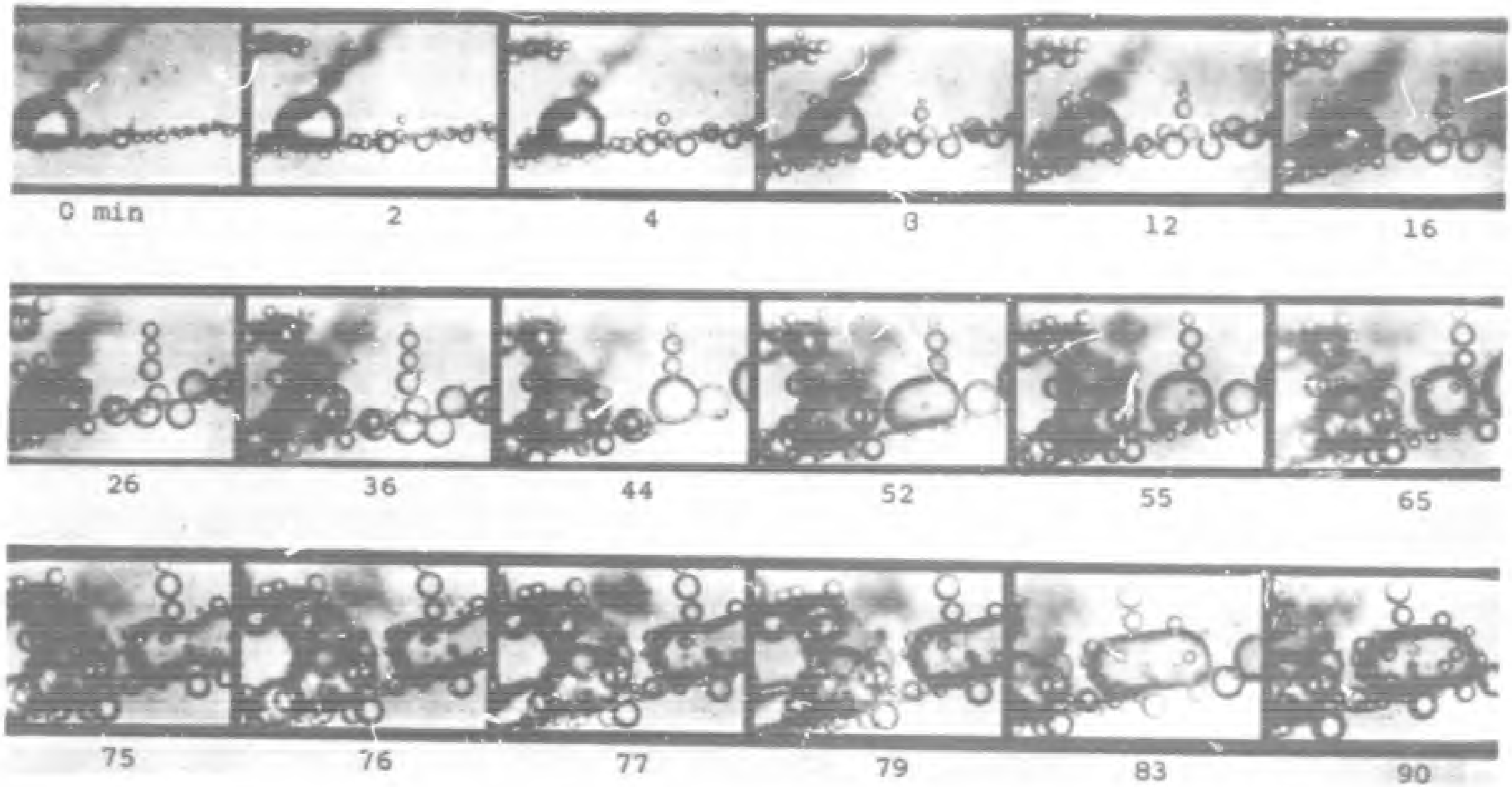


Figure 18

DROP COALESCENCE ON A TREATED FIBERGLASS FIBER

Fiber diameter, 5-6 microns
Emulsion, JP-5-water (1000 ppm)
Local velocity, 3.4 fpm
Film No. 10
Temperature, 75°F
Flow direction, page bottom to top

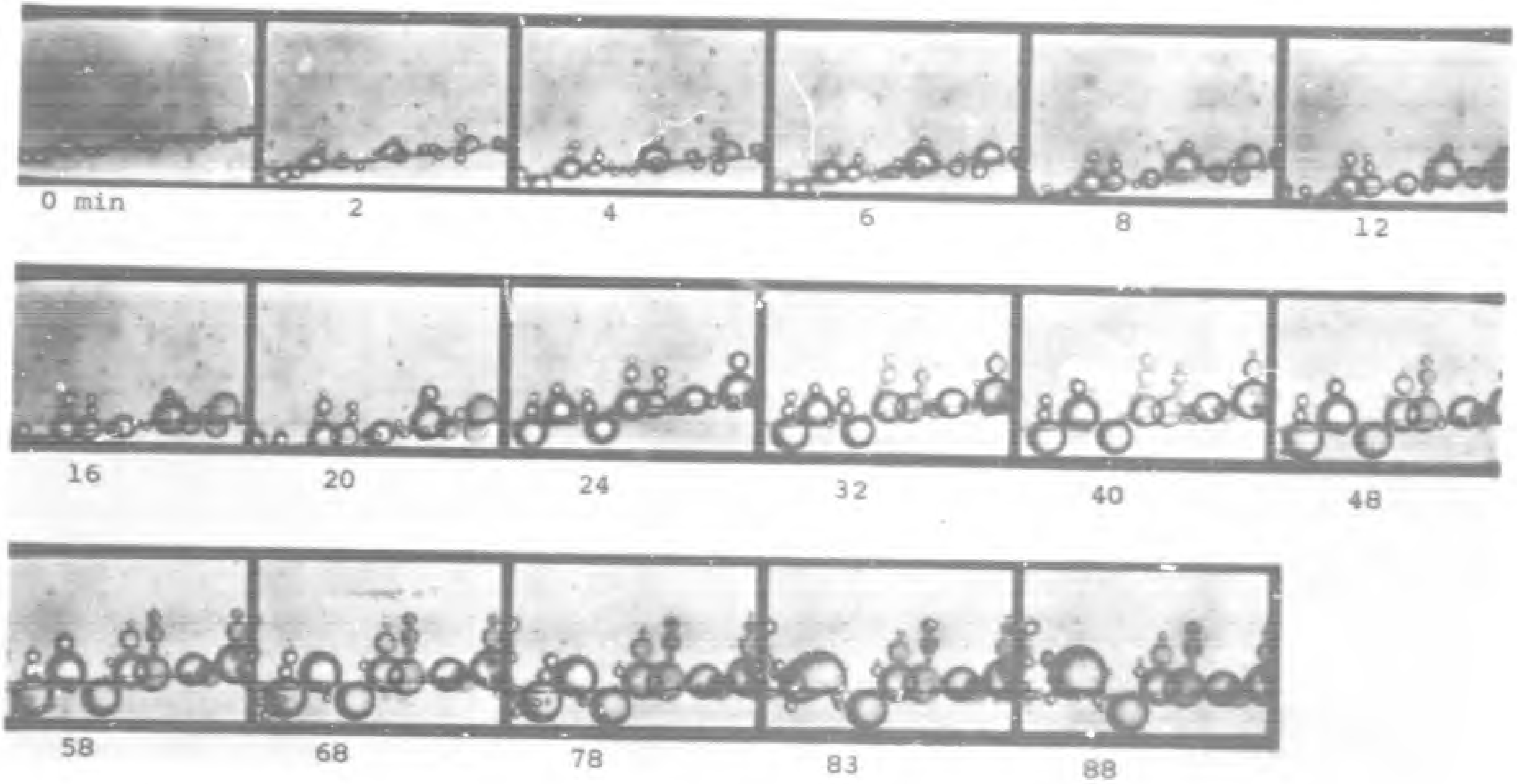


Figure 19

DROP COALESCENCE ON AN UNTREATED FIBERGLASS FIBER

Fiber diameter, 6-7 microns
Emulsion, JP-5-water (1000 ppm)
Local velocity, 3.4 fpm
Film No. 12
Temperature, 76°F
Flow direction, page bottom to top

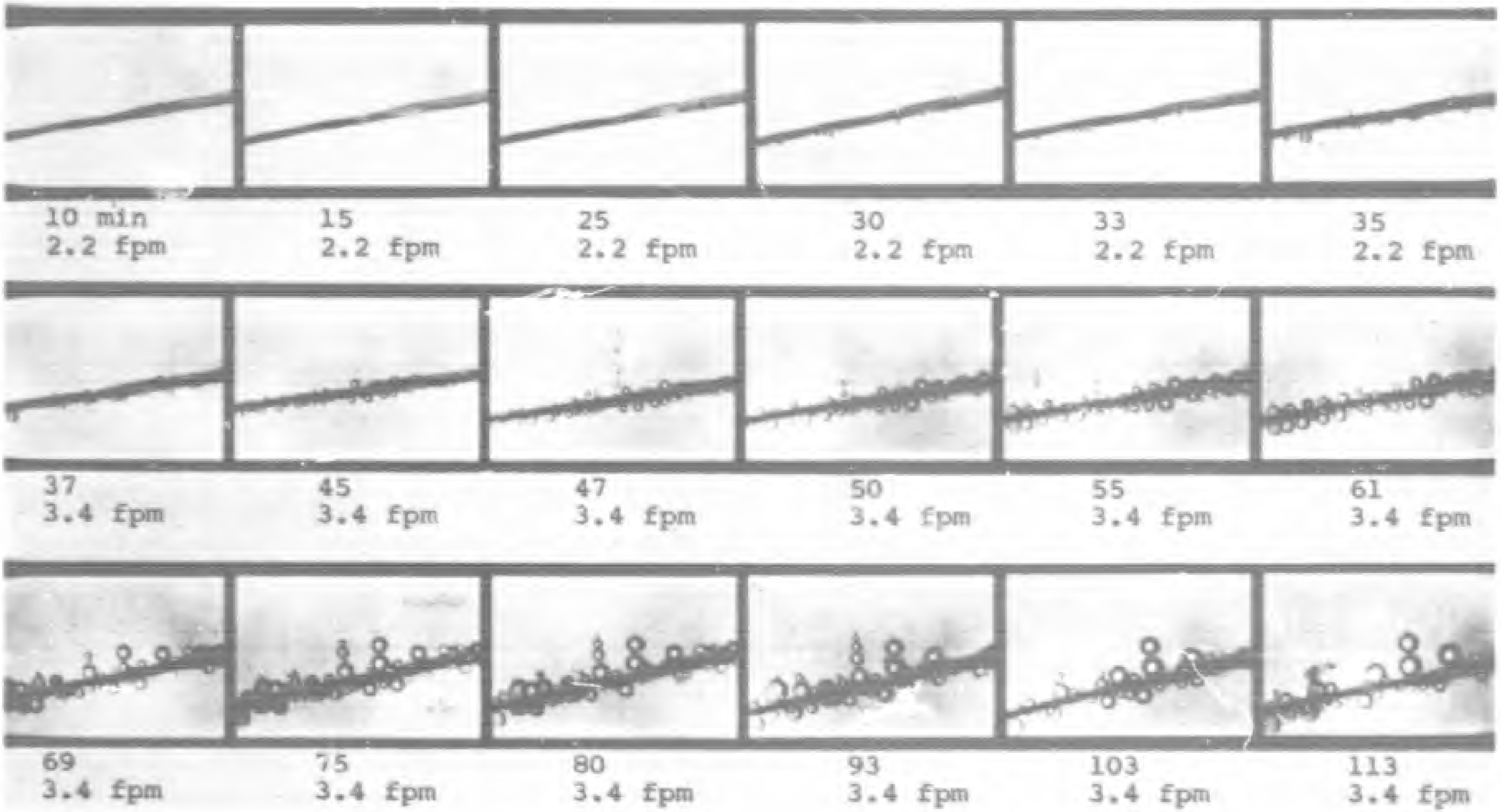


Figure 20

DROP COALESCENCE ON A TEFLON FIBER

Fiber diameter, 16-17 microns
Emulsion, JP-5-water (500 ppm)
Local velocity, 2.2 to 3.4 fpm
Film No. 1
Temperature, 76°F
Flow direction, page bottom to top

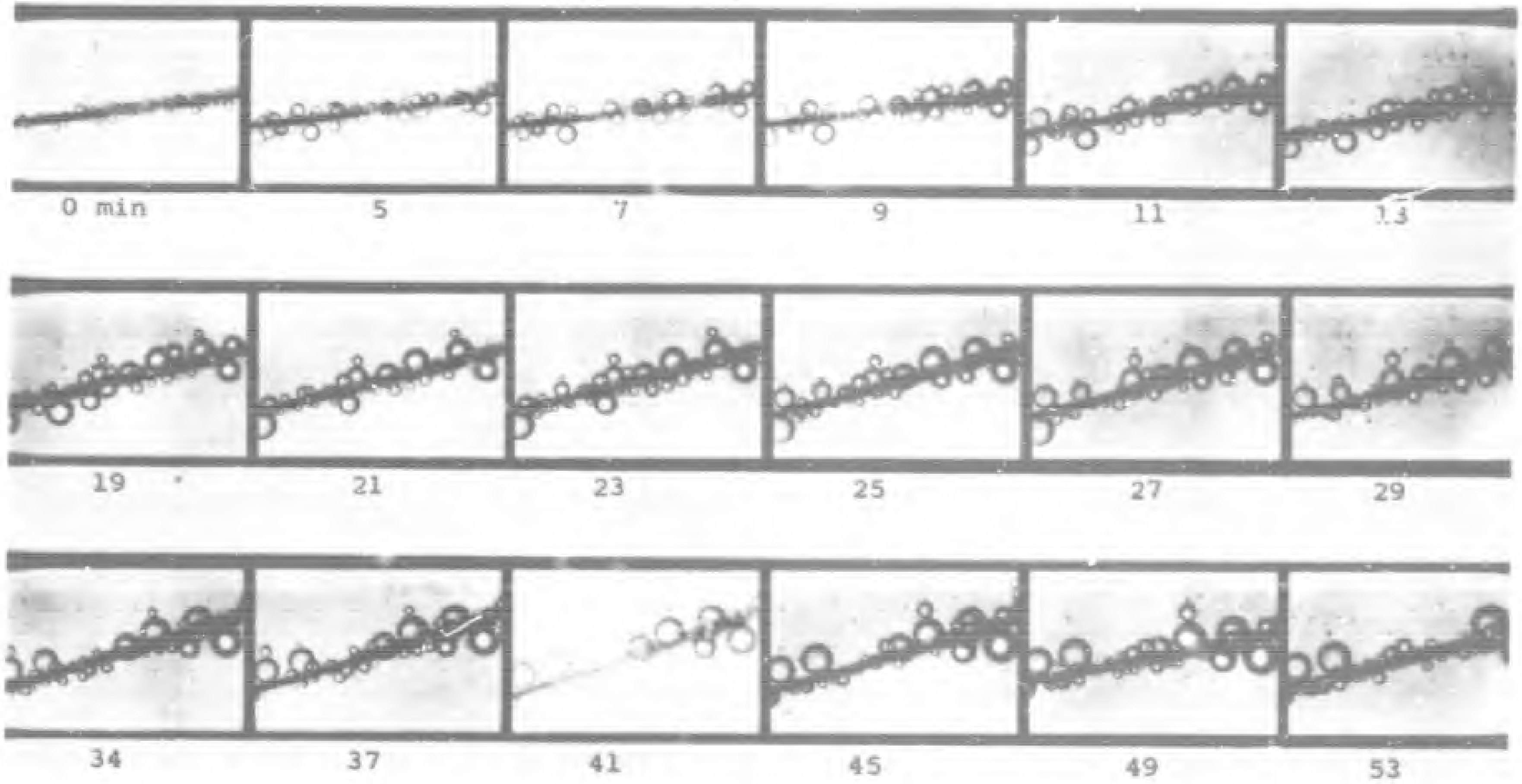


Figure 21

DROP COALESCENCE ON A TEFLON FIBER

Fiber diameter, 16-17 microns
Emulsion, JP-5-water (1000 ppm)
Local velocity, 3.4 fpm
Film No. 3
Temperature, 76°F
Flow direction, page bottom to top

