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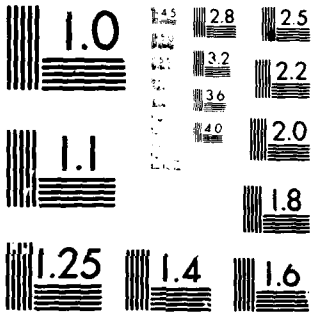

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FUEL PROPERTY EFFECTS ON COMBUSTOR PERFORMANCE

FINAL REPORT
No. MED114

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by
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and
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Under contract to
Naval Air Propulsion Center
Trenton, New Jersey

Contract No. N00140-77-C-1345

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March 1980

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: MED114

2. GOVT ACCESSION NO.: AD-A084 017 (9)

3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): (6) FUEL PROPERTY EFFECTS ON COMBUSTOR PERFORMANCE

5. TYPE OF REPORT & PERIOD COVERED: Final Report

6. PERFORMING ORG. REPORT NUMBER: MED114

7. AUTHOR(s): (10) C.A. Moses, D.W. Naegeli

8. CONTRACT OR GRANT NUMBER(s): (15) N00140-77-C-1345

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Southwest Research Institute
Mobile Energy Division
P.O. Drawer 28510
San Antonio, Texas 78284

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: (12) 54

11. CONTROLLING OFFICE NAME AND ADDRESS:
U.S. Naval Air Propulsion Center
Trenton, New Jersey

12. REPORT DATE: Mar[redacted]80 (11)

13. NUMBER OF PAGES: 48

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (14) SWRI-MED114

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES: The first phase of this program, reported in Interim Report AFLRL No. 101, AD No. A054229, entitled," Effect of High Availability Fuels on Combustor Properties," was performed under Contract No. DAAK70-78-C-0001 and was monitored by U.S. Army Mobility Equipment Research and Development Command, DRDME-GL, Fort Belvoir, VA.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Turbine - Fuels Research
Fuel Composition - Soot Formation
Ignition - Fuel Effects
Flame Stability - Fuel Effects

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Two combustor rigs have been used to study the sensitivities of combustor operation to the physical and chemical properties of fuels. Eighteen fuels including synfuels were used to accentuate the properties of concern: composition, viscosity, and boiling-point distribution. Flame radiation and smoke were best correlated by hydrogen content rather than hydrocarbon structure; the soot formation was due to gas-phase reactions. Lean-blowout conditions were about the same for all fuels except that gasoline could be

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UNCLASSIFIED 411 163

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Cont'd)

burned leaner at idle conditions. Ignition limits were more sensitive to volatility than viscosity. Gaseous emissions and combustion efficiency were not significantly affected by fuel properties although some sensitivity to boiling point distribution was evident. In all performance areas, the syncrude fuels correlated in the same ways as the petroleum-derived fuels except for the NO_x emissions from the nitrogen containing shale oil fuel.

SUMMARY

In this program, two combustor rigs have been used to study the sensitivity of combustor performance to the physical and chemical properties of fuels. The purpose was to determine the impact of broadening fuel specifications and of using nonspecification fuels in emergencies. For this program, 18 fuels, including three synfuels, were used to accentuate the properties of concern: composition, viscosity, and boiling point distribution. The combustors were instrumented for flame radiation, liner temperature, and exhaust emissions; testing included ignition, stability, and combustion efficiency.

Hydrogen content was the most effective correlating parameter for radiation and smoke; sensitivities to hydrocarbon structure were secondary. The syncrude fuels correlated the same way as the petroleum fuels. Higher end points did not affect the correlation, indicating that the soot formation was due to gas-phase reactions not liquid-phase pyrolysis. Results indicate clean-burning combustors should have low sensitivity to hydrogen content.

Stability was about the same for all fuels except that gasoline could be burned leaner at idle conditions. The more volatile fuels could be ignited under leaner conditions.

Combustion efficiency, CO, and UBH were dependent more on the high end of the distillation curve than on viscosity. NO_x was most sensitive to front end volatility.

The most serious combustion problems appear to be (1) increased smoke for some engines if hydrogen content is reduced and (2) an increase in ignition requirements for fuels with higher flash points, especially in cold weather.

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FOREWORD

This work was conducted for the U.S. Naval Air Propulsion Laboratory, Trenton, NJ, with the technical direction of Mr. Larry Maggitti, under Contract No. N00140-77-C-1345. The work was performed at the U.S. Army Fuels and Lubricants Research Laboratory with the cooperation of the Energy and Water Resources Laboratory of the U.S. Army Mobility Equipment Research and Development Command (MERADCOM), Fort Belvoir, VA.

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I. INTRODUCTION

Uncertainties in the production and supply of petroleum products have caused the U.S. Navy, as well as other organizations responsible for aviation fuel supply and specifications, to study the problems in obtaining adequate supplies of jet fuel. Such problems could be caused by shortages of acceptable products, i.e., fuels which meet specifications, either worldwide or in specific areas such as on board an aircraft carrier.

There are several possible solutions to these problems. For example, broadening the fuel specifications would allow more fuel to be defined as "acceptable." The use of nonpetroleum crudes, such as those derived from coal, tar sands, or oil shale, as refinery feed stocks would provide a larger base from which all distillates could be extracted, thus reducing the level of competition for the best cuts. In the extreme, nonaviation fuels occasionally might have to be used to extend supplies temporarily, for example, the blending of marine diesel with JP-5 on board an aircraft carrier.

There is one basic difficulty with all these "solutions": They imply the operation of aircraft turbine engines on fuels for which they were not designed. As a class, gas turbine engines can be designed to operate reliably on any fuel that can be supplied at controlled rates. In general, the large industrial-type turbines are relatively insensitive to most fuel properties, physical and chemical. The aviation-type turbines, however, are more critical of fuel quality and are designed to perform only on high-quality, light distillate fuels, e.g., JP-4, JP-5, and Jet A. These specifications have evolved over the last 30 years as compromises among the technical requirements of combustion chamber performance, materials compatibility, and fuel handling and the needs for availability and low cost; the result has been an adequate supply of fuels with fairly uniform properties and the virtual elimination of combustion and handling problems. All engines now in production or under development were designed for satisfactory performance and life on the current specifications for petroleum distillate fuels. Some of these engines may not be able to tolerate the changes implied by a broadened fuel specification, e.g., higher liner temperatures or lower rates of vaporization. Operation on other fuels may or may not lead to a reduction in performance or increased

maintenance requirements; however, at present there is a general lack of knowledge on fundamental relationships between fuel composition, properties and performance, making a prior judgments on the acceptability of nonspecification fuels somewhat tenuous. The current specifications may not cover these same problems for syncrude fuels of different composition. Alternately, the specifications may be unnecessarily strict in some areas.

Two of the basic questions that might be asked are:

- Which are the important physical and chemical properties that need to be controlled and which are superfluous or effectively redundant?

- If the specifications are relaxed, or nonspecification fuels used, what will be the impact on engine performance, reliability, and maintenance, as well as fuel storage stability and handling?

Among the properties of greatest concern are the fuel composition, the distillation curve, and the viscosity. The first property is generally associated with flame radiation and exhaust smoke; the last two affect atomization and vaporization and, therefore, ignition, gaseous emissions, combustion efficiency, and flame stability. Fuel-bound nitrogen is one new fuel property which has emerged from the use of syncrude fuels, primarily shale oil, because of the additional NO_x found in the exhaust.

These problems are also being studied extensively at AVCO/Lycoming in the Combustor Design Group and in the Combustion Laboratory at Purdue University, both funded by the U.S. Army to aid in the development of turbine engines which are more fuel tolerant. The work at AVCO/Lycoming is primarily a combustor hardware modeling and design study to learn how to burn very viscous fuels in the range of No. 4 fuel oil or heavier in small gas turbines. The Purdue effort approaches the problems from the more fundamental standpoint of combustion modeling; they have been very successful in developing correlating parameters in terms of several characteristic times for significant events in the combustion process. The primary ones are:

- fuel droplet lifetime
- shear layer mixing time
- chemical kinetic times

The reader is referred to Mellor[1]*, Tuttle, et al.[2], and Plee, et al.[3] for more detailed information on these correlations and the fuel effects that enter into these correlations.

The combustor studies at the U.S. Army Fuels and Lubricants Research Laboratory, located at Southwest Research Institute, are concerned with the details of the fuel itself, i.e., the specific chemical and physical properties which lead to combustion problems. This study, sponsored by the Naval Air Propulsion Center, Trenton, NJ, is concerned with the effects of fuel properties on combustion problems as opposed to fuel system or handling problems. The specific questions to be answered are:

(1) How will flame radiation and smoke be affected by increasing the allowable aromatic content?

(2) How are flame radiation and smoke affected by the type of aromatics that are present, i.e., single, double, or triple ring, substituted, etc., or other hydrocarbon structures?

(3) How will combustion performance be affected by raising the end point of the distillation curve?

(4) How do the combustion performance/fuel property correlations for syncrude fuels compare with the correlations for conventional petroleum-based fuels?

(5) What problems might arise from using emergency blends of gasoline/JP-5/marine diesel in aircraft turbines?

---

* Superscript numbers in parentheses refer to the list of references at the end of this report.

II. EXPERIMENTAL PROGRAM

In this study, two different combustor rigs were used along with eighteen different fuels specially blended to accentuate different properties. The areas investigated for fuel sensitivity were:

- Ignition
- Stability (lean blow out)
- Flame radiation
- Exhaust smoke
- Gaseous emissions (CO, UBH, and NO_x)
- Combustion efficiency

A. Combustor Facilities

This work was performed in the combustor facility of the U.S. Army Fuels and Lubricants Research Laboratory located at Southwest Research Institute. This facility was designed to study fuel-related problems in the operation of turbine engines. The air supply system provides a clean, smooth flow of air to the combustion test cell at rates up to 1.1 kg/s at pressures to 16 atm and temperatures to 1100K (unvitiated). Turbine flowmeters and strain-gauge pressure transducers are used to measure flow properties of the air and fuel. Thermocouples are referenced to a 339K (150°F) oven. Data reduction is performed on-line with test summaries available immediately; these summaries provide average flow data as well as standard deviations (typically less than 1 percent of average value), exhaust temperature profiles, emissions data, and combustion efficiency.

Exhaust emissions are sampled and handled according to SAE-ARP 1179 for smoke number and SAE-ARP 1256 for gaseous emissions, with the exception of the NO/NO_x measurements which are done by chemiluminescence. Details of the methods and facilities used in combustor monitoring, data reduction, and emissions measurements are given in a previous report by Moses and Naegeli.[4]

B. Combustor Rigs

A Phillips-designed, 2-inch-diameter, high-temperature/pressure research combustor was used to study fuel sensitivities of flame radiation and smoke under conditions of high combustion efficiency where these problems are the most severe. Table 1 presents the matrix of operating conditions used for

TABLE 1. MATRIX OF OPERATING CONDITIONS FOR TWO-INCH RESEARCH COMBUSTOR

Pressure, atm	Temperature, K	Ref Velocity, m/sec	Heat Input Rate, kj/kg air
2	533	23	209
5	811	46	419
10	---	69	837
15	---	--	---

Note: Some combinations of the above parameters are not attainable due to stability or excessive exhaust temperatures.

this combustor. Figure 1 is a schematic of the burner showing the pressure atomizer, air dilution holes, film cooling, radiation sensor, and exhaust probes for emissions and temperature. Flame radiation measurements in this combustor were made using a Leeds and Northrup Rayotube Model 8890-S detector through sapphire windows mounted in the combustor housing. The radiation measurements are broadband out to 6.5 microns, sufficient to include the strong CO_2 radiation at 4.3 microns. The viewing angle is quite small, and the measurements are sensitive to changes in flame length. However, the flame length is essentially constant for a given set of flow conditions, and the fuel flow rates were adjusted according to the heat of combustion to give constant heat input rates and therefore flame temperatures. It is therefore believed that, while correlations of radiation to flow conditions might be open to question, the fuel sensitivities should be unaffected.

The 2-inch combustor does not operate well at off-design or marginal combustion conditions where atomization and vaporization can become controlling parameters. A combustor fabricated from T-63 engine hardware was therefore used to study the fuel sensitivities of ignition, stability, efficiency, pattern

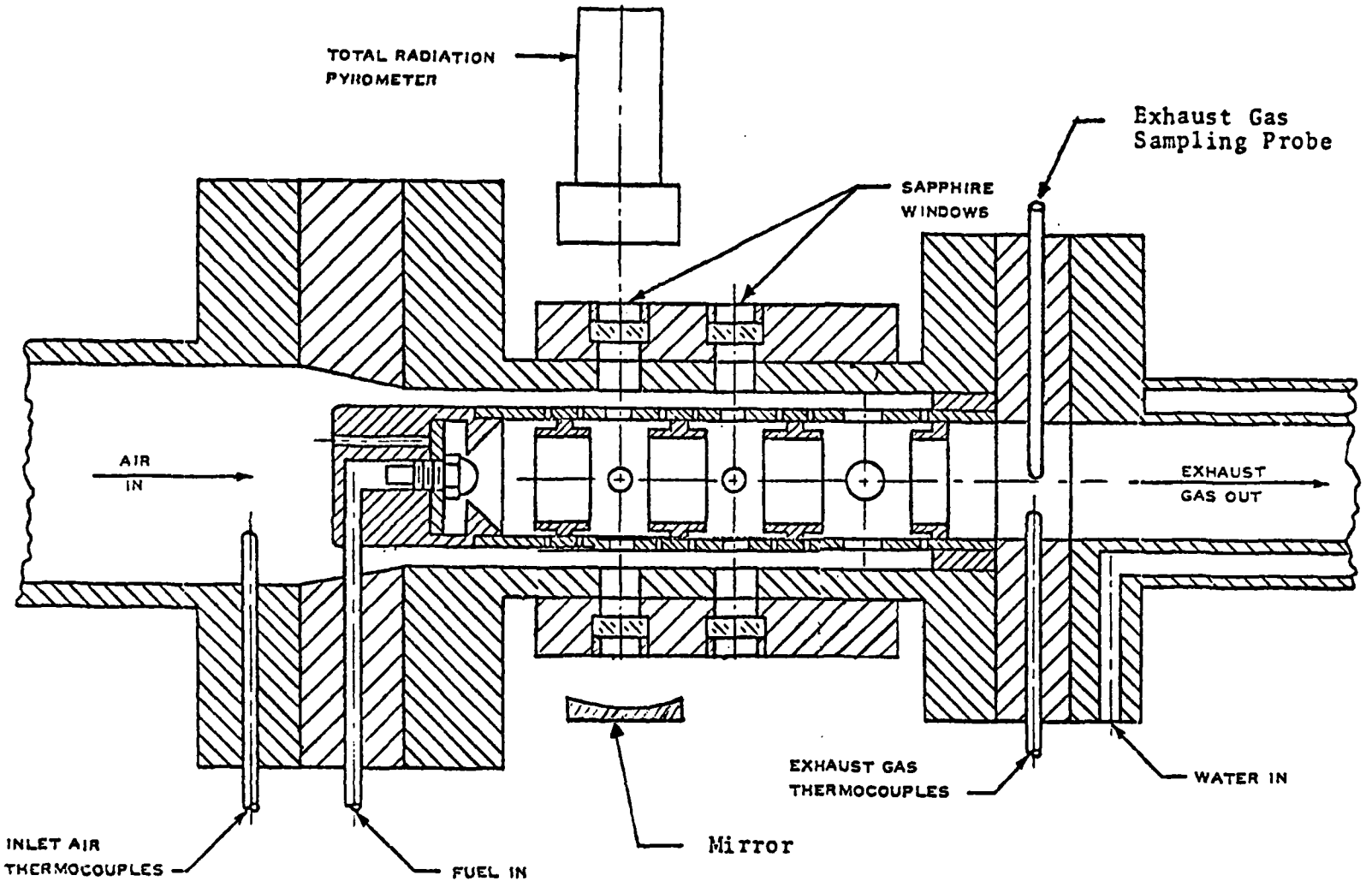


FIGURE 1

PHILLIPS 2 – INCH COMBUSTOR

factor, and gaseous emissions and to verify the results of the radiation and smoke experiments in a production combustor. Table 2 presents the operating conditions which represent the air flow conditions in the actual engine for six different power points (idle to full power). Figure 2 is a schematic of this combustor can, showing also the location of the radiation sensor and liner thermocouples.

