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FUEL QUALITY COMBUSTION ANALYSIS

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by

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16. Abstract

A high-pressure research combustor operating over a wide range of burner inlet conditions was used to determine the effects of fuel molecular structure on soot formation. Six test fuels with equal hydrogen content (12.8%) were blended to stress different molecular components and final boiling points. The fuels containing high concentrations (20%) of polycyclic aromatics and partially saturated polycyclic structures such as tetralin, produced more soot than would be expected from a hydrogen content correlation for typical petroleum-based fuels. However, fuels containing naphthenes such as decalin agreed with the hydrogen content correlation. The contribution of polycyclic aromatics to soot formation was equivalent to a reduction in fuel hydrogen content of about one percent. The fuel sensitivity to soot formation due to the polycyclic aromatic contribution decreased as burner inlet pressure and fuel/air ratio increased.

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FOREWORD

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FUEL QUALITY COMBUSTION ANALYSIS

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SUMMARY

Previous studies have shown that hydrogen content is generally a good correlating parameter for soot formation from petroleum base gas turbine fuels. However, it has been suggested that the polycyclic ring structures found in synthetic fuels from coal and oil shale may deviate from the hydrogen content correlation. The purpose of the present work was to determine the effects of fuel molecular structure on soot formation by using six test fuels prepared with equal hydrogen content (12.8 ± 0.2%) but with significantly different molecular compositions. The fuels were blended to stress the effects of polycyclic aromatics, tetralin, decalin, and increased final boiling point. The fuels were tested in a Phillips 2-inch high-pressure research combustor over a wide range of burner inlet parameters. Combustion performance measurements included flame radiation, exhaust smoke, gaseous emissions (UBH, CO, and NO_x), and combustion efficiency. It was found that fuels containing high concentrations ($\approx$20%) of polycyclic aromatics and partially-saturated polycyclic aromatic structures such as tetralin, produced more soot than would be expected from a simple hydrogen content correlation; at this concentration, the effect of the polycyclic compounds was equivalent to a reduction in fuel hydrogen content of about one percent. Soot production from fuels containing high concentrations of fully saturated ring structures, such as decalin, agreed with the hydrogen correlation. Increased final boiling point did not affect soot formation. The sensitivity of polycyclic aromatic content to soot formation decreased as burner inlet pressure and fuel/air ratio increased; there did not seem to be an effect of burner inlet temperature. The results suggest that the mechanism for soot formation involves some rate-controlling pressure-dependent reaction steps.

INTRODUCTION

The purpose of this effort is to investigate the effects of hydrocarbon structure on flame radiation (and smoke) using fuels which have the same hydrogen content but which vary in composition and structure. This effort is part of an overall program to devise a laboratory method for the determination of fuel combustion quality of aircraft turbine fuels destined for use in the future. The present performance tests for determining relative burning quality of fuels are based on their sooting tendency in a smoke lamp and are of questionable value in their specification for gas turbine engines. For these and other reasons it has been strongly suggested that a measure of hydrogen content is all that is required to give a good measure of combustion quality (best relationship with engine smoking tendency and temperature of hot section parts). It is also being suggested that a value for hydrogen content be written into the jet fuel specifications. The scope of this study is to indicate under what conditions, and to what extent, fuel variation at the same hydrogen content will have on flame radiation and smoke emission.

BACKGROUND

Presently, gas turbine aircraft account for about 12% of transportation fuels, but projections indicate that consumption will vary from 15% in the 1990's to as much as 30% by the year 2000 (1,2). Considering the growth potential of aircraft fuels and the dwindling supply of petroleum near the end of the century, the production of synthetic jet fuels from the vast reserves of oil shale and coal in the U.S. is almost inevitable.

While petroleum has been seen as an excellent source of hydrocarbons in the gasoline boiling range, the less volatile syncrudes from oil shale and coal would appear to be more appropriate sources of Jet A and other middle distillate fuels. The intrinsic problem is that syncrudes typically have a very high aromatic content (greater than 35%) and the production of non-sooting turbine fuels requires extensive hydrotreating. In contrast with petroleum distillates, the finished fuels from syncrudes are also rich in naphthenes and relatively low in paraffin content. Depending on the extent of hydrotreating, the aromatics in syncrudes could be hydrogenated directly to naphthenes such as decalin or stopped at some intermediate stage where only part of the polycyclic aromatic molecule becomes saturated, such as tetralin. These significant differences in the composition of jet fuels from syncrudes could cause problems in combustors not predictable on the basis of correlating parameters used in specifications for petroleum-based fuels.

Soot formation in gas turbine engines is observed in the form of exhaust smoke and increased combustion chamber liner temperature, i.e, radiant heat transfer from incandescent carbon particles (3,5). The flame radiation intensity is a function of the gas temperature and the flame emissivity which depends on soot concentration. Exhaust smoke is what remains after about 98% (4) of the soot is oxidized in the secondary and quench zones of the combustor; the oxidation rate which depends largely on operating conditions such as inlet temperture, is essentially independent of fuel properties and follows a rate law that is pseudo first order in the soot concentration.

For petroleum base fuels, hydrogen-to-carbon ratio and aromatic content have been acceptable correlating parameters for exhaust smoke and liner temperature (2,6,7). However, because of the dramatic changes in fuel composition that are destined to come, there is concern over the adequacy of parameters such as aromatic content in assigning fuel specifications. This stems from the fact that there is no one agreed on mechanism for the formation of soot in flames (8,9). The theories of soot formation in the gas phase range from that of hydrocarbon polymerization followed by dehydrogenation of ring clusters to that of hydrocarbon pyrolysis and the subsequent polyermization of low-molecular-weight, acetylenic-type, free-radical species. Liquid phase pyrolysis with the formation of cenospheres has also been proposed although recent work by the authors suggests this is not an effective mechanism (7).

Recent work by Graham et. al. (10) has shown that the amount of soot formed from various hydrocarbons depends on the concentration of soot precursor species and on temperature. In short, they advocate that aromatic and naphthenic compounds can form soot either with preservation of the ring structure or, at high temperatures (>1800K), by fragmentation of the ring to small radicals, with a slower subsequent formation rate to soot.

The mechanism involving hydrocarbon polymerization, i.e., ring preservation, would be sensitive to molecular structure. The reaction path leading to low molecular weight acetylenic species and their subsequent recombination into soot, would seem to be relatively insensitive to structure, and suggests that H/C ratio should be a good correlating parameter for soot formation if this is the dominant path.

Several recent studies (11-15) have shown that hydrogen content (H/C ratio) is a more appropriate correlating parameter than the traditional properties, smoke point and aromatic content, for comparing the soot formation of one fuel with another; however, some perturbations in the data suggest that there are secondary effects due to molecular structure.

APPROACH

To examine the effect of fuel properties on soot formation, six fuels with identical hydrogen content but markedly different molecular composition have been prepared and tested in a Phillips 2-inch high pressure research combustor. Emphasis is placed on tri- and dicyclic aromatics versus monocyclic aromatics, on naphthenes (decalin), and on partially hydrogenated polycyclic aromatics (tetralin). Final boiling point was also varied because liquid-phase pyrolysis of fuel droplets has also been considered as a possible mechanism for soot formation.

The fuels were studied in a two-inch diameter research combustor, described below, under a variety of operating conditions, all at very high combustion efficiency, simulating the environment and ranges of flow, pressure, and temperature for which most aircraft turbine engines are designed. Flame radiation and smoke from the combustion were measured to study the effect of hydrocarbon structure on soot formation.

EXPERIMENTAL FACILITIES AND METHODS

This work was performed in the turbine fuels research combustor laboratory in the U.S. Army Fuels and Lubricants Research Laboratory (AFLRL) located at Southwest Research Institute. The AFLRL combustor facility was especially designed for the study of 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/sec with pressures to 1620 kPa and temperatures to 1088K at all flow rates. The fuel delivery system is capable of pumping fuels ranging in properties from gasoline to No. 5 fuel at flow rates up to 4 liters and pressures up to 6890 kPa. The data reduction is performed on-line with test results available immediately; up to 50 channels of thermocouple and transducer signals can be sampled.

The system has been designed for maximum flexibility and growth. Conceivably, any combustion chamber and associated rig can be "plugged-in," instrumented, and operated within the air flow capabilities of the laboratory. A detailed description of the facility is given in reference 12.

In this particular examination of fuel properties and combustion performance, the Phillips-designed high-pressure 2-inch combustor was employed.

The Phillips 2-Inch Combustor

Figure 1 is a schematic of the Phillips 2-inch combustor. Basically, this combustor is a straight-through cylindrical type, with fuel atomization by a single-orifice, oil-burner-type pressure atomizer. The combustor liner is constructed from 2-inch, Schedule 40, Inconel pipe. Film cooling of surfaces exposed to the flame is accomplished by internal deflector rings. The combustor rig actually used is a more rugged version of the original Phillips rig; some major design changes were incorporated for the purpose of reaching higher inlet temperatures (1500°F), namely, the uprating of the flanges to the 1500# class and fabricating them and the combustor housing from 316 stainless steel.

Operating Conditions

The combustor was operated over a matrix of test conditions which were combinations of the nominal air/fuel flow conditions given below:

Pressures, kPa	507, 1013, 1520, 1823
Temperatures, K	533, 644, 811, 922, 1066
Reference Velocity, m/s	30.5, 61
Fuel/air ratio	0.008, 0.012, 0.016, 0.020, 0.024

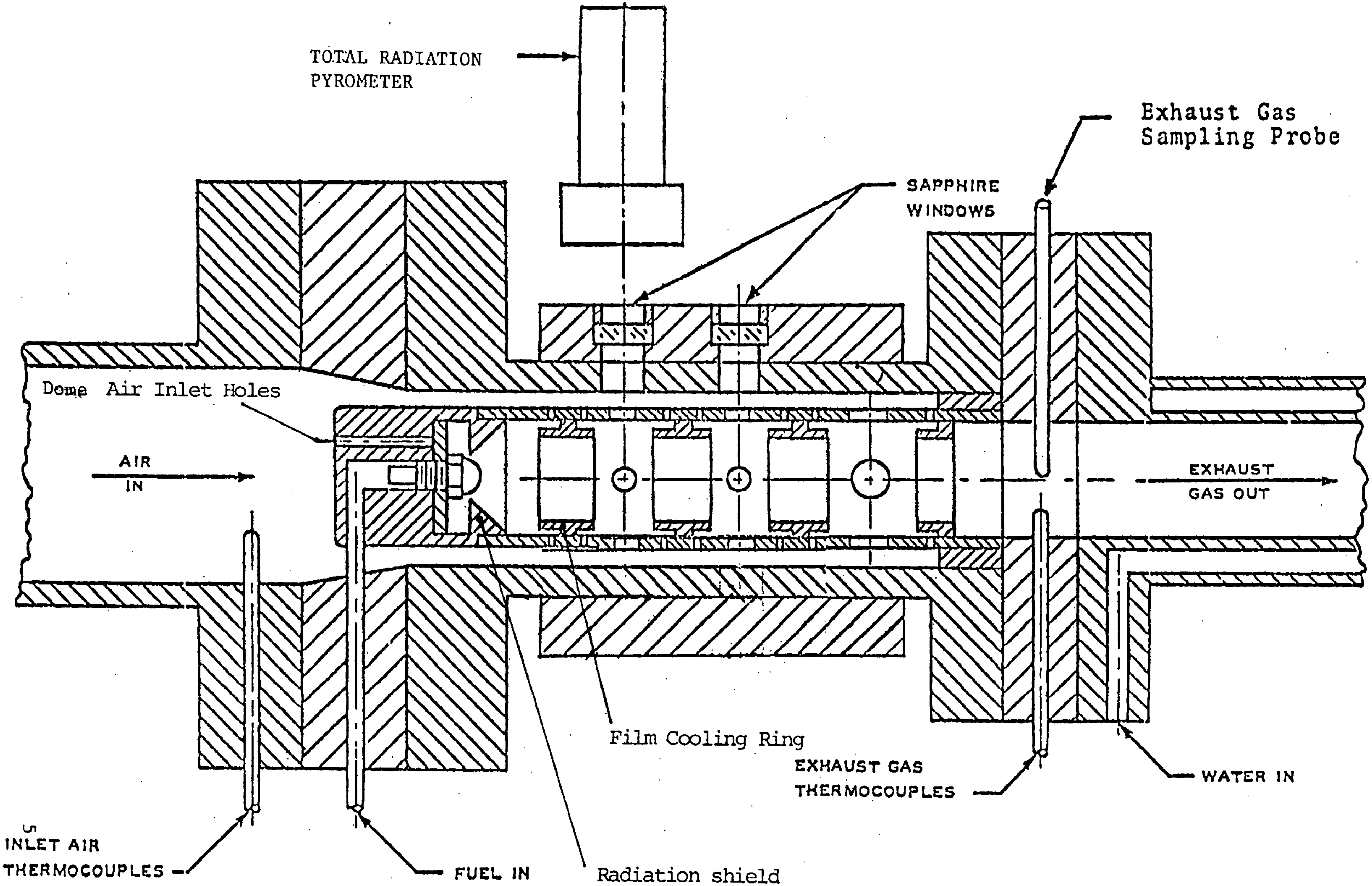


FIGURE 1

PHILLIPS 2 - INCH COMBUSTOR

The details of the tests and the fuel nozzle sizes used to maintain constant atomization characteristics are given in Appendix A. Previous experiments (12) have shown that nozzle size has a significant effect on combustion performance. The nozzle influences fuel droplet vaporization by its effect on the droplet spray Sauter mean diameter (SMD) and the amount of droplet penetration into the combustion zone. With the given combustor configuration and the variety of hollow cone spray nozzle, it was impossible to keep both droplet penetration and SMD constant. However, the nozzle size could be selected such that the SMD was the same at each test condition.

It has been shown (12) that the SMD of a hollow cone spray nozzle depends on the viscosity, ϑ , the mass flow rate, M, and the differential nozzle pressure, ΔP, by the relation

$$\mathrm{SMD} \approx \vartheta^{0.3} M^{0.2} / \Delta P^{0.35}$$

For a given fuel, the SMD is constant if the ratio $M^{0.2} / \Delta P^{0.35}$ is maintained a constant for all test conditions. The nozzle sizes listed in Appendix A were calculated such that the SMD produced by them would be essentially constant.

Coke Formation and Excessive Exhaust Temperatures

It was found in several of the 5 atm test conditions that coke formation in the primary zone region of the liner was a serious problem. It was believed that fuels 3 and 4 with high concentrations of methyl naphthalenes were largely responsible for the coking; however, separate experiments were not done to confirm this. It appears that at 5 atm the flame zone is larger than at the higher pressures and the tendency for fuel droplets to precipitously pyrolyze on the liner wall and build up coke is very high; coke formation was a relatively minor problem for the higher pressure test conditions. The problem of coke formation was resolved, for the most part, by making some minor changes in the primary zone section of the burner. The burner components and configuration are shown in Figure 1. The changes include (1) increasing the diameter of the dome inlet holes from 1/4 inch to 5/16 inch, (2) drilling nine 1/8 inch air inlet holes symmetrically in the radiation shield and (3) removing the film cooling ring from the primary zone. Removing the film cooling ring was most beneficial in preventing carbon deposition. The effect of these changes was to slightly reduce the primary zone equivalence ratio and eliminate the protruding surface of the film cooling ring. In the original burner, about 30 percent of the inlet air entered the primary zone so that the fuel/air ratio there would be equal to the overall fuel/air ratio divided by 0.33. It is estimated that about 35 percent of the air entered the primary zone of the modified burner.

Some of the higher pressure runs done with the original burner were repeated with the modified burner and it was found that the levels of flame radiation and exhaust smoke and their sensitivity to fuel properties were not seriously affected by changes in the burner.

Nine of the test conditions were not possible because of excessive exhaust temperatures ($\simeq$ 1350K). In some of the runs, where the exhaust temperatures were borderline, the combustor was operated at high temperatures for brief periods; in these cases, it was only possible to record radiation and make a single spot smoke number measurement.

A summary of the test conditions indicating the problems that occurred and changes that were made to avoid coking and excessive exhaust temperatures is given in Appendix A.

Test Fuels

The six test fuels were blended with essentially identical hydrogen contents (12.8 ± 0.2%) but with as much variation in molecular structure as possible. Emphasis was placed on aromatic type (mono, di, and tricyclic), decalin, tetralin content and final boiling point. A summary of the test fuels including two reference fuels 0 and 7 is shown below in Table 1.

