

# The Influence of Fuel Hydrogen Content Upon Soot Formation in a Model Gas Turbine Combustor

T. T. Bowden

J. H. Pearson

R. J. Wetton

Shell Research Limited,  
Thornton Research Centre,  
Chester, England

*The sooting tendencies of various fuel blends containing either single-ring or polycyclic aromatics have been studied in a model gas turbine combustor at a pressure of 1.0 MPa and varying values of air/fuel ratio. Sooting tendencies were determined by flame radiation, exhaust soot, and infra-red absorption measurements. The results of this study have indicated that, even for fuels containing high concentrations of naphthalenes or tetralins (>10 percent v), fuel total hydrogen content correlates well with fuel sooting tendency. The present results are explained by a hypothesis that assumes that the majority of soot is formed in regions of high temperature, low oxygen content, and low fuel concentration, e.g., the recirculation zone.*

## Introduction

Recent work utilizing a number of experimental configurations, including well-stirred reactors [1], model combustors [2, 3, 4], and full-scale combustors [5, 6, 7, 8], has indicated that fuel total hydrogen content provides an effective means of predicting the sooting tendencies of many fuels in gas turbine equipment. However, there have been suggestions that this may not be the case for fuels containing significant concentrations of fused ring polycyclic aromatics, such as naphthalenes and tetralins [9, 2, 3]. As it is possible that some future aviation turbine fuels may contain higher concentrations of polycyclic aromatics than present day fuels, it is important to determine whether a compositional limit exists for these components below which hydrogen content will remain a satisfactory predictor of combustion performance. That such a limit may exist has been suggested by earlier work [3]. However, these studies were performed at a single value of air/fuel ratio and since other results [2] have demonstrated that air/fuel ratio can significantly influence the response of combustion systems to fuel molecular composition, work is continuing on the investigation of the sensitivity of fuel combustion performance to molecular composition over a wider range of air/fuel ratios than previously reported.

In particular, the effect on combustion performance of increasing the concentration of naphthalenes and tetralins in aviation turbine fuels, as compared to fuels containing only single-ring aromatics, has been studied.

## Experimental

The high-pressure aviation combustion facility and

associated instrumentation have been fully described elsewhere [2, 3]. Recently, the range of measurements taken have been extended to include determinations of flame spectral emissivities, and hence soot concentrations, by a scanning infrared emission/absorption technique. This latter system has been incorporated to overcome a shortcoming associated with the correlation of combustion performance with flame total radiation, a technique commonly used in the study of combustor response to fuel composition. The reason for this shortcoming is easily appreciated when the relationships between flame temperature, flame emissivity, and flame soot concentrations are considered.

Making the assumptions that the radiation from the flame is predominantly from soot and that the soot acts as a gray emitter, flame radiation, flame emissivity, and soot concentration are related by equations of the form

$$R_f = \sigma e_f T_f^4 \quad (1)$$

$$e_f = 1 - \exp(-klc) \quad (2)$$

- $R_f$  = flame radiation
- $e_f$  = flame emissivity
- $T_f$  = flame temperature
- $k$  = absorption coefficient
- $l$  = optical path length
- $c$  = soot concentration
- $\sigma$  = Stefan-Boltzmann constant

From the form of equation (2), it can be seen that, as soot concentration increases, so emissivity tends toward 1. Ultimately, therefore, emissivity and hence radiation will become independent of the concentration of soot produced by a fuel during combustion, with the result that measurements of flame radiation will cease to truly measure variation in fuel-sooting tendency. As this situation is most likely to occur at high combustion pressures and/or low values of air/fuel

Contributed by the Gas Turbine Division of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS for presentation at the 29th International Gas Turbine Conference and Exhibit, Amsterdam, The Netherlands, June 4-7, 1984. Manuscript received at ASME Headquarters December 13, 1983. Paper No. 84-GT-6.

ratio, it is essential that measurements at such conditions include a determination of emissivity.

The position is further complicated when it is realized that neither of the assumptions made earlier regarding flame radiation is truly valid. Soot does not act as a gray emitter, i.e., it shows a marked variation in emissivity with wavelength [10], neither does the soot provide the only source of radiation from a flame, since gases such as water vapor and carbon dioxide can contribute significantly to flame radiation. To overcome these inaccuracies, measurements of emissivity need to be made over narrow wavelength intervals and, if contributions from sources of radiation other than soot are to be avoided, these wavelengths must be ones in which absorption bands of water or carbon dioxide are either absent or very weak.

