AD-776 965

A TECHNIQUE FOR EVALUATING FUEL MIST FLAMMABILITY

Bernard R. Wright, et al

Southwest Research Institute

Prepared for:

Coating and Chemical Laboratory

December 1973

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A TECHNIQUE FOR EVALUATING FUEL MIST FLAMMABILITY

INTERIM REPORT
AFLRL NO. 25

by

B. R. Wright
L. L. Stavinoha
W. D. Weatherford, Jr.

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prepared by

U. S. Army Fuels and Lubricants Research Laboratory
Southwest Research Institute
San Antonio, Texas

under contract to

U. S. Army Coating and Chemical Laboratory
Aberdeen Proving Ground, Maryland

Contract No. DAAK02-73-C-0221

December 1973

21

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U.S. Army Fuels and Lubricants Research Laboratory Southwest Research Institute San Antonio, Texas	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP N/A

3. REPORT TITLE

A Technique for Evaluating Fuel Mist Flammability

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Interim Report

5. AUTHOR(S) (First name, middle initial, last name)

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William D. Weatherford, Jr.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1973	21 plus 4 prelims	5

8a. CONTRACT OR GRANT NO. DAAK02-73-C-0221 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) AFLRL No. 25 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Approved for public release; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Coating and Chemical Laboratory, MERDC Aberdeen Proving Ground, Maryland

13. ABSTRACT

Experimental apparatus and procedures for evaluating the mist flammability of neat and fire-safety fuels have been developed. The apparatus, which was developed as part of this laboratory's fuel safety program, is capable of evaluating fuel mist flammability under conditions ranging from low air shear to extremely high air shear. Fuel is delivered through a capillary at a controlled rate, and three impinging air streams form a mist at the point of impingement. The fuel mist passes through an overwhelming ignition source to avoid marginal ignition. Flashback from the ignition source toward the fuel capillary is interpreted as a measure of mist flammability. Flashback is recorded utilizing a video camera and tape recorder. These results can then be carefully evaluated at some later time by measuring directly from a graduated scale located beyond the flame. Correlation of results with simulated full-scale helicopter crash tests appears to be excellent. In its present form, the technique provides a rapid and reliable laboratory research tool. It is not intended as a standardizable interlaboratory test method at this time.

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DD FORM 1 NOV 65 1473

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Mist Flammability Fire-Safety Fuels Flashback Fuel Flammability						

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FOREWORD

This report was prepared at the U.S. Army Fuels and Lubricants Research Laboratory, Southwest Research Institute, under DOD Contract No. DAAK02-73-C-0221. The project was administered by the Coating and Chemical Laboratory, U.S. Army Mobility Equipment Research and Development Center, Aberdeen Proving Ground, Maryland 21005, with Mr. C. F. Schwarz serving as project monitor. The project was conducted under the cognizance of Drs. T. E. Sullivan and James Bryant, U.S. Army Office of Chief of Research and Development.

Acknowledgment is given to Mr. C. M. Urban for his participation in the development of the test apparatus and facilities, to Dr. R. J. Mannheimer for his contributions to the development of the capillary rheological measurement technique, to Mr. J.P. Pierce for his meticulous attention to detail while conducting the experiments involved in the development and utilization of the mist flashback technique, and to Mr. D.C. Babcock for producing the photographs used in this report. Acknowledgment is also given to Messrs. F.W. Schaekel, H.L. Ammlung, R.D. Quillian, Jr., and J.T. Gray for their encouragement, comments, and suggestions.

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I. INTRODUCTION

Casualties and materiel losses due to fire frequently occur following an otherwise survivable crash of fixed- or rotary-wing aircraft. Investigations subsequent to crashes have shown that, generally, the most important parameters influencing postcrash fires include fuel properties, ignition sources, dispersion effects, and the nature of the crash environment. Since fuel properties can be isolated and evaluated, the U.S. Army Fuels and Lubricants Research Laboratory has addressed the problem of fuel dispersion and ignition under conditions representative of survivable crashes. Initially, studies were centered on fuel emulsions, but this approach was abandoned due to handling problems and instability of the emulsions themselves. Effort was redirected toward additives that would not substantially alter the physical properties of the base fuel, but would enhance the firesafety characteristics. These studies led to the development of test techniques for defining flame spread rates, fuel-impact dispersion fire effects, and mist-flame propagation properties. The technique developed to evaluate fuel mist-flame propagation properties is the subject of this report.

II. BACKGROUND

Several techniques and devices(1-3)* have been developed and are being used to evaluate the spray flammability (mist-flammability) of fuels and hydraulic fluids. Among these are high-pressure test apparatus which are cumbersome and awkward to use. Some low-pressure device techniques appear to be only cursory and are inadequate for distinguishing between various fuels and between fuel blends that would be subjected to various shear conditions. Simple impact or sling tests all have some drawbacks or they are not designed to give precise evaluations.

Other flammability procedures that have been evaluated in recent years include hot manifold (hot pipe), spontaneous ignition, and flashpoint. While all of these procedures offer some merit, they do not necessarily relate to the shearing conditions which produce a flammable mist in a survivable crash situation. Since kerosine-type fuels are normally below their flashpoint, there should be no ignition upon impact; however, many crashes have occurred that have been followed by deadly fires. Kerosine-type fuels include Jet A-1 and also JP-8 (tentative military specification) which is the same as Jet A-1 but includes anti-icing and other additives.

Careful evaluations have shown that the formation of mists is the chief cause of fires with low-volatility fuels, and, if this misting condition could be alleviated, loss of life due to postcrash fires could be reduced.(4-5) However, before the problem of mist formation could be eliminated, some means of accurately evaluating mist-flammability had to be developed. It was intended to develop quantitative evaluations which could not only distinguish between neat fuels and fuel-additive blends, but also could accurately assess the difference in mist-flammability between neat fuels. Since JP-8-type fuels have a broad chemical composition, it was believed that some fuels would be more responsive to additive treatment than others, and this difference needed to be assessed. Therefore, a highly accurate and repeatable evaluation was needed to fulfill these requirements.

*Superscript numbers in parentheses refer to the List of References at the end of this report.

III. EXPERIMENTAL

A. Fuel Mist-Flashback Test Facility

The fuel mist-flashback apparatus and various supporting auxiliary equipment are housed in a concrete block structure of approximately 400 sq ft that was designed specifically for this application. As indicated in Figure 1, the building is partitioned into two similar sections connected via a window in the partition. One room houses the mist-flashback apparatus, which is situated near the connecting window, thus allowing the flames generated in the test procedure to burn in the adjacent room.

