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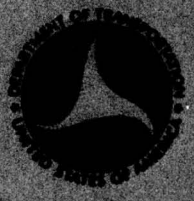
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LEVEL II

EXPERIMENTAL STUDY OF FLAME CONTROL DEVICES FOR CARGO VENTING SYSTEMS

D. P. CROWLEY

R. P. WILSON, JR.



FINAL REPORT

SEPTEMBER 1978

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16. Abstract

Experiments were performed to determine the critical dimensions of flame arrestor elements which will prevent flames from traveling into bulk cargo tanks through the venting system. Based on the tests, the design criteria are more stringent than proposed by Wilson and Atallah (DOT Report CG-D-157-75). The passageway diameter apparently must be less than 40% of the published laminar-flame quenching diameter of the product (fuel) to be vented. In addition, the length of the arrestor apparently must be greater than 1000 D_H^2, where D_H is the critical passageway diameter in inches. This second criterion applies to methane, acetaldehyde, toluene, methyl alcohol, gasoline, and butane flames of up to 200 ft/sec approach flame speed. For acetylene/air and ethylene/air, no available arrestor exhibited consistent quench for the present test conditions. Experiments were also performed to determine the conditions for using steam injection or a high-velocity relief valve to prevent flame passage into a vent system.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

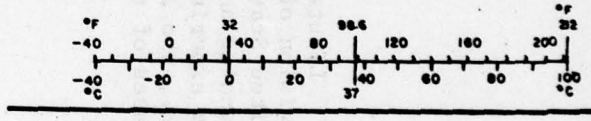
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.96	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



ACKNOWLEDGEMENTS

Lieutenant Michael Flessner of the Marine Safety Branch, Division of Applied Technology, Office of Research and Development, United States Coast Guard, contributed substantially in both the planning and interpretation of the experiments reported herein. The experimental tests were conducted by William Lyle of Arthur D. Little, Inc., who also modified the test facility as necessary for various phases of the work.

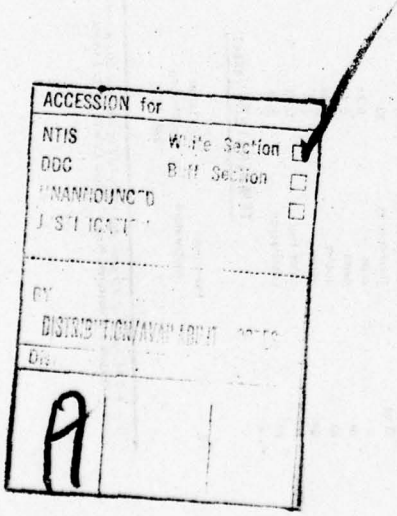


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I. BACKGROUND AND SUMMARY OF FINDINGS

A. Background

Flammable mixtures of cargo vapor and air are expelled from cargo tank venting systems, particularly during the loading process. In order to prevent flame ingestion from an ignition source on deck, flame control devices are installed at or near the vent exits, and these devices are designed to meet Coast Guard specifications.

As part of a wide-ranging study of vent system hazards (Contract No. DOT-CG-42357-A), Arthur D. Little, Inc. has examined, through theory and experiment, how flame arrestors must be designed in order to stop flames for common hydrocarbon products. The theoretical findings were published earlier as DOT Report No. CG-D-157-75 (Wilson and Atallah (1975)), and the present report complements that work with a comprehensive set of empirical tests covering three aspects of flame control devices:

- Critical design values of passageway diameter and length adequate to stop flames of methane/air and ethylene/air: Arrestor types included perforated plate, parallel plate, and crimped ribbon.
- Relationship of product type to arrestor design criteria: Devices which have been proven to control flames of methane/air or ethylene/air may not necessarily work on products having different carbon/hydrogen ratio, flame temperature, or laminar flame velocity. Tests were performed on mixtures of air with ten product fuels: ethyl ether, methyl alcohol, acetaldehyde, gasoline, toluene, carbon disulfide, butadiene, hydrogen sulfide, acetylene, and butane.
- Non-obstructive control devices: Performance tests were carried out on the high-efflux-velocity nozzle and the steam snuffer, each of which offers the advantage of minimum restrictions to the flow.

The findings of this experimental program are summarized below.

Reference should be made to two-related Arthur D. Little, Inc. studies of flame arrestors, performed for USCG as part of the present contract: First, the performance of seven (7) commercially available flame arrestors was tested for butane and gasoline flames (Wilson and Crowley (1978a)); the motivation for this work was the potential need for arrestors in gasoline vapor recovery systems. Second, measurements were made of arrestor heat-up by a flame which is stopped but stabilized (not extinguished) (Wilson and Crowley (1978a)), with a view to determining possible revisions to the design criteria to insure that arrestors can control stabilized flames for some reasonable period.

B. Summary of Findings

Test results showed that the maximum safe aperture diameter ranges from 30-70% of the published laminar-flame quenching diameter for practical flame configurations in cargo venting systems. The following values were found for the fuels tested:

Fuel	Quenching diameter*	Largest D_H which gave consistent quench	Fraction of the quenching diameter
Methane	.110"	.057"	50%
Ethylene	.060"	less than .018"	less than 30%
Acetaldehyde	.063"	.035"	56%
Toluene	.100"	.069"	69%
Methyl alcohol	.051"	.035"	69%
Gasoline vapor	.094"	.043"	46%
Butane	.015"	.038"	36%
Ethyl ether	.089"	(.015")	(17%)**
Carbon disulfide	.028"	.021"	75%
Hydrogen sulfide	.051"	(.015")	(30%)**
Acetylene	.028"	less than .015"	less than 54%
Butadiene	.059"	(.015")	(25%)**

*See Wilson and Atallah (1975).

**Range of D_H tested was limited; maximum safe D_H may be larger.

The finding that the limiting diameter is only a fraction of the reported quenching diameter is corroborated by many earlier investigations including Swan et al (1932), Holm (1933), Palmer (1958), Mansfield et al (1956), Scott et al (1962), and Muller-Hillebrand (1938). The implication is that the quenching diameter itself is not a reliable design guideline because all practical flame configurations are turbulent, even for very short run-up lengths. Arrestors must be designed with apertures of diameter less than about 40% of the smallest quenching diameter of the products (fuels) to be vented.

In addition, another criterion for flame quenching is required; this second criterion accounts for the deceleration of a flame and the transition from turbulent to laminar propagation. For this second criterion, the test results for methane support a correlation of the form $L/D_H^2 > 1000\ in^{-1}$, as proposed by Wilson and Atallah. The value $1000\ in^{-1}$ includes a safety factor and is applicable for flame speeds up to 200 ft/sec. Typical passageway dimensions which meet this design criterion are:

$L = 1.0$ in
$D_H = .032$ in

The actual experimentally determined borderline combinations of (L, D_H) were different for parallel plate and crimped ribbon:

Parallel plate	.....	$L/D_H^2 = 600\ in^{-1}$
Crimped ribbon	.....	$L/D_H^2 = 300\ in^{-1}$

This is attributed to differences in the boundary layer heat transfer mechanisms. These values of critical L/D_H^2 are consistent with the boundary layer growth explanation of Wilson and Atallah (1975), which gave $L/D_H^2 = .01\ S_t/\nu$ in any units. The values of 600 and 300 in^{-1} are larger than corresponding dimensions of arrestors which quenched methane/air flames according to Wolfhard and Brusak (1960), Maekawa (1975),

Hulsberg (1975), and Busch (1975); but agree with the experimental data of Loisson et al (1954).

The experimental results showed that there was no arrestor in our collection which could consistently quench ethylene/air flames, and therefore the L/D_H^2 criterion could not be tested for ethylene. The arrestor of L = 1.5 in, D_H = .015 in appeared to be borderline; the L/D_H^2 of this arrestor was 6700 in^{-1}, a factor of 20 greater than obtained for crimped ribbon/methane-air. The flame speeds were generally higher and more erratic (400 $\pm$ 300 ft/sec) in the ethylene/air tests. Published data by Busch (1957) and Langford, Palmer, and Tonkin (1961) show that certain arrestors will quench ethylene/air flames if the flame speeds are low enough (below 20 ft/sec).

Crimped-ribbon arrestor tests for acetaldehyde, toluene, methyl alcohol, gasoline vapor, and butane support a suggested design criterion of $L/D_H^2 > 1000$ in^{-1}, with observed minimum L/D_H^2 values ranging from 184 to 1040 in^{-1}. Limited test results showed that ethyl ether, carbon disulfide, hydrogen sulfide, and butadiene apparently require arrestors of smaller passageway diameter and larger length, with observed minimum L/D_H^2 values ranging from 1700 to 6700 in^{-1}. For acetylene-air mixtures, none of the arrestors showed consistent quench, down to D_H = .015" and L = 1.5".

C. Non-Obstructive Device Tests

A continuous steam flow of 30 lb/hr (13.8 cfm), which was approximately two times the volumetric mixture flow through the test section, was more than adequate to quench ethylene/air flames ignited 4-1/2 feet downstream of the injector. For pulsed steam injection, up to 2.7 cu ft of steam (which exceeds the test section volume) was inadequate to quench ethylene/air flames. However, for methane/air, a pulsed injection of 0.4 cu ft of steam (approximately 1/5 the test section volume) was just sufficient to quench the flame.

A high-velocity relief valve preset for 1.5 psi was tested by igniting the vented flammable mixture downstream of the valve. The tests were designed to see whether flashback could be prevented under the most demanding operating conditions (e.g., flow rates down to 2.5 cfm, compared to nominal design flows of 100 cfm). The results showed that flame blow-off occurred for methane/air flows exceeding 6.4 cfm, and below this value, flames stabilized but did not flashback through the valve seat.

II. EXPERIMENTAL METHODS

A. Test Facility Description

1. General

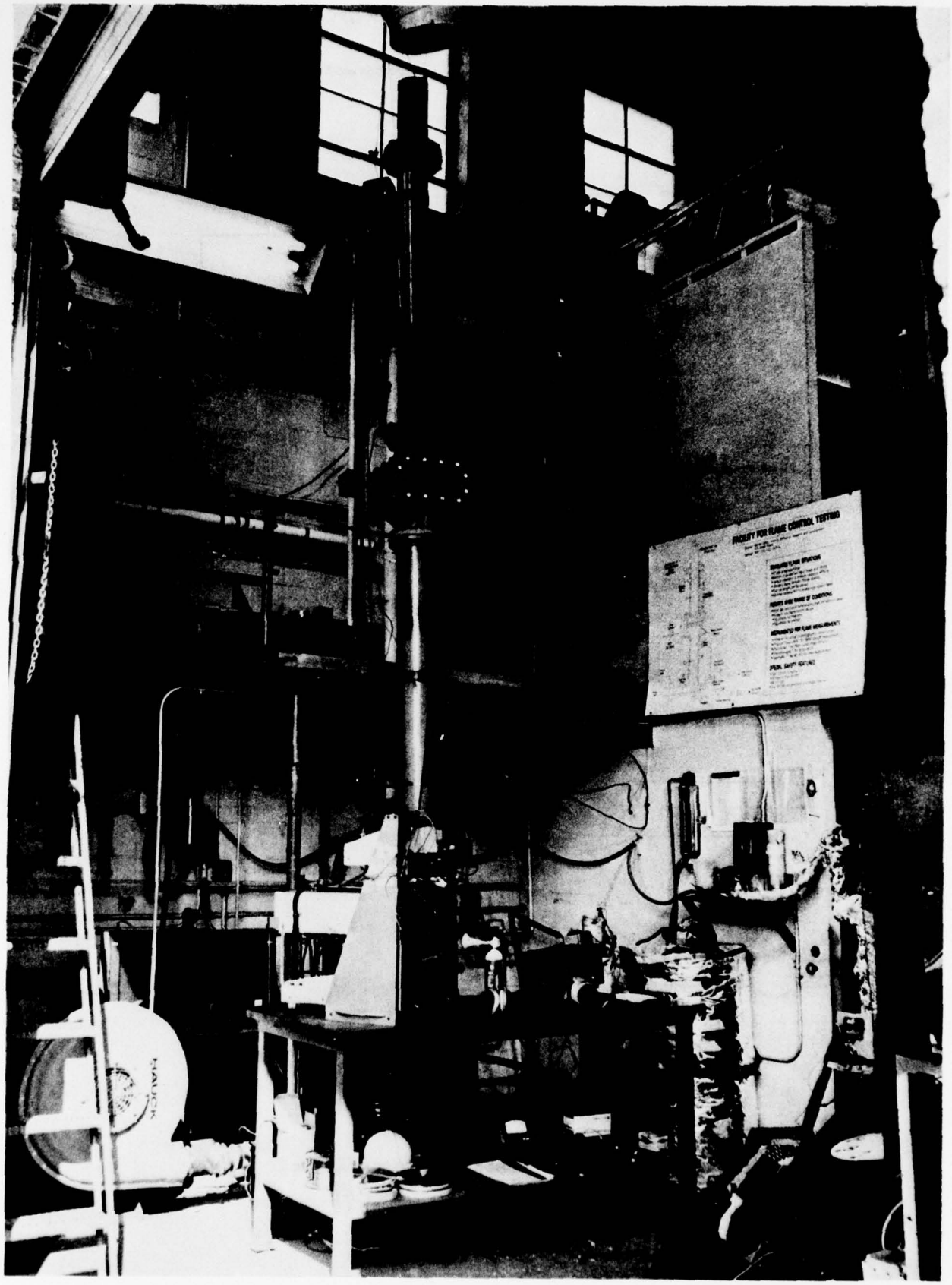
The flame arrestor apparatus consists of a 6" cylindrical test section, controls and instrumentation. A controlled flow of a specified flammable gas mixture is allowed to pass through the test section (containing the flame arrestor) and is ignited at the start of the test by a spark discharge. The resulting combustion wave accelerates toward the arrestor. The performance of the arrestor is automatically recorded. A photograph and schematic of the apparatus are given in Figures 1 and 2, respectively.

2. Test Section

Referring to Figure 2, the test section consists of 6-inch diameter vertical pipe (schedule 40), 17 feet high, with a flame arrestor housing located midway up the pipe. Provisions for both mixture preparation and pressure relief are at the base of the pipe which is connected to a 6-inch "Tee." A 6-inch diameter by 6-feet-long pipe extends horizontally from the Tee and is capped with an airtight 3-mil polyethylene blow-out membrane. Its purpose is to relieve the pressure rise during combustion. The remaining leg of the Tee is connected to a compressed air supply with appropriate flow conditioning devices.

The actual flame arrestor device is located midway up the vertical pipe section, 7.75 feet up from the top of the Tee. To permit testing of special arrestor designs fabricated at ADL, a special universal arrestor mount was fabricated using a Varec 50SG arrestor housing. (See Figure 3.)

The flame run-up distance could be controlled by adjusting the ignitor location using pipe sections of various lengths above the flame arrestor. In standard configuration, the ignitor was placed 56" above the arrestor housing flange near the top of a 64" section of pipe. This


FACILITY FOR FLAME CONTROL TESTING

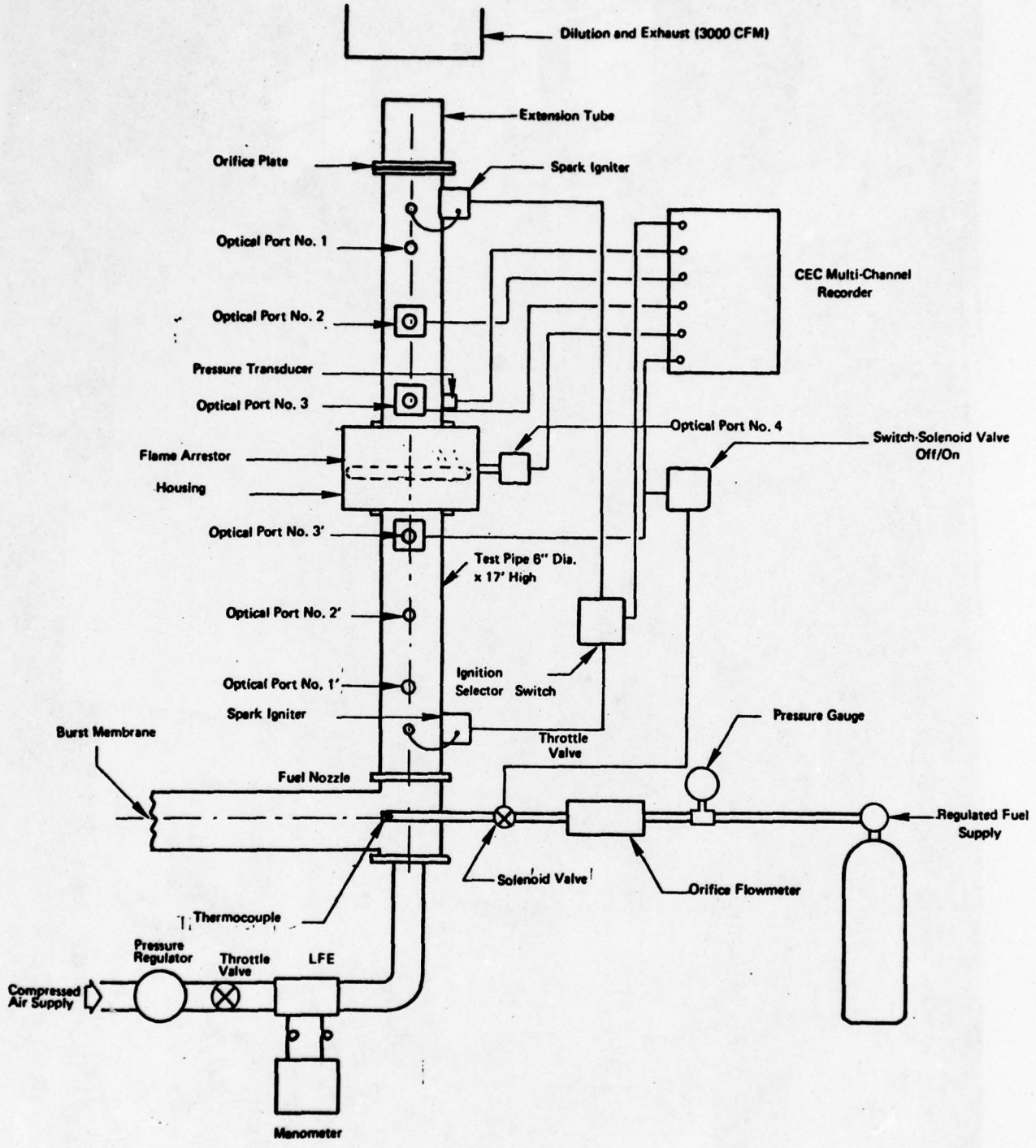


FIGURE 2. FLAME ARRESTOR TEST APPARATUS

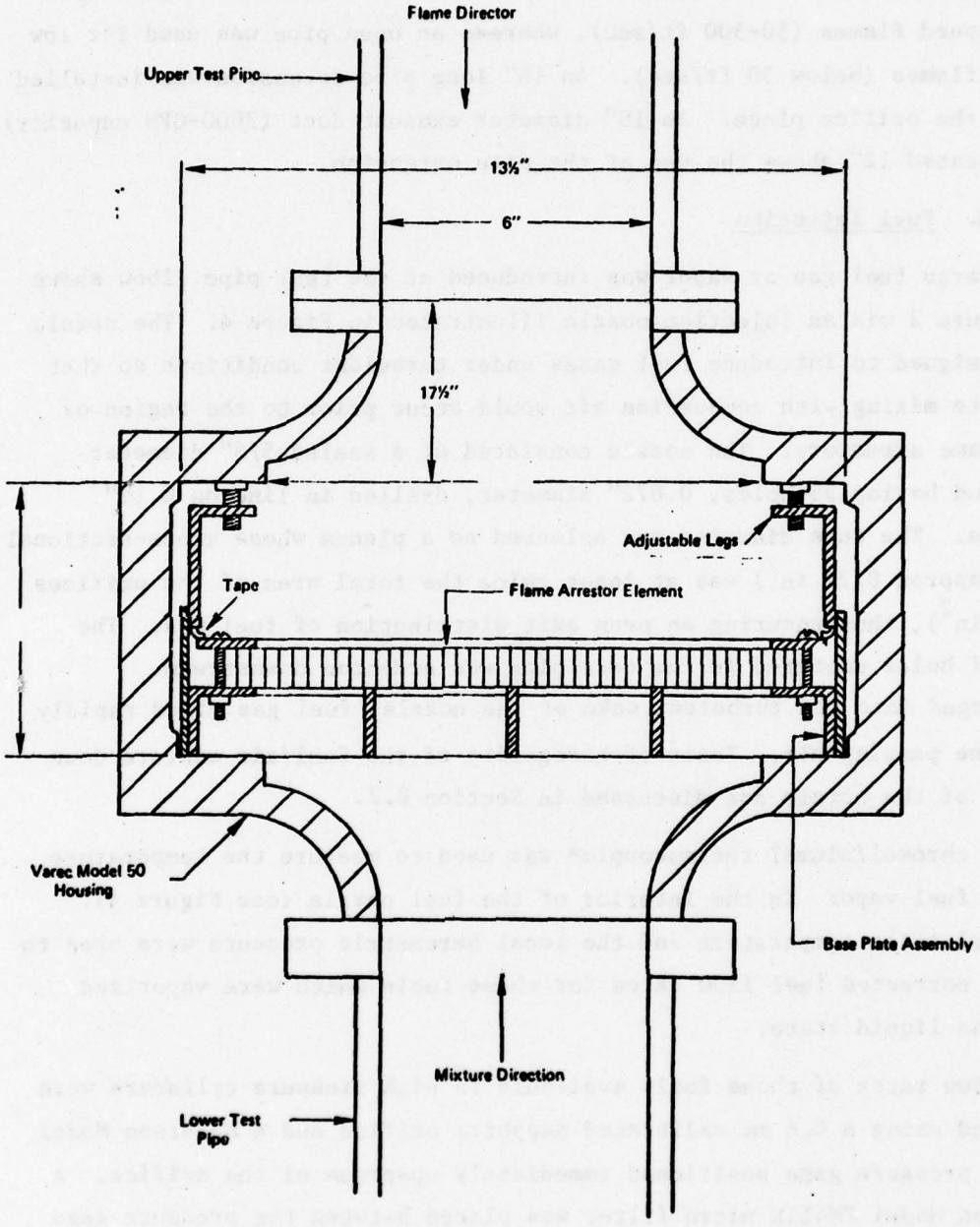


FIGURE 3 HOUSING FOR EXPERIMENTAL FLAME ARRESTORS

arrangement put the ignitor 66-68" from the arrestor, depending on arrestor thickness. An orifice plate was attached 8" above the ignitor in order to control the expansion of burned gas and thereby control flame acceleration. For example, a 3" diameter orifice was used to generate high speed flames (50-500 ft/sec), whereas an open pipe was used for low speed flames (below 50 ft/sec). An 18" long pipe extension was installed above the orifice plate. An 18" diameter exhaust duct (3000-CFM capacity) was located 12" above the end of the pipe extension.

3. Fuel Injection

Cargo fuel gas or vapor was introduced at the test pipe elbow shown in Figure 2 via an injection nozzle illustrated in Figure 4. The nozzle was designed to introduce fuel gases under turbulent conditions so that adequate mixing with combustion air would occur prior to the region of the flame arrestors. The nozzle consisted of a sealed 5/8" diameter tube and having 25 holes, 0.072" diameter, drilled in line on 0.15" centers. The tube diameter was selected as a plenum whose cross-sectional area (approx 0.27 in^2) was at least twice the total area of the orifices (0.10 in^2), thus ensuring an even exit distribution of fuel gas. The line of holes centered in the test pipe was oriented downstream. Discharged into the turbulent wake of the nozzle, fuel gas mixed rapidly with the passing air. Tests of homogenity of the fuel/air mixture downstream of the nozzle are discussed in Section B.2.

A chromel/alumel thermocouple* was used to measure the temperature of the fuel vapor in the interior of the fuel nozzle (see Figure 4). The fuel inlet temperature and the local barometric pressure were used to obtain corrected fuel flow rates for those fuels which were vaporized from the liquid state.

Flow rates of those fuels available in high pressure cylinders were obtained using a 0.6 mm calibrated sapphire orifice and a Matheson Model 635612 pressure gage positioned immediately upstream of the orifice. A Matheson Model FM411X micro filter was placed between the pressure gage

*Omega Engineering, inconel sheath type

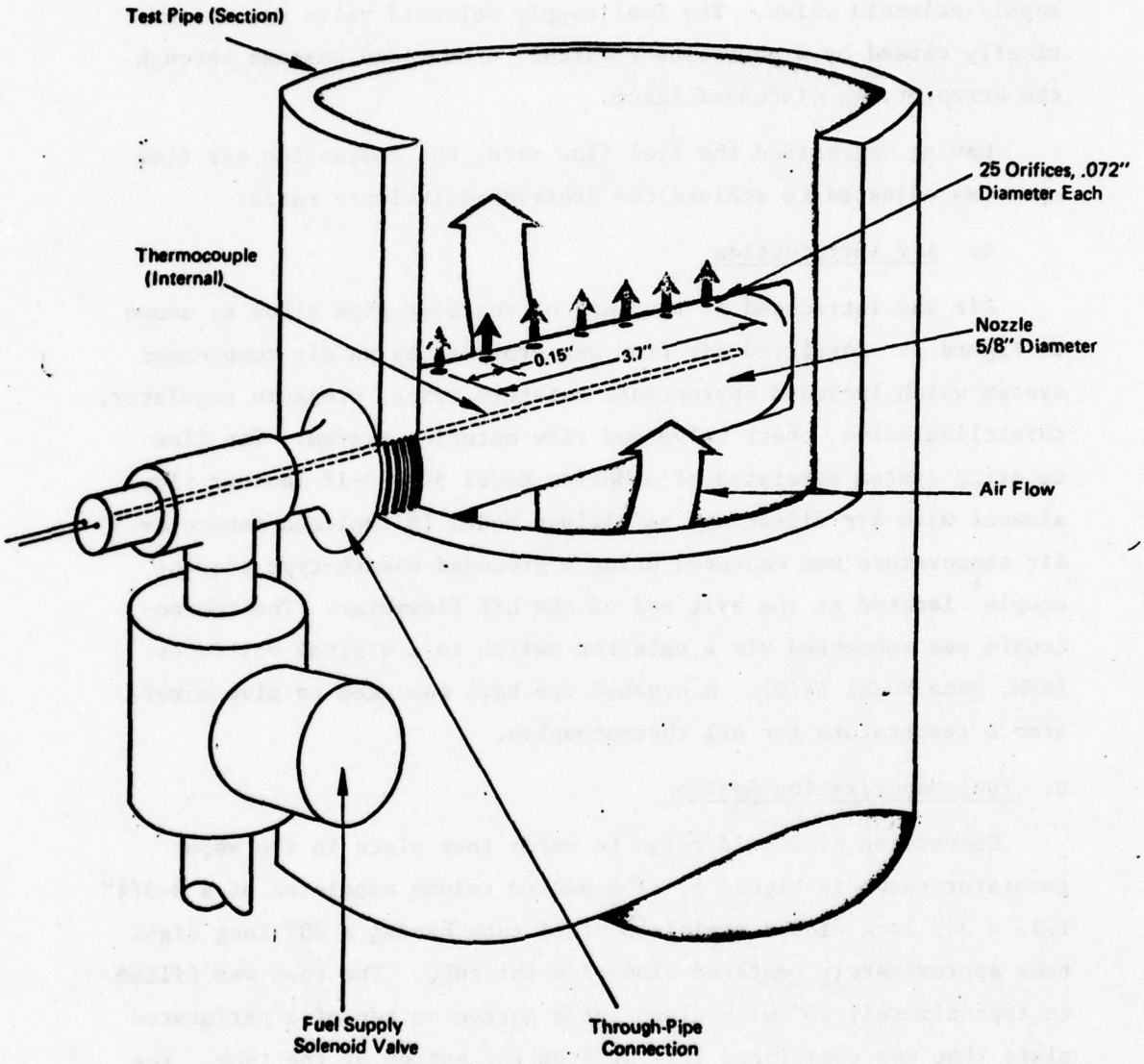


FIGURE 4 FUEL VAPOR SUPPLY NOZZLE

and the fuel supply regulator to prevent foreign matter from obstructing the 0.6 mm orifice.

After adjusting for proper flow rate conditions, fuel vapor was introduced into the test pipe upon manual activation of the fuel supply solenoid valve. The fuel supply solenoid valve was automatically closed by a photosensor circuit upon flame passage through the arrestor, as discussed later.

Having determined the fuel flow rate, the combustion air flow rate was adjusted to achieve the desired equivalence ratio.

4. Air Introduction

Air was introduced at the base of the test pipe elbow as shown in Figure 2. Regulated air flow was provided by an air compressor system which included appropriate moisture traps, pressure regulator, throttling valve, check valve and flow metering system. The flow metering system consisted of a Meriam Model 50MW20-1F laminar flow element with air filter and an Ellison Model 1N inclined manometer. Air temperature was measured using a grounded sheath-type thermocouple* located at the exit end of the LFE flowmeter. The thermocouple was connected via a selector switch to a digital voltmeter (DVM, Dana Model 4470). A crushed ice bath was used to give a reference temperature for all thermocouples.