Flame radiation measurements in the T-63 combustor are made with a sensor fabricated by Hy-Cal Engineering; again the measurements are broadband out to 6.5 microns. As shown in Figure 2, the sensor is mounted on the combustor wall and has a 150-degree viewing angle; it is therefore insensitive to changes in flame structure.

C. Test Fuels

The test fuels can be divided into three groups: one group each to study the effects of composition, physical properties, and crude source. The fuels are described in Table 3 and the fuel properties are given in Table 4.

Table 4 has two descriptions of the aromatic fraction: (1) the weight percent aromatics and (2) the weight percent aromatic-ring carbon. The aromatic content was measured by high-performance liquid chromatography. This procedure is more accurate than the FIA procedure, especially for distillate fuels. The weight fraction of fuel molecules containing aromatic rings is determined. The weight percent aromatic-ring carbon is determined by ultraviolet absorption spectroscopy and tells the weight percent of carbon atoms contained in the aromatic ring; the aliphatic and naphthenic groups attached to the aromatic ring are excluded. As an example, in pure xylene, only 67.92 wt% of the carbon is in the aromatic ring structure.

The first fuel was a Jet A fuel used primarily as a reference fuel. Jet A was also used to stabilize combustor operating conditions before burning the special test fuels, which were available only in limited quantity. Test data are included on this fuel because it had a boiling range similiar to the special test fuels but an exceptionally low aromatic and high hydrogen content. Fuels Nos. 2 through 6 were blended from a JP-5 base fuel to determine the

TABLE 2. T-63 COMBUSTOR RIG OPERATING CONDITIONS

Mode	% Power	BIP kpa (psia)	BIT K(°F)	ωa kg/s(lb/s)	ωf kg/m(lb/m)	F/A	FF	BOT °K(°F)
Ground Idle	10	230(33.4)	422(300)	0.64(1.40)	0.42(0.92)	0.0109	1.158	833(1040)
---	25	283(41.1)	452(353)	0.75(1.65)	0.54(1.20)	0.0121	1.145	922(1200)
Descent	40	329(47.8)	478(397)	0.86(1.90)	0.68(1.49)	0.0131	1.163	972(1290)
Cruise	55	369(53.6)	494(430)	0.93(2.06)	0.93(2.06)	0.0145	1.141	1033(1400)
Climb/Hover	74	418(60.7)	518(472)	1.02(2.24)	1.01(2.23)	0.0166	1.123	1122(1560)
Takeoff	100	477(69.2)	547(524)	1.10(2.42)	1.30(2.87)	0.0198	1.094	1244(1780)

BIP: Burner inlet air pressure

BIT: Burner inlet air temperatue

ω_a : Air flow rate

ω_f : Fuel flow rate

F/A: Fuel/air ratio

FF : $\omega_a \sqrt{BIT}/BIP$

BOT: Typical burner outlet temperature

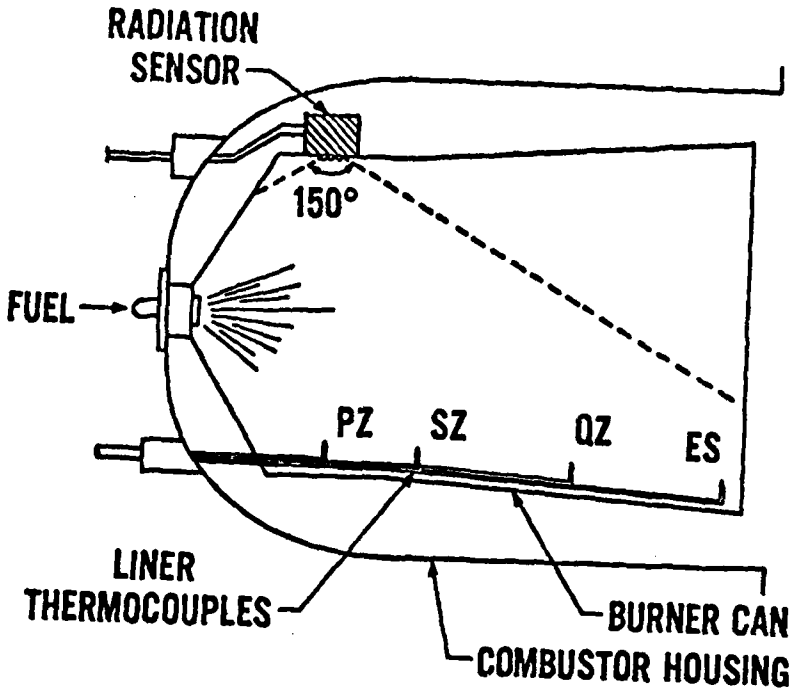


FIGURE 2. **T-63 COMBUSTOR**

TABLE 3. FUEL BLEND CHARACTERISTICS

Fuel No.	Description
1	Jet A - Used for adjusting combustor operating conditions.
2	Base Fuel - JP-5 with 1 to 2% olefins, 2 to 3% naphthalenes and 10-15 percent aromatics. Fuels 3 to 7 are derived by adding materials to this fuel.
3	16-mm smoke point obtained by adding dicyclic polynuclear aromatics to base fuel.
4	16-mm smoke point obtained by increasing naphthalene to 4% and adding monocyclic aromatics as necessary to JP-5 base fuel.
5	Addition of 40% aromatics typical of petroleum distillates in JP-5 distillation range (smoke point must be less than 19mm).
6	Specification maximum for aromatics (25%) and olefins (5%) typical of petroleum distillates in the JP-5 distillation range (smoke point below 19mm permissible).
7	Distillation end point of 580°F, achieved by adding compounds typical of petroleum distillates in the required range (variations in other specification limits permissible - except aromatic content).
8	Synthetic JP-5 from Oil Shale.
9	Synthetic JP-5 from Coal.
10	Synthetic JP-5 from Tar Sands.
11	JP-5 Base fuel for blending Fuels 12-14.
12	JP-5 plus 10% DFM(1).
13	JP-5 plus 20% DFM(1).
14	JP-5 plus 40% DFM(1).
15	DFM(1).
16	Leaded gasoline.
17	DFM(2).
18	DFM(1) plus 30% leaded gasoline.

TABLE 4. SUMMARY OF FUEL PROPERTIES

	1	2	3	4	5	6	7	8	9	10
Heat of Combustion, Net (Btu/lb)	18753	18484	18192	18389	18147	18537	18597	18405	18258	18543
Carbon, wt%	85.68	85.94	86.74	86.60	87.26	86.53	86.38	86.20	86.69	86.61
Hydrogen, wt%	14.32	13.68	13.06	12.86	11.99	12.91	13.60	13.32	13.24	13.32
Nitrogen, wt%		0.006	0.006	0.010	0.005	0.02	0.007	0.10	0.004	0.004
Oxygen, wt%		0.43	0.03	0.36	0.28	0.35	None	0.28	None	None
Sulfur		0.022	0.024	0.023	0.026	0.026	0.025			
Aromatic Ring Carbon, by UV										
Single Ring, wt%		5.7	7.65	10.5	16.6	11.3	5.7	15.1	7.5	7.0
Double Ring, wt%		1.2	7.81	4.9	9.4	4.5	1.6	1.7	0.3	0.1
Triple Ring, wt%		0.01	0.03	0.01	0.03	0.05	0.06	0.02	0.02	0.01
Total Aromatic Ring Carbon, wt%		6.91	15.49	15.5	26.03	15.85	7.36	16.82	7.82	7.11
HPLC Analysis										
Total Saturates, wt%	91.9	89.1	76.4	73.2	62.2	74.6*	88.1	74.0	82.7	84.5
Total Aromatics, wt%	8.1	10.9	23.6	26.7	37.8	21.9*	11.9	23.0	17.3	15.5
Total Olefins, wt%		0.0	0.0	0.0	0.0	3.5*	0.0	3.0	0.0	0.0
Viscosity at -35°F, cSt	**	8.25	8.45	8.53	11.56	9.04	15.35	7.76	8.90	12.77
Flash Point, °C	62.2	61	64	61	66	62	62	55	59	65
Specific Gravity at 60°F		0.8108	0.8270	0.8216	0.8541	0.8285	0.8071	0.8055	0.8485	0.8285
Smoke Point, mm	24	26	16	16	12	16.5	23	17	17	18
Boiling Point at 98%, °C		271	279	277	284	281	321	295	278	288
H/C Ratio	2.01	1.91	1.81	1.78	1.65	1.79	1.89	1.85	1.83	1.85

* by FIA
** 172 at 40°C

TABLE 4. SUMMARY OF FUEL PROPERTIES (Cont'd)

	11	12	13	14	15	16	17	18
Heat of Combustion, Net (Btu/lb)	18501	18644	18618	18625	18493	18783	18405	18699
Carbon, wt%	86.33	86.48	86.85	86.77	86.69	85.71	86.23	86.55
Hydrogen, wt%	13.52	13.47	13.44	13.38	13.21	14.29	13.20	13.51
Aromatic Ring Carbon, by UV								
Single Ring, wt%	9.77	9.63	9.49	9.21	8.36	17.75	8.11	12.7
Double Ring, wt%	2.23	2.32	2.41	2.59	3.13	1.78	3.59	2.75
Triple Ring, wt%	0.01	0.03	0.05	0.08	0.19	0.01	0.31	0.17
Total Aromatic Ring Carbon, wt%	12.01	11.98	11.95	11.88	11.68	19.54	12.01	15.62
HPLC Analysis								
Total Saturates, wt%	80.8	80.1	79.5	78.1	74.0	70.9*	75.3	74.2*
Total Aromatics, wt%	19.2	19.9	20.5	22.9	26.0	22.2*	24.7	24.7*
Total Olefins, wt%	0.0	0.0	0.0	0.0	0.0	6.9*	0.0	1.1*
Viscosity at -20°C, cSt	5.55	6.23	7.06	8.85	---	0.88	---	5.17
at 0°C, cSt	3.45				10.44		9.03	
at 40°C, cSt	1.57				3.27		3.02	
Flash Point, °C	61	62	62	64	73	---	76	---
Specific Gravity at 60°F	0.8236	0.8270	0.8299	0.8348	0.8550	0.7332	0.8438	0.8179
Smoke Point, mm	18.7	17.3	18.2	16.2	15.2	15.8	15.3	16
Boiling Point at 98%, °C	284	331	351	369	385	236	403	384
H/C Ratio	1.88	1.85	1.79	1.79	1.78	2.00	1.84	1.84

* by FIA

effects of aromatic content, types of aromatics, and end point. All other properties were within the JP-5 specifications with the possible exception of freeze point. To obtain more realistic fuels, the blending stocks were mixtures of aromatics typical of the JP-5 boiling range rather than pure compounds. Fuels Nos. 8 through 10 were supplied by the U.S. Naval Air Propulsion Center (NAPC) as fuels which met the JP-5 specification, but had been refined from coal, oil shale, and tar sand crudes.

Fuels Nos. 11 through 18 were diesel marine fuels, leaded gasoline, and blends thereof with JP-5 base fuel to represent possible extremes of emergency fuels. The analytical data in Table 4 shows that, except for gasoline (Fuel No. 16), the hydrogen and aromatic contents of these last fuels fall into a relatively narrow range. However, their physical properties, including viscosity, final boiling point, and boiling point distribution, are significantly different. A more detailed description of the boiling point distribution data for Fuel Nos. 11 through 18 is shown in Table 5.

III. RESULTS AND DISCUSSIONS

A. Flame Radiation

Several fuel properties were considered in seeking a suitable correlating parameter for flame radiation (and exhaust smoke). Aromatic content has been widely used in recent years; ring-carbon content was considered because if aromatics are significant in soot production, it is the carbon contained in rings rather than side chains which would be important; and finally hydrogen content. The fuel specification of smoke point was not used because it is not a fundamental fuel property. Figure 3 shows the radiation measurements correlated with these parameters from a typical experiment with the 2-inch combustor. Only Fuel Nos. 1 through 10 are plotted because these are the fuels which stressed changes in hydrogen content and aromatics. Hydrogen and aromatic content appear to be of about equal value as correlating parameters; comparatively, the correlation with ring carbon is quite poor. The inadequacy of ring carbon as a correlating parameter suggests that the aromatic ring structure per se is not the important fundamental parameter. For this reason, hydrogen content was selected as the correlating parameter for flame radiation and smoke in this study.