TABLE 1. FUEL COMPOSITIONS

Fuel No.	Hydrogen	Composition (Percent by Weight)
0	14.22	Jet A (reference fuel)
1	12.80	Jet A with 31.11% mixed xylenes
2	12.82	Jet A with 35% decalin and 21.97% mixed xylenes
3	12.82	Jet A with 25.0% methyl naphthalene LG-3
4	12.81	Jet A with 5% DFM and 24.14% methyl naphthalene LG-3
5	12.88	Jet A with 5% DFM, 0.5% anthracene and 27.8% mixed xylenes
6	12.83	Jet A with 5% DFM, 23.06% tetralin and 5% mixed xylenes
7	11.64	DFM with 17.8% mixed xylenes, 5.9% methyl naphthalene LG-3, 10% tetralin, and 12.0% anthracene oil (reference fuel)

It was originally planned that fuel 5 should contain 3% anthracene. However, due to its limited solubility, only 0.5% anthracene could be dissolved in the fuel. This was the only difficulty that arose in fuel blending.

The base fuel, Jet A, which was used in blending all of the fuels except number 7, had a final boiling point of 579K. In blending fuels 4, 5, and 6 with increased end point, the final boiling point of Jet A base fuel was increased to 616K by adding 5% diesel fuel marine (DFM).

The fuel blending agents methyl naphthalene LG-3 and anthracene oil mentioned in Table 1 were complex mixtures consisting largely of polycyclic aromatic molecules. The remaining blending agents, mixed xylenes, decalin, tetralin, and anthracene were essentially pure compounds. The properties of the blending agents are listed in Table 2. These fuel properties were used in calculating the final compositions of the test fuels listed above in Table 1.

TABLE 2. FUEL PROPERTIES OF BLENDING MATERIALS

Blending Agent	Weight Percent Hydrogen	Specific Gravity (60°F)	Aromatic Ring Carbon (wt%)		
			Monocyclic	Dicyclic	Tricyclic
Methyl Naphthalenes LG-3	8.29	0.9726	17.8	60.8	0.4
Anthracene Oil	11.90	0.90	10.5	9.7	2.7
Mixed Xylenes	9.45	0.8701	67.5	0.68	0.01
Decalin	13.04*	0.8834	0	0	0
Tetralin	9.08*	0.9713	54.54*	0	0
Anthracene	5.62*		0	0	94.38*
DFM	13.20	0.8550	8.11	3.59	0.31
Jet A	14.22	0.8010	3.6	2.3	0.02

---

* Calculated from empirical formula.

The physical and chemical properties of the test fuels shown in Table 3 were determined, for the most part, by the AFLRL facilities. The hydrogen contents were determined at Wright Patterson Air Force Base with low resolution NMR, a highly accurate method that is rapidly gaining acceptance (16). It is interesting to note that the hydrogen contents of the test fuels, which were based on the hydrogen contents of the blending agents, came out almost exactly as calculated. This remarkable consistency lends much support to the accuracy of the low resolution NMR technique. The carbon, nitrogen, and oxygen analysis were done by Galbraith Laboratories.

EXPERIMENTAL RESULTS

Since the main objective of this study was to measure the effects of fuel properties, namely molecular structure, on flame radiation and exhaust smoke, the Phillips-2 inch high pressure research combustor was used because of its high combustion efficiency. In fact, essentially all of the test runs exhibited combustion efficiencies of more than 99.5 percent so that the emissions of carbon monoxide and unburned hydrocarbons were negligible and did not show a dependence on fuel properties.

Combustion efficiencies are calculated from the exhaust gas analysis according to a relationship developed by Hardin (18):

$$\eta_b = \left[1 - \left(\frac{A \bullet f(UBH) - 121{,}745 \bullet f(CO) - 38{,}880 \bullet f(NO) - 14{,}644 \bullet f(NO_2)}{A \bullet [f(CO2) + f(CO) + f(UBH)]}\right)\right] \bullet 100$$

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 NO_x measurements for fuels 0 to 6 were independent of fuel properties. Previous studies (12) have shown that NO_x concentrations increase with increased flame temperature and fuel-bound nitrogen. The relatively high concentration of fuel-bound nitrogen in reference Fuel 7 did indeed give a higher NO_x emissions index.

The measurements of flame radiation and exhaust smoke were generally quite good and followed anticipated trends previously observed with the Phillips 2 inch combustor (12). Initially, there was a problem of coking in the low pressure test conditions, but this was adequately

TABLE 3. SUMMARY OF FUEL PROPERTIES

Fuel Type	A	1	2	3	4	5	6	7
Heat of Combustion, Net (J/g)	43,575	42,138	42,260	42,704	42,657	42,655	42,016	41,593
Carbon, wt%	85.78	87.15	87.11	87.01	87.08	86.93	87.05	88.18
Hydrogen, wt%	14.22	12.80	12.82	12.82	12.81	12.88	12.83	11.64
Nitrogen, wt%		0.001	0.003	0.004	0.003	0.002	0.004	0.063
Oxygen, wt%		0.05	0.06	0.16	0.10	0.16	0.08	0.12
Sulfur, wt%		0.003	0.003	0.007	0.007	0.030	0.036	
Aromatics by U.V.								
Single ring, wt%	4.6	26.4	19.0	7.3	7.3	24.0	20.5	23.5
Double ring, wt%	1.3	1.9	1.2	20.0	19.3	1.9	2.08	10.3
Triple ring, wt%	0.02	0.002	0.001	0.08	0.08	0.49	0.02	0.65
Total, wt%	5.92	28.302	20.201	27.38	26.68	26.39	22.60	34.45
HPLC Analysis								
Saturates, wt%	91.9	63.7	76.6	69.5	68.7	66.2	62.9	42.0
Aromatics, wt%	8.1	36.3	23.4	30.6	31.3	33.8	27.1	58.0
Aromatics by F.I.A.								
Aromatics, vol%		35.9	22.9	27.6	27.8	33.3	31.8	---
Olefins, vol%		1.6	1.7	1.4	1.2	2.1	1.6	---
Saturates, vol%		62.5	75.4	71.0	71.0	64.5	66.6	---
Viscosity at 313K (cSt)	1.68	1.11	1.28	1.57	1.62	1.22	1.52	2.33
Flash Point, (K)	335	311	314	339	338	312	328	318
Specific Gravity	0.801	0.8212	0.8418	0.8403	0.8388	0.8323	0.8428	0.8860
Freeze Point, (K)		228	220	231	230	293*	230	---
Smoke Point, mm	24	15.4	16.2	12.5	13.8	15.3	15.2	9.1
Final Boiling Point, (K)	582	598	582	630	658	629	634	841

---

* Crystalization of anthracene gave an apparent high melting point.

resolved by making minor changes in the primary zone of the burner as previously discussed.

The flame radiation and exhaust smoke data were reduced by the use of a radiation index (R) and a smoke index (S) for each fuel at a given combustor test condition; the indices are defined as follows:

$$R = \frac{\text{Flame Radiation from Test Fuel}}{\text{Flame Radiation from Reference Fuel}}$$

and

$$S = \frac{\text{Exhaust Smoke from Test Fuel}}{\text{Exhaust Smoke from Reference Fuel}}$$

where the reference fuel is the base fuel Jet A. Figure 2 illustrates how the radiation index varied with the fuels for several representative test conditions. The pattern is typical of all the tests, namely that the R values for test fuels 1 and 2 were almost identical and that of Fuel 5 was slightly higher; Fuels 6, 3, and 4 burned with significantly higher radiation in that order. The values for Fuel 7 are even higher but that is due in part to the lower hydrogen content. It is shown in Figure 3 that the smoke indices follow the same pattern.

The variation in R (or S) among Fuels 1 through 6 is due to a sensitivity to fuel properties other than hydrogen content. Generally, this fuel sensitivity is greatest at test conditions producing higher levels of flame radiation which is in agreement with the results of earlier studies with this combustor.

Since qualitatively the relationships between the fuels shown in Figures 2 and 3 is generally observed in all of the test runs, the mean values of R and S can be used as characteristic data to correlate with fuel properties. The mean values of R and S are given below in Table 4.

TABLE 4. LIST OF MEAN RADIATION AND SMOKE INDICES

Fuel Number	0	1	2	3	4	5	6	7
Mean Radiation Index	1.0	1.22	1.23	1.43	1.45	1.26	1.35	1.64
Mean Smoke Index	1.0	1.60	1.55	2.00	2.02	1.58	1.90	2.33

Before moving on to various attempts to correlate possible differences in fuel composition and molecular structure with the average indices of flame radiation and exhaust smoke, it is important to first examine the correlations that may occur with the physical fuel properties such as viscosity and final boiling point. It is also important to consider smoke point as a possible correlating parameter even though it is not a fundamental fuel property because it is an accepted fuel specification.

Figure 4 presents the correlations found in this study of the radiation and smoke indices (R and S) with smoke point. The correlation coefficients of $r^2 = 0.94$ and 0.92 for R and S respectively, are surprisingly good considering the nature and accuracy of the smoke point procedure (±1 mm).