B. Fuel Vaporization System

Conversion of liquid cargo to vapor took place in the vapor generator shown in Figure 5. The packed column consisted of a 3-3/4" I.D. x 30" long closed stainless steel tube having a 20" long sight tube approximately centered alongside the tube. The tube was filled to approximately 20" with glass beads packed on top of a perforated plate that was positioned 1/2" up from the bottom of the tube. The column was filled with 1.8 liters of the liquid cargo under test

*Omega type CAIN-116G024

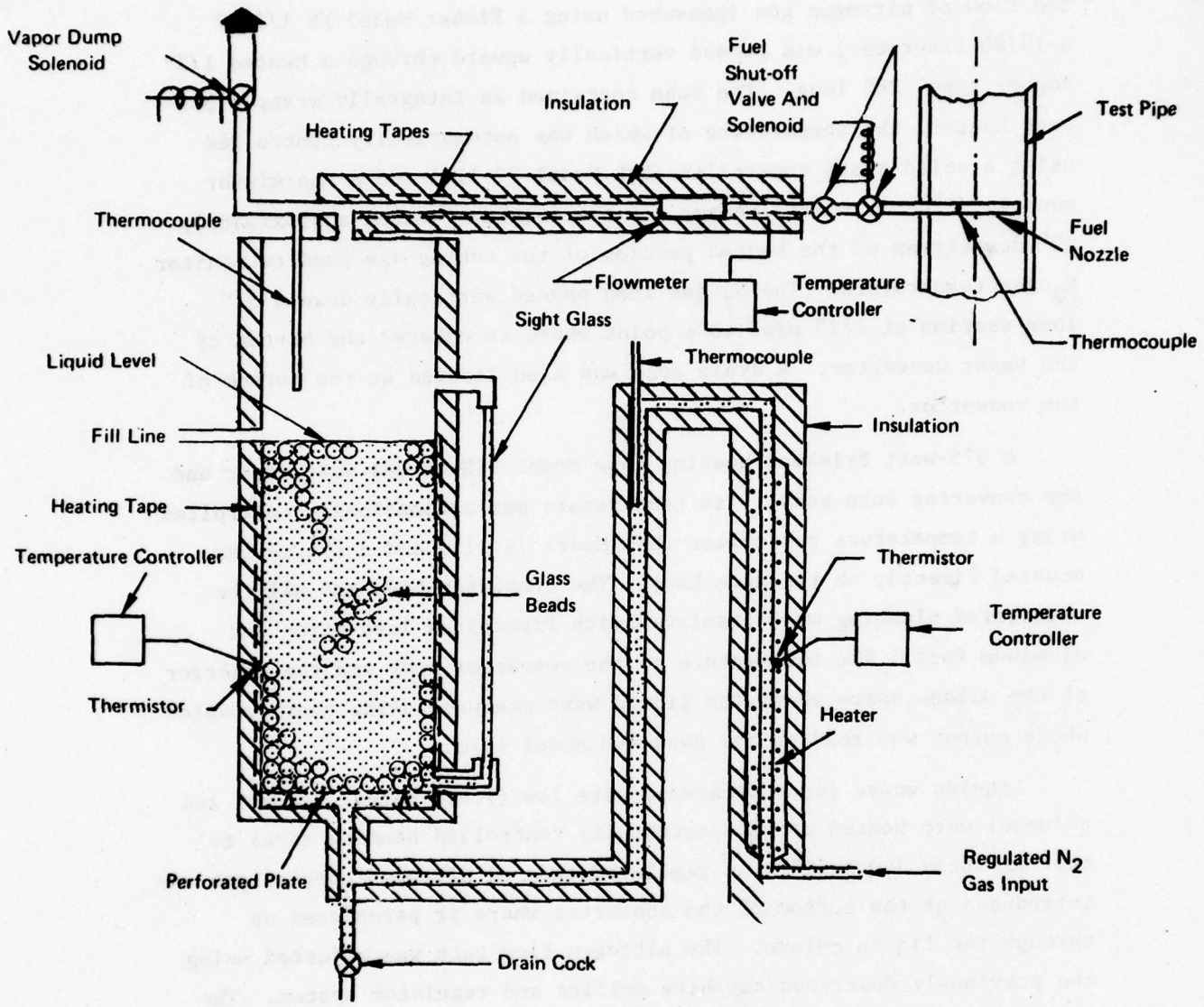


FIGURE 5 LIQUID CARGO VAPOR CONVERTER

(replenished when the level dropped to a 1.1 liter mark). A regulated flow of nitrogen gas (measured using a Fisher Model FS 1/2-27 G-10/80 flowrater) was passed vertically upward through a heated 1/2" copper tube, 28" long. The tube contained an integrally wrapped 500-watt heater, the temperature of which was automatically controlled using a solid state controller (RFL Model 72-115) and a thermistor mounted directly on the heater. A thermometer located approximately 12" downstream of the heated portion of the tubing was used to monitor N_2 gas temperature. The N_2 gas then passed vertically down a 31" long section of 1/2" pipe to a point where it entered the bottom of the vapor converter. A drain cock was also located at the bottom of the converter.

A 575-watt Briskeat heating tape Model BIH-16 was wrapped around the converter tube body. Its temperature was automatically controlled using a temperature controller (RFL Model 72-115) and a thermister mounted directly on the tube body. The converter body and all the associated plumbing were insulated with fiberglass insulation and aluminum foil. The temperature of the converter body and the interior of the ullage space above the liquid were measured using thermocouples whose output was read on the Dana DVM Model 4470.

Liquids whose vapor pressures were low (i.e., methyl alcohol and toluene) were heated using electrically controlled heating tapes to approximately 110 $\pm$ 10°F. A regulated flow of nitrogen carrier gas was introduced at the bottom of the converter where it percolated up through the liquid column. The nitrogen flow rate was adjusted using the previously described sapphire orifice and regulator system. The mixture of vapor and carrier gas, whose temperature was measured in the converter ullage space using a chromel/alumel thermocouple,* was transferred via heated plumbing through a heated rotameter** to the injection nozzle. The temperature of the plumbing and flowmeter were adjusted to prevent vapor condensation from taking place.

---

*Omega Engineering, inconel sheath type.

**Fisher Porter Model 1103.

Vapor flow rate was estimated based on rotameter reading, vapor pressure characteristics of the liquid cargoes, ullage temperature, fuel inlet temperature and local barometric pressure. The following expression was used:

$$\dot{Q}_{mix} = \dot{Q}_{air} \sqrt{\frac{1}{SG_{mix}} \left(\frac{P}{29.92\text{" Hg}}\right) \left(\frac{530°R}{T_r}\right)}$$

where:

$\dot{Q}_{mix}$ = N_2/vapor mixture flow, CFM corrected to standard condition

$\dot{Q}_{air}$ = uncorrected N_2/vapor mixture flow from rotameter calibration curve for air, CFM

SG = specific gravity of N_2/vapor mixture at flowmeter (see expression for SG below)

T_r = temperature of the mixture at the rotameter, estimated as an average of T_{vap} and the measured temperature at the nozzle

T_{vap} = vapor mixture temperature at the converter, ^oR

P = local barometric pressure, in Hg

The specific gravity of the mixture was calculated from the following expression:

$$SG = \frac{P^i_{vap}}{1 \text{ atm}} \frac{MW_i}{MW_{air}} + \left(1 - \frac{P^i_{vap}}{1 \text{ atm}}\right) \frac{MW_{N_2}}{MW_{air}},$$

where p^i_{vap} is the vapor pressure of component i at T_r, and MW is molecular weight.

The preset N_2 flow rate of 0.525 SCFM was then subtracted from $\dot{Q}_{mix}$ to obtain the vapor flow rate in SCFM. The estimated accuracy of $\dot{Q}_{mix}$ was ±5% or better.

The use of nitrogen carrier gas slightly diluted the oxygen in the air. For the methyl alcohol tests which were conducted at 3 SCFM total flow rate, the use of 0.525 SCFM nitrogen reduced the oxygen concentration to about 18%. For toluene tests (8 SCFM), the oxygen concentration was reduced to about 20%. Neither reduction is considered to be significant for arrestor performance nor the flame speed is sensitive to this small oxygen change.

For liquids whose vapor pressures were relatively high, e.g., carbon disulfide, acetaldehyde, and ethyl ether, no carrier gas was used. Rather, the vapor generated by heating the liquid was allowed to flow directly to the injector nozzle. The above flow correction was applied, except that N_2 carrier gas corrections were unnecessary.

C. Controls and Instrumentation

1. Summary of Instrumentation

A summary of the instrumentation is given in Table 1.

The liquid converter tank heaters and the inline gas heaters (595-watt, Briskeat-BIH-61 tapes wrapped over an electrically insulated layer) were controlled using Variac autotransformers.

2. Ignition Controls

Ignition of the flammable gas mixtures was accomplished using a spark ignition system located 56" above the upper flange of the arrestor housing (8" down from the orifice plate flange). The spark ignitor was an Auburn Model 1-33. A side wire was welded to the ignitor so that the actual spark was discharged at the center line of the test pipe. The spark gap at the center point was approximately 0.06". Power to the ignitor was provided by a high-voltage ignition transformer (Jefferson Electric Model 638-171, 110 vac-250 ma primary, 10,000 V-23 ma secondary). The transformer was connected via a selector switch to an ignition switch.

TABLE 1

SUMMARY OF INSTRUMENTATION

Variables Measured	Measuring Instrument	Accuracy
Air flow rate	Meriam 50 MY 15-4 Flowmeter with Meriam A844 Manometer	± 0.5%
Air temperature	Omega CAIN-116G-24 Thermocouple	± 2°F
Gas flow rate	Meriam 50W201F flowmeter with Ellison IN Manometer	± 0.5%
Gas temperature	Omega CAIN-116G-24 Thermocouple with Dana 4470 Digital Voltmeter	± 2°F
Flame speed	ADL fabricated photodetector system with EG&G HUV 1000 B sensors - 3 units	5% of value
Flame-through event	ADL fabricated photodetector system with EG&G HUV 1000 B sensor - 1 unit	Positive detection
Test chamber pressure	Kulite XTS-190-200 pressure transducer & ADL fabricated operational circuitry	± 0.5 psi
Spark ignition event Gas Solenoid valve shut off event Photodetector event signals Pressure transducer signals	CEC 5-125 Oscillograph Recorder, 8 channel	Unspecified
Barometric pressure	National weather service - local area	Unspecified

3. Flame Detectors

Four optical detector systems assembled by ADL were used to detect the progress of the flame through the test pipe. The electronic circuitry for the detectors was that specified by the manufacturer of the detector (EG&G Model HUV-1000B with amplifier). The detectors were housed in a light-tight aluminum box 3" x 4" x 5" with a 7/8" dia x 3" long extension tube (see Figure 6). The extension tube, the purpose of which was to isolate the photodetector circuit from the heat of the test pipe, was slip fitted over an Auburn Type P-50 observation window that was threaded into the test pipe (1/2" NPT) in a direction normal to the pipe axis. A horizontal viewing slit in the window restricted the angle of view of the detector element in order to achieve more precise measurements of the position of the flame front.

The system was arranged so that the optical detector locations could be readily interchanged depending on whether ignition took place in the upper or lower test pipe sections. Figure 2 shows the location of the various ports for the detectors. When ignition occurred in the upper test pipe, ports 2, 3, and 4 were used for detecting flame passage, while port 3' was used for detection of flame-through at the arrestor. The optical detector in port 3' was also connected via a power amplifier to the fuel solenoid valve. In the event of flame-through, the fuel solenoid automatically shut off.

4. Pressure Measurement

The test assembly was also provided with a means of measuring the instantaneous pressure levels generated in the test pipe by the combustion of the gases. For this, a Kulite Model XTS-190-200 pressure transducer and appropriate circuitry (recommended by the manufacturer) was used. Like the optical detectors, the location of the pressure transducer could be readily changed according to the test circumstance. The transducer was mounted in 1/4" NPT elbow fitting and the elbow fitting was threaded into the test pipe (see Figure 7). In this way the transducer was located out of the path of direct radiation from the

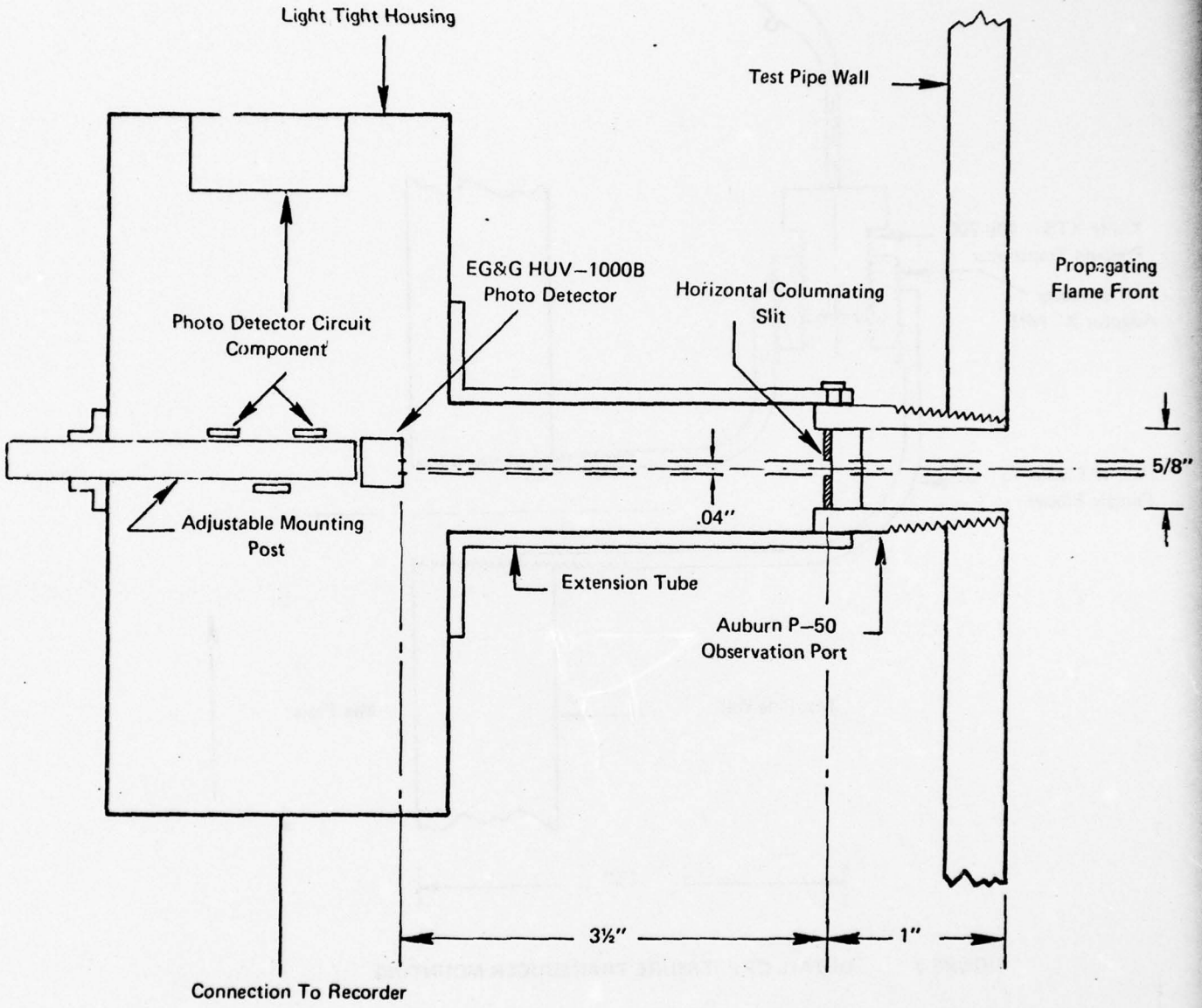


FIGURE 6 PHOTODETECTOR ARRANGEMENT

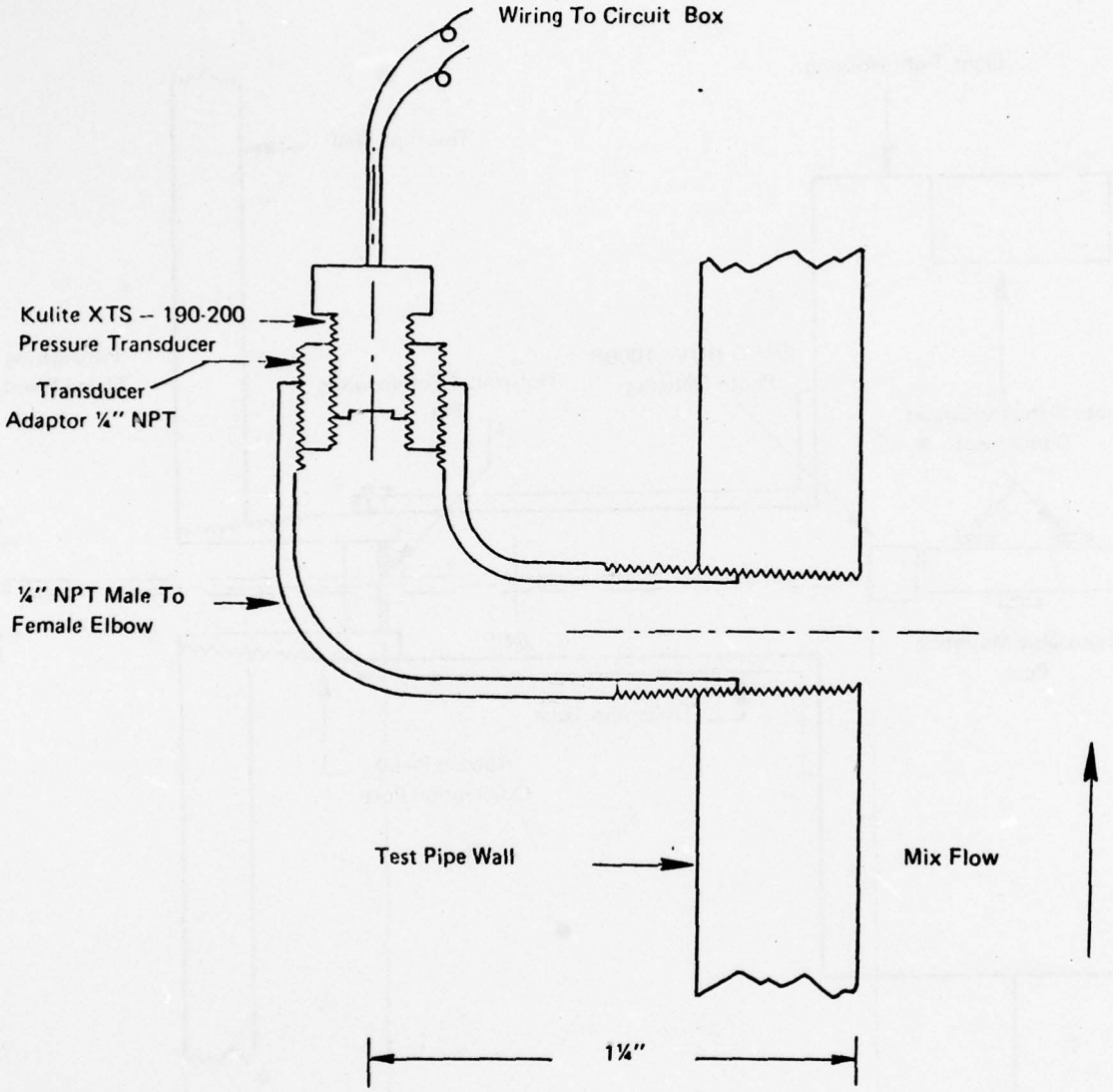


FIGURE 7 DETAIL OF PRESSURE TRANSDUCER MOUNTING

flames. (In early tests direct radiation appeared to have an effect on the transducer signals.) The transducer was located 44" from the arrestor, at the same station as optical port 2.

5. Operating Procedure

In conducting a test, the following sequential procedure was followed:

(1) A safety check of the test site was made which included:
- Access to fire extinguishers,
- Wearing of hard hats, glasses and ear protection,
- Locating danger warnings and restricted area barriers, and
- Turning on flashing red lights in critical area of the test site.

(2) A check of the optical detector and pressure detector battery condition was made.

(3) The Main Power Switch was turned on.

(4) The recorder power and optical, pressure detector power, switches were turned on ignition power and DVM power.

(5) The selection of the upper ignition source was made.

(6) The arrestor element was installed in the housing (after it had previously been prepared for testing) and the housing cover was secured.

(7) For liquid cargoes, the fuel supply and inline heaters were activated and allowed to come to thermal equilibrium at approximately 100°F and 120°F, respectively.

(8) The air compressor was turned on and, after allowing sufficient time to charge the air supply reservoir, it was adjusted to achieve the appropriate flow rate. Corrections to the flow rate for barometric pressure and air temperature were made, based on the manufacturer's (Meriam Instrument) operating instructions. Air was allowed to flow continuously for the entire test series during a given day.

(9) a) Gaseous Cargoes: The gas supply tank was opened by means of the fuel solenoid valve and manual valve at the gas regulator. The fuel-adjustment valve was opened to achieve the directed fuel flow rate (corrected for barometric pressure and gas temperature).

b) Liquid Cargoes: The fuel shut-off valve and solenoid valve were opened. This was followed by a measurement of the fuel flow rate. Corrections for barometric pressure and fuel gas temperature were also made. The air flow rate was subsequently changed to achieve the appropriate equivalence ratio.

(10) A pneumatic-horn signal was given 10 seconds before ignition.

(11) In rapid sequence:

- The recorder chart was turned on (generally to 16"/sec speed for adequate trace resolution).
- The ignitor energized--followed immediately by combustion.
- The recorder was turned off (after approximately 1 second).

(12) The automatic switch for shutting the fuel solenoid valve was manually overridden (if it had not operated automatically) within 1 second. Otherwise, a standing flame could damage the arrestor or the instrumentation.

(13) The manual fuel flow throttling valve was then shut off within 5 seconds of spark discharge.

(14) The recorder trace was examined for evidence of flame-through, flame speed, and combustion pressure (see below).

6. Data Acquisition

An 8-channel recorder (CEC Model 5-124) was used to record signals from the instrumentation. The three optical detectors and the pressure detectors were connected directly to the recorder. The signal from the flame-through detector was, as mentioned above, connected to a power amplifier to shut off the fuel solenoid. This signal was also connected to the recorder so that the flame-through event could be

recorded. A signal from the ignition switch was also connected to the recorder to measure the existence and duration of the spark discharge. Figure 8 is an illustration of the typical data obtained from the recorder. The explanation of the trace is as follows:

Trace A: The length of the 60-cycle trace indicated the time interval that the ignition source was energized.

Trace B: The 60-cycle portion indicates that the fuel solenoid valve is open, the steady portion to the right of the 60-cycle trace indicates automatic solenoid shut-off or flame-through.

Traces C, D and E : Flame passage traces from optical detectors 4, 3, and 2, respectively (typical). The distances between detectors is known and thus flame velocity between these points are determined (also flame acceleration).

Trace F: Instantaneous pressure trace--for the subject tests the peak value of the trace was converted to peak pressure by calibration.

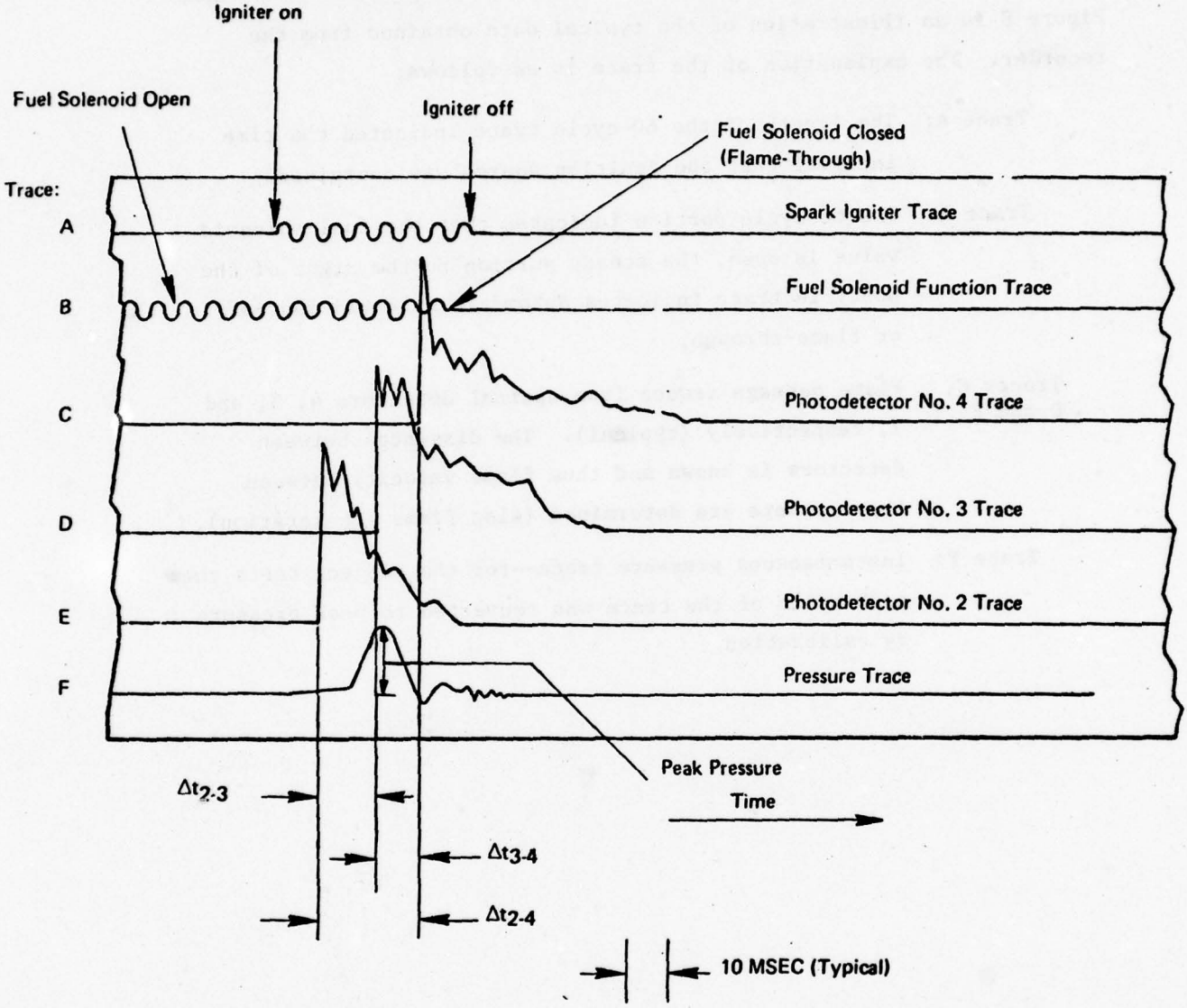


FIGURE 8 TYPICAL TEST DATA RECORDING

D. System Characteristics

1. Effect of Downstream Flow Restriction Orifice on Flame Speed

The design of the test apparatus includes provisions for assessing the performance of arrestors through the use of orifices placed between the test pipe and pipe extension (see Figure 2) in both low flame speed and high flame speed regimes. A series of tests was performed using methane/air mixtures to establish two specific flame speed regimes at which all arrestors were to be tested. With fuel/air equivalence ratio adjusted to $\phi = 1.1$, it was found that without any constriction in the test pipe, flame speeds of approximately 5 ft/sec were measured at approximately 2 ft from the arrestor location. By using a 3" dia. orifice, flame speeds of approximately 70 ft/sec were achieved. Insofar as was possible, test conditions were adjusted for each arrestor and with each cargo to achieve flame speeds in these two regimes. Adjustments included run-up length and degree of constriction of the test pipe.

2. Mixture Homogeneity Tests

Because of the importance of ensuring good mixing of the test gas and combustion air during all tests, a check was made of the homogeneity of two test gases approximately 18" above the fuel injection nozzle and immediately beneath the flame arrestor housing. The tests were performed by substituting nitrogen gas in place of combustion air and substituting oxygen in place of fuel gas. Oxygen concentration was then measured as simulated fuel concentration. Bottled dry nitrogen was introduced upstream of the laminar-flow element normally used to measure combustion air flow rates. A regulated supply of oxygen was introduced upstream of the 0.6 mm sapphire orifice metering system. Flow rates for each gas were adjusted to be equivalent to that of methane and air mixtures at $\phi = 1.1$. An oxygen meter operated in conjunction with a gas sampling and drying system was used for determining the percent oxygen and variation in O_2/N_2 percentages of the mixture. Any variations in the O_2/N_2 ratio were detected by traverse sampling across the interior radius of the test pipe at two axial locations. The results of the gas sampling are shown below in Table 2.

TABLE 2

DETAILS OF GAS MIXTURE HOMOGENEITY TESTS

USING OXYGEN/NITROGEN MIXTURES

Gas Test No.	Oxygen Flow Rate (SCFM)	Nitrogen Flow Rate (SCFM)	Total Gas Flow Rate (SCFM)	Percent Oxygen in Mixture (%)	Measured Oxygen Percentage in Mixture (%)	Gas Sampling Location: Distance Downstream of Fuel Nozzle (in)	Gas Sampling Location: Radial Scan Position (Inches from pipe ℄)
1	0.228	8.05	8.28	2.75	2.75	18	0
2	0.214	8.09	8.30	2.58	2.65	18	0
3	0.228	8.05	8.28	2.75	2.80	18	0
4	0.228	8.05	8.28	2.75	2.80	18	1
5	0.228	8.05	8.28	2.75	2.80	18	2
6	0.230	8.01	8.24	2.79	2.80	18	-2
7	0.228	7.98	8.21	2.78	2.80	18	0
8	0.760	7.98	8.74	8.69	8.60	18	0
9	1.100	8.00	9.10	12.10	12.1	90	-2
10	1.100	8.00	9.10	12.10	12.1	90	0
11	1.100	8.00	9.10	12.10	12.0	90	2

From the above table it can be seen that complete mixing of gas and air takes place well upstream of the arrestor test section.

3. Effect of Equivalence Ratio Variations on Flame Speed

To confirm the relationship between equivalence ratio and flame speed, which is expected to peak just on the rich side of stoichiometric, a series of low flame speed (5 ft/sec) tests was performed using methane/air mixtures. The data, illustrated in Figure 9, has the expected peak, with reproducibility of flame speed approximately 0.5 ft/sec or 10%. The flame speeds shown are based on V_{23}.

4. Effects of Gas Temperature on Flame Speed and Safe Arrestor Dimensions

A series of preliminary low-speed tests was conducted with mix temperatures ranging from 70 to 185°F in order to determine if the temperature of the gas mixture due to ambient temperature variations had a significant effect on flame velocity. Electric heaters were wrapped around the test pipe from the air inlet to the flame arrestor housing. The total test pipe length was in turn insulated with fiberglass blanket insulation. In addition, an electric heater element was wrapped around the air inlet pipe and in the gas stream approximately 12" downstream of the arrestor housing were used in conjunction with electric power controllers to establish proper test temperatures.