**Theory and Experimental Method Utilized for Emission/Absorption Measurements.** The orientation of the optical system of the IR emission/absorption spectrometer relative to the combustor is shown in Fig. 1.

The experimental procedure and theory involved in emission/absorption measurements has been described by other workers [11] and only a brief mention will be given here.

For the absorption measurement, a reference source is employed behind the flame tube. The transmitted reference source intensity,  $I(\lambda)$ , at wavelength,  $\lambda$ , is equal to the reference intensity,  $I_o(\lambda)$ , times the fraction of  $I_o(\lambda)$  remaining after absorption in the flame, i.e.,

$$I(\lambda) = I_o(\lambda)(1 - a(\lambda)) \quad (3)$$

where  $a(\lambda)$  is the spectral absorptivity of the gas, which for a gas in local thermal equilibrium (l.t.e.) equals the spectral

emissivity  $\epsilon(\lambda)$  at the same wavelength. Hence,  $\epsilon(\lambda)$  may be calculated once  $I(\lambda)$  and  $I_o(\lambda)$  have been measured.

The next parameter to be determined is the gas spectral emission  $I_g(\lambda)$ . From Kirchoff's radiation law, which applies for gases in l.t.e., the ratio of the gas spectral emission,  $I_g(\lambda)$ , to the gas emissivity,  $\epsilon(\lambda)$ , at the same wavelength is equal to the spectral emission,  $I_b(\lambda)$ , of a black body at the same temperature, i.e.,

$$I_b(\lambda) = I_g(\lambda) / \epsilon(\lambda) \quad (4)$$

where

$$I_b(\lambda) = C_1 \lambda^{-5} \left[ \exp\left(\frac{C_2}{\lambda T_g} - 1\right) \right]^{-1} \quad (5)$$

$C_1$  and  $C_2$  are the first and second radiation constants. The absolute gas temperature  $T_g$  may then be obtained, averaged along the line of sight, as

$$T_g = \frac{C_2 / \lambda}{\ln \left[ 1 + \frac{I_o - I}{A I_g} \exp \left[ \frac{C_2}{\lambda T_b} - 1 \right] \right]} \quad (6)$$

where  $T_b$  is the black-body furnace temperature.

In the present arrangement, the black-body reference source also provides an absolute calibration once allowances for apertures, window absorption, and inverse square law are made via the constant  $A$  in equation (6). Since  $\epsilon(\lambda)$  and  $I_g(\lambda)$  are both wavelength-dependent, the method has to be monochromatic.

In the present work, the monochromator used was a Spex "Minimate" instrument having a 50 line/mm grating. A Pye Unicam IR-50 Goly cell detector with a thallium-bromiodide window was used and chopped at 15 Hz for optimum signal/noise ratio. Detector signals were amplified before their input to a Bentham Type 223 phase-sensitive detector. Phase reference was provided by variable frequency Bentham 218F optical choppers. Analogue output voltages from the phase-sensitive detector were digitized and stored by a Hewlett-Packard 9845T microcomputer which served to both treat the data and control the monochromator Spex Minidrive 1673 stepping motor. Reference radiation signals  $I_o(\lambda)$  were provided by a Land, Type LCF, furnace operated at 1450°C. The furnace emissivity over the wavelengths of interest was measured, by comparison with an Electro-Optical Industries, Inc., type WS155 black-body standard, to be 0.99. Utilizing the chopper between the flame-tube and the black-body furnace,  $I(\lambda)$  was measured by the Goly cell detector. For the measurement of  $I_g(\lambda)$ , the chopper between the flame and the monochromator was used.

Radiation from both the flame and the reference source was transmitted to the monochromator via a fiber optic light guide, this method was utilized to eliminate misalignment between the flame tube and the monochromator caused by vibration and thermal expansion of the combustor.