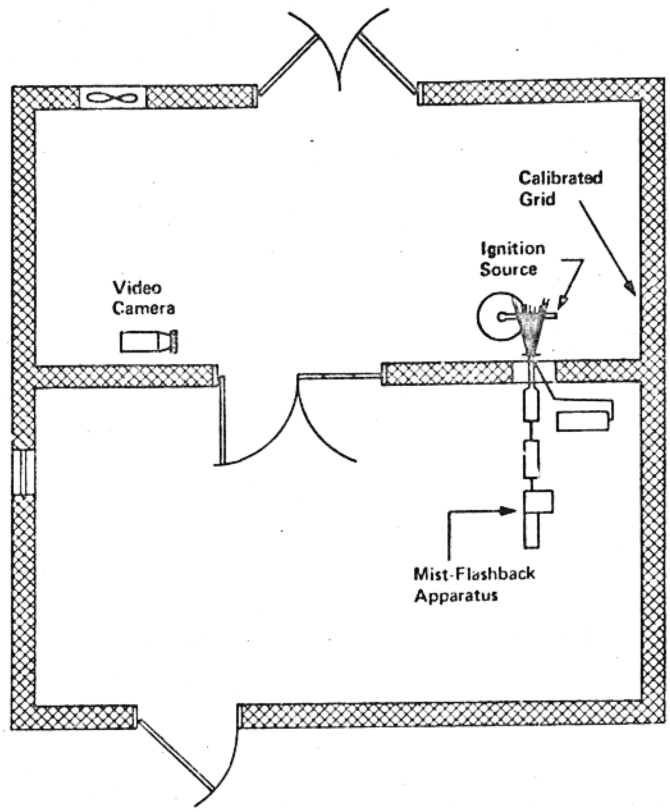


FIGURE 1. SCHEMATIC OF MIST-FLASHBACK FACILITY

The second room contains the ignition source, the reference grid, and video camera used in recording each experiment. A forced air, heating and cooling unit is used to maintain constant temperature in the laboratory. This system is specifically designed to supply the laboratory with air that is vented directly to the outside. This one-pass design is required since the vented air is quite often filled with smoke. This special ventilation situation is considered as a test parameter in each evaluation since part of the secondary combustion air is supplied via the test apparatus window.

B. Mist-Flashback Apparatus

The mist-flashback apparatus (Figure 2) is composed of the fuel and air systems, the ignition source, and the data recording system. Detailed drawings of the apparatus components are presented in the Appendix. The fuel system comprises a fuel capillary, fuel cylinder, and a hydraulic drive cylinder. A piston in the hydraulic drive cylinder is connected by a calibrated rod to a second piston located in the fuel cylinder. The piston in the fuel cylinder causes positive displacement of fuel when the hydraulic drive cylinder is operated. A variable-speed transmission drives the gear pump supplying fluid to the

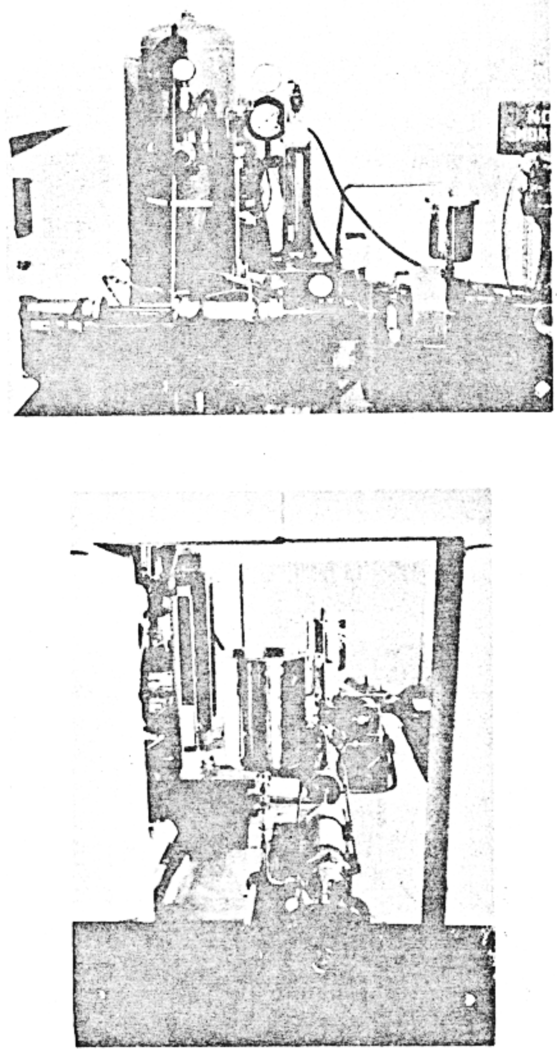


FIGURE 2. MIST-FLASHBACK APPARATUS

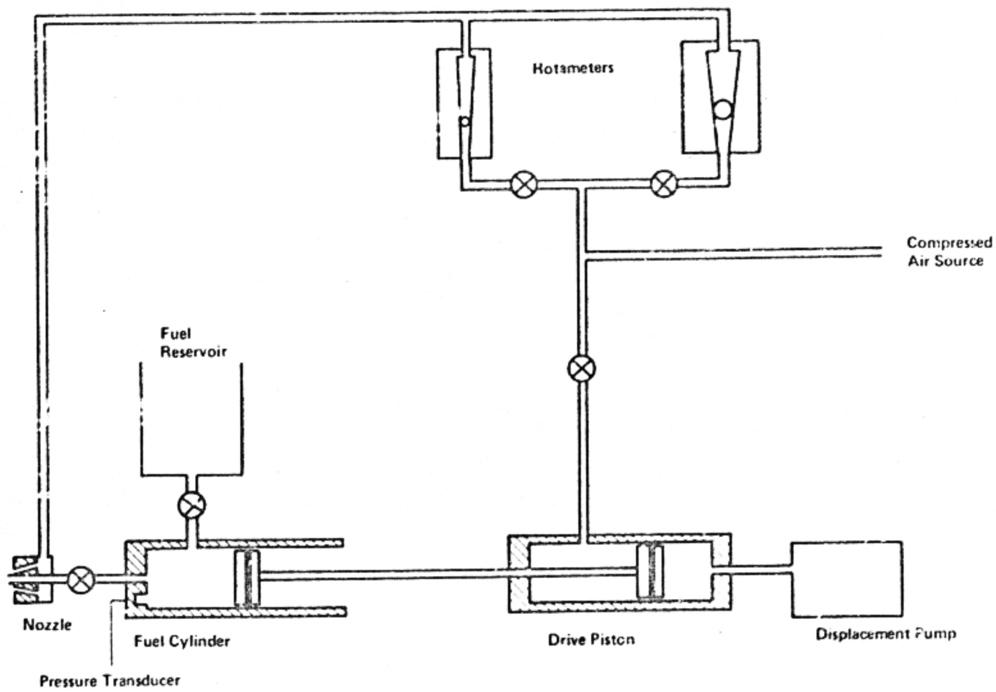


FIGURE 3. SCHEMATIC DIAGRAM OF MIST-FLASHBACK APPARATUS

hydraulic drive cylinder. Speed settings on the transmission have been calibrated for flow rate from the fuel cylinder. The body of the fuel cylinder has been drilled and tapped to accept a fuel-fill line and a fuel-delivery line. The fuel-delivery line includes a shutoff ball valve and a stainless steel fuel capillary (Figure 3). The tip of the fuel capillary fits through a hole in the center of the air nozzle in the air system. Alternate fuel capillaries are provided so that the capillary length and diameter can be varied. The dimensions of the capillary used in the reported procedure are 0.0298 in. I.D. X 2.35 in long.