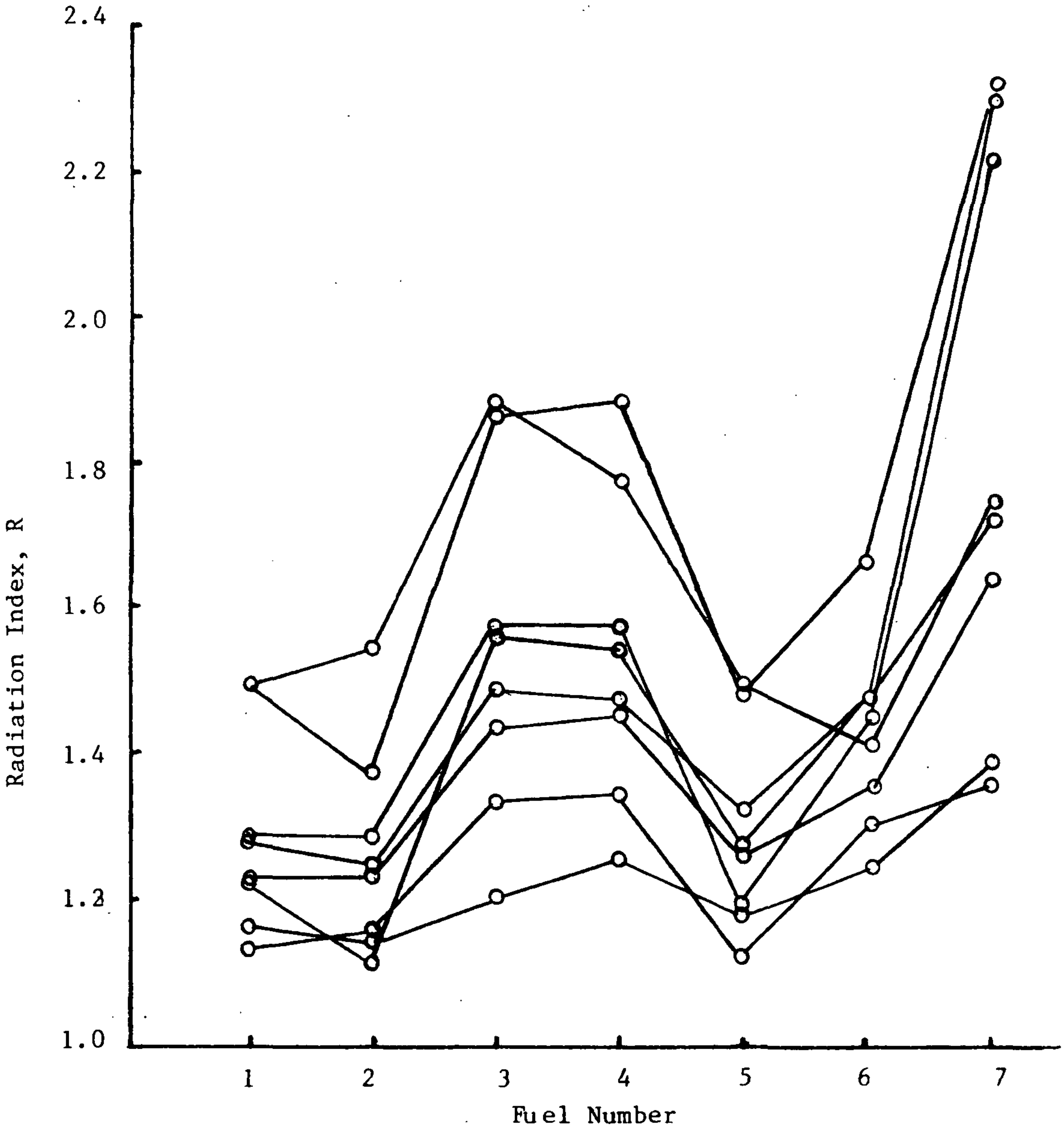


FIGURE 2. RELATIVE FLAME RADIATION INDICES FOR TEST FUELS

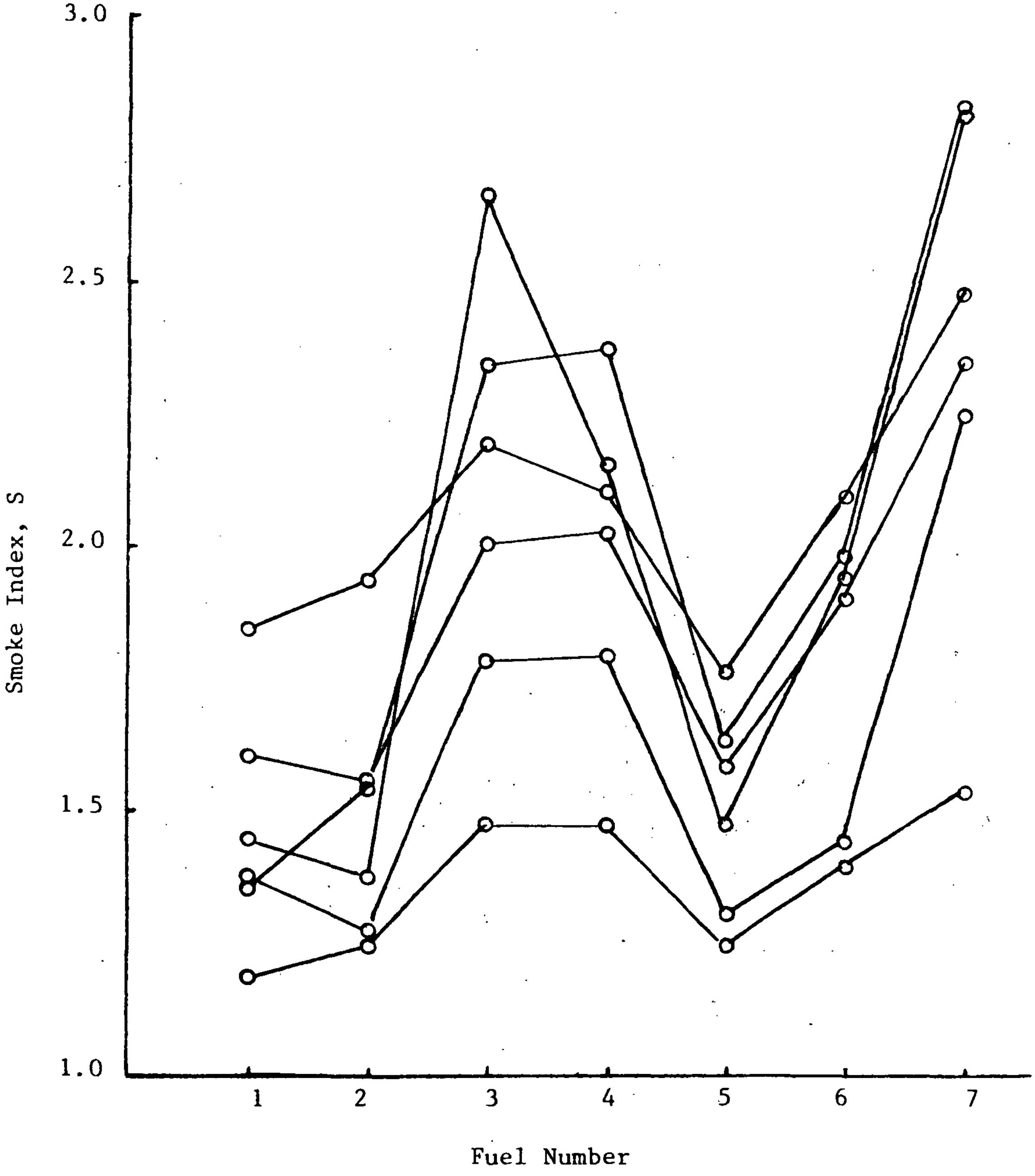


FIGURE 3. RELATIVE EXHAUST SMOKE INDICES FOR TEST FUELS

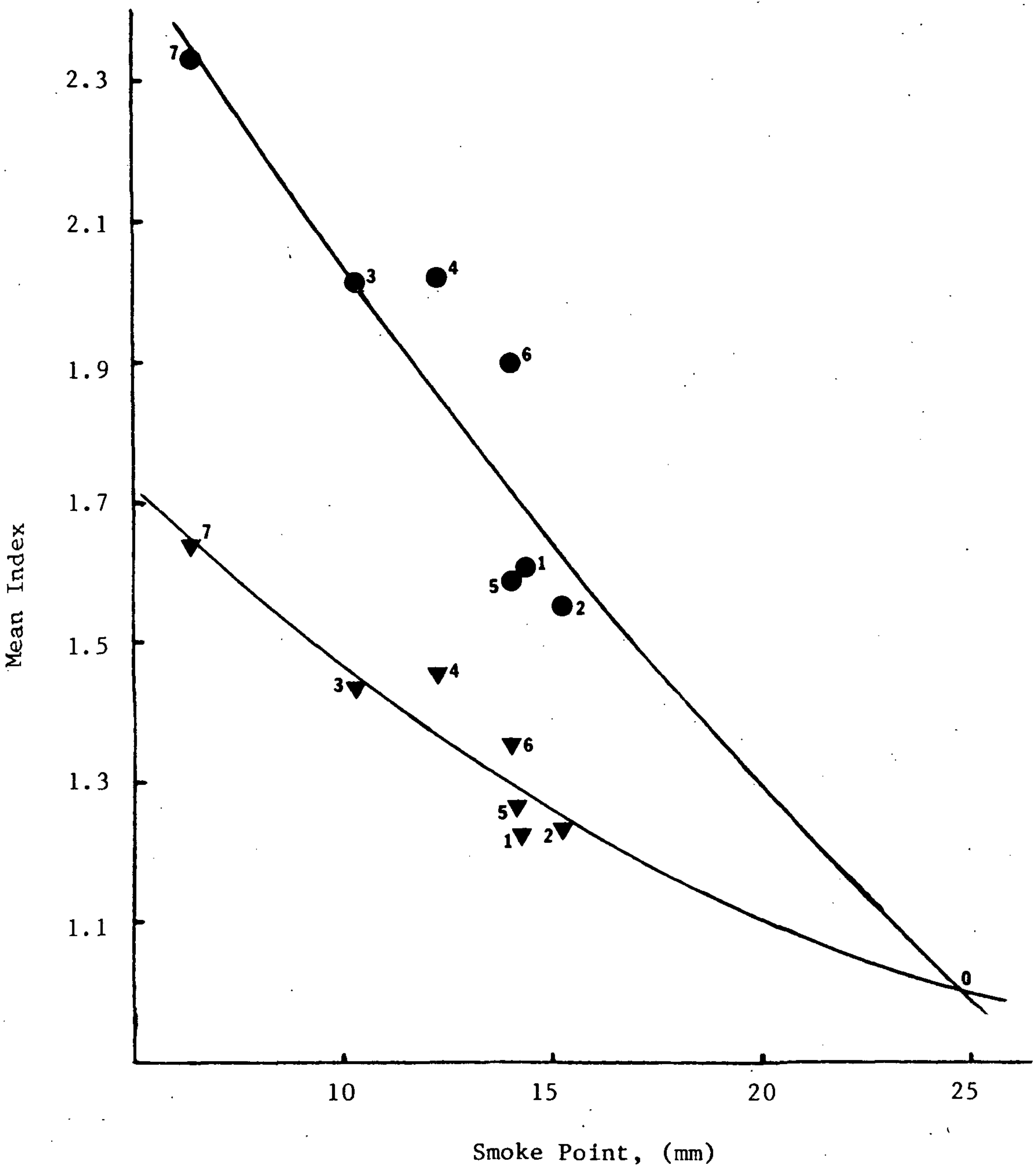


FIGURE 4. EFFECT OF SMOKE POINT ON THE MEAN INDICES OF SMOKE AND RADIATION: ● = SMOKE INDEX: ▼ = RADIATION INDEX

A surprisingly good correlation was obtained with viscosity (see Figure 5), but this was found to be a coincidence because subsequent experiments in which the viscosity was varied by changing fuel temperature showed no difference in the measured flame radiation. At several test conditions the temperature of Fuel 0 was measured at the nozzle inlet with a small thermocouple that had been inserted in the fuel line about 10 inches upstream from the nozzle. The fuel temperature was varied over a range of about 30°C by reducing the flow of cooling water through the fuel line water jacket adjacent to the nozzle. The changes in viscosity with temperature were as large, if not greater than the differences that existed between the test fuels. Thus, as mentioned above, it was concluded that the correlations shown in Figure 5 were coincidental.

Viscosity affects fuel atomization and thus, the rate of fuel vaporization. When fuel vaporization is affected by much larger changes in droplet size (SMD) and spray penetration, the fuel air mixing in the primary zone is changed and this affects soot formation. Previous studies (12) in the Phillips 2-inch combustor have shown that changing the size of the atomizing fuel nozzle at a given test condition has a significant effect on the flame radiation and exhaust smoke. In the present work the test conditions were originally designed (see page 6) to eliminate SMD as a variable in the experiments. In order to examine both effects SMD and spray penetration (i.e., significant change in fuel vaporization rate), several test conditions were run with different sized spray nozzles. It is evident from the results shown in Figure 6, where viscosity is used as an illustrative correlating parameter, that the level of radiation changed when different fuel nozzles were used but the slopes of the curves remained the same. Thus, the differences in radiation indices between the six test fuels were not affected by large changes in the rate of fuel vaporization.

Boiling point distribution also influences fuel droplet vaporization. In comparing the radiation and smoke indices of fuels that have different final boiling points, but otherwise similar properties, i.e., Fuel 1 with 5 and 3 with 4, it is apparent that the effect of end point is negligible. It is concluded that the differences in radiation and smoke observed among Fuels 1 to 6 are insensitive to the fuel properties and operating parameters which affect fuel-droplet vaporization and the chemical composition is therefore the appropriate area to look for correlations. Aromatic content has been the traditionally accepted chemical property for controlling soot formation. The correlations of total aromatics by HPLC and total aromatic ring carbon by U.V. spectroscopy are shown in Figures 7-10. It can be seen from the poor correlation coefficients, r^2, given in the figures, that neither total aromatics nor total aromatic ring carbon can account for the observed differences in the mean indices of radiation and smoke from the six test fuels.

The greater soot forming tendency of Fuels 3 and 4 containing high concentrations of dicyclic aromatics and Fuel 6 with tetralin suggests that the high concentrations of polycyclic aromatics in these fuels is the cause of the increased soot formation. Fuels 1, 2, and 5 contain very low concentrations of polycyclic aromatics and their indices of