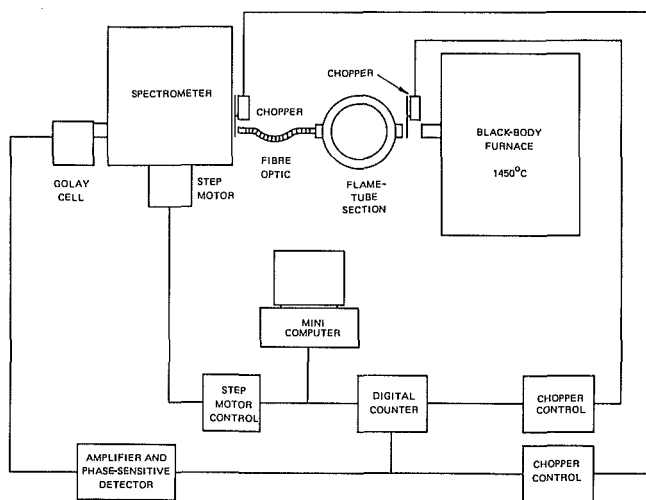


Fig. 1(a) Experimental configuration for emission/absorption determinations

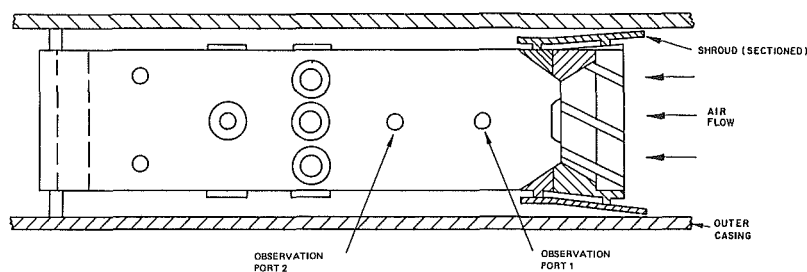


Fig. 1(b) Small-scale flame tube showing observation ports for flame radiation and emission/absorption measurements

**Table 1 Properties of fuel blends**

		Jet A1	Jet A1 + 5% kerex	Jet A1 + 10% kerex	Jet A1 + 15% kerex	Jet A1 + 20% kerex	Jet A1 + 5% tetralin	Jet A1 + 10% tetralin	Jet A1 + 5% 1-methyl-naphthalene	Jet A1 + 10% 1-methyl-naphthalene
[H] content, %w		13.77	13.62	13.56	13.40	13.28	13.53	13.32	13.41	13.06
Aromatics, %v		18.8	22.56	24.18	27.85	32.26	22.26	25.93	22.80	25.61
Smoke point, mm		27	23	21	19	19	22	19	21	17
Naphthalene content, %v		2.64	3.23	3.02	3.1	3.37	2.39	2.63	8.07	13.1
Specific gravity		0.7962	0.8078	0.8101	0.8143	0.8170	0.8105	0.8188	0.8132	0.8255
Vk at 40°C, cSt		1.241	1.264	1.248	1.261	1.242	1.272	1.277	1.280	1.290
ASTM Dist., °C										
IBP		159.5	165.0	164.5	167.0	162.5	158.5	160.0	158.5	163.0
10%		173.5	176.5	176.5	179.0	177.0	174.0	175.0	175.0	178.5
20%		184.5	183.0	182.5	185.0	183.0	182.0	182.0	181.5	186.5
30%		192.0	189.0	188.5	190.0	188.0	187.0	188.5	188.5	193.5
40%		199.0	194.5	193.5	195.0	193.5	193.5	193.5	195.0	200.5
50%		205.0	200.0	199.5	200.0	198.5	199.5	199.0	200.5	207.5
60%		210.5	206.0	205.0	206.0	204.5	205.5	204.5	207.5	213.5
70%		217.0	212.5	211.5	212.5	210.5	212.5	210.5	214.5	220.0
80%		225.0	221.0	219.0	220.0	218.0	220.0	218.5	222.0	227.5
90%		234.0	230.5	229.5	230.0	228.5	231.5	229.9	231.0	236.5
FBP		249.0	249.5	248.0	249.5	249.5	249.5	250.0	249.5	251.5

Soot concentrations within the combustor were calculated from the relationship between spectral absorption coefficient and soot volume fraction [10]

$$k_\lambda = \frac{36\pi nK}{(n^2 - K^2 + 2)^2 + 4n^2K^2} \frac{f_v}{\lambda} \quad (7)$$

where  $f_v$  = volume fraction of soot, and  $n$  and  $K$  are the constants of the complex refractive index of soot ( $m = n - iK$ ). The refractive indices used were calculated from the dispersion equations presented by other workers [12]; these equations provide the most accurate representation of soot optical properties derived to date. The spectral absorption coefficient was obtained from the spectral emissivity using the equation

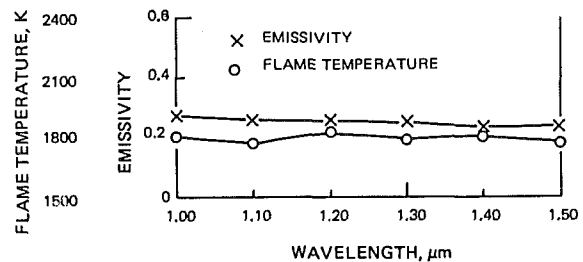
$$\epsilon_\lambda = 1 - \exp(-k_\lambda l) \quad (8)$$

where  $l$  = optical pathlength. Using a density for soot of  $1.86 \times 10^3 \text{ kg m}^{-3}$  [13], a mass concentration of soot can be determined.