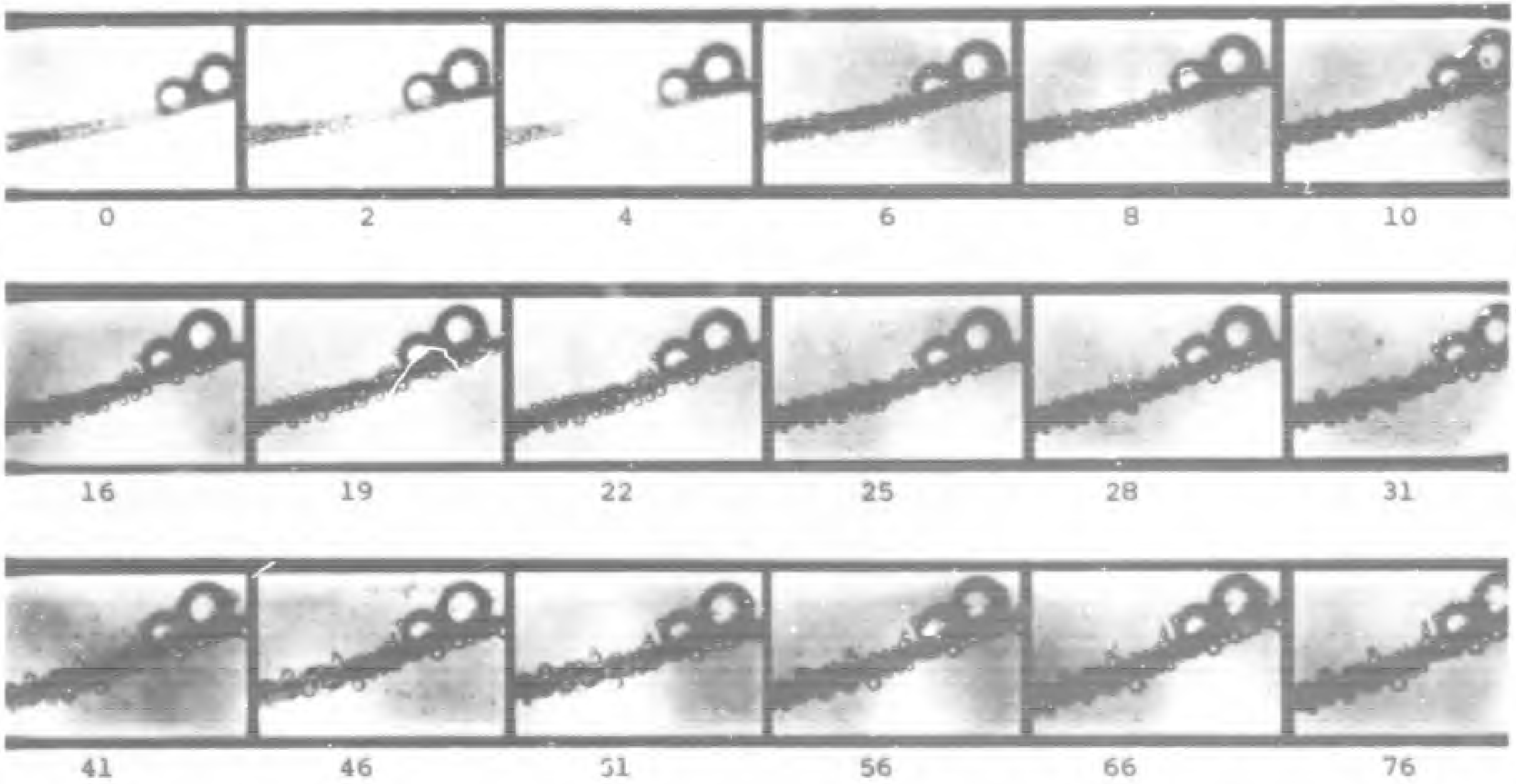


Figure 22

DROP COALESCENCE ON DACRON FIBERS

Fiber diameter, 11-12 microns
Emulsion, JP-5-water (500 ppm)
Local velocity, 3.4 fpm
Temperature, 76°F
Film No. 7
Flow direction, page bottom to top

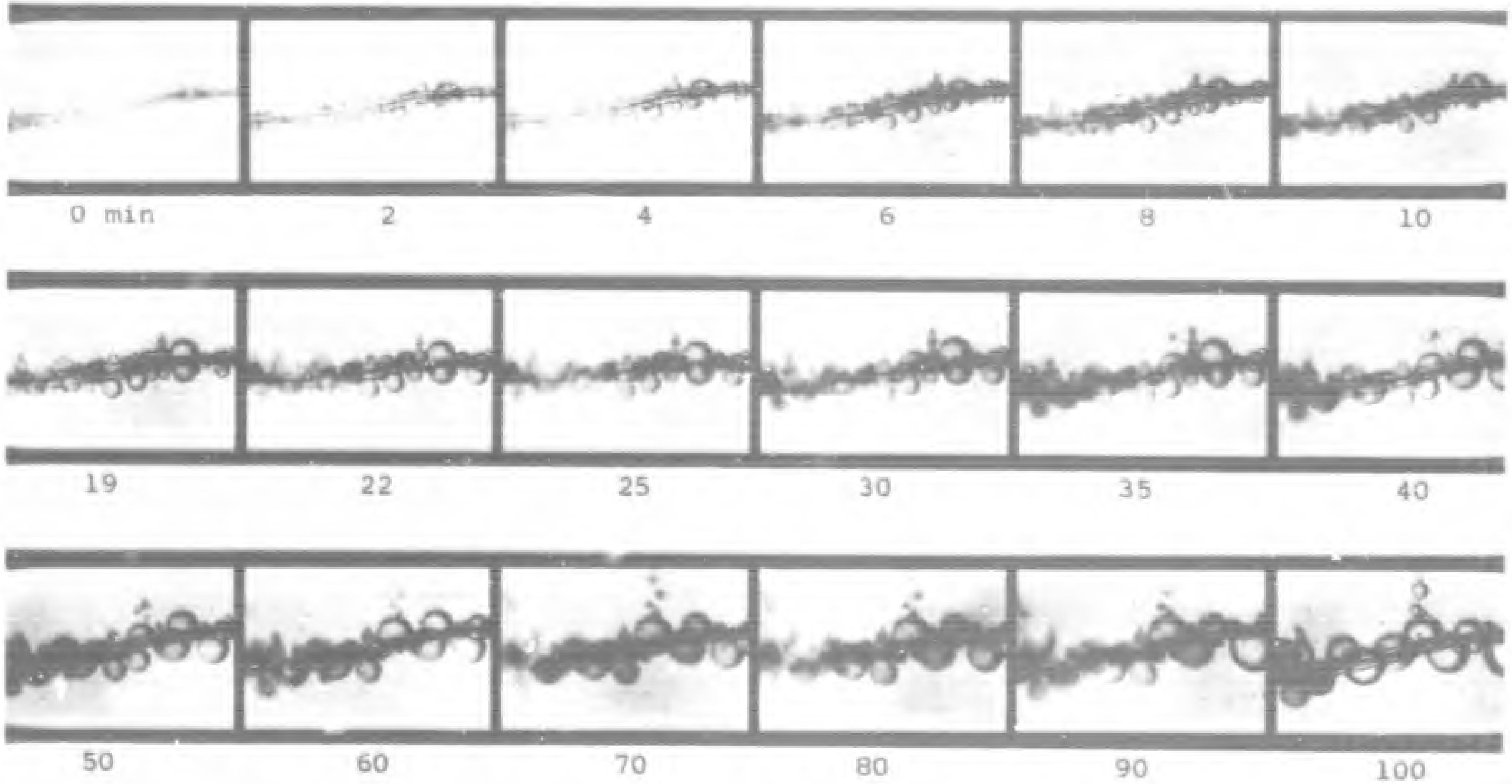


Figure 23

DROP COALESCENCE ON DACRON FIBER

Fiber diameter, 11-12 microns
Emulsion, JP-5-water (1000 ppm)
Local velocity, 3.4 fpm
Temperature, 76°F
Film No. 8
Flow direction, page bottom to top

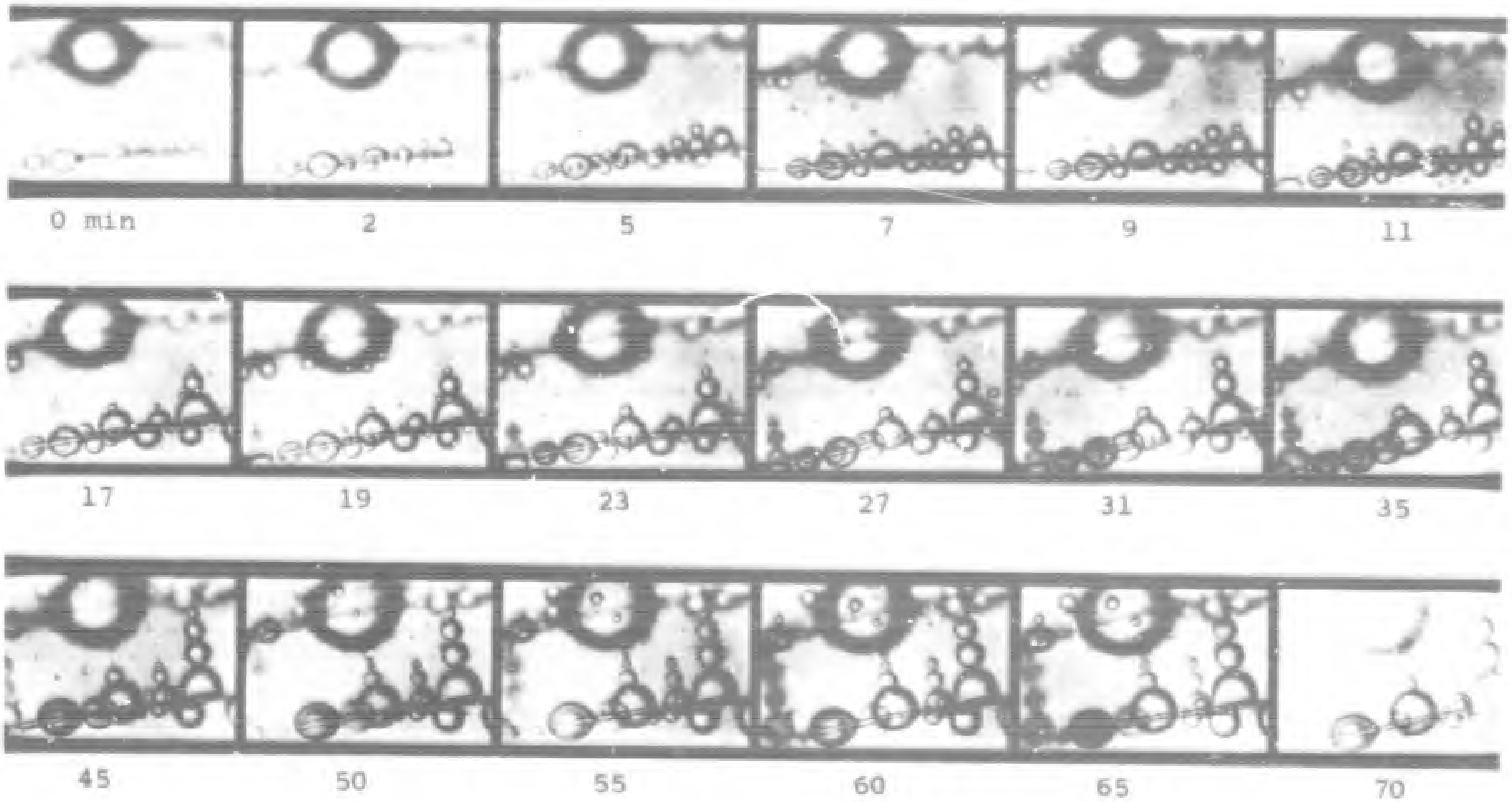


Figure 24

DROP COALESCENCE ON A NYLON FIBER

Fiber diameter, 16-17 microns
Emulsion, JP-5-water (1000 ppm)
Local velocity, 3.4 fpm
Temperature, 76°F
Film No. 4
Flow direction, page bottom to top

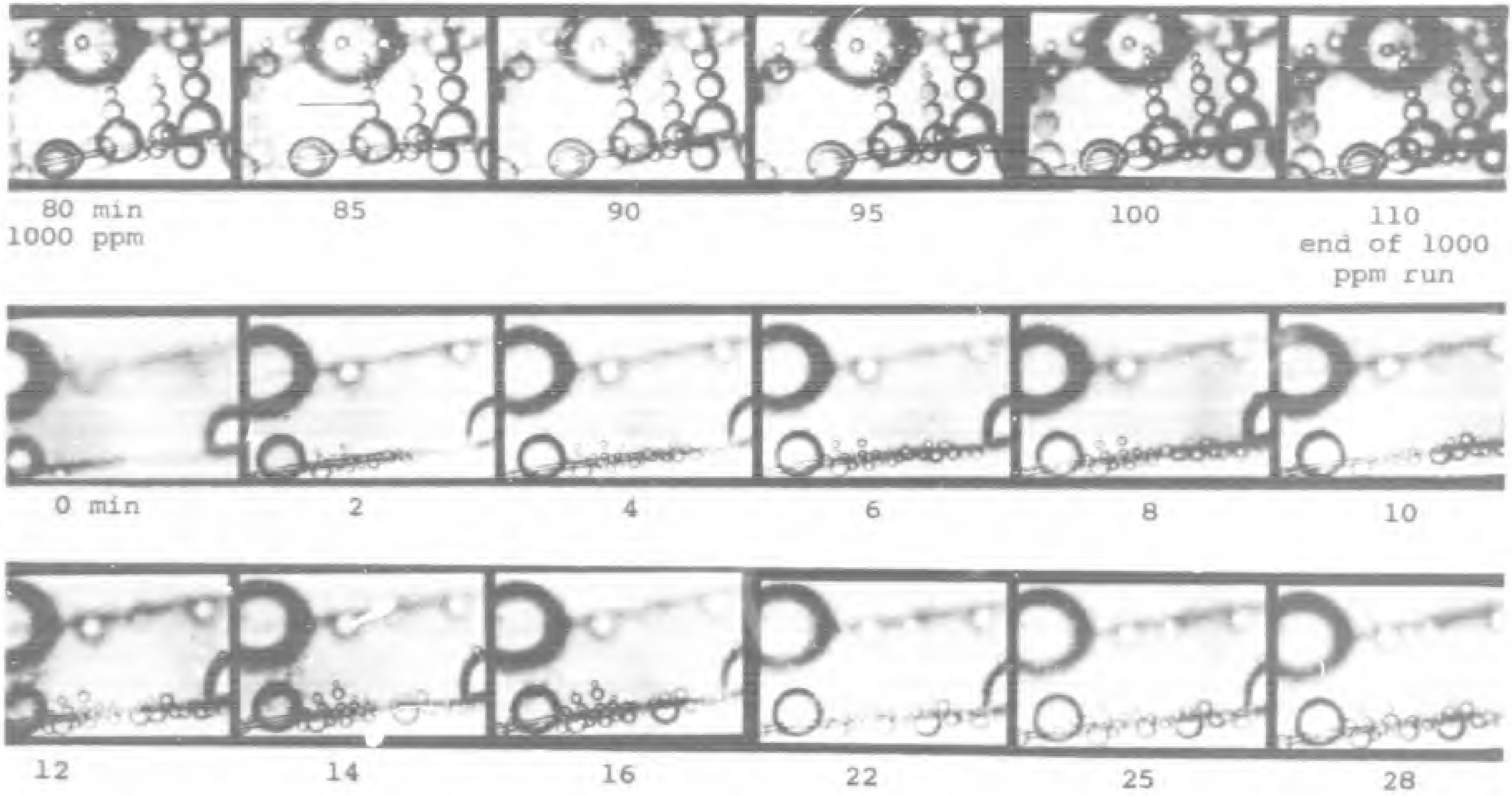


Figure 25

DROP COALESCENCE ON A NYLON FIBER

Fiber diameter, 16-17 microns
Emulsion, JP-5-water (500 ppm)
Local velocity, 3.4 fpm
Temperature, 76°F
Film No. 5
Flow direction, page bottom to top