TABLE 5. SUMMARY OF BOILING POINT DISTRIBUTION
BY ASTM D 2887, METHOD: SD/SE3

	F	U	E	L				
% Off	#11 (°C)	#12 (°C)	#13 (°C)	#14 (°C)	#15 (°C)	#16 (°C)	#17 (°C)	#18 (°C)
IBP	140	139	139	143	135	-6	149	7
5	174	174	175	180	189	28	200	61
10	184	184	186	193	212	40	220	94
15	191	192	194	201	227	59	235	123
20	197	198	200	208	238	66	246	154
25	202	203	206	215	249	74	257	179
30	207	208	212	222	258	86	266	202
35	212	214	217	228	266	94	273	221
40	217	219	223	235	273	100	281	237
45	221	224	229	241	281	110	288	250
50	226	230	235	248	288	119	296	261
55	232	236	240	255	295	129	303	272
60	236	240	246	261	302	143	310	282
65	241	246	252	267	308	149	316	292
70	246	252	258	274	315	162	325	302
75	251	257	263	283	322	169	333	311
80	256	262	270	294	331	176	342	321
85	261	268	277	308	340	188	352	333
90	267	275	295	324	351	200	364	346
95	274	297	322	347	367	215	382	364
FBP	305	368	382	401	412	274	429	417

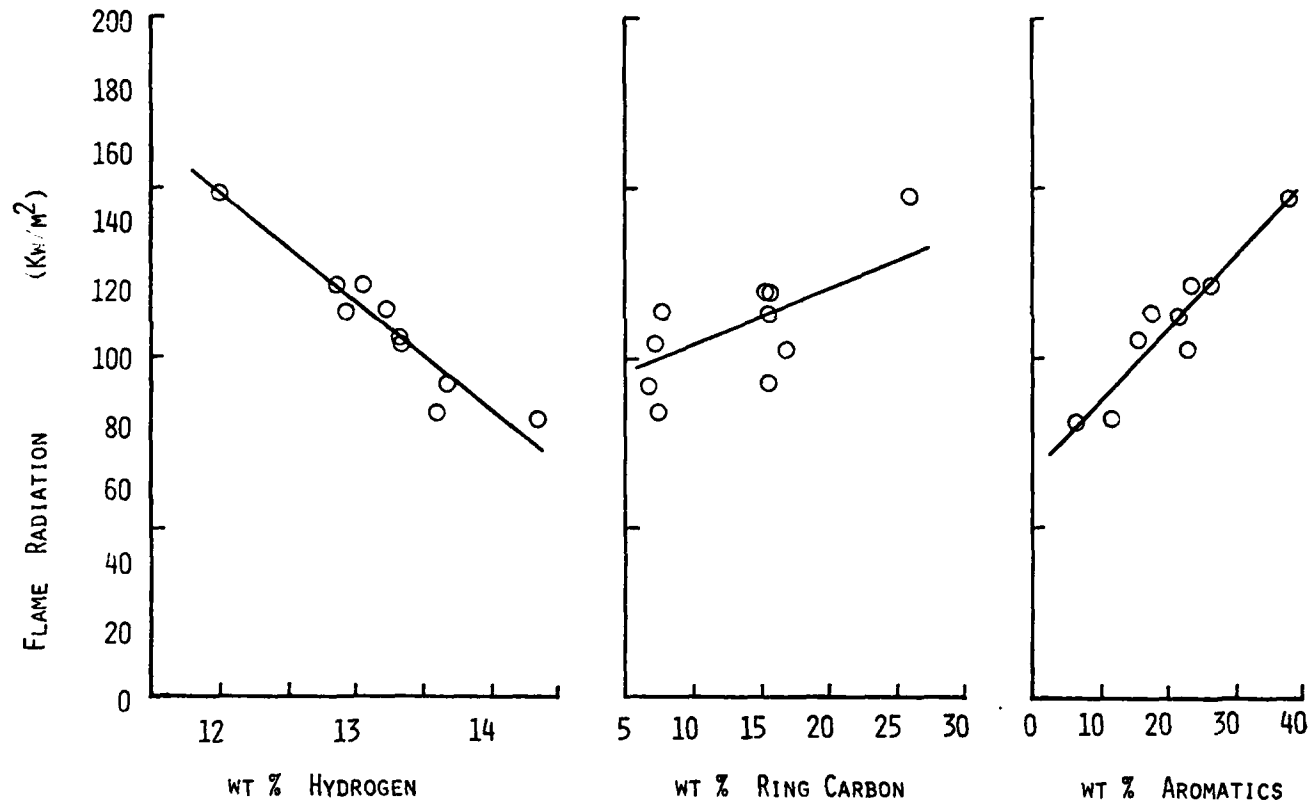


FIGURE 3. CORRELATIONS OF FLAME RADIATION WITH FUEL PROPERTIES

Figure 4 illustrates the general effects of combustor operating conditions on flame radiation and on the fuel-hydrogen correlation for the 2-inch combustor; again only the first 10 fuels which emphasized hydrogen content are shown. Figure 4a shows an effect on the pressure and temperature of the inlet air holding fuel-air ratio and reference velocity constant; increases in both factors result in increases in flame radiation: pressure because of an increase in soot production and therefore emissivity; temperature because of the fourth-power dependence in the Stefan-Boltzmann Law. Figure 4b shows the anticipated increase in radiation resulting from an increase in fuel-air ratio. Finally, Figure 4c shows the effect of increasing the reference velocity; the resulting increase in primary-zone mixing reduces the soot production rates and lowers the flame radiation.

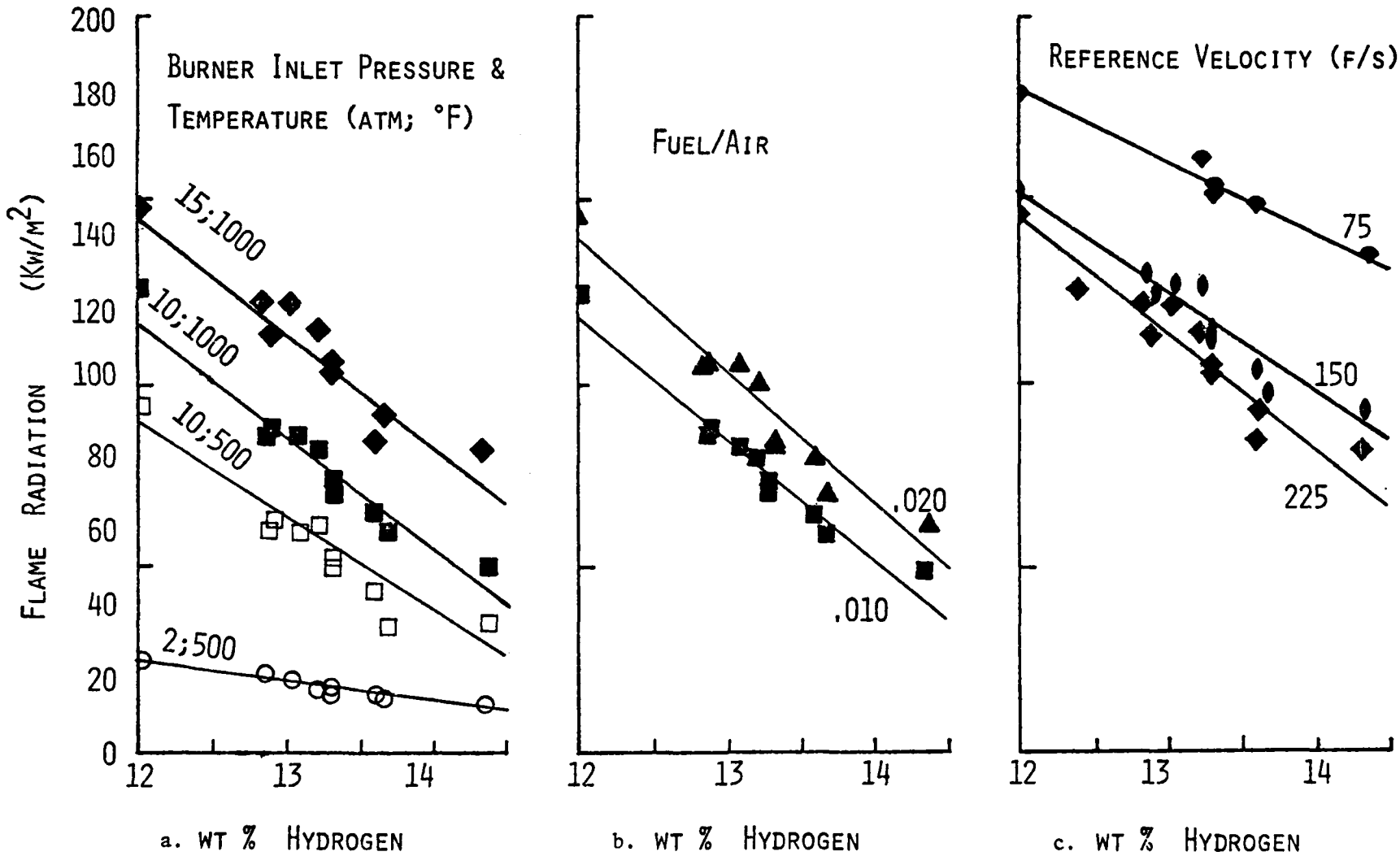
Flame radiation measurements were also made on Fuel Nos. 11 to 18, except for Fuel No. 16 which could not be pumped at some flow rates because of its low lubricity. These fuels were blended to express significant differences in physical properties such as viscosity and boiling point distribution; their compositions, aromatic content, and hydrogen content were very similar. As seen in Figure 5, the relatively small differences in the flame radiation levels observed for these fuels appeared to be in proportion to the relatively small differences in their hydrogen contents; the significant differences in physical properties among these fuels had little effect on their tendencies to form soot.

B. Fuel Sensitivity

Since the correlations of radiation with hydrogen content can be assumed to be linear over a narrow range of hydrogen content (±1%), the fuel sensitivity may be simply expressed as the slope of the line dR/dH. This sensitivity is low at conditions of low flame radiation and increases as the radiation level increases. The sensitivity decreases at very high radiation, where conditions are such that the emissivity of the flame is approaching unity. At that condition, there would be no fuel sensitivity. The effect of flame radiation intensity on fuel sensitivity (dR/dH) is shown in Figure 6; the radiation levels are taken at a hydrogen content of 13 percent. Other values could have been used just as easily. The significance of this figure is that it suggests that engines with combustors of low luminosity (clean combustors) should have low sensitivity to hydrogen content and therefore be tolerant of a

FIGURE 4

EFFECTS OF COMBUSTOR OPERATING CONDITIONS ON FLAME RADIATION



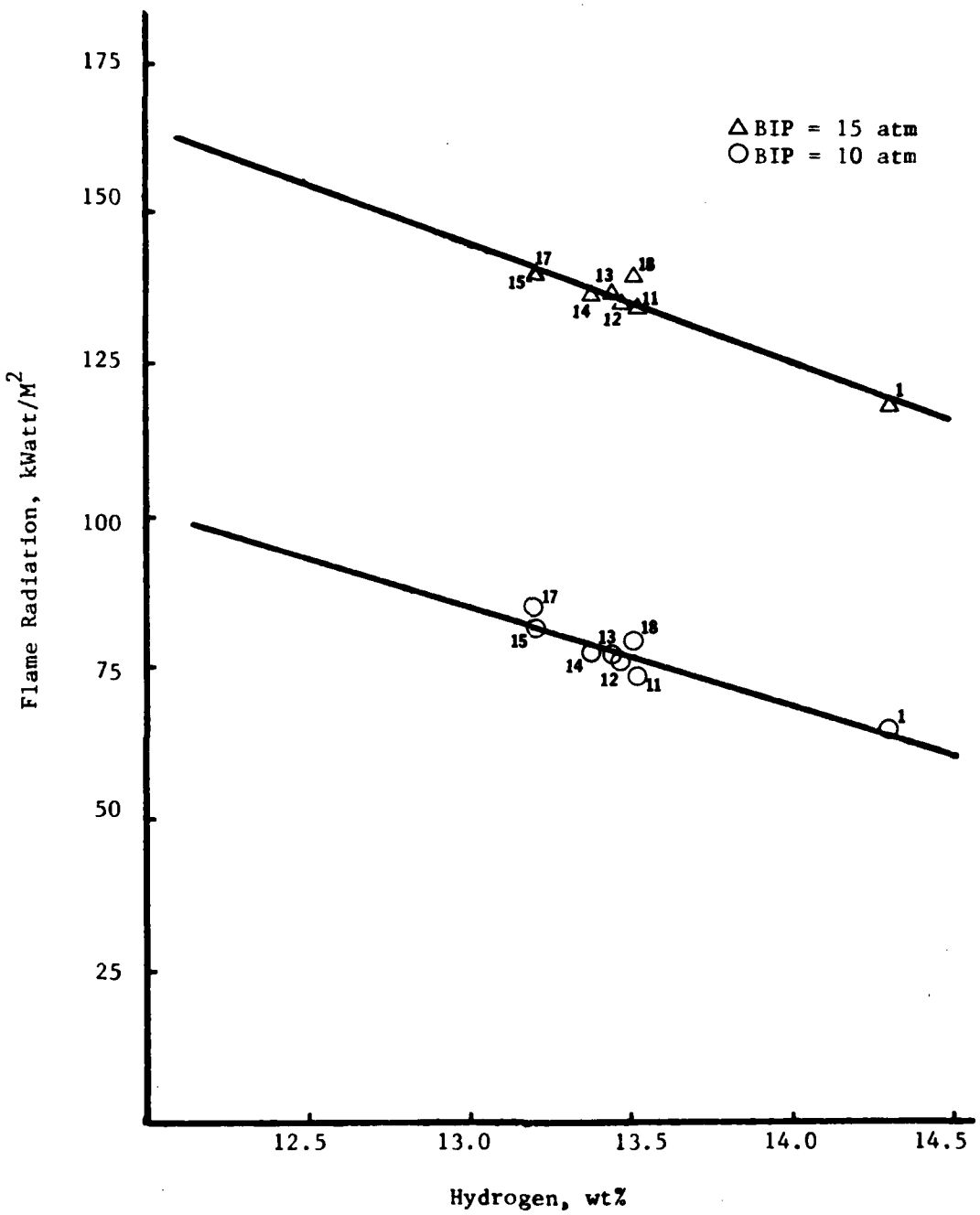
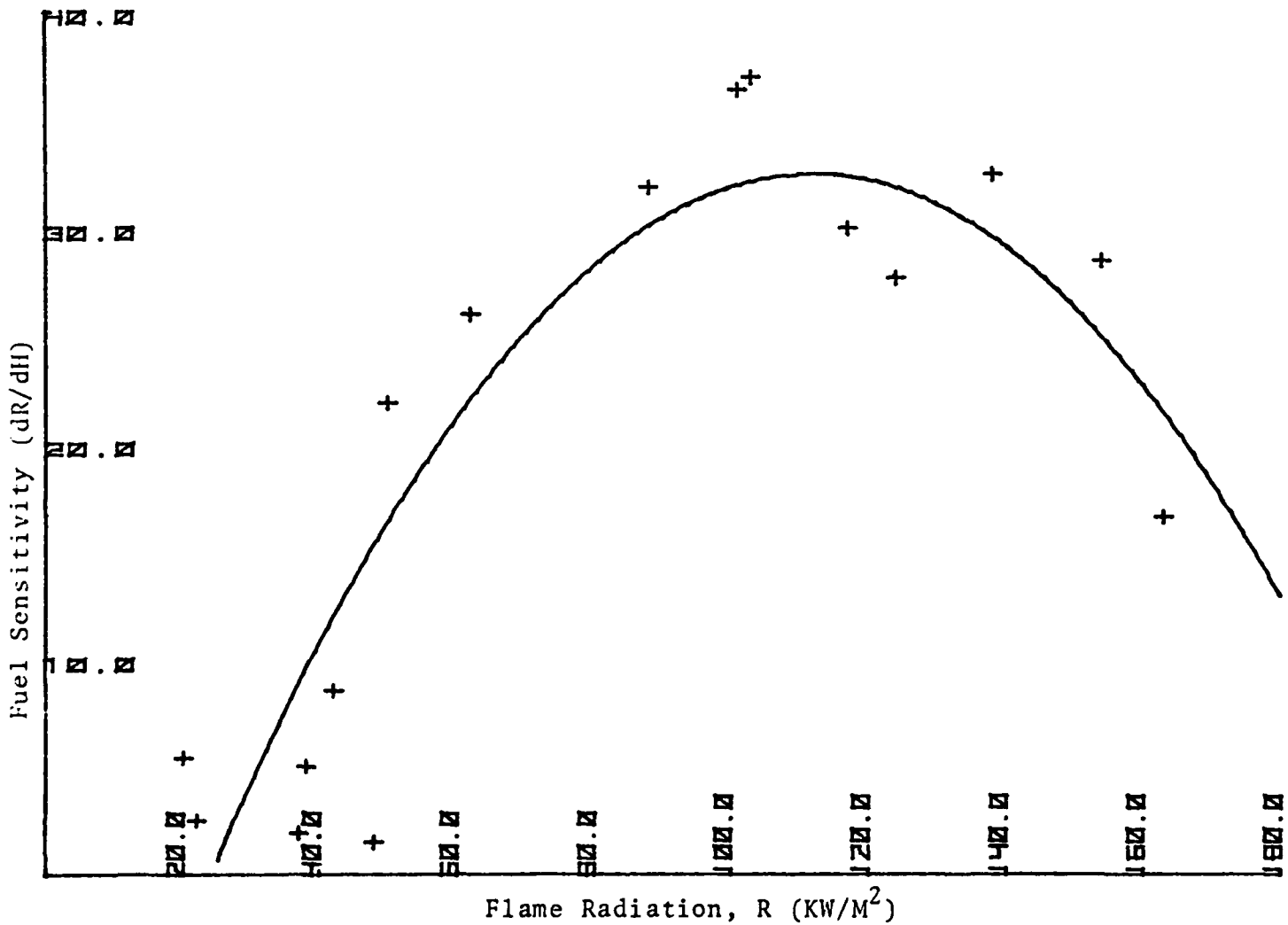