In order to minimize signal noise, the experimental procedure adopted was to step the monochromator, automatically, to discrete wavelengths, i.e., 1, 1.1, 1.2, 1.3, 1.4, and 1.5  $\mu\text{m}$ , and signal average over approximately 500 separate readings at each value of wavelength.

A total of nine fuels were utilized in the experimental program, five of the fuels containing varying amounts of single-ring aromatics, obtained by blending a standard Jet A1 with a highly aromatic solvent, the other four fuels contained 5 and 10 percent wt tetralin and 5 and 10 percent wt 1-methylnaphthalene, respectively. Details of the test fuels are given in Table 1. The fuels were burnt at combustion conditions of 1.0 MPa, 400°C inlet air temperature and air/fuel ratios of 50/1, 45/1, and 40/1. In addition to the exhaust soot concentrations, flame radiation, from observation port 1, and flame-tube temperatures were measured at each condition and with each fuel. For all the experiments, the monochromator was aligned with observation port 2 and viewed a region of the combustor which earlier work, utilizing thermocouple scans, had shown to have an essentially flat temperature profile. It is preferable that the monochromator should view through such a region, since large temperature gradients make the interpretation of properties determined by integration across the line of sight very difficult.

In order to compensate for run-to-run variation, test fuels were burnt in groups of two, bracketed by a reference fuel run, i.e.,  $R, T_1, T_2, R$ , and the results for the test fuel blends were nondimensionalized with respect to the reference fuel as follows:



JET A1 AFR 45/1 PRESS 1 MPa AIR TEMP 400°C

WAVELENGTH/ $\mu\text{m}$	EMISSIVITY	TEMP./K	SOOT	Fv
1.0	0.273	1808	2.11E	-06
1.1	0.259	1770	2.05E	-06
1.2	0.254	1820	2.06E	-06
1.3	0.250	1790	2.08E	-06
1.4	0.234	1809	1.98E	-06
1.5	0.240	1777	2.01E	-06
MEAN	0.252	1796	2.05E	-06

**Fig. 2 Trace of emissivity and temperature as derived from emission absorption technique**

$$\text{Normalized flame-tube temperature (NFTT)} = \frac{T_{\text{test}} - T_{\text{ref}}}{T_{\text{ref}} - T_{\text{int}}} \quad (9)$$

where  $T_{\text{test}}$  = flame tube temperature produced by test fuel  
 $T_{\text{ref}}$  = flame tube temperature produced by reference fuel  
 $T_{\text{int}}$  = inlet air temperature

$$\text{Normalized flame radiation temperature (NFR)} = \frac{R_{\text{test}}}{R_{\text{ref}}} \quad (10)$$

where  $R_{\text{test}}$  = radiation produced by test fuel  
 $R_{\text{ref}}$  = radiation produced by reference fuel

$$\text{Normalized exhaust soot concentration (NES)} = \frac{S_{\text{test}}}{S_{\text{ref}}} \quad (11)$$

where  $S_{\text{test}}$  = soot concentration produced by test fuel  
 $S_{\text{ref}}$  = soot concentration produced by reference fuel

$$\text{Normalized flame emissivity (NFE)} = \frac{E_{\text{test}}}{E_{\text{ref}}} \quad (12)$$

where  $E_{\text{test}}$  = emissivity produced by test fuel  
 $E_{\text{ref}}$  = emissivity produced by reference fuel

$$\text{Normalized flame soot (NFS)} = \frac{FS_{\text{test}}}{FS_{\text{ref}}} \quad (13)$$