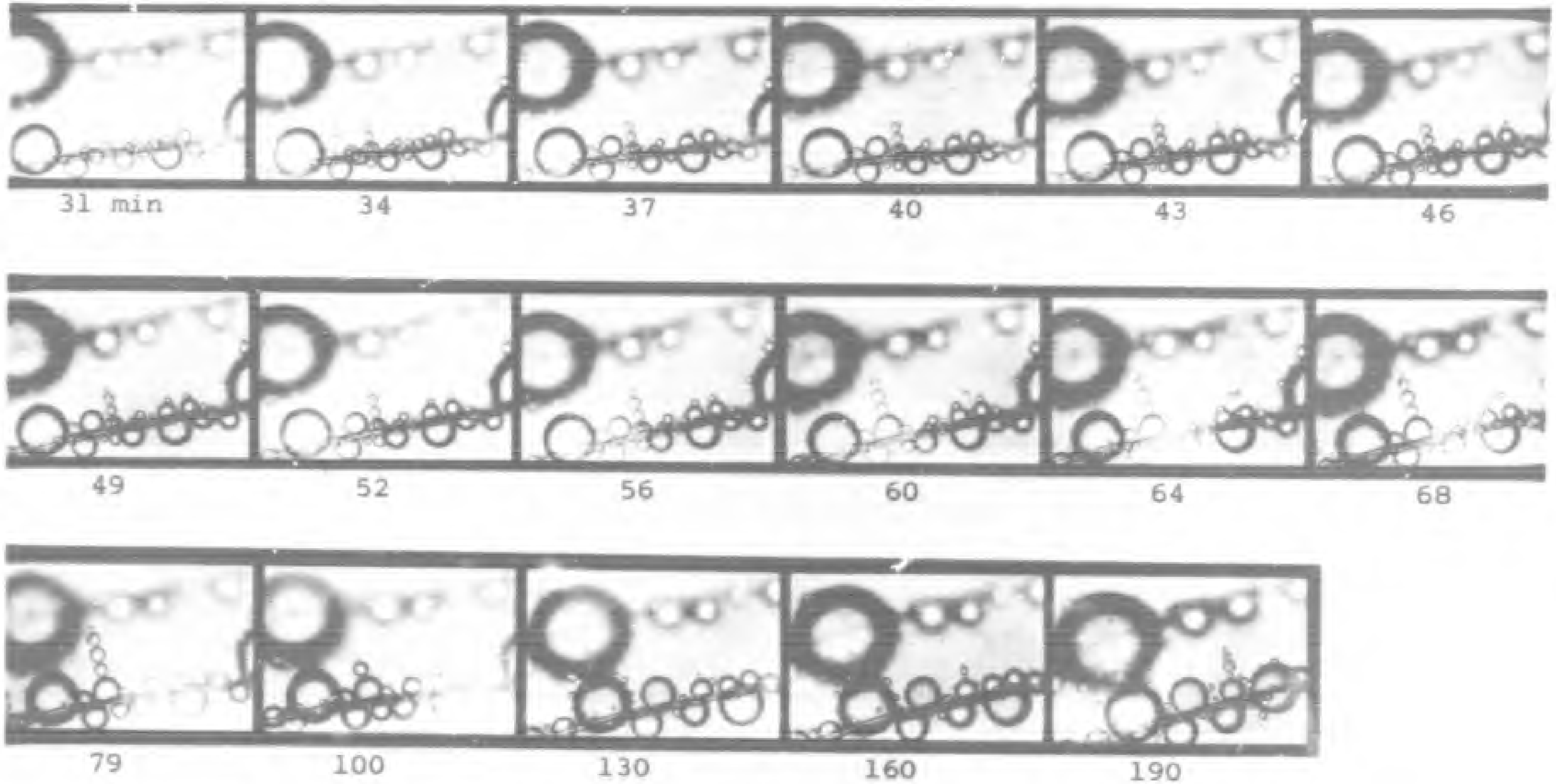


Figure 26

DROP COALESCENCE ON A NYLON FIBER

Fiber diameter, 16-17 microns
Emulsion, JP-5-water (500 ppm)
Local velocity, 3.4 fpm
Temperature, 76°F
Film No. 6
Flow direction, page bottom to top

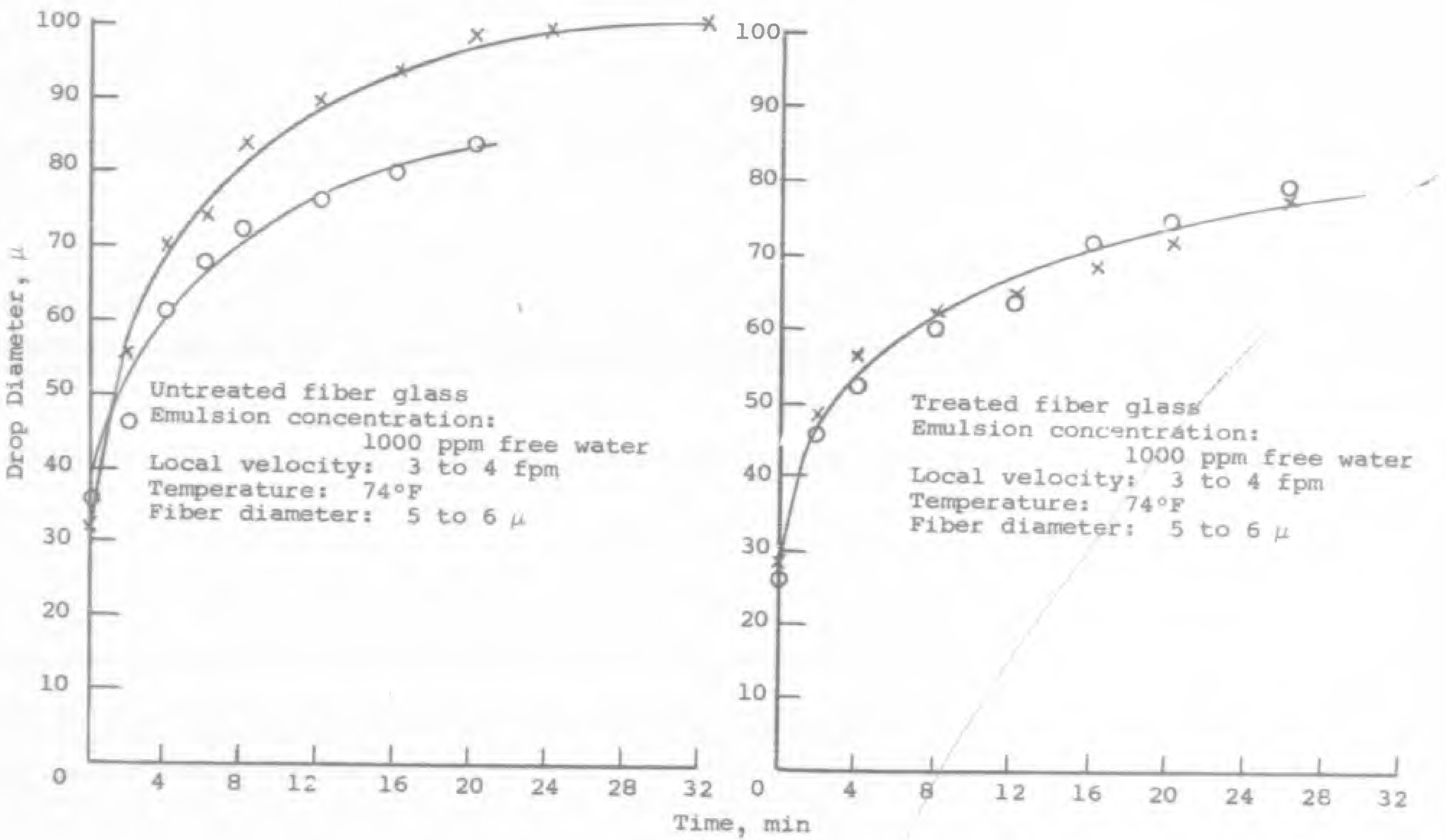


Figure 27

GROWTH RATE OF WATFR DROPS ON GLASS FIBERS IN JP-5 FUEL

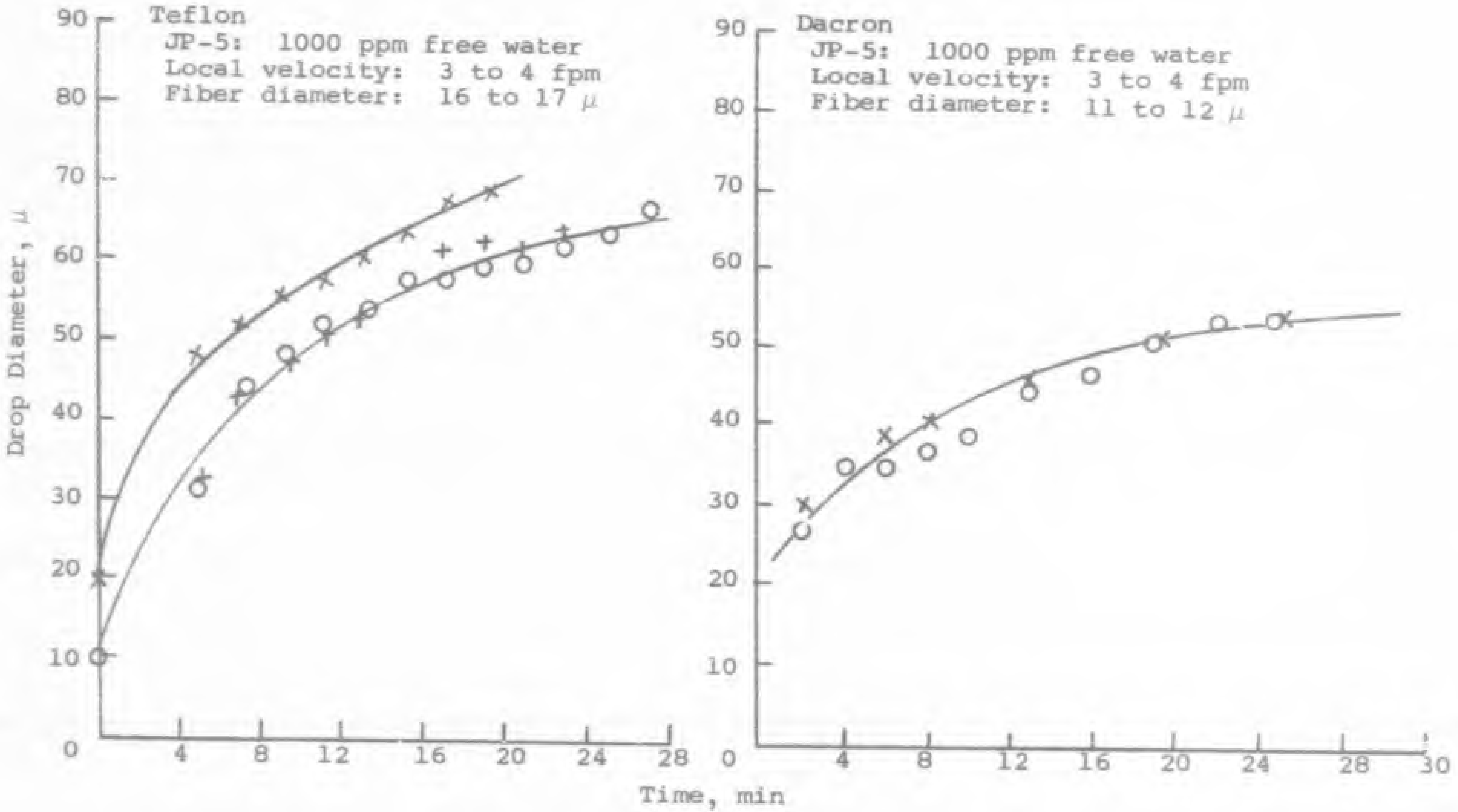


Figure 28

GROWTH RATE OF WATER DROPS ON PLASTIC FIBERS IN JP-5 FUEL

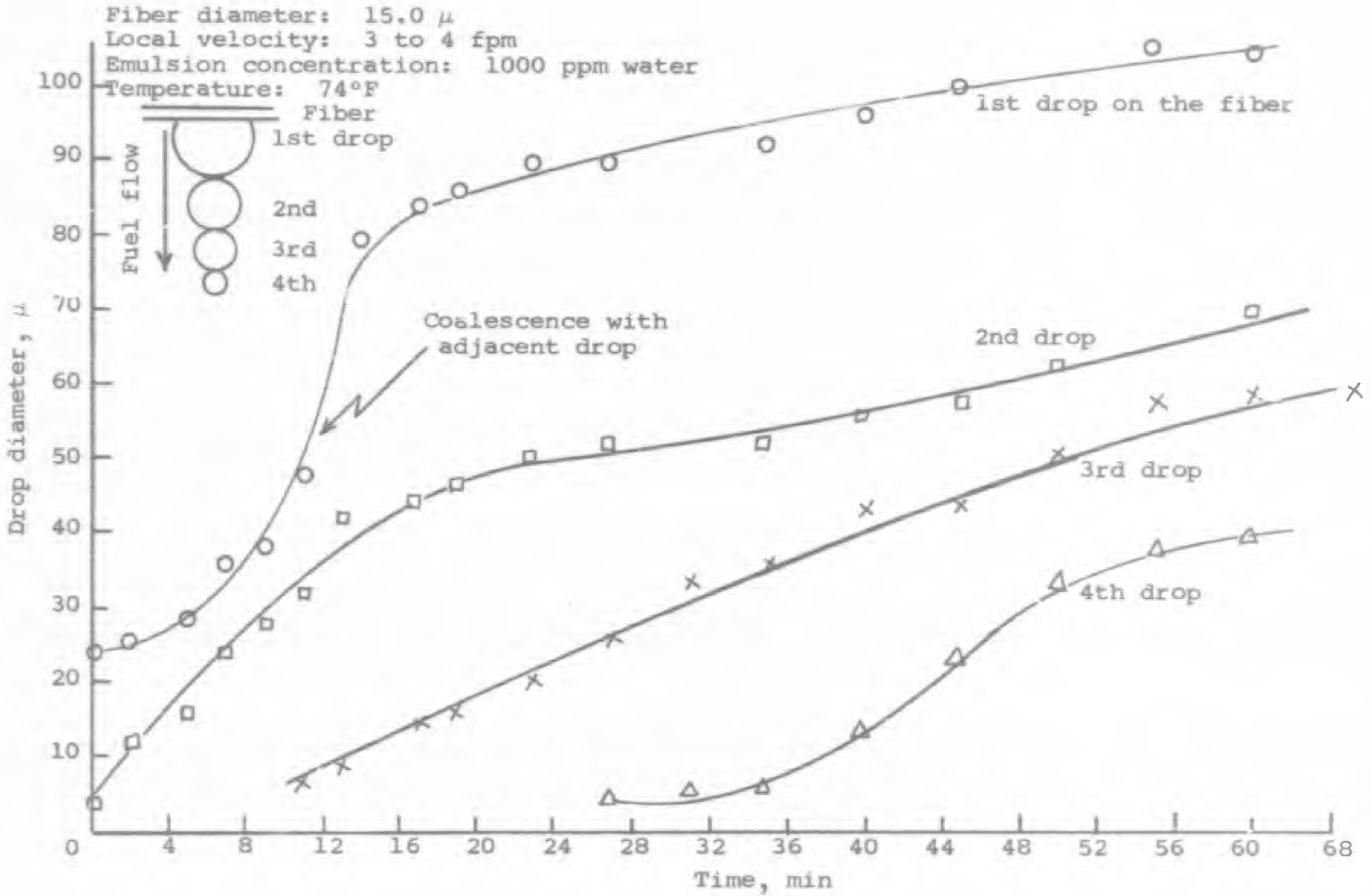


Figure 29

GROWTH RATES OF WATER DROPS ON A NYLON FIBER IN JP-5 FUEL

After studying the photographs and the droplet growth rate curves, it is obvious that considerable time could be spent interpreting the accumulated data. For instance, by knowing the water droplet size distribution of the emulsion, the approximate droplet-capturing efficiency of the single fiber can be calculated. However, because of the time limitations due to the many other studies in this program, our analysis of the results is limited. The major observations in this study are as follows:

(1) With treated fiber glass in a 1000-ppm free water emulsion, there appeared to be a minimum velocity below which there is little or no coalescence.

(2) On single fibers, the drops appeared to grow by acquiring free water from the main stream rather than from the surface of the fiber.

(3) The coalescence of adjacent drops on single fibers was a very slow process and often required as much as 30 min to occur. This was especially true on plastic fibers such as nylon where adjacent drops could sit for several hours and still not coalesce.

(4) Water drops could be made to coalesce and grow on hydrophobic fibers such as Teflon.

(5) The growth rate comparison based on the observed results was as follows: glass fibers have the fastest initial growth rate, followed by Teflon, nylon, then Dacron.

(6) The maximum-size drop that could be held by a single fiber at a local flow rate of 3 to 4 fpm varied considerably among the fibers.

    (a) Drops with a diameter greater than 65 to 75 μ could not be held by the Teflon fiber.

    (b) Drops on treated and untreated fiber glass could grow to sizes as large as 400 to 500 μ.

(c) Drops on the Dacron fiber grew to 60 μ. They were not released; however, they appeared to stop growing.

(d) With nylon fiber there was considerable chain formation. The drop next to the fiber grew to 100 μ. After 2 hr there was no noticeable release of the chains from the fibers.

Of all the fibers studied, it is evident that the glass fibers appeared to be best suited for use in a F/S. Water droplets on glass fibers had the fastest initial growth rate, and they also grew to sizes that are necessary for a successful F/S operation. The 75- to 100-μ size droplets grown on the plastic fibers are too small for successful removal in a fuel system. However, one must be careful in speculating how a single fiber will behave in a packed bed where conditions are very different. The present study did not include determining the effects of fiber diameters, fiber orientation, or the effects of adjacent fibers. There is no doubt that this area of research could be extended considerably, especially attempts to correlate coalescence on single fiber and in packed beds.

a. Droplet Chain Formation

Undoubtedly the most surprising observation in the single-fiber study was the formation of droplet chains on the nylon fiber. It also appeared that the drops had a tendency to form chains on other types of fibers; however, this was considerably less than with the nylon fibers. This chain formation is illustrated in Figures 25 and 30.