FIGURE 5. EFFECT OF BURNER INLET PRESSURE ON FLAME RADIATION; BIT=810K, V=69m/s, F/A=0.01

FIGURE 6 . FUEL SENSITIVITY OF FLAME RADIATION



broadened specification fuel. Similarly, combustors with very high luminosity probably will not be affected as their emissivity is already very close to unity.

Figure 7 presents the radiation data for the T-63 engine combustor operated at the six power points given in Table 2. Data from all of the test fuels are presented together here. The trends are the same as those found with the research combustor: at idle where the radiation is low, the sensitivity is small and increases as the power level increases. A linear fit is quite good except that Fuel No. 16 is always significantly higher than the correlation. This fuel was the leaded gasoline, and presumably the lead or lead oxide is contributing heavily to the radiation.

Several points about the fuel sensitivity of flame radiation are worth noting. Since hydrogen content is such a good correlating parameter, the details of the hydrocarbon structure of these test fuels have at most a minor effect on the soot formation. Furthermore, the viscosity and boiling point distribution have no significant effects even with end points as high as 675K. This lack of effect means that the soot-forming reactions are gas-phase rather than liquid-phase pyrolysis. There are no significant differences between the syncrude fuels and the petroleum fuels.

The major effect of increased flame radiation is higher liner temperatures. Figure 8 shows the increase in the T-63 liner temperature at the full power condition as hydrogen content decreases at four different locations on the combustor wall. The greatest effect is seen to be at the primary zone; at this point, the wall temperatures are lower and perhaps the increase is not enough to be detrimental. At the exhaust skirt, where the temperatures are much higher, very little effect was found, suggesting that combustors may be able to tolerate the higher flame radiation without sacrificing liner integrity. Figure 9 shows the increase in liner temperature at the primary zone over the inlet air temperature for the higher power points as a function of flame radiation. At the other positions, the difference is much greater. However, the radiant heat transfer is much less, so the curves would have a smaller slope.