In conducting the tests, flow conditions and temperatures were adjusted and allowed to come to steady state prior to conducting combustion tests. Test temperatures ranged from near room temperature to approximately 185°F as measured downstream of the arrestor housing. The results of the tests, as illustrated in Figure 10, show that for this specific test apparatus and temperature range, the mixture temperature apparently does not have a significant effect on flame speed, within the experimental error of the system. The range of temperatures tested was too limited to show the power-law dependence of flame speed on mixture temperature expected from theory [see Wilson and Atallah (1975)]. Since this temperature range is as large as that of ambient temperature variations for venting operations, we expect no substantial change in flame speed due to ambient temperature variations. Therefore since $D_H \sim 1/T$, a single arrestor design should be equally safe for all temperatures.

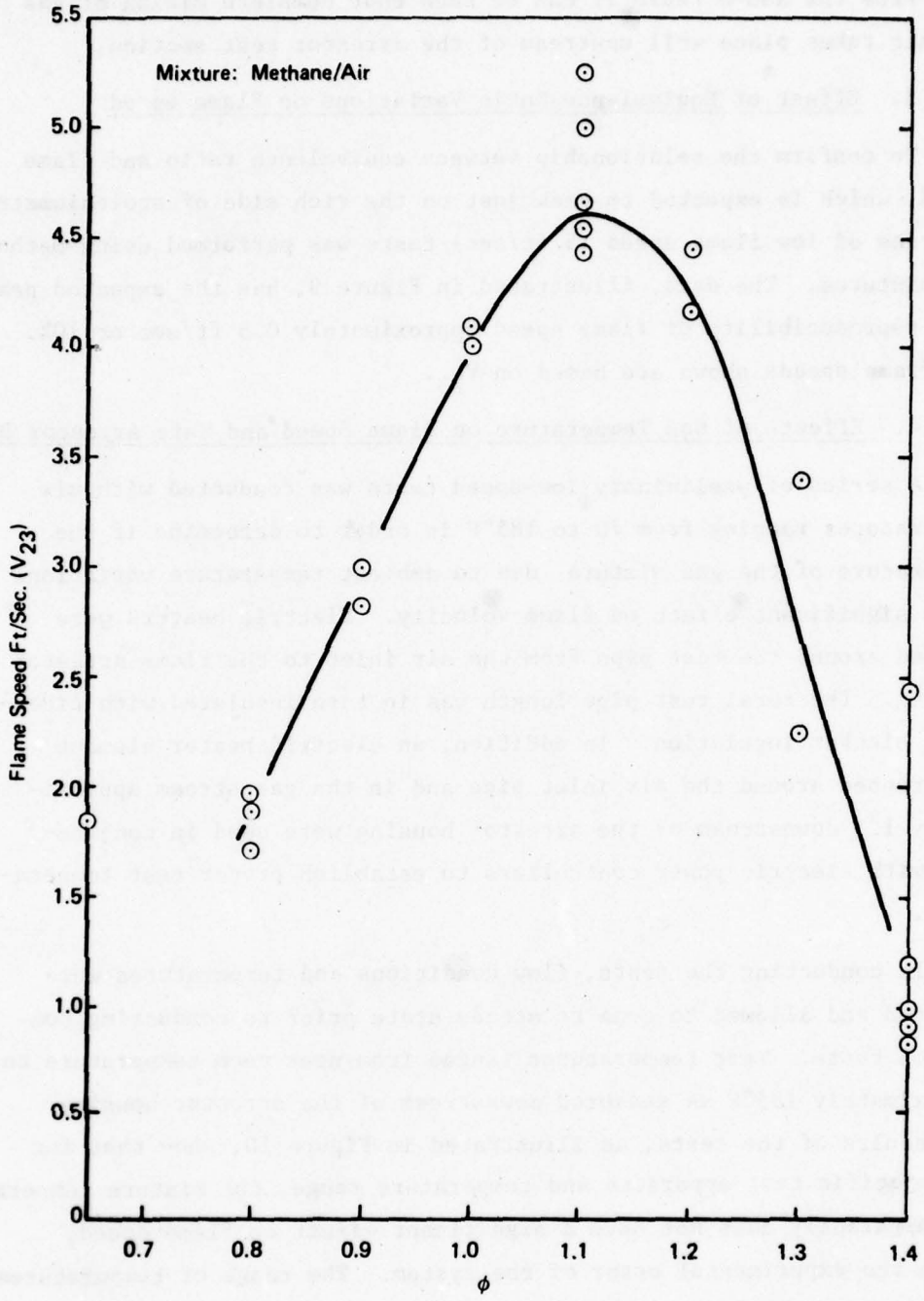


FIGURE 9 EFFECT OF EQUIVALENCE RATIOS ON FLAME SPEED

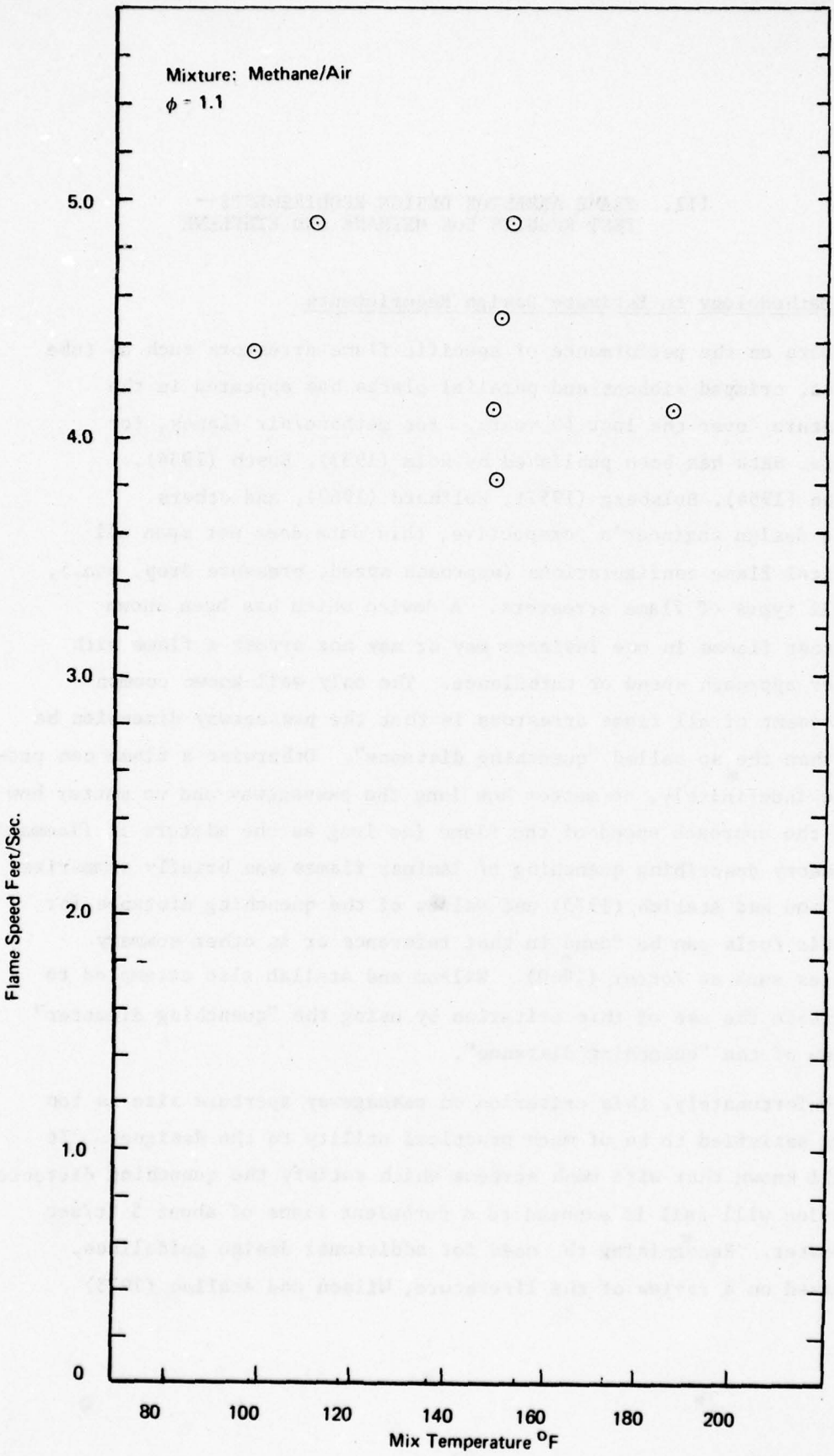


FIGURE 10 EFFECT OF MIX TEMPERATURE ON FLAME SPEED

III. FLAME ARRESTOR DESIGN REQUIREMENTS-- TEST RESULTS FOR METHANE AND ETHYLENE

A. Methodology to Estimate Design Requriements

Data on the performance of specific flame arrestors such as tube bundles, crimped ribbons and parallel plates has appeared in the literature over the last 40 years. For methane/air flames, for example, data has been published by Holm (1933), Busch (1934), Loisson (1954), Hulsberg (1957), Wolfhard (1960), and others. From a design engineer's perspective, this data does not span all practical flame configurations (approach speed, pressure drop, etc.), nor all types of flame arrestors. A device which has been shown to arrest flames in one instance may or may not arrest a flame with greater approach speed or turbulence. The only well-known common requirement of all flame arrestors is that the passageway dimension be less than the so called "quenching distance". Otherwise a flame can propagate indefinitely, no matter how long the passageway and no matter how great the approach speed of the flame (as long as the mixture is flammable). The theory describing quenching of laminar flames was briefly summarized by Wilson and Atallah (1975) and values of the quenching distance for specific fuels can be found in that reference or in other summary articles such as Potter (1960). Wilson and Atallah also attempted to facilitate the use of this criterion by using the "quenching diameter" in lieu of the "quenching distance".

Unfortunately, this criterion on passageway aperture size is too easily satisfied to be of much practical utility to the designer. It is well known that wire mesh screens which satisfy the quenching distance criterion will fail if exposed to a turbulent flame of about 5 ft/sec or greater. Recognizing the need for additional design guidelines, and based on a review of the literature, Wilson and Atallah (1975)

proposed an additional criterion for a minimum passageway length:

$$L \geq K S_t D_H^2, \qquad (3\text{-}1)$$

where S_t is the turbulent flame speed at the arrestor and K is a coefficient which must be fit from empirical data. This L/D_H^2 correlation had been suggested by Palmer, and Wilson and Atallah found that a value of $K = .02$ sec/cm^2 seemed to fit the results of a number of investigations on propane/air flame arrestors. Furthermore, the form of eqn. (3-1) could be explained in terms of laminar boundary layer growth within the passageway (which gave $K = .01\ \nu^{-1}$, where ν is the kinematic viscosity). The Reynolds analogy of relating heat extraction to momentum extraction also is consistent with an $L/D_H^2 \sim S_t$ criterion, which suggests that the pressure drop is a measure of flame arrestor effectiveness. Cohen (1960) raised this possibility in a discussion of Palmer's work on flame arrestors, and Palmer at that time confirmed that an L/D^2 correlation for pressure drop would probably be appropriate but would be difficult to apply to packed bed arrestors.

The purpose of the present test series was to test this proposed criterion for methane by systematically varying the passageway length and diameter. The value of the constant K was to be empirically determined for methane/air flames, and additional tests were to be run on ethylene to see if K was larger than for methane, as expected. Finally, several types of arrestors (passageway geometries) were tested in order to check the applicability of eqn. (3-1) for various arrestors.

B. Experimental Conditions

Four types of arrestors were evaluated during this test series:

- Screen
- Perforated plate (stacked)
- Parallel plate
- Crimped ribbon

The passageway dimensions of the arrestors are listed in Table 3. The arrestor mounting base was modified slightly to permit testing of the various arrestor elements using a Varec Model 50SG arrestor housing. The modifications were mainly concerned with securing the arrestor elements to the mounting base in a manner that prevented flame passage through gaps at the circumference of the test arrestor.

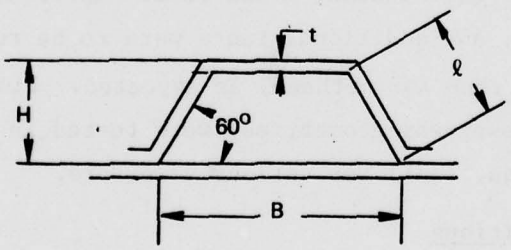
For perforated plate arrestors, the hydraulic diameter of the passageways is simply the diameter of the circular perforations. For screens, plates, and crimped ribbon, the hydraulic diameters were determined using the relationship

$$D_H = \frac{4A}{P} ,$$

where

A = cross-sectional area of the aperture, and
P = perimeter of the aperture

Examples of the determination of the D_H are given as follows. The crimped ribbon arrestors fabricated by Ferrotherm Corporation consisted of half-hexagonal shaped arrestor cells. Accordingly, the effective hydraulic diameter was determined using the following relationships:



$A = 1/2\ (H - t)\ (\ell + B)$

$B = \ell + 2\ell \cos 60° = 2\ell$

$P = 5\ell$

$D_H = 4A/P = 4(1/2)\ (H - t)\ 3\ell/5\ell$

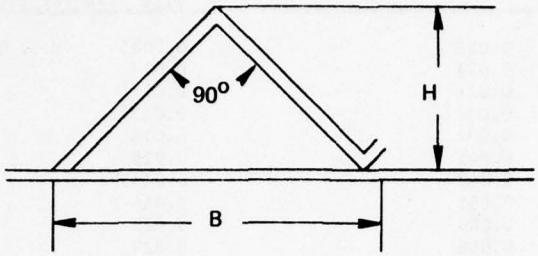
$$D_H = 1.2\ (H - t)$$

TABLE 3

PASSAGEWAY DIMENSIONS OF ARRESTORS TESTED

Arrestor	Mesh	D_H (in)	L (in)	Remarks Wire Diameter (in)	
Screens	38	0.018	-	0.0085	M.S. Tyler, Inc.
	30	0.021	-	0.012	
	26	0.027	-	0.011	
	22	0.032	-	0.0135	
	20	0.032	-	0.016	
	18	0.041	-	0.015	
	16	0.049	-	0.0135	
	14	0.055	-	0.016	
	12	0.060	-	0.023	
	11	0.068	-	0.023	
	10	0.080	-	0.020	
	8	0.105	-	0.020	
Perforated Plates	-	0.020	0.018	Single layer	ERDLE Perforating Company
	-	0.062	0.048	"	
	-	0.072	0.048	"	
	-	0.107	0.062	"	
	-	0.072	0.26	Stacked plates	
	-	0.072	0.40	"	
	-	0.107	0.56	"	
	-	0.062	0.18	"	
Parallel Plates	-	0.015	0.25	0.045" thick	Fabricated at ADL
	-	0.015	1.50	" plates	
	-	0.021	0.50	"	
	-	0.023	0.25	"	
	-	0.023	0.50	"	
	-	0.028	1.50	"	
	-	0.031	1.06	"	
	-	0.035	0.50	"	
	-	0.035	1.06	"	
	-	0.035	1.56	"	
	-	0.035	2.00	"	
	-	0.045	0.50	"	
	-	0.045	1.00	"	
	-	0.056	2.00	"	
	-	0.071	0.50	"	
	-	0.071	1.06	"	
	-	0.071	2.00	"	
	-	0.112	1.02	"	
Crimped Ribbon	-	0.015*	0.75	-	Ferrotherm Mfg, SST material, half hex crimp
	-	0.015*	1.50	-	
	-	0.016	0.25	-	
	-	0.016	0.375	-	
	-	0.021	0.75	-	
	-	0.035	0.25	-	*Commercially available from Amal Ltd.
	-	0.035	0.375	-	
	-	0.035	0.50	-	
	-	0.038*	1.50	-	
	-	0.050	0.75	-	
	-	0.054	1.50	-	
	-	0.054	2.00	-	
	-	0.069	0.88	-	
	-	0.069	1.25	-	
	-	0.069	2.00	-	
	-	0.069	2.62	-	
	-	0.078	1.00	-	

Effective hydraulic diameters for the Amal arrestors, which have triangular passageways, were determined using the following relationships:



$B = 2H$

$A = 1/2BH$

$P = B + (2) H \sqrt{2}$

$D_H = 4 (1/2) BH/(B + 2\sqrt{2} H) = 4 H^2/2H (1 + \sqrt{2}) = 2H/(1+\sqrt{2}) = .83 H$

Methane/air and ethylene/air mixtures were used during this test series. Fuel/air ratios were $\phi = 1.1$ for all tests. Mixture velocities were adjusted to 0.5 ft/sec through the 6" diameter test section. Ignition was always downstream of the arrestor. The run-up length and pipe constriction area were adjusted to produce flame speeds of 5-25 ft/sec for "low speed" tests and 50-200 ft/sec for "high speed" tests.

C. Results of Methane/Air Tests

A series of tests at low flame speed (5 ft/sec) was performed with single-layer screens and perforated sheets, searching for the largest mesh size which would arrest a methane-air flame. The results are given in Figure 11, and show that the critical screen size is between 14 and 12 mesh. Accounting for the finite wire diameter, the aperture size which is critical apparently lies between .055 and .061 inch, or about 50% of the theoretical quenching diameter for methane/air (.11 inches). This finding is consistent with other investigators' findings. For example, Muller-Hillebrand (1938) noted that the maximum allowable aperture for acetylene/air was only 40% of the theoretical quenching diameter.

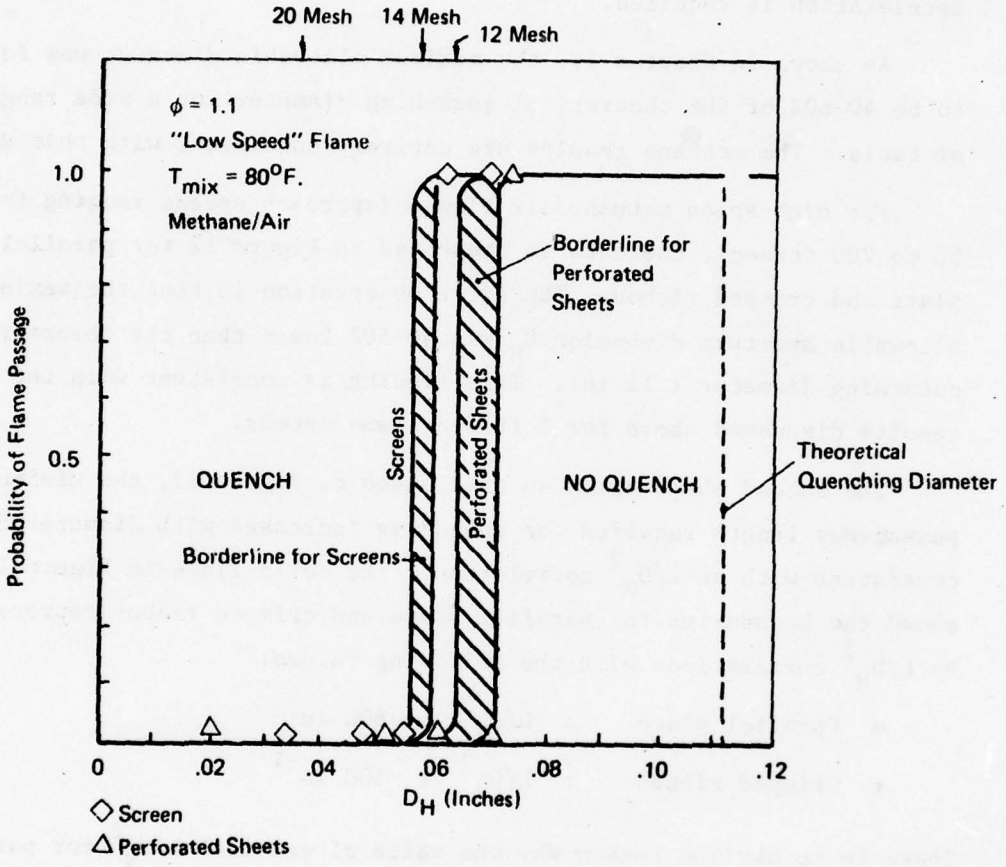


FIGURE 11 FLAME QUENCH DATA FOR LOW SPEED METHANE/AIR FLAMES

The implication from these tests is that the diameter criterion is not adequate to design flame screens against even the lowest conceivable flame speeds. In all practical situations, the laminar flame speed (30 cm/sec for CH_4) is greatly exceeded by the actual flame speed, and therefore some additional criterion accounting for flame deceleration is required.

As shown in Chapter IV, the maximum allowable diameter was found to be 40-60% of the theoretical quenching diameter for a wide range of fuels. The methane results are entirely consistent with this data.

For high-speed methane/air flames (approach speeds ranging from 50 to 200 ft/sec), the data is presented in Figure 12 for parallel plate and crimped ribbon. The first observation is that the maximum allowable aperture dimension D_H was 40-50% lower than the theoretical quenching diameter (.11 in). This finding is consistent with the results discussed above for 5 ft/sec flame speeds.

The second observation is that based on Figure 12, the minimum passageway length required for quenching increases with diameter D_H consistent with an L/D_H^2 correlation. The solid lines in Figure 12 shows the boundaries for parallel plate and crimped ribbon represented by L/D_H^2 correlations with the following values:

- Parallel plate : $L/D_H^2 = 600\ in^{-1}$
- Crimped ribbon : $L/D_H^2 = 300\ in^{-1}$

There is no obvious reason why the value of critical L/D_H^2 for parallel plates should be twice that of crimped ribbon. Presumably, differences in the heat transfer rate within the boundary layer for the two geometries account for this difference. If so, the Reynolds analogy would predict that the pressure drop of a given length of parallel plate should be less than that of crimped ribbon. This was, however, not evaluated in this program. Another possible explanation is that the use of hydraulic diameter to apply the L/D_H^2 correlation universally to arrestors of different geometry is quite arbitrary and may introduce some error for certain arrestor geometries. For example, Berlad and Potter (1954) indicate that the critical quenching dimension for parallel

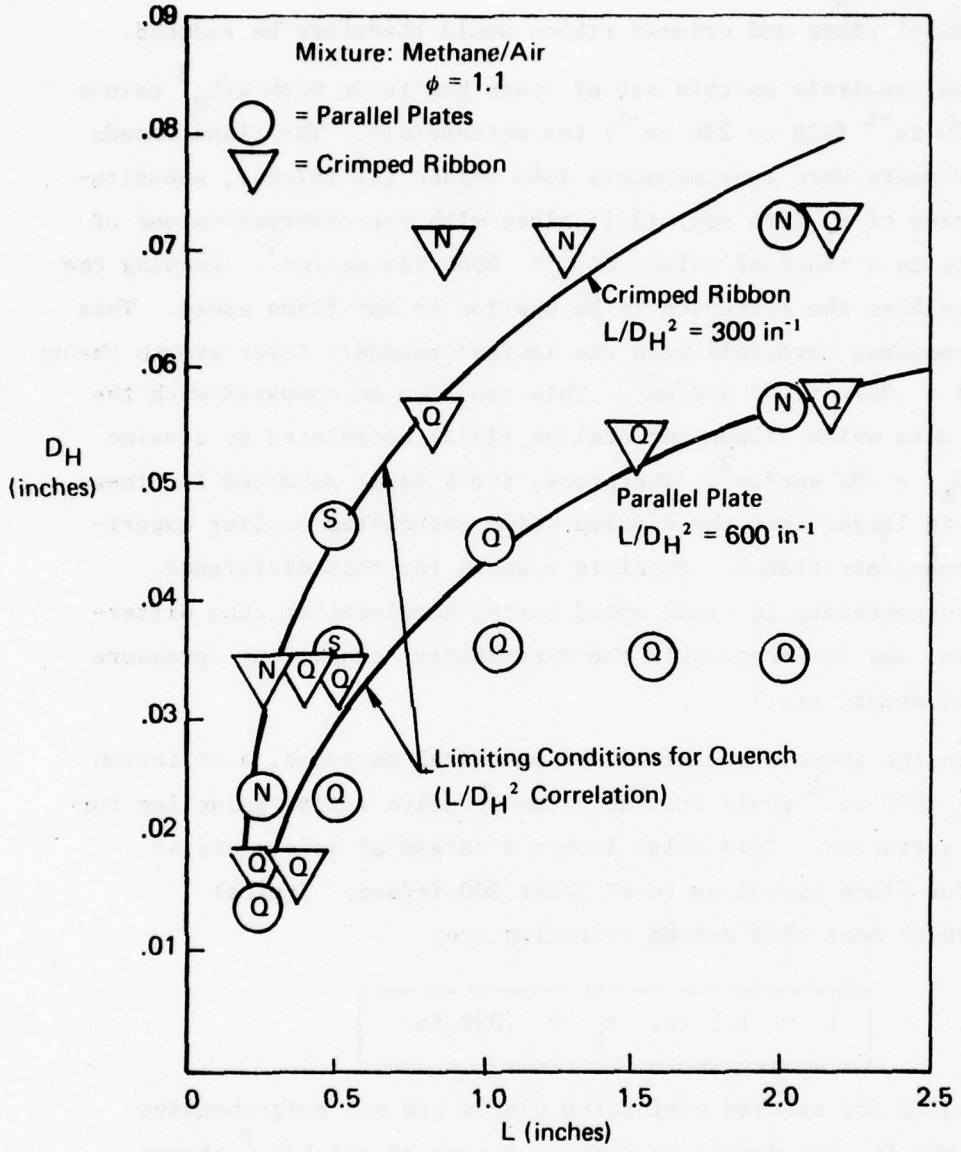


FIGURE 12 FLAME QUENCH DATA FOR METHANE/AIR FLAMES

plates is a factor of 0.613 of the tube diameter, whereas Wilson and Atallah (1975) suggested a factor of 0.710. Applying Berlad and Potter's formula to the present data, the equivalent value of L/D_H^2 for parallel plates would be $L/D_H^2 = 445$ in^{-1} instead of 600 in^{-1}. The discrepancy between parallel plate and crimped ribbon would therefore be reduced.

The final analysis on this set of tests has to do with L/D_H^2 values of 300 to 600 in^{-1} (118 to 236 cm^{-1}) for methane/air. The flame speeds in our experiments were approximately 2040 cm/sec (67 ft/sec); substituting this value of S_t into eqn. (3-1) along with the observed values of L/D_H^2 results in a range of values of K = .058-.116 sec/cm^2. Knowing the value of K enables the criterion to be applied to any flame speed. This value of K compares favorably with the laminar boundary layer growth theory which gave $K = .01/\nu = .07$ sec/cm^2. This can also be compared with the propane/air data which Wilson and Atallah (1975) correlated by a value of $K = L/S_t D_H^2 = .02$ sec/cm^2. Therefore, the K value reported for these experiments is larger than the K value which correlated earlier experiments on propane/air flames. Possible reasons for this difference include the uncertainty in flame speed during acceleration, the difference in fuels, and differences in the experimental conditions (pressure rise, pipe diameter, etc.)

Based on the above discussion, for practical purposes, a criterion that $L/D_H^2 \geq 1000$ in^{-1} would provide a conservative design guideline for methane/air arrestors. This value leaves a margin of safety and is applicable for flame speeds up to at least 200 ft/sec. Typical dimensions which meet this design criterion are:

$$L = 1.0 \text{ in}, \quad D_H = .032 \text{ in.}$$

The results for stacked perforated plates are not comprehensive enough over the (L, D_H) domain to provide a test of the L/D_H^2 theory. As shown in Figure 13, the largest-D_H arrestor with consistent quench was of dimensions $D_H = .072$ in, $L = 0.4$ in. This corresponds to a value of $L/D_H^2 = 77$ in^{-1}, which is much lower than the values determined for crimped ribbon and parallel plates. Some misalignment of the stacked plates, giving a smaller effective D_H than the actual hole diameter, was observed on 80-90% of the holes found on a given stack.

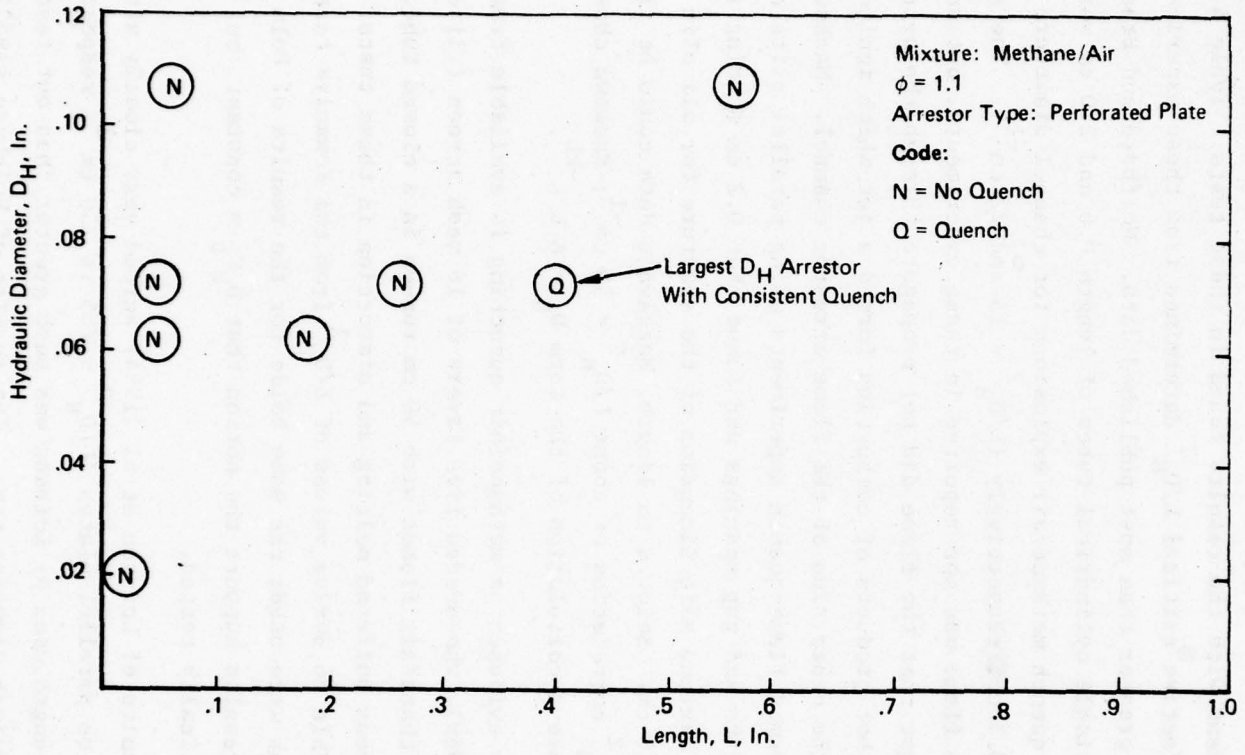


FIGURE 13 QUENCHING CHARACTERISTICS OF PERFORATED PLATE ARRESTORS IN METHANE/AIR MIXTURE FLAMES

This was possibly a partial cause for the abnormally low value of L/D_H^2. Again, the lower required L/D_H^2 would be consistent with a higher pressure drop for perforated plates than for crimped ribbon (for a given length), and different heat transfer rates per unit length of boundary layer according to the Reynolds analogy.