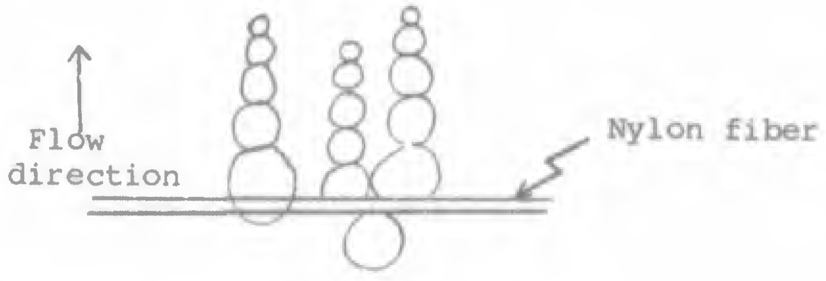


Figure 30

FORMATION OF DROPLET CHAINS ON NYLON FIBERS

It appeared that there was partial coalescence at the junction of the droplets; however, this condition did not change for at least 2 hr, which was the total experimental period. This condition probably could have existed much longer. The cause of the chain formation is unknown. It is probably caused by electrostatic forces.

b. Effects of Sodium Sulfonate

During preliminary experiments with photographing droplet growth or coalescence on plastic fibers, a brief study was made of the effects of 5 ppm of sodium sulfonate on coalescence. JP-5 emulsions that were used contained 100 and 1000 ppm of free water. Observations made during this study were as follows:

(1) A JP-5 100-ppm free water emulsion containing 5 ppm sodium sulfonate that was aged overnight would not coalesce or form droplets upon Dacron, nylon, or Teflon fibers.

(2) After replacing the emulsion above with a similar JP-5 emulsion containing no sodium sulfonate, the droplets coalesced readily on the three plastic fibers.

(3) When a flowing JP-5 1000-ppm free-water emulsion was used, large droplets were formed on Dacron, nylon, and Teflon fibers. The addition of 5 ppm of sodium sulfonate to the system caused the droplet growth to stop. Over a 20-min period, all the small drops were released from the fibers. Also, most of the big drops were gone from the Teflon fibers. All signs of chain formation on the nylon fibers were gone.

On the basis of these results, it is evident that considerable information can be gained from single-fiber studies by using additive-containing fuels. This could also include the effects of physical variables such as velocity, temperature, time, and concentration. Considerations of these experiments have been delayed until work has been completed on fiber bed studies.

2. Coalescence in Fiber Beds

Before discussing the results obtained with coalescence in fiber beds, it is necessary to caution the reader about interpreting or using the data presented. This study was done primarily to investigate the coalescence phenomena and not to gather data for designing a F/S. Before data can be used for such purposes, it is necessary to make coalescence experiments over longer time periods and to also use fuel with additives. Another problem is how to extrapolate or design a packed fiber bed layer in a F/S cartridge that would simulate the small fiber pad in the experimental coalescer cell. There is no doubt that the data presented indicate how the design of a coalescer cartridge should proceed. However, much more data are needed. One of the future goals of this program is to acquire such information.

Because of the large number of experiments that were performed, a list (Table 8) has been prepared that includes all of the experiments. This list also shows the order in which the data are presented in this report. It also reveals the tremendous amount of work that is necessary to characterize a certain type of fiber in a packed bed coalescer. The possible combinations of bed depth, bed density, fiber diameter, type of fiber, fuel flow rate and free water concentration are very large. This does not include fuel properties, additive effects, temperature, aging and nonuniform bed densities. One may consider other variables, however in this study the main variables are bed depth, bed density, type of fiber, fuel flow rate and free water concentration.

a. Treated Fiber Glass

A series of experiments were conducted in which JP-5 water emulsions were coalesced in treated but unbonded fiber glass beds. The treated glass fiber was similar to the material used in the Water Separometer. It is composed of 4- to 5-μ glass fibers purchased from the American Air Filter Company, trade number 50FG.

The experiments consisted of coalescing 0.1, 1.0, and 3.0-vol. % free water-JP-5 emulsions in 1/16-, 1/8-, and 1/4-in. glass fiber beds. For each bed thickness, three densities of 6, 10, and 14 lb/cu ft were used in the tests. The total time of each run varied from 15 min to 1 hr. Results of the work are summarized in Figures 31, 32, and 33 and Tables 9 through 11.

The main observations made during this study are:

(1) The 1/16-in. bed is very sensitive to an increased flow rate, but it is affected only slightly by a change in the bed density or free water concentration.

Table 8

COMPLETED COALESCENCE EXPERIMENTS

Temperature: 68 to 72°F
Flow rates: 2, 4, 6 ft/min

Material	Bed Depth, in.	Bed Density, lb/cu ft	Fuel-Water Emulsion, Vol. % water	Comments
Treated fiber glass, 4 to 5 μ diameter	0.062	6, 10, 14	0.1, 1.0, 3.0	
	0.125	6, 10, 14	0.1, 1.0, 3.0	
	0.250	6, 10, 14	0.1, 1.0, 3.0	
Untreated fiber glass	0.125	14	0.1, 1.0, 3.0	6-7 μ diameter
	0.125	14	0.1, 1.0, 3.0	.75-.49 μ diameter
Commercial unit	-	9.5 to 15.0	0.1	Effects of various layer were determined
Teflon felt, 16 to 17 μ	0.50	55.0	0.1, 1.0, 3.0	
Nylon fiber, 16 to 17 μ	0.125	14.0	0.1	
	0.50	14.0	0.1, 1.0, 3.0	
Dacron fiber, 11 to 12 μ	0.50	14.0	0.1, 1.0, 3.0	
Dacron felt, 20-μ fiber	0.125	24.7	0.10	
	0.186	24.7	0.10	
	0.25	24.7	0.10	
	0.50	24.7	0.10	
Cotton, 9 to 11 μ	0.125	10.0	0.10	
	0.250	10.0	0.10	
	0.50	10, 14, 20	0.10, 1.0, 3.0	

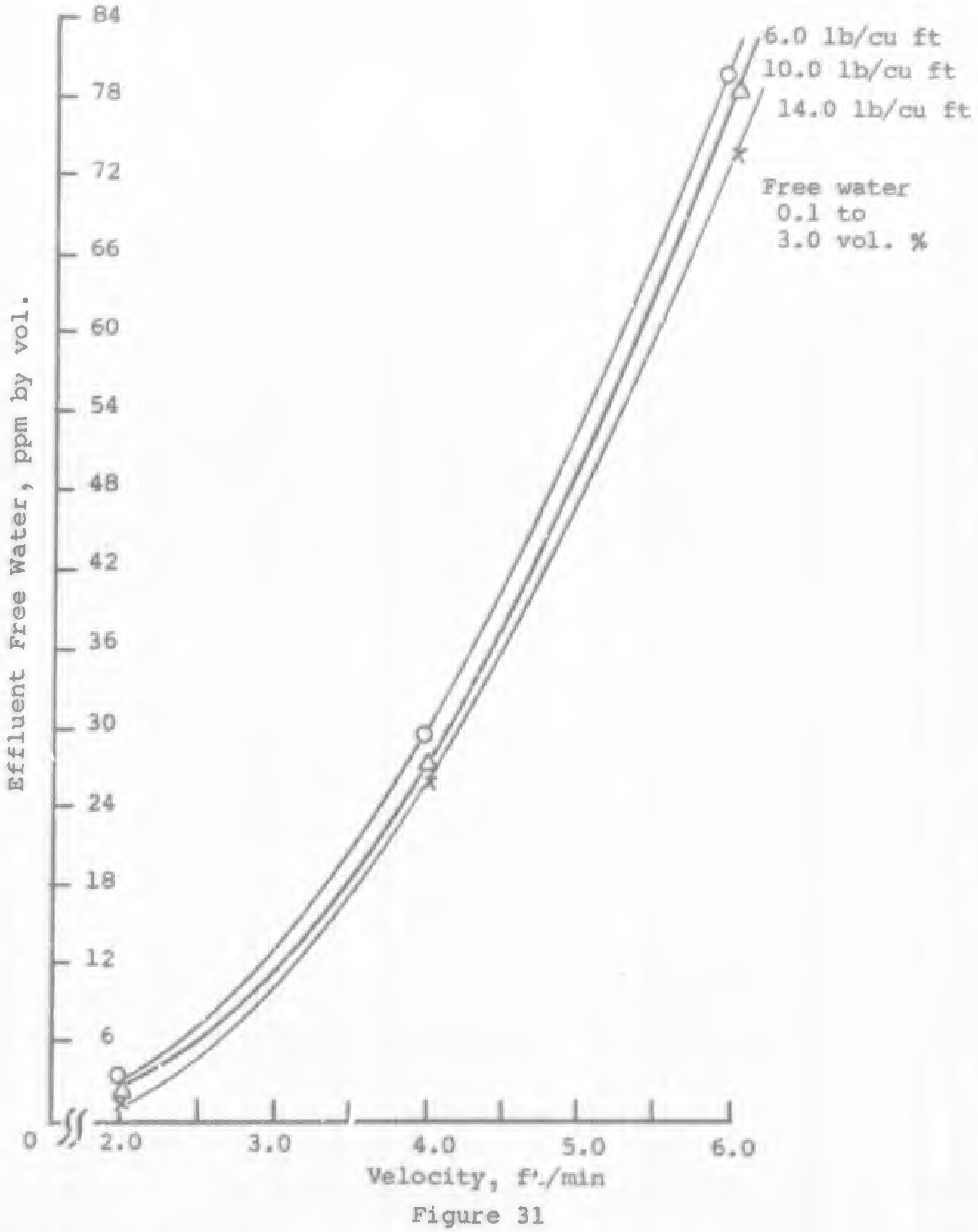


Figure 31

COALESCENCE OF FREE WATER FROM JP-5
USING A 1/16-IN.-THICK TREATED FIBER GLASS BED

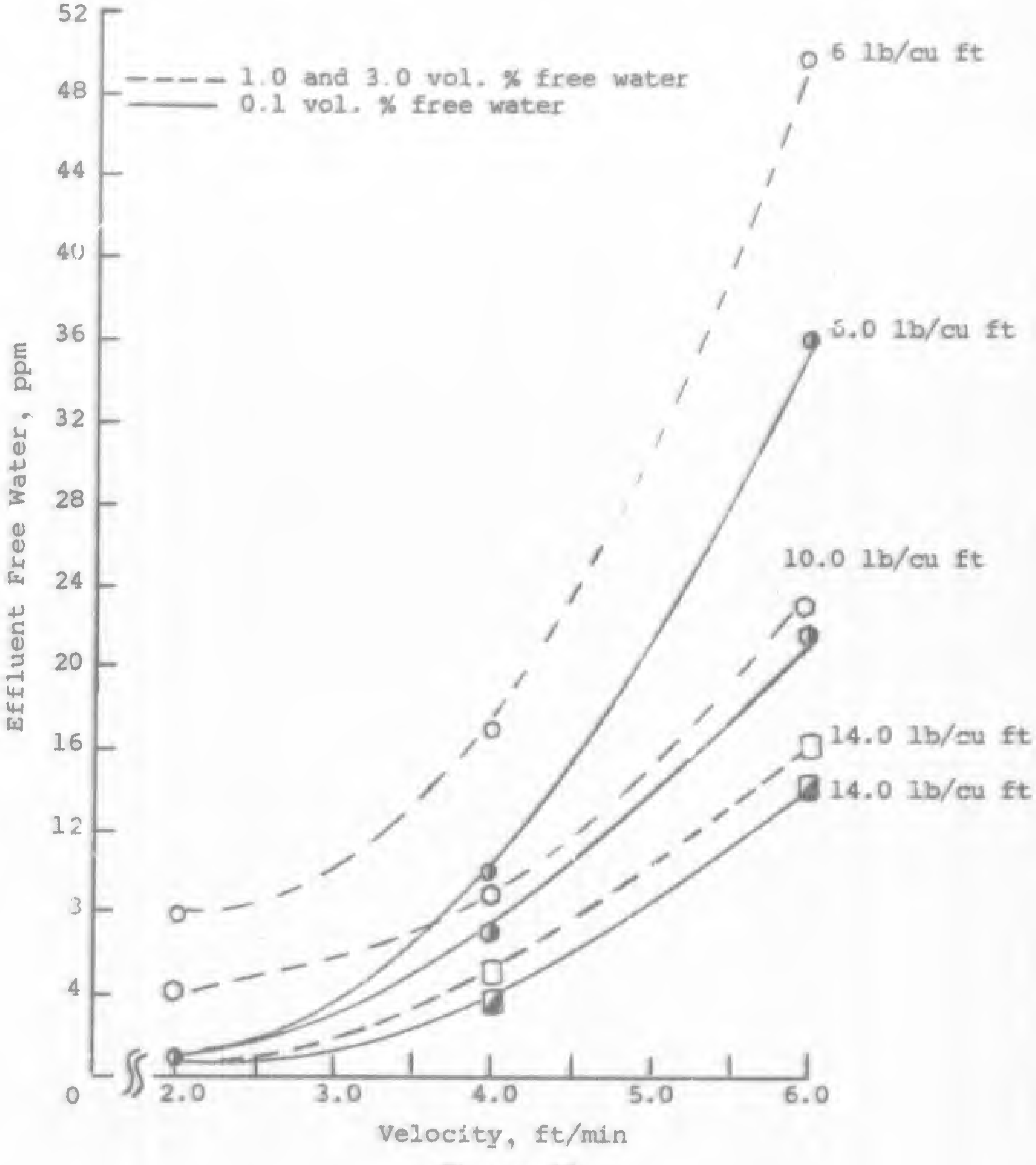


Figure 32

COALESCENCE OF FREE WATER FROM JP-5
USING A 1/8-IN.-THICK TREATED FIBER GLASS BED

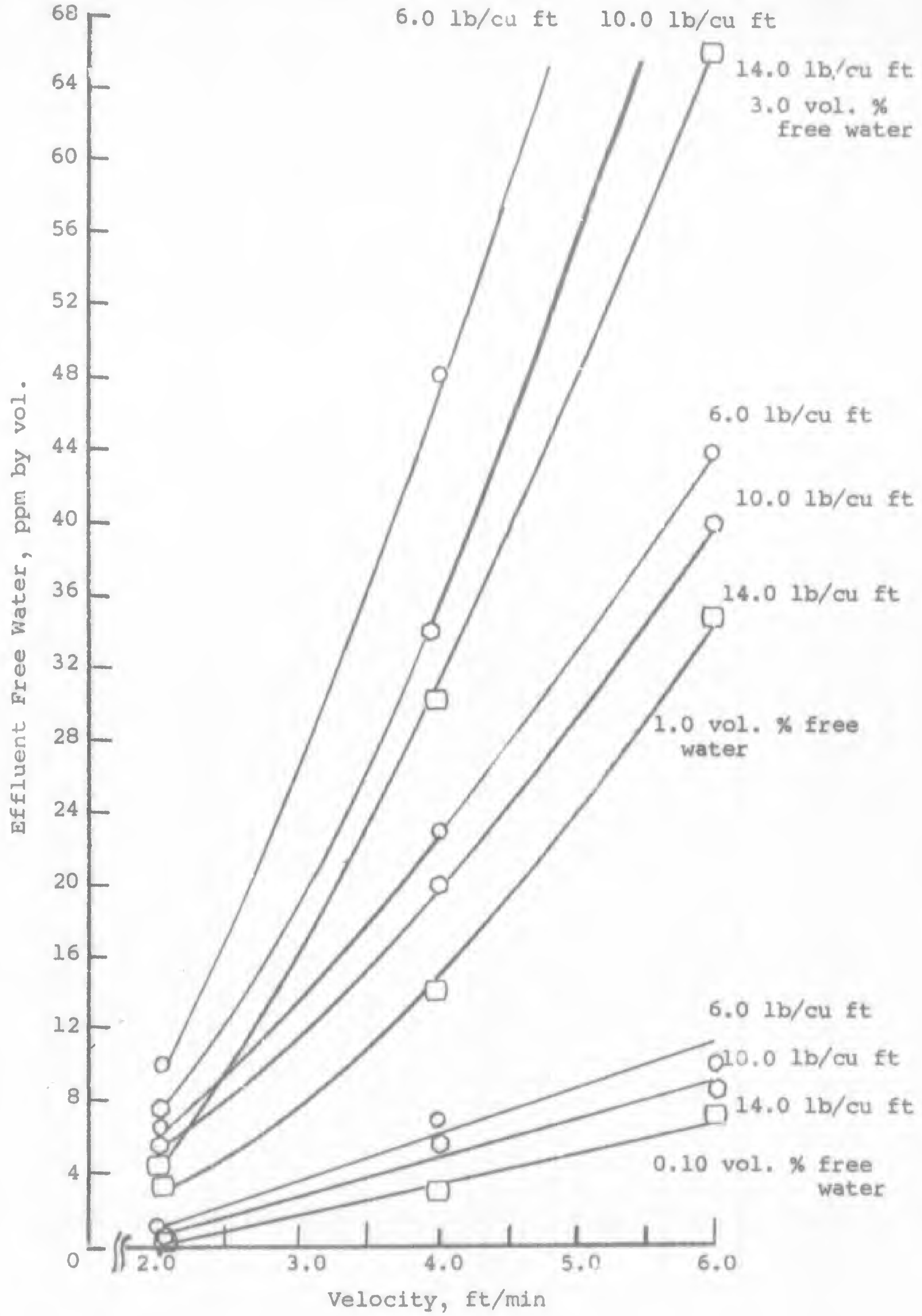


Figure 33

COALESCENCE OF FREE WATER FROM JP-5
USING A 1/4-IN.-THICK TREATED FIBER GLASS BED

Table 9

COALESCENCE OF WATER FROM JP-5 FUEL USING A 1/16-IN.-THICK TREATED FIBER GLASS BED
(Temperature: 70 to 72°F)