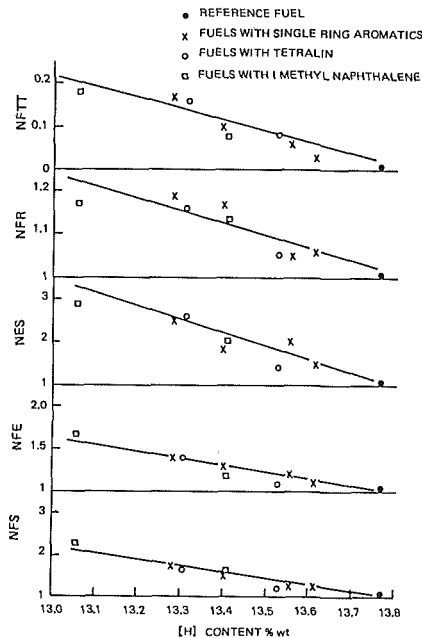
**Table 2 Results of combustion tests on fuel blends**

Fuel	NFTT	NFR	NES	NFE	NFS	Air/fuel ratio
Jet A1 + 5% kerec	0.015	1.04	1.20	1.10	1.25	50/1
Jet A1 + 10% kerec	0.030	1.06	1.30	1.10	1.30	50/1
Jet A1 + 15% kerec	0.022	1.18	1.45	1.35	1.55	50/1
Jet A1 + 20% kerec	0.038	1.17	1.95	1.55	1.62	50/1
Jet A1 + 5% tetralin	0.032	1.05	1.40	1.30	1.30	50/1
Jet A1 + 10% tetralin	0.030	1.07	1.50	1.50	1.50	50/1
Jet A1 + 5% 1 MN <sup>a</sup>	0.020	1.07	1.50	1.35	1.20	50/1
Jet A1 + 10% 1 MN	0.030	1.13	1.70	1.75	1.80	50/1
Jet A1 + 5% kerec	0.020	1.06	1.50	1.10	1.25	45/1
Jet A1 + 10% kerec	0.020	1.05	2.00	1.20	1.25	45/1
Jet A1 + 15% kerec	0.090	1.17	1.70	1.30	1.50	45/1
Jet A1 + 20% kerec	0.110	1.19	2.50	1.35	1.75	45/1
Jet A1 + 5% tetralin	0.050	1.05	1.30	1.10	1.15	45/1
Jet A1 + 10% tetralin	0.100	1.16	2.60	1.40	1.65	45/1
Jet A1 + 5% 1 MN	0.080	1.12	2.00	1.15	1.55	45/1
Jet A1 + 10% 1 MN	0.140	1.17	3.00	1.65	2.20	45/1
Jet A1 + 5% kerec	0.030	1.01	1.41	1.25	1.20	40/1
Jet A1 + 10% kerec	0.060	1.03	1.90	1.15	1.15	40/1
Jet A1 + 15% kerec	0.100	1.05	1.60	1.30	1.45	40/1
Jet A1 + 20% kerec	0.165	1.08	2.60	1.33	1.50	40/1
Jet A1 + 5% tetralin	0.080	1.04	1.90	1.20	1.22	40/1
Jet A1 + 10% tetralin	0.160	1.04	2.60	1.20	1.23	40/1
Jet A1 + 5% 1 MN	0.080	1.06	2.00	1.30	1.40	40/1
Jet A1 + 10% 1 MN	0.160	1.12	2.40	1.30	1.50	40/1

<sup>a</sup>1 MN = 1 - methyl-naphthalene

**Table 3 Absolute values of combustion parameters obtained for reference at each air/fuel ratio**

Air/fuel ratio	Flame-tube temperature	Flame radiation	Exhaust soot concentration	Emissivity	Flame soot concentration
50/1	1144 K	518 kW·m <sup>-2</sup>	2.4 × 10 <sup>-4</sup> mg·liter <sup>-1</sup>	0.175	6.0 × 10 <sup>-4</sup> g·liter <sup>-1</sup>
45/1	1143 K	697 kW·m <sup>-2</sup>	3.1 × 10 <sup>-4</sup> mg·liter <sup>-1</sup>	0.225	7.2 × 10 <sup>-4</sup> g·liter <sup>-1</sup>
40/1	1156 K	792 kW·m <sup>-2</sup>	7.31 × 10 <sup>-4</sup> mg·liter <sup>-1</sup>	0.389	1.3 × 10 <sup>-3</sup> g·liter <sup>-1</sup>