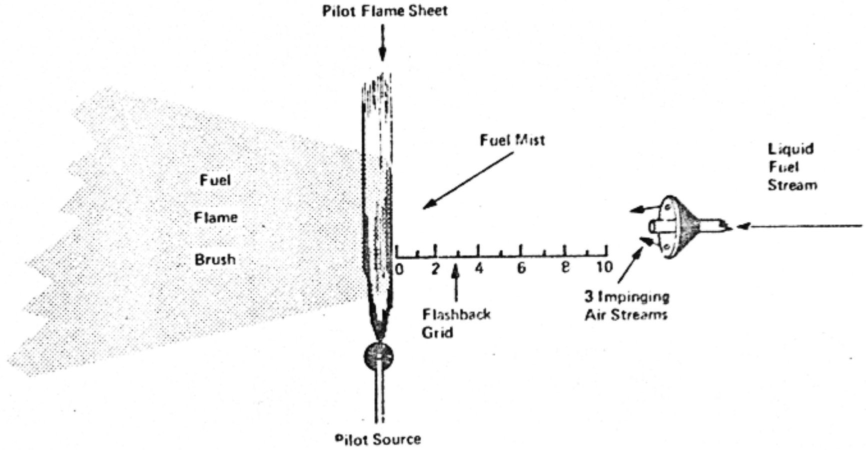


FIGURE 4. SCHEMATIC OF MIST-FLASHBACK MEASUREMENT SYSTEM

The air nozzle and auxiliary equipment comprising the air system are also diagramed in Figure 3. The air nozzle contains three 0.04 in. I.D. × 0.5 in. long air capillaries symmetrically located 0.31 in. from the center of the air nozzle face and aligned to intersect the nozzle's centerline axis at an angle of 13 deg at a point 0.7 in. from the tip of the fuel capillary. This nozzle is stock item No. 0-7342055 from Spraying Systems Co., Wheaton, Illinois. The fuel capillary extends through a hole drilled in the center of the air nozzle. Air is supplied at predetermined flow rates to the air nozzle. Air flowing through the three capillaries in the air nozzle is referred to as the mist-air and is relied upon to cause misting of the fuel passing through the point of air impingement. The total airflow rate through the three capillaries may be varied to effect different degrees of misting. The mist-flashback measurement system is illustrated schematically in Figure 4.

Depending upon the relative fuel and air rates, flames may propagate upstream from the pilot flame toward the fuel/air source. This flashback phenomenon is utilized as a measure of the mist flammability. A graduated scale flashback grid is positioned so that the extent of flashback can be measured by observation along a horizontal line of sight perpendicular to the fuel air jet.

The ignition source is a natural gas, air-aspirating horizontal burner. It is constructed of 1-1/4-in. pipe with an air aspirator similar to the venturi used in domestic furnaces. There are 14 holes, each approximately 1/8 in. in diameter and spaced 1 in. apart. The gas is regulated to provide a sheet of flame approximately 14 in. high through which the sample is injected. Thus, the sample is subjected to a constant overpowering ignition source to ensure repetitive ignition from test to test. The source is positioned 10 in. from the tip of the nozzle, and the height is adjusted to allow the sample to pass through the center of the flame sheet.

The phenomena are recorded for each evaluation utilizing a video camera (with zoom lens) and a video tape recorder, thus allowing subsequent video playback for accurate data reduction. This playback allows careful, accurate measurement of the data and also allows comparison between runs to be made at some later date. The recording camera is placed approximately 10 ft from the pilot with its axis perpendicular to the axis of the sample flame. The sample is burned for approximately 5 sec, and this event is recorded on tape for each experiment. Figure 5 shows the arrangement of these pieces of equipment during an actual experiment.

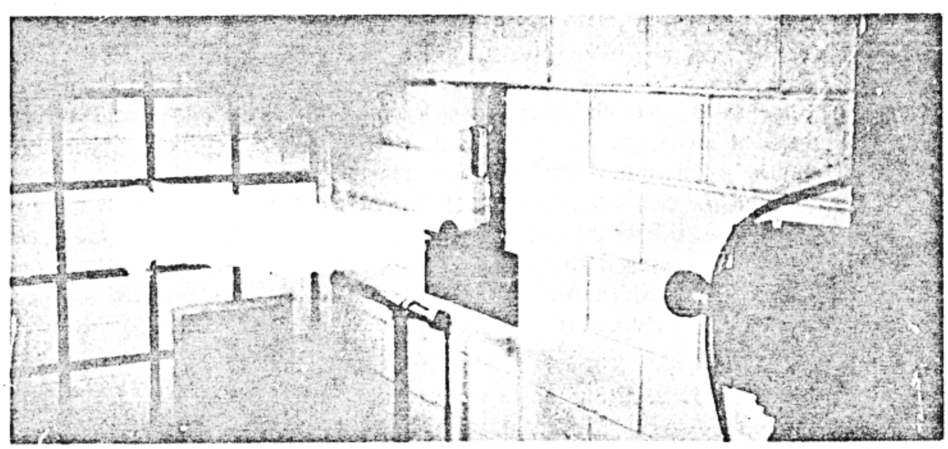


FIGURE 5. PHOTOGRAPH OF MIST-FLASHBACK EXPERIMENT

An additional feature of this apparatus is its capability of being used as a viscometer as well as a flammability test device. A pressure transducer (Figure 3) is installed in the head of the fuel cylinder, and, by optimizing the length and diameter (L/D) of the capillary tube, the viscosity of both Newtonian and non-Newtonian fuels can be measured. This information is often required to evaluate the effect of certain additives on the base fuel properties.

C. Test Procedure

The test procedure is divided basically into three operations: (1) sample preparation and equilibration, (2) obtaining the experimental data, and (3) reduction and interpretation of the data. When the samples to be evaluated are neat fuels, they are equilibrated overnight at an ambient room temperature of 74° to 75°F, thus ensuring uniformity of sample temperature. When blends of antimisting agents are to be evaluated, the appropriate blends are prepared carefully to ensure complete solution of the additive. Experience has shown that some additives are harder to solubilize than others, and complete solubility is imperative for this evaluation. The blends are then equilibrated at the same temperature as the neat fuels.

The fuel cylinder is filled with the candidate sample by forcing the drive piston to the rear with air pressure on the front side. This procedure must be done slowly to prevent air bubbles from being formed as the fuel cylinder is filled. At this point, the pilot flame is ignited and adjusted for proper height, and the video recorder and camera are activated. Because of the sometimes intermittent nature of the mist-flashback phenomena, the following procedure has been adopted for quantitative measurement of mist-flashback. Using a fixed liquid fuel flow rate (150 ml/min), a constant air rate of 1 SCFM is established in the impinging air streams, and a tape recording of about 5 sec duration is made of the flame phenomena. This initial air rate develops marginal misting with neat kerosine-type fuels. The air rate is then increased to 1.5 SCFM, and a second tape recording is made. The third and highest air rate of 2 SCFM is then established, and a tape recording is again made. This last air rate provides extreme atomization and tends to blow back the flashback phenomena. Hence, the three air rates encompass conditions ranging from relatively low to extremely high shear.

As mentioned previously, the flashback phenomena are recorded using the video camera and recorder. Generally, the entire series of evaluations is completed before any data reduction is begun. For each air setting, both the maximum and minimum flashbacks are examined. A rating (rounded to the nearest inch) is assigned for the maximum and for the minimum flashback at each of the three different air rates. Before a rating is given, the same extent of maximum or minimum flashback must be observed at least twice. The rating assignment is repeated for each of the triplicate experiments. When two out of three triplicate ratings are the same, this rating becomes the assigned rating for that air rate; otherwise the triplicate ratings are averaged to obtain the assigned rating for that air rate. The six assigned ratings thus obtained (maximum and minimum flashback at each of the three different air rates) are then averaged to obtain the mean mist-flashback rating, in inches.