Inlet Free Water, vol. %	Bed Density, lb/cu ft	Fuel Velocity,[a] ft/min	Pressure Drop, psi	Effluent Free Water, ppm by vol.	Total Run Time, min
0.1	6	2	2.3-2.5	1.5	20
		4	3.7-4.3	30	18
		6	5.4-5.5	80	11
0.1	10	2	2.8-3.2	2	18
		4	5.5-6.2	28	30
		6	7.0-7.5	80	13
0.1	14	2	3.8-4.0	1	25
		4	9.8-10.2	28	13
		6	11.9-12.2	70	9
1.0	6	2	2.7-2.8	3.5	20
		4	4.4-4.4	31	17
		6	5.3-5.5	81	13
1.0	10	2	3.4-3.5	4	15
		4	6.1-6.2	28	21
		6	7.6-7.8	78	23
1.0	14	2	4.9-5.1	2	21
		4	8.3-8.8	30	27
		6	9.8-9.9	72	9
3.0	6	2	2.7-3.0	2.5	15
		4	4.3-4.5	28	15
		6	5.3-5.5	84	13
3.0	10	2	3.7-3.7	4	18
		4	5.5-6.1	28	21
		6	7.4-7.8	78	19
3.0	14	2	4.7-5.0	3	15
		4	8.2-8.7	28	17
		6	11.0-11.2	80	14

[a] Linear velocity through supporting screen with area of 51% openings.

Table 10

COALESCENCE OF WATER FROM JP-5 FUEL USING A 1/8-IN.-THICK TREATED FIBER GLASS BED
(Temperature: 70 to 72°F)

Inlet Free Water, vol. %	Bed Density, lb/cu ft	Fuel Velocity,[a] ft/min	Pressure Drop, psi	Effluent Free Water, ppm by vol.	Total Run Time, min
0.10	6.0	2	3.0-3.4	1	18
		4	6.3-7.4	10	18
		6	9.7-10.2	36	13
0.10	10.0	2	3.9-4.2	1	13
		4	7.0-7.3	7	11
		6	9.8-10.2	22	8
0.10	14.0	2	5.3-5.6	1	26
		4	10.2-11.3	3.5	15
		6	13.8-14.1	14	12
1.0	6.0	2	3.7-3.8	9	14
		4	6.8-7.8	17	12
		6	9.5-9.9	50	10
1.0	10.0	2	4.9-5.4	5	18
		4	11.2-11.4	9	12
		6	15.1-15.3	22	18
1.0	14.0	2	6.11-6.4	1	18
		4	10.0-10.9	5	15
		6	14.0-14.5	16	11
3.0	6.0	2	3.5-3.8	10	11
		4	8.0-8.2	18	9
		6	10.3-10.6	52	9
3.0	10.0	2	5.5-6.1	3.5	14
		4	12.9-13.1	8	12
		6	17.9-18.0	22	8
3.0	14.0	2	6.3-6.7	1	19
		4	11.2-11.9	5	12
		6	16.8-17.0	14	11

[a] Linear velocity through supporting screen having 51% openings.

Table 11

COALESCENCE OF WATER FROM JP-5 FUEL USING A 1/4-IN.-THICK TREATED FIBER GLASS BED

(Temperature: 70 to 72°F)

Inlet Free Water, vol. %	Bed Density, lb/cu ft	Fuel Velocity,[a] ft/min	Pressure Drop, psi	Effluent Free Water, ppm by vol.	Total Run Time, min
0.1	6.3	2	1.0-1.4	0	34
		4	4.0-5.0	7	21
		6	7.5-8.5	10	15
0.1	10.0	2	3.0-4.4	1	26
		4	8.0-9.8	6	16
		6	13.2-15.2	9	14
0.1	14.1	2	6.8-7.3	0.5	24
		4	14.0-14.2	2.5	15
		6	19.4-20.6	7.5	11
1.0	6.3	2	2.2-2.5	6	15
		4	6.5-7.4	23	16
		6	12.0-12.0	44	17
1.0	10.0	2	4.0-4.2	6	19
		4	14.0-14.0	20	16
		6	22.1-24.5	40	18
1.0	14.1	2	9.0-9.1	2.5	7
		4	18.3-19.7	14	12
		6	26.2-26.3	35	10
3.0	6.3	2	3.2-3.4	10	12
		4	6.0-6.2	48	12
3.0	10.0	2	6.0-6.3	7	16
		4	19.5-20.8	34	11
		6	26.5-26.5	95	6
3.0	14.1	2	10.1-10.6	3.5	24
		4	21.0-22.0	30	15
		6	27.0-27.9	66	11

[a] Linear velocity through supporting screen with area of 51% openings.

(2) An increase in bed thickness to 1/8 or 1/4 in. showed that the higher-density bed was definitely a better coalescer than the lower-density bed.

(3) The effect of bed density is more apparent with a high-free-water (3.0 vol. %) emulsion than with a low-free-water emulsion (0.1 vol. %).

(4) Overall coalescence performance appears to go through a maximum. A 1/8-in.-thick bed appears to be considerably better than a 1/16- or 1/4-in. bed; this pertains to a uniform fiber glass bed with a flow rate of 2 to 6 ft/min.

(5) A flow rate of approximately 2 ft/min appears to be a critical value; above this, an increase in velocity results in a substantial increase in effluent free water.

A study of these observations reveals that they are in agreement with published results. Sareen and others (ref. IV-29) and Voyutskii (ref. IV-31) have indicated that the coalescence occurs mainly inside the fibrous bed. They also showed that for each system there is a critical velocity above which the emulsion or partially coalesced drops begin to pass rather than the dispersion medium alone. Sareen also showed that for a given type of fiber bed, there is an optimum bed depth to be used if complete separation is desired. This observation was also noted in our study.

In these experiments, the maximum fuel velocity at which the effluent free water concentration was below 5 ppm (ref. VII-7) was approximately 3 ft/min. This observation pertains solely to the system and to the conditions used in these experiments. It is very probable that this velocity may be increased with the use of a different type of fiber bed.

Although an increase in bed density resulted in better coalescence, the change also resulted in an undesirable increase in pressure drop. In a 1/8-in.-thick bed (Table 10) with a 14 lb/cu ft density, the pressure drop ranged from 7 to 17.0 psi for velocities of 2 to 6 ft/min, respectively. This was for an inlet free water content of 3.0 vol. % in the fuel.

One noticeable observation in Tables 9 through 11 is that during each run, the pressure drop stayed rather constant. The small change indicates that the system reached an equilibrium fairly rapidly. It is difficult to tell what might have happened if the runs had been prolonged for several hours. The fuels used contained no additives, and hence the results might have been the same. Future work with fuel containing various types of additives will help clarify this question.

b. Untreated Fiber Glass

A series of experiments were made by using untreated fiber glass. The purpose of this work was to compare its coalescing properties with treated fiber glass and also to investigate the effects of changing the fiber diameter. By using untreated fiber glass beds with a 6 to 7 μ fiber diameter and a 0.5 to 0.8 μ diameter fiber, experiments were performed that were similar to those done with treated fiber glass. However, work was done only with 1/8-in.-thick beds with a density of 14.0 lb/cu ft.

Experimental results (Figure 34 and Table 12) show that there was little difference between the coalescing properties of treated or untreated fiber glass. The coalescence performance of the untreated fiber glass may have been slightly less than that of the treated fiber glass. However, the fiber diameter of the untreated fiber was slightly greater than that of the treated fiber. This similarity in coalescence was also observed in the single-fiber study. There, the droplet growth rates were approximately the same. Also, both types of single fibers held drops that grew to sizes of several hundred microns. It should be pointed out, however, that all of these studies were made with additive-free fuel. The presence of additives may have produced different results.

The effects of changing the fiber diameter is shown rather vividly in Figure 34. This is not an unexpected observation, since the effect of decreasing the fiber diameter is a well-known fact. The patent literature is one source where this fact is very evident. Voyutskii (ref. IV-31) claimed that in a packed bed the most important factor is not the distance between the fibers but the internal surface of the filter. The filtration or coalescence is accomplished not by mechanical removal of the disperse phase, but by the adsorption and adherence of the water droplets to the surface of the fiber. It appears that this work is in agreement with this theory. It can be stated that the small-diameter fiber bed should give better mechanical filtration and hence possibly a better coalescence

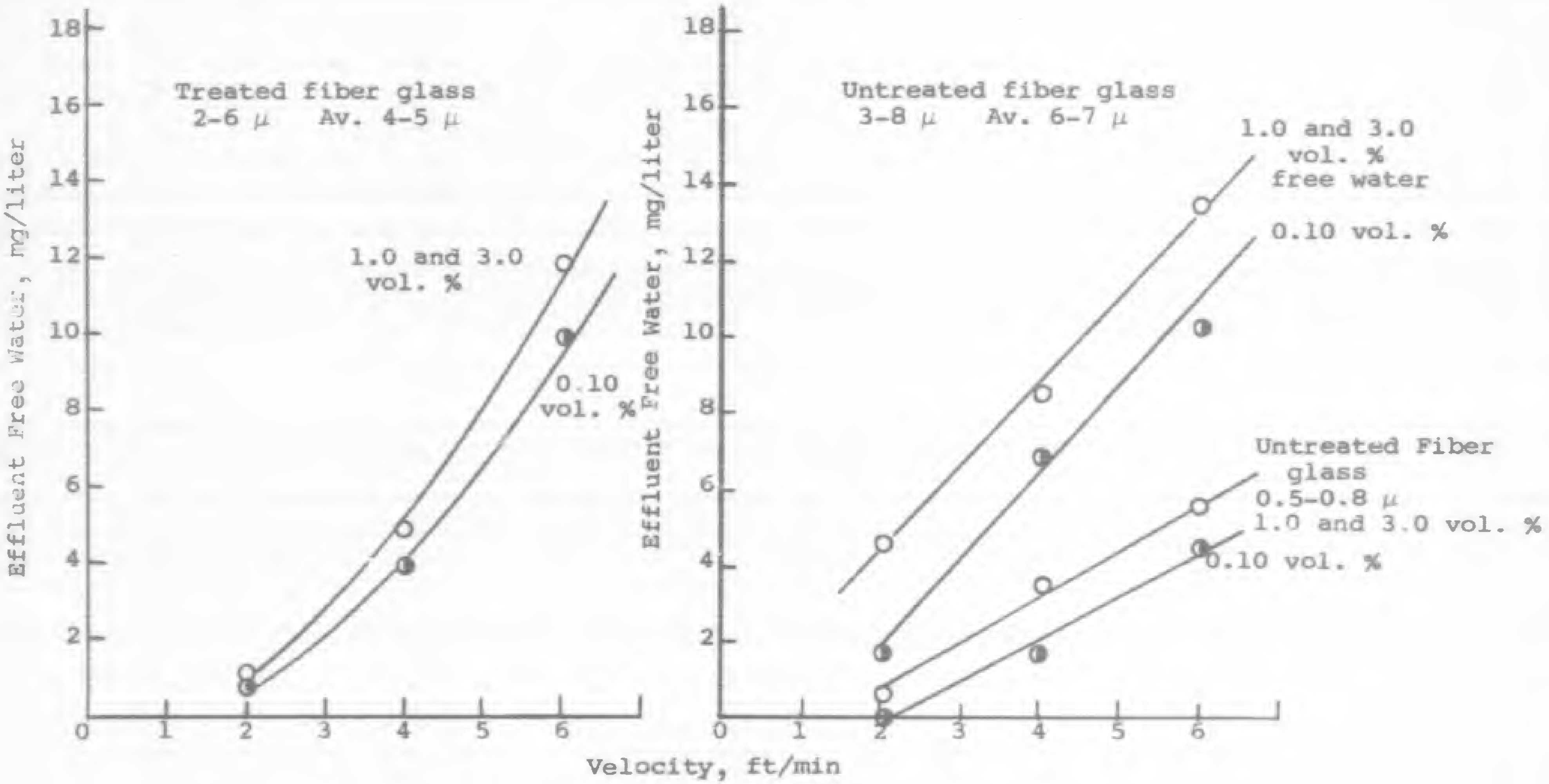


Figure 34

COALESCENCE OF FREE WATER FROM JP-5 FUEL USING A 1/8-IN.-THICK FIBER GLASS BED
(Bed density: 14.0 lb/cu ft
Temperature: 66 to 70°F
Water pH: 6.0)

Table 12

COALESCENCE OF WATER FROM JP-5 FUEL USING A 1/8-IN.-THICK UNTREATED FIBER GLASS BED

Temperature: 66 to 70°F
Bed density: 14.0 lb/cu ft

Fibers, μ	Inlet Free Water, vol. %	Fuel Velocity,[a] ft/min	Pressure Drop, psi	Effluent Free Water, ppm by vol.	Total Run Time, min
3-8	0.10	2	1.8-2.3	1.8	60
		4	2.9-3.0	7.0	30
		6	3.4-3.4	10.2	20
3-8	1.0	2	2.3-2.4	4.5	60
		4	3.3-3.4	8.5	30
		6	4.0-4.3	13.5	22
3-8	3.0	2	7.5-7.6	5.0	30
		4	3.8-3.8	8.5	19
		6	4.4-4.5	13.5	16
0.49-0.75	0.10	2	4.2-5.4	0	60
		4	9.1-10.4	1.7	28
		6	13.4-13.8	4.5	23
0.49-0.75	1.0	2	5.8-6.3	0.8	30
		4	11.4-11.6	3.4	28
		6	15.8-15.9	5.5	20
0.49-0.75	3.0	2	6.9-7.0	0.8	30
		4	14.3-14.4	3.6	20
		6	19.5-19.5	5.1	20

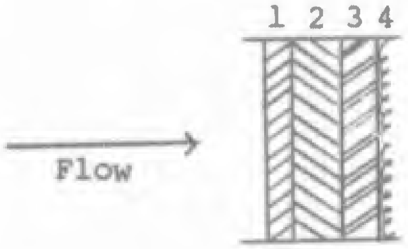
[a] Linear velocity through supporting screen having 51% openings.

performance. However, the single-fiber studies showed that coalescence can occur without mechanical filtration. Also, in the treated fiber glass experiments, the use of a 1/4-in. bed with a 14.0 lb/cu ft density resulted in unsatisfactory coalescence. The pressure drops in the 1/4-in. bed and in the 1/8 in. untreated fine fiber glass bed were similar.

Although the use of the smaller-diameter fiber resulted in a substantial increase in coalescence efficiency, it also resulted in an increase in pressure drop. There is no doubt that the most of the pressure drops observed in this study were too great for practical application in a F/S cartridge. This is also one of the reasons why it is difficult to design a F/S cartridge that operates at a linear velocity greater than 2 ft/min.

c. Commercial Test Filter

A commercial bonded fiber glass F/S was disassembled, and sections of the layers in the element were placed in the coalescer cell in the same order as they were in the original element. However, the inner dirt filtering layer was not used in the test. Figure 35 shows the arrangement.



1. 1st coalescer, 0.11 in., 15.0 lb/cu ft
2. 2nd coalescer, 0.19 in., 12.7 lb/cu ft
3. Separator, 0.14 in., 9.5 lb/cu ft
4. Cotton sock

Figure 35

CONSTRUCTION OF COMMERCIAL BONDED FIBER GLASS ELEMENT

In this first evaluation, a 1000-ppm free water JP-5 fuel emulsion was used in all tests. The tests consisted of taking out various sections of the fiber glass layers and determining the effect of their removal upon coalescence of the emulsion. Compression of the fiber glass layers was kept constant by replacing the thickness of the removed sections with polyethylene gaskets.