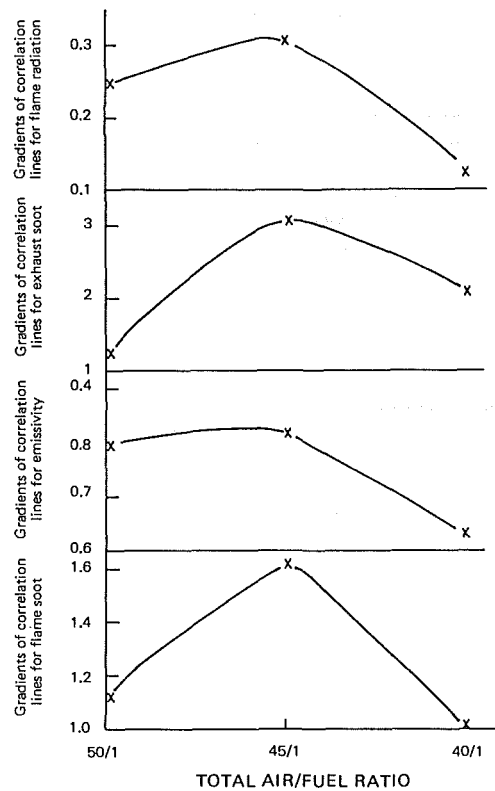
**Fig. 3 Combustion characteristics observed for test fuels at an AFR of 45/1 inlet pressure = 1.0 MPa, inlet air temp. 673 K**

$FS_{test}$  = flame soot produced by test fuel  
 $FS_{ref}$  = flame soot produced by reference fuel

For the purposes of this paper the values of flame soot and flame emissivity reported are those averaged over all the wavelengths utilized.

**Results**

Figure 2 gives a typical trace obtained from the



**Fig. 4 Sensitivity of combustion parameters to variation in hydrogen content at the values of AFR utilized**

emission/absorption spectrometer. As can be seen, the emissivity exhibits a marked decrease with increasing wavelength, a phenomenon that has been suggested in other

work [10] and which further emphasizes the need for measurements of emissivity to be monochromatic. Additionally, it is comforting to note both the good agreement between soot concentrations calculated at each wavelength, a result which provides support for the use of the refractive index values as used herein, and the uniform values of flame temperature calculated at each wavelength, an observation which indicates a flat temperature profile [11] at the observation port utilized.

The results of the combustion tests are given in Table 2, and the mean absolute values of the combustion parameters measured, obtained for the reference fuel runs, are given in Table 3, from which the absolute values for each test fuel may be derived.

The general form of the results obtained during the combustion tests is shown in Fig. 3, which gives the values obtained at an air/fuel ratio of 45/1 versus fuel hydrogen content.

Figure 4 shows the combustor sensitivity to fuel composition, as described by the gradient of the correlation lines for flame radiation, exhaust soot concentration, and flame soot concentration, against hydrogen content, at each of the values of air/fuel ratio utilized.

The results given in Figs. 3 and 4 show a number of interesting features:

1 The fuels containing 1-methylnaphthalene and tetralin exhibit a relationship between hydrogen content and combustion performance, in terms of the parameters measured, equivalent to that of those fuels containing predominantly single-ring aromatics, an observation common to all experimental conditions.

2 The sensitivity of the parameters measured to the fuel hydrogen content rank in the following order; exhaust soot > flame soot > emissivity > flame radiation

3 Flame soot concentration, when corrected to the condition applying for exhaust gas sampling, are approximately 3000 times higher than exhaust soot concentrations.

4 The sensitivity of combustion performance to variation in fuel total hydrogen content appears to peak at an AFR of approximately 45/1.

## Discussion of Results

The results using the model combustor suggest that fuels can tolerate quite high concentrations of naphthalenes or tetralins (>10 percent v) before hydrogen content ceases to adequately correlate with combustion performance, a con-

clusion supported by earlier work [3]. These concentrations are much higher than are found in conventional Jet A1 fuels and the results, if repeated in practice, would cast some doubt on the appropriateness of the present specification requirement for naphthalenes (<3 percent v).

It is encouraging to note that the sensitivities of the parameters measured to fuel hydrogen content are those that would be expected from the arguments presented in section 2, i.e., that owing to the functional relationship between soot concentration and flame radiation, the latter parameter should be a weaker function of fuel hydrogen content than should actual soot concentration. Interestingly, flame radiation, which was measured at port 1, is a less sensitive parameter than is flame emissivity, which was measured at port 2. This phenomenon is probably due to the higher soot concentration that will exist at the port 1 position as compared with that of the port 2 position. Higher soot concentration leads to a more opaque flame, which, from the arguments presented earlier, will exhibit less dependence, in terms of its thermal radiation, upon soot concentrations than will a region of relatively lower soot concentration. That soot concentrations drop dramatically with increasing distance down the flame tube is shown by the large difference between flame soot, measured at port 2, and exhaust soot. This result indicates that although low soot emission can be achieved by increasing soot consumption in the secondary zone of a combustor, design changes to accomplish this will not necessarily lead to lower values of flame soot concentrations and hence lower primary zone radiation. Attempts to decrease soot emission should concentrate on primary zone redesign in order to achieve low soot emission and low flame radiation.