The mean mist-flashback rating ranges from 0 to approximately 0.8 in. for fuel blends containing effective amounts of AM-1 antimisting additive and up to approximately 8 in. for neat fuels. Based upon extensive experimental observations, the maximum difference in mist-flashback ratings among replicate tests does not exceed 0.2 in., either for neat base fuel or for base fuels containing 0.2 percent AM-1. This repeatability represents the minimum increment (actually 1/6 in.) involved in the above-described rating assignment procedure.

IV. DISCUSSION

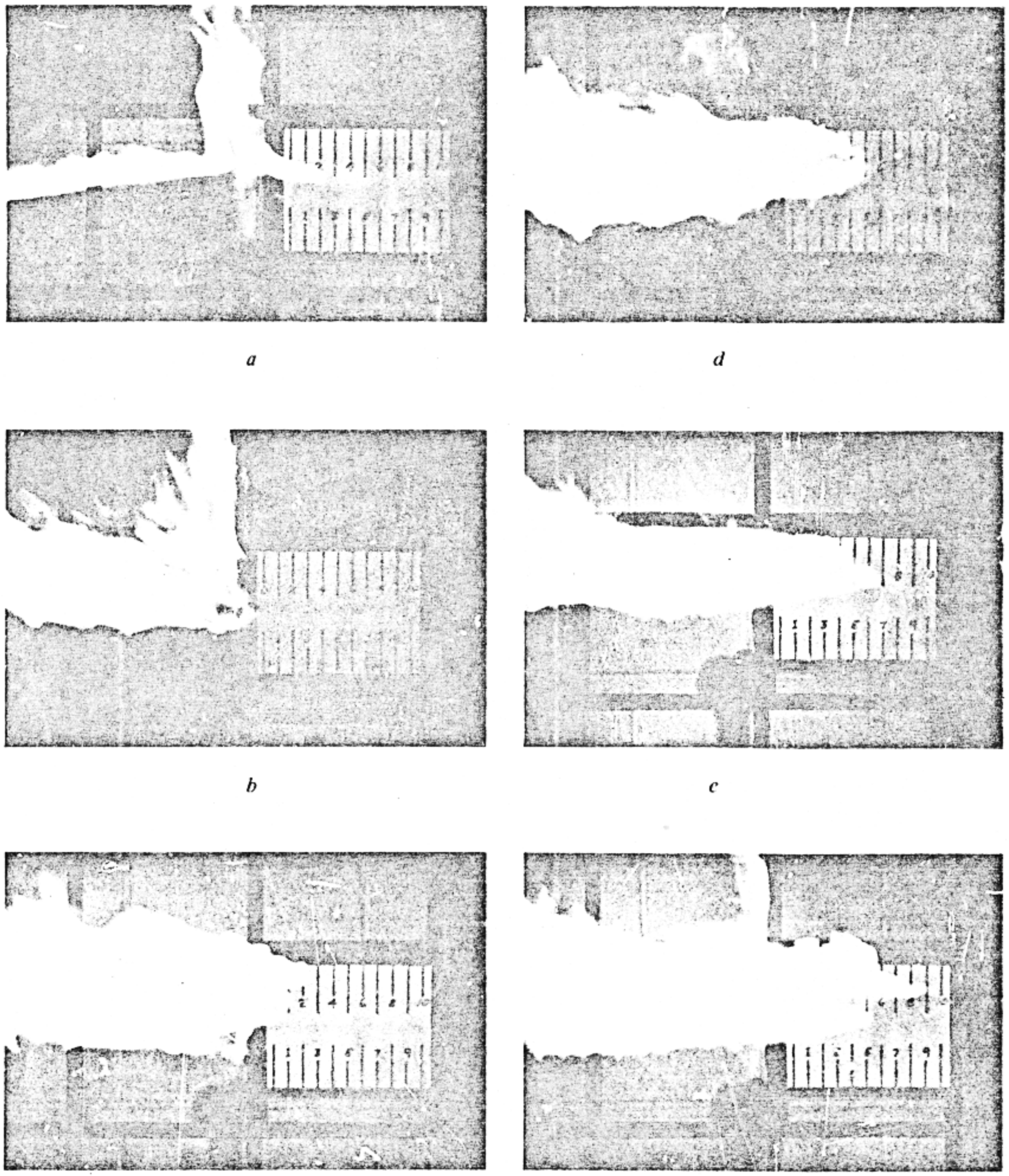
In the mist-flashback test, the flame propagation characteristics of fuel mists are evaluated by delivering fuel at a fixed flow rate through a known length and diameter capillary tube situated in the center of the air nozzle. This nozzle provides intersecting impingement of three air streams with the fuel stream. The resulting mixture travels horizontally through a pilot flame. Figure 6 shows characteristic types of flames which result from different mist-airflow rates for different types of fuels. Ignition without misting airflow (Figure 6a) occurs with fuels such as gasoline or JP-4 that have a high vapor pressure at room temperature. The low-volatility kerosine-type fuels do not respond the same since only fumes can be ignited in this procedure without misting airflow.

Photographs b through f of Figure 6 show typical flame configurations using a JP-8 fuel and varying the rate of misting air. By increasing the shearing airflow rate, the amount of misting is increased, thus causing more extensive flashback to occur. It should be noted that the air rate could be increased to a level where the flashback would be literally blown toward the pilot flame (not shown), thus decreasing the actual flashback measurement

Early test technique development involved optimization of both fuel and airflow rates. The extremities, including both low and high shear regimes, appear to correlate with similar situations in actual aircraft crashes. Once these optimizations were accomplished, the technique proved quite repeatable as well as providing a method of distinguishing the mist-flammability of various neat fuels.

The sensitivity of this measurement technique is best illustrated by describing results obtained with a series of 14 base fuel samples, all meeting Jet A-1 or the tentative JP-8 specification. In Figure 7, it can be seen that the extent of mist-flashback (i.e., the average inches of flashback) ranges from 6-1/2 to 8 inches. It is of interest to mention that high-volatility fuels such as JP-4 produce a mean flashback of about 8 in. in this test procedure. Hence, the most flammable JP-8 fuel shown in this figure is almost indistinguishable from JP-4 under misting conditions. On the other hand, the majority of the fuel samples were significantly less flammable in the mist form. As illustrated in the figure, the flashpoint of these various samples ranged from 114° to 148°F, and no correlation between flashpoint and mist flashback is evident. The controlling physico-chemical property for mist-flammability has not yet been established. As indicated in this figure, a rough correlation is obtained between mist-flashback and the product of surface tension and density; hence, the data are presented on this basis as a graphical convenience.