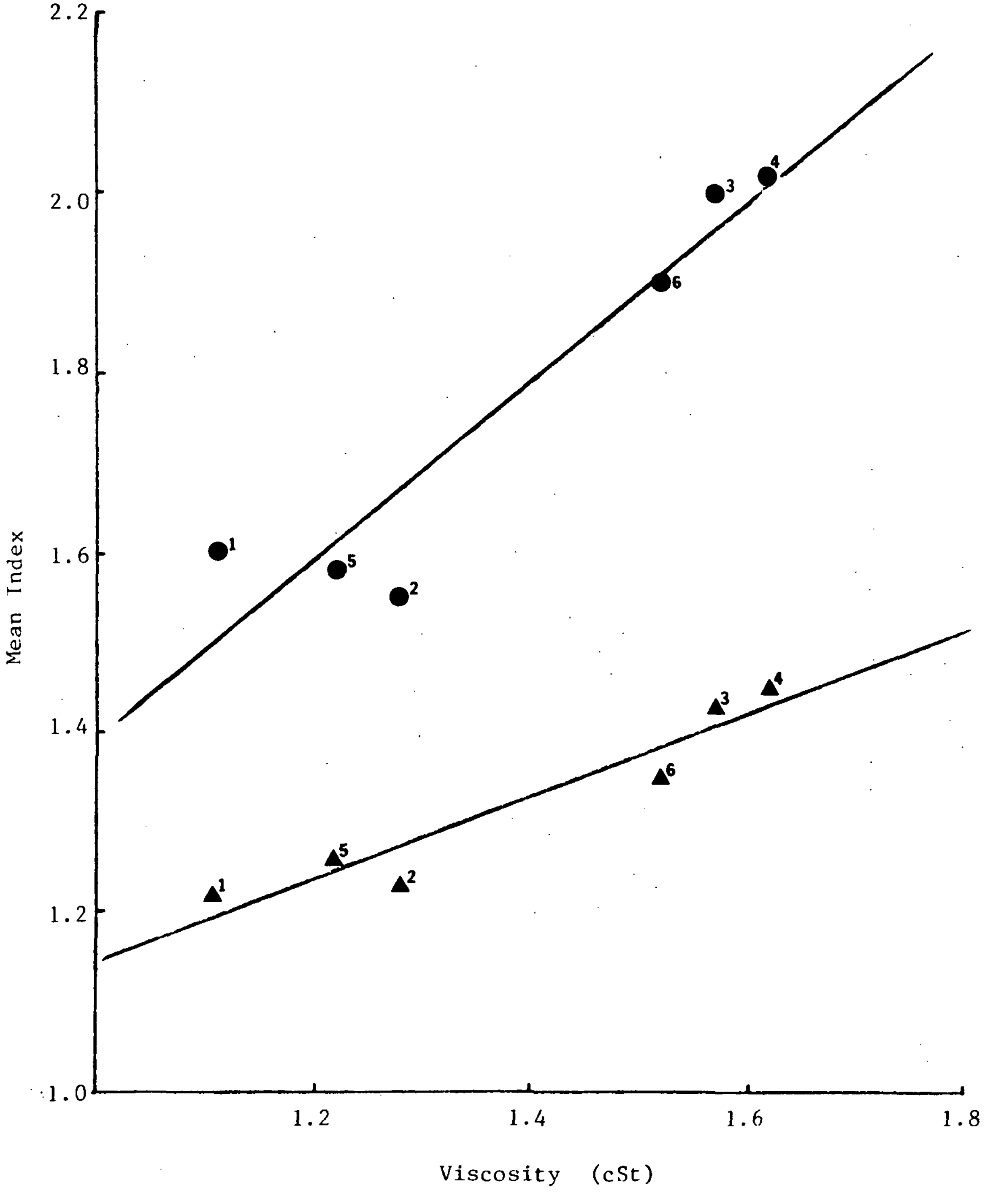


FIGURE 5. EFFECT OF VISCOSITY ON THE SMOKE AND RADIATION INDICES

▲ = Radiation Index ● = Smoke Index

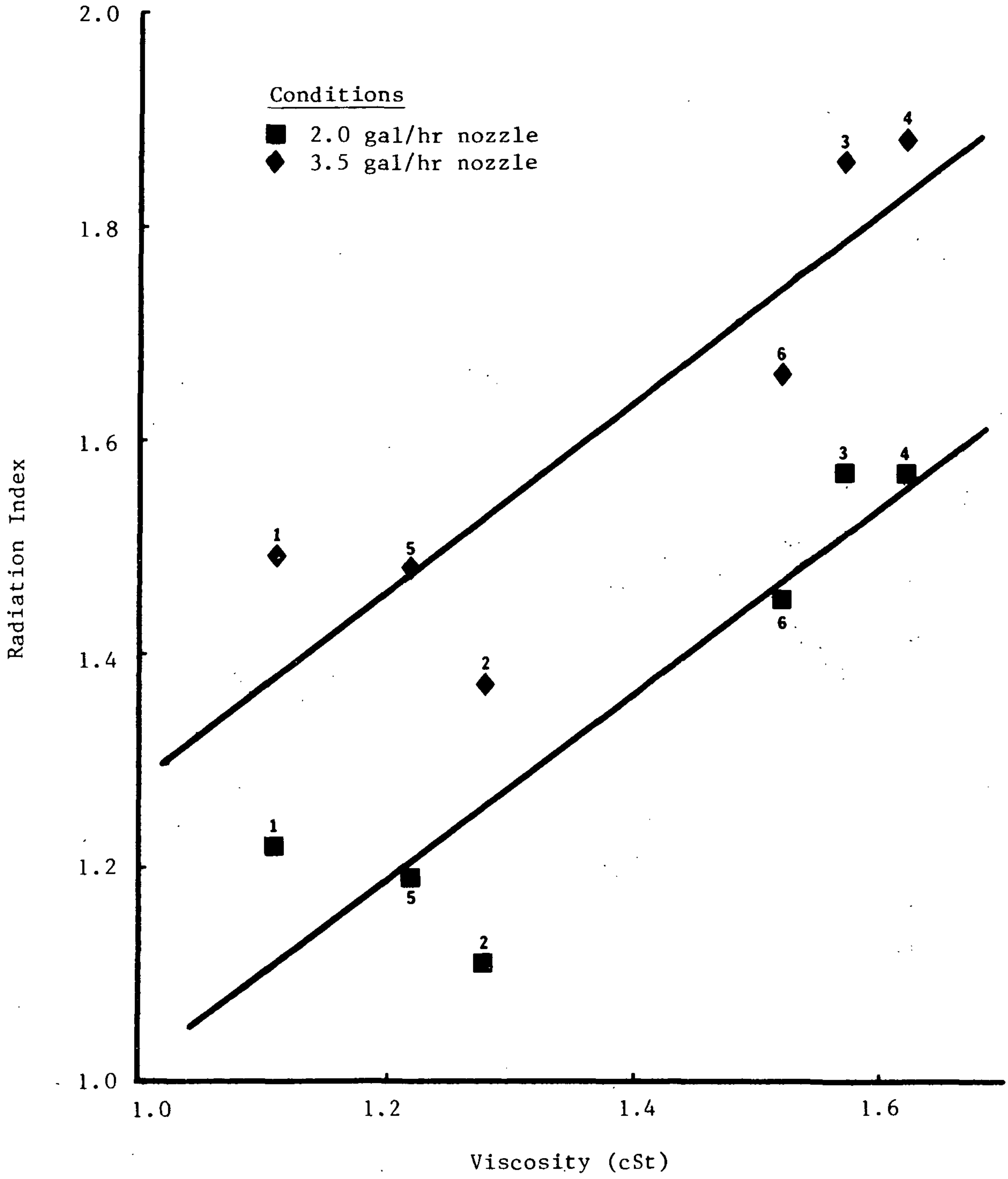


FIGURE 6. EFFECT OF DIFFERENT DEGREES OF ATOMIZATION ON RADIATION INDEX

FIGURE 7. CORRELATION OF MEAN FLAME RADIATION INDEX WITH TOTAL AROMATIC CONTENT

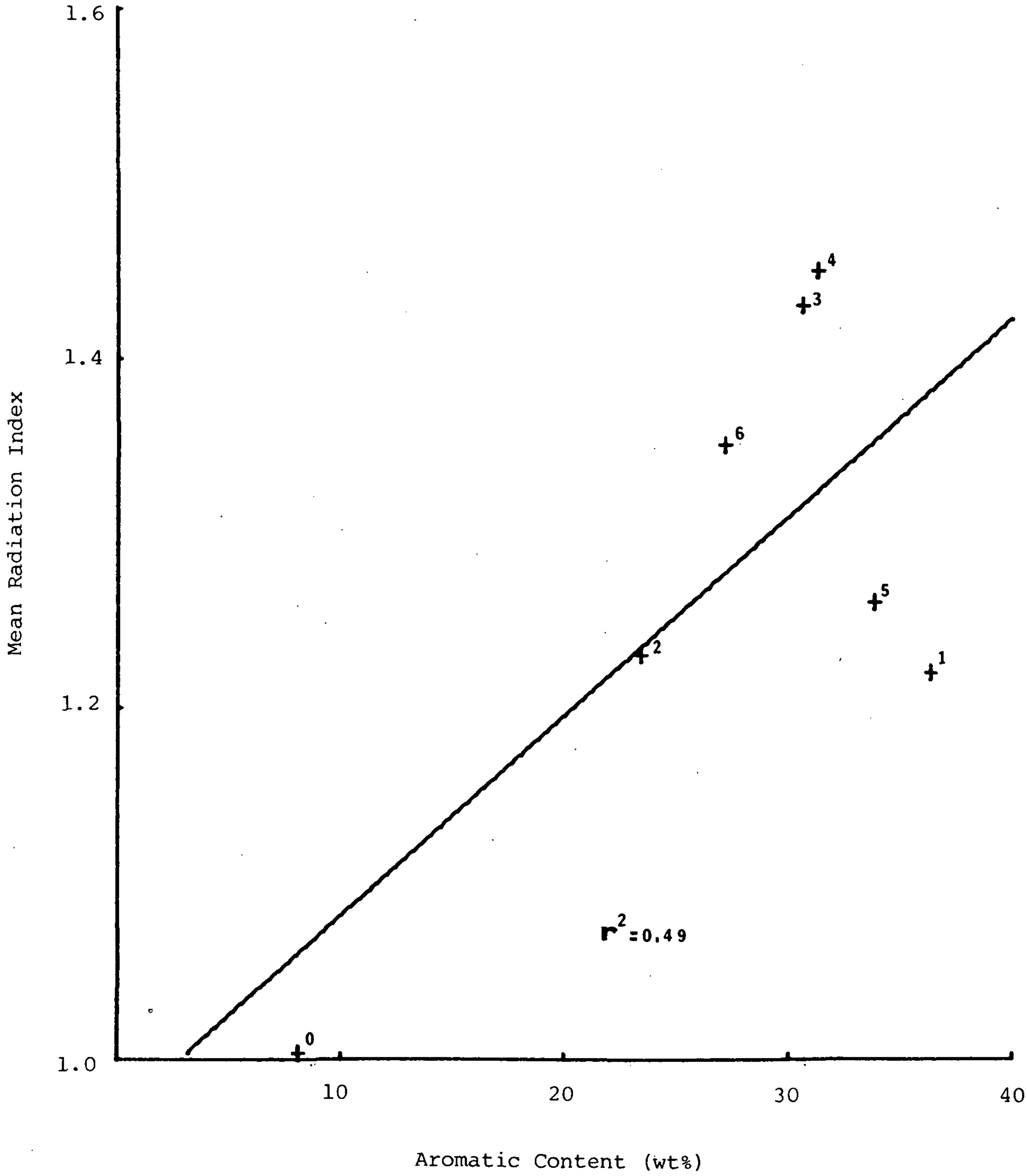


FIGURE 8. CORRELATION OF MEAN EXHAUST SMOKE INDEX WITH TOTAL AROMATIC CONTENT

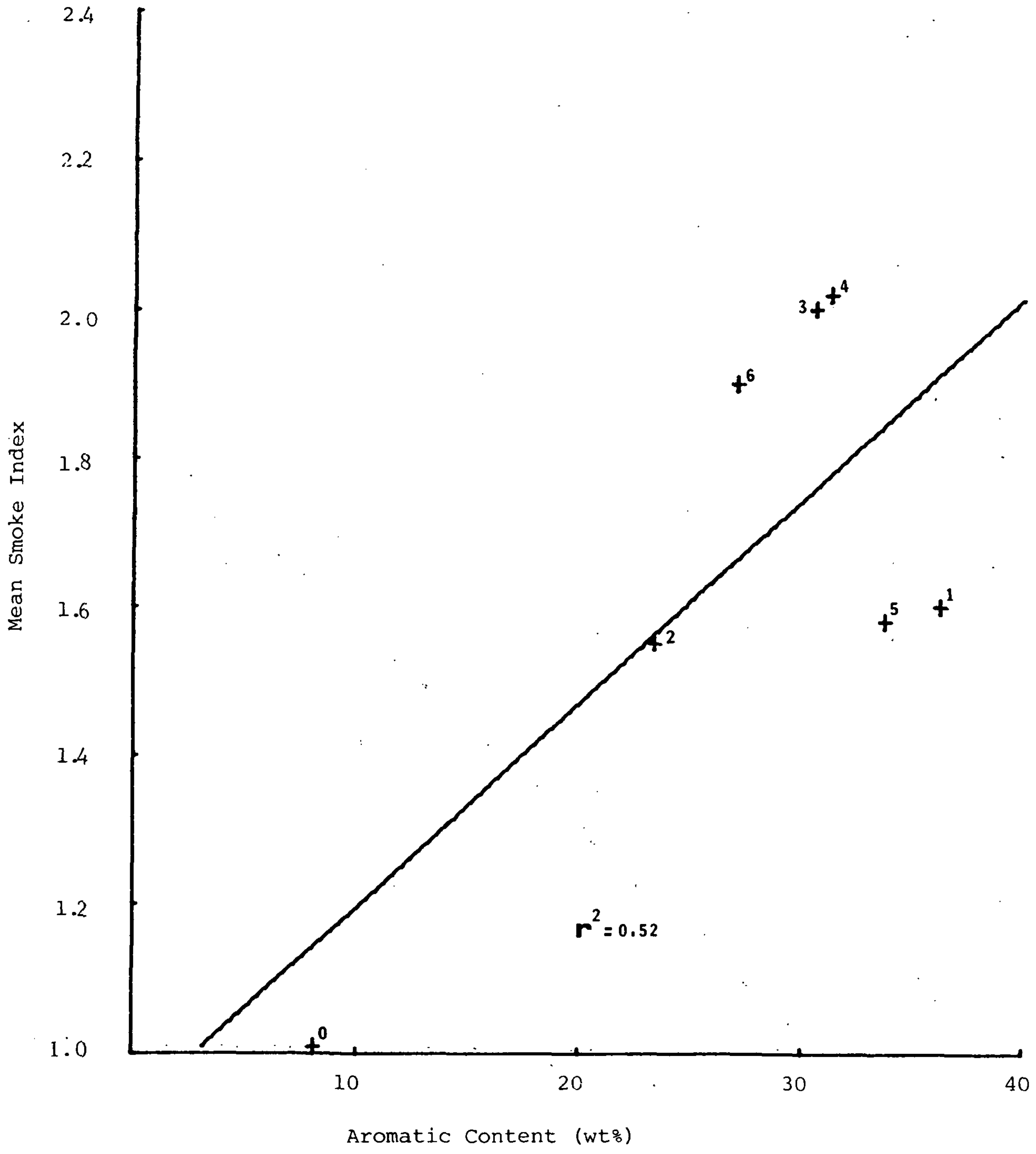


FIGURE 9. CORRELATION OF MEAN FLAME RADIATION INDEX WITH TOTAL AROMATIC RING CARBON

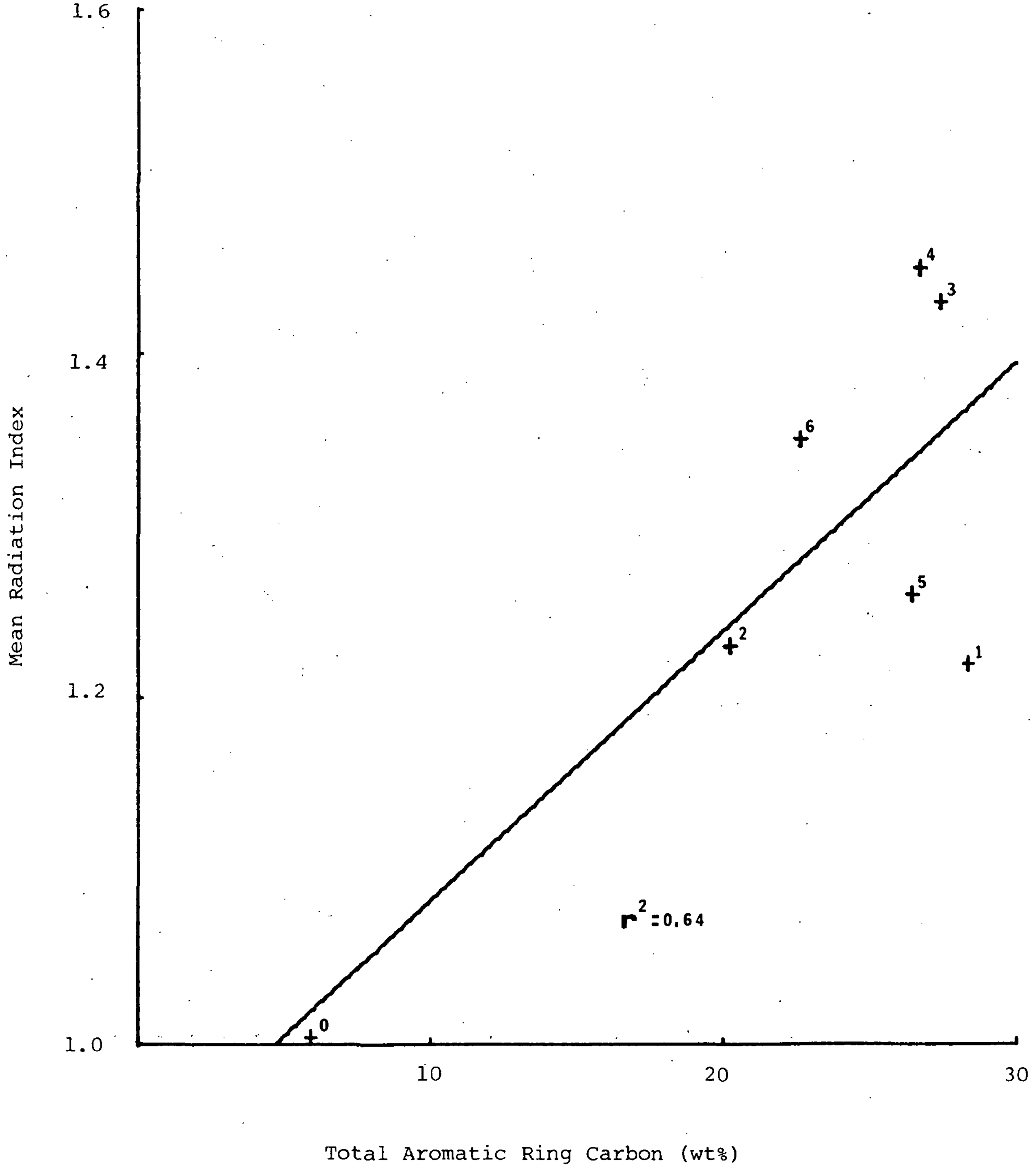
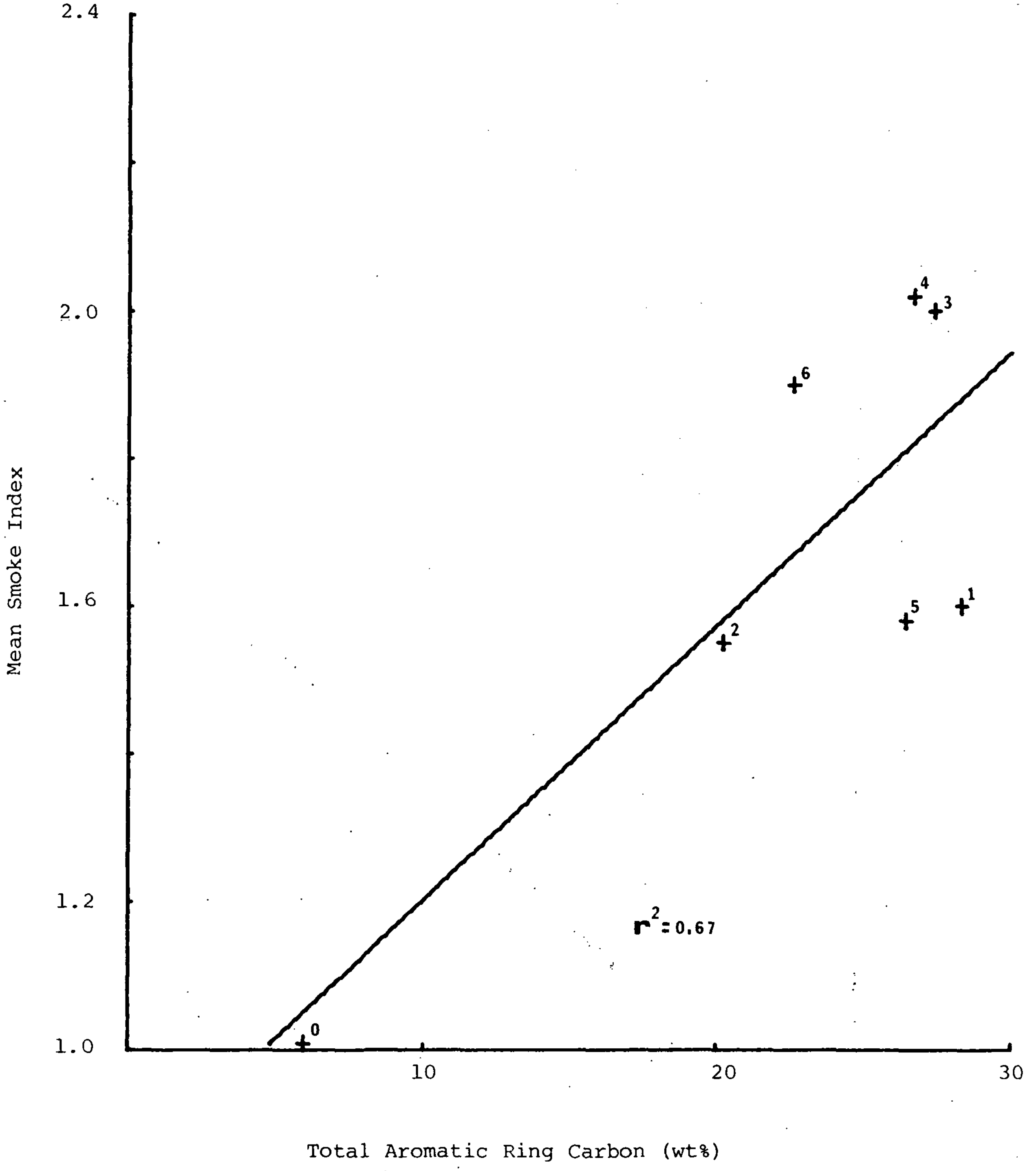


FIGURE 10. CORRELATION OF MEAN EXHAUST SMOKE INDEX WITH TOTAL AROMATIC RING CARBON



radiation and smoke are correspondingly lower. Except for the decalin in Fuel 2, the compositions of Fuels 0, 1, 2, and 5 are typical of petroleum based middle distillates. The fact that Fuel 2 behaved in essentially the same way as the Fuels 1 and 5 although having lower aromatics indicates that high concentrations of decalin (Naphthenes) also have a tendency to form soot.

Figures 11 and 12 show correlations of the mean radiation index and smoke index with hydrogen-content. These correlations are based on a least squares fit of Fuels 0, 1, 2, and 5 because these fuels are expected to conform to a simple hydrogen-content correlation; they consist mainly of saturates and single ring aromatics which is typical of the petroleum-derived fuels that have been previously found to correlate well with hydrogen-content in this combustor and by others as mentioned earlier (11-14). ΔR and ΔS are the deviations of the data points from the hydrogen content correlation. Figures 13 and 14 show a least squares fit of the ΔR and ΔS values, excluding those for Fuels 6 and 7, plotted against the polycyclic-aromatic-ring-carbon contained in the fuels.

Fuels 6 and 7 containing large amounts of tetralin deviate significantly from the correlations when their polycyclic-aromatic-ring-carbon contents listed in Table 3 are used.

If the tetralin in these fuels is treated as if it were naphthalene, the polycyclic-aromatic-ring-carbon contents of Fuels 6 and 7 increase from 2.10 to 23.06 and 10.95 to 20.04 respectively, and the data points 6' and 7' are obtained. The results suggest that tetralin exhibits some dicylic aromatic behavior. Based on the results for Fuel 6 where the deviations ΔR and ΔS are most accurate, i.e., they were not extrapolated from the hydrogen content correlation as was the case for Fuel 7, the dicyclic character of tetralin appears to be about 60% that of naphthalene (see 6" in Figures 13 and 14), i.e., the ratio of the six aromatic-ring-carbon atoms in tetralin to the ten in naphthalene.

The apparent dicyclic aromatic behavior of tetralin indicates that the soot forming intermediates derived from it are similar to those derived from naphthalenes. Benjamin et. al. (17) have shown that naphthalene is a major product of the pyrolysis of tetralin at 873K. In the precombustion reactions it is possible that the first step in the oxidative pyrolysis of tetralin is dehydrogenation of the saturated ring.