The published data on methane/air quench experiments are more or less consistent with the results found in these tests. Table 4 shows that the effective critical L/D_H^2 determined from these experiments is somewhat greater than most published data. Wolfhard and Brusak (1960) found that single cylindrical tubes of length 0.6 and 2.0 cm were just adequate to quench methane/air explosions for channel diameters of 0.2 cm and 0.3 cm, respectively (L/D_H^2 = 15 and 22 cm^{-1}). The approach speed of the flame was not reported in these experiments, but schlieren photos suggest that the flame did not propagate through the arrestor; rather, the hot products of combustion formed a jet which ignited the mixture on the other side of the flame arrestor channel. Maekawa (1975) performed flame-quench experiments using parallel slits of various lengths and gap spacings and found that 0.2 cm spacing (.28 cm D_H) was the maximum safe dimension of the aperture for all slit lengths exceeding 4.0 cm. Below 4 cm length, Maekawa's data could be fitted with an L/D_H^2 correlation of about L/D_H^2 = 50 cm^{-1}; Maekawa chose instead to use a correlation of the form $D_H = A\ L\ e^{-kL}$.

Further evidence on methane/air quenching is available from Komamiya (1969), who needed five layers of 16 mesh screen (.11 cm D_H) to quench methane/air flames with 50 cm run-up in a closed tube. The first 2 screens suffered melting and distortion in these tests. It is not possible to derive values of L/D_H^2 from the Komaniya tests since screens were used; the same holds for the results of Holm (1933). The latter results support the notion that $D_H S_t$ = constant, but this was not systematically tested.

The results of Loisson et al (1954) agreed very closely with our experiments on parallel plates (L/D_H^2 = 255 vs 236 cm^{-1}, respectively). The run-up length used by Loisson was much greater than our tests, and he used a 10-inch diameter pipe. The results of Hulsberg (1957) are

TABLE 4

PUBLISHED QUENCH DATA ON METHANE/AIR FLAMES

Author	Maximum Dimensions D_H (cm)	L (cm)	Arrestor Type	L/D_H^2 (cm^{-1})	Remarks
Wolfhard and Brusak (1960)	0.20	0.6	Single tube	15	
	0.30	2.0	" "	22	
Maekawa (1975)	0.28	4.0	Multiple slit	50	
Komamiya (1969)	0.11 (5 layers)		Multiple screens	-	High pressure rise
Holm (1933) as reported by Scott et al (1962)	0.50	-	Screen	-	3 ft/sec flame speed
	0.08	-	Screen	-	20 ft/sec flame speed
	0.05	-	Screen	-	30 ft/sec flame speed
Loisson et al (1954)	.14	5.0	Parallel plates	255	25-cm diam. pipes; 1000-cm run up length
Hulsberg (1957)	.12 (2 layers)		Packed .6 cm spheres	83	Assume D_H = 1/5 sphere diameter
	.18 (5 layers)		Packed .9 cm spheres	140	
Busch (1957), as reported by Rozlovskii and Zakaznov (1971)	.26	1.0	Single slit	15	No pressure rise
	.12-.13	1.0	Single slit	60-100	With pressure rise
Current Experiments	See Fig. 12: .15	1.0	Parallel plate	236	L/D_H^2 criteria relates L and D_H
	.11	1.0	Crimped ribbon	118	

somewhat difficult to interpret because the L and D_H of a passageway through packed spheres is not uniquely defined. Making the assumption that D_H = 1/5 of the sphere diameter and L equals the sphere diameter, we get values for L/D_H^2 ranging from 83-140 cm^{-1} from his experimental results, a range which is not far out of line with the present experimental data.

D. Results of Ethylene/Air Tests

A series of tests was conducted with wire mesh screens at relatively low flame speed (10-100 ft/sec, with most runs between 20 and 40 ft/sec). None of the screens which were tested was able to quench ethylene/air flames, down to 38 mesh (D_H = .018"). In some cases, the screen buckled and opened up along the edge. The published quenching diameter for ethylene/air is .060" (Simon et al (1953)); which means that these test results show that the flames could not be quenched by passageways 70% less than the theoretical quenching diameter. This finding corroborates the conclusion reached for methane/air, namely that the quenching distance criterion is inadequate as a design guide because all practical flame configurations are turbulent and not laminar, even for very short run-up lengths.

A second series of tests was conducted with parallel plate and crimped ribbon arrestors at higher flame speeds. The results of these runs are given in Figure 14. None of the arrestors was able to consistently quench ethylene/air flames. The crimped ribbon arrestors of D_H = .015" showed partial effectiveness, in that the 3/4" long arrestor quenched 1 out of 3 and the 1-1/2" long arrestor quenched 5 out of 19 tests. The latter arrestor corresponds to an L/D_H^2 = 6700 in^{-1}, which is about factor of ten higher than the value of L/D_H^2 which was found adequate for quenching methane/air.

One problem experienced during these tests which might affect the results was the irreproducibility of the flame speed. An examination of the detailed results in Table A-3 shows that the average flame speed V_{23} varied from 12 to 714 ft/sec for the parallel plate tests and from

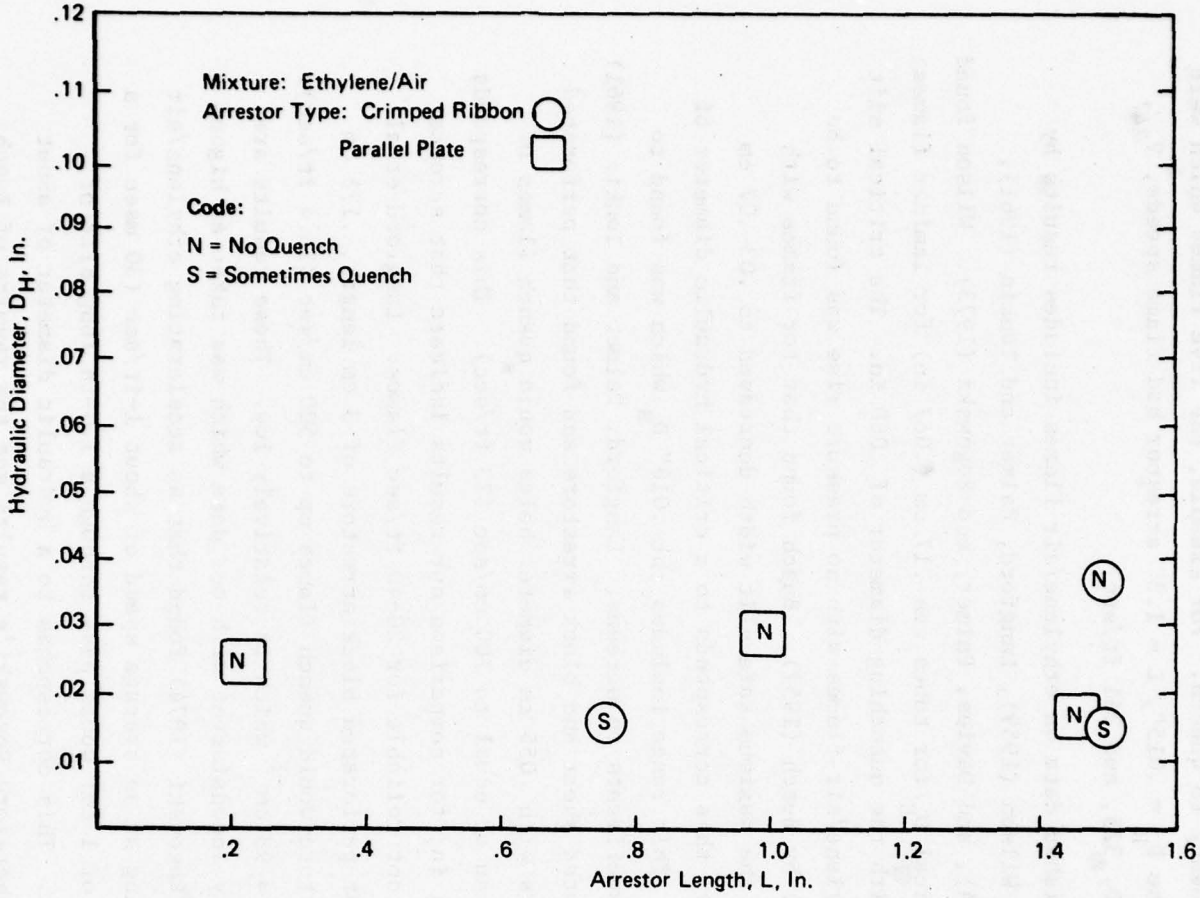


FIGURE 14 QUENCHING CHARACTERISTICS FOR ETHYLENE/AIR FLAMES

18 to 1000 ft/sec for the crimped ribbon tests. Pressure rises varied from 2 to 30 psi. There was no discernible correlation between flame speed and tendency to quench. For example, the five flames which were quenched by the D_H = .015", L = 1.5" arrestor had flame speeds, V_{24}, of 98, 41, 360, 325, and 361 ft/sec.

The published data on ethylene/air flames includes results by Busch (1957), Wilson (1959), Langford, Palmer and Tonkin (1961), Rogowski (1974), and Davies, Palmer, and Rogowski (1973). Wilson found that the critical D_H for tubes was .17 cm (.067 in) for laminar flames; this agrees with the quenching diameter of .060 in. The critical slit width for ethylene/air flames with no pressure rise was found to be .11 cm (.043") by Busch (1957). Busch found that for flames with pressure rise the maximum safe slit width decreased to .03-.07 cm (.012-.028 in); this corresponds to a critical hydraulic diameter of .017-.039 in. This range includes the .018" D_H which was found to fail in our experiments on screens. Langford, Palmer and Tonkin (1961) tested perforated sheet and block arrestors and found that perforated sheet arrestors with .055 cm diameter holes would quench flames of speeds less than or equal to 700 cm/sec (23 ft/sec). This corresponds to a D_H = .021 in; for comparison our results indicate that screens of .018" were not reliable for 20-40 ft/sec flames. Langford et al also found that perforated block arrestors of 3 cm length, .175 cm (.069 in) aperture would quench flames up to 500 cm/sec (16.4 ft/sec). This is $L/D_H^2 = 98\ cm^{-1}$ which is relatively low. These results are not necessarily inconsistent with our data which was taken at higher flame speed. Rogowski (1974) found that an accelerating ethylene/air flame travelling at an average speed of about 1-ft/sec (30 msec for a run up length of 1 cm) would pass through a 1.0-in long slit of .030-in height. This corresponds to a hydraulic diameter of about .042 in, and therefore Rogowski's results and the results of Busch (1957) both indicate that the maximum experimental safe D_H is just under .040" for ethylene/air flames with pressure rise.

Davies et al (1973) performed experiments on higher speed ethylene/air flames using metal foam arrestors. Flames up to 1400 ft/sec approach speed could be quenched, depending on the grade of the arrestor--see table below. The minimum L/D_H^2 values were 8400 and 1600 in^{-1} for the Grade 45 and 20 arrestors, respectively, based on twice the geometric length of the metal foam plug. These values of L/D_H^2 are of the same order of magnitude as that of the crimped ribbon arrestor shown to be marginal in the present program (6700 in^{-1}).

Estimated path length*	L/D_H^2	Estimated average cell diameter**	Type of foam	Pressure drop for 5.8 ft/sec air	Maximum flame speed quenched (ethylene/air)
1.0	1600 in^{-1}	.025"	Grade 20	5 mm H_2O	230 ft/sec
1.0	8400 in^{-1}	.011"	Grade 45	13 mm H_2O	1400 ft/sec

*Estimated at twice the geometric length of the foam plug.

**The cell diameter in inches is approximately 50% of the inverse of the grade of the foam.

In summary, our results backed up with other published data show that there is no arrestor available which can consistently quench ethylene/air flames of speed greater than about 20 ft/sec. Below 20 ft/sec flame speed, screens are not reliable down to 38 mesh, but crimped ribbon or perforated block arrestors of certain dimensions have been shown to be effective.

Because of the scarcity of "quench" data points, it was not possible to test the L/D_H^2 criterion.

IV. FLAME ARRESTOR DESIGN REQUIREMENTS-- TEST RESULTS FOR TEN PRODUCTS

A. Test Conditions

Tests were performed to bracket the critical dimensions of arrestor passageways just sufficient for quenching flames of various products (fuels) in air. Crimped ribbon arrestors were used for those flame tests. Various sized restrictions were used at the ignition end of the test pipe in order to achieve approach flame velocities of approximately 50-200 ft/sec. (Actual approach speeds are listed in Appendix A-4). For liquid cargoes, it was necessary to conduct a series of preliminary tests in order to establish the proper fuel/air ratio conditions for achieving the flame velocities in this range. Selected tests were also carried out using screens with low flame approach speeds of approximately 5 ft/sec.

B. Test Results and Discussion

The results of this series of tests on ten fuels are summarized in Table 5. The results of tests using gasoline/air and butane/air mixtures were also reported in Wilson and Crowley (1978) and are repeated here to facilitate comparison with other fuels.

The first observation from Table 5 is that the experimentally determined maximum passageway diameter which will quench a flame is consistently lower than the laminar quenching diameter, ranging from a 32 to 62% reduction for the first five fuels. For the last five fuels in Table 5, the maximum safe diameter was 70-85% lower than the laminar quenching diameter, but the choice of crimped ribbon sizes was not wide enough to reliably isolate the "borderline" diameter dimension. Recall from Chapter III that for methane/air, the crimped ribbon data showed that the maximum D_H arrestor which would consistently quench was of dimensions D_H = .069 in, L = 2.0 in (see Figure 12).

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TABLE 5

SUMMARY OF FLAME ARRESTOR TESTS
FOR TEN FUELS

Fuel	Laminar Quenching Diameter** (in)	Maximum Safe D_H, According to Experiments*** w/Crimped Ribbon (in)	Minimum Safe L, Corresponding to listed D_H (in)	Apparent Minimum L/D_H^2 † (in^{-1})
Acetaldehyde	.063	.035	.375	306
Toluene	(.100)††	.069	.875	184
Methyl alcohol	.051	.035	.375	306
Gasoline vapor	.094	.043	1.380	746
Butane	.105	.038	1.500	1040
Ethyl ether	.089	.015	.750	3300
Carbon Disulfide	.028	.021	.750	1700
Hydrogen sulfide	.051	.015	1.500	6700
Acetylene	.028	(minimum available D_H did not consistently quench)		-
Butadiene	.059	.015	1.500	6700

* All tests conducted in air at 1 atm initial pressure.

** Based on 1.4 times the published parallel-plate quenching distance [See Wilson and Atallah (1975)].

*** Hydraulic diameter D_H determined from crimp geometry by taking four times cross-sectional area divided by perimeter. Actual crimp heights given in Table A-4.

† These values are deemed to be conservative because of the limited number of (L, D_H) combinations tested.

†† Estimate.

This maximum D_H is 38% below the laminar quenching diameter (.11 inches), and was tested with a relatively long passageway (2 inches). Another borderline dimension for crimped ribbon tests of methane-air flames was D_H = .050 in, L = .75 in; for this length the critical diameter was 55% lower than the laminar quenching diameter. Even for low speed (5 ft/sec) methane/air flames, Figure 11 showed that the maximum safe diameter was about 50% lower than the laminar quenching diameter. In summary, all of our test results suggest that arrestors should be designed with passageway diameters no more than 40-60% of the theoretical quenching diameter. This corroborates the findings of Swan et al (1932), Holm (1933), Palmer (1958), Mansfied (1956) and Scott et al (1962), as discussed in Wilson and Atallah (1975), p. 30.

The second observation from Table 5 is that the minimum values of L/D_H^2 determined experimentally for the first five fuels ranged from 184 to 1040 in^{-1}, which are in the same range as the values of L/D_H^2 for methane/air taken from Figure 12 for crimped ribbon. For crimped ribbon and parallel-plate arrestors, the minimum L/D_H^2 was 300 in^{-1} and 600 in^{-1}, respectively for methane/air. In short, the experimental results seem to support a minimum value of L/D_H^2 for common hydrocarbon fuels, which for design purposes should be taken at L/D_H^2 = 1000 in^{-1}, to be conservative.

This design criteria would <u>not</u> safely apply to the last five fuels in Table 5:

- Ethyl ether
- Carbon disulfide
- Hydrogen sulfide
- Acetylene
- Butadiene

These fuels apparently require arrestors of smaller passageway diameter and longer length. This result is understandable for acetylene and hydrogen sulfide, which have very low theoretical quenching diameters (high flame speeds). However, the result is somewhat surprising for fuels such as ethyl ether and butadiene which have flame speeds lower than methyl alcohol which appears to obey the $L/D_H^2 = 1000\ in^{-1}$ criterion. In the case of ethyl ether, whenever the flame was not stopped by the (.035", .375") arrestor, the flame speed, V_{34}, appeared to be excessive (300-600 ft/sec for runs 102677-03,-04 and -06; see Table A-4). For butadiene, no comparable explanation could be found. Clearly the range of crimped ribbon arrestors was too limited to explore this anomaly within the current program.

In summary, if the two criteria for flame-arrestor design suggested by Wilson and Atallah (1975) are applied to the test results, the passageway dimensions are as follows:

1st criterion: Effective passageway diameter D_H not to exceed 40% of theoretical quenching diameter, $60\ \alpha/S_\ell$, where α is the thermal diffusivity (cm^2/sec) and S_ℓ is the laminar flame speed.

2nd criterion: Effective L/D_H^2 of passageway must be at least $1000\ in^{-1}$ for acetaldehyde, toluene, methyl alcohol, gasoline vapor, butane, and methane. L/D_H^2 must exceed $3000\ in^{-1}$ for carbon disulfide, hydrogen sulfide, and acetylene. More experiments are needed to resolve the minimum L/D_H^2 for butadiene and ethyl ether.

As a practical matter, of the ten fuels tested, the first five listed in Table 5 could be controlled with an arrestor of dimensions

$$\boxed{L > 1.00",\ D_H < 0.030"}$$

This assumes that excessive heating of the arrestor due to prolonged exposure to flames has not occurred.

For acetylene/air mixtures, none of the arrestor designs available to us (D_H down to .015") could consistently quench high-speed flames, and substantial pressure rise was seen. This was also the case for ethylene/air flames (see Figure 14).

Table 6 compares the test results of safe dimensions for ten products with the critical parameters of commercially available arrestors. These arrestors were tested during a previous phase of the program (Wilson and Crowley, 1978). It can be seen that except for certain Amal arrestors and except for toluene, methyl alcohol, and acetaldehyde, the D_H required to consistently quench flames from the various products (fuels) are smaller than the D_H values available with the commercial arrestors. However the lengths of certain commercial arrestors (Varec and Shand and Jurs) exceed the range of arrestor lengths tested in the current program. Since actual tests were not performed using the commercially available arrestors on the various products, additional tests would have to be performed before the adequacy of these arrestors can be verified. If the L/D_H^2 correlation holds, then these arrestors would be expected to be adequate.

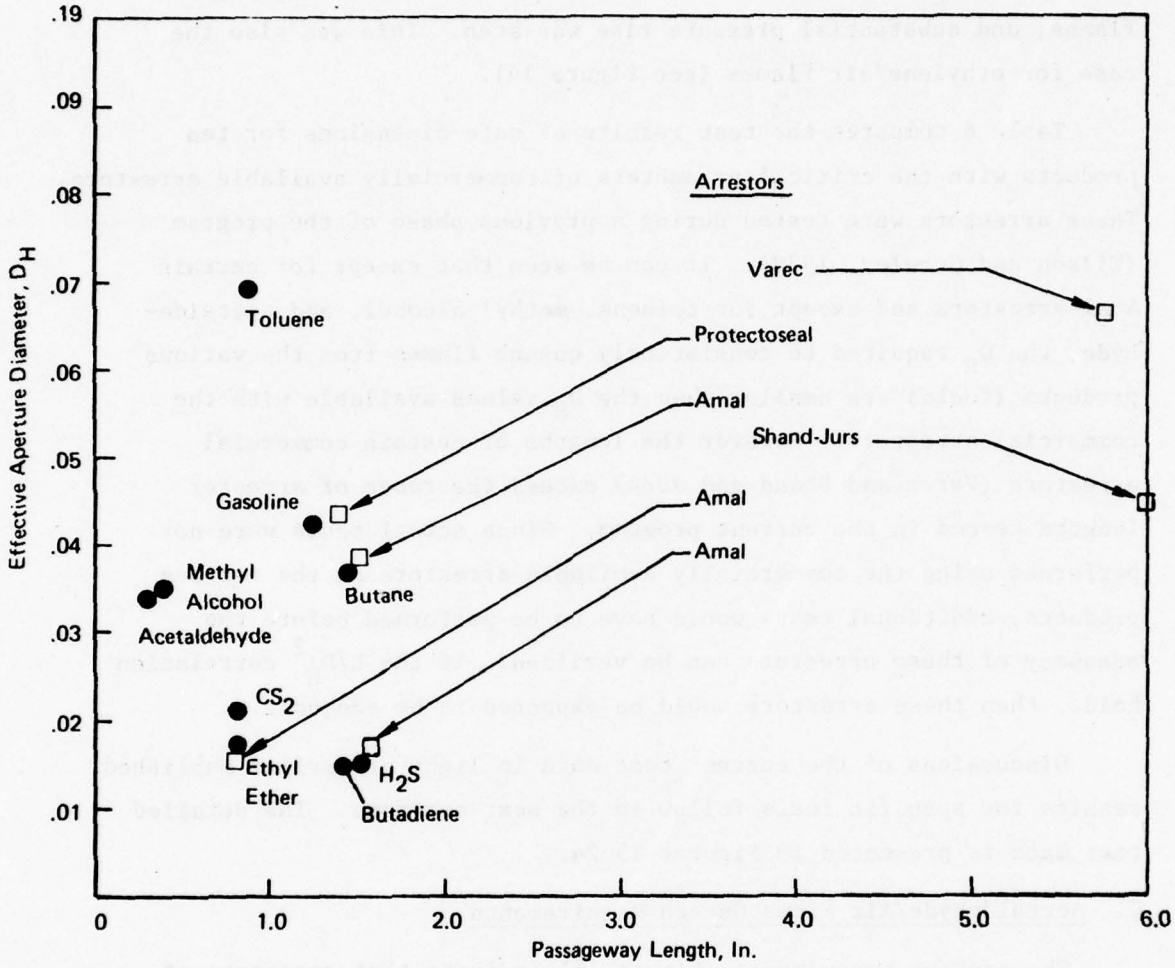
Discussions of the current test data in light of earlier published results for specific fuels follow in the next sections. The detailed test data is presented in Figures 15-24.

C. Acetaldehyde/Air Flame Quench Requirements

The present experiments (Figure 18) indicate that arrestors of $D_H < .035$ in and $L/D_H^2 > 306$ in^{-1} are adequate to quench acetaldehyde/air flames. The approach speed of the flame in these tests was 50 to 120 ft/sec, except for one run (see Table A-4 for complete data). For comparison, Langford, Palmer and Tonkin (1961) tested acetaldehyde/air flames with three perforated-plate arrestors of .022, .039 and .069 inch cylindrical apertures. The passageway "length" (simply the plate thickness) was less than the aperture size. The results were expressed in terms of the maximum flame velocity which could be quenched; both the .022 in and the .039 in apertures could quench flames moving at

