Role of Fuel Chemical Properties on Combustor Radiative Heat Load

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In an attempt to study rigorously the fuel chemical property influence on combustor radiative heat load, United Technologies Research Center (UTRC), under contract to NASA Lewis Research Center, has conducted an experimental program using 25 test fuels. The burner was a 12.7-cm-diam cylindrical device fueled by a single pressure-atomizing injector. Fuel physical properties were de-emphasized by selecting injectors that produced highly atomized and hence rapidly vaporizing sprays. The fuels were specified to cover the following wide ranges of chemical properties: hydrogen, 9.1–15% (wt); total aromatics, 0–100% (vol); and naphthalene, 0–30% (vol). They included standard fuels, specialty products, and fuel blends. Fuel naphthalene content exhibited the strongest influence on radiation of the chemical properties investigated. Smoke point was a good global indicator of radiation severity.

Introduction

AVIATION gas turbine engines combust high-quality fuel. The principal fuels for either commercial service, Jet A, or for military service, JP4 and JP5, were developed to possess excellent combustion characteristics while offering appropriate considerations for ease of ignition, safe handling, and low-temperature fluidity. The jet fuel specification assures obtaining this performance by controlling several key physical and chemical properties. The original specification was established to obtain these features while assuring adequate supplies of reasonably priced fuel derived from domestic petroleum reserves. The availability of domestic crude oil has continuously decreased in recent times, however, forcing an increase in the quantity of petroleum imported to the United States. In the last decade, the cost and availability of such imports have not been stable. Gas turbine users have experienced more than a fourfold increase in unit fuel costs, placing a premium on developing aircraft gas turbine systems that can offset the fuel cost burden. One part of an overall evaluation of a fuel-tolerant system is an investigation of the influence of fuel properties on the performance, emissions, and heat rejection of the combustor. Since 1975 numerous investigations[1–11] have been conducted to quantify such influences. The studies have used laboratory model combustors, full engine hardware, actual fuel, hydrocarbon specialty products (i.e., solvents), and blends of these two material classes. Such efforts have identified areas that would probably be affected by changing fuel properties, such as liner temperatures, exhaust smoke emissions, and low-power (idle) emissions. Unfortunately, the fuel variations studied have resulted in simultaneous changes in the physical and chemical properties. Physical properties (specific gravity, viscosity, and surface tension) would predominantly affect the fuel atomization process and, hence, alter the distribution and rate of vaporization of the fuel. Chemical properties (hydrogen, aromatic, or naphthalene content) would influence the fuel oxidation process, altering the type, concentration, and rate of consumption of chemical species within and exiting the combustor. Depending on the dominant mechanisms within the burner, changes in the fuel may or may not produce an interpretable change in a parameter of interest.

United Technologies Research Center (UTRC) has conducted an experimental program under contract to NASA Lewis Research Center to investigate the influence of fuel chemical properties on the heat load on a gas turbine combustor. Fuel physical properties were de-emphasized by using injectors capable of achieving highly atomized and hence rapidly vaporizing fuel sprays for each of 25 test fuels. The fuels were specified to cover wide ranges in fuel hydrogen, total aromatic, and naphthalene content; a limited number of fuels were blended to achieve parametric variations of these properties. Combustion tests were performed with a constant burner design at a simulated high-power gas turbine operating condition using all 25 test fuels. Fuel spray characterization studies supplemented the combustion tests. This paper summarizes the results of this investigation.

Test Fuels

The ASTM standard specification (ASTM D-1655) defines acceptable limits for many properties of turbine engine fuel for civilian use. Fuel combustibility is assured by bounding the aromatic and naphthalene contents and the smoke point. Hydrogen content is not a fuel specification parameter. Many previous studies, however, have determined that the results of changing fuel chemical properties correlate with the fuel hydrogen content. Therefore, in this investigation, attention was focused on the fuel chemical composition as represented by the hydrogen, total aromatics, and naphthalene contents. The smoke point was not considered to be a fundamental parameter, but rather resulted from the hydrocarbon mix of the fuel. Indeed, the three chemical property classes—hydrogen, total aromatics, and naphthalenes—were also gross parameters of the fuel. Obviously, hydrogen content alone does not specify the type of hydrocarbon molecules contained in the fuel. Similarly, "total aromatics" and "naphthalenes" do not pinpoint the type of aromatics, etc. As reflected by the ASTM specification, it has been assumed that the three major property classifications selected dominate the combustion characteristics and hence are the proper ones for evaluation. The 25 test fuels were selected to provide wide ranges of variation in these properties. Table 1 provides a list of the fuels and their chemical properties as determined from consistent chemical analyses.

Four of the test fuels were products commonly used in gas turbine combustors: Jet A, JP4, JP5, and JP7. Each of these was a high-quality, petroleum-derived fuel produced in accor-

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dance with ASTM and USAF specifications. Four additional fuels within this category were: ERBS, JP4-S, JP4-A, and DF2. ERBS (Experimental Referee Broad Specification) fuel evolved from a NASA-directed workshop on alternative hydrocarbon fuels.[12] Unlike most fuel specifications, which place upper limits on certain chemical properties, a single level (and tolerance) of hydrogen content is specified for ERBS. JP4-S was a JP4 specification product derived from oil shale resources. JP4-A, like JP4, was a petroleum-derived fuel satisfying the USAF specification but with a high aromatic content. The DF2 fuel was a better quality No. 2 fuel oil.