Figure 8 presents results for the three current candidate antimisting additives for use in JP-8 or Jet A-1 fuels. Recalling from the previous figure that the neat fuels produced a mean mist flashback of 6-1/2 to 8 in., it is striking to note that the small quantities of the antimisting additives produce such a drastic reduction (to less than 1 in.), in the mean flashback. The domestic-source additive AM-1 and the British additive FM-4 appear superior to the domestic-source additive XD-8132 in this procedure. However, such differences between these additives are not evident in impact dispersion test procedures. Little or no flame effects are observed with these additives in the latter tests. It is of interest to note that



a *d*

b *e*

c *f*

FIGURE 6. PHOTOGRAPHS DEPICTING VARIOUS DEGREES OF MIST-FLASHBACK

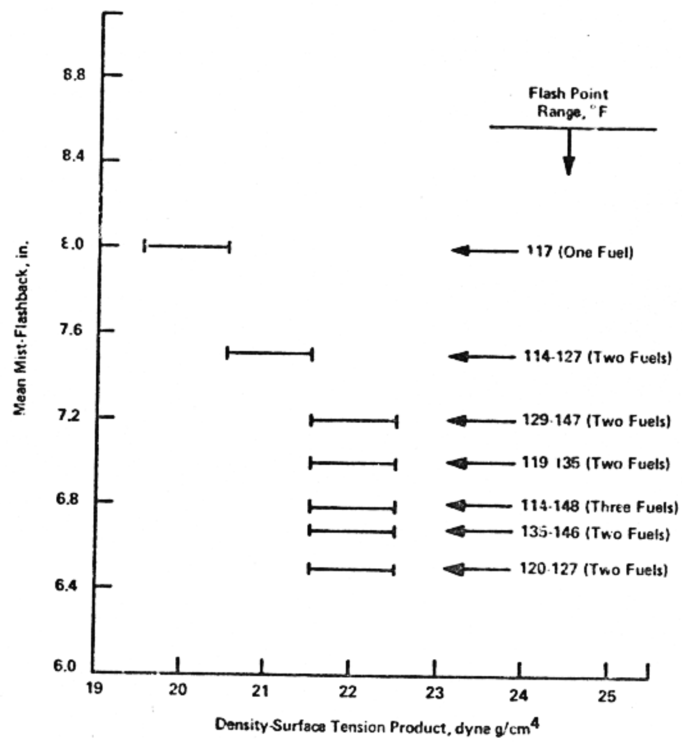


FIGURE 7. MIST-FLASHBACK CHARACTERISTICS OF VARIOUS JP-8 AND JET A-1 FUELS

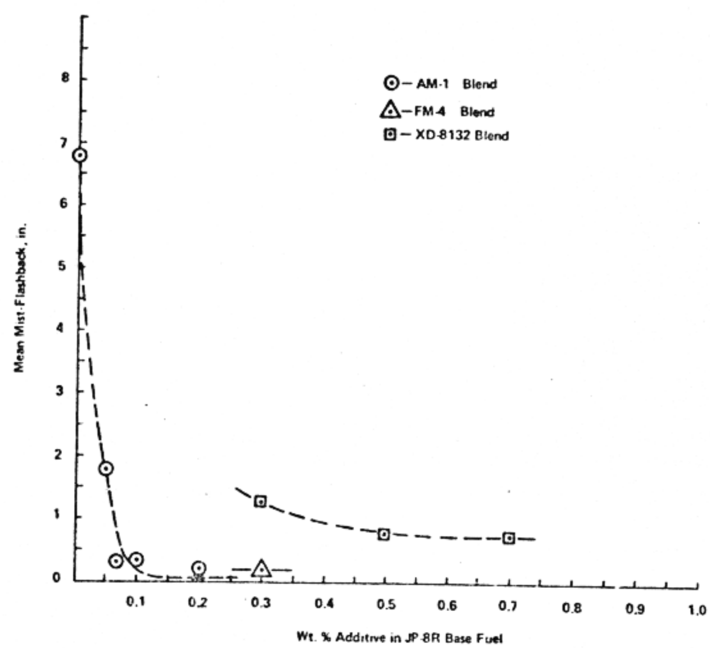


FIGURE 8. RELATIVE MIST-FLASHBACK OF SOME ANTIMISTING ADDITIVES

TABLE I. COMPARISON OF MIST-FLASHBACK MEASUREMENTS WITH LABORATORY AND SIMULATED FULL-SCALE MIST FLAMMABILITY TEST RESULTS

Fuel Blend	Mist Flammability (Mist Flashback mean in.)	Impact Flammability (Impact Dispersion rating)[a]	Simulated Full-Scale Helicopter Crash Test (Mist Fireball Rating)[b]
JP-8R/Neat	6.8	D	SMF
JP-8R/0.07% AM-1	0.3	B	NMF
JP-8R/0.2% AM-1	0,0.2	A	NMF
JP-8R/0.3% FM-4	0.2	A	NMF
Jet A-1/0.7% XD-8132[c]	3.7	D	SMF
Jet A-1/0.7% XD-8132[d]	0.8	A	NMF

[a]A. No pilot flame enlargement
B. Pilot flame dimensions less than doubled.
C. Pilot flame dimensions more than doubled.
D. Pilot flames totally obscured by transient mist fireball.

[b]Tests conducted (in duplicate or more) for C&CL by Dynamic Science, Phoenix, Arizona, Mr. Maurice Shaw, Project Manager.
SMF: Substantial mist fireball.
NMF: No mist fire.

[c]Fuel blend provided by NAFEC and tested by Dynamic Science after storage at Phoenix for 2 months prior to test. (Storage temperature range 80° to 115°F.)

[d]Same fuel batch as above tested by Dynamic Science after storage at Phoenix for only 6 days prior to test.

these mist flashback test results appear to correlate with simulated full-scale helicopter crash tests (tests conducted for the Army by Dynamic Science, Phoenix, Arizona). Comparisons of mist flashback data with impact dispersion data of this laboratory and with the results observed by Dynamic Science are presented in Table I. Under the conditions of these simulated crash tests, it is apparent that a mist flashback rating of 0.8 in. or less indicates that a fuel blend will not produce a mist in which flames can propagate. Insufficient data are available to establish the critical mist flashback rating for effective mist flammability suppression. However, this critical rating appears to be between 0.8 and 3.7 inches.

V. CONCLUSIONS AND RECOMMENDATIONS

The mist-flashback apparatus has proven to be a reliable, highly repetitive apparatus for evaluating the mist-flammability of liquids. This flammability property is most important in ballistic impact and postcrash fire situations. Even though the fuel may be below its flash point, it may lead to catastrophic fire because of the misting qualities of the fuel. As mentioned previously, before the misting qualities of a fuel could be evaluated and/or modified, a procedure such as the mist-flashback technique was needed. Also, with the introduction of antimisting additives, their relative effectiveness needed to be evaluated. For this type of application, an accurate procedure, requiring small volumes of sample, was required. It is felt that the developed apparatus and procedures fulfill these requirements. The technique is not intended to be a standardizable interlaboratory test method. Rather, it was developed as a research tool in support of the fuel flammability studies of this laboratory. However, such a standardizable test method could be developed in the future, utilizing the principles and background information presented in this report. Possible application of this technique to basic combustion research is anticipated. Relationship of particle size to combustibility of fuels could be explored using the mist-flashback apparatus in conjunction with an appropriate device to determine droplet size. Also, it is felt that this apparatus could be very easily adapted to evaluation of the combustibility of hydraulic fluids since such fluids could be exposed to similar shearing conditions upon rupture of pressurized lines. In this latter application, downstream burning (beyond the pilot) should be considered as well as any flashback that may occur. It is believed that this technique may be more quantitative than D3119-72T procedures used for evaluating hydraulic fluid flammability.

The developed mist-flashback technique appears to correlate with simulated full-scale helicopter crash tests. Therefore, it is recommended that this procedure be used for evaluating all candidate antimist agents in the Army's Modified Fuel Program.

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4. Pinkel, I. I., et al., "Mechanism of Start and Development of Aircraft Crash Fires," NACA Report No. 1133, 1953.