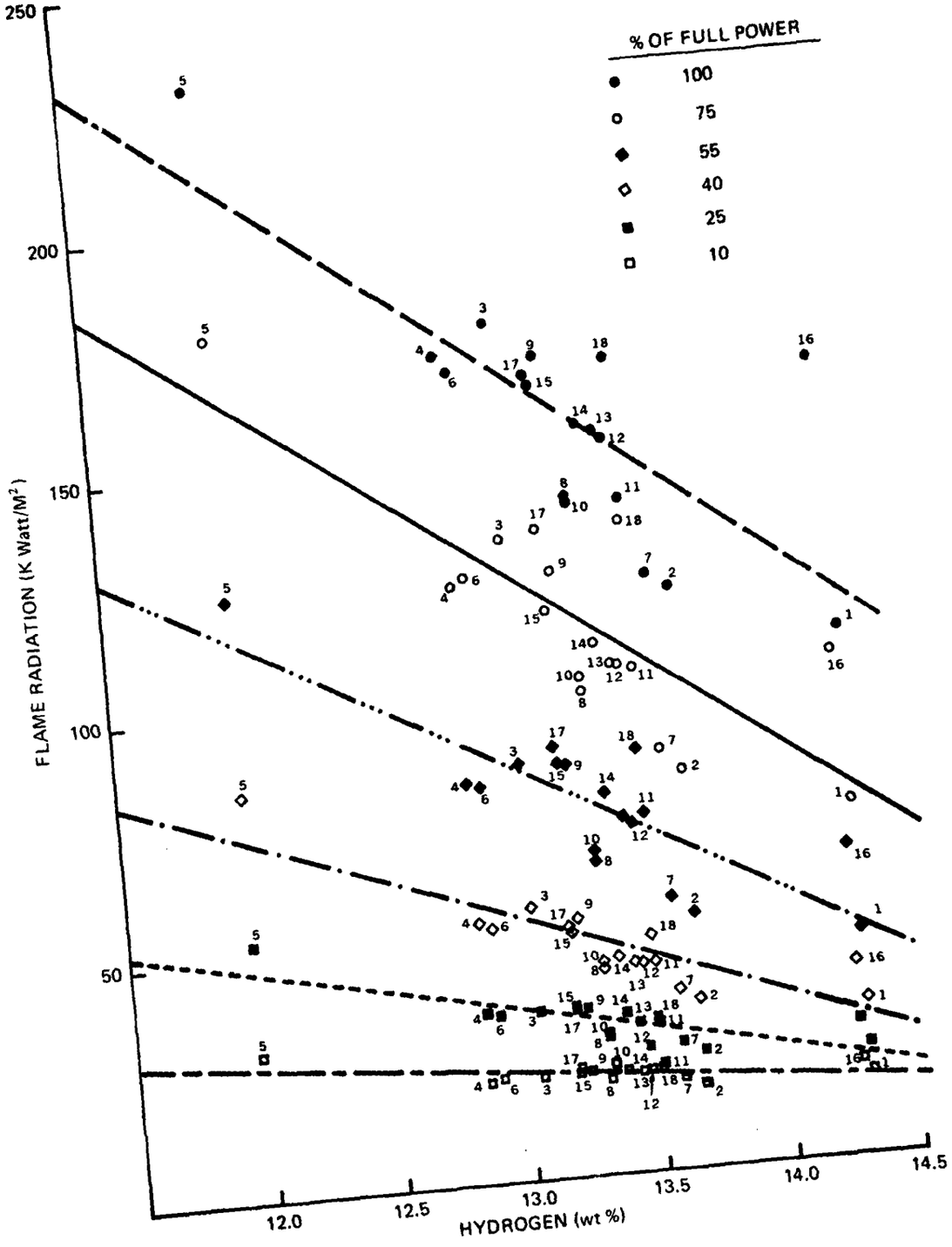


FIGURE 7. EFFECT OF HYDROGEN CONTENT ON FLAME RADIATION, T-63 BURNER

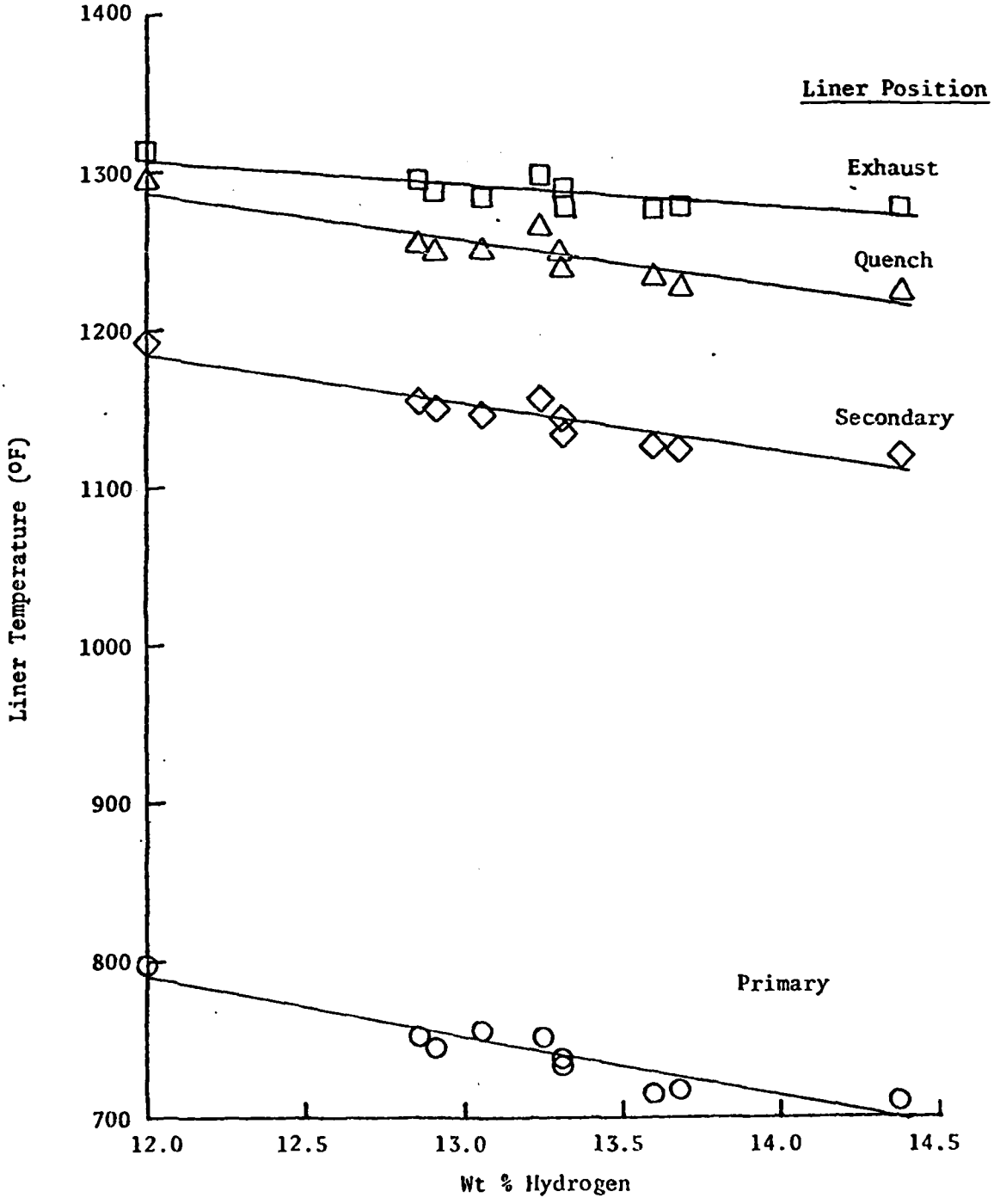


FIGURE 8. EFFECT OF HYDROGEN CONTENT ON LINER TEMPERATURE AT DIFFERENT POSITIONS ON THE COMBUSTOR

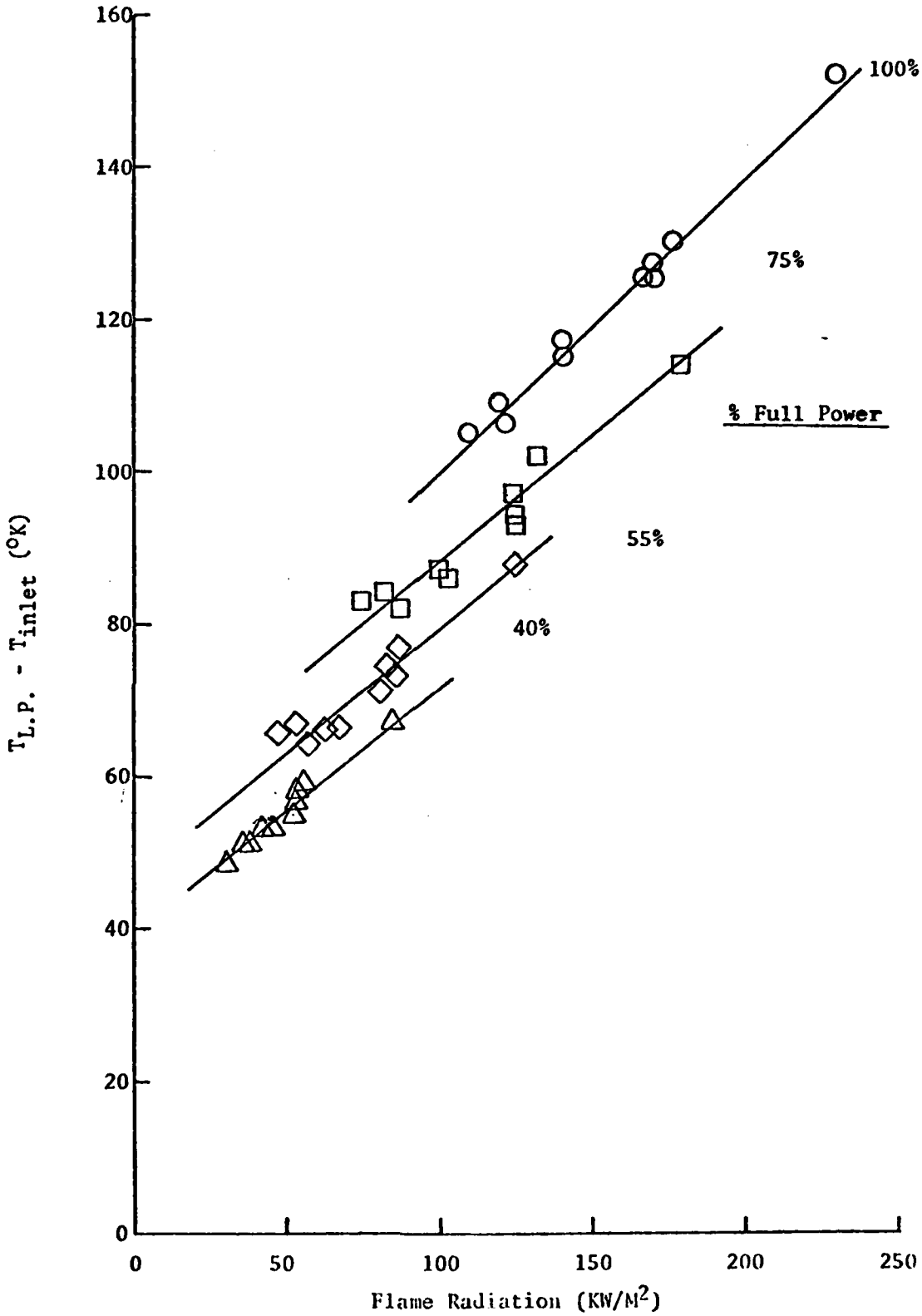


FIGURE 9 EFFECT OF FLAME RADIATION ON COMBUSTOR LINER TEMPERATURE AT THE PRIMARY ZONE

C. Exhaust Smoke

The measurements of exhaust smoke from Fuels Nos. 1 through 10 in the Phillips research combustor are discussed in an earlier report.[4] This work may be summarized as follows: smoke was found to be strongly dependent on burner inlet temperature. Higher burner inlet temperatures reduced exhaust smoke because of increased temperature in the secondary and quench zones where free carbon is oxidized. Increasing combustor pressure and fuel-air ratio increased the smoke levels as is typical with real combustors. Reference velocity can have two effects on smoke; one, in terms of the turbulent mixing in the primary zone which reduces the production of soot and, two, the residence time in the secondary and quench zones for the oxidation of the free carbon. It was found generally that smoke levels were inversely proportional to reference velocity, indicating that primary zone mixing was the stronger effect.

Exhaust smoke is simply that soot which is not oxidized in the secondary and quench zones. It follows that sensitivity to fuel properties should be the same as that of the flame radiation. In fact, it was found that for the fuels as a whole, hydrogen content was the best correlating parameter. While the petroleum-based Fuels Nos. 1 through 7 correlated equally with hydrogen content, aromatics, and ring carbon, the syncrudes Fuels Nos. 8 through 10 correlated significantly better with hydrogen content.

When Fuel Nos. 11 through 18, except for Fuel No. 16 (gasoline), were tested in the Phillips burner, the hydrogen content continued to be a strong correlating parameter for smoke as was expected. Figure 10 illustrates this for one operating condition. The operating condition used for this illustration was one of high smoke and high sensitivity to hydrogen content; at the lower smoke levels, there was very little change in smoke among the fuels in agreement with the conclusions of the earlier work on Fuels No. 1 through 10.

In the T-63 combustor, the exhaust smoke from all Fuel Nos. 1 through 18, except for gasoline Fuel No. 16, gave a good correlation with hydrogen content (see Figure 11). The high values of smoke and radiation for gasoline have been attributed to PbO_2 particulates. These results correspond with

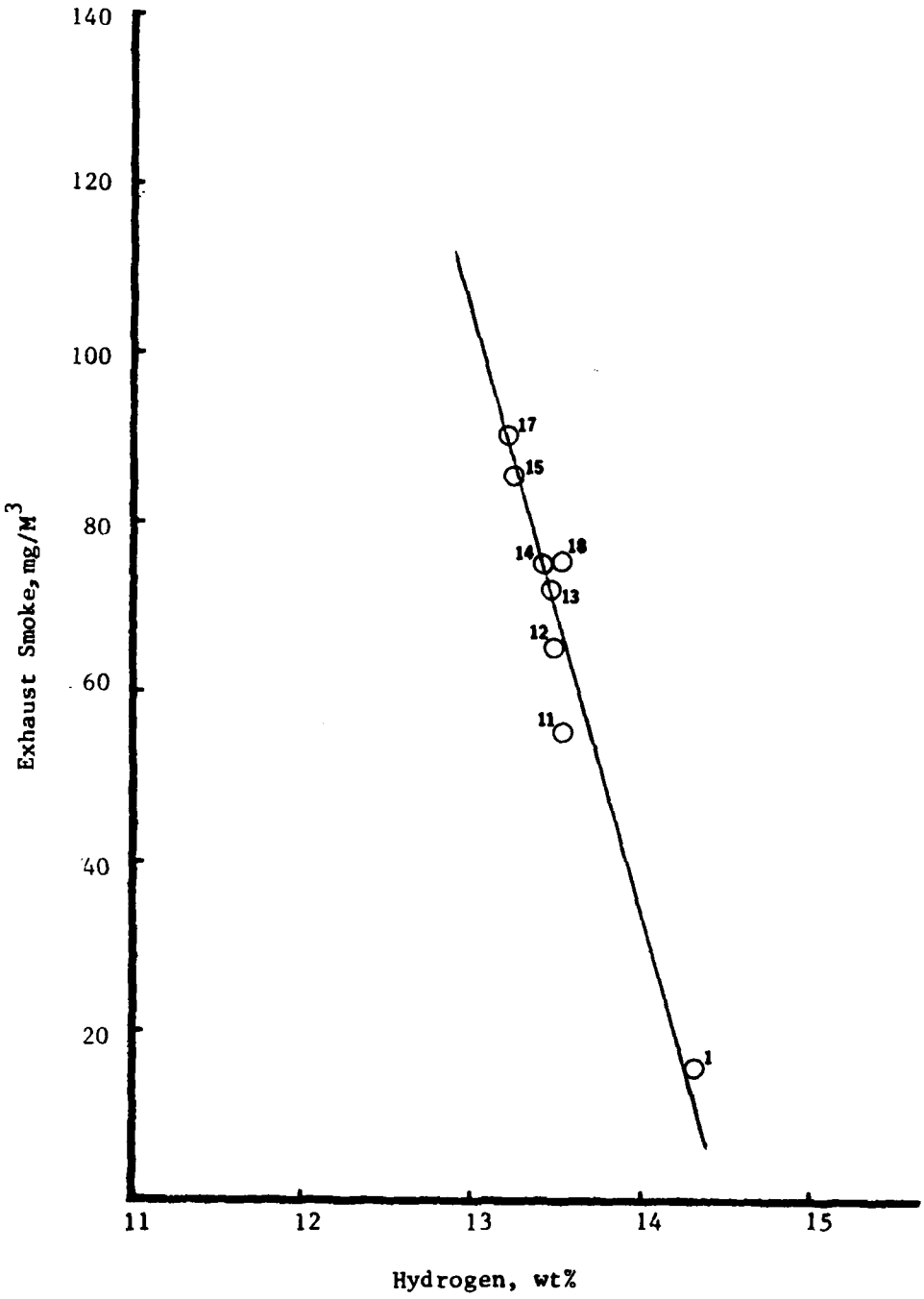


FIGURE 10. CORRELATION OF EXHAUST SMOKE WITH HYDROGEN CONTENT; BIP=10 atm, BIT=533K, Vref=23 M/sec, F/A=0.01

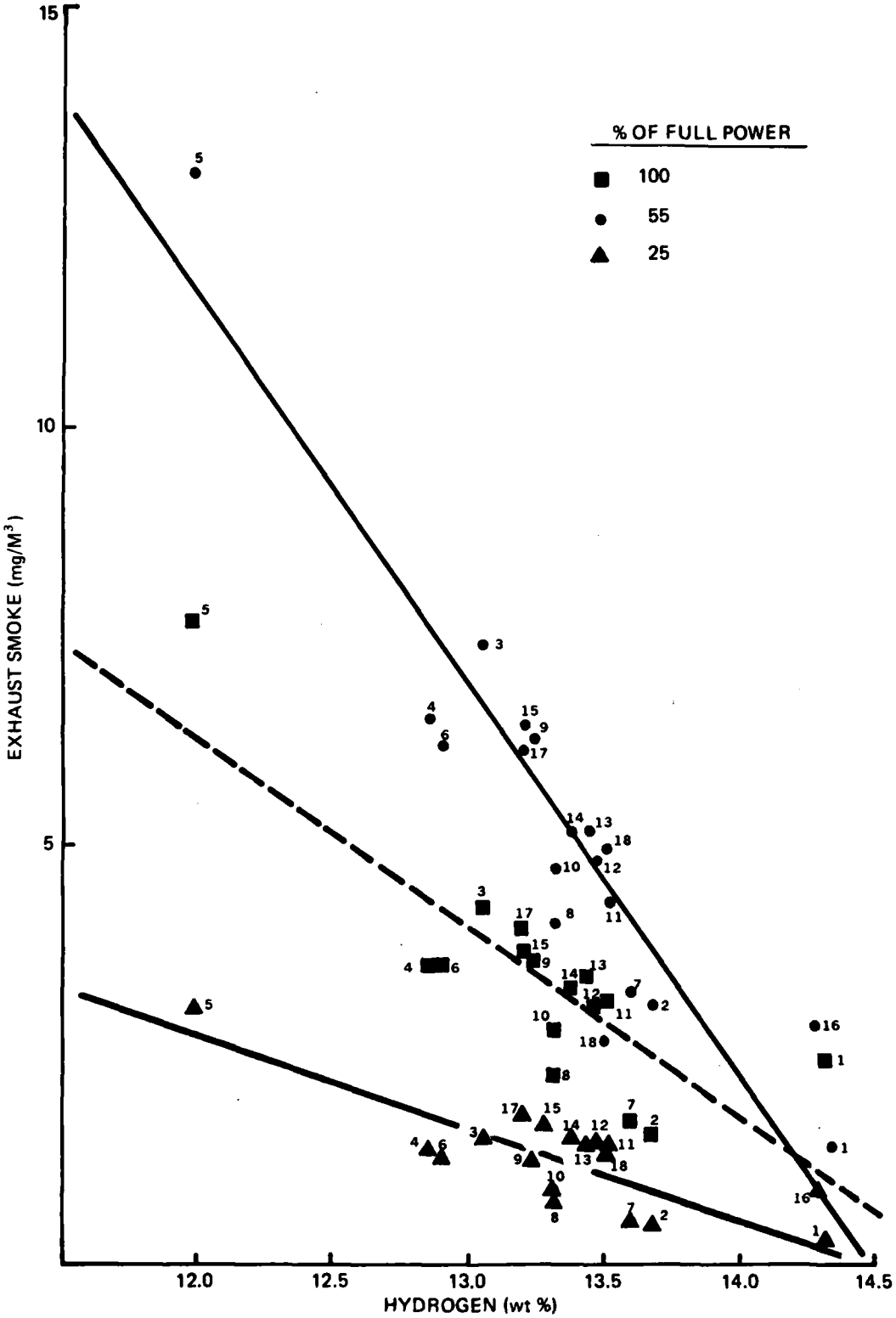


FIGURE 11. EFFECT OF HYDROGEN CONTENT ON EXHAUST SMOKE, T-63 BURNER

those observed in the research combustor and confirm that fuel properties such as viscosity and boiling point distribution are not significant correlating parameters for soot formation.

D. Fuel Sensitivities

As stated earlier, exhaust smoke is that soot which is not oxidized in the secondary and quench zones. Thus, it follows that sensitivities to fuel properties should be similar to those of the flame radiation. This is, in fact, true as shown in Figures 12 and 13 for the research combustor and the T-63, respectively. However, the fuel sensitivity dS/dh does not fall off towards zero at high smoke levels because there is no upper bound as emissivity is for flame radiation. The conclusions are the same, namely, that clean-burning engines will probably be less affected by decreases in hydrogen content, and that the syncrude and blended fuels exhibit no unusual combustion features despite the difference in chemical and physical properties.

The mechanism for soot formation appears to be based almost entirely on chemical properties. Hydrogen content seems to be more important than molecular structure, indicating that carbon is formed from low molecular weight fragments such as C_2, C_2H, CH, etc. For middle distillate fuels, including DFM, the results indicate that particulates formed by liquid phase pyrolysis are not significant.

E. Ignition Characteristics

For this investigation, the ignition characteristics are presented as the time required for ignition at a given fuel flow rate, all air flow conditions being held constant. The air flow rates were typical of T-63 start-up conditions:

air flow rate	= 0.18 kg/s	(0.4 lb/s)
air pressure, BIP	= 1.4 atm	(21 psia)
air temperature, BIT	= 26°C	(78°F)

Fuel flow rates were established in a bypass line before opening the solenoid valve to the combustor nozzle; the ignitor was turned on at the same time.