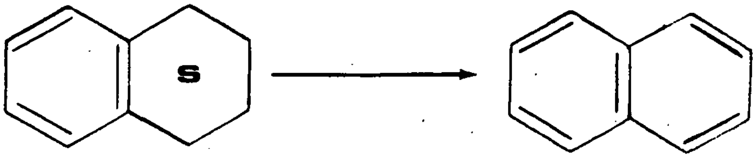


FIGURE 11. CORRELATION OF MEAN RADIATION INDEX WITH HYDROGEN CONTENT

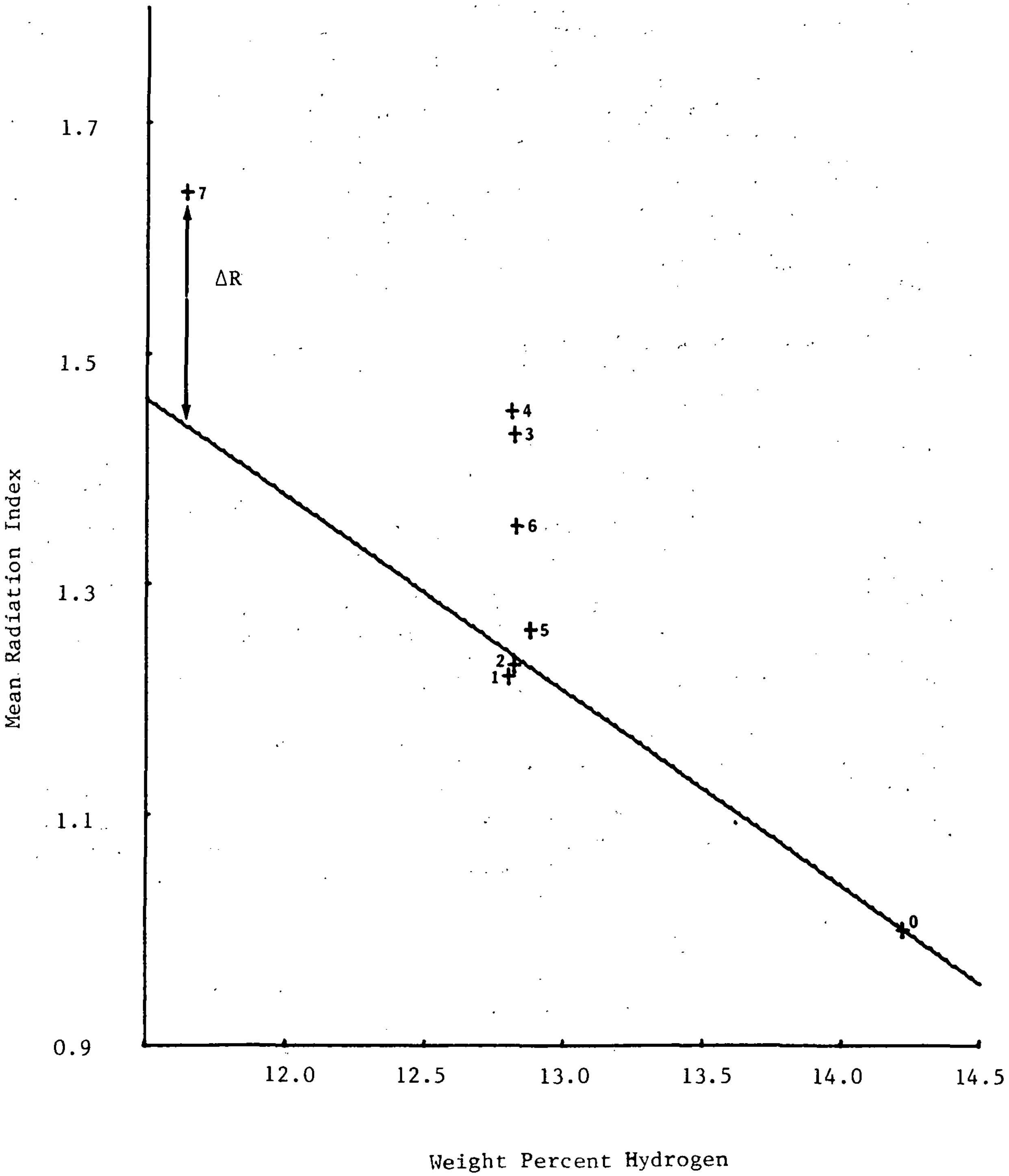
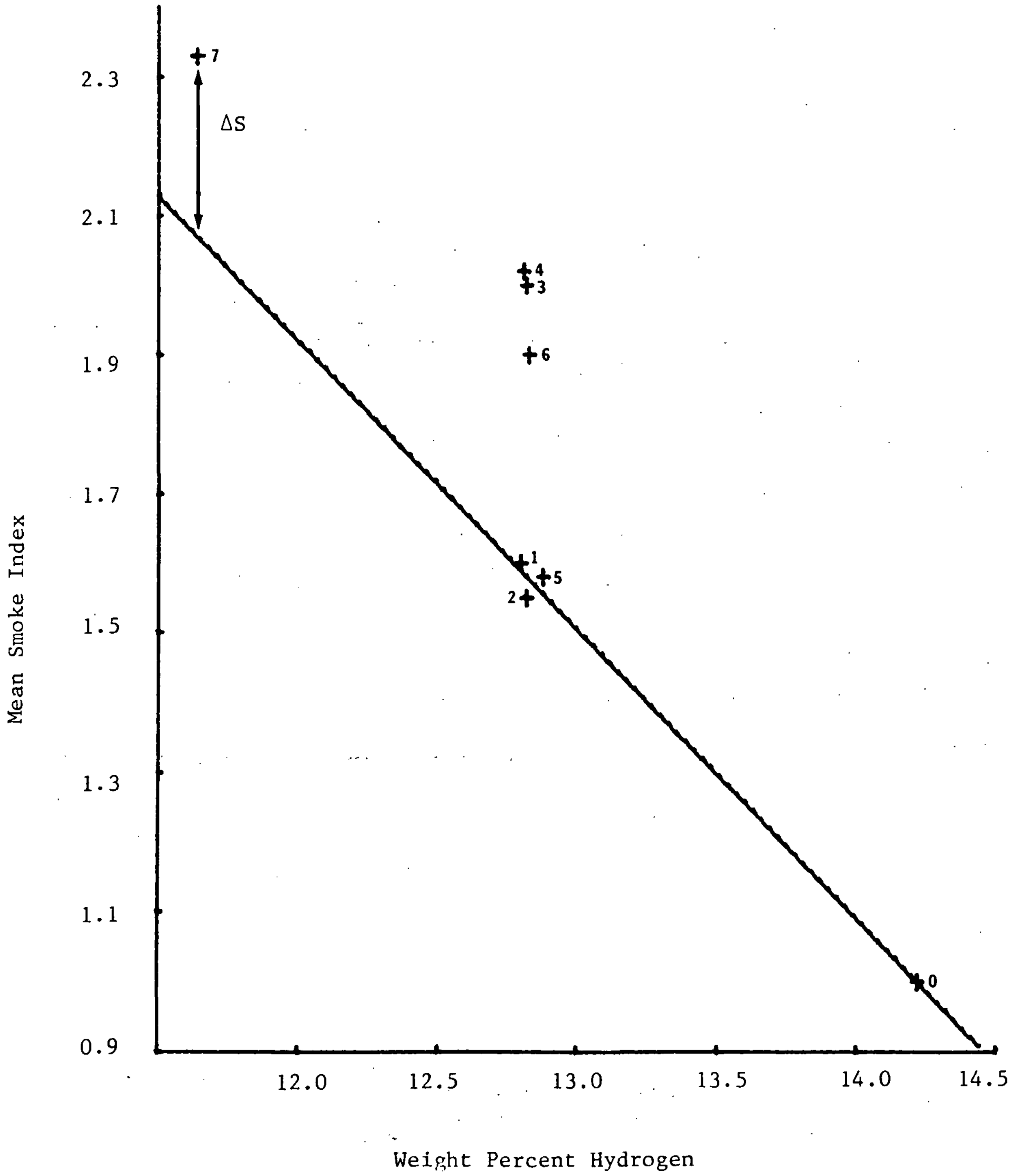


FIGURE 12. CORRELATION OF MEAN SMOKE INDEX WITH HYDROGEN CONTENT



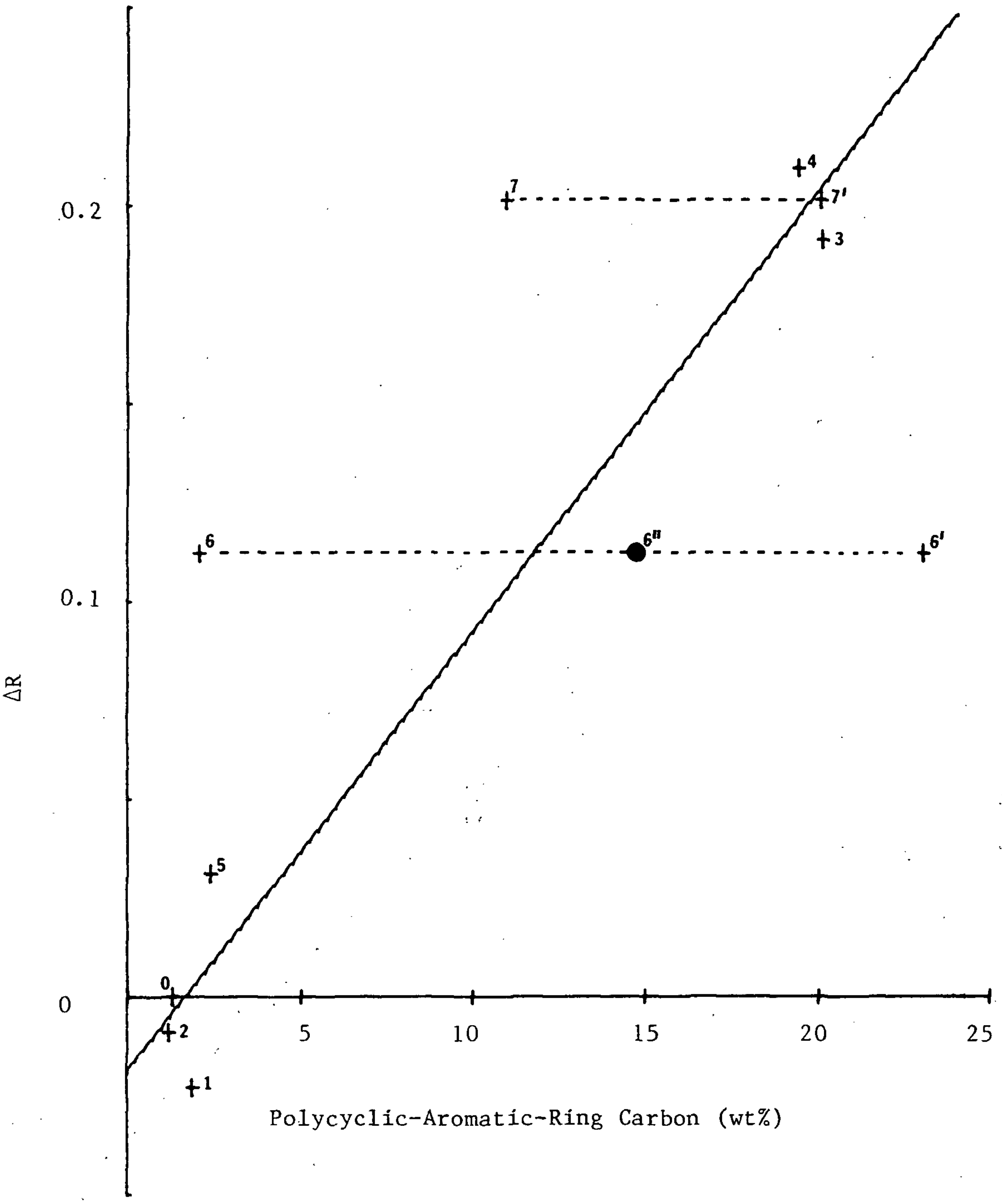


FIGURE 13. CORRELATION OF THE DEVIATION (ΔR) IN RADIATION-INDEX FROM HYDROGEN-CONTENT-CORRELATION WITH POLYCYCLIC-AROMATIC-RING-CARBON

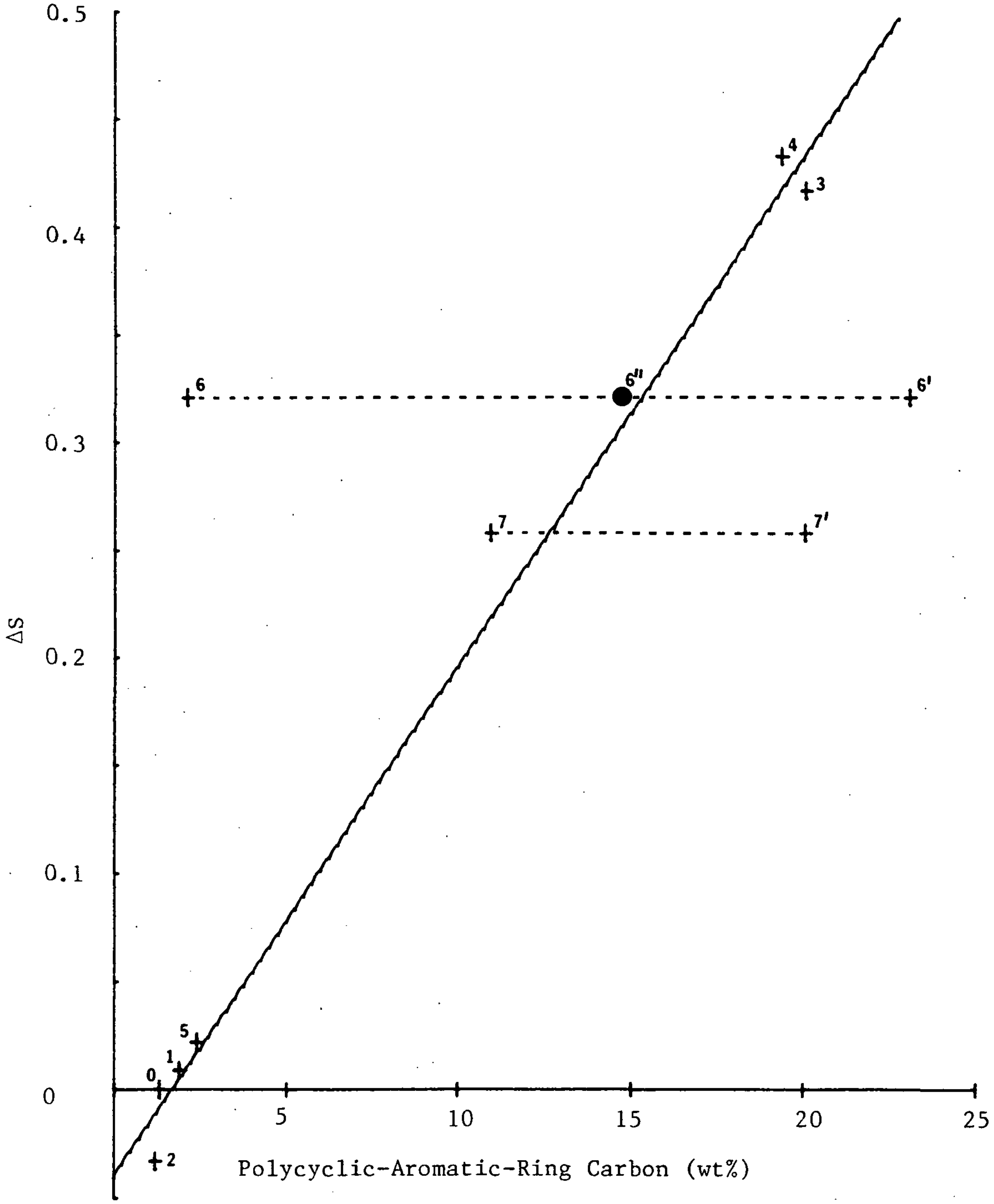


FIGURE 14. CORRELATION OF THE DEVIATION (ΔS) IN SMOKE-INDEX FROM HYDROGEN-CONTENT-CORRELATION WITH POLYCYCLIC-AROMATIC-RING-CARBON

Fuel Sensitivity to Operating Conditions

The results show that fuels containing high concentrations of polycyclic aromatics and tetralin exhibit significantly greater soot formation than would be expected from a hydrogen content correlation for fuels containing at most only small amounts of polycyclic aromatics. Since Fuels 1, 2, and 5 have relatively small amounts of polycyclic aromatics and closely follow the hydrogen correlation, and Fuels 3, 4, and 6 deviate significantly, the sensitivity of the polycyclic contribution to combustor conditions can be shown by comparing the R and S values of Fuels 3, 4, and 6 with those of 1, 2, and 5. Thus, a fuel sensitivity may be defined as the differences between the sums of the R and S values of Fuels 3, 4, and 6 and Fuels 1, 2, and 5, i.e., the fuel sensitivities would be (R3+R4+R6-R1-R2-R5) and (S3+S4+S6-S1-S2-S5).

The effects of operating parameters on the fuel sensitivity with respect to radiation are shown in Figures 15-17. The results show that fuel sensitivity is not affected by burner inlet temperature, but it is reduced significantly by increased burner inlet pressure and fuel/air ratio. Similar fuel sensitivities to smoke index are shown in Figures 18 and 19. A figure illustrating the effect of burner inlet temperature on the fuel sensitivity to smoke is not shown because of insufficient data. Note, exhaust smoke concentrations decrease rapidly as burner inlet temperature increases. When the smoke numbers are small ($<$ 10), there is considerable scatter in the data so that it is difficult to find data that will show the dependence on burner inlet temperature.

DISCUSSION

The results show that fuels containing high concentrations of polycyclic aromatics form more soot than would be anticipated on the basis of a hydrogen content correlation for typical petroleum base fuels. Partially hydrogenated polycyclic aromatics such as tetralin were also found to form higher than expected amounts of soot. However, if the polycyclic ring is completely saturated as in the case of decalin, the fuel behaves much like a typical petroleum based fuel and hydrogen content is adequate. This will be an important point to consider in the refining of syncrudes which are rich in polycyclic aromatics and require substantial hydrotreating.