Results of the test (Figure 36) show that the removal of various sections greatly effected coalescence. The most critical layer is the first, high-density (15.0 lb/cu ft) coalescer layer

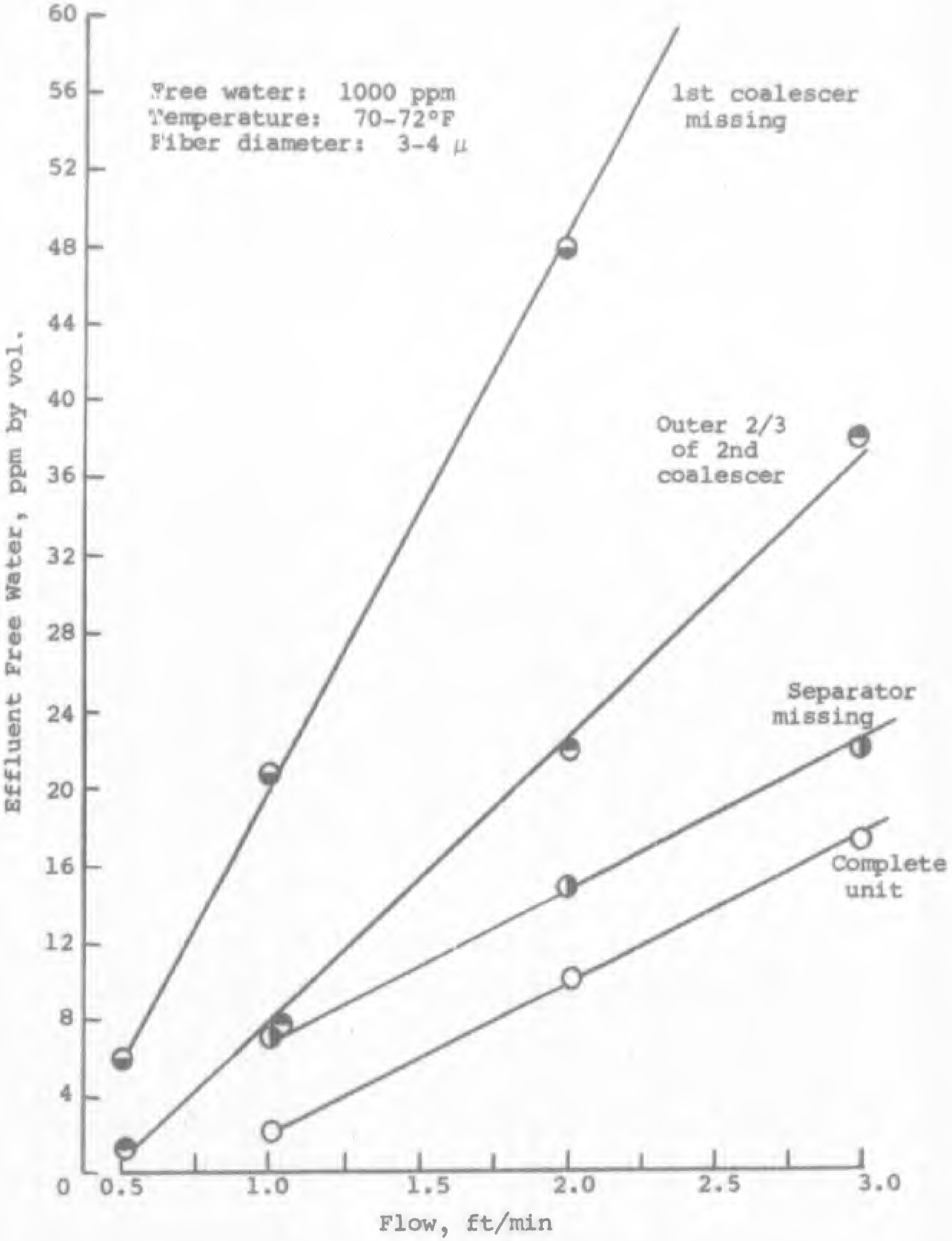


Figure 36

COALESCENCE OF FREE WATER FROM JP-5 FUEL USING A COMMERCIAL F/S and is followed by the second, lower-density (12.7 lb/cu ft) coalescer layer. A missing separator layer resulted in an increase of 5 ppm of effluent free water.

The construction of the F/S element is interesting for two reasons. First, the coalesced droplets are led through a glass fiber matrix that has a decreasing density (increasing pore size). Second, the densities of the glass fiber layers are considerably greater than the value of 6 to 8 lb/cu ft which is considered by many to be the average for F/S.

A comparison of the coalescence performance between this commercial filter and the 1/8-in. thick treated fiber glass bed shows that the 1/8-in. bed is the best coalescer (Figures 32 and 36). Reasons for this difference were not apparent until a microscopic examination was made of the various layers in the commercial element. This investigation showed that all of the coalescer and separator layers were made from the same type of fiber. However, the density of each layer was varied by regulating the amount of bonding resin and also by the compression used during the curing of the fiber glass layer. The diameter of the glass fiber in the commercial unit was 3 to 4 μ, which is slightly smaller than the 4 to 5 μ-diameter fibers in the 1/8-in.-thick bed. However, the effective diameter of the glass fibers in the commercial unit is not known. Many of the fibers were covered with resin modules; some were cemented together in the form of a parallel fiber bundle; and others formed part of a random cluster of fibers. There is no doubt that the effect of resin bonding is to decrease the overall coalescing performance of the fiber glass layer.

The actual performance of the commercial unit (Table 13) is undoubtedly better than that indicated in this study. In the complete unit, the inner ribbed dirt filtering layer consists of bonded glass fibers with an 8 to 9-μ-diameter glass fiber. The density of this bed is approximately 14.0 lb/cu ft. There is no doubt that this layer aids the coalescence operation.

This brief study has shown how considerable information can be obtained by taking a commercial F/S element and studying its construction. A much broader study of the various types of cartridges presently used in the field would reveal considerably more information. The literature contains essentially no data of this type. The patent literature also contains surprisingly little information. The accumulated information could then be compared with the large amount of published data obtained during the testing of such a unit. It appears that most government reports deal with evaluating a coalescing fuel system by using commercial elements. As far as we know, none of them pertains to work of the type done in this report.

Table 13

COALESCENCE OF FREE WATER FROM JP-5 FUEL USING A COMMERCIAL F/S

Temperature: 68 to 70°F
Emulsion: 0.10 vol. % water
Fiber diameter: 3 to 4 μ

	Flow Rate, ft/min	Pressure Drop, psi	Effluent Free Water, ppm by vol.	Total Run Time, min
Complete Unit - no dirt filter	1.0	1.8-2.1	2	42
	2.0	4.0-4.0	10	17
	3.0	6.0-6.1	17	11
Separator layer missing	1.0	2.0-2.2	7.0	38
	2.0	4.1-4.3	15	23
	3.0	6.0-6.0	22	15
1st coalescer layer missing	0.5	-	6	5
	1.0	1.2-1.2	21	12
	2.0	2.9-3.2	48	8
	3.0	3.1-3.2	130	12
Outer 1/3 of 2nd coalescer layer missing	0.5	0	1	-
	1.0	1.0-1.2	7	26
	2.0	2.8-3.2	22	15
	3.0	4.0-4.1	38	10
Outer 2/3 of 2nd coalescer layer missing	1.0	1.3-1.3	7	16
	2.0	2.9-3.0	19	10
	3.0	3.9-4.1	38	13
2nd coalescer layer missing	1.0	1.20-1.4	7	25
	2.0	2.5-2.8	20	11
	3.0	3.0-3.2	104	14

d. Plastic Fiber Beds

A series of experiments were conducted in which various types of plastic fiber beds were used to coalesce free water from JP-5 fuel. Experimental beds were made from loose fibers by first mixing a fiber-water slurry in a Waring Blender and then filtering the fibers onto a filter paper. After drying the fibers, circular pads were stamped out with the use of a cutter punch. This punch was also used to cut out pads from the felt materials. Results are the coalescence experiments are given in Figures 37, 38, and 39 and Tables 14 and 15.

Although considerable information has been obtained about the use of plastic fiber beds as free water coalescers, it is difficult to compare their performance with that of the fiber glass beds or even with each other. The main problem is the large difference in the fiber diameters. In this study, the glass fiber diameters ranged from 0.5 to 8 μ, and the plastic fiber diameters ranged from 11 to 20 μ. Also, except for the Dacron felt study, all of the work was done with the use of 1/2-in.-thick beds. A summary of the experiments with the plastic fibers follows.

(1) Teflon Felt

Experiments (Table 14 and Figure 37) have shown that free water can be successfully coalesced from JP-5 fuel with the use of Teflon felt beds. This was done by using a high-density (55.0 lb/cu ft) 1/2-in.-thick bed made from fibers with a diameter of 16 to 17 μ. The coalescence performance was very sensitive to flow rate, and it depreciated very rapidly at flow rates greater than 2 ft/min. However, the study did show that at velocities of 2 ft/min, successful coalescence could be maintained for long periods (2 hr). This and the pressure drop data indicated that the bed had reached an equilibrium that was maintained for a long period. It was necessary to make a long run in order to eliminate the possibility that coalescence was taking place by sheer mechanical filtration. This mechanism would result in a water loading of the bed, and it would not be detected in a short run.

Table 14 shows that at velocities greater than 4 ft/min, the pressure drops were very excessive (20 to 30 psi). What effect this large pressure drop has on coalescence is unknown. In fact, many more experiments would have to be performed before one can get a good evaluation of the coalescing ability of a Teflon fiber bed. This includes the study of bed depth, bed density, and fiber diameter.