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APPENDIX

Detailed Drawings of Mist-Flashback Apparatus

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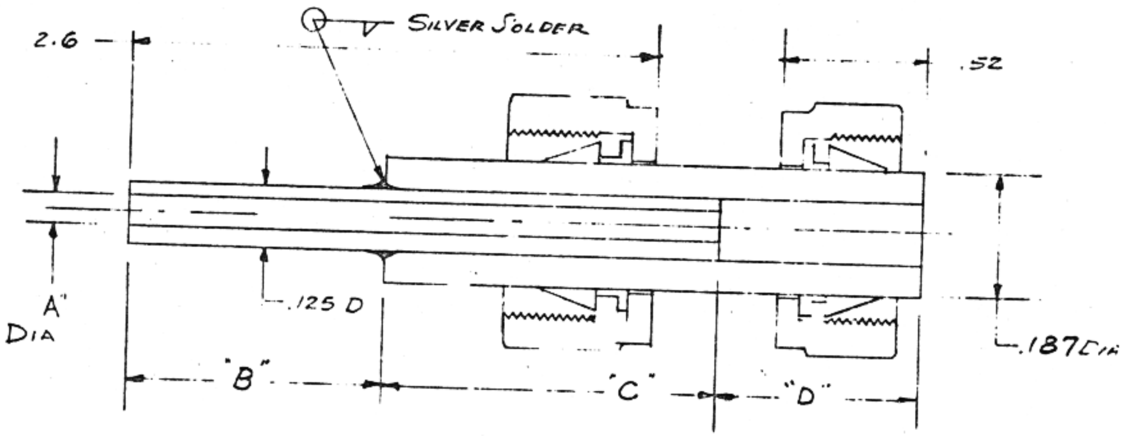

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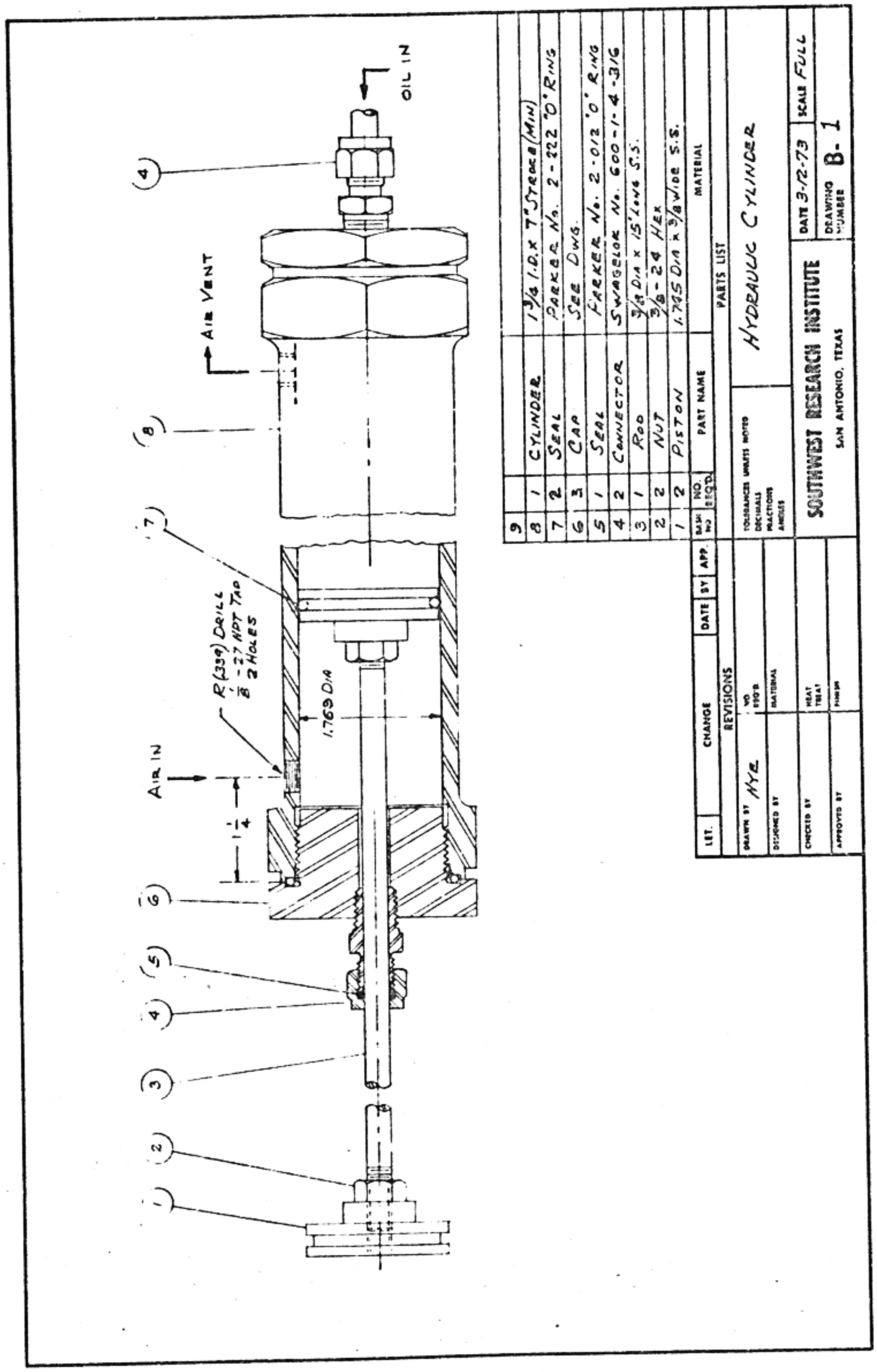