FIGURE 12 FUEL SENSITIVITY OF EXHAUST SMOKE

(based on Fuels 1-10)

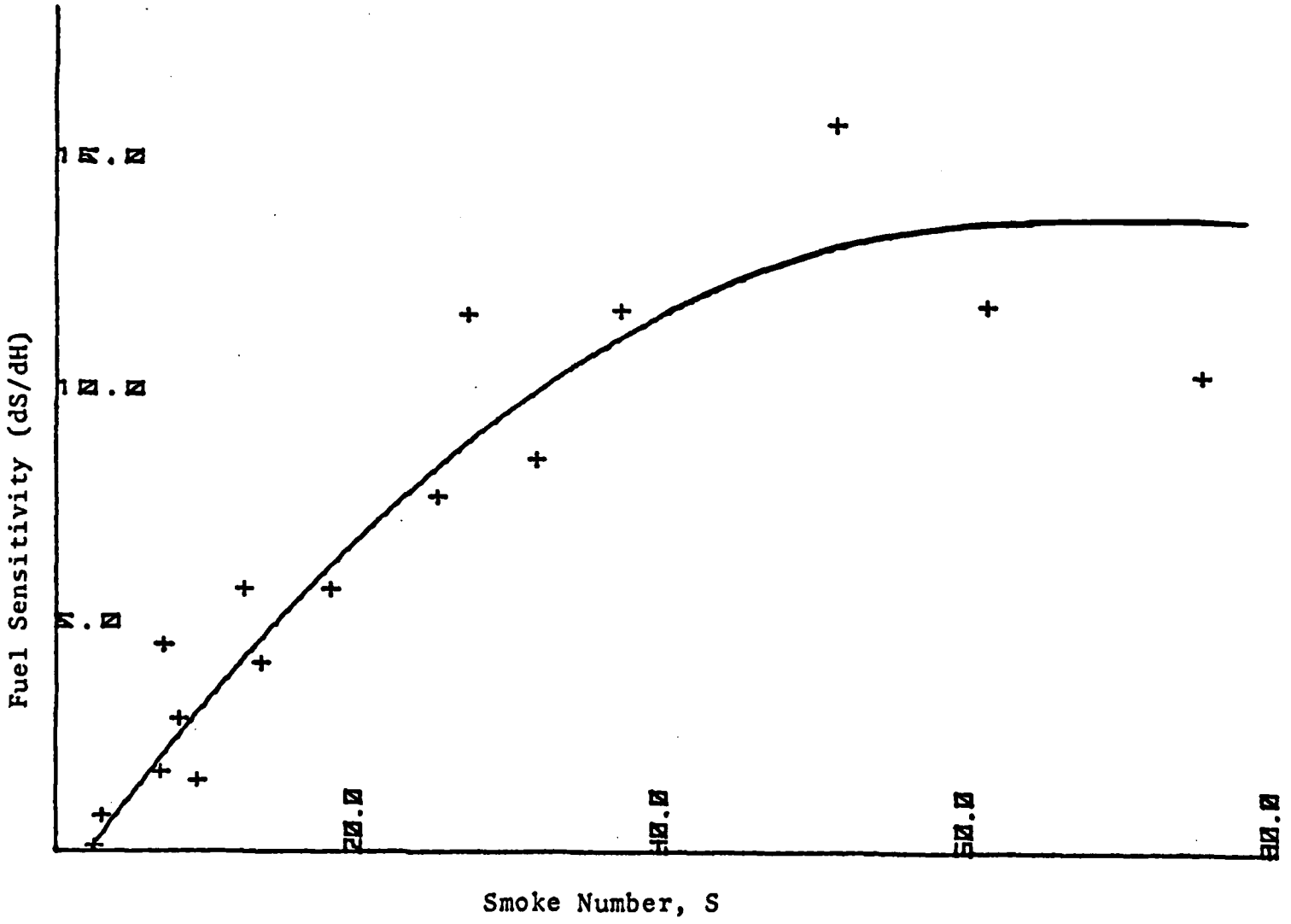
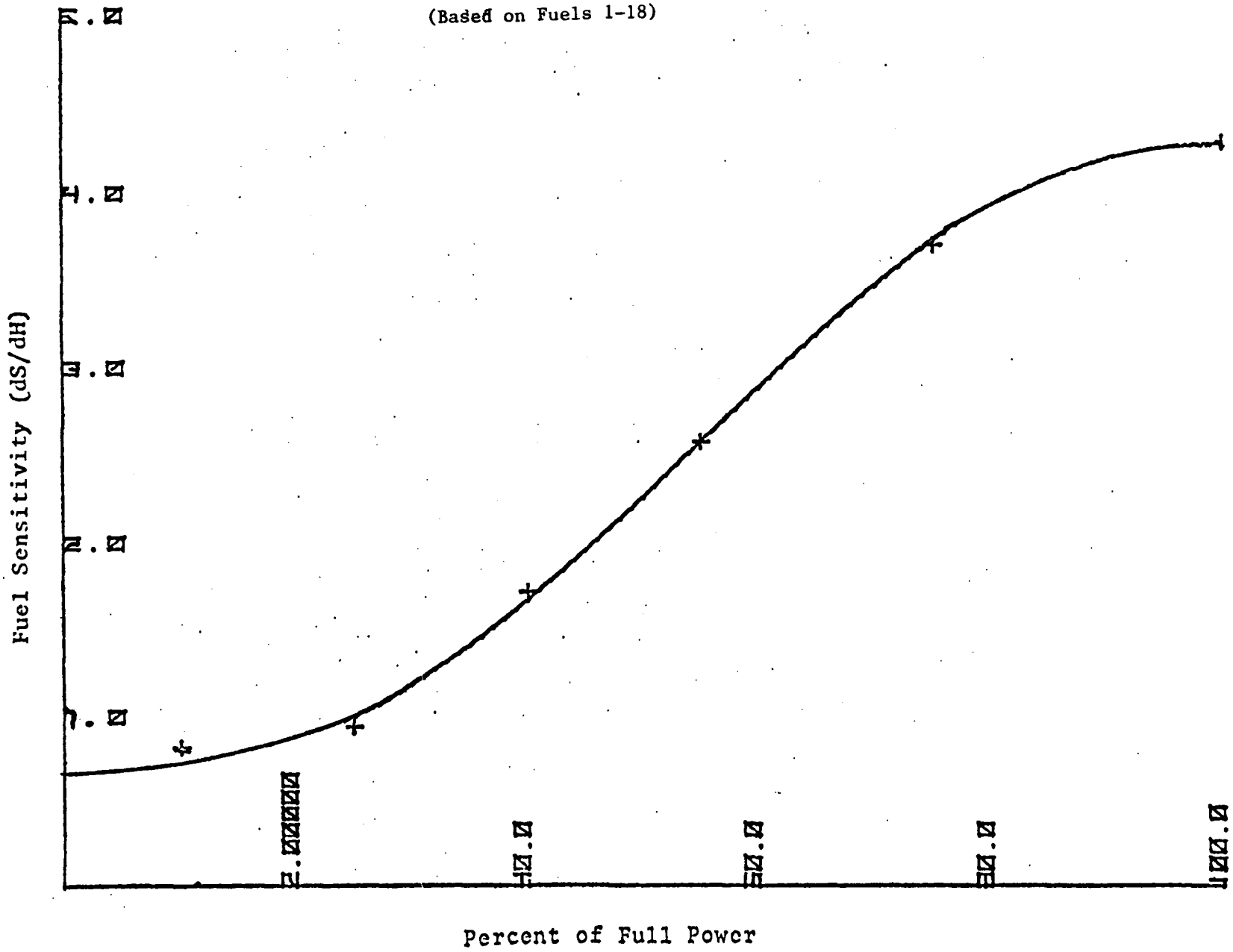


Figure 13 Fuel Sensitivity of Smoke

(Based on Fuels 1-18)



If ignition did not occur within thirty seconds, the test was termed a "no-start".

Ignition tests with the JP-5-type fuels including the syncrude JP-5's (Fuels Nos. 1-10) showed no differences; this is not surprising since they all had about the same viscosities and flash points (front-end volatility). The discussion will therefore be directed toward the blends of JP-5, marine diesel, and gasoline. Figure 14 shows the relative requirements for ignition among the fuels; individual data points have been left off for clarity. Using curve 16 (gasoline) as an example, at very low fuel-air ratios (fuel flow rate), ignition could not be achieved; finally at a fuel-air ratio of 0.02, ignition became almost instantaneous and remained so for all higher fuel flow rates. The next curve, No. 18 [DFM(1) + 30% gasoline], required higher fuel flow rates before ignition could be achieved. Once the threshold was reached, however, ignition was instantaneous for all higher values. This was true for the other fuels. Unfortunately, the temperature of the inlet air could not be controlled. As the ambient air temperature rose during the test, so did that of the inlet air. The change was only a matter of a few degrees but fuel vaporization and, hence, ignition can be very sensitive to air temperature. It is felt that this fact explains the relative positioning of the ignition limits for Fuels Nos. 11, 12, 13, and 14. At constant temperature, there probably would have been a general shift toward higher fuel-air ratio as more DFM was added and the viscosity increased. While this shift precludes a quantitative evaluation, it seems likely that blending the DFM into the JP-5 would not seriously degrade the ignition requirements at ground start on warm days. Whether or not altitude relight or cold start would be seriously affected is not known but bears investigation.

The ignition limits for the pure DFM s were essentially the same and higher than the rest of the fuels, as expected, due to both a higher viscosity and the lower volatility. Adding 30 percent gasoline to the DFM substantially lowered the ignition limits to below the JP-5; approximately 10 to 15 percent might have been sufficient.

	Fuel #	Description
○	11	JP-5
□	12	JP-5 + 10% DFM(1)
◇	13	JP-5 + 20% DFM(1)
△	14	JP-5 + 40% DFM(1)
◺	15	DFM(1)
◺	16	Leaded Gasoline
◻	17	DFM(2)
◇	18	DFM(1) + 30% Gasoline

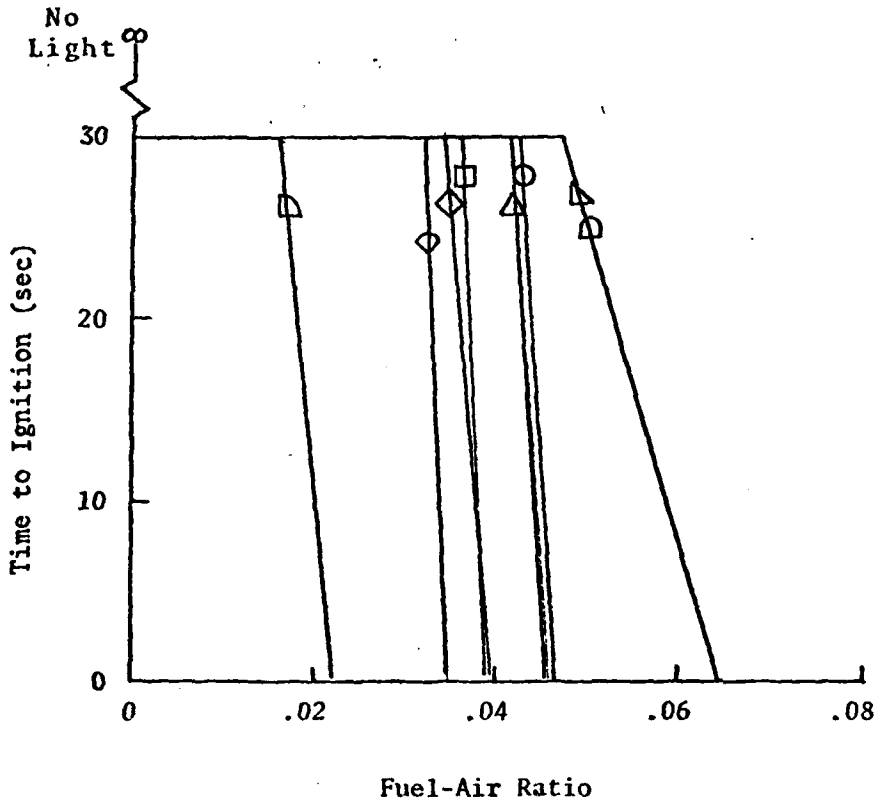


FIGURE 14 FUEL EFFECTS ON FUEL-AIR RATIO REQUIRED FOR IGNITION

F. Flame Stabilization (lean blow out) Characteristics

The experiments on flame stabilization were conducted by operating the T-63 combustor at the appropriate air flow conditions as given in Table 2. The fuel flow rate was started at a level above the blow-out condition but significantly lower than the nominal operating value. The purpose of this was for ease of testing since the pressure drop across the burner changes as the heat input changes and hence the air flow rate changes. Starting at the nominal fuel flow conditions only means the operator has further to go before blow-out and a more difficult time maintaining air flow conditions. At least three blow-outs were conducted for each fuel at each point; the averages are presented.

As with the ignition and combustion equipment, only those fuels which are physically different, i.e., the JP-5/DFM/gasoline blends, showed any effect on the lean blow-out characteristics. Figure 15 compares the lean blow-out equivalence ratios for these fuels at four different representative T-63 engine power points. Those points are 10, 40, 55, and 100 percent. In this figure, engine power is represented by the air-loading parameter, Θ , developed by Lefebvre[5]; actually Θ^{-1} is used following the work of the Purdue group, e.g., Dodds, et al.[6] Some physical fuel effects are evident in Figure 15; these effects are much more pronounced at higher values of Θ^{-1} (representing lower power conditions). The gasoline could be burned leaner at the idle condition than the other fuels, but the difference disappears at full power; this is felt to be the result of the higher inlet air temperature at full power. At the lower idle condition temperatures, the gasoline would vaporize and mix much faster than the heavier fuels. The higher temperatures at the full power condition would cause the heavier fuels to vaporize faster, while having little effect on a high-volatility fuel. The stability characteristics of the other fuels have a slight ranking as shown by the lines for the Jet A, JP-5, and DFM (1 and 2) with reduced stability, respectively, according to their general boiling range and viscosity. These differences are not great, and quantitative relationships would be tenuous. Generally, one can say that blending DFM with JP-5 did not degrade the stability of combustion; however, blending gasoline with DFM did improve or widen the stability limits somewhat.