TABLE 6

DIMENSIONS OF COMMERCIALLY AVAILABLE ARRESTORS COMPARED TO TEST DATA ON SAFE DIMENSIONS



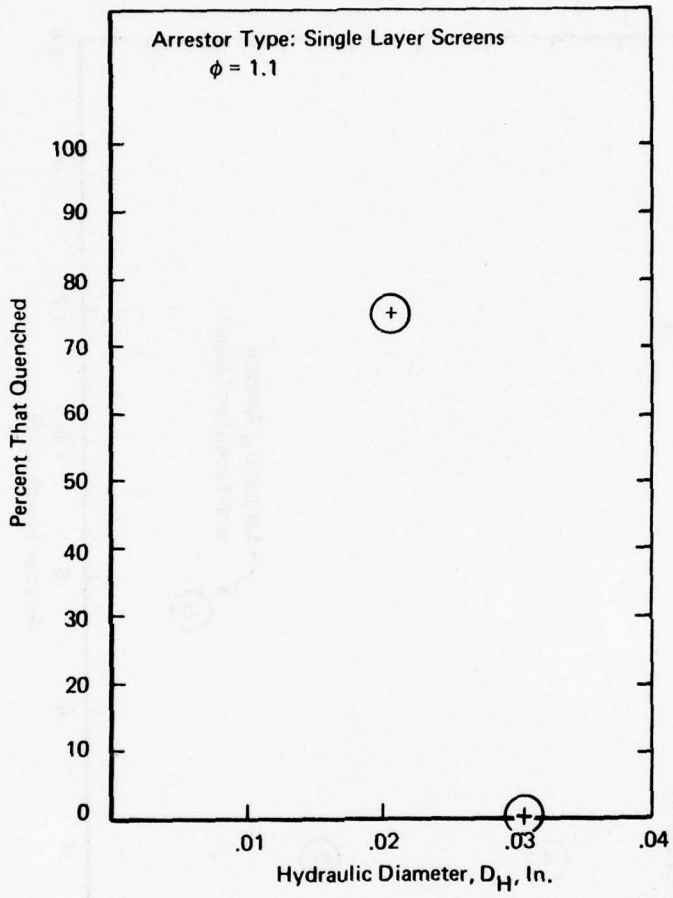


FIGURE 15 QUENCHING CHARACTERISTICS FOR ETHYL ETHER/AIR FLAMES

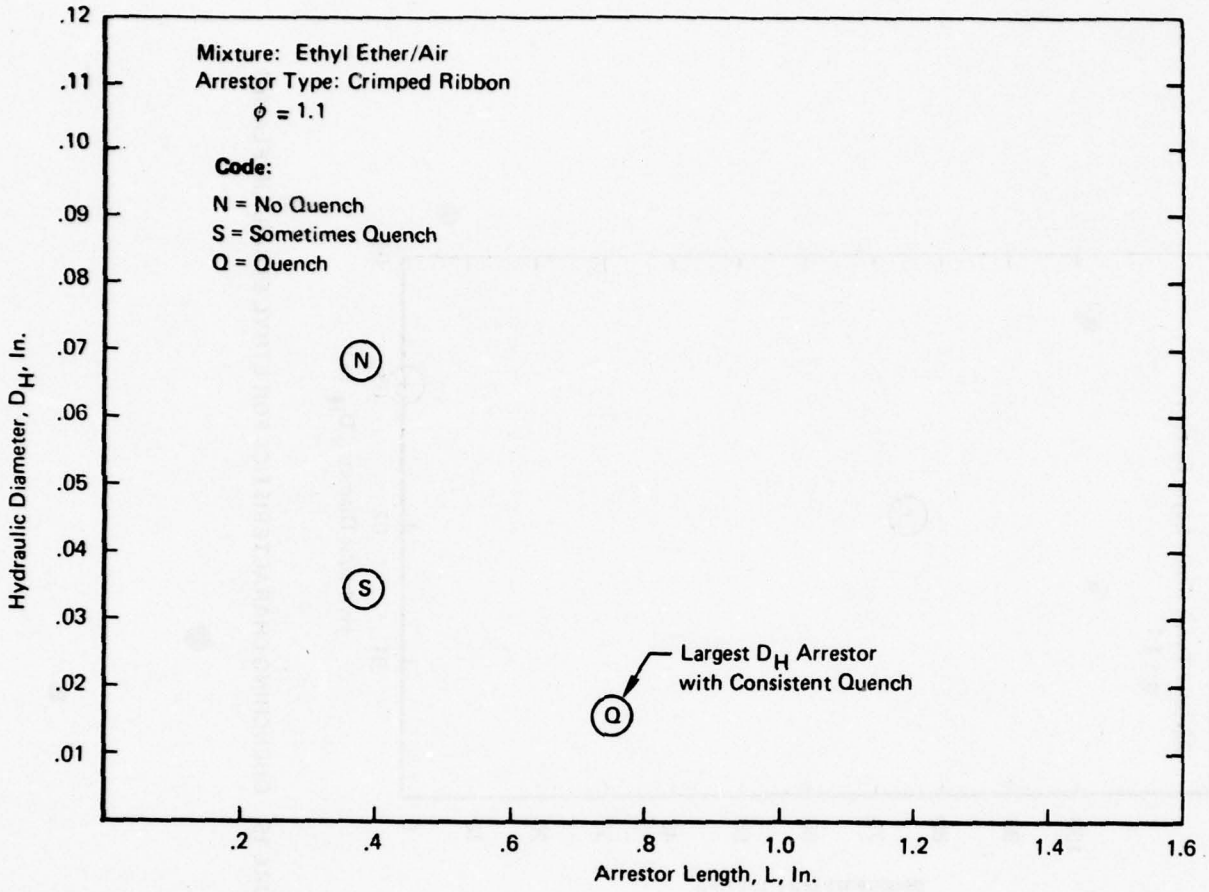


FIGURE 16 QUENCHING CHARACTERISTICS FOR ETHYL ETHER/AIR FLAMES

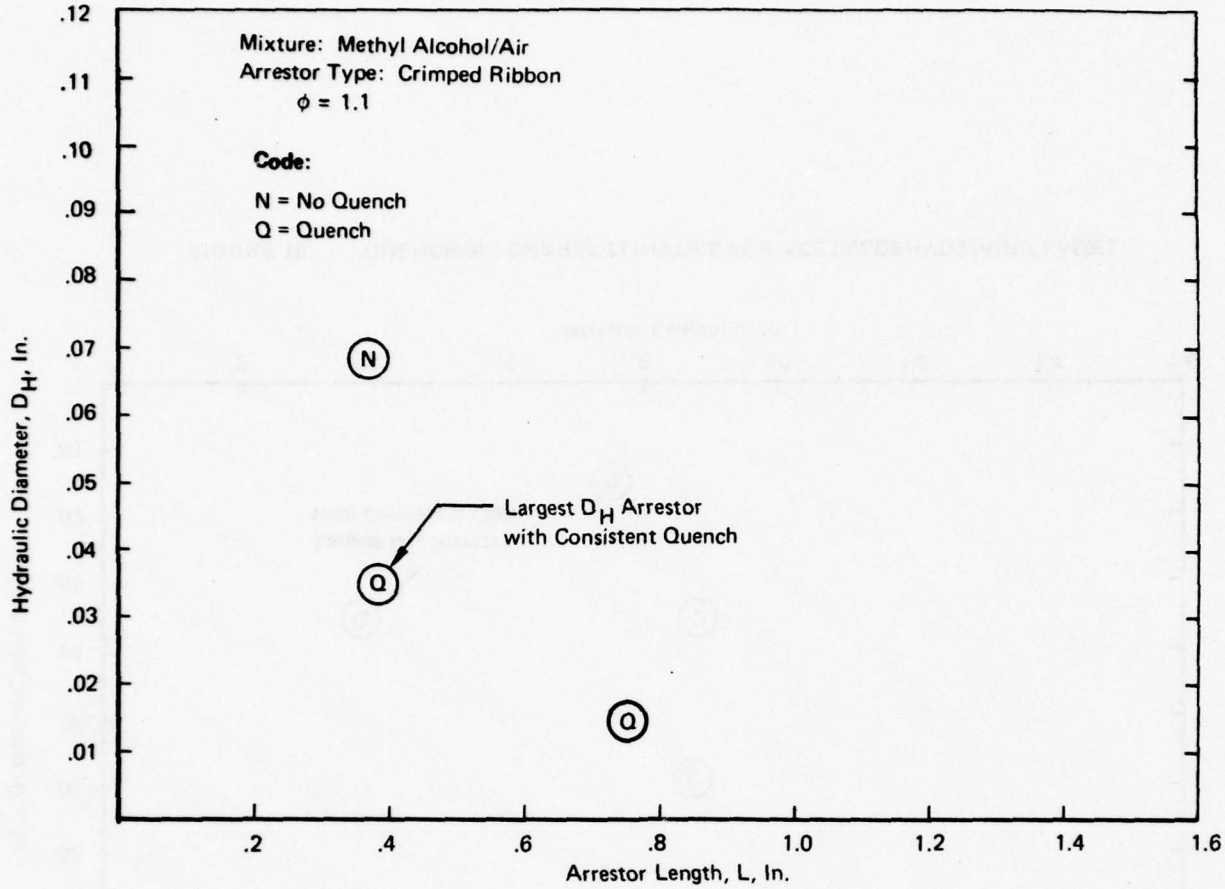


FIGURE 17 QUENCHING CHARACTERISTICS FOR METHYL ALCOHOL/AIR FLAMES

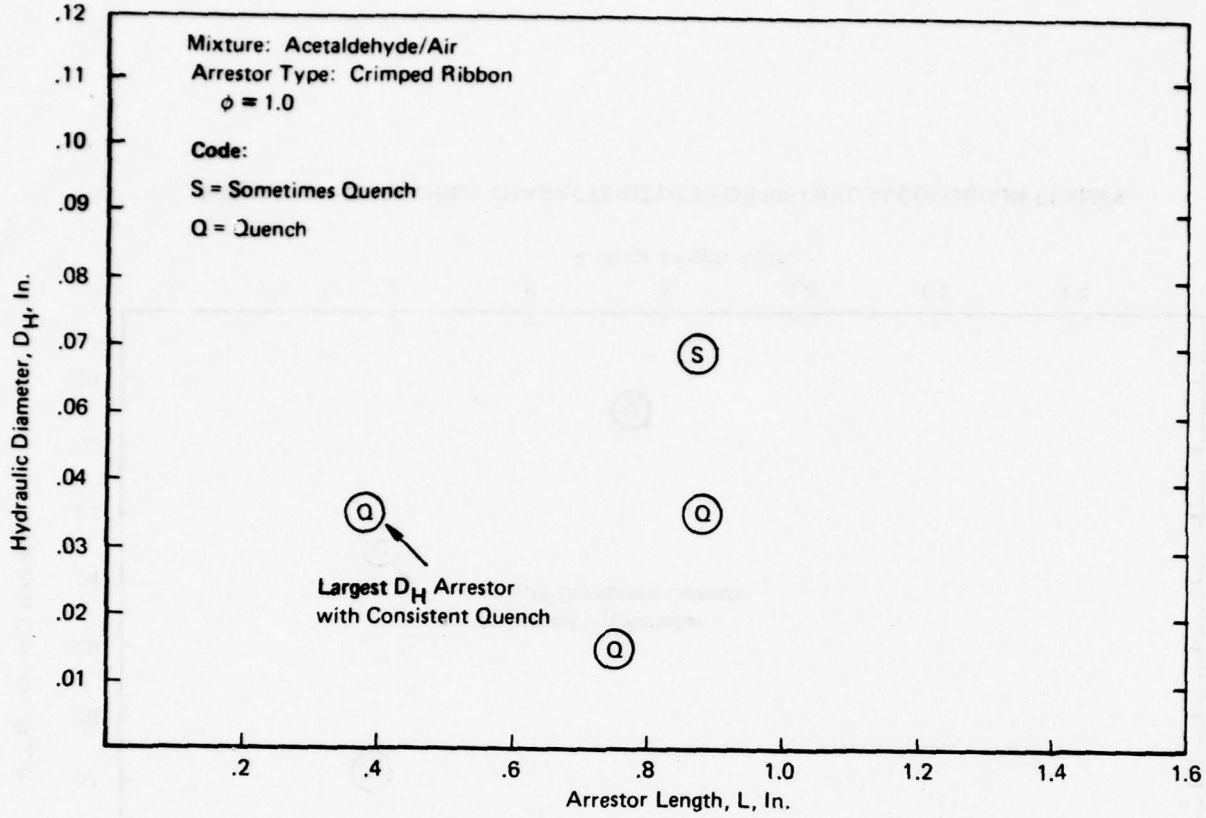


FIGURE 18 QUENCHING CHARACTERISTICS FOR ACETALDEHYDE/AIR FLAMES

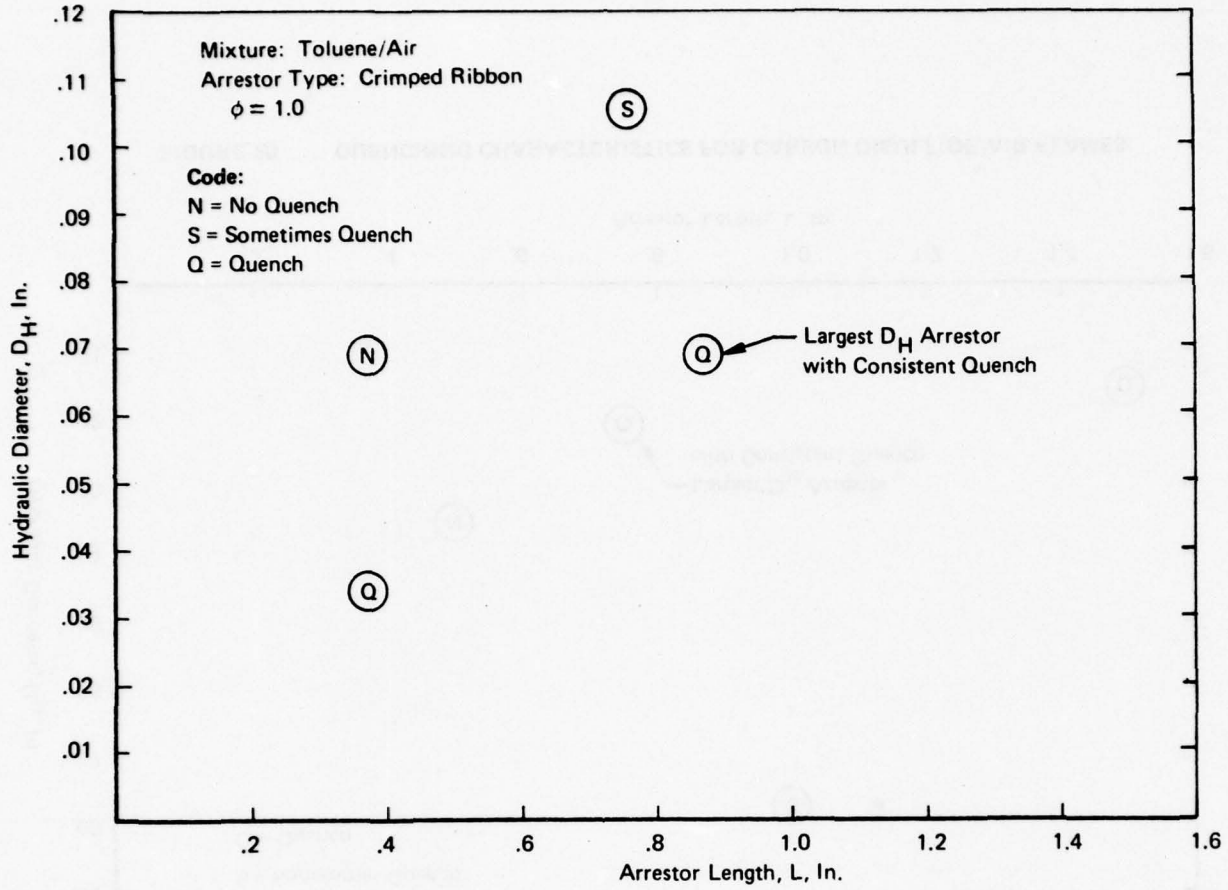


FIGURE 19 QUENCHING CHARACTERISTICS TOLUENE/AIR FLAMES

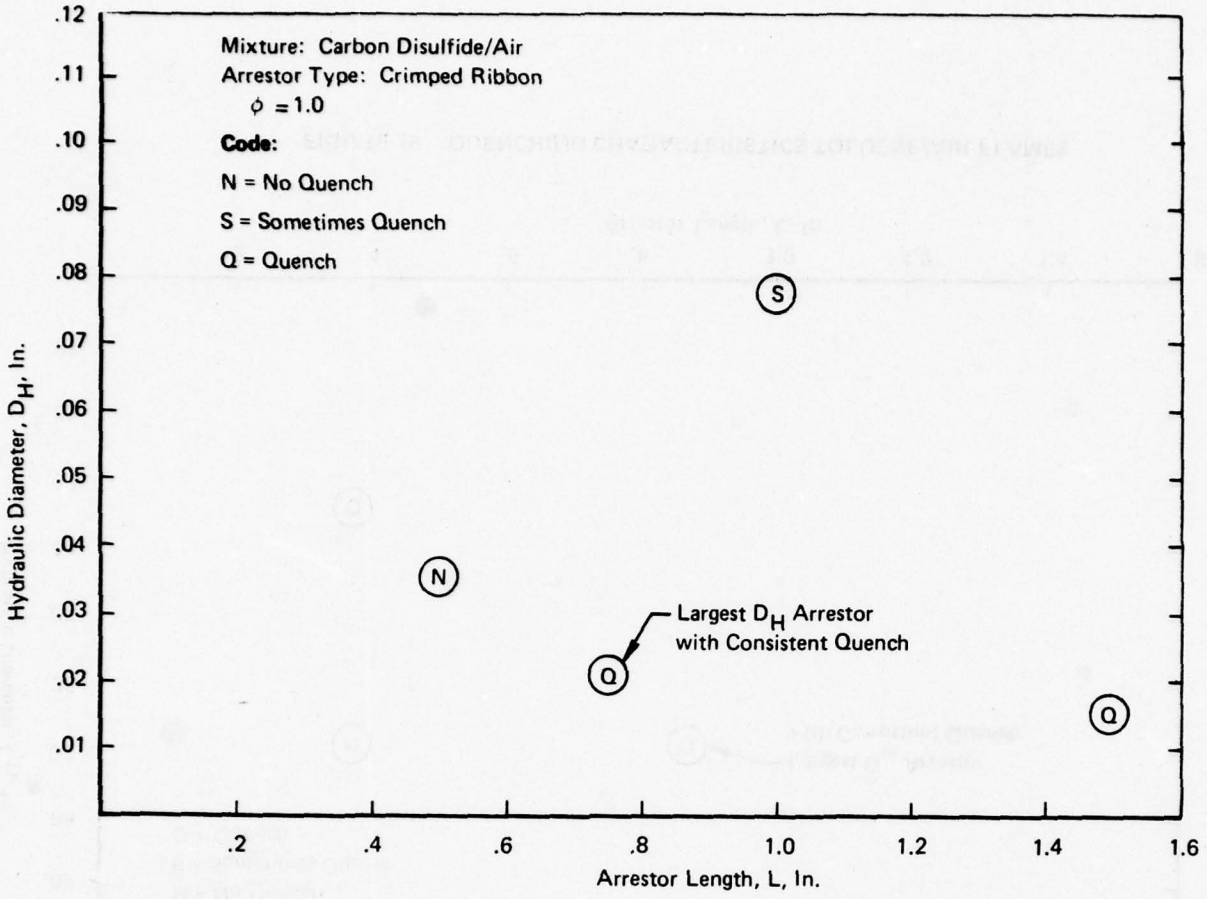


FIGURE 20 QUENCHING CHARACTERISTICS FOR CARBON DISULFIDE/AIR FLAMES

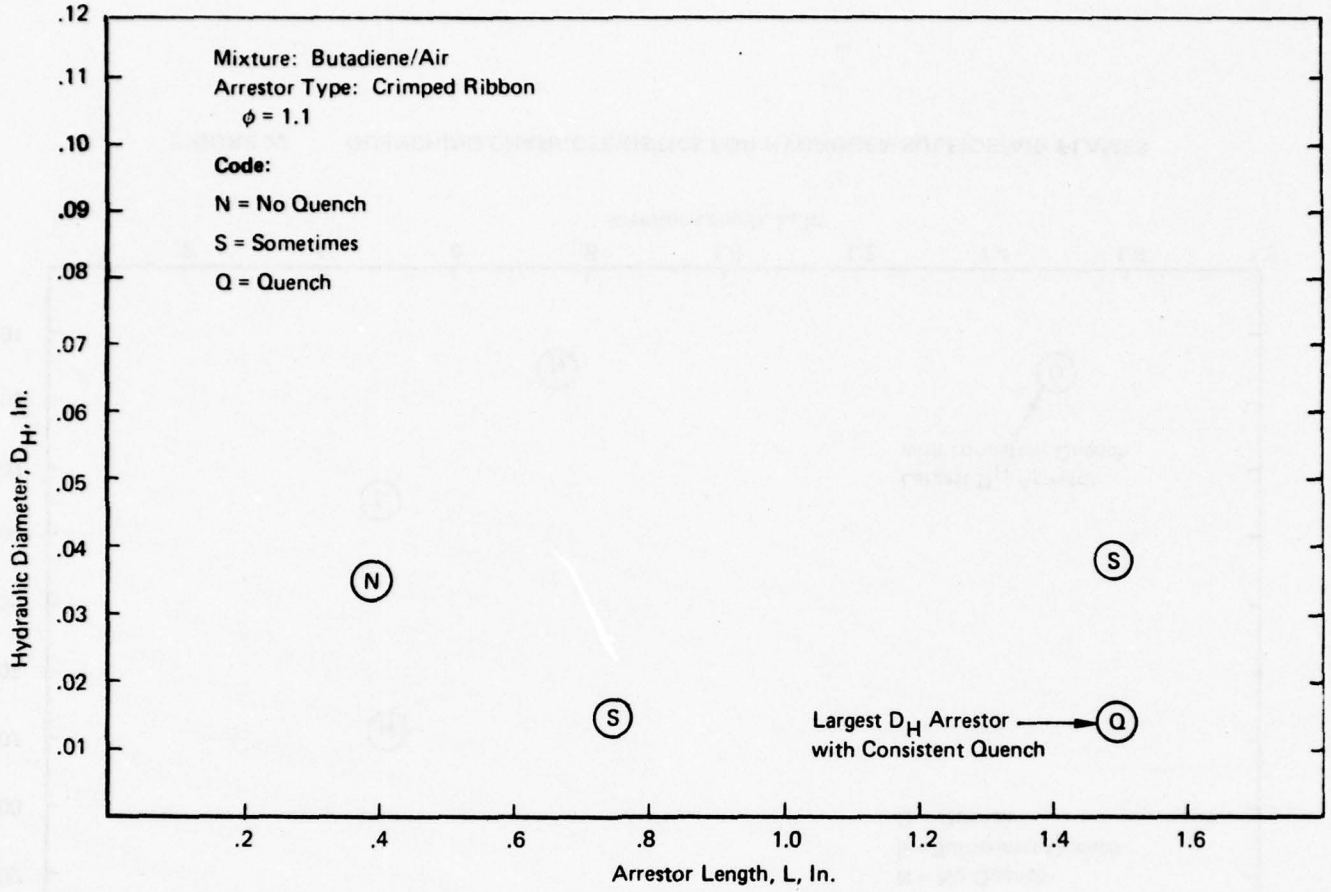


FIGURE 21 QUENCHING CHARACTERISTICS FOR BUTADIENE/AIR FLAMES

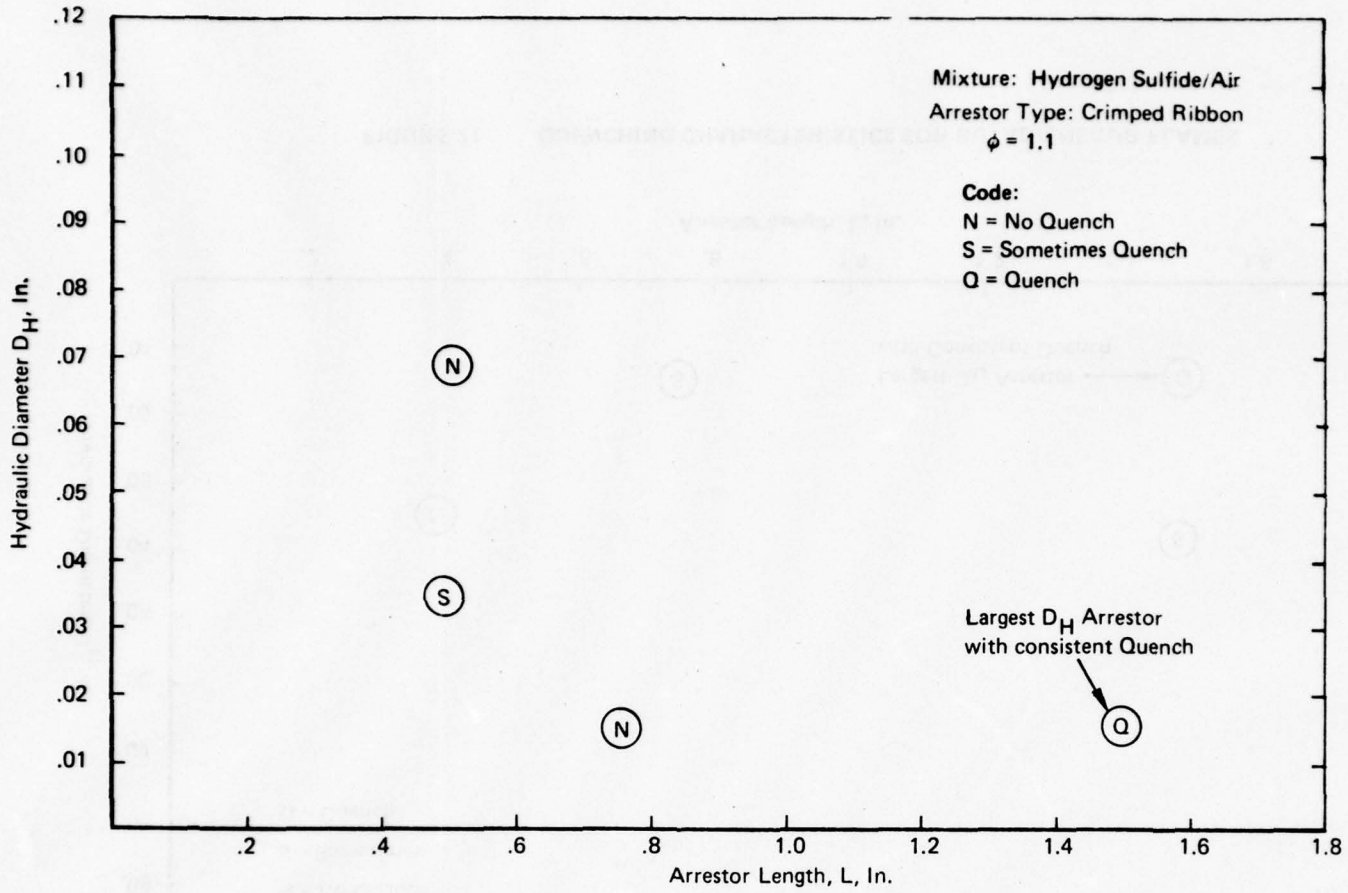


FIGURE 22 QUENCHING CHARACTERISTICS FOR HYDROGEN SULFIDE/AIR FLAMES

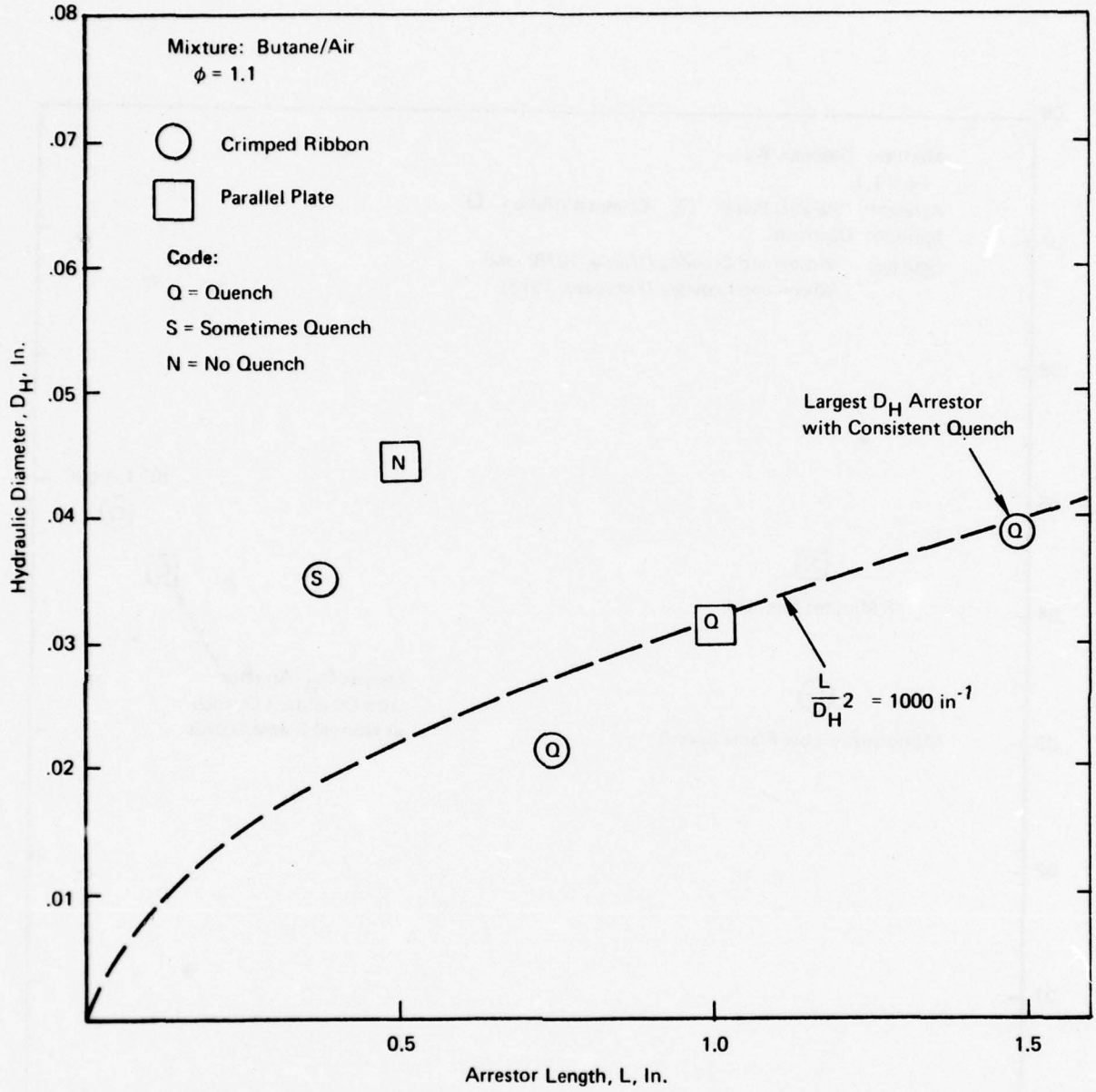


FIGURE 23 QUENCH CHARACTERISTICS FOR BUTANE/AIR FLAMES

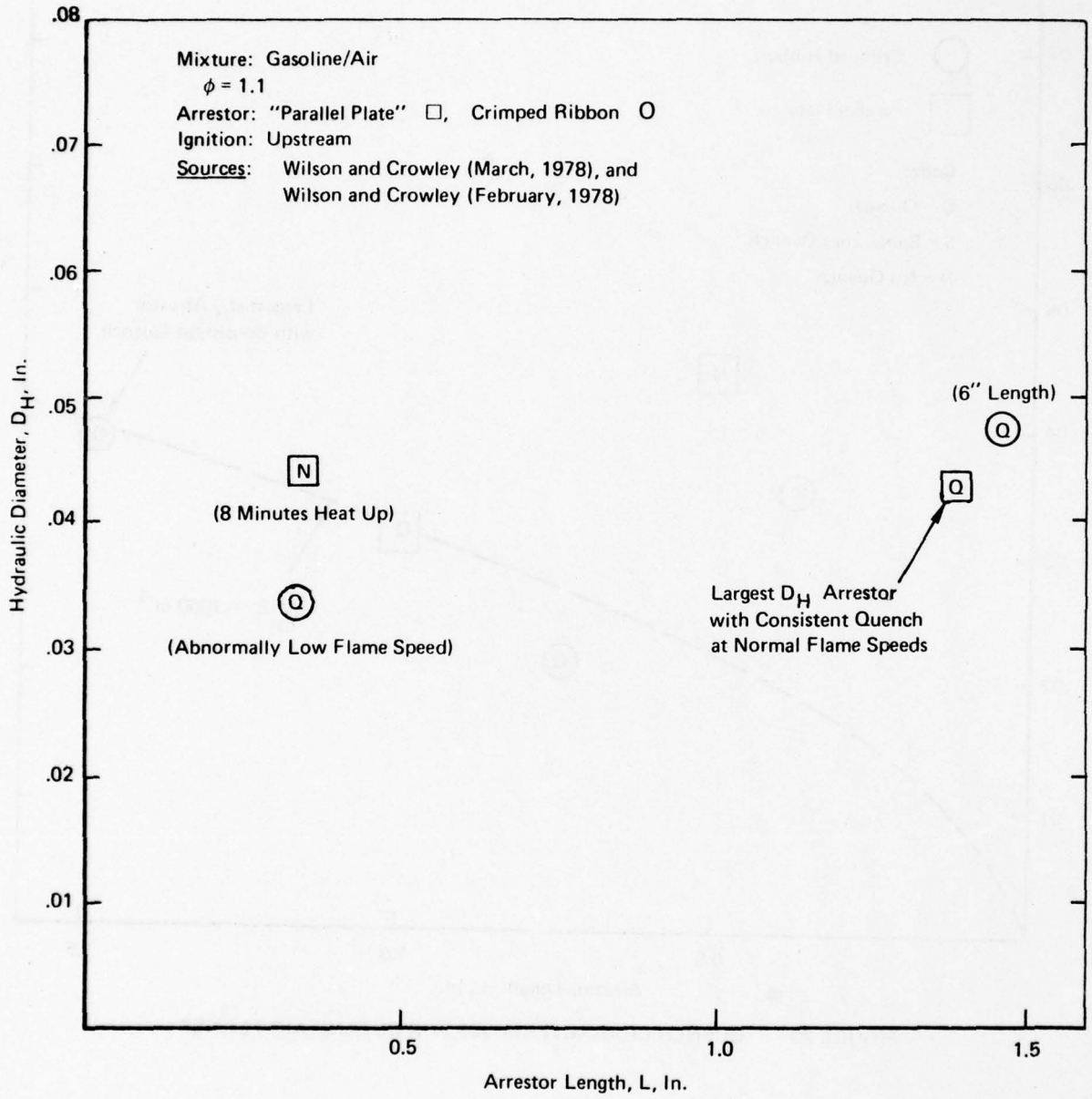


FIGURE 24 QUENCH CHARACTERISTICS FOR GASOLINE VAPOR/ AIR FLAMES

25 ft/sec or less; the .069 in apertures could not stop flames of any speed down to 4 ft/sec. Therefore, the results of Langford et al. corroborate our findings that the minimum D_H is approximately .035 in; however, the flame speeds were too low and arrestors too thin to test the L/D_H^2 criterion.

D. Butane/Air Flame Quench Requirements

The present experiments (Figure 23) indicate that arrestors of $D_H < .038$ in and $L/D_H^2 > 1000$ in^{-1} are adequate to quench butane/air flames. The approach speeds of the flame for these tests ranged from 60 to 300 ft/sec, with a few isolated tests conducted at 420 ft/sec (see Wilson and Crowley, 1978).