The final observation, that combustor sensitivity to fuel hydrogen content peaks at an AFR of approximately 45/1, is particularly interesting as it provides further clues as to the mechanism of soot formation in gas turbines. In earlier work [2, 3], it was suggested that a major region of soot formation in gas turbines could be the recirculation zone where hot products of combustion are mixed with unburnt fuel, thus providing ideal conditions for pyrolysis and hence the production of soot. It was further suggested that the soot-forming sensitivity of a particular combustor to the molecular composition of a fuel depended on the volume concentration of the fuel in the pyrolysis region. This hypothesis was based on shock tube studies [14], which had shown that, in the temperature range of 1600-1900 K, low hydrocarbon concentration,  $\leq 2 \times 10^{23}$  carbon atoms  $m^{-3}$ , caused very large differences in sooting tendencies between polycyclic

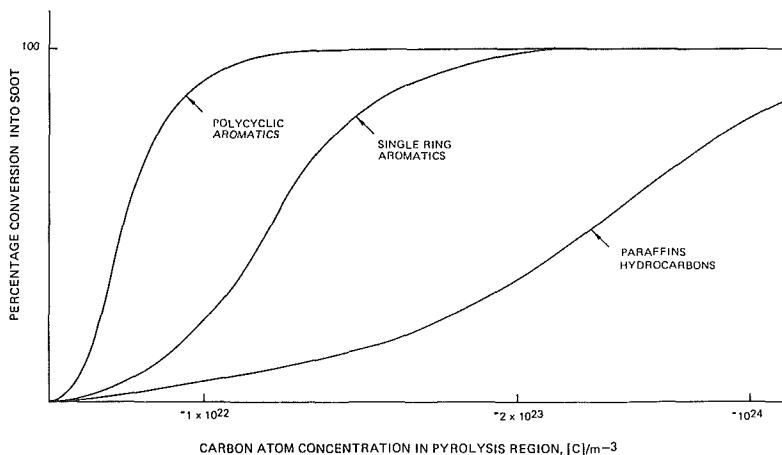


Fig. 5 Schematic representation of sooting tendencies, during pyrolysis, of various hydrocarbon as a function of carbon atom concentration (temperature ~ 1800 K)

aromatics, single-ring aromatics and paraffins, while at higher concentration,  $\sim 10^{24}$  carbon atoms  $m^{-3}$ , the sooting tendencies of most hydrocarbon types became very similar. The general form of the conclusions of this work are summarized in Fig. 5, which shows schematically soot conversion efficiencies versus hydrocarbon concentration for different hydrocarbon types. It can be seen that gradually increasing the concentration of a combination of hydrocarbons during pyrolysis would at first accentuate the differences between the sooting tendencies of the components; however, continued increase in the concentration would ultimately decrease the differences between the soot concentrations produced by the different hydrocarbons. As decreasing the AFR in a combustor will have the effect of increasing the fuel concentration in the recirculation zone, it can be seen that the present results are consistent with the hypothesis that significant quantities of soot are formed, by pyrolysis, in the recirculation zone, as this is one of the few regions in the combustor where high temperatures, low fuel concentration, and low oxidizing environments can exist for significant lengths of time.

It is pertinent to note that recent work using a model combustor [15], covering a wide range of fuel compositions and operating conditions, has shown that long residence times and high inlet air temperatures also decrease the sensitivity of soot formation to fuel molecular composition. As shock tube pyrolysis [14, 16] studies have indicated that high pyrolysis temperatures,  $>2000$  K, and long reaction times,  $>5$  ms, tend to decrease the differences observed between the sooting tendencies of different hydrocarbons, then it can be seen that the foregoing work, from a different source, also supports the present hypothesis.

The foregoing hypothesis could also explain the reason why, in the present work, the fuels containing naphthalene and tetralin showed little difference in their sooting tendencies compared with fuels containing only single-ring aromatics, for, if it is assumed that pyrolysis was occurring at concentrations at which the sooting tendencies of polycyclic and monocyclic aromatics were only slightly different, then very high concentrations of polycyclic aromatics would be required before any variation in soot formation (or concentration) would be observed. Additionally, the latter argument explains the differences between the present work and earlier studies [2] in which the presence of high concentration of naphthalenes and tetralins were seen to significantly affect combustion performance. As this earlier work utilized a much lower combustion pressure, 0.35 MPa, than the present studies, it is probable that fuel concentrations in the pyrolysis zones, were also substantially lower, thus leading to an accentuation of the differences in the sooting tendencies of polycyclic aromatics compared to single-ring aromatics.