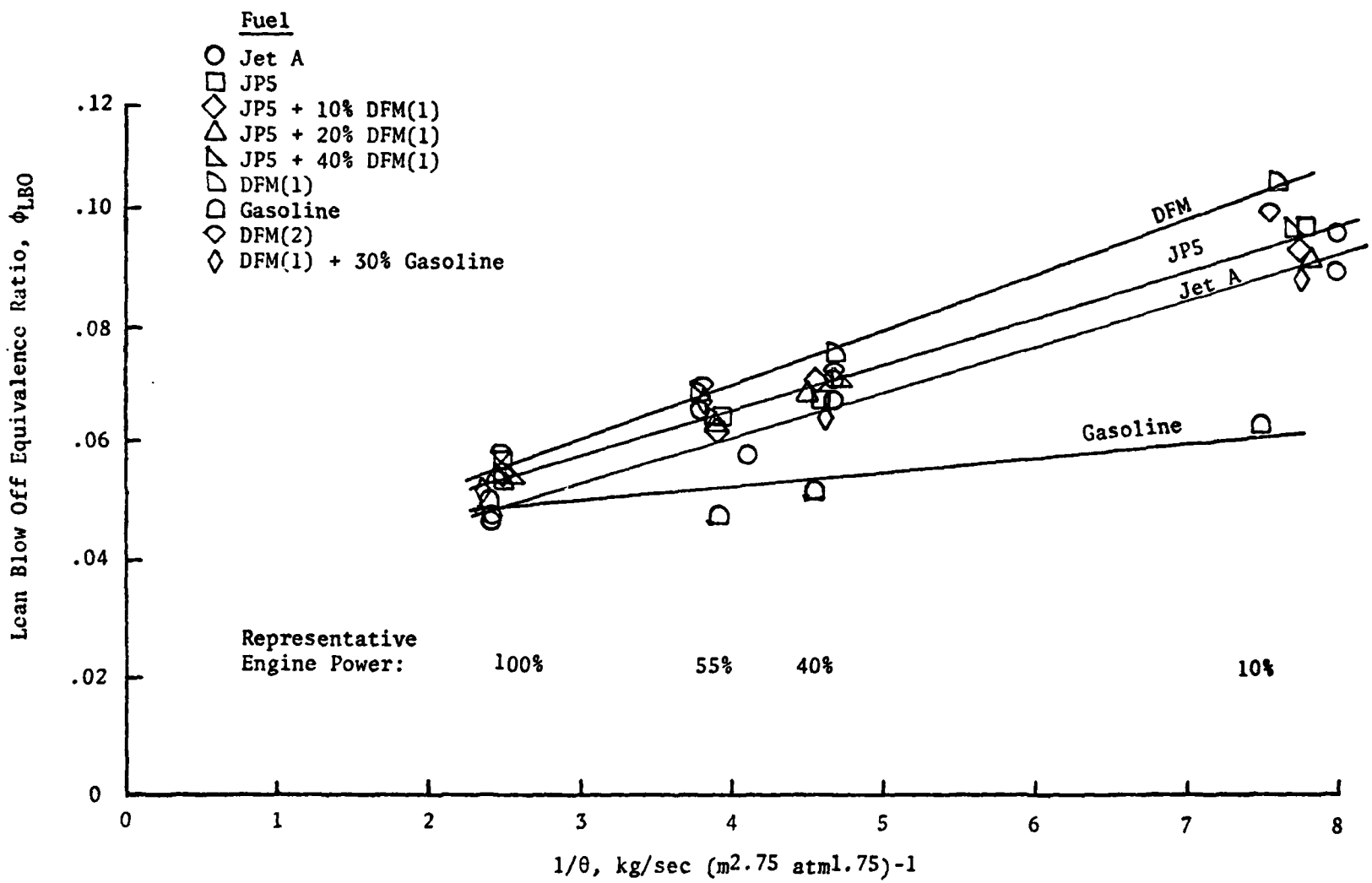


FIGURE 15 FUEL EFFECTS ON COMBUSTION STABILITY

Relative to the studies by Mellor's group at Purdue, this work was evidently in the regime where fuel-droplet penetration of the recirculation-zone shear layer is not significant even with the heavier DFM fuels so that increasing viscosity and boiling range reduces the stability limits of the combustor. This agrees with the results of earlier studies by Moses[7], Marchionna and Opdyke[8], and Plee, et al.[9] but contradicts the results of Plee, et al.[3] in a study where fuel penetration became important and stability was improved for heavier fuels. The characteristic time correlations of Mellor have not been calculated for this study but will be presented in a future publication.

G. Combustion Efficiency and Gaseous Emissions

Combustion efficiency (n_c) is calculated from the exhaust gas analysis according to a relationship developed by Hardin[10]:

$$n_c = \left[1 - \frac{A \cdot f(UBH) - 121{,}745 \cdot f(CO) - 38{,}880 \cdot f(NO) - 14{,}654 \cdot f(NO_2)}{A \cdot [f(CO_2) + f(CO) + f(UBH)]}\right] \cdot 100\%$$

where f(i) is the concentration of "i" in the exhaust and A is a constant based on the heat of combustion and hydrogen/carbon ratio of the fuel. The JP-5 Fuels Nos. 1 through 10 exhibited the same efficiencies and emission levels at all power points in the T-63 combustor; this was expected since it is the physical properties of viscosity and boiling point distribution that would affect atomization and vaporization. The one exception was the JP-5 derived from shale oil which contained 0.1% fuel-bound nitrogen. The conversion efficiency of fuel-bound nitrogen was essentially constant for all of the T-63 operating conditions; in the 2-inch combustor, however, conversion efficiency ranged from 21 to 82 percent with primarily an inverse dependency on inlet air temperature in agreement with Blazowski.[11] The lack of temperature dependency in the T-63 combustor may be due to the lower air temperatures as that is the only apparent difference.

The general patterns of the exhaust emissions followed expected trends: CO and UBH are highest at low power conditions due to lower temperatures and poorer mixing while NO_x increases with power because of the increase in primary zone flame temperature, a combination of higher inlet air temperature and fuel-air ratio.

The effect of fuel properties on the unburned hydrocarbons is shown in Figure 16. There is a general trend of increasing viscosity leading to increased UBH but the important characteristic appears to be the higher boiling point fractions of the fuel since the gasoline/DFM blend (Fuel No. 18) has the lowest viscosity (see Table 4) except for the pure gasoline but gives UBH levels similar to the pure DFMs. The fuel effect is predominant at the lower power conditions, indicating that the combustion is evaporation controlled under those conditions while reaction rate limited at the upper power levels.

The carbon monoxide/fuel relationships are shown in Figure 17 and follow the same pattern as the UBH, with the heavier fuels producing more CO. The DFM with 30 percent gasoline again ranks more with the pure DFM than with the lower viscosity fuels. The fuel effects are again most significant at the low power conditions.

Combustion inefficiency is predominantly related to the concentrations of CO and UBH in the exhaust (Global production of NO_x is an endothermic reaction that contributes slightly to inefficiency and is accounted for in the calculations). It is, therefore, not surprising that the fuel effects on combustion efficiency follow the same trends as discussed above and shown in Figure 18. The gasoline burned most efficiently; adding DFM to the JP-5 reduces the efficiency but the effect is only very large at idle conditions. The pure DFMs burned the least efficiently, and the addition of gasoline did not improve the combustion.

Figure 19 shows the fuel effects on NO_x. The term "energy-specific NO_x" is used to indicate that NO_x emissions index has been further normalized to account for differences in the heat of combustion among the fuels; the attempt here is to keep the heat release constant so that differences are caused by vaporization and mixing processes. One major difference between the NO_x and the CO/UBH fuel relations is that the fuel effects are essentially constant over the operating range. Although there is a significant amount of scatter in the data, the fuels with more high-boiling-point compounds produce more NO_x with the obvious exception of pure gasoline (Fuel No. 16). The higher boiling fractions means more droplet-cloud diffusion-flame combustion.