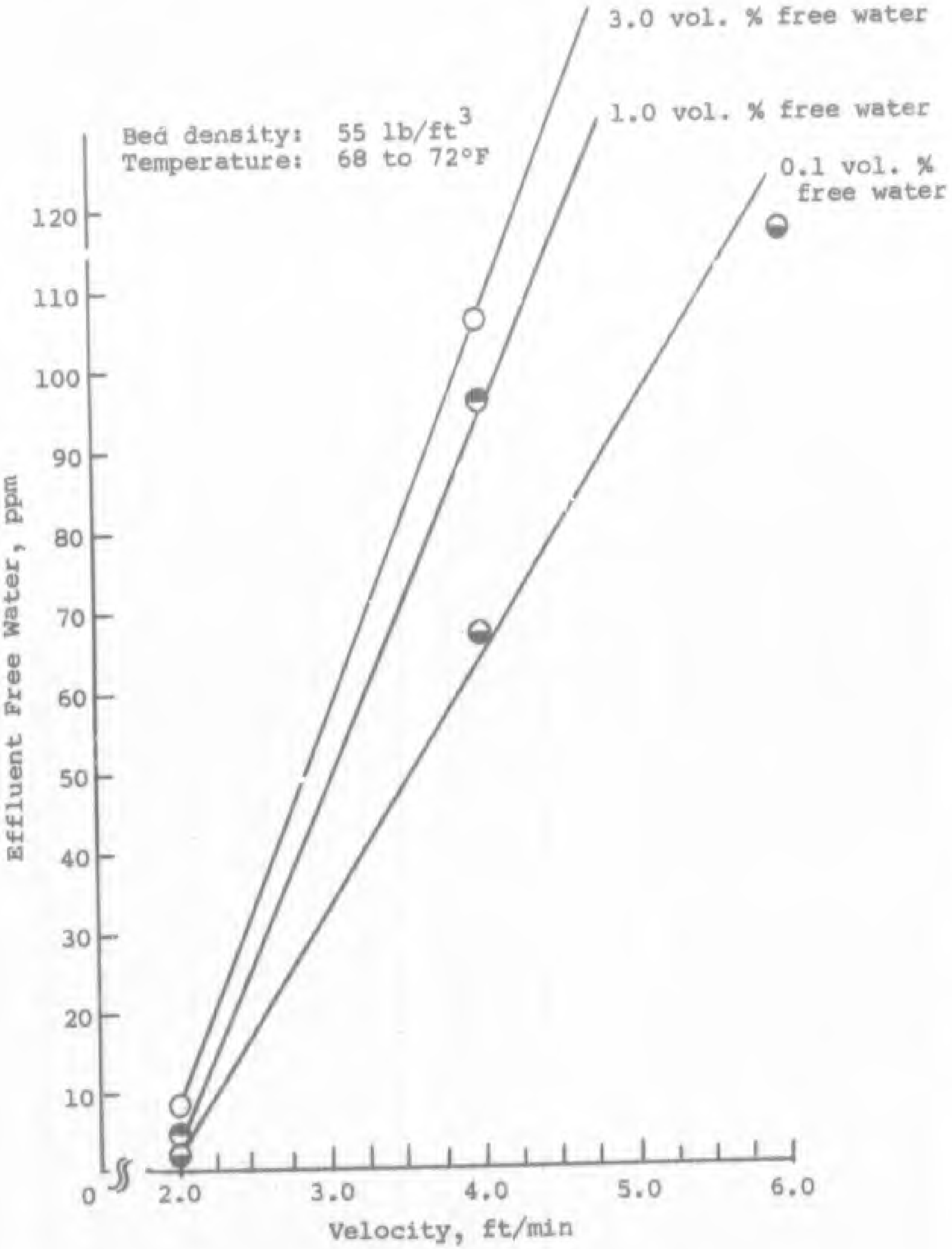


Figure 37

COALESCENCE OF FREE WATER FROM JP-5 FUEL USING A 1/2-IN.-THICK TEFLON FELT BED

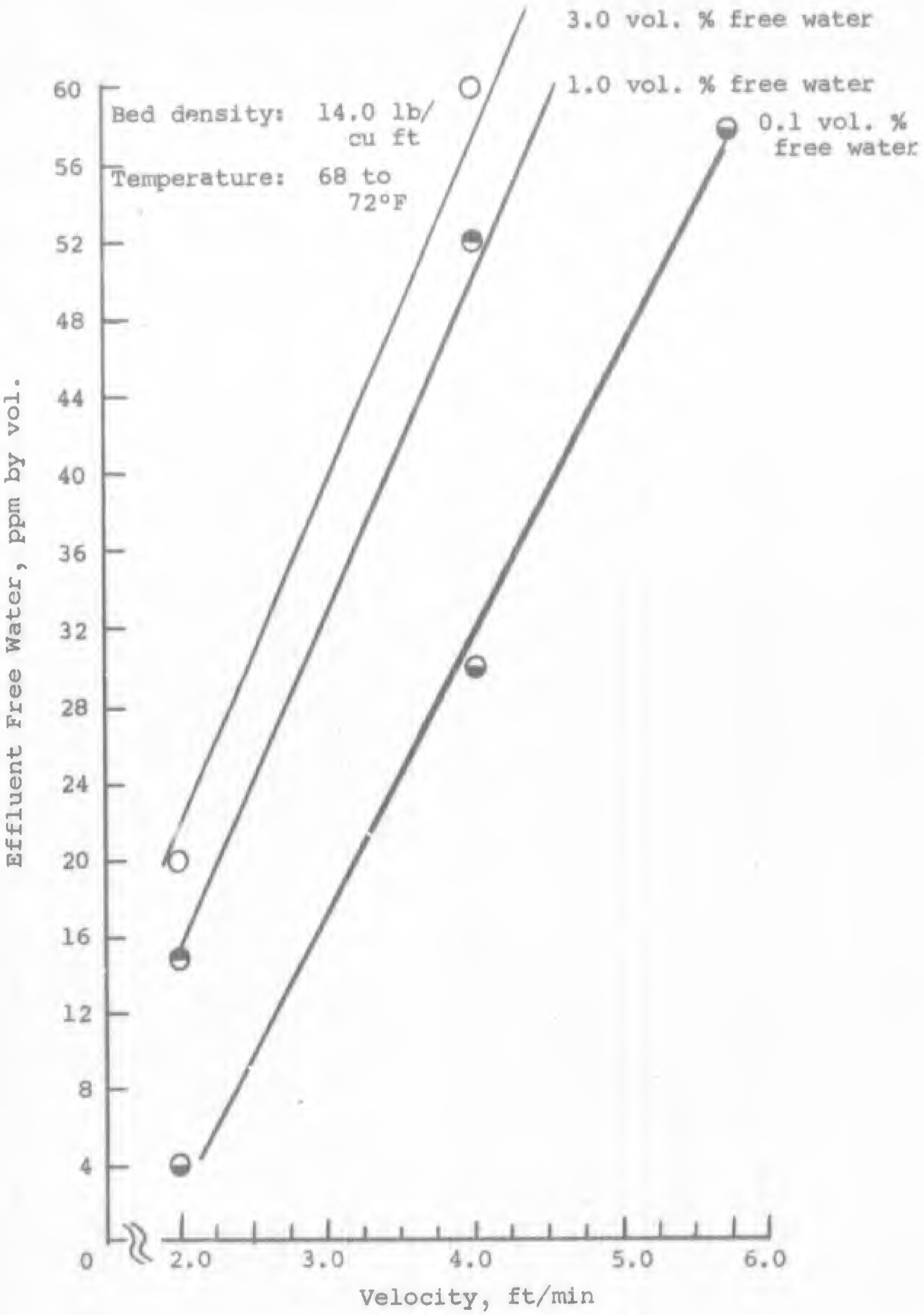


Figure 38

COALESCENCE OF FREE WATER FROM JP-5 FUEL USING A 1/2-IN.-THICK NYLON FIBER BED

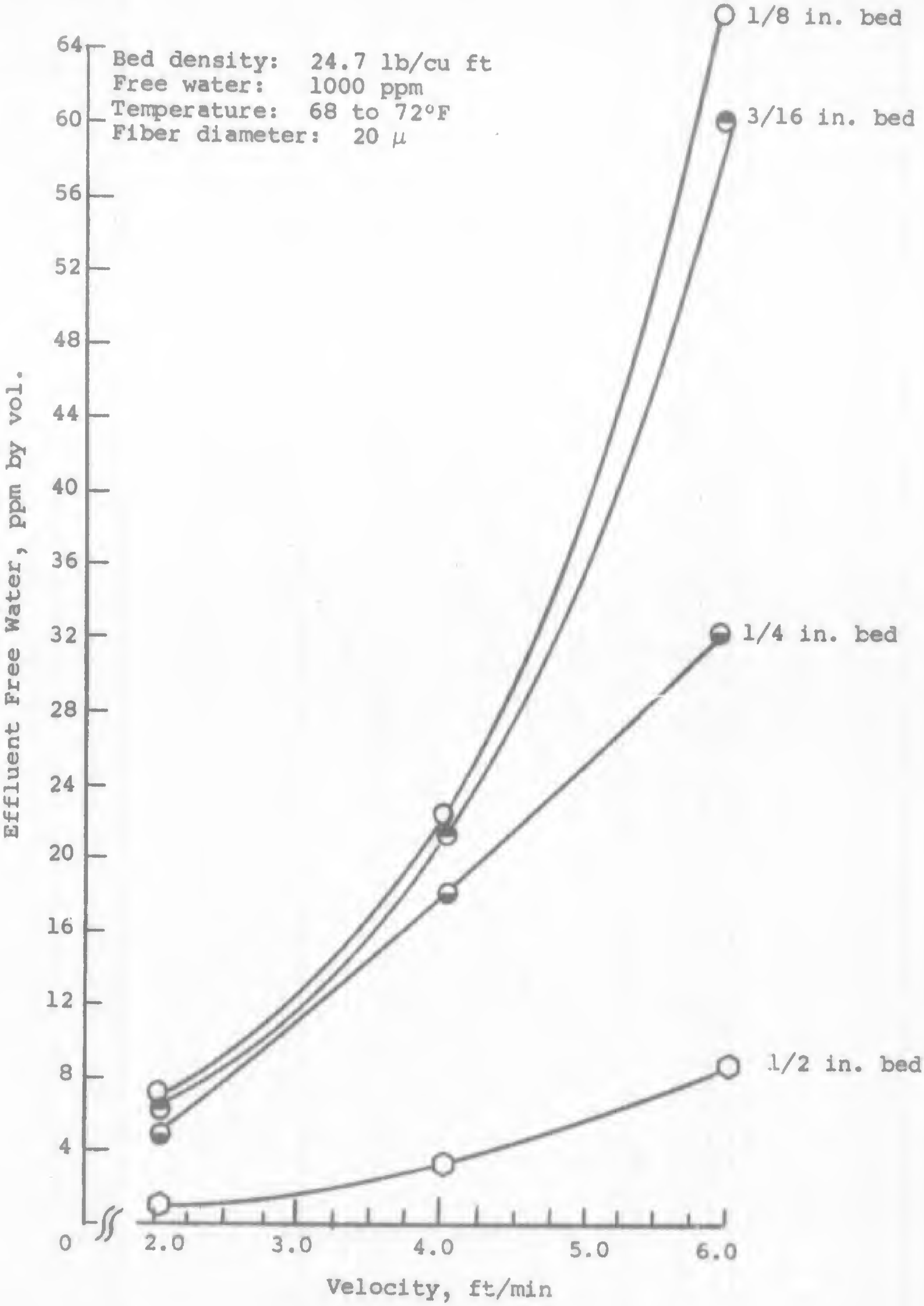


Figure 39

COALESCENCE OF FREE WATER FROM JP-5 FUEL
USING DACRON FELT BEDS

Table 14

COALESCENCE OF JP-5 WATER EMULSIONS USING 1/2-IN.-THICK NYLON OR TEFLON BEDS

(Temperature: 68 to 72°F)

Material	Inlet Free Water, vol. %	Velocity,[a] ft/min	Pressure Drop, psi	Effluent Free Water, ppm by vol.	Total Run Time, min
Nylon fiber,[b] bed density 14.0 lb/cu ft	0.10	2	2.1-2.5	4.0	62
		4	3.3-3.5	30	26
		6	4.5-4.4	58	25
Nylon fiber,[b] bed density 14.0 lb/cu ft	1.0	2	2.7-3.0	15	22
		4	3.9-4.0	52	25
		6	4.8-4.9	78	18
Nylon fiber,[b] bed density 14.0 lb/cu ft	3.0	2	3.0-3.1	20	17
		4	4.3-4.4	60	22
		6	4.8-5.0	80	17
Teflon felt,[c] bed density 55.0 lb/cu ft	0.10	2	7.6-9.6	1.8	118
		4	20.0-23.0	66	24
		6	28.0-30.0	115	15
Teflon felt,[c] bed density 55.0 lb/cu ft	1.0	2	9.8-11.1	3.4	71
		4	23.5-25.0	96	25
Teflon felt,[c] bed density 55.0 lb/cu ft	3.0	2	10.7-10.8	8.5	30
		4	25.0-25.4	105	27

[a] Linear velocity through supporting screen with 51% openings.

[b] Fiber diameter 16 to 17 μ.

[c] Fiber diameter 16 to 17 μ.

Table 15

COALESCENCE OF JP-5 WATER EMULSIONS USING DACRON FIBER AND DACRON FELT BEDS

(Temperature: 68 to 72°F)

Material	Bed Thickness, in.	Velocity,[a] ft/min	Inlet Free Water, vol. %	Pressure Drop, psi	Effluent Free Water, ppm by vol.	Total Run Time, min
Dacron felt,[b] bed density 24.7 lb/cu ft	0.125	2	0.10	2.0-2.1	6.8	25
		4	0.10	2.8-3.1	22	22
		6	0.10	3.6-3.7	66	18
Dacron felt,[b] bed density 24.7 lb/cu ft	0.187	2	0.10	2.3-2.8	6.8	35
		4	0.10	3.7-3.8	22	18
		6	0.10	4.4-4.7	60	17
Dacron felt,[b] bed density 24.7 lb/cu ft	0.25	2	0.10	2.5-3.1	5.1	27
		4	0.10	4.0-4.1	18	20
		6	0.10	4.8-4.9	32	20
Dacron felt,[b] bed density 24.7 lb/cu ft	0.50	2	0.10	2.8-3.1	0.8	45
		4	0.10	4.7-4.9	3.4	24
		6	0.10	5.8-6.1	8.5	21
Dacron fiber[c] bed, bed density 14.0 lb/cu ft	0.50	2	0.10	2.1-2.7	3.4	60
		4	0.10	3.1-3.2	12	30
		6	0.10	4.1-4.3	14	21
Dacron fiber[c] bed, bed density 14.0 lb/cu ft	0.50	2	1.0	2.9-2.9	5.4	24
		4	1.0	3.9-4.1	12	21
		6	1.0	4.9-5.0	14	15
Dacron fiber[c] bed, bed density 14.0 lb/cu ft	0.50	2	3.0	2.9-3.1	5.4	26
		4	3.0	4.5-4.6	10	20
		6	3.0	5.2-5.4	14	15

[a] Linear velocity through supporting bed screen with 51% openings.

[b] Made with 20 μ-diameter fibers.

[c] Fiber diameter is 11 to 12 μ.

(2) Nylon Fiber

Results (Figure 38 and Table 14) obtained with Nylon fiber were somewhat similar to those obtained with the Teflon fiber bed. An increase in fuel velocity resulted in a rapid decrease in coalescence efficiency. The Teflon bed showed a better coalescence performance at 2 ft/min; however, at higher fuel flow rates, the Nylon bed was the best coalescer. It is very difficult to compare these two fiber beds because of the large difference in bed densities. It is possible that the Teflon bed density is too high for coalescence at the higher flow rates.

In this study, the pressure drops through the fiber beds were fairly low. However, the coalescence performance at 2 ft/min was unsatisfactory. This may have been due to a nonuniform bed or to the large diameter of the fiber. There is no doubt that nylon fiber beds can be used to successfully coalesce free water from fuel. However, much experimentation is needed before the physical nature of a satisfactory coalescence bed can be determined.

(3) Dacron Fiber

Two sets of experiments were made by using Dacron felt pads and loose Dacron fibers. Results of the work (Figure 39 and Table 15) are interesting. Coalescence performance with the Dacron fiber bed was much better than that observed with Teflon or nylon. This was probably due to the small diameter of the fiber. The Dacron fibers have a diameter of 11 to 12 μ, and the nylon and Teflon fibers have a diameter of 16 to 17 μ.

An interesting observation made with the Dacron fiber bed is that the coalescence performance was essentially the same for an inlet free water concentration of 0.1, 1.0, and 3.0 vol. %. Reasons for this performance are not understood.

Work with the Dacron felts showed that by using the proper bed parameters, it is possible to successfully coalesce free water from fuel by using a bed made from Dacron fibers with a 20-μ diameter. Figure 39 shows the effects of increasing the bed depth. These curves show that most of the coalescing is occurring inside the bed rather than at the inlet of the bed. Unfortunately, the work was done only with the use of 0.10 vol. % free water in the fuel.

The pressure drop through the 1/2-in. Dacron felt bed was rather low (2 to 6 psi at 2 to 6 ft/min. This was not unexpected because of the fairly large fiber diameter (20 μ). Actually, the change in pressure drop with the change in bed thickness was far less than the decrease in coalesence because of the decrease in bed thickness.

e. Cotton Fibers

Cellulose fibers is a medium that has been used in commercial F/S for many years. Because most of the more successful F/S units use glass fiber, the use of cellulose as a coalescence medium is decreasing rapidly. In some units it is being used as a dirt-filtering medium rather than a coalescing medium.

Cellulose fiber is a unique material since it has properties that are very different from all other types of fibers. In addition to being extremely hydrophilic, it has the unique property of swelling in the presence of free water. The fiber volume can double itself, forming a complex fiber/liquid interface. In fact, because the water penetrates inside the fibers, the fiber can be considered a membrane rather than an impermeable solid. Because of this property, it is often difficult to apply the same coalescence theory to cellulose media and to other types of media such as glass fibers.

In order to characterize cellulose fibers as a coalescence medium, a series of experiments were made by using cotton fibers rather than paper fibers. Cotton fibers are much longer than the short paper fibers, and hence cotton fiber beds will not disintegrate in the presence of free water. This is the main reason most paper coalescing media are composed of paper fibers with a light application of resin. The experiments in this study consisted of investigating the effects of bed thickness and bed density.

The bed thickness study (Figure 40 and Table 16) showed that the coalescing ability of a 10 lb/cu ft bed is greatly affected by the bed thickness. Figure 40 shows that the use of a 1/2-in.-thick bed resulted in good coalescence, even at a flow of 4.0 ft/min. There is no doubt that an increase in free water concentrate would have resulted in an increase in effluent free water. However, this increase would not have been large. This is indicated in the bed density study. In order to eliminate the possibility that the free water was removed by the adsorption of free water into the cellulose fiber, a 3-1/2-hr run was made in the 1/2-in. bed study. Results of this run did not reveal any differences with the shorter runs.

The pressure drops observed in the bed thickness studies were lower than expected. One of the reasons paper beds in F/S are thin is that water adsorption results in swelling, which causes excessive flow resistance. The 2.0 to 3.7 psi pressure drop range observed in this study is not excessive.

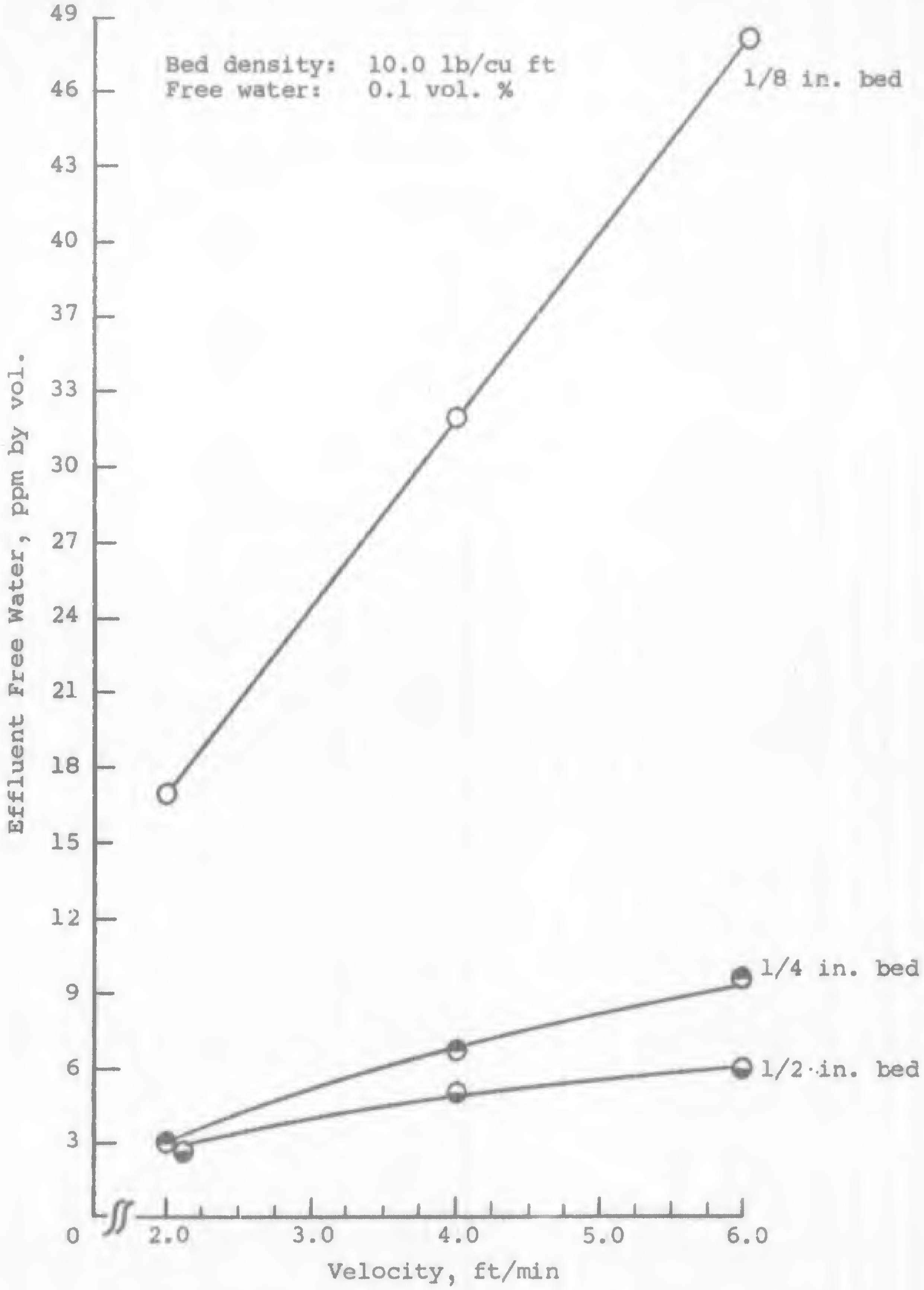


Figure 40

COALESCENCE OF FREE WATER FROM JP-5 FUEL USING VARIOUS THICKNESS COTTON FIBER BEDS

Table 16

COALESCENCE OF FREE WATER FROM JP-5 FUEL USING VARIOUS THICKNESSES OF COTTON FIBER BEDS

Temperature: 68 to 72°F
Bed density: 10.0 lb/cu ft
Fiber diameter: 9 to 11 μ
Inlet free water: 0.10 vol. %

Bed Thickness, in.	Fuel Velocity,[a] ft/min	Pressure Drop, psi	Effluent Free Water, ppm by vol.	Total Run Time, min
1/8	2	2.0-2.1	17	59
1/8	4	2.6-2.6	32	19
1/8	6	3.2-3.3	100	14
1/4	2	2.0-2.0	3	24
1/4	4	2.4-2.8	7	17
1/4	6	2.9-3.0	10	11
1/2	2	2.0-2.4	3	220
1/2	4	3.2-3.3	5	45
1/2	6	3.6-3.7	6	27

[a] Linear velocity through supporting bed screen with 51% openings.