In an earlier study with the Phillips 2 inch combustor (12), it was found that the flame radiation from oil shale and tar-sand based syncrudes correlated with hydrogen content in the same manner as petroleum based fuels; however, the radiation from a coal-derived fuel averaged about 8 percent higher than the correlation. Coal derived syncrudes are particularly rich in polycyclic aromatics so that it is very possible that the coal derived fuel contained a relatively high concentration of partially hydrogenated dicyclic aromatic molecules. This is further supported by the recent work of Jackson and Blazowski (11) in which several fuels of different hydrogen content and composition were tested in a T-56 combustor. In general they found, based on liner temperature, that hydrogen content was an excellent correlating parameter for the test fuels. However, particular fuel groups with the same hydrogen content indicated that fuels containing high concentrations of tetralin

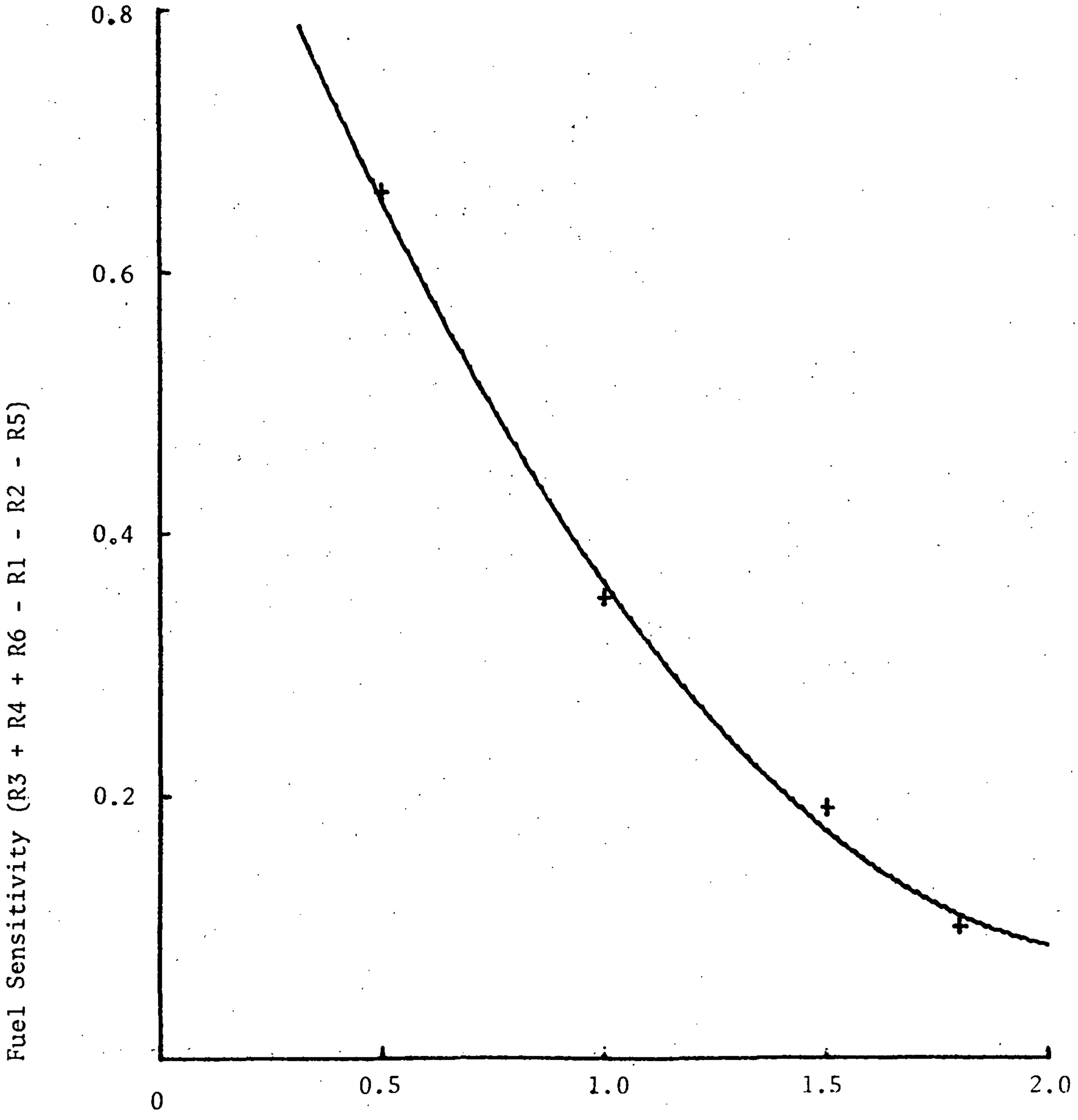


FIGURE 15. Effect of Burner Inlet Pressure on Fuel Sensitivity
T = 644K; F/A = 0.011; V = 61 m/sec.

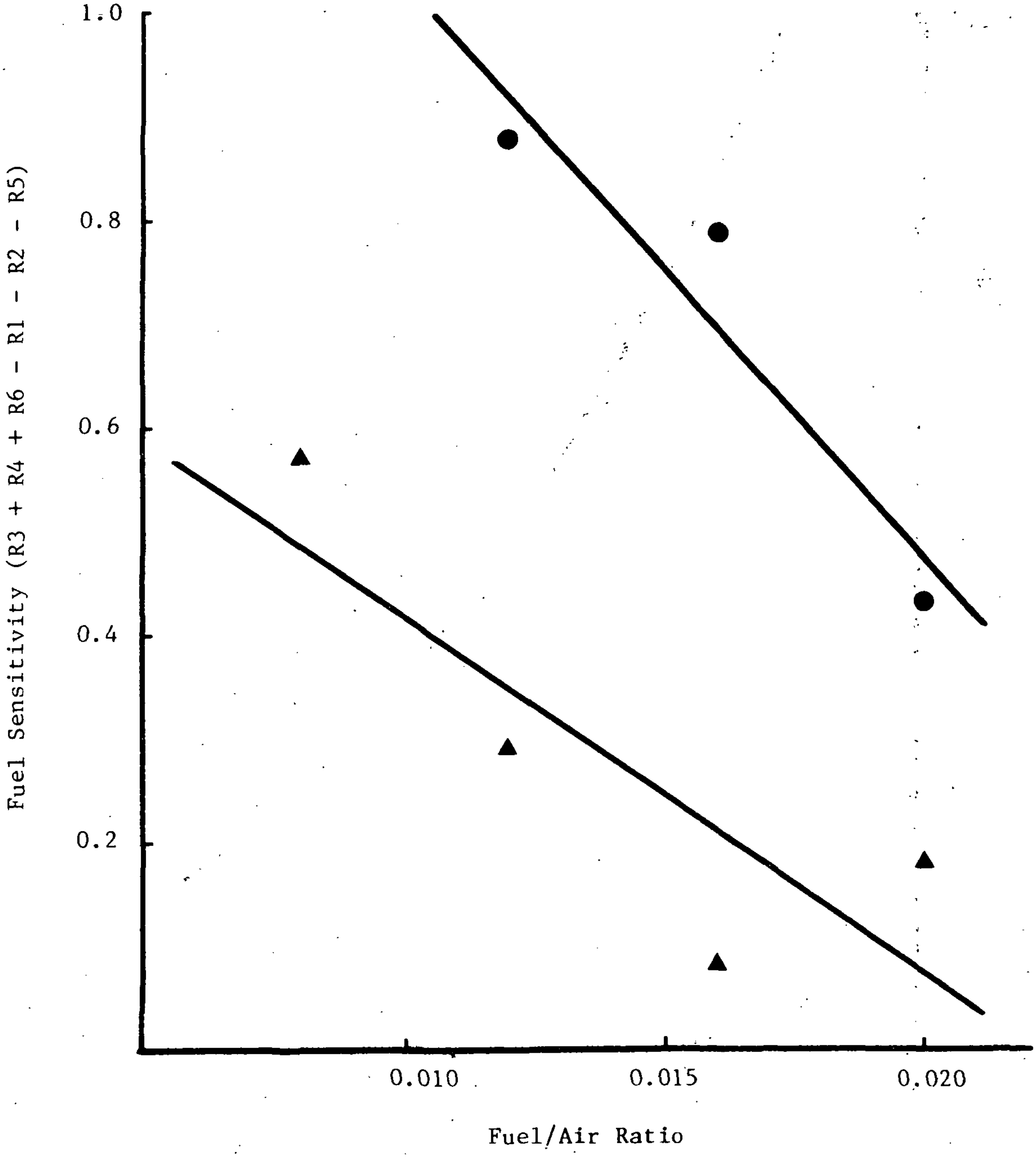


FIGURE 16. EFFECT OF FUEL/AIR RATIO ON FUEL SENSITIVITY
●-P = 0.5 MPa, T = 644K, V = 61 m/sec.;
▲-P = 1 MPa, T = 644K, V = 61 m/sec.

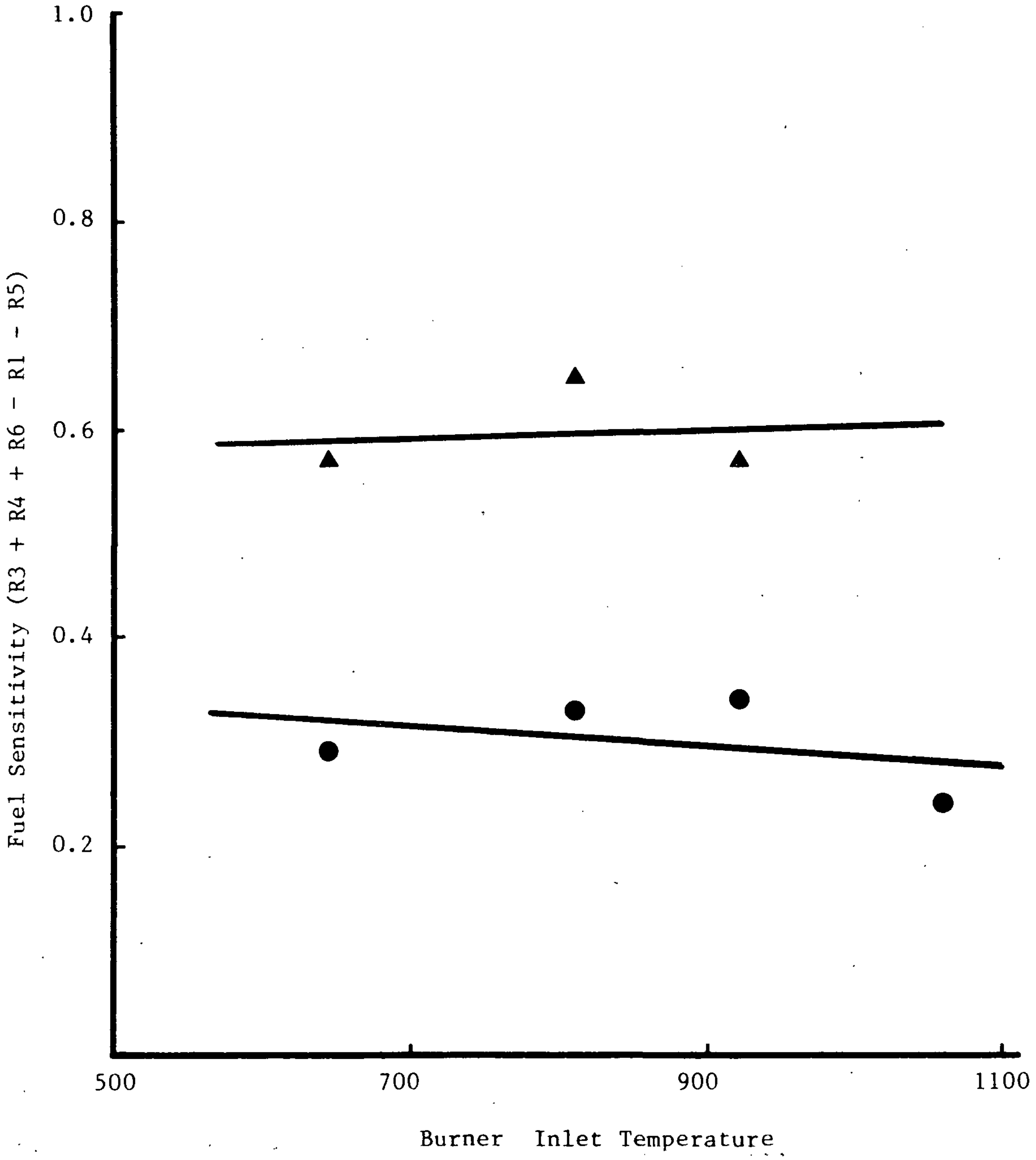


FIGURE 17. EFFECT OF BURNER INLET TEMPERATURE ON FUEL SENSITIVITY
▲-P = 1 MPa, F/A = 0.008, V = 61 m/sec;
●-P = 1 MPa, F/A = 0.012, V = 61 m/sec.

FIGURE 18. EFFECT OF BURNER INLET PRESSURE ON THE FUEL SENSITIVITY TO EXHAUST SMOKE: BIT = 644K, V = 61 m/sec and F/A = 0.016