If the present hypothesis is correct, then leaner primary zones could lead to engines which could be very sensitive to moderate concentrations of polycyclic aromatics; it is therefore important that work should be performed to accurately identify and eliminate the soot-forming regions within gas turbine equipment in order to prevent such a possibility from occurring.

## Conclusions

The results using the Thornton model combustor indicate that:

(a) Under the experimental conditions adopted, both naphthalene and tetralin concentrations of  $>10$  percent v can be tolerated in jet fuels before hydrogen content ceases to correlate with their combustion performance.

(b) Determination of flame radiation, as a measure of combustor performance, should include a measurement of emissivity.

(c) Sensitivity of soot concentration to fuel hydrogen content is greater than that of flame radiation.

(d) Combustor sensitivity to fuel hydrogen content exhibits a maximum value with variation in AFR.

(e) The results are consistent with a hypothesis that soot is mainly formed in high-temperature pyrolysis regions, such as the recirculation zone.

## Acknowledgments

The authors wish to thank the management of Shell Research Limited for permission to publish the paper and the British Ministry of Defense for their support in this work.

## References

- Blazowski, W. S., "Dependence of Soot Production on Fuel Blend Characteristics and Combustion Conditions," ASME Paper 79-GT-155.
- Bowden, T. T., and Pearson, J. H., "The Effect of Hydrocarbon Structure Upon Fuel Sooting Tendency in a Turbulent Spray Diffusion Flame," ASME Paper 83-GT-90.
- Bowden, T. T., and Pearson, J. H., "The Influence of Fuel Composition Upon Soot Emissions and Flame Radiation in a Model Gas-Turbine Combustor," Paper C70/83, *International Conference on Combustion in Engineering*, Vol. 2, I Mech. E. Conference Publication 1983-3.
- Moses, C. A., and Naegeli, D. W., "Fuel Property Effects on Combustor Performance," ASME Paper 79-GT-178.
- Gleason, C. C., and Bahr, D. W., "Evaluation of Fuel Character Effects on the J79 Engine Combustion System," AFAPL-TR-79-2015, June 1979.
- Gleason, C. C., and Bahr, D. W., "Evaluation of Fuel Character Effects on the F101 Engine Combustion System, final report," AFAPL-TR-79-2018, June 1979.
- Bahr, D. W., "Comparison-Effects of Broadened Property Jet Fuels on Older and Modern J79 Combustors," ASME Paper 83-GT-81.
- Butze, H. F., and Smith, A. L., "Effect of Fuel Properties on Performance of a Single Aircraft Turbojet Combustor and Simulated Idle, Cruise and Takeoff Conditions," NASA TM 73780.
- Naegeli, D. W., and Moses, C. A., "Effect of Fuel Molecular Structure on Soot Formation In Gas Turbine Engines," ASME Paper 80-GT-62, Mar. 1980.
- Dalzell, W. H., and Sarofim, A. F., "Optical Constants of Soot and Their Application to Heat-Flux Calculations," *ASME Journal of Heat Transfer*, Vol. 91, 1969, p. 100.
- Tourin, R. H., *Spectroscopic Gas Temperature Measurement*, Elsevier Publishing Company, 1966.
- Lee, S. C., and Tien, C. L., "Optical Constants of Soot in Hydrocarbon Flames," *Proceedings of the 18th Sym. (Int.) Combustion*, 1981.
- Encyclopaedia of Chemical Technology*, Kirk Othmer Ed., 2d ed., Wiley, New York, Vol. 4, 1964, p. 251.
- Graham, S. C., Homer, J. B., and Rosenfeld, J. L. J., "The Formation and Coagulation of Soot Aerosols Generated by the Pyrolysis of Aromatic Hydrocarbons," *Proc. Roy. Soc.*, A344, 1975.
- Naegeli, D. W., Dodge, L. G., and Moses, C. A., *AFLRL-158*, Dec. 1981.
- Wang, T-S., "Soot Formation from Toluene," Ph.D. thesis, Department of Chemical Engineering, Louisiana State University and Agricultural and Mechanical College, May 1980.