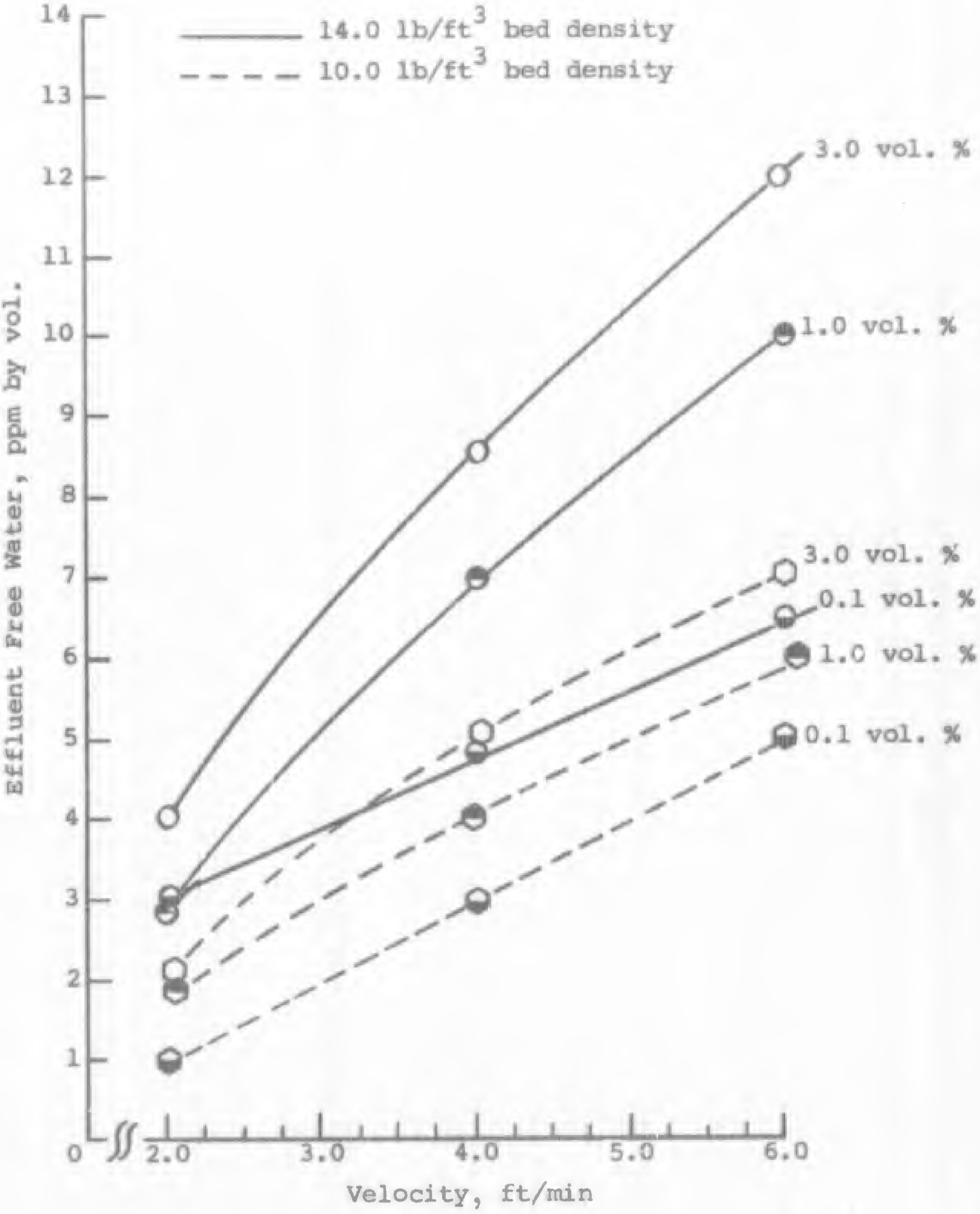


Figure 41

COALESCENCE OF FREE WATER FROM JP-5 FUEL USING
1/2-IN.-THICK COTTON FIBER BEDS

Table 17

COALESCENCE OF FREE WATER FROM JP-5 FUEL USING 1/2-IN.-THICK COTTON FIBER[a] BEDS

(Temperature: 68 to 72°F)

	Fuel Velocity,[b] ft/min	Inlet Free Water, vol. %	Pressure Drop, psi	Effluent Free Water, ppm by vol.	Total Run Time, min
Bed density, 10.0 lb/cu ft	2	0.10	2.0-2.4	3	220
	4		3.2-3.3	5	45
	6		3.6-3.7	6.5	27
Bed density, 10.0 lb/cu ft	2	1.0	2.4-2.5	3	35
	4		3.5-3.5	7	30
	6		3.7-3.8	10	11
Bed density, 10.0 lb/cu ft	2	3.0	2.4-2.7	4	26
	4		3.5-3.6	8.5	21
	6		4.0-4.2	12	11
Bed density, 14.0 lb/cu ft	2	0.10	2.8-2.9	1	30
	4		3.6-3.8	3	60
	6		4.6-4.7	5	24
Bed density, 14.0 lb/cu ft	2	1.0	2.8-3.0	2	27
	4		4.0-4.2	4	25
	6		5.0-5.2	6	18
Bed density, 14.0 lb/cu ft	2	3.0	2.8-3.0	2	30
	4		4.5-4.5	5	15
	6		5.2-5.3	7	15
Bed density, 20.0 lb/cu ft	2	0.10	3.4-4.2	0	67
	4		8.3-8.4	4.5	29
	6		11.0-11.5	8.5	25
Bed density, 20.0 lb/cu ft	2	1.0	4.8-4.9	1	30
	4		8.8-8.9	5.5	25
	6		12.3-12.4	10.5	21
Bed density, 20.0 lb/cu ft	2	3.0	4.7-5.2	2	31
	4		9.1-9.1	6.5	30
	6		12.5-12.6	12.5	20

[a] Fiber diameter 9 to 11 μ.

[b] Linear velocity through supporting bed screen with 51% openings.

The bed density study (Table 17) made with 1/2-in.-thick beds showed that there is a maximum bed density above which coalescence decreases. Figure 41 shows that a 14.0 lb/cu ft bed was definitely a better coalescer than a 10.0 lb/cu ft bed. However, the coalescence efficienty of the 20.0 lb/cu ft bed was similar to that of the 10.0 lb/cu ft bed. These definite differences are shown in this study; however, the amount of effluent free water was fairly small in all studies. A maximum of 12.5 ppm was observed in the effluent from the 20.0 lb/cu ft bed at a fuel velocity of 6.0 ft/min.

The greatest differences in the bed density study were observed in the pressure drop measurements. Pressure drop ranges for the 10, 14, and 20.0 lb/cu ft beds were 2.0 to 4.2, 2.8 to 5.3, and 3.4 to 12.6 psi, respectively. From this it is evident that the pressure drop in the 20.0 lb/cu ft bed had become excessive at the higher flow rates.

VI. CONCLUSIONS

On the basis of the various studies carried out in this program, the following conclusions have been made.

A. Literature Research

The published literature contains little information on the coalescence mechanism of micron-size droplets that are suspended in a fuel flowing through a packed fiber bed.

(1) Much literature is devoted to studying the coalescence of two or more drops in a static system.

(2) Considerable literature deals with studying wetting angles, interface properties, or effects due to additives.

(3) Currently, no accepted theory exists on the mechanism of drop coalescence in a fibrous bed.

(4) The U.S. patent literature contains almost no performance data and only a small amount of design information.

B. Physical Properties of Jet Fuels

The interfacial tension and the electrical conductivity of the fuel vary widely with the type of additive in the fuel. There appears to be no general correlation between these two properties.

(1) Several ppms of Na-Sul EDS or Gulf Agent 178 greatly affect the interfacial tension, but 30 to 40 ppm of Topanol A or Santolene C has little effect on IFT.

(2) Less than 1 ppm of petroleum sulfonate will cause a 100 to 200% increase in fuel conductivity, but 50 to 70 ppm of other additives will cause less than a 100% increase in conductivity.

(3) Petroleum sulfonates have a great effect on fuel conductivity but only a mild effect upon the interfacial tension.

C. Electrokinetics

The electrokinetics of fuel flowing through a fiber bed is a little understood phenomenon that may play a vital role in the coalescence mechanism.

(1) The amount and sign of the current generated in the fiber bed depends upon the type and amount of additive in the fuel.

(2) Additives that have a great effect on fuel conductivity also have a great effect on streaming current generation. This is especially true of sodium sulfonates, which also greatly affect the coalescence operation.

(3) An addition of 20 to 30 ppm of free water to the fuel results in a considerable increase in current generation.

(4) A conductivity of 10^{-13} mhos cm^{-1} seems to be the approximate optimum value for obtaining maximum current generation in a glass fiber bed.

(5) A measurement of the streaming current in a fiber bed is an excellent method for determining changes that would be occurring at the surface of the fiber.

(6) The coalescence mechanism always takes place with electrokinetic changes in the coalescence system.

D. Coalescence Study

A successful coalescence study was conducted by developing analytical techniques and designing coalescence equipment that made it possible to perform useful small-scale experiments.

(1) A method was developed that made it possible to obtain a quick, accurate analysis of the free water in jet fuel.

(2) A system was developed for preparing a standard emulsion with a known droplet-size distribution.

(3) A coalescer cell and fuel system were developed for rapidly evaluating the variables in a fuel system.

(4) A miniature cell was built for studying drop coalescence on single fibers.

E. Single-Fiber Study

The single-fiber study showed that droplet growth rate on single fibers may depend considerably upon the nature of the fiber and also upon the nature of additives in the fuel.

(1) The maximum size drop that could be held by a single fiber at a local flow rate of 3 to 4 ft/min varied considerably amont the fibers. Drops on Teflon fibers grew to 70 to 75 μ, and drops on glass fibers grew to 400 to 500 μ.

(2) The initial growth rates were as follows: glass fibers had the fastest initial growth rate followed by Teflon, nylon, and then Dacron.

(3) Water droplets in a JP-5 fuel containing 5 ppm sodium sulfonate could not be made to coalesce on various types of single fibers.

F. Coalescence on Single Fibers

A study of droplet coalescence on single fibers revealed some unexpected results.

(1) The coalescence of adjacent drops on single fibers was often a very slow process. This was especially true on plastic fibers such as nylon where adjacent drops could set for several hours without coalescing.

(2) On single fibers the drops appeared to grow almost entirely by acquiring free water from the mainstream rather than from the surface of the fiber.

(3) With treated fiber glass, there appeared to be a minimum velocity below which there is little or no coalescence.

(4) On the nylon fiber chains of water droplets developed. These droplets did not coalesce but grew by acquiring water droplets from the main fuel stream.

G. Treated Fiber Glass

Work with treated fiber glass beds made with fibers with a 4 to 5 μ diameter resulted in the following conclusions. These observations pertain to additive-free JP-5 water coalescence.

(1) For a bed thickness range of 1/16 to 1/4 in., the use of a bed density of 14.0 lb/cu ft produced better coalescence than a 6.0 lb/cu ft density.

(2) For a specific fiber diameter there appears to be an optimum bed thickness for obtaining complete coalescence and a reasonably low pressure drop.

(3) A flow rate of 1 to 2 ft/min appears to be a critical value; above this, an increase in velocity, bed thickness, or bed depth may result in a substantial increase in effluent free water.

(4) The effects of bed density and flow rates are more apparent with a high free-water emulsion (3.0 vol. %) than with a low free-water emulsion (0.1 vol. %).

H. Untreated Fiber Glass

A brief study of the use of untreated fiber glass for coalescing free water from additive free JP-5 fuel revealed the following observations:

(1) The coalescing ability of treated and untreated fiber glass beds are very similar.

(2) As the fiber diameter is decreased, more complete coalescence is obtained.

I. Commercial Test Filter

Work with a multilayer commercial F/S revealed that each layer contributes to overall coalescence performance of the unit.

(1) The coalesced droplets are led through a glass fiber matrix that has a decreasing density (increasing pore size).

(2) The fine glass (3 to 4 μ) high-density layer (15.0 lb/cu ft) was the most critical. However, the thin lower-density outer layer was necessary for the unit to meet military specifications.

J. Plastic Fiber Beds

Successful coalescence of free water from jet fuel was achieved with Teflon, nylon, and Dacron fiber beds.

(1) Coalescence was achieved with the use of 1/2-in.-thick high-density (55 lb/cu ft) Teflon felt beds and an emulsion velocity of 2.0 ft/min.

(2) Successful coalescence was achieved with the use of a 1/2-in.-thick (14.0 lb/cu ft) nylon fiber bed (16 to 17 μ fibers) and an emulsion velocity of 2.0 ft/min. An increase in velocity resulted in a rapid decrease in coalescence.

(3) Successful coalescence was achieved with the use of a 1/2-in.-thick, high-density (24.7 lb/cu ft) Dacron felt bed and an emulsion velocity range of 2 to 6 ft/min.

K. Cotton Fiber Beds

Cotton is an excellent medium for coalescing free water from additive-free JP-5 fuel.

(1) The coalescing performance of a 1/2-in.-thick 14.0 lb/cu ft bed is better than that of a 1/8-in.-thick, 14.0 lb/cu ft treated glass fiber bed.

(2) The swelling of the cotton fiber did not produce any excessive pressure drops.

(3) For a bed thickness of 1/2 in., there is an optimum bed density for complete coalescence.

(4) The coalescing performance of a cotton fiber bed (9 to 11 μ fibers) is greatly affected by changes in bed depth.

VII. RECOMMENDATIONS

The work in this report represents the first phase of a research program concerned with studying F/S phenomena. During the course of this study, many possible research avenues have been opened for further studying the basic mechanism of droplet coalescence in F/S. These include electrokinetic studies, coalescence on single fibers, and coalescence in fiber beds. These studies must be augmented by investigating the filtration of solid contaminants. This is one of the original goals of the program.

Because of the many possible avenues of research, it is necessary to choose a program to fit the budgeted funds and time of this contract. Immediate future work will consist of studying the effects of fuel additives or contaminants on droplet coalescence in fiber beds. The equipment and analytical techniques developed in this phase will be used in the proposed study. Data obtained in the proposed work will be correlated with the information in the report.

It is also expected that the future course of the program will be determined by decisions made during future steering committee meetings.

VIII. ACKNOWLEDGEMENTS

This report covers the contract period of April 20, 1966, to April 19, 1967. Mr. C. C. Singleterry, Head, Fuels and Lubricants Branch of the Naval Air Systems Command, is the contract monitor. The work is being conducted under Contract No. NOw 66-0468-d.

John Bitten is the project leader and Edward Fochtman, Manager of Chemical Engineering Research, is providing administrative supervision. The experimental work was done by John Bitten, David Jones, and Victor Ivanuski. Mr. George Yamate photographed the drop coalescence on single fibers.

Appreciation is expressed to Dr. William Langdon who provided technical advice, and who also built the coalescer cell and other analytical equipment used in the program. Gratitude is also expressed to Dr. R. C. Kintner of the Illinois Institute of Technology, and to the members of the Steering Committee who furnished technical advice during the course of the program.

Data on this project are recorded in IITRI Logbooks C17199 and C17612.

APPENDIX

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13. ABSTRACT

An annual review is presented of a research program concerned with studying the filter/separator phenomena. The study consisted of reviewing published information, determining physical properties of jet fuels, performing electrokinetic experiments, and studying the coalescence of drops on single fibers and in packed fiber beds.

The literature search revealed little new information about the coalescence of emulsions in fiber beds. No accepted theory exists on the mechanism of the coalescence of micron-size droplets in the passage of an emulsion through a fiber bed.

An exploratory study was made of the generation of streaming curren by JP-5 fuel flowing through fiber beds. The sign and magnitude of the current is dependent upon the type of fiber, fuel conductivity, type of fuel additives and the physical property of the fiber bed.

A photographic technique was used to measure the coalescence and water droplet growth rates on various types of single fibers placed in a flowing JP-5-water emulsion. The drops appeared to grow by acquiring free water from the main stream rather than from the surface of the fiber. Coalescence studies with glass fibers showed that for a specific fiber diameter there appears to be an optimum bed thickness for obtaining complete coalescence and a reasonably low pressure drop. Little difference was found between treated and untreated glass fiber beds.

Successful coalescence of free water from jet fuel was achieved with
(cont.)

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Coalescence						
Electrokinetics						
Electrostatics						
Electroconductance-Fuel						
Fibers						
Filter/Separators						
Fiberglass						
Fuel Additives						
Fuel Analyses						
Fuel Contamination						
Fuel Filters						
Interfacial Tension						
Patents - Fuel Filters						
Surfactants						
Testing Fuel Filters						

Abstract
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1/2-in.-thick Teflon, nylon and Dacron fibrous beds. The overall performance of these beds as emulsion coalescers was considerably less than the coalescence performance observed in beds made up of glass beds. Studies showed that cotton is an excellent media for coalescing free water from jet fuel.