The unpublished results of Broschka and Will (1976) are the only available comparison point for these butane/air data. The experimental conditions for their tests were such that detonation was likely, as evidenced by the observed pressure rises of several atmospheres. It was found that an arrestor of $D_H \simeq .049$-in. was not effective but that an arrestor of $D_H \simeq .037$-in. was effective under certain conditions. Both arrestors had passageways of very long length, easily satisfying our suggested $L/D_H^2 > 1000$ in.$^{-1}$ criteria. In general, the results of Broschka and Will corroborate our findings of a maximum passageway diameter of about 0.038 in, since their tests at $D_H = .037$ in. were borderline for much more severe flame strength.

E. Acetylene/Air Flame Quench Requirements

The present experiments suggest that there is no commercially available arrestor of the crimped-ribbon type which can reliably quench acetylene/air flames. Of the 6 tests with the Amal arrestor of dimensions $D_H = .015$ in, $L = 1.50$ in, two resulted in flame quench, and this indicates that this particular arrestor is of "borderline" dimensions. It has an L/D_H^2 of 6700 in^{-1}. Flame speeds for these tests were large (400 ft/sec), but detonation was not encountered. The pressure rises were 5-14 psi which is comparatively low.

Muller-Hillebrand (1938) tested for the single-gap thickness which would quench acetylene/air explosions of 140 psi and found the maximum gap to be .008 in, which is consistent with our result. Miller and Penny (1960) reported that Schmidt and Haberl (1955) have developed a wetted Raschig-ring arrestor of 48" length (1" ring size) which was effective against acetylene/air detonation of 5700 ft/sec. Supposing that the Raschig rings nest in such a way to produce an effective gap of .01 in, certainly this arrestor would satisfy any L/D_H^2 criterion of the magnitude shown in Table 5. Miller and Penny also make reference to a 1" thick steel wool arrestor for acetylene detonation.

A reticulated metal foam has been reported by Barton, Carver and Roberts (1975) to quench acetylene/oxygen detonations. The foam is 1.58-in. thick and is formed by compressing a foam of 80 pores/in. (pore size = .0125 in. minus wall thickness) by a factor of five in density. The resulting pore size was presumably less than .008 in. (the Muller-Hillebrand value of critical aperture). Based on D_H = .008 in., the L/D_H^2 for this arrestor was 24,500 $in.^{-1}$, a factor of four greater than the "borderline" value of the present experiments. The difficulty of arresting acetylene explosions has prompted Linde to use a hydraulic arrestor (see Sutherland and Wegert, 1973).

In summary, the design requirements for acetylene arrestors appear to be $D_H < .008$ in. and $L/D_H^2 > 10{,}000$ to 20,000 $in.^{-1}$ (value uncertain).

F. Ether/Air Flame Quench Requirements

The present experiments indicated a value of $D_H < .015$ in. for ethyl ether flames, a value which is almost certainly more conservative than necessary since very few D_H values were tested (see Figure 16). Arrestors of $D_H = .035$ in. appeared to be borderline (quenching the flame in 1 out of 4 tests), however, in all three tests which were "no quench" the flame accelerated to relatively high approach speeds (V_{34} = 232, 312, 625 ft/sec; see Table A-4 for data). Therefore, more experimental work is needed to better define the maximum safe D_H, which on the basis of fuels with comparable laminar flame speed would be expected to be no less than $D_H = .03$ in.

By way of comparison, Genkin (1967) tested layers of gravel and obtained 0% quench probability for 0.59-0.71 in. gravel size, 56% quench probability for 0.35-0.47 in. gravel size, and 100% quench probability for 0.31-0.35 in. gravel size. All beds were 8" in height. For a packed bed of spheres, D_H = .102 times the sphere diameter, therefore, Genkins' results correspond to a maximum safe diameter of

$$D_H < .03 \text{ in.}$$

The length of the bed corresponded to $L/D_H^2 = 8300$ in^{-1} which is probably well above the minimum necessary length criterion.

Langford, Palmer, and Tonkin (1961) also tested ether/air flames using perforated plates. It was found that arrestors of .022 in. aperture could quench flames up to 34 ft/sec and arrestors of .039 in. aperture could quench flames up to 15 ft/sec.

In summary, the present experimental result is that D_H = .035 in appears borderline for flames in the 230-625 ft/sec range. This is consistent with Genkin's result that D_H < .031 in for 100% quench and Langford et al.'s result that an arrestor of very short length and .039 in passageway diameter is marginal. The L/D_H^2 minimum is yet to be determined but appears to be greater than for the ether/air value of 326 in^{-1} corresponding to D_H = .035 in, L = 0.4 in, but less than the value of 3300 in^{-1} reported in Table 5.

G. Gasoline Vapor/Air Flame Quench Requirements

The present experiments which were reported by Wilson and Crowley (1978), Figure 24, are very limited on gasoline/air but indicate that the Protectoseal arrestor (D_H = .043 in, L = 1.38 in) quenches consistently. Flame speeds on these tests were comparable to methane/air (24-62 ft/sec). However, the tests were run with upstream ignition which is more severe than the conditions for other fuels which have been discussed. It is well known that a major component of gasoline vapor is butane, and therefore the quench requirements of gasoline are expected to be comparable to butane (D_H < .038 in and L/D_H^2 > 1000 in^{-1} for butane, according to our tests). This comparison holds up well since these butane quench requirements are slightly more stringent than the Protectoseal dimension can satisfy.

Earlier published results for gasoline air include those of (a) Clothier (1956), who found that a crimped ribbon of .021 in height, .049 in base, and 1.00 length ($D_H \simeq .022$ in, $L = 1.00$ in) could arrest petrol/air, (b) Swan et al. (1932), who found that minimum requirements were $D_H < .047$ in for $L = 0.8$ in and $D_H < .059$ in for $L = 2$ in ($L/D_H^2 = 362$ in^{-1} and 474 in^{-1}, respectively) and (c) Schampel and Steen (1975), who recommend $D_H < .028$ in and $L > 0.4$ in for explosion arrestors.

V. TESTS OF NON-OBSTRUCTIVE DEVICES FOR FLAME CONTROL

A. Steam Snuffing Tests

1. Modifications to Test Apparatus

The flame arrestor test apparatus was modified to allow the injection of steam so that critical steam flows required to arrest flames of methane/air and ethylene/air mixtures could be measured. Provisions were incorporated to introduce both transient and continuous steam flow. The modification consisted of installing a steam injection nozzle,* centered in the test pipe, coincident with the upper flange of the Varec arrestor housing, as shown schematically in Figure 25. The nozzle was connected to a steam supply using insulated 3/4" NPT piping that extended through the wall of the arrestor housing. As shown in Figure 25, the steam system consisted of a steam regulator, a primary flow control valve, a system pressure gage, a snuffer solenoid valve, a steam by-pass solenoid valve, and a by-pass flow control valve. The by-pass line allowed steam to be directed into the exhaust system until the start of the injection test.

As shown in Figure 25, modifications to the test apparatus also included a flame detection and steam control system. The system was designed to permit either a transient injection of a fixed quantity of steam synchronized with a travelling flame front, or a continuous supply of steam. Shown in Figure 25, the flame detection system consisted of an optical detector installed 10-3/4" below the uppermost spark igniter (Optical Port No. 1 shown in Figure 25). A second detector located at Optical Port No. 2 (Figure 25) was used to confirm the development of a moving flame front. Another detector at Port 3' was used to record the passage or absence of flames upstream of the arrestor housing indicating non-quenching or quenching, respectively, of the flames by the steam. In Pulsed Mode, approximately 0.3 sec prior to ignition,

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*Bete Model TF14FC

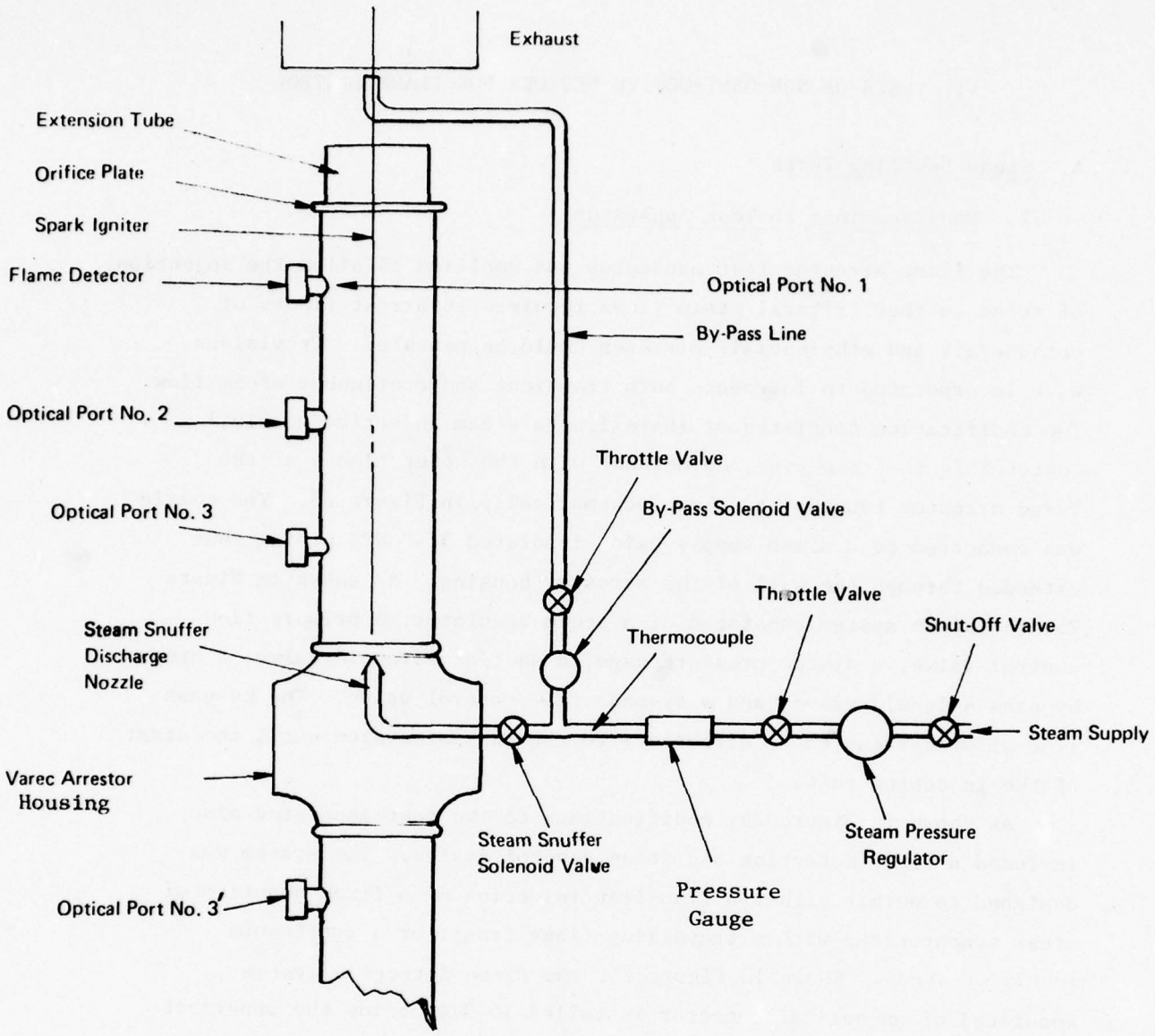


FIGURE 25 TEST APPARATUS ARRANGED FOR STEAM SNUFFER TESTS

the operation was arranged so that it diverted the steam flow from the by-pass to the test section for a preset time. In Continuous Mode, steam was initiated 20 sec prior to ignition and injected continuously into the apparatus.

2. Test Procedure

Prior to conducting tests, the by-pass control valve was adjusted to achieve the same flow through the by-pass system as in the snuffer system. Steam flows were measured using the Bete-nozzle pressure drop as calibrated by the manufacturer. The Bete-nozzle, Model TF14FC, is designed to distribute a "solid-cone" spray of steam within a 120° cone.

For all tests, steam was allowed to flow continuously through the by-pass line for a period of approximately 5 minutes prior to the start of a flame test. This was done to permit the plumbing components to reach a temperature sufficiently high to avoid steam condensation as much as possible.

For Pulsed Mode tests, after the 5-minute steam pre-heat period, a regulated flow of gas and air was established in the apparatus. The gas/air flow was allowed to continue for 2 minutes to purge the apparatus of air and combustion products from preceeding tests. To initiate a test, steam was injected into the apparatus 0.3 to 0.5 sec before the activation of the spark igniter. The timer limited the quantity of steam that was injected in each test. In each test, flame development was confirmed by detection at Optical Port No. 2 (Figure 25). Tests were conducted at constant steam pressure drop (flow), but the injection time period was adjusted to achieve a minimum quantity of steam for quenching.

For Continuous Mode tests, after the 5-minute steam pre-heat period, a regulated flow of gas and air was established in the apparatus. As in Pulsed Mode procedures, a gas/air flow was allowed to stabilize for 2 minutes. At the end of 2 minutes, a known flow rate of steam was introduced into the apparatus and permitted to flow for a period of approximately 20 sec before ignition. This period was sufficient to insure that the test pipe had been completely penetrated by the steam/

fuel/air mixture. Approximately 20 sec after steam was initiated, the spark igniter was discharged. In this way, ignition of the gas/air mixtures was achieved.

3. Test Results and Discussion

The results of the Pulsed Mode tests are listed in Table 7. The minimum quantity of steam for quenching flames using the pulsed method was found to be .0144 pounds. On a volumetric basis, the test section is approximately 2.0 cubic feet, and the minimum amount of steam was .40 cubic feet. This is not unreasonable, considering that the steam jet must undergo mixing in order to quench the flame. The success of quenching in Pulsed Mode depends on the time-dependent fluid mechanics of establishing a steam jet which covers the entire cross section of the 6" pipe. We also caution that the Pulsed Mode test data is probably unique to this particular nozzle and 6" pipe arrangement. To illustrate the significance of mixing, note that the injection rates required to quench ethylene flames were less than 30 lb/hr for continuous injection, whereas up to 71 lb/hr in Pulsed Mode would not quench the flame.

Attempts to quench flames of ethylene/air mixtures using Pulsed Mode steam injection were not successful for up to 0.099 lb (2.7 cubic feet) of steam. However, it was noted that during test No. 25 (0.1639 lb or 4.55 cubic feet) flame-through did not occur until after steam injection had been shut off.

Ethylene/air flames were quenched using Continuous Mode injection at 30-60 lb/hr of steam. For comparison, the air flow rate was 26 lb/hr and the fuel rate was 1.8 lb/hr. Therefore, the dilution of the mixture by 30 lb/hr of steam was about 1:1 on a mass basis. The adiabatic flame temperature would be reduced substantially by this much steam; certainly below 2000°F.

The current results indicate that a ratio of steam to fuel of 16.7 is more than adequate to prevent propagation of ethylene/air flames. This agrees with the results of Gerstein, Carlson, and Hill (1954), who found that 16.7 lb water/lb fuel could prevent detonation of methane/air mixtures in a double injection ring arrangement, 1 ft apart. For two injection rings 5 ft apart, the required water-fuel ratio was reduced to 6.8. Initial pressures in the Gerstein experiments were .33-.40 atm.

TABLE 7

STEAM SNUFFER TEST RESULTS

PULSED MODE OPERATION

TEST CONDITIONS: Fuel - Methane
ϕ = 1.1
Mixture Velocity - 0.5 Ft/Sec
Orifice Diameter - 3 in.

Test No.	Steam Flow Rate Lb/Hr	Steam Injection Time Period (Sec)	Total Steam Injected (lb)	Pre-Fire Steam Injection Period (Sec)	Quench Yes	Quench No	Remarks
1	0	0	0	0	Baseline		V_{23}= 44 ft/sec
2	69.3	1.0	0.0192	0.56	x		
3	69.3	0.50	0.0096	0.50		x	
4	69.3	0.50	0.0096	0.52		x	
5	69.3	0.75	0.0144	0.38	x		
6	71.2	0.75	0.0144	0.28	x		
7	71.2	0.75	0.0144	0.51	x		
8	71.2	0.65	0.0128	0.42		x	
9	71.2	0.65	0.0128	0.45		x	
10	71.2	0.65	0.0128	0.36		x	
11	71.2	0.70	0.0138	0.44		x	Approx. 3 sec delay before flame-through
12	70.1	0.70	0.0136	0.50	x		
13	71.2	0.70	0.0138	0.44		x	Approx. 3 sec delay before flame-through

Table 7 (Continued)

PULSED MODE OPERATION

TEST CONDITIONS: Fuel - Ethylene
ϕ = 1.1

Test No.	Mixture Velocity ft/sec	Steam Flow Rate Lb/Hr	Steam Injection Time Period (Sec)	Total Steam Injected (lb)	Pre-Fire Steam Injection Period (Sec)	Orifice Dia (in)	Quench Yes	Quench No	Remarks
14	0.5	71.2	1.0	0.0198	0.68	4.0	x		
15	0.5	70.0	1.0	0.0194	3.0	4.0	x		
16	0.5	71.2	1.0	0.0198	3.0	4.0	x		
17	0.5	71.2	5.0	0.0990	5.0	4.0	x		
18	0.5	71.2	5.0	0.0990	5.0	6.0	x		
19	0.25	71.2	5.0	0.0990	5.0	6.0	x		
20	0.50	52.0	5.0	0.0722	0.0	6.0	x		
21	0.50	50.0	5.0	0.0694	0.83	6.0	x		
22	0.50	60.0	5.0	0.0833	0.50	6.0	x		
23	0.50	58.0	5.0	0.0806	1.0	6.0	x		
24	0.50	58.0	5.0	0.0806	2.0	6.0	x		
25	0.50	59.0	10.0	0.1639	2.0	6.0	x		Flame-through occurred after steam shutoff

Table 7 (Continued)

CONTINUOUS MODE OPERATION

TEST CONDITIONS: Fuel - Ethylene
ϕ = 1.1
Mixture Velocity - 0.5 Ft/Sec
Orifice Diameter - 4 in.
Ethylene flow rate = 1.81 lb/hr

Test No.	Steam Flow Rate (lb/hr)	Steam Flow Period Before Firing (Sec)	Quench Yes	Quench No	Remarks
1	0	0			V_{23} = 49 ft/sec
2	59.0	28	x		Momentary fire at pipe exit
3	50.2	20	x		" " " " "
4	40.7	20	x		" " " " "
5	30.0	23	x		" " " " "

Muller-Dethlefs and Schlader (1976) showed that a steam/fuel ratio of 7/1 reduces the laminar burning velocity of propane/air from 40 to 28 cm/sec and reduces the flame temperature from 2180°K to 1890°K, a difference of 290°K = 522°F. This reduction is less than would be expected by steam acting as a pure heat sink, because there is an exothermic shift in the water-gas equilibrium.

B. High Velocity Valve Tests

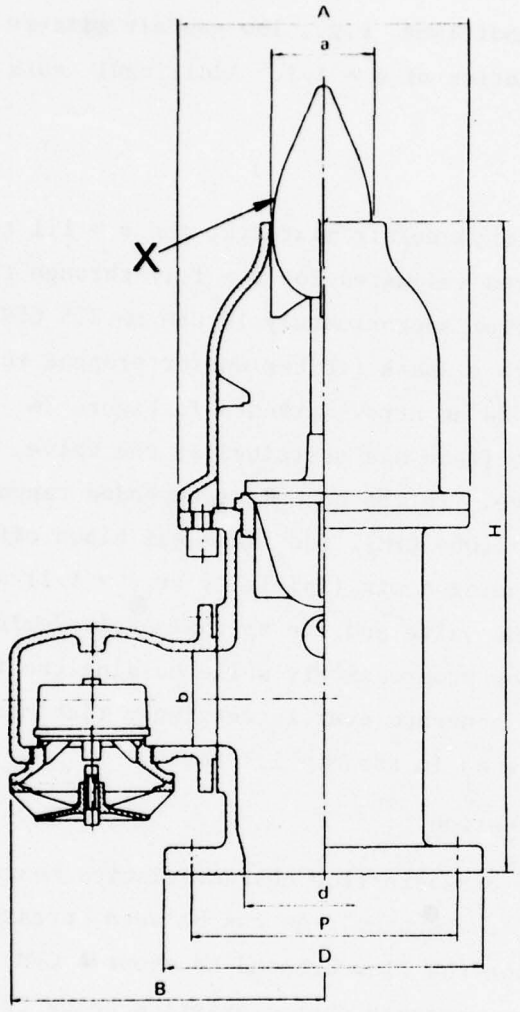
1. Apparatus Description

A Pres-Vac High Velocity Relief Valve,* Type HS6-M (shown in Figure 26), was tested for operation using both methane/air and ethylene/air mixtures on the flame arrestor apparatus. The relief valve was preset at the factory to relieve on a nominal pressure load of 1-1/2 psig. At this relief pressure, it is designed to accommodate the gas displaced by a liquid loading rate of approximately 11,000 barrels per hour, assuming a 6" pipe vent. This pressure drop corresponds to a velocity at the "throat" of the valve of 430 ft/sec, against which the flame must propagate.

The flame arrestor test apparatus was arranged to accommodate the relief valve by removing the upper section of the test apparatus including the Varec arrestor housing and all the components above it. A 3-foot flanged pipe section (6" dia, schedule 40) was fixed to the test apparatus in place of the upper test section and the relief valve was installed on top of the 3-foot section. A spark igniter (the same used for flame arrestor tests) was placed in the region of the valve exit stream. A mercury manometer was installed in the test pipe to measure pipe pressure during tests. The relief valve tests were

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*The valve was made available to Arthur D. Little, Inc., by the Waukesha Bearings Corp., Waukesha, Wisconsin, for evaluation during this program.



All dimensions are in inches. B.C. designates Bolt Circle.

a (dia.)	b (dia.)	d (dia.)	A (dia.)	H	B	D (dia.)	P (B.C.)	Holes (qty.-dia.)
6	7-1/4	9	16-1/8	31-5/16	17-1/2	14-9/16	12-13/16	(8) - 7/8

Source: Catalogue W–16, Relief Valve, Ullage Covers, Flame Arrestors, Waukesha Pres-Vac.

FIGURE 26 TYPE HS HIGH VELOCITY RELIEF VALVE

designed to see whether flashback could be prevented by the valve under the most demanding operating conditions, e.g., low gas/air mixture flow rates (6 CFM) and equivalence ratios of $\phi = 1.1$. Additional tests were performed with ϕ variations.

2. Test Procedure

For both methane/air and ethylene/air mixtures, the $\phi = 1.1$ tests involved flowing gas/air mixtures (adjusted for $\phi = 1.1$) through the relief valve at rates ranging from approximately 10 CFM to 2.5 CFM and igniting the vented mixture with a spark igniter and/or propane torch. The point of ignition is shown as an arrow marked X in Figure 26. Observations were made to see if the flame was sustained at the valve, blown off, or passed through the valve. In the normal recommended range of valve operation (approximately 1,000 CFM), the flame was blown off. The rich mixture tests involved flowing a mix (initially at $\phi = 1.1$) at approximately 10 CFM through the valve and, in approximately 2-minute intervals, reducing the air flow progressively while holding the fuel flow constant in an attempt to generate ever increasingly rich mixtures. The same observations were made as in the $\phi = 1.1$ tests.

3. Test Results and Discussion

Figure 27 illustrates the pressure/flow characteristics measured during non-combustion tests of the system. As can be seen, pressure began to fall below 1.4 psi when the flow dropped to about 4 CFM. No attempt was made to investigate pressure characteristics below this flow level.

Test results for methane/air mixtures at $\phi = 1.1$ are listed in Table 8. As can be seen, at mixture flow rates above 0.54 ft/sec (6.4 CFM), no sustained flame occurred. Evidence of a flammable mixture was shown by observing a luminous flame upon application of the propane torch where it impinged upon the relief valve float cone in the vicinity marked X in Figure 26. At flow rates progressively lower than 6.4 CFM, sustained

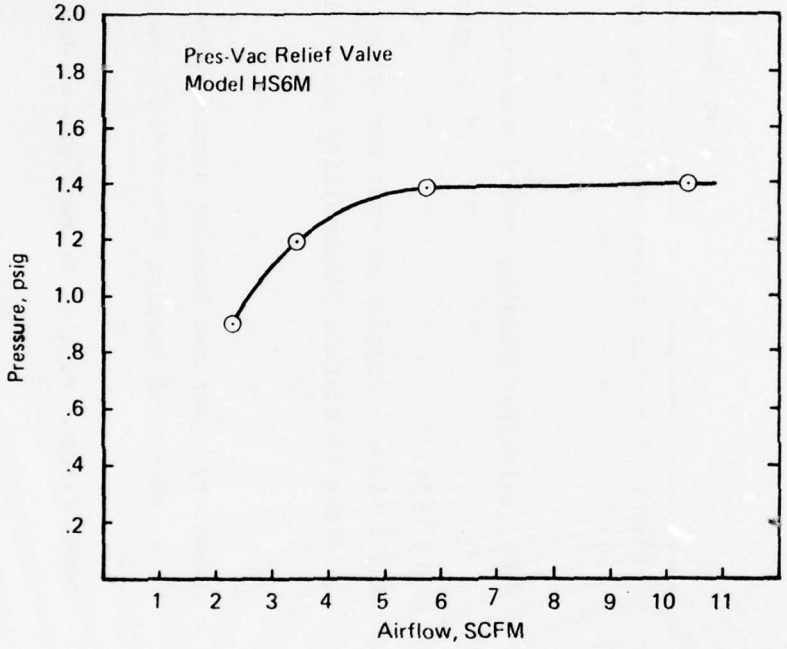


FIGURE 27 RELIEF PRESSURE CHARACTERISTICS AT LOW FLOW

TABLE 8

HIGH VELOCITY RELIEF VALVE TEST RESULTS

Relief Valve: Pres-Vac Model HS6M

Stoichiometric Tests

Test No.	Fuel	ϕ	Mixture Velocity (ft/sec)	Test Observations
1	Methane	1.0	0.87	Evidence of mixture flammability using propane torch @ "x" (Figure 26)
2	"	1.0	0.75	" " " " " " " "
3	"	1.0	0.65	" " " " " " " "
4	"	1.0	0.54	Weak sustained burning around cone--torch ignited
5	"	1.0	0.44	" " " " " --spark ignited
6	"	1.0	0.33	Very weak " " " " " "
7	"	1.0	0.22	Small flame ringlet at exit gap around base of cone
8	Ethylene	1.0	0.84	Evidence of mixture flammability using propane torch @ "x" (Figure 26)
9	"	1.1	0.72	" " " " " " " "
10	"	1.0	0.62	" " " " " " " "
11	"	1.0	0.53	Momentary sustained burning around cone--torch ignited
12	"	1.0	0.42	Weak sustained burning around cone--spark ignited
13	"	1.0	0.32	" " " " " " "
14	"	1.0	0.21	Small flame ringlet at exit gap around base of cone

Table 8 (Continued)

Fuel-Rich Tests

Test No.	Fuel	ϕ	Mixture Velocity (ft/sec)	Test Observations
15	Methane	1.0	0.87	Evidence of mixture flammability using propane torch @ "x" (Figure 26)
16	"	1.0	0.76	" " " " " " " "
17	"	1.2	0.67	" " " " " " " "
18	"	1.4	0.58	Weak sustained burning around cone--torch ignited
19	"	1.7	0.48	Sustained burning around cone--increased volume--torch ignited
20	"	2.1	0.38	" " " " " " " "
21	"	2.8	0.28	" " " " " " " "
22	Ethylene	1.0	0.84	Evidence of mixture flammability using propane torch @ "x" (Figure 26)
23	"	1.2	0.73	" " " " " " " "
24	"	1.3	0.64	Sustained burning around cone--torch ignited
25	"	1.6	0.55	" " " " --spark ignited
26	"	1.9	0.45	Increased burning around cone--yellow flames
27	"	2.4	0.35	" " " " " "

burning existed around the periphery of the cone in the form of a small blue ring at the exit annulus. At the lowest flow rate, the height of the flame ring was approximately 1/8" high. No flashback occurred.

The results of the ethylene/air tests using Continuous Mode procedures are also listed in Table 8. The flame characteristics of the ethylene/air flame were similar to those for methane/air flames except that they were more luminous (blue). No flashback occurred.

In tests performed with rich methane/air and ethylene/air mixtures, it was observed that enrichened mixtures at very low velocities resulted in sustained burning around the top of the valve. The continued burning heated the relief valve cone for the duration of the tests (up to 30 seconds). However, no flashback occurred during any of the tests. The extent of the continuous burning on the valve cone, the cone temperature, and the effect of these factors on flashback potential was not investigated.

APPENDIX A

TABULATION OF TEST DATA

Data obtained from individual tests performed during the program are listed in Tables A-1 through A-4 according to the following key:

Data on Effect of Equivalence Ratio on Flame Speed	A-1
Data on the Effect of Gas Temperature on Flame Speed	A-2
Tests Results for Methane and Ethylene	A-3
Tests Results for Ten Products (Fuels)	A-4

Table A-1

Data on Effect of Equivalence Ratio on Flame Speed

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23} ($\frac{ft}{sec}$)	Quench Y	Quench N	REMARKS
070103	Single screen	14 mesh x .016 wire	.055	-	-	Methane	1.10	5.94	6	4.2	✓		
070104	"	"	"	-	-	"	.90	5.78	"	2.8	✓		ϕ variation check
070105	"	"	"	-	-	"	.90	5.78	"	2.9	✓		"
070106	"	"	"	-	-	"	1.50	6.15	"	0	-		" - No Fire
070107	"	"	"	-	-	"	1.48	6.14	"	0	-		" "
070108	"	"	"	-	-	"	1.45	6.11	"	0	-		" "
070109	"	"	"	-	-	"	1.40	6.08	"	0	-		" "
070110	"	"	"	-	-	"	1.30	6.01	"	2.9	✓		ϕ variation check
070111	"	"	"	-	-	"	1.35	6.04	"	0	-		" - No Fire
070112	"	"	"	-	-	"	1.30	5.99	"	0	-		" "
070113	"	"	"	-	-	"	1.28	5.98	"	3.0	✓		ϕ variation check
070114	"	"	"	-	-	"	1.28	5.99	"	2.5	✓		"
070201	"	"	"	-	-	"	1.3	6.01	"	0	-		No Fire
070202	"	"	"	-	-	"	1.28	6.00	"	3.8	✓		ϕ variation check
070203	"	"	"	-	-	"	.83	5.74	"	2.3	✓		"
070204	"	"	"	-	-	"	.72	5.68	"	.6	✓		"
070205	"	"	"	-	-	"	.62	5.62	"	0	-		No Fire
070206	"	12 mesh x .020 wire	.063	-	-	"	.83	5.75	"	2.52	✓		ϕ variation check
070207	"	"	"	-	-	"	1.24	5.75	"	0	-		" - No Fire

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively.