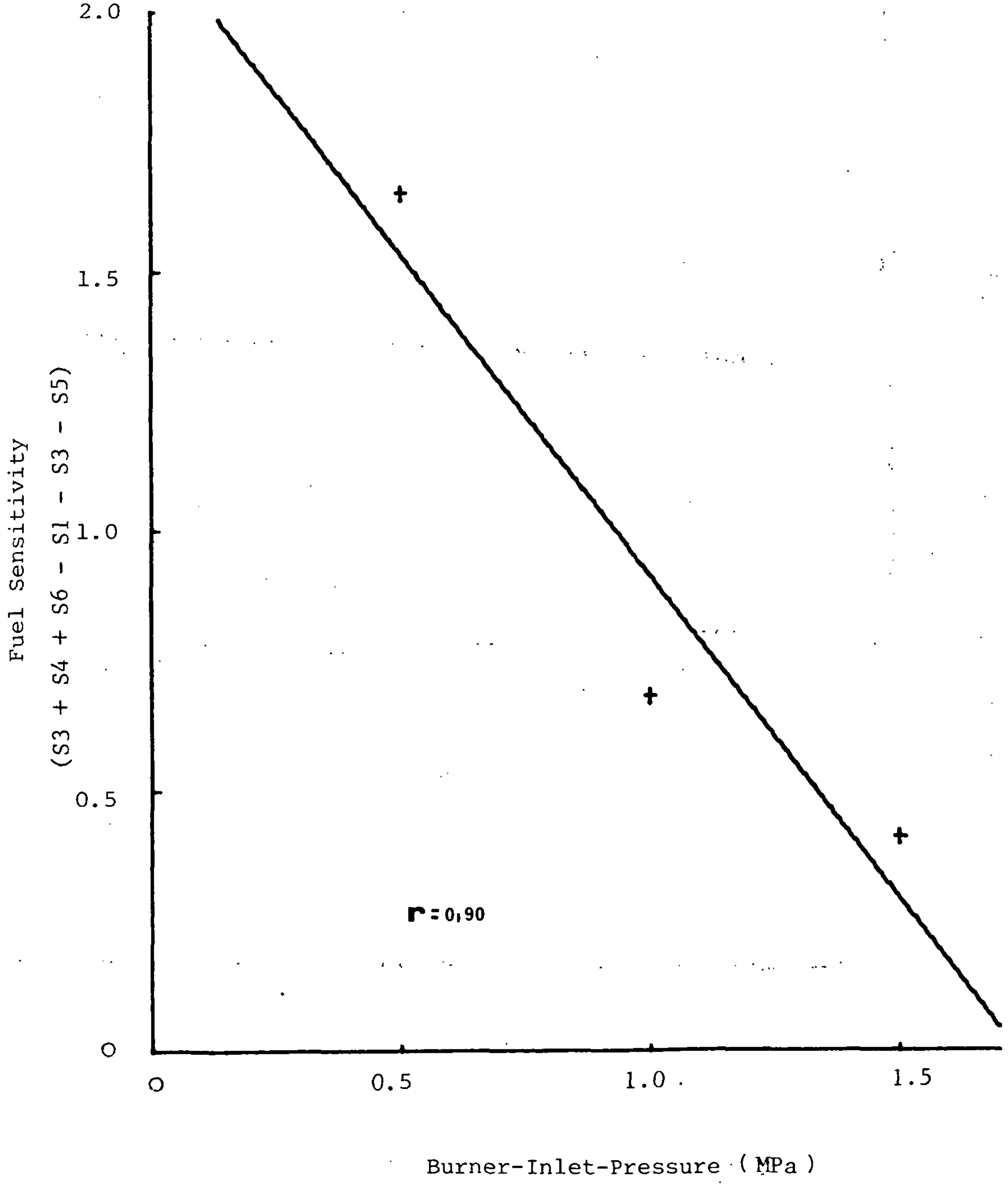
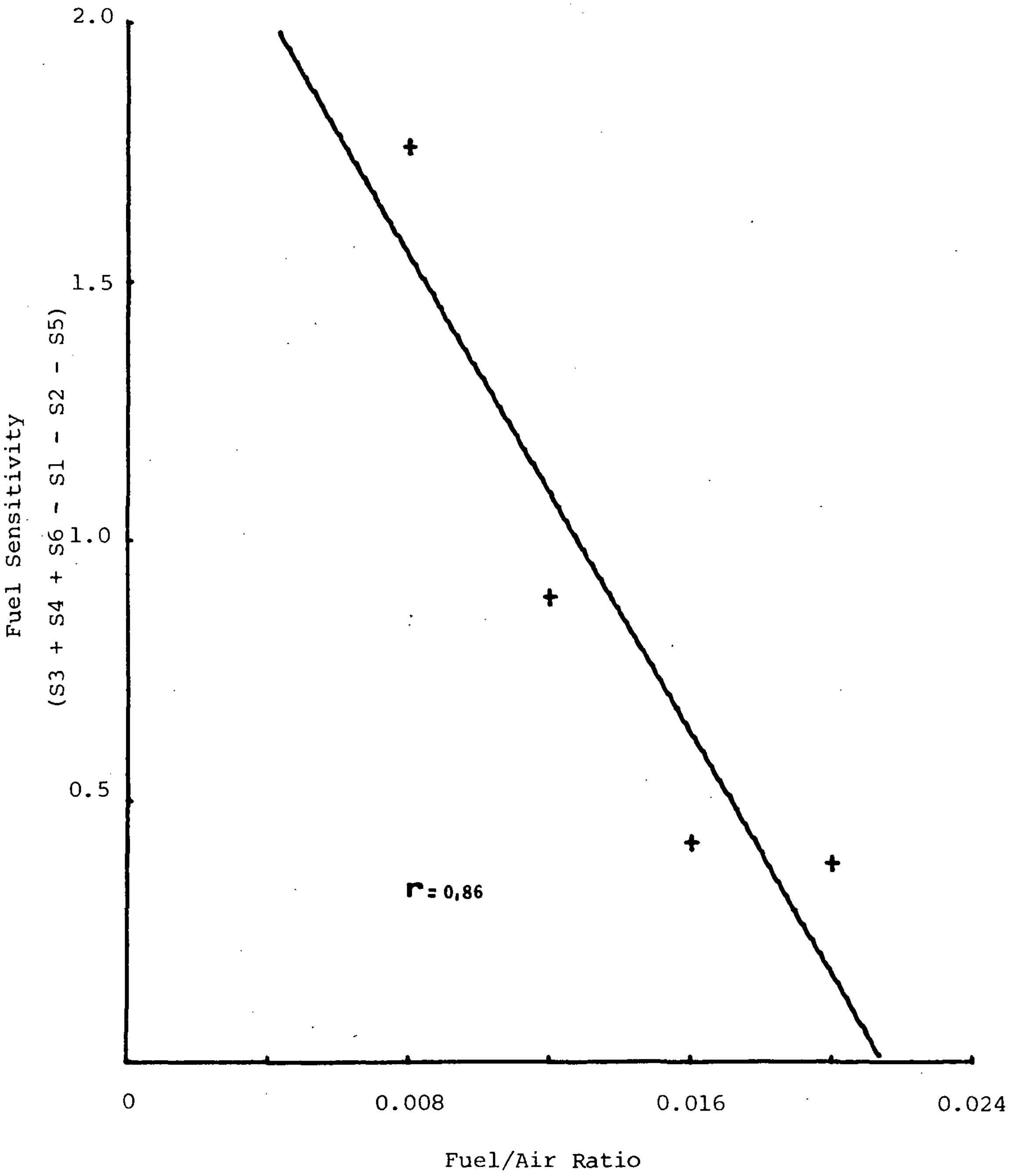


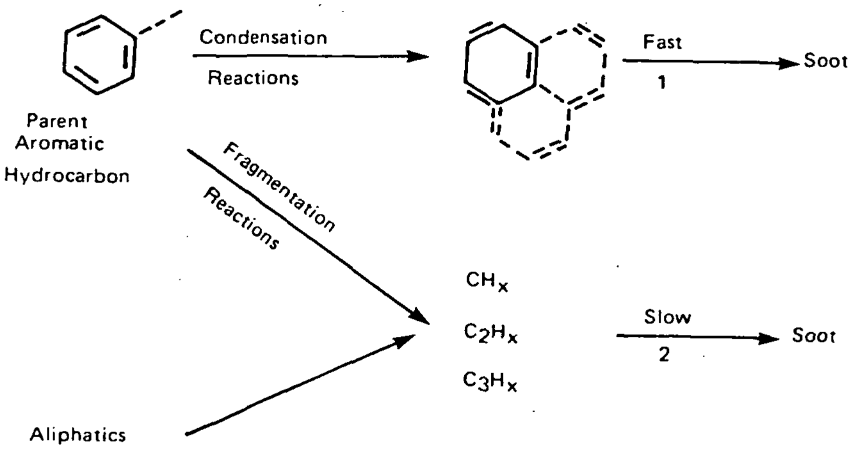
FIGURE 19. EFFECT OF FUEL/AIR RATIO ON THE FUEL SENSITIVITY TO EXHAUST SMOKE: BIP = 1.5 MPa, BIT = 644K and V = 61 m/sec



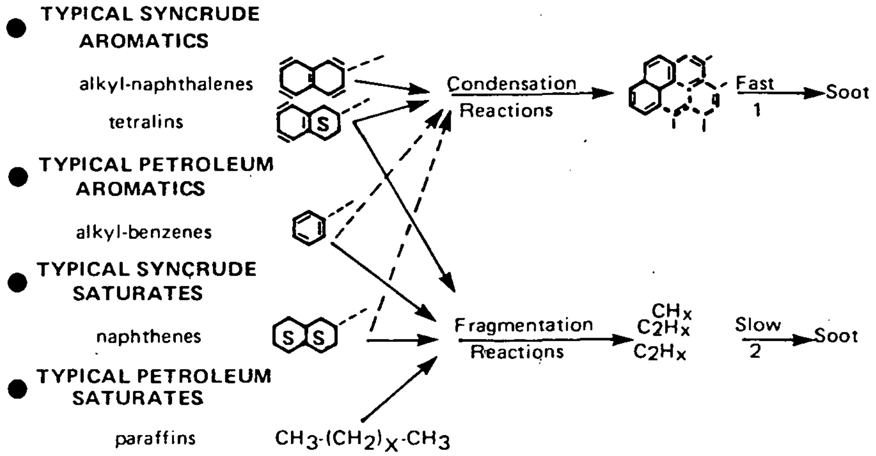
exhibited higher than average liner temperature. It is interesting to note that their results also indicated that fuels containing equal amounts of both monocyclic and dicyclic aromatics did not appear to form soot more readily than fuels prepared with monocyclic aromatics exclusively. Similar results were obtained in studies (6,12) with the Phillips 2-inch combustor in which two fuels of essentially the same hydrogen content were prepared; the weight percent monocyclic and dicyclic ring carbon contents of one fuel were 10.5 and 4.9 and the others were 7.7 and 7.8, respectively. Both fuels gave the same flame radiation and exhaust smoke.

In view of this and the results of the present work, it would appear that polycylic aromatics tend to be more effective in forming soot only when they are in very high concentrations, in this case, in the range of 20 percent. The linear correlations of ΔR and ΔS with polycyclic aromatic ring carbon shown in Figures 13 and 14 may actually show significant curvature.

While several specific mechanisms have been proposed for soot formation in flames, there are two general theories: (1) soot forms by the polymerization of dehydrogenated fuel molecules that have not lost their original structure through pyrolysis, and (2) soot forms from the pyrolysis products of fuel molecules. The recent work of Graham et. al. (10) suggests that both the above mechanisms play a role in the formation of soot. This is shown more clearly below where it is seen that aromatics have the choice of undergoing condensation with other carbonaceous fragments or decomposing into lower molecular weight species.



The dehydrogenation and fragmentation of the aliphatics adds to the low molecular weight species that eventually recombine into soot. This picture is adequate when discussing the soot formation from the combustion of petroleum distillate fuels in turbine combustors because the chemical constituents are almost entirely paraffins and single-ring aromatics. The results of this study suggest that the picture will be more complicated with hydro-treated high-aromatic fuels containing single- and double-ring aromatics, saturated and partially-saturated ring compounds such as decalin and tetralin. Since naphthalenes produced more soot than the hydrogen correlation, they probably undergo primarily condensation reactions; whereas decalin, and single-ring aromatics, are correlated by hydrogen content and therefore undergo primarily fragmentation reactions like paraffins. Since tetralin appears to correlate as though it were naphthalene, the picture might now look more like the following:



The effects of pressure and fuel/air ratio on the "naphthalene contribution" to soot that was observed in this study may be explained by the effects that pressure and soot-precursor concentration could have on the relative rates of soot production from aromatic ring structures and low molecular weight fragmentation products. A detailed kinetic mechanism would be required to explain the reduction in fuel sensitivity with fuel/air ratio. It would appear from the above scheme that the soot formed via fragmentation products in step 2 is strongly dependent on free radical species that are not very important in step 1 where aromatic ring structures serve as initial growth sites. While the effect of fuel/air ratio will remain unclear until a more comprehensive mechanism is derived for soot formation in flames, the effect of pressure on fuel sensitivity may be explained by a more generalized kinetic theory.

If soot is formed primarily from recombination reactions as opposed to displacement reactions, certain reaction rates could be very pressure dependent. When low molecular weight species such as atoms recombine, a small amount of kinetic energy must be removed in the collision or the atoms will simply dissociate. When small molecular fragments recombine, a stabilizing collision by a third body (atom or molecule) is required, but if at least one relatively high molecular weight molecule is involved in the combination the third body is not required because the excess energy can be temporarily stored in the many vibrational modes of the newly formed molecule. Thus, higher pressure would increase the rate of soot formation from the low molecular weight fragmentation products, but it would not affect the reactions involving high molecular weight ring structures. If step 2 in the reaction scheme given above is greatly enhanced by pressure the direct growth of the polyring structure via step 1 would become much less important. Recent work by Friswell (14) on the turbine combustion of several fuels of different hydrogen content shows that the sensitivity of hydrogen content to exhaust smoke is also reduced by increased pressure. In essence, he proposes a similar mechanism, i.e., higher pressures increase the rate of soot formation from aliphatic compounds relative to aromatic structures.

It is well known that soot formation rates are increased as pressure is raised, but the reason for this is highly speculative. In a non-turbulent system increased pressure reduces the rate of diffusion and could conceivably increase soot formation by decreasing the rate of mixing. However, the rate of mixing in a turbulent system is dominated by eddy diffusion which is independent of molecular weight and pressure. While this might explain why soot formation is found to be independent of end point as long as the soot forming reactions occur in the gas phase, it does not explain the pressure dependence of soot formation. The theory previously discussed that certain rate controlling reaction steps in the soot formation process are pressure dependent is more consistent with the results of this study.

CONCLUSIONS

- While the results do not contend the importance of the hydrogen content correlations, there is strong evidence that molecular structure can play a significant role in soot formation.

- Fuels with high concentrations of polycyclic aromatics formed more soot than would be expected from a hydrogen content correlation; a 20% naphthalene content can be expected to result in about a 20% increase in flame radiation and a 30% increase in smoke number over a simple hydrogen correlation. This is equivalent to a reduction in fuel hydrogen content of about 1%.

- The soot forming tendency of partially-hydrogenated aromatics such as tetralin is intermediate between that of single ring and double ring aromatics.

- Fuels with naphthenic compounds such as decalin correlated with hydrogen content in the same way as petroleum base fuels.

- Increase in final boiling point did not affect soot formation.

- The added contribution of polycyclic aromatics to soot formation decreases as burner inlet pressure and fuel/air ratio are increased. The effect of burner inlet temperature appears to be negligible.

- The soot forming tendencies of fuels with small concentrations of naphthalenes and tetralin appear to follow a hydrogen correlation. Not enough information is available to determine a precise relationship between the increased radiation and the concentration of polycyclic ring compounds.

- Flame radiation and exhaust smoke were well correlated with the smoke point of the fuels despite the strong differences in molecular structure.

RECOMMENDATIONS

- It would be of benefit to test fuels 1 to 6 in a conventional type burner to be assured that the same effects of fuel molecular structure will be observed in practical combustors. The T-63 combustor would be ideal for this purpose because of its relatively low requirements for fuel and air.

- In this work, a linear correlation was assumed for the dependence of soot formation on polycyclic-aromatic-ring-carbon. The test fuels contained either very low or very high concentrations of polycyclic aromatics and tetralin. Future studies should include several test fuels containing varied concentrations of polycyclic aromatics and/or tetralin type compounds so that the concentration dependence can be determined. This could be important; for example, the effect of polycyclic aromatics may be relativly unimportant at low and intermediate concentrations but the effect could become much stronger as concentrations approach the 15 to 25 percent range.

- The effect of molecular structure, namely polycyclic aromatics, should be examined at several hydrogen contents. The effect of hydrogen content on the importance of polycyclic aromatics could be helpful in assigning fuel specifications to future synthetic fuels.

- A study should be undertaken to update the smoke point measurement method. In the present study it was found that the flame radiation and exhaust smoke were well correlated with the smoke point of the fuels despite the strong differences in molecular structure. This lends merit to the smoke point measurement because the test fuels were each blended with the same hydrogen content. The smoke point method is basically good because the measurement is made in a real flame. However, the quiescent nature of the flame is not realistic and the accuracy and resolution of the measurement should be improved. The method of detecting incandescent carbon in the flame also needs to be improved; a radiation or luminosity measurement would give greater sensitivity and accuracy.

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APPENDIX A

I Summary of Operating Conditions

II Summary of Test Conditions, Problems, and Changes

SUMMARY OF OPERATING CONDITIONS

Run	P(atm)	T(K)	Velocity (ft/sec)	Fuel/Air ratio	Ma (lbs/min)	Ms (lbs/min)	Mf (gal/hr)	P (psi)	Capacity Calc. Gal/hr	Nozzle Size gal/hr
1	5	533	100	0.008	0.45	0.216	1.55	106	1.50	1.5
2	5	533	100	0.012	0.45	0.324	2.33	133	2.02	2.0
3	5	533	100	0.016	0.45	0.432	3.11	157	2.48	2.5
4	5	533	100	0.020	0.45	0.540	3.88	178	2.91	3.0
5	5	533	100	0.024	0.45	0.648	4.66	197	3.32	3.5
6	5	533	200	0.008	0.901	0.432	3.11	157	2.48	2.5
7	5	533	200	0.012	0.901	0.648	4.66	197	3.32	3.5
8	5	533	200	0.016	0.901	0.865	6.23	231	4.10	4.0
9	5	533	200	0.020	0.901	1.08	7.78	262	4.81	5.0
10	5	533	200	0.024	0.901	1.30	9.36	291	5.48	5.5
11	5	644	100	0.008	0.373	0.179	1.29	100	1.29	1.25
12	5	644	100	0.012	0.373	0.268	1.93	120	1.76	1.75
13	5	644	100	0.016	0.373	0.358	2.58	141	2.17	2.0
14	5	644	100	0.020	0.373	0.448	3.23	160	2.55	2.5
15	5	644	100	0.024	0.373	0.537	3.87	177	2.90	3.0
16	5	644	200	0.008	0.746	0.358	2.58	141	2.17	2.0
17	5	644	200	0.012	0.746	0.537	3.87	177	2.90	3.0
18	5	644	200	0.016	0.746	0.716	5.15	208	3.57	3.50
19	5	644	200	0.020	0.746	0.895	6.44	236	4.19	4.0
20	5	644	200	0.024	0.746	1.07	7.70	261	4.77	5.0
21	10	644	200	0.008	1.49	0.716	5.15	208	3.57	3.5
22	10	644	200	0.012	1.49	1.07	7.70	261	4.77	5.0
23	10	644	200	0.016	1.49	1.43	10.30	307	5.88	6.0
24	10	644	200	0.020	1.49	1.79	12.89	348	6.91	7.0
25	10	644	200	0.024	1.49	2.15	15.48	385	7.89	8.0
26	15	644	200	0.008	2.24	1.08	7.78	262	4.81	5.0
27	15	644	200	0.012	2.24	1.61	11.59	328	6.40	6.5
28	15	644	200	0.016	2.24	2.15	15.48	385	7.89	8.0
29	15	644	200	0.020	2.24	2.69	19.37	437	9.27	9.5
30	15	644	200	0.024	2.24	3.22	23.2	483	10.55	10.5
31	10	811	200	0.008	1.18	0.566	4.07	275	2.45	2.5
32	10	811	200	0.012	1.18	0.85	6.12	229	4.04	4.0
33	10	811	200	0.016	1.18	1.13	8.14	269	4.96	5.0
34	10	811	200	0.020	1.18	1.42	10.22	305	5.85	6.0
35	15	811	200	0.008	1.78	0.854	6.15	230	4.06	4.0
36	15	811	200	0.012	1.78	1.28	9.22	288	5.43	5.50
37	15	811	200	0.016	1.78	1.71	12.31	339	6.7	7.0
38	15	811	200	0.020	1.78	2.14	15.4	384	7.86	8.00
39	10	922	200	0.008	1.04	0.50	3.6	170	2.76	3.0
40	10	922	200	0.012	1.04	0.75	5.4	214	3.69	3.5
41	10	922	200	0.016	1.04	1.00	7.2	251	4.54	4.5
42	15	922	200	0.008	1.56	0.75	5.4	214	3.69	3.5
43	15	922	200	0.012	1.56	1.12	8.06	267	4.93	5.0
44	15	922	200	0.016	1.56	1.50	10.8	315	6.09	6.0
45	10	1066	200	0.008	0.901	0.432	3.11	157	2.48	2.5
46	10	1066	200	0.012	0.901	0.65	4.65	197	3.31	3.5
47	15	1066	200	0.008	1.35	0.65	4.65	197	3.31	3.5
48	15	1066	200	0.012	1.35	0.97	6.9	247	4.39	4.5
49	18	644	200	0.011	2.14	1.54	11.1	328	6.52	6.5