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6 3 CAP SEE DWG.
5 1 SEAL PARKER No. 2-012 'O' RING
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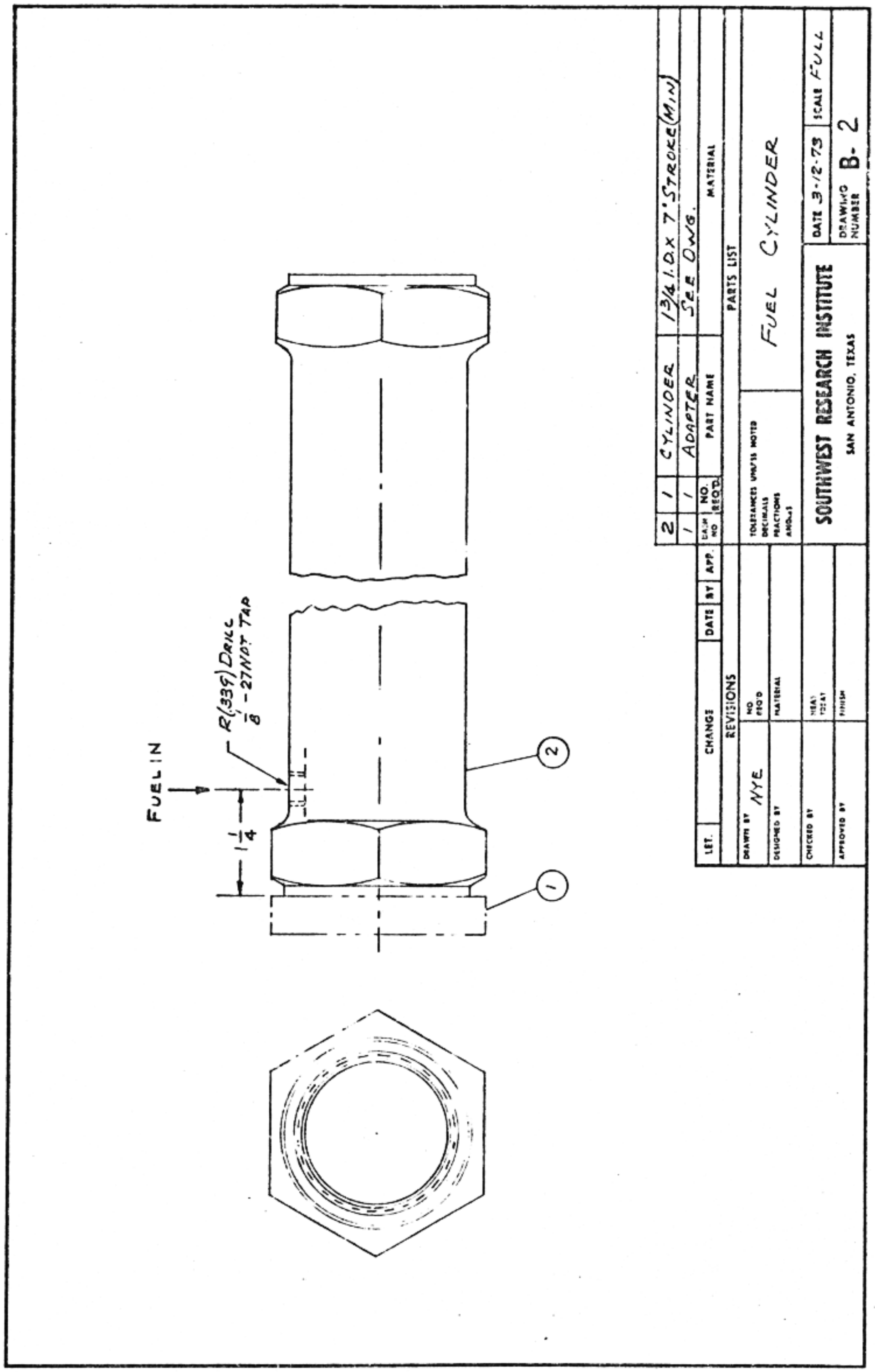
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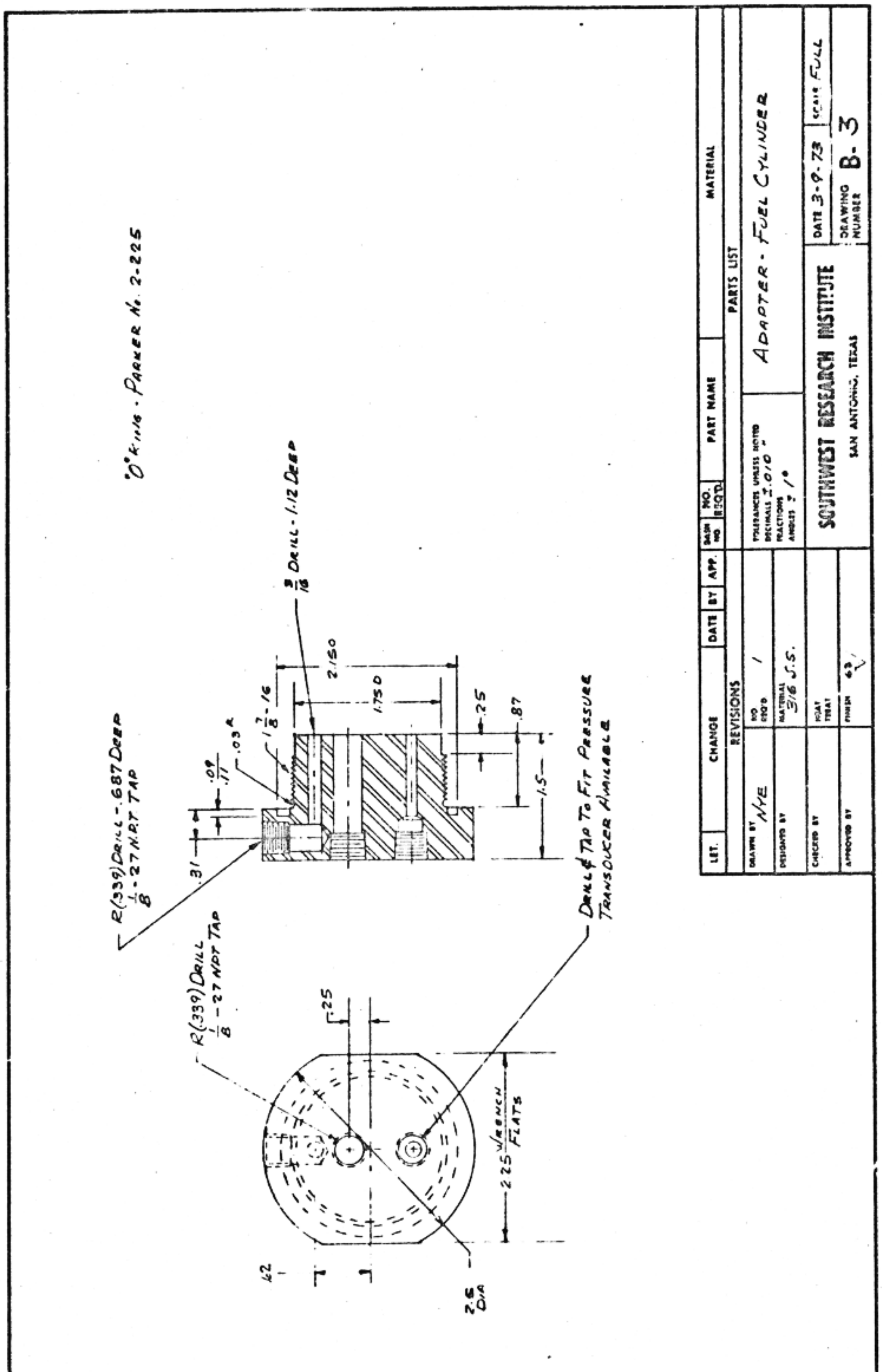
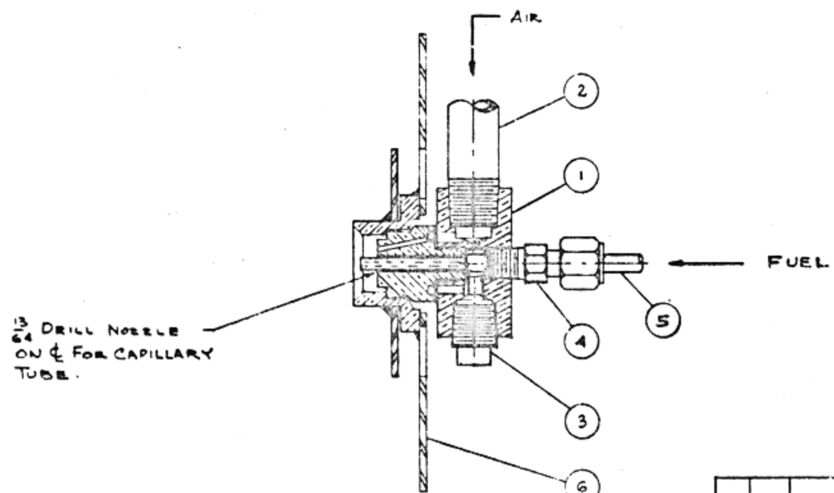
SCALE FULL
DRAWING NUMBER B-2