Table A-1 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23} $(\frac{ft}{sec})$	Quench Y	Quench N	REMARKS
070901	Single screen	14 mesh x .016 wire	.055	-	-	Methane	1.1	5.92	6	4.44	✓		All tests w/o orifice, w/18" extension, ℄ spark & 90 sec. firing delay
070902	"	"	"	-	-	"	1.1	5.91	"	5.26	✓		
070903	"	"	"	-	-	"	1.2	5.97	"	4.17	✓		
070904	"	"	"	-	-	"	1.2	5.97	"	-	✓		
070905	"	"	"	-	-	"	1.2	5.97	"	4.44	✓		
070906	"	"	"	-	-	"	1.0	5.83	"	4.08	✓		
070907	"	"	"	-	-	"	1.0	5.83	"	4.00	✓		
070908	"	"	"	-	-	"	1.3	6.01	"	3.39	✓		
070909	"	"	"	-	-	"	1.3	6.01	"	2.22	✓		
070910	"	"	"	-	-	"	0.9	5.76	"	2.82	✓		
070911	"	"	"	-	-	"	0.9	5.76	"	2.99	✓		
070912	"	"	"	-	-	"	1.4	6.07	"	.85	✓		
070913	"	"	"	-	-	"	1.4	6.07	"	.98	✓		
070914	"	"	"	-	-	"	0.8	5.70	"	1.90	✓		
070915	"	"	"	-	-	"	0.8	5.70	"	1.96	✓		
071202	"	12 mesh x .020 wire	.063	-	-	"	1.1	5.76	"	4.44	✓		
071203	"	"	"	-	-	"	1.1	5.76	"	4.65		✓	
071204	"	"	"	-	-	"	0.8	5.57	"	1.9	✓		
071205	"	"	"	-	-	"	1.1	5.76	"	5.0		✓	
071206	"	"	"	-	-	"	1.4	5.95	"	.92	✓		
071207	"	10 mesh x .020 wire	.08	-	-	"	1.4	5.95	"	1.2	✓		
071208	"	"	"	-	-	"	1.1	5.77	"	4.54		✓	
071209	"	10 mesh x .02 wire	.08	-	-	"	0.65	5.51	"	1.85	✓		
071301	"	8 mesh x .02 wire	.10	-	-	"	1.4	6.03	"	2.44		✓	

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively.

Table A-1 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23} $(\frac{ft}{sec})$	Quench Y	Quench N	REMARKS
071302	Single screen	8 mesh x .020 wire	.10	-	-	Methane	0.8	5.65	6	1.72		✓	
071501	"	12 mesh x .020 wire	.063	-	-	"	0.8	5.79	"	1.3	✓		Purpose: confirm ϕ variation effects
071502	"	"	"	-	-	"	0.8	5.79	"	1.3	✓		" "
071503	"	"	"	-	-	"	1.4	6.16	"	2.0	✓		" "
071504	"	"	"	-	-	"	1.4	6.16	"	1.5	✓		" "
071505	"	10 mesh x .020 wire	.08	-	-	"	0.8	5.77	"	1.3	✓		" "
071506	"	"	"	-	-	"	0.8	5.77	"	1.3	✓		" "
071507	"	"	"	-	-	"	1.4	6.14	"	1.8	✓		" "
071508	"	"	"	-	-	"	1.4	6.14	"	1.7	✓		
071509	"	8 mesh x .020 wire	.11	-	-	"	0.8	5.75	"	1.5		✓	" "
071510	"	"	"	-	-	"	0.8	5.75	"	1.3		✓	" "
071511	"	"	"	-	-	"	1.4	6.14	"	2.3	✓		" "
071512	"	"	"	-	-	"	1.4	6.14	"	2.7	✓		" "
063001	"	16 mesh x .0135 wire	.049	-	-	"	1.13	5.84	"	5.0	✓		
063002	"	"	"	-	-	"	1.13	5.84	"	4.2	✓		
063003	"	"	"	-	-	"	1.13	5.84	"	4.4	✓		
063004	"	"	"	-	-	"	1.10	5.82	"	4.4	✓		Changed ϕ
063005	"	"	"	-	-	"	1.10	5.82	"	5.2	✓		
063006	"	14 mesh x .016 wire	.055	-	-	"	1.10	5.82	"	5.6	✓		
063007	"	"	"	-	-	"	1.10	5.82	"	4.3	✓		
070101	"	"	"	-	-	"	1.10	5.96	"	4.7	✓		
070102	"	"	"	-	-	"	1.10	5.94	"	4.9	✓		

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively.

Table A-2

Data on the Effect of Gas Temperature on Flame Speed

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	Mix. Temp. (°F)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23} $(\frac{ft}{sec})$	Quench Y	Quench N	REMARKS
070705	Single screen	14 mesh x .016 wire	.055	-	-	Methane	1.1	5.89	187	6.0	4.1	✓		
070706	"	"	"	-	-	"	"	"	149	"	"	✓		
070707	"	"	"	-	-	"	"	5.90	150	"	3.8	✓		
070801	"	"	"	-	-	"	"	5.93	99	"	4.4		✓	1/8" dia. hole in screen
070802	"	12 mesh x .020 wire	.063	-	-	"	"	5.90	113	"	5.6		✓	Effects of Mixture Temperature
070803	"	"	"	-	-	"	"	"	112	"	4.9		✓	" "
070807	"	"	"	-	-	"	0.8	5.67	146	"	2.0	✓		" "
070808	"	"	"	-	-	"	"	"	149	"	2.2	✓		" "
070808	"	"	"	-	-	"	1.1	5.85	151	"	4.5		✓	" "
070818	"	"	"	-	-	"	"	"	153	"	4.9		✓	" "
070811	"	"	"	-	-	"	1.35	6.01	155	"	3.1	✓		" "
070812	"	10 mesh x .020 wire	.08	-	-	"	"	"	158	"	2.8	✓		" "
070813	"	"	"	-	-	"	"	"	151	"	2.9	✓		" "
070814	"	"	"	-	-	"	0.8	5.67	156	"	2.2		✓	" "
070815	"	"	"	-	-	"	"	"	159	"	2.4	✓		" "
070816	"	"	"	-	-	"	"	5.66	156	"	2.5	✓		" "
070817	"	"	"	-	-	"	"	"	157	"	"	✓		" "
070818	"	"	"	-	-	"	1.35	6.00	157	"	3.1	✓		" "
070819	"	8 mesh x .020 wire	.105	-	-	"	"	"	152	"	2.2	✓		" "
070820	"	"	"	-	-	"	"	"	154	"	3.2	✓		" "
070821	"	"	"	-	-	"	0.8	5.66	157	"	2.7		✓	" "
070822	"	"	"	-	-	"	"	"	"	"	2.4		✓	" "

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively.

Table A-3

Test Results for Methane and Ethylene

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23} $(\frac{ft}{sec})$	Quench Y	Quench N	REMARKS
061807	Single screen	8 mesh x .020 wire	.105	-	-	Methane	1.10	6.03	6	4.5		✓	
070601	"	12 mesh x .02 wire	.063	-	-	"	1.1055	5.91	"	3.92		✓	
070602	"	"	"	-	-	"	0.80	5.71	"	1.78	✓		
070603	"	"	"	-	-	"	0.80	5.71	"	2.15	✓		
070604	"	"	"	-	-	"	1.25	5.98	"	3.86	✓		
070605	"	"	"	-	-	"	1.25	5.98	"	3.42	✓		
070606	"	"	"	-	-	"	1.25	5.98	"	3.72	✓		
070607	"	11 mesh x .023 wire	.0679	-	-	"	1.25	5.97	"	0.0	-		No Fire - 2 Attempts
070608	"	"	"	-	-	"	1.25	5.97	"	2.88	✓		
070609	"	"	"	-	-	"	1.25	5.97	"	3.01	✓		
070610	"	"	"	-	-	"	0.80	5.69	"	2.10	✓		
070611	"	"	"	-	-	"	1.10	5.87	"	4.65		✓	
070612	"	10 mesh x .020 wire	.08	-	-	"	0.80	5.68	"	2.40		✓	
070613	"	"	"	-	-	"	1.25	5.97	"	3.27	✓		
070614	"	"	"	-	-	"	1.25	5.97	"	2.47		✓	
070701	"	11 mesh x .023 wire	.068	-	-	"	0.8	5.73	"	1.53	✓		
070702	"	"	"	-	-	"	0.8	5.73	"	2.15	✓		
070703	"	"	"	-	-	"	1.25	5.98	"	-		✓	
070704	"	"	"	-	-	"	1.25	5.98	"	4.33		✓	

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively.

Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23} $(\frac{ft}{sec})$	Quench Y	Quench N	REMARKS
080201	Single screen	14 mesh x .016 wire	.055	-	-	Ethylene	1.1	5.80	6	100.		✓	
080202	"	"	"	-	-	"	1.1	5.77	"	80.		✓	
080203	"	"	"	-	-	"	1.1	5.77					
080204	"	"	"	-	-	"	0.8	5.90	"	20.		✓	
080205	"	"	"	-	-	"	1.4	5.77	"	15.		✓	
080206	"	18 mesh x .015 wire	.041	-	-	"	1.1	5.77	"	32.		✓	
080207	"	"	"	-	-	"	1.1	5.77	"	32.		✓	
080208	"	"	"	-	-	"	1.1	5.77	"	53.		✓	
080209	"	"	"	-	-	"	0.8	5.66	"	19.		✓	
080210	"	"	"	-	-	"	1.4	5.89	"	13.		✓	
080211	"	22 mesh x .0135 wire	.032	-	-	"	1.1	5.76	"	40.		✓	
080212	"	"	"	-	-	"	1.1	5.75	"	22.		✓	
080213	"	"	"	-	-	"	1.1	5.75	"	29.		✓	
080214	"	"	"	-	-	"	0.8	5.64	"	10.		✓	
080215	"	"	"	-	-	"	1.4	5.87	"	26.		✓	Screen buckled - openings at side
080216	"	26 mesh x .011 wire	.027	-	-	"	1.1	5.74	"	100.		✓	
080217	"	"	"	-	-	"	1.1	5.74	"	50.		✓	
080218	"	"	"	-	-	"	1.1	5.74	"	100.		✓	Screen buckled - openings at side
080219	"	"	"	-	-	"	0.8	5.62	"	19.		✓	
080220	"	"	"	-	-	"	1.4	5.85	"	20.	✓		
082005	"	30 mesh x .012 wire	.021	-	-	"	1.1	5.73	"	-		✓	
082006	"	"	"	-	-	"	1.1	5.73	"	31.		✓	

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively.

Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23} ($\frac{ft}{sec}$)	Quench Y	Quench N	REMARKS
082007	Single screen	30 mesh x .012 wire	.021	-	-	Ethylene	1.1	5.73	6	36.		✓	
082008	"	38 mesh x .0085 wire	.018	-	-	"	1.1	5.73	"	36.		✓	
082009	"	"	"	-	-	"	1.1	5.73		38.		✓	
082010	"	"	"	-	-	"	1.1	5.72	"	40.		✓	
110301	"	"	"	-	-	"	1.1	5.84	"	25.		✓	
110302	"	"	"	-	-	"	1.1	5.84	"	25.		✓	
110303	"	"	"	-	-	"	1.1	5.84	"	25.		✓	
061701	"	20 mesh x .016 wire	.034	-	-	Methane	1.11	5.97	"	4.6	✓		
061702	"	"	"	-	-	"	1.11	5.97	"	4.4	✓		
061703	"	"	"	-	-	"	1.11	5.97	"	3.8	✓		
061704	"	"	"	-	-	"	1.11	5.97	"	4.2	✓		
061705	"	16 mesh x .0135 wire	.049	-	-	"	1.11	5.97	"	4.5	✓		
061706	"	"	"	-	-	"	1.11	5.97	"	4.8		✓	3 sec. delay before screen failed
061707	"	"	"	-	-	"	1.11	5.97	"	4.8	✓		
061708	"	"	"	-	-	"	1.11	5.97	"	4.2	✓		
061801	"	12 mesh x .023 wire	.060	-	-	"	1.10	6.03	"	4.3		✓	
061802	"	"	"	-	-	"	1.10	6.03	"	4.7		✓	
061803	"	"	"	-	-	"	1.10	6.03	"	4.3		✓	
061804	"	"	"	-	-	"	1.10	6.03	"	4.6		✓	
061805	"	"	"	-	-	"	1.10	6.03	"	4.4		✓	
061806	"	8 mesh x .020 wire	.105	-	-	"	1.10	6.03	"	4.5		✓	

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively.

Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23} ($\frac{ft}{sec}$)	Quench Y	Quench N	REMARKS
071303	Single Screen	8 mesh x .02" wire	.10	-	-	Methane	1.1	5.83	4.0	4.2		✓	No pipe extension used
071304	"	"	"	-	-	"	"	"	"	4.0		✓	" "
071305	"	"	"	-	-	"	"	"	6.0	4.1		✓	" "
071306	"	"	"	-	-	"	"	"	"	4.3		✓	" "
071307	"	"	"	-	-	"	"	"	3.0	"		✓	" "
071308	"	"	"	-	-	"	"	"	"	4.7		✓	" "
071309	"	"	"	-	-	"	"	"	2.0	12.9		✓	" "
071401	"	"	"	-	-	"	"	5.92	"	16.7		✓	" "
071402	"	"	"	-	-	"	"	5.91	"	7.4		✓	" "
071403	"	"	"	-	-	"	"	"	1.0	200		✓	" "
071404	"	"	"	-	-	"	"	"	"	"		✓	" "
071405	"	"	"	-	-	"	"	"	2.0	25		✓	" "
071406	"	"	"	-	-	"	"	"	"	11		✓	" "

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively.

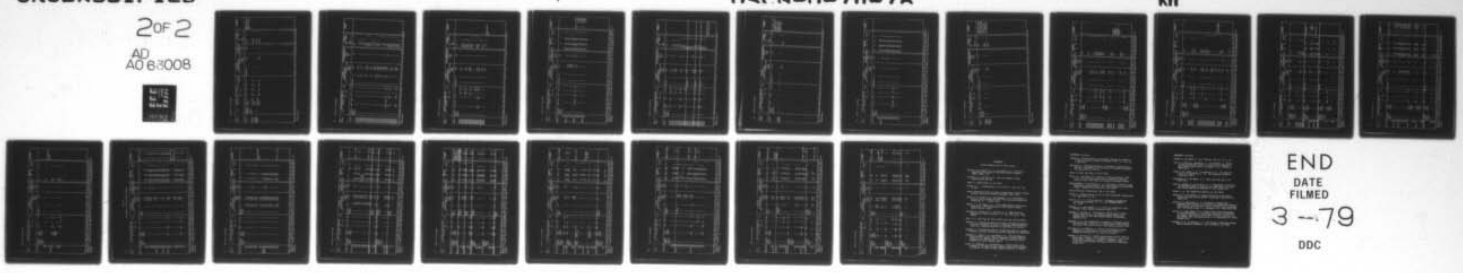
Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	Blockage (%)	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23} ($\frac{ft}{sec}$)	Quench Y	Quench N	REMARKS
080401	Single Perforated Plate	.02" dia. holes	.02	-	-	74	Methane	1.1	6.05	3.0	50.0		✓	
080402	"	"	"	-	-	-	"	"	6.04	"	66.6		✓	
080403	"	.062" dia. holes	.062	-	-	59	"	"	"	"	"		✓	
080404	"	"	"	-	-	-	"	"	"	"	"		✓	
080405	"	.072" dia. holes	.072	-	-	54	"	"	"	"	"		✓	
080406	"	"	"	-	-	-	"	"	6.03	"	"		✓	
080407	"	.107" dia. holes	.107	-	-	55	"	"	"	"	"		✓	
083106	"	.02" dia. holes	.02	-	-	74	"	"	6.06	"	4.9	✓		
083107	"	"	"	-	-	-	"	"	"	"	5.6	✓		
083108	"	.062" dia. holes	.062	-	-	59	"	"	"	"	5.4	✓		
083109	"	"	"	-	-	-	"	"	6.10	"	4.6	✓		
083110	"	.072" dia. holes	.072	-	-	54	"	"	"	"	5.4		✓	
083111	"	"	"	-	-	-	"	"	"	"	4.7		✓	
090201	Stacked Perforated Plates	"	.072	0.26	3.67	54	Methane	1.1	6.07	3.0	66.6		✓	
090202	"	"	"	"	"	"	"	"	"	"	62.5		✓	
090203	"	"	"	0.40	5.50	"	"	"	"	"	47.6	✓		Holes don't line up exactly

V^*_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively.

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Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	Blockage (%)	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23} ($\frac{ft}{sec}$)	Quench Y	Quench N	REMARKS
090204	Stacked Perforated Plates	.072" dia. holes	.072	0.40	5.50	54	Methane	1.1	6.07	3.0	57.1	✓		Holes don't line up exactly
090205	"	.107" dia. holes	.107	0.56	5.27	55	"	"	"	"	100.0		✓	
090206	"	"	"	"	"	"	"	"	"	"	62.5		✓	
090207	"	.062" dia. holes	.062	0.18	2.84	59	"	"	6.08	"	80.0		✓	

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively.

Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23} ($\frac{ft}{sec}$)	Quench Y	Quench N	REMARKS
071513	Parallel plate (steel)	.080 " gap	.112	2.0	17.9	Methane	1.1	5.94	2.0	33.3		✓	
071514	"	"	"	"	"	"	1.4	6.15	"	1.2	✓		
071515	"	"	"	"	"	"	"	"	"	1.5	✓		
071601	"	"	"	"	"	"	0.8	5.73	"	2.0	✓		
071602	"	"	"	"	"	"	"	"	"	1.9	✓		
071603	"	"	"	"	"	"	"	"	"	2.2	✓		
071604	"	"	"	"	"	"	1.1	5.91	"	28.6		✓	
071605	"	"	"	"	"	"	"	5.89	"	28.6		✓	
071606	"	"	"	"	"	"	"	"	"	33.3		✓	
071607	"	"	"	"	"	"	1.4	6.07	"	2.0	✓		
071608	"	"	"	"	"	"	"	"	"	1.1	✓		
071609	"	"	"	"	"	"	"	6.06	"	1.3	✓		
071610	"	"	"	"	"	"	1.1	5.76	"	42.6		✓	
071611	"	"	"	"	"	"	0.9	5.63	"	2.6	✓		
071612	"	"	"	"	"	"	1.0	5.70	"	8.3		✓	
071613	"	"	"	"	"	"	1.2	5.81	"	-		✓	
071614	"	"	"	"	"	"	"	5.80	"	5.5		✓	
071615	"	"	"	"	"	"	1.1	5.74	"	5.1		✓	
071616	"	"	"	"	"	"	1.4	5.93	"	1.5	✓		
072801	"	0.051" gap	.071	"	28.2	"	1.1	5.85	3.0	57.1		✓	
072802	"	"	"	"	"	"	"	"	"	100.0		✓	
073001	"	.04	.056	"	35.7	"	"	6.0	"	66.6		✓	
080301	"	"	"	"	"	"	"	6.07	"	25.0		✓	
080302	"	"	"	"	"	"	"	"	"	62.5		✓	
080303	"	"	"	"	"	"	"	6.06	"	50.0		✓	
081001	"	.025	.035	"	57.1	"	"	5.85	"	62.5	✓		
081002	"	"	"	"	"	"	"	"	"	28.5	✓		

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively.

Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23} $(\frac{ft}{sec})$	Quench Y	Quench N	REMARKS
081003	Parallel plate (steel)	.025" gap	.035	2.0	57.1	Methane	1.1	5.86	3.0	57.1	✓		
081601	"	"	"	1.56	44.6	"	"	5.90	"	66.6	✓		
081602	"	"	"	"	"	"	"	"	"	62.5	✓		
081603	"	"	"	"	"	"	"	"	"	64.5	✓		
081801	"	"	"	1.063	30.3	"	"	5.99	"	62.5	✓		
081802	"	"	"	"	"	"	"	"	"	28.5	✓		
081803	"	"	"	"	"	"	"	5.98	"	62.5	✓		
081907	"	"	"	0.50	14.3	"	"	6.03	"	66.6		✓	
081908	"	"	"	"	"	"	"	"	"	"	✓		
081909	"	"	"	"	"	"	"	"	"	"	✓		
081910	"	"	"	"	14.2	"	"	"	"	62.5		✓	
081911	"	"	"	"	14.3	"	"	6.01	"	66.6		✓	
082401	"	.015	.023	"	22.2	"	"	5.97	"	"	✓		
082402	"	"	"	"	"	"	"	"	"	"	✓		
082403	"	"	"	"	"	"	"	5.96	"	62.5	✓		
082404	"	"	"	"	"	"	"	"	"	"	✓		
082405	"	"	"	"	"	"	"	5.97	"	6.9	✓		Questionable run

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively.

Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V_{23}*	V_{34}	V_{24}	Quench Y	Quench N	REMARKS
090677-01	Parallel plate (steel)	.022" gap	.031	1.06	34.2	Ethylene	1.1	5.70	6.0		20			✓	
-02	"	"	"	"	"	"	"	"	"	29	83	38		✓	
-03	"	"	"	"	"	"	"	"	"	29	74	38		✓	
090777-01	"	"	"	"	"	"	"	5.77	5.0	32	43	35		✓	
-02	"	"	"	"	"	"	"	5.89	"	12	12	12	✓		
-03	"	"	"	"	"	"	"	5.94	"	28	42	33	✓		
-04	"	"	"	"	"	"	"	5.93	4.0	57	625	88		✓	
-05	"	"	"	"	"	"	"	"	"	48	208	68		✓	Press = 8 psi
090977-01	"	.011" gap	.015	1.5	100	"	"	5.23	6.0	69	35	50		✓	" 3 psi
-02	"	"	"	"	"	"	"	"	"	50	42	47		✓	" 15 psi
-03	"	"	"	"	"	"	"	"	"	29	29	29		✓	" 6 psi
-04	"	"	"	"	"	"	"	"	"	45	64	51		✓	" 14 psi
-05	"	"	"	"	"	"	"	"	"	41	42	41		✓	" 18 psi
091277-03	"	"	"	"	"	"	"	"	"	22	21	22		✓	" 2 psi
-04	"	"	"	"	"	"	"	"	"	17	16	16		✓	

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively. Similarly V_{34} is the flame speed based on point 3 (17") and point 4 (2") from the opposite side of the arrestor. Likewise, V_{24} is the flame speed based on point 2 (41") and point 4 (2") from the opposite side of the arrestor.

Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23} ($\frac{ft}{sec}$)	Quench Y	Quench N	REMARKS
092101	Parallel plate (steel)	.015" gap	.021	.5	23.9	Methane	1.1	5.88	3.0	9.5	✓		
101301	"	.051	.071	1.06	15.0	"	"	5.91	6.0	4.5	✓		
101302	"	"	"	"	"	"	"	"	"	4.3	✓		
101303	"	"	"	"	"	"	"	5.90	"	3.6	✓		
101501	"	"	"	.50	7.0	"	"	5.91	"	4.9	✓		
101502	"	"	"	"	"	"	"	"	"	4.5	✓		
101503	"	"	"	"	"	"	"	"	"	6.9	✓		
102604	"	.016	.023	.25	10.9	"	"	6.03	3.0	60.6		✓	
102605	"	"	"	"	"	"	"	"	"	66.7		✓	
102606	"	"	"	"	"	"	"	"	"	62.5		✓	
102901	"	"	"	"	10.87	"	"	5.83	"	667		✓	
102902	"	"	"	"	"	Ethylene	"	"	"	400		✓	
102902	"	"	"	"	"	"	"	"	"	714		✓	
102904	"	"	"	"	"	"	"	"	"	250		✓	
110101	"	"	"	"	"	"	"	5.79	6.0	25		✓	
110103	"	"	"	"	"	"	"	5.87	"	24.4		✓	
110401	"	.20	.028	1.5	53.6	Methane	"	5.79	"	25		✓	
110402	"	"	"	"	"	"	"	"	"	30.8		✓	
110403	"	"	"	"	"	"	"	"	"	29.6		✓	
102901	"	.016	.023	.25	10.9	Ethylene	"	5.83	3.0	667		✓	
102902	"	"	"	"	"	"	"	"	"	400		✓	
102903	"	"	"	"	"	"	"	"	"	714		✓	
102904	"	"	"	"	"	"	"	"	"	714		✓	250 ft/sec.vel at upper pipe level

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively.

Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23} $(\frac{ft}{sec})$	Quench Y	Quench N	REMARKS
110101	Parallel plate (steel)	.016	.023	.25	10.9	Ethylene	1.1	5.79	6.0	25		✓	Low speed test--arrestor was found to be damaged from above tests
110102	"	"	"	"	"	"	"	"	"	-		✓	" "
110103	"	"	"	"	"	"	"	5.87	"	24.4		✓	

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively.

Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23}	V_{34}	V_{24}	Quench Y	Quench N	REMARKS
110777-17	Parallel plate (steel)	.032" gap	.045	1.0	22.2	Methane	1.1	5.88	3.0	39	50	42	✓		
-18	"	"	"	"	"	"	"	"	"	57	104	69	✓		
-19	"	"	"	"	"	"	"	"	"	24	20	22	✓		
110977-01	"	"	"	"	"	"	"	"	2.5	34	36	34	✓		
-02	"	"	"	"	"	"	"	"	"	8	10	9	✓		
-03	"	"	"	"	"	"	"	"	"	28	32	29	✓		
-04	"	"	"	"	"	"	"	"	1.5	80	46	62	✓		
-05	"	"	"	"	"	"	"	"	"	42	34	39	✓		
-06	"	"	"	"	"	"	"	"	"	8	20	10	✓		
-07	"	"	"	"	"	"	"	"	"	105	48	72	✓		
-08	"	.011" gap	.015	.25	16.7	"	"	"	"	12	26	14	✓		
-09	"	"	"	"	"	"	"	"	"	61	52	57	✓		
-10	"	"	"	"	"	"	"	"	"	53	54	53	✓		
-11	"	"	"	"	"	"	"	"	"	22	20	21	✓		
-12	"	"	"	"	"	"	"	"	"	44	50	46	✓		

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively. Similarly V_{34} is the flame speed based on point 3 (17") and point 4 (2") from the opposite side of the arrestor. Likewise, V_{24} is the flame speed based on point 2 (41") and point 4 (2") from the opposite side of the arrestor.

Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23} ($\frac{ft}{sec}$)	Quench Y	Quench N	REMARKS
083101	Plastic parallel plates	.025 " gap	0.035	1.0	28.67	Methane	1.1	6.13	3.0	62.5		✓	Plastic plates were more flexible than steel plates. Data too sparce to be conclusive.
083102	"	"	"	"	"	"	"	"	"	57.1		✓	
083103	"	"	"	"	"	"	"	"	"	66.6	✓		
083104	"	"	"	"	"	"	"	6.08	"	57.1		✓	
083105	"	"	"	"	"	"	"	"	"	66.6	✓		

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively.

Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V_{23}*	V_{34}	V_{24}	Quench Y	Quench N	REMARKS
081604	Crimped Ribbon Ferro-therm	.063 crimp height	.070	1.25	17.96	Methane	1.1	5.99	3.0	55.5				✓	
081605	"	"	"	"	"	"	"	"	"	62.5				✓	
081606	"	"	"	"	"	"	"	"	"	"				✓	
081901	"	"	"	"	"	"	"	6.05	"	"				✓	
081902	"	"	"	"	"	"	"	6.04	"	"				✓	
081903	"	"	"	"	"	"	"	"	"	19.0				✓	
081904	"	"	"	0.88	12.64	"	"	6.02	"	66.6				✓	
081905	"	"	"	"	"	"	"	"	"	100.0				✓	
081906	"	"	"	"	"	"	"	"	"	66.6				✓	
082001	"	"	"	2.625	37.72	"	"	6.03	"	62.5				✓	
082002	"	"	"	"	"	"	"	5.98	"	66.6				✓	
090901	"	.0313" crimp height	.035	0.50	14.25	"	"	6.13	"	"			✓		
090902	"	"	"	"	"	"	"	6.06	"	"			✓		
090903	"	"	"	0.25	7.12	"	"	"	"	36.3			✓		
090904	"	"	"	"	"	"	"	6.07	"	66.6				✓	Arrestor damaged
090905	"	"	"	"	"	"	"	"	"	"				✓	Arrestor damaged - replaced
091001	"	"	"	"	"	"	"	5.97	"	14.6			✓		
091002	"	"	"	"	"	"	"	"	"	66.6				✓	
091003	"	"	"	"	"	"	"	"	"	"				✓	
091301	"	.0156" crimp height	.0164	0.375	22.94	"	"	6.04	"	-				✓	

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively. Similarly V_{34} is the flame speed based on point 3 (17") and point 4 (2") from the opposite side of the arrestor. Likewise, V_{24} is the flame speed based on point 2(41") and point 4 (2") from the opposite side of the arrestor.

Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	*V_{23}	RESULTS V_{34}	V_{24}	Quench Y	Quench N	REMARKS
091302	Crimped Ribbon Ferro-therm	.0156" crimp height	.0164	0.375	22.94	Methane	1.1	6.04	3.0	66.6			✓		
091303	"	"	"	"	"	"	"	"	"	"			✓		
091304	"	"	"	0.25	15.29	"	"	6.03	"	62.5			✓		
091305	"	"	"	"	"	"	"	"	"	117.6			✓		
091306	"	.0313" crimp height	.0351	0.375	10.68	"	"	6.02	"	62.5			✓		
091307	"	"	"	"	"	"	"	"	"	12.5			✓		
091308	"	"	"	"	"	"	"	6.01	"	62.5			✓		
091309	"	"	"	0.25	7.12	"	"	5.99	"	15.3			✓		
091310	"	"	"	"	"	"	"	"	"	66.6				✓	
092301	"	"	.035	"	"	"	"	6.10	"	64.5				✓	
092302	"	"	"	"	"	"	"	"	"	66.7				✓	
092303	"	"	"	"	"	"	"	"	"	"				✓	
092304	"	"	"	"	"	"	"	6.06	"	"				✓	
092404	"	"	"	"	"	"	"	6.10	"	"				✓	
092405	"	"	"	"	"	"	"	"	"	"				✓	
092406	"	"	"	"	"	"	"	6.08	"	-				✓	Flame speed not recorded
092407	"	"	"	"	"	"	"	6.07	"	66.7				✓	
092408	"	"	"	"	"	"	"	"	"	62.5				✓	
100801	"	.062" crimp height	.069	.87	12.6	"	"	5.98	6.0	4.6			✓		
101201	"	"	"	"	"	"	"	6.11	"	4.4			✓		
101202	"	"	"	"	"	"	"	"	"	5.2			✓		

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively. Similarly V_{34} is the flame speed based on point 3 (17") and point 4 (2") from the opposite side of the arrestor. Likewise, V_{24} is the flame speed based on point 2(41") and point 4 (2") from the opposite side of the arrestor.

Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V_{23}*	V_{34}	V_{24}	Quench Y	Quench N	REMARKS
101504	Crimped Ribbon Ferro-therm	.047" crimp height	.050	.75	12.6	Methane	1.1	5.91	6.0	4.6			✓		
101505	"	"	"	"	15	"	"	"	"	3.9			✓		
101506	"	"	"	"	"	"	"	"	"	4.0			✓		
102601	"	"	"	"	"	"	"	6.02	3.0	66.7			✓		
102602	"	"	"	"	"	"	"	"	"	60.6			✓		
102603	"	"	"	"	"	"	"	"	"	66.7			✓		
090777-06	Crimped Ribbon Amal	.018" crimp height	.015	1.5	1.00	Ethylene	"	5.93	6.0	56	250	79		✓	Press=8psi
090877-01	"	"	"	"	"	"	"	5.85	"	59	156	77		✓	" =14psi
-02	"	"	"	"	"	"	"	"	"	105	89	98	✓		" =21psi
-03	"	"	"	"	"	"	"	"	"	2				✓	
091277-05	"	"	"	"	"	"	"	"	"	23	27	25		✓	Press=2psi
-06	"	"	"	"	"	"	"	"	"	18	25	20		✓	
-07	"	"	"	"	"	"	"	"	"	25	42	30		✓	
110777-12	Crimped Ribbon Ferro-therm	.047" crimp height	.054	"	27.7	Methane	"	5.88	3.0	53			✓		
-13	"	"	"	"	"	"	"	"	"	53			✓		
-14	"	.078" crimp height	.088	1.0	11.4	"	"	"	6.0	4	4	4	✓		
-15	"	"	"	"	"	"	"	"	"	4	5	4	✓		
-16	"	"	"	"	"	"	"	"	"	5	4	5	✓		

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively. Similarly V_{34} is the flame speed based on point 3 (17") and point 4 (2") from the opposite side of the arrestor. Likewise, V_{24} is the flame speed based on point 2(41") and point 4 (2") from the opposite side of the arrestor.

Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	*V_{23}	RESULTS V_{34}	V_{24}	Quench Y	Quench N	REMARKS
091377-03	Crimped Ribbon Amal	.018" crimp height	.015	1.5	100	Ethylene	1.1	5.70	6.0	14	22	16		✓	Press = 3 psi
-04	"	"	"	"	"	"	"	"	"	14	25	17		✓	" = 3 psi
091477-01	"	"	"	"	"	"	"	"	4.0	46	52	47		✓	" = 4 psi
-02	"	"	"	"	"	"	"	"	"	39	42	41	✓		" = 4 psi
-03	"	"	"	"	"	"	"	"	"	50	96	61		✓	" = 4 psi
091977-04	"	"	"	"	"	"	"	5.69	"	500	250	360	✓		" =30 psi
-05	"	"	"	"	"	"	"	5.68	"	250	625	325	✓		" =12 psi
-06	"	"	"	"	"	"	"	5.67	"	1000	178	361	✓		" =20 psi
-07	"	"	"	"	"	"	"	5.68	"	48	53	66		✓	" = 4psi
-08	"	"	"	"	"	"	"	5.67	"	25	27	25		✓	" = 3 psi
-09	"	"	"	"	"	"	"	5.65	"	50	73	57		✓	" =16 psi
092977-01	"	.045" crimp height	.038	"	39.5	"	"	5.82	3.5	1000	625	812		✓	" =28 psi
-02	"	"	"	"	"	"	"	"	"	250	113	170		✓	" =18 psi
-03	"	"	"	"	"	"	"	"	"	400	295	208		✓	" =27 psi
093077-01	"	.018" crimp height	.015	.75	50	"	"	5.73	"	133	312	171		✓	" =25 psi
-02	"	"	"	"	"	"	"	"	"	111	89	101		✓	" =11 psi
-03	"	"	"	"	"	"	"	"	"	111	125	116	✓		
110777-01	Crimped Ribbon Ferro-therm	.047" crimp height	.054	2	37.0	Methane	"	5.88	3.0	7	5	6	✓		
-02	"	"	"	"	"	"	"	"	"	18	-	-	✓		
-03	"	"	"	"	"	"	"	"	"	27	-	-	✓		
-04	"	"	"	"	"	"	"	"	"	18	-	-	✓		

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively. Similarly V_{34} is the flame speed based on point 3 (17") and point 4 (2") from the opposite side of the arrestor. Likewise, V_{24} is the flame speed based on point 2(41") and point 4 (2") from the opposite side of the arrestor.

Table A-3 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	*V_{23}	RESULTS V_{34}	V_{24}	Quench Y	Quench N	REMARKS
110777-05	Crimped Ribbon Ferro-therm	.047" crimp height	.054	2	37.0	Methane	1.1	5.88	3.0	16	-	-	✓		
-06	"	"	"	"	"	"	"	"	"	38	-	-	✓		
-07	"	"	"	"	"	"	"	"	"	-	-	-	✓		No record obtained
-07 (repeat)	"	"	"	"	"	"	"	"	"	33			✓		
-08	"	.062" crimp height	.069	"	29	"	"	"	"	36			✓		
-09	"	"	"	"	"	"	"	"	"	51			✓		
-10	"	"	"	"	"	"	"	"	"	35			✓		
-11	"	"	.054	1.5	27.8	"	"	"	"	34			✓		

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively. Similarly V_{34} is the flame speed based on point 3 (17") and point 4 (2") from the opposite side of the arrestor. Likewise, V_{24} is the flame speed based on point 2 (41") and point 4 (2") from the opposite side of the arrestor.

Table A-4

Test Results for Ten Products (Fuels)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V_{23}*	V_{34}	V_{24}	Quench Y	Quench N	REMARKS
091577-01	Crimped Ribbon Amal.	.018" crimp height	.015	1.5	100	Buta-diene	1.1	6.25	4.0	8	8	8	✓		Press = 1 psi
-02	"	"	"	"	"	"	"	6.46	"	11	10	11		✓	" 1 "
-03	"	"	"	"	"	"	"	6.57	"	6	10	8		✓	" 2 "
-04	"	"	"	"	"	"	"	6.30	"	11	9	10	✓		" 2 "
-05	"	"	"	"	"	"	"	6.46	3.0	154	416	203	✓		" 12 "
-06	"	"	"	"	"	"	"	6.57	"	133	312	163	✓		" 21 "
-07	"	"	"	"	"	"	"	"	3.5	17	19	18	✓		" 2 "
-08	"	"	"	"	"	"	"	6.25	"	118	104	112	✓		" 21 "
091677-01	"	"	"	"	"	"	"	6.19	"	34	96	45	✓		" 3 "
-02	"	"	"	"	"	"	"	"	"	133	250	162	✓		" 21 "
-03	"	"	"	"	"	"	"	"	"	50	83	56		✓	" 3 "
-04	"	"	"	"	"	"	"	"	"	54	125	69		✓	" 6 "
091977-01	"	"	"	"	"	"	"	6.02	"	181	625	250	✓		" 25 "
-02	"	"	"	"	"	"	"	"	"	153	416	228	✓		" 25 "
-03	"	"	"	"	"	"	"	"	"	83	113	81	✓		" 21 "
092977-04	"	.045	.038	"	39.5	"	"	5.97	"	500	625	535		✓	" 28 "
-05	"	"	"	"	"	"	"	6.00	"	80	38	56		✓	" 18 "
-06	"	"	"	"	"	"	"	"	"	-	-	-		✓	Lost recorder trace
-07	"	"	"	"	"	"	"	6.01	"	57	57	57		✓	Press =17 psi
-08	"	"	"	"	"	"	"	6.02	"	43	50	46	✓		" 3 "
-09	"	"	"	"	"	"	"	"	"	286	73	135	✓		" 6 "
-10	"	"	"	"	"	"	"	6.03	"	29	46	34		✓	" 3 "
-11	"	.018	.015	.75	50	"	"	6.04	"	285	625	361	✓		" 3 "
-12	"	"	"	"	"	"	"	"	"	59	113	72		✓	" 14 "
-13	"	"	"	"	"	"	"	"	"	27	38	31		✓	" 3 "

*V_{23} is the average flame speed between points 2 and 3 located 41" and 17" from the opposite face of the arrestor, respectively. Similarly V_{34} is the flame speed based on point 3 (17") and point 4 (2") from the opposite side of the arrestor. Likewise, V_{24} is the flame speed based on point 2(41") and point 4 (2") from the opposite side of the arrestor.

Table A-4 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V_{23}*	V_{34}	V_{24}	Quench Y	Quench N	REMARKS
101177-01	Crimped Ribbon Amal.	.018" crimp height	.015	.75	50	Methyl Alcohol	1.5	2.71	3.0	2	3		✓		
-02	"	"	"	"	"	"	1.6	2.74	"	3			✓		
-03	"	"	"	"	"	"	1.5	3.24	"	2	2		✓		
-04	"	"	"	"	"	"	1.8	2.36	"	3	4		✓		
-05	"	"	"	"	"	"	2.3	1.96	"	2	3		✓		
-06	"	"	"	"	"	"	1.6	2.81	1.5	9	16		✓		
-07	"	"	"	"	"	"	2.2	1.95	"	4	8		✓		
-08	"	"	"	"	"	"	1.6	2.57	"	5	11		✓		
-09	"	"	"	"	"	"	1.3	3.22	"	-	-		✓		Lost recorder trace
-10	"	"	"	"	"	"	1.4	3.23	"	2	2				
-11	"	"	"	"	"	"	1.9	2.91	"	-	12		✓		
101177-01	"	"	"	"	"	"	1.6	2.83	"	11	20		✓		
101277-01	"	"	"	"	"	"	2.0	3.23	0.62	50	59		✓		
-02	"	"	"	"	"	"	1.4	2.88	"	16	18		✓		
-03	"	"	"	"	"	"	1.6	2.93	"	16	19		✓		
-04	"	"	"	"	"	"	2.0	3.06	"	17	14		✓		
-05	"	"	"	"	"	"	1.6	3.45	"	67	62		✓		
-06	"	"	"	"	"	"	1.5	3.39	"	-	83		✓		
-07	"	"	"	"	"	"	"	3.96	"	64	62		✓		
-08	"	"	"	"	"	"	0.87	6.14	"	133	156		✓		Press = 9 psi
-09	"	"	"	"	"	"	0.77	6.83	"	6	8		✓		

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Table A-4 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V_{23}*	V_{34}	V_{24}	Quench Y	Quench N	REMARKS
101277-10	Crimped Ribbon Amal	.018" crimp height	.015	.75	50	Methyl Alcohol	1.1	5.12	.62			35	✓		
101377-01	"	"	"	"	"	"	1.0	5.38	1.0	111	83	98	✓		Press = 6 psi
-02	"	"	"	"	"	"	.87	6.14	"	59	44	52	✓		
-03	"	"	"	"	"	"	1.04	5.14	"	87	54	70	✓		" 8 "
-04	"	"	"	"	"	"	.60	5.33	"	47	45	46	✓		" 3 "
-05	"	"	"	"	"	"	.71	5.16	"	No Fire					
-06	"	"	"	"	"	"	.77	5.19	"	No Fire					
-07	"	"	"	"	"	"	.71	4.75	"	14	13		✓		
-08	"	"	"	"	"	"	.88	4.73	"	47	44	46	✓		
-09	"	"	"	"	"	"	.91	4.75	"	61	65	62	✓		Press = 4 psi
-10	"	"	"	"	"	"	.92	"	"	67	50	59	✓		" 3 "
-14	"	"	"	"	"	"	.98	2.85	"	62	42	52	✓		" 3 "
101877-01	"	"	"	"	"	Buta-diene	1.1	6.24	3.5	125	312	162	✓		" 21 "
-02	"	"	"	"	"	"	1.0	6.15	"	67	113	79		✓	" 6 "
-03	"	"	"	"	"	"	"	"	"	133	104	120	✓		" 24 "
101977-01	Crimped Ribbon Ferro-therm	.032"	.035	.375	10.7	Methyl Alcohol	1.2	2.91	1.0	64	96	74	✓		" 3 "
-02	"	"	"	"	"	"	"	2.83	"	26	16	20	✓		" 5 "
102177-01	"	"	"	"	"	"	1.1	2.79	"	67	70	68	✓		" 3 "
-02	"	"	"	"	"	"	1.3	2.89	"	53	73	79	✓		" 3 "
102477-01	"	"	"	"	"	Buta-diene	1.1	6.48	"	111	81	98		✓	" 18 "
-02	"	"	"	"	"	"	"	6.44	"	105	113	108		✓	" 12 "

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Table A-4 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23}	V_{34}	V_{24}	Quench Y	Quench N	REMARKS
102477-03	Crimped Ribbon Ferro-therm	.032" crimp height	.035	.375	10.7	Buta-diene	1.1	6.45	1.0	142	416	190		✓	Press =35 psi Inspection showed arres-tor destroyed
102577-01	"	.062"	.069	"	5.4	Methyl Alcohol	1.3	2.95	"	50	96	61		✓	Press =12 psi
-02	"	"	"	"	"	"	"	3.04	"	91	50	69		✓	" 18 "
-03	"	"	"	"	"	"	"	3.01	"	77	42	58		✓	" 18 "
102677-01	"	"	"	"	"	Ethyl Ether	1.2	5.22	.62	154	156	155		✓	" 21 "
-02	"	"	"	"	"	"	"	"	"	105	69	88		✓	" 22 "
-03	"	.032"	.035	"	10.7	"	"	5.17	"			232		✓	" 39 "
111877-01	Crimped Ribbon Amal	.018"	.015	.75	50	Acetal-dehyde	1.1	5.00	1.5	154	156	155	✓		" 6 "
-02	"	"	"	"	"	"	"	"	"	200	208	203	✓		" 14 "
-03	"	"	"	"	"	"	"	"	3.0	57	125	72	✓		" 15 "
-04	"	"	"	"	"	"	"	"	"	62	104	74	✓		" 13 "
-05	"	"	"	"	"	"	"	"	"	56	178	76	✓		" 13 "
112177-01	Crimped Ribbon Ferro-therm	.032"	.035	.88	25	"	"	"	"	53	125	69	✓		" 5 "
-02	"	"	"	"	"	"	"	"	"	61	156	79	✓		" 8 "
-03	"	"	"	"	"	"	"	"	"	111	83	92	✓		" 15 "
-04	"	.062"	.069	"	12.7	"	"	"	"	118	74	96	✓		" 10 "
102677-04	"	.032"	.035	.375	10.7	Ethyl Ether	1.2	5.22	.62	53	312	79		✓	

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Table A-4 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V_{23}*	V_{34}	V_{24}	Quench Y	Quench N	REMARKS
102677-1A	Crimped Ribbon Ferro-therm	.062" crimp height	.069	.375	5.4	Ethyl Ether	1.2	5.22	2.0	15	15	15		✓	Press = 3 psi
102677-05	"	.032"	.035	"	10.7	"	"	5.20	.62	51	139	68	✓		" 14 "
-06	"	"	"	"	"	"	"	"	"	54	625	83		✓	" 12 "
102777-01	Crimped Ribbon Amal	.018"	.015	.75	5.0	"	"	5.17	"	181	179	180	✓		" 15 "
-02	"	"	"	"	"	"	"	5.09	"	53	178	72	✓		
-03	"	"	"	"	"	"	"	5.08	"	54	96	65	✓		Press = 9 psi
103177-01	Single Screen	22 mesh x .013" wire	.031	-	-	"	"	"	6.0	-	16	-		✓	
-02	"	"	"	-	-	"	"	"	"	4	8	5		✓	
-03	"	"	"	-	-	"	"	"	"	6	12	8		✓	
-04	"	"	"	-	-	"	"	"	"	5	10	6		✓	
110277-01	"	"	"	-	-	"	"	"	"	16	27	19		✓	Lower spark location
-02	"	"	"	-	-	"	"	"	"	25	78	33		✓	" "
110477-01	"	30 mesh x .011"wire	.022	-	-	"	"	"	"	11	14	12	✓		
-02	"	"	"	-	-	"	"	"	"	20	14	17		✓	
-03	"	"	"	-	-	"	"	"	"	7	8	8	✓		
-04	"	"	"	-	-	"	"	"	"	8	9	9	✓		
112177-05	Crimped Ribbon Ferro-therm	.062" crimp height	.069	.88	12.7	Acetal-dehyde	1.1	5.0	3.0	153	250	180		✓	
-06	"	"	"	"	"	"	"	"	"	111	139	120		✓	

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Table A-4 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V_{23}*	V_{34}	V_{24}	Quench Y	Quench N	REMARKS
112177-07	Crimped Ribbon Ferro-therm	.032" crimp height	.035	.375	10.7	Acetal-dehyde	1.1	5.0	3.0	100	104	101	✓		Press = 9 psi
-08	"	"	"	"	"	"	"	"	"	28	21	25	✓		" 3 "
-09	"	"	"	"	"	"	"	"	"	44	66	50	✓		" 3 "
-10	"	"	"	"	"	"	"	"	"	56	104	68	✓		" 3 "
112377-05	"	"	"	"	"	Toluene	"	7.92	1.5	19	23	20	✓		" 3 "
-06	"	"	"	"	"	"	"	7.91	"	3.7			✓		
-07	"	"	"	"	"	"	"	7.92	"	3.5			✓		
-08	"	"	"	"	"	"	"	"	"	25	10	15	✓		
-09	"	"	"	"	"	"	"	7.93	"	7			✓		
-10	"	"	"	"	"	"	"	7.94	1.0	9			✓		
-11	"	"	"	"	"	"	"	7.93	"	37	83	47	✓		Press = 3 psi
-12	"	"	"	"	"	"	"	"	"	42	69	49	✓		" 3 "
-13	"	"	"	"	"	"	"	7.92	"	51	24	36	✓		" 3 "
112877-01	"	.062"	.069	"	5.4	"	1.4	7.94	"	4	11	5	✓		
-02	"	"	"	"	"	"	"	"	"	39	114	52		✓	Press = 3 psi
-03	"	"	"	"	"	"	"	"	"	62	104	74		✓	" 15 "
-04	"	"	"	"	"	"	"	"	"	54	125	69		✓	" 15 "
-05	"	"	"	.875	12.7	"	"	"	"	62	32	46	✓		" 3 "
-06	"	"	"	"	"	"	"	"	"	71	66	69	✓		
-07	"	"	"	"	"	"	"	"	"	59	96	69	✓		
-10	"	.093"	.106	.75	7.1	"	"	"	"	67	78	71		✓	
-11	"	"	"	"	"	"	"	"	"	62	78	68		✓	

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Table A-4 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	RESULTS V^*_{23}	V_{34}	V_{24}	Quench Y	Quench N	REMARKS
010578-01	Crimped Ribbon Amal.	.018" crimp height	.015	1.5	100	Acety-lene	1.0	3.18	6.0	53	312	77		✓	Press = 14 psi
-02	"	"	"	"	"	"	"	3.20	"	80	59	71	✓		
011278-01	"	"	"	"	"	"	"	3.07	"	Not obtained				✓	Arrestor damaged
011678-01	"	"	"	.75	50	Hydrogen sulfide	1.1	2.64	3.0	5	4	4		✓	
-02	"	"	"	"	"	"	"	2.62	"	4	4	4		✓	
-03	"	"	"	"	"	"	"	2.66	1.5	14	19	16		✓	
-04	"	"	"	1.5	100	"	1.2	2.63	"	46	62	52	✓		
-05	"	"	"	"	"	"	"	"	"	10	21	13	✓		
011678-06	"	"	"	"	"	"	"	"	"	11	24	14	✓		
011778-01	Crimped Ribbon Ferro-therm	.032	.035	0.5	14.2	"	"	2.68	"	22	27	24	✓		
-02	"	"	"	"	"	"	1.1	2.61	"	10	27	13	✓		
-03	"	"	"	"	"	"	1.2	2.67	"	74	114	86		✓	
-04	"	"	"	"	"	"	"	2.68	"	60	74	65	✓		
-05	"	"	"	"	"	"	"	2.74	"	67	96	76		✓	
011978-01	"	.062	.069	"	7.2	"	"	2.68	"	31	24	28		✓	Press = 13 psi
-02	"	"	"	"	"	"	"	2.75	"	100	125	102		✓	" 14 "
-03	"	"	"	"	"	"	"	"	"	77	114	88		✓	" 29 "
012478-01	Crimped Ribbon Amal.	.018	.015	1.5	100	Carbon Disul-fide	1.0	6.73	6.0	5.1	12.5		✓		
-02	"	"	"	"	"	"	1.3	6.52	"	5.3	6.6			✓	
-03	"	"	"	"	"	"	1.1	8.34	3.0	74	78		✓		Press = 15 psi

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Table A-4 (continued)

Test Number	ARRESTOR CHARACTERISTICS Type	Opening	D_H (in)	L (in)	L/D_H	MIXTURE CHARACTERISTICS Fuel	ϕ	Mixture Flow Rate (SCFM)	FLOW RESTRICTION Orifice dia. (in)	V_{23}^*	RESULTS V_{34}	V_{24}	Quench Y	Quench N	REMARKS
012478-04	Crimped Ribbon Amal.	.018" crimp height	.015	1.5	100	Carbon Disul-fide	1.0	8.36	3.0	67	89		✓		Press = 15 psi
-05	"	"	"	"	"	"	0.99	8.33	"	40	33		✓		" 2 "
-06	"	.024	.021	.75	35.7	"	0.75	8.22	"	-	-		✓		Poor recorder trace
-07	"	"	"	"	"	"	1.0	6.19	"	11	27		✓		Press = 2 psi
-08	"	"	"	"	"	"	1.1	5.96	"	142	69		✓		" 5 "
-09	"	"	"	"	"	"	"	5.98	"	18	12		✓		
012578-01	Crimped Ribbon Ferro-therm	.032	.035	.50	"	"	1.3	6.02	"	32	36			✓	" 6 "
-02	"	"	"	"	14.2	"	1.1	7.22	"	83	69			✓	" 18 "
-03	"	"	"	"	"	"	1.4	7.41	"	64	125			✓	" 11 "
-04	"	.078	.088	1.0	11.4	"	0.97	7.22	"	61	139			✓	" 11 "
-05	"	"	"	"	"	"	0.95	7.11	"	67	83		✓		" 16 "
-06	"	"	"	"	"	"	1.0	7.16	"	61	114			✓	" 16 "
012778-01	Crimped Ribbon Amal.	.018	.015	1.5	100	Acety-lene	"	3.05	6.0	91	417			✓	" 5 "
-02	"	"	"	"	"	"	"	3.07	"	74	438			✓	" 8 "
-03	"	"	"	"	"	"	"	"	"	69	300		✓		" 8 "

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REFERENCES

(Listed Alphabetically by First Author)

Barton, R. R., Carver, F. W. S., and Roberts, T.A., "The Use of Reticulated Metal Foam as Flash-Back Arrestor Elements," RARDE, London, 1975.

Broschka, G. L. and Will, R. G., Amoco Oil Company, private communication, May 1976.

Busch, H., Explosivtoffe, 5, 135 (1957).

Clothier, W. C., Communication to Proc I Mech E., 1956, Vol. 170, p. 851.

Cohen, Discussion of paper by Palmer at Symposium on Chemical Process Hazards, Institute of Chemical Engineers, 1960, p. 80.

Davies, J. P., Palmer, K. N., and Rogowski, Z. W., "Performance of Metallic Foam as Flame Arrestors," Fire Prevention Science and Technology, No. 5, London, 1973.

Genkin, J. R. and Sarnev, S. P., "The Flame-Quenching Properties of Flame Traps," SMRE Translation No. 5482, Safety in Mines Research Establ. (1967).

Gerstein, M., Carlson, E. R., and Hill, F. U., "Natural Gas-Air Explosions at Reduced Pressure," Ind. Eng. Chem. 46, p. 2558, (1954).

Holm, J. M., Phil. Mag. 14, 18-56 (1932); ibid. 15, 329-359 (1933).

Hulsberg, F., "Research on Capacity of Layers of Granulated Material to Prevent Propagation of Flames of Explosive Gaseous Mixtures," Reuve de L' Industrie Minerale, Vol. 39 (1957), pp. 373-376.

Komamiya, K., "The Quenching Ability of Flame Arrestors for n-hexane," Research Institute of Industrial Safety, Japan RR-17-4, March 1969.

Langford, B., Palmer, K. N., and Tonkin, P. S., "The Performance of Flame Arrestors Against Flames Propagating in Various Fuel/Air Mixtures," Fire Research Note No. 486, Fire Research Station, Boreham Wood, Herts, England (1961).

Loison, R., Chaineaux, L., and Delclaux, J., "Study of Some Safety Problems in Fire Damp Drainage," Eighth International Conference of Directors of Safety in Mines Research, Paper No. 37 (1954).

REFERENCES (continued)

Maekawa, M., "Flame Quenching by Rectangular Channels as a Function of Channel Length for Methane-Air Mixture," Comb. Sci. Tech. 11 p. 141, 1975.

Mansfield, W., "Crankcase Explosions: Development of New Protective Devices," Proceedings of the Institution of Mechanical Engineers, Vol. 170 (1956), pp. 825-844.

Mayer, E., Comb. and Flame 1, 438-52 (1957).

Miller, S. A. and Penny, E., Institute of Chemical Engineers, 1960, p. 92. See also "German Techniques for Handling Acetylene," FIAT Tech. Rep. #720, London, Her Majesty's Stationary Office.

Müller-Dethlefs, K. and Schlader, A. F., "The Effect of Steam on Flame Temperature, Burning Velocity, and Carbon Formation in Hydrocarbon Flames," Combustion and Flame 27, p. 205 (1976).

Müller-Hillebrand, Elecktroteck Z 59, p. 116 (1938).

Palmer, K., "Flame Arrestors for Gas or Vapour Explosions," Engineering, Vol. 185 (1958), p. 438.

Potter, A. E., Jr., "Flame Quenching," in Progress in Combustion Science and Technology, Vol. I, p. 145, Pergamon Press, N.Y. (1960).

Rashbash, D. J. and Rogowski, Z. W., "Relief of Explosions in Duct Systems," Instn. Chemical Engineers, 1960, p. 59.

Rogowski, Z. and Ames, S., "Performance of Metal Foam as a Flame Arrestor When Fitted to Gas-Explosion-Relief Vents," Fire Research Note No. 931, Fire Research Station (Borehamwood, England), 1972.

Rogowski, Z. W., "The Transmission of Explosion of Flammable Gas/Air Mixtures Through a Flame Gap on a Vented Vessel," Fire Research Note #1018, Fire Research Station (Borehamwood, England), 1974.

Rozlovskii, A. and Zakaznov, V., "Effect of Gas Expansion During Combustion on the Possibility of Using Flame Arrestors," Combustion and Flame, Vol. 17 (1971), pp. 215-221.

Schampel, K. and Steen, H., "Flame Arresting High Velocity Valves on Cargo Tanks of Tankers for Inflammable Liquids," p. 441, Fourth International Symposium on Transport of Hazardous Cargoes by Sea and Inland Waterway, DOT Report CG-D-24-76, AD-A023505, October 1975.

REFERENCES (continued)

Schmidt, H. and Haberl, K., Tech. Überwach. 1955, No. 12, p. 423.

Scott, G., Perlee, H., Martindill, G., and Zabetakis, M., "Review of Fire and Explosion Hazards of Flight Vehicle Components," ASD Technical Report 61-278, (Supplement 1), U.S. Bureau of Mines (1972).

Simon, D. M., Belles, F. E., and Spakowski, A. E., IVth Symposium (Inter'l) on Combustion, p. 126. The Combustion Institute: Pittsburgh (1953).

Sutherland, M. E. and Wegert, H. W., Chem. Eng. Prog. 69, p. 48, April 1973.

Swan, A., Helmore, W., and Clothier, W. C., "Experiments on Reduction of Fire Risk by Means of Induction Pipe Flame Traps," U.K. Aero Res. Council Reports and Memoranda No. 1484, August 1932.

Wilson, C. A., Ind. Engineering Chemical, 51, 560 (1959).

Wilson, R. P. and Atallah, S., "Design Criteria for Flame Control Devices for Cargo Venting Systems," Final Report, DOT-CG-157-75, August 1975.

Wilson, R. P. and Crowley, D. P., "Performance of Commercially Available Flame Arrestors for Butane/Air and Gasoline/Air Mixtures," DOT-CG-42357A, ADL 77396-13-14, Office of Research and Development, USCG, 400 Seventh Street, S.W., Washington, D.C. 20590, March 1978.

Wilson, R. P. and Crowley, D. P., "Flame-Arrestor Design Requirements for Prolonged Exposure to Methane/Air, Butane/Air, and Gasoline Air Flames," DOT-CG-42357A, ADL-77396-15, Office of Research and Development, USCG, 400 Seventh Street, S.W., Washington, D.C. 20590, February 1978.

Wolfhard, H. G., and Bruszak, A. E., "The Passage of Explosions Through Narrow Cylindrical Channels," Comb. and Flame 4, 149 (1960).