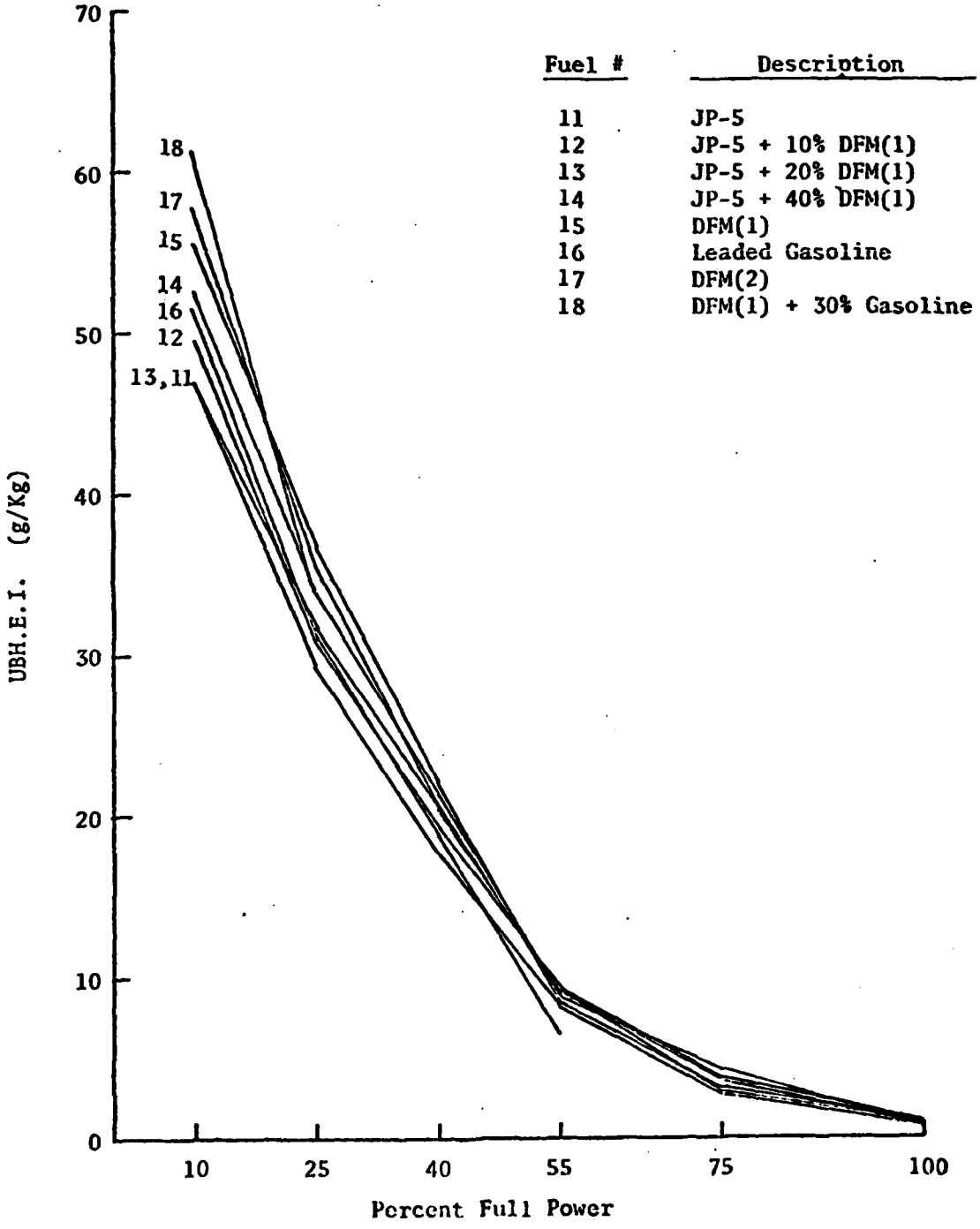


FIGURE 16 FUEL EFFECTS ON UNBURNED HYDROCARBONS EMISSION INDEX

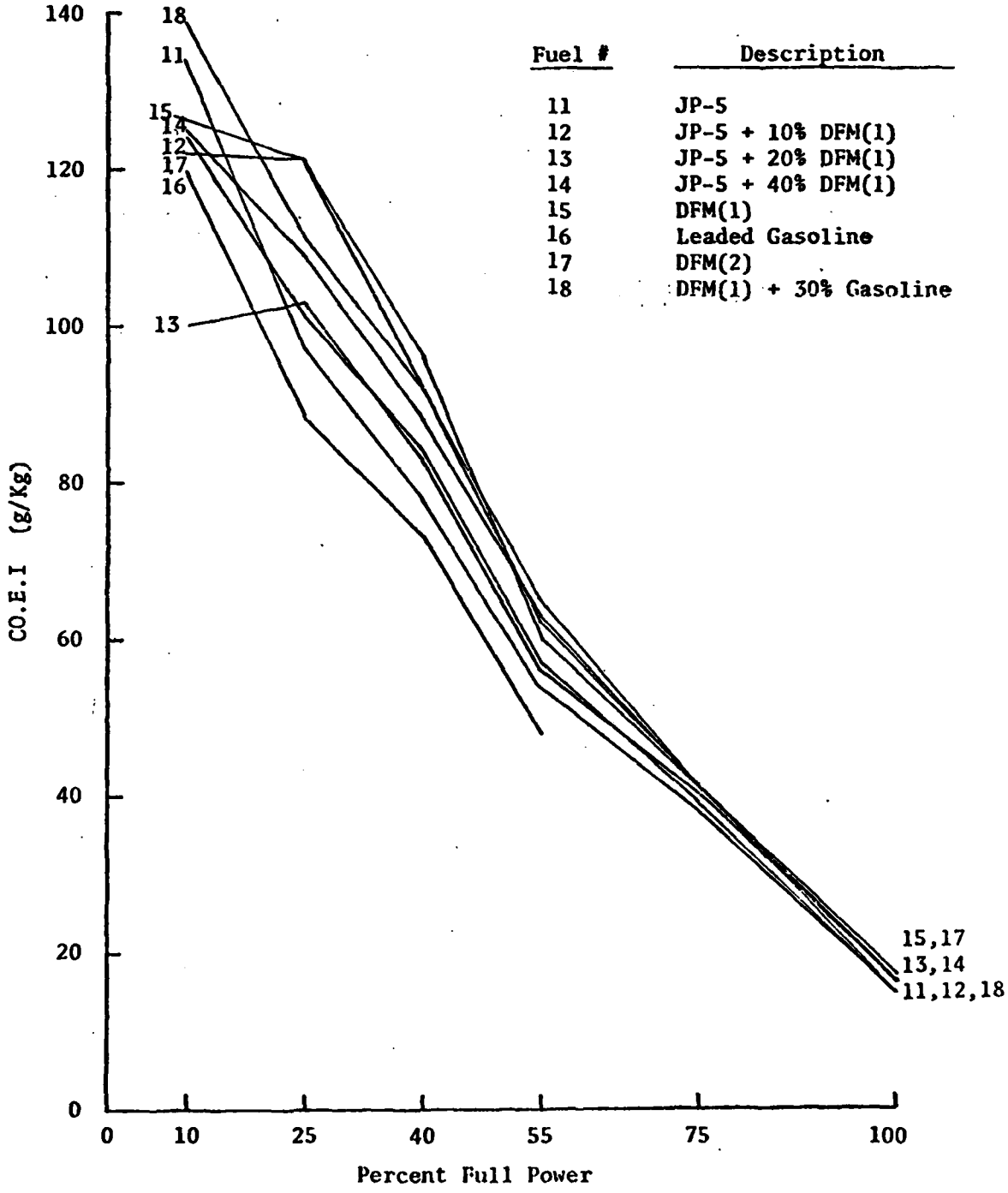


FIGURE 17 FUEL EFFECTS ON CO EMISSIONS INDEX

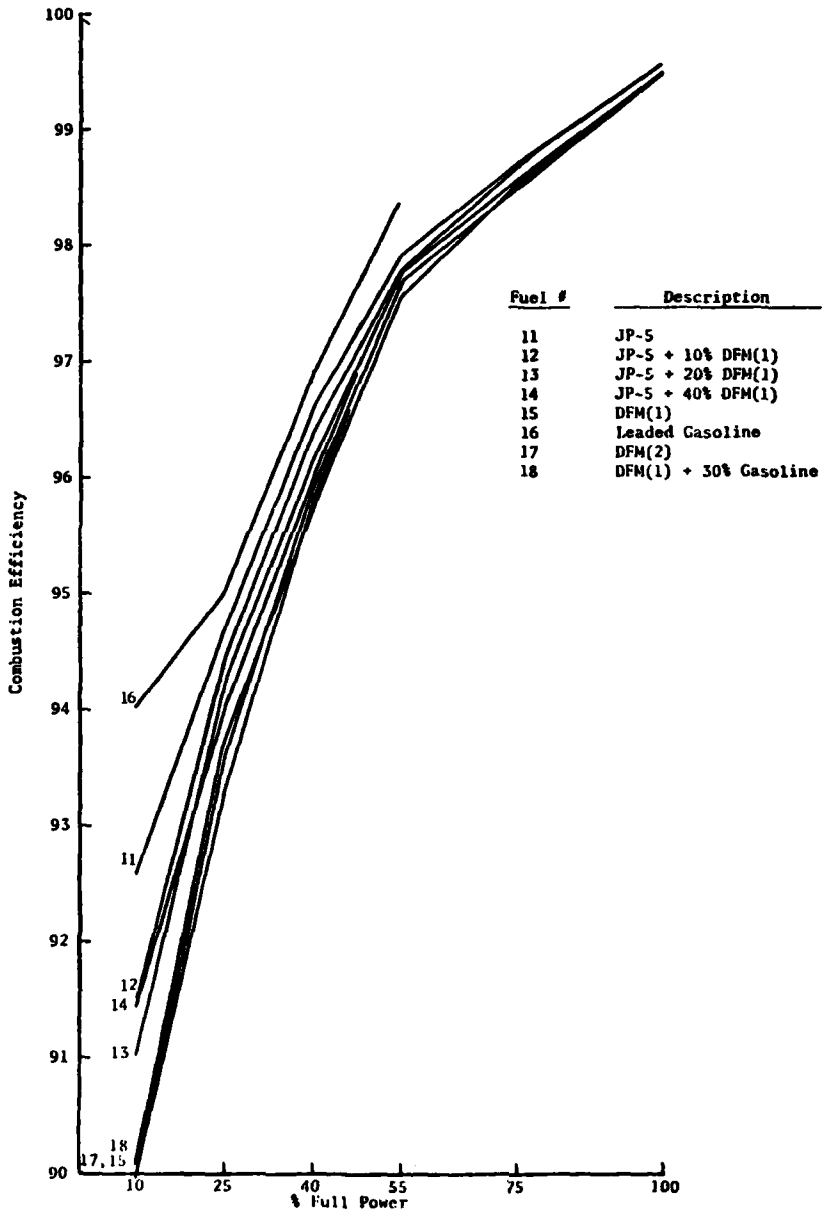


FIGURE 18. FUEL EFFECTS ON COMBUSTION EFFICIENCY

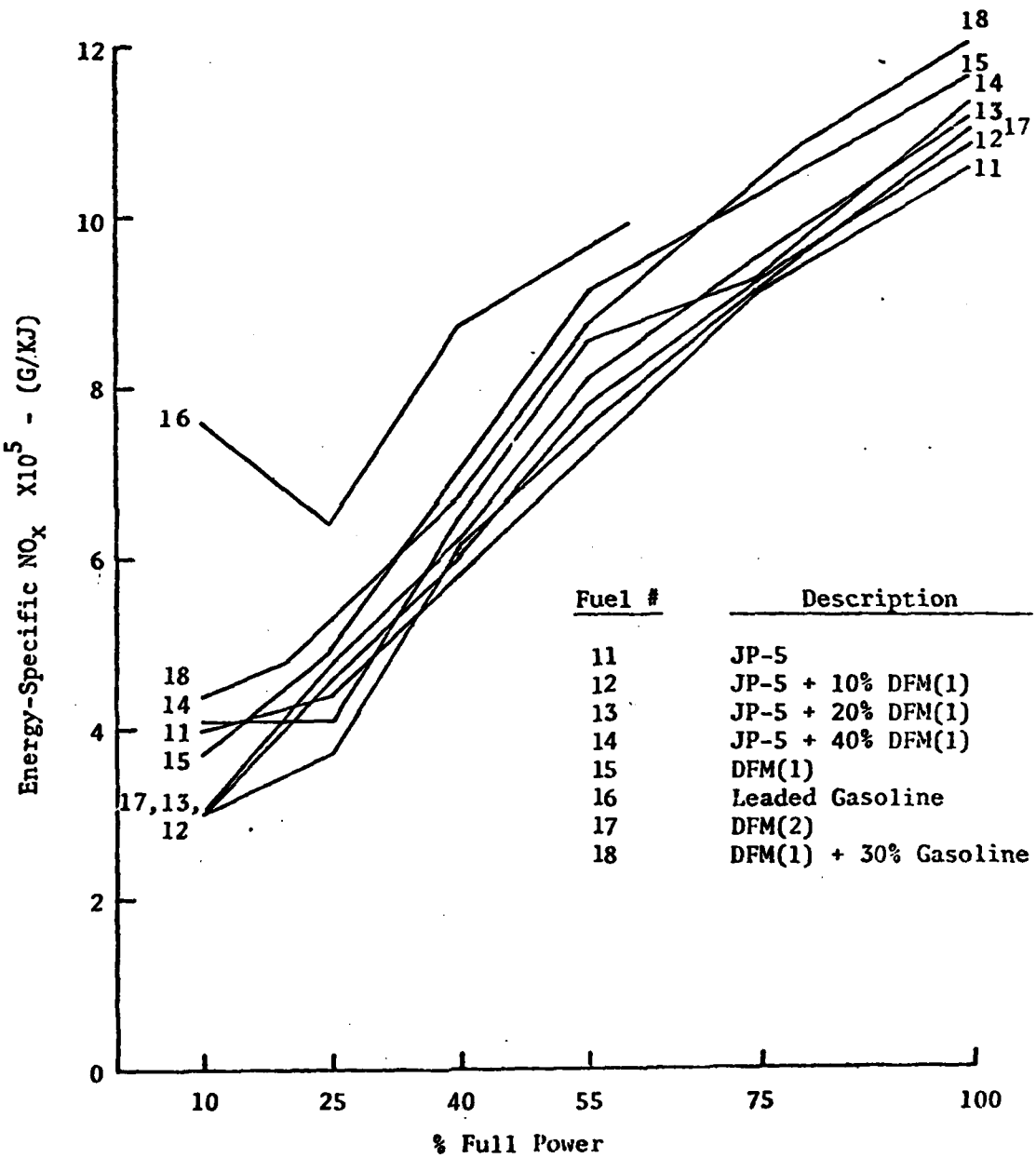


FIGURE 19 FUEL EFFECTS ON ENERGY-SPECIFIC NO_x

In the research combustor, the gaseous emissions from Fuels Nos. 11 through 18 were essentially independent of fuel properties. The UBH and CO emissions were very low as evidenced by the consistently high values of combustion efficiency (> 99%). The NO_x emissions were significant in magnitude, depending strongly on temperature (see Figure 20), but there were no detectable effects on fuel properties. The fluctuation in the high temperature (1060K) data points shown in Figure 20 may be attributed to scatter. The gasoline Fuel No. 16 is not shown because, as mentioned earlier, it was only tested in a limited number of runs in the Phillips burner.

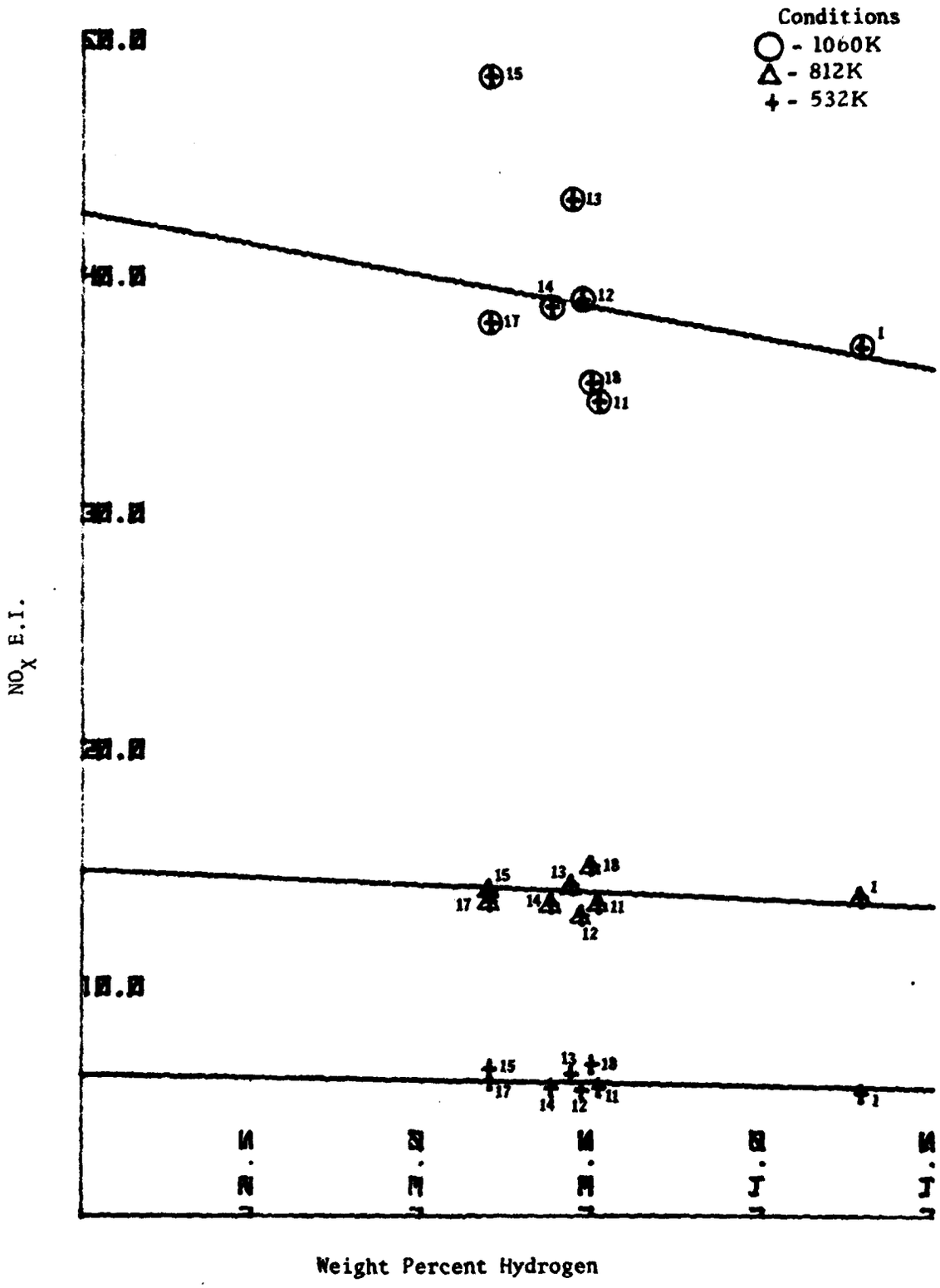
In the emissions studies, the basic fuel effect among the fuels tested in the T-63 combustor appears to be the vaporization rate of the fuel with initial drop size being of secondary importance. Although this study did not cover the whole range of distillates normally used in aircraft engines, it is the lighter fuels, JP-4 and JP-8, which are missing. Since most of the fuel effects are caused by the higher boiling point materials (NO_x from gasoline being the exception), the conclusions reached would probably not have been changed had these fuels been included. Burning DFM or blending DFM into JP-5 will lead to higher gaseous exhaust emissions of all kinds--CO, UBH, and NO_x. The increases in CO and UBH will be predominantly at idle conditions. The actual percentage increases will depend on the combustor design but probably will not be significant. It is not obvious from this work whether low emissions combustors would be any more or less sensitive to the fuel properties studied.

IV. CONCLUSIONS

The following conclusions were drawn from the results of the smoke and flame radiation experiments:

- Soot formation is dependent primarily on the hydrogen content of the fuel and perhaps only secondarily on the detailed hydrocarbon structure; this correlating parameter will be equally valid for syncrude fuels and petroleum fuels.

FIGURE 20. Effect of Inlet Temperature on NO_X Emissions Index



- Soot formation is primarily due to gas phase reactions in light and middle distillate fuels with end points below 400°C.

- The flame radiation and smoke in clean burning combustors will have low sensitivity to hydrogen content.

- The liner temperature in the primary zone is the most sensitive to flame radiation.

The following conclusions are drawn regarding the effects of the physical properties of fuels on combustor performance from the T-63 combustor studies:

- Ignition requirements are primarily affected by the front-end volatility of the fuel, more so than viscosity (drop size) in the range of fuels investigated.

- Higher boiling range fuels can reduce stability, but the effect is primarily at idle conditions.

- Combustion efficiency, CO, and UBH depend more on the higher boiling point components of the fuel than on viscosity in the ranges studied; these fuel effects are greatest at lower power conditions.

- NO_x also increases with an increase in the higher boiling point components. Fuels with very high volatility and low end points can significantly raise the primary-zone equivalence ratio and temperature and hence NO_x production.

The following conclusions are drawn regarding the effects of using gasoline and DFM as emergency fuels or JP-5 extenders:

- The most significant effect in using DFM as a pure fuel will be in ignition, primarily in colder weather; difficulties in altitude relight are also envisioned, but could not be studied in this program. Blending 10 to 15 percent gasoline with the DFM should give about the same ignition characteristics as JP-5.

- Blending DFM with JP-5 in concentrations as high as 40 percent will probably not have a serious impact on ignition in moderate temperatures. There may be serious problems in cold weather and altitude, but they could not be evaluated in this program. Again, the addition of a small amount of gasoline would alleviate that problem.

- The use of DFM as either a pure fuel or as an extender should not affect liner durability or exhaust smoke unless the hydrogen content is exceptionally low (high aromatic content).

- Leaded gasoline produces very high flame radiation, which will have an impact on liner durability. Also, there may be problems from lead deposits and sulfidation (hot corrosion) if sulfur is present. The most serious immediate impact will probably be on the pump and fuel control because of the low lubricity.

- The impact of using either DFM or gasoline on gaseous emissions will probably not be significant.

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