"O" Ring - Parker No. 2-225
3/16 Drill - 1.12 Deep
R(339) Drill - .687 Deep
1/8 - 27 NPT Tap
R(339) Drill
1/8 - 27 NPT Tap
Drill & Tap To Fit Pressure Transducer Available
2.25 Wrench Flats
2.6 Dia
2.150
1.750
1 7/8 - 16
.03 R
.25
.87
1.5
.31
REVISIONS
PARTS LIST
Drawn by Nye
Material 316 S.S.
Tolerances unless noted
Adapter - Fuel Cylinder
Southwest Research Institute
San Antonio, Texas
Date 3-9-73
Scale Full
Drawing Number B-3



DASH NO	NO. REQ'D	PART NAME	MATERIAL
6	1	SHIELD	5" DIA 16 GA. ST. ATTACH AS REQ'D
5	1	CAPILLARY	DWG. NO.
4	1	CONNECTOR	SWAGELOK NO. 300-1-2-316
3	1	PLUG	1/4" PIPE (LIQUID PORT)
2	1	NIPPLE	1/4" PIPE - LENGTH AS REQ'D.
1	1	ATOMIZER	SPRAYING SYSTEM CO. PNEU. ATOM. 1/4"-2850

PARTS LIST

LET.	CHANGE	DATE	BY	APP.

REVISIONS

DRAWN BY NYE | NO REQ'D
DESIGNED BY | MATERIAL
CHECKED BY | HEAT TREAT
APPROVED BY | FINISH

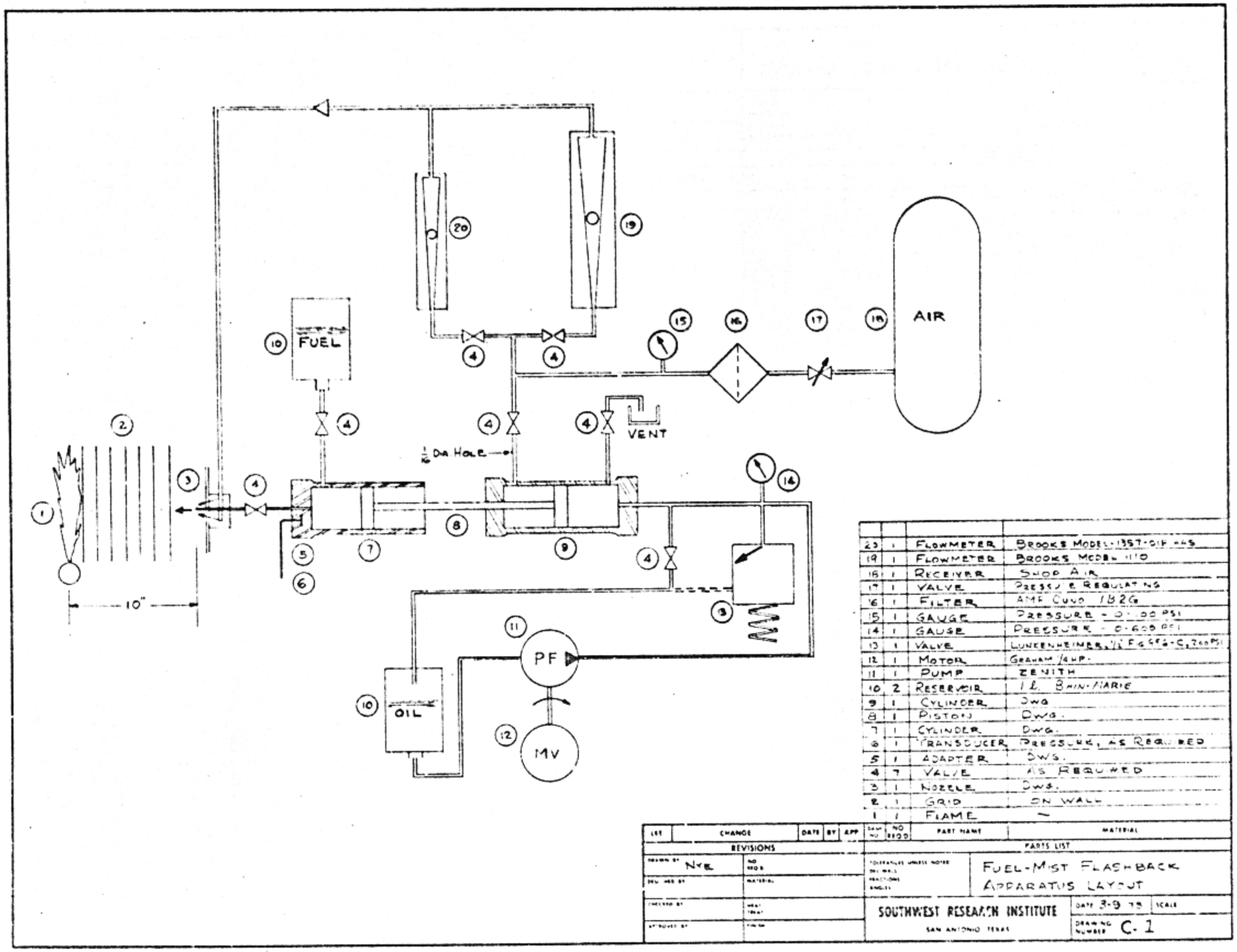
TOLERANCES UNLESS NOTED
DECIMALS
FRACTIONS
ANGLES

NOZZLE ASSEMBLY

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO, TEXAS

DATE 3-12-73 | SCALE FULL

DRAWING NUMBER B-4


AIR
FUEL
OIL
VENT
1/16 DIA HOLE
10"
PF
MV
20 | 1 | FLOWMETER | BROOKS MODEL-1357-01F-4-S
19 | 1 | FLOWMETER | BROOKS MODEL 1110
18 | 1 | RECEIVER | SHOP AIR
17 | 1 | VALVE | PRESSURE REGULATING
16 | 1 | FILTER | AMF CUNO 1B2G
15 | 1 | GAUGE | PRESSURE - 0-100 PSI
14 | 1 | GAUGE | PRESSURE - 0-600 PSI
13 | 1 | VALVE | LUNKENHEIMER, 1/2" FIG 556-C, 200 PSI
12 | 1 | MOTOR | GRAHAM 1/4 HP.
11 | 1 | PUMP | ZENITH
10 | 2 | RESERVOIR | 1 L. BAIN-MARIE
9 | 1 | CYLINDER | DWG
8 | 1 | PISTON | DWG.
7 | 1 | CYLINDER | DWG.
6 | 1 | TRANSDUCER | PRESSURE, AS REQUIRED
5 | 1 | ADAPTER | DWG.
4 | 7 | VALVE | AS REQUIRED
3 | 1 | NOZZLE | DWG.
2 | 1 | GRID | ON WALL
1 | 1 | FLAME | —
PART NAME
MATERIAL
PARTS LIST
REVISIONS
CHANGE
DATE
BY
APP
DRAWN BY NYE
FUEL-MIST FLASHBACK APPARATUS LAYOUT
SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO TEXAS
DATE 3-9-73
SCALE
DRAWING NUMBER C-1

END

DATE

FILMED

5-11-74

NTIS