SUMMARY OF TEST CONDITIONS, PROBLEMS AND CHANGES

Run	P(atm)	T(K)	Velocity (ft/sec)	Fuel/Air ratio	Case
1	5	533	100	0.008	1
2	5	533	100	0.012	2
3	5	533	100	0.016	2
4	5	533	100	0.020	2****
5	5	533	100	0.024	3
6	5	533	200	0.008	2
7	5	533	200	0.012	2
8	5	533	200	0.016	2
9	5	533	200	0.020	3
10	5	533	200	0.024	3
11	5	644	100	0.008	2
12	5	644	100	0.012	2
13	5	644	100	0.016	2
14	5	644	100	0.020	2
15	5	644	100	0.024	3
16	5	644	200	0.008	2
17	5	644	200	0.012	2
18	5	644	200	0.016	2
19	5	644	200	0.020	2*
20	5	644	200	0.024	3
21	10	644	200	0.008	1
22	10	644	200	0.012	1
23	10	644	200	0.016	1
24	10	644	200	0.020	1
25	10	644	200	0.024	3
26	15	644	200	0.008	1***
27	15	644	200	0.012	1
28	15	644	200	0.016	1
29	15	644	200	0.020	1***
30	15	644	200	0.024	3
31	10	811	200	0.008	1
32	10	811	200	0.012	1
33	10	811	200	0.016	2
34	10	811	200	0.020	3
35	15	811	200	0.008	1
36	15	811	200	0.012	1***
37	15	811	200	0.016	2
38	15	811	200	0.020	3
39	10	922	200	0.008	1
40	10	922	200	0.012	2
41	10	922	200	0.016	3
42	15	922	200	0.008	1
43	15	922	200	0.012	2
44	15	922	200	0.016	3
45	10	1066	200	0.008	2
46	10	1066	200	0.012	2
47	15	1066	200	0.008	2
48	15	1066	200	0.012	2
49	18	644	200	0.011	1

LEGEND

Case 1 No Change in Combustion design.
Case 2 Combustor design was changed.
Case 3 Exhaust temperatures were excessive.

SPECIFIC REMARKS

* Only radiation was measured.
** Radiation intensity was erratic at set at a condition
*** Radiation intensity was erratic and some coke was found in the liner on the cooling ring.
**** Severe coking and melting of the liner.

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APPENDIX B

I Summary of Flame Radiation Data

II Summary of Exhaust Smoke Data

III Summary of NO_x Emissions Index Data

SUMMARY OF FLAME RADIATION DATA

FLAME RADIATION (WATTS/M^2)

Run No.	Jet A	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Remarks
1	51.6	62.7	62.8	65.4	69.9	65.0	70.3	80.1	
2	56.0	58.1	74.6	62.2	81.7	80.0	94.4	77.2	
3	76.5	80.1	53.0	79.4	90.2	64.5	79.4	86.7	
4*	66.2		45.9	89.5	87.7	88.8	66.2		
6	21.1	21.9	25.2	31.7	33.6	22.5	29.4	41.1	
7	22.5	27.4	25.0	35.3	35.3	26.8	32.7	51.8	2.0 nozzle, modified burner
7	42.6	56.1	57.0	80.4	81.5	62.5	68.0	90.5	3.5 nozzle
7	50.5	75.4	69.0	93.7	94.9	74.8	84.0	117.1	3.5 nozzle, modified burner
7	23.0	29.3	30.7	43.2	42.8	32.6	37.0	47.5	5.0 nozzle, modified burner
8*	25.7	42.1	36.1	41.9	42.5	30.6	41.8		
8	45.5	66.7	68.6	91.5	78.5	76.3	74.6	111.3	
9	40.9	56.2	51.9	61.7	61.5	59.5	58.8	61.5	
11	60.0	66.9	73.5	88.7	91.2	73.7	79.5	108.3	
12	57.5	67.3	71.5	76.9	82.4	61.0	70.4	84.4	modified burner
12	81.6	87.0	99.5	111.3	118.1	98.4	103.8	123.3	
13	56.0	90.1	74.1	84.3	63.8	62.4	76.9		
13	53.2	63.4	86.6	117.8	40	59.8	62.8	67.7	modified burner
14	95.0	116.6	100.2	83.2	80.1	120.5	153.7	110.9	
16	35.7	52.5	40.5	78.9	88.2	38.0	78.5	96.4	
16	32.5	32.8	33.7	40.6	41.7	31.4	36.5	45.5	modified burner
17	58.0	71.9	78.4	105.2	96.3	86.0	93.5	107.0	
17	58.0	74.4	74.2	90.4	89.4	73.7	85.3	99.5	modified burner
18	60.1	74.3	70.3	91.3	94.5	74.7	88.0	114.7	
18	74.7	104.4	85.9	101.8	117.2	91.3	96.1	127.5	modified burner
19	50.0	74.7	77.0	93.9	88.3	74.6	65.1	110.9	
21	112.2	132.8	136.7	156.3	159.3	137.2	155.1	182.7	
22	96.7	121.8	113.5	128.7	128.1	118.8	125.8	145.1	5.0 nozzle
22	72.7	92.8	90.5	107.5	106.9	96.1	102.6	127.1	3.5 nozzle
22	85.9	106.0	105.0	117.3	118.6	107.3	114.3	130.8	7.0 nozzle
23	77.3	95.0	94.4	96.8	99.2	108.1	98.3	91.8	
24	65.4	84.4	84.1	89.3	89.7	87.1	88.4	95.8	
26	109.4	121.3	141.8	161.1	151.1	140.1	158.9	174.0	
27	50.9	70.6	65.7	69.2	64.1	57.4	58.5	61.3	6.5 nozzle
27	92.3	110.6	113.4	121.5	123.8	115.8	120.1	137.6	5.0 nozzle
28	100.5	117.0	114.4	120.9	125.3	118.8	124.2	139.5	
29	72.6	83.3	74.0	80.8	85.4	78.6	80.9	87.8	
31	133.5	121.6	155.0	181.6	188.5	156.4	183.2	213.4	
32	139.8	166.9	165.9	176.7	186.5	166.3	183.2	202.3	
33	95.9	117.5	116.6	127.8	127.5	120.4	125.4	140.4	
35	135.4	154.1	165.3	186.3	190.7	157.9	181.9	205.8	
36	184.9	218.4	216.8	219.2	217.9	218.4	214.6	227.8	
37	150.1	178.1	176.2	184.7	185.6	176.2	179.9	202.2	
39	111.0	125.3	127.3	147.9	148.3	124.7	143.9	151.1	
40	147.4	169.5	179.3	193.2	191.9	176.3	191.5	217.6	
42	110.4	83.1**	112.4	148.1	178.1	133.1	169.6	203.5	
43	114.8	128.2	133.3	142.0	145.5	136.7	145.7	161.7	
45	76.6	65.0	77.1	102.9	117.9	84.2	102.7	152.6	
46	151.6	164.0	175.0	185.4	189.1	179.9	151.2	204.2	
47	78.8	88.2	90.3	90.7	91.2	82.7	87.3	102.1	
48	87.4	66.7	82.6	106.3	112.4	96.1	101.1	146.7	
49	131.1	164.5	156.1	164.8	162.8	155.9	161.4	177.3	

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* only radiation

** fuel/air ratio was 0.0073 while others were 0.008 and above

SUMMARY OF EXHAUST SMOKE DATA

SMOKE NUMBER

Run No.	Jet A	1	2	3	4	5	6	7	Remarks
1	12.1	12.4	35.1	29.4	35.0	45.4	48.1	77.0	
2	21.9	26.5	49.2	32.0	30.1	41.5	44.0	74.2	
3	29.2	59.7	36.7	54.8	60.9	50.8	63.4	50.9	
6	9.8	2.3	1.65	3.2	4.0	3.3	8.4	11.5	
7	16.6	22.4	25.1	38.9	39.3	27.1	32.9	46.8	3.5 gal/hr nozzle
7	13.0	17.3	18.2	33.8	23.8	20.3	22.0	20.1	5.0 gal/hr nozzle
7	3.1	12.2	14.9	10.6	7.6	5.5	7.9	12.2	2.0 gal/hr nozzle
8	16.0	28.3	28.7	37.3	36.8	24.6	38.1		
8	26.1	35.8	33.1	46.4	46.7	34.0	37.6	58.6	repeat, modified burner
9	37.2	40.2	50.8	49.6	44.3	41.6	57.5		
11	2.7	12.0	10.6	3.7	3.9	2.8	5.6	57.9	
12	42.3	69.2	49.8	75.1	67.1	51.8	53.7	68.8	
13	7.0	10.8	14.7	17.8	17.6	12.9	22.6		
13	35.8	24.2	26.6	21.9	55.6	52.2	54.8	32.4	repeat
14	33.2	39.9	16.8	33.3	59.8	50.2	44.4	25.8	
16	11.5	16.3	10.78	21.2	25.0	19.9	22.7	26.4	
16	3.5	4.22	1.6	1.4	2.7	2.9	4.5	2.1	repeat, modified burner
17	6.4	15.1	19.0	24.5	28.7	14.1	25.8	21.6	
17	6.9	7.8	6.2	4.91	4.61	4.5	3.7	16.4	fuel/air ratio = 0.011
18	18.2	29.5	28.6	47.2	42.0	39.3	38.3	57.8	
19	12.4	21.8	21.1	30.6	44.7	26.5	15.6	45.3	
21	9.9	17.0	15.6	18.2	20.7	12.3	16.4	22.4	
22	20.1	29.0	27.5	53.5	43.2	29.6	38.9	56.4	5.0 gal/hr nozzle
22	6.0	11.1	8.6	10.1	9.2	6.7	9.8	11.5	3.5 gal/hr nozzle
22	22.4	30.0	34.2	42.8	40.5	29.2	38.3	44.6	7.0 gal/hr nozzle
22	9.4	18.0	14.6	16.2	16.9	12.0	14.9	19.8	fuel/air ratio = 0.011
23	31.2	37.2	42.6	50.1	50.3	45.9	46.4	68.8	
24	22.3	41.1	43.1	48.9	46.8	39.2	46.7	55.4	
26	14.4	17.8	13.4	23.0	24.8	18.0	26.8	35.6	
27	37.5	44.3	46.4	55.2	55.0	46.4	52.3	57.9	6.5 gal/hr nozzle
27	36.2	30.8	26.3	39.8	38.6	16.7	35.8	30.0	5.0 gal/hr nozzle
28	41.4	56.9	55.1	59.8	64.1	59.0	64.1	71.9	
29	46.3	61.1	58.1	69.9	65.4	65.3	66.7	72.1	
31	10.1	4.0	8.2	12.4	17.4	8.12	18.7	20.2	
32	4.1	4.5	5.3	25.5	8.0	5.7	7.3	13.0	
33	5.9	12.6	9.3	13.3	12.2	9.3	11.7	13.4	
35	1.9	2.6	1.7	1.7	2.2	1.6	2.9	2.0	
36	9.0	8.0	9.0	13.5	10.5	5.2	14.1	15.2	
37	9.9	17.2	16.1	16.2	14.9	14.4	16.4	15.1	
39	5.2	5.4	6.7	6.5	5.8	5.4	5.4	8.9	
40	6.7	9.7	5.9	10.8	4.6	5.2	4.1	12.0	
42	7.6	6.6	13.1	32.1	17.7	9.5	8.3	13.2	
43	2.4	9.32	3.9	4.2	2.7	1.7	2.0	3.6	
46	3.5	2.3	1.6	2.6	1.7	0.7	1.0	1.8	
47	3.6	3.0	3.0	1.3	2.0	2.3	1.4	1.3	
48	4.5	4.6	2.1	4.3	1.6	4.7	1.8	2.8	
49	27.7	29.3	25.8	35.3	34.8	29.8	31.0	37.1	fuel/air ratio = 0.011

SUMMARY OF NO$_x$ EMISSIONS INDEX DATA

NO$_x$ EMISSIONS INDEX (G/KG OF FUEL)

Run No.	0	1	2	3	4	5	6	7	Remarks
1	6.4	5.1	5.4	6.1	6.1	5.7	5.8	6.4	
2	7.1	6.5	7.0	7.2	7.5	6.6	6.5	7.9	
3	4.0	3.8	4.9	4.6	4.8	4.9	5.8	5.9	
6	5.3	4.4	4.9	5.0	5.4	4.4	5.2	6.7	
7	3.0	3.1	3.2	4.6	3.6	3.7	3.7	5.2	5.0 nozzle
7	5.6	4.5	5.3	5.6	5.9	5.2	5.9	6.9	2.0 nozzle
7	5.4	5.4	5.3	5.6	5.2	5.7	5.6	6.5	3.5 nozzle
8	5.1	5.2	5.5	5.7	5.3	5.5	5.3	7.1	
9	5.0	5.0	5.3	5.4	5.6	5.4	5.8	7.3	
11	12.0	12.2	10.8	10.5	10.8	11.3	10.9	11.7	
12	10.2	8.7	9.0	10.2	11.0	8.4	9.7	10.2	
13	10.2	9.4	10.6	11.8	10.4	10.5	10.3	12.3	
14	11.0	5.8	7.5	7.6	7.9	8.3	10.4	8.2	
16	10.3	9.7	10.1	10.4	10.6	10.6	11.6	12.3	
17	9.9	10.7	9.7	9.7	9.6	9.8	9.1	9.9	
18	9.8	9.6	9.5	9.9	10.3	9.8	10.4	11.0	
21	12.4	12.3	12.5	12.5	12.5	12.4	12.9	13.0	
22	10.7	9.7	10.7	11.0	11.7	10.6	11.0	12.0	5.0 nozzle
22	9.8	11.3	10.4	11.5	10.9	11.0	11.4	13.2	3.5 nozzle
22	13.1	12.9	12.9	13.1	14.8	13.8	14.1	16.0	7.0 nozzle
23	9.6	9.4	8.6	9.1	9.7	8.5	9.4	11.0	
24	9.2	8.9	8.7	8.2	8.6	9.5	8.7	10.4	
26	12.2	12.6	11.1	14.9	12.5	12.5	12.4	13.7	
27	11.0	10.1	9.7	10.3	10.8	10.8	10.7	11.3	6.5 nozzle
27	12.7	13.8	13.9	13.9	14.2	15.2	14.2	15.4	
28	10.0	10.5	10.4	10.6	11.1	11.5	11.5	12.6	
29	11.1	12.2	12.4	11.7	12.3	12.4	12.2	12.6	
31	21.5	24.3	24.8	22.0	25.6	21.2	27.0	26.4	
32	23.7	24.1	24.5	23.2	25.6	24.1	24.5	25.7	
33	19.5	22.8	21.1	23.2	25.2	22.4	25.3	29.0	
35	25.2	28.4	30.4	29.9	32.1	31.3	32.1	34.0	
36	22.2	21.4	23.7	26.2	26.1	23.5	25.3	30.8	
37	26.9	28.1	29.1	31.4	32.6	29.8	30.8	32.9	
39	42.6	41.7	44.1	43.3	41.2	47.4	42.2	41.6	
42	49.7	49.8	54.9	47.0	52.9	55.3	52.0	53.7	
43	15.2	13.6	14.1	16.5	17.5	39.5	43.3	50.8	
45	71.7	73.3	77.2	74.7					
47	107.6	101.9	104.0	108.9	112.0	112.2	109.7	114.5	

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