In order to extend the ranges of the chemical properties of interest, six of the test fuels were specialty products: decalin, tetralin, xylene tower bottoms (XTB), blending stock (BLS), Gulf Mineral Seal Oil (GMSO), and UTRC1. Both decalin and tetralin were pure, double-ring hydrocarbon solvents procurred from E. I. duPont de Nemours. Decalin is a product of the complete hydrogenation of naphthalene to naphthene. Tetralin results from partial hydrogenation of naphthalene to result in a fused, double 6-carbon ring structure, with one ring being saturated and the other unsaturated. XTB consisted of various single-ring aromatic compounds (alkylbenzenes), while GMSO was a relatively high final-boiling-point oil consisting mostly of normal and monocyclic paraffins. BLS was a mixture of XTB and a gas oil that NASA had obtained to use for modification of fuel properties and contained substantial single- and double-ring aromatic compounds. UTRC1 was a commercial solvent, EXXON Isopar M, chosen by UTRC to meet the requirements for a high-hydrogen-content fuel void of aromatic compounds.

Eleven of the test fuels were blends of common fuels and specialty products. Five fuels were prepared to provide blends with additional chemical properties: AFAPL2, AFAPL6, ERBLS1, ERBLS2, and ERBLS3. For these, as for the common fuels and specialty products, simultaneous variation in hydrogen, total aromatics, and naphthalene contents resulted. The first two fuels were supplied by the U.S. Air Force Aero Propulsion Laboratory, WPAFB, and consisted of JP4, XTB, and A-400 solvent and JP5, DF2, and A-400 solvent, respectively. (A400 is an aromatic solvent containing approximately 50% naphthalenes.) The latter three blends were different volume mixtures of ERBS and BLS; these fuels were blended by UTRC. Six blends were specially prepared to avoid this multiple property variation. The specification for these parametric blends resulted from an extensive computer screening exercise. Ten potential blending components were identified, with samples of each analyzed to provide consistent chemical property data. The final blend was limited to four components. Goal levels for hydrogen, total aromatics, and naphthalenes (and allowable tolerances) were input to a computer code, which analyzed four-component permutations of the ten candidates. As finally specified, these blends constituted either two- or three-point parametric variations from a reference fuel. These sequences were: hydrogen—ERBLS1/UTRC 2A and ERBS/UTRC 7A; total aromatics—ERBLS1/UTRC 3B and ERBS/UTRC 8A; naphthalene—ERBS/UTRC 9A/UTRC 9B. The components of these blends are reported in Ref. 13.

Test Combustor and Radiation Instrumentation

The test combustor embodied the features of a gas turbine burner. It was a high-heat-release device, with a strong

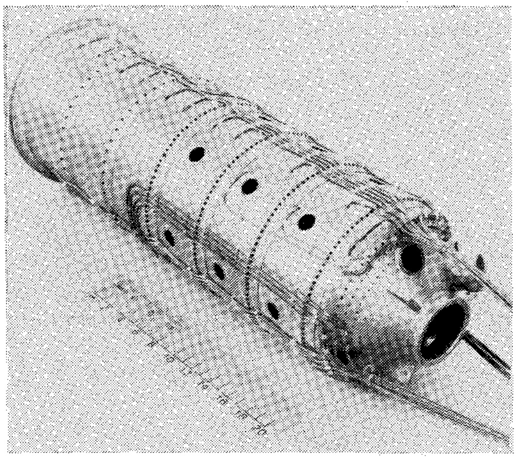

Fig. 1 Generic gas turbine combustor.

Table 1 Test fuel

Designation	Hydrogen, wt.%	Total aromatics, vol.%	Naphthalenes, vol.%
UTRC 2A	11.87	34.9	16.0
ERBLS1	12.35	38.4	16.6
UTRC 7A	12.53	26.2	14.9
JP7	14.39	2.5	0.0
JP4-shale	14.39	15.1	0.3
JP4	14.57	15.7	0.5
DF2	13.46	22.9	7.9
AFAPL 6	13.41	21.4	6.7
AFAPL 2	13.56	31.0	3.6
UTRC 3B	12.41	24.9	14.5
UTRC 8A	12.84	16.5	13.4
ERBLS2	11.89	47.3	20.5
UTRC 9A	12.89	30.7	1.5
UTRC 9B	13.10	30.1	7.3
Tetralin	9.14	100.0	1.5
Xylene tower bottoms (XTB)	9.64	100.0	0.1
Blending stock (BLS)	10.36	76.0	29.7
ERBLS3	11.38	59.2	26.5
ERBS	12.94	28.4	13.5
Decalin	13.10	0.2	0.0
JP4-A	14.16	23.1	0.6
Jet A	13.69	15.9	1.9
JP5	13.88	16.5	2.2
Gulf mineral seal oil (GMSO)	14.14	9.9	1.1
UTRC 1	14.97	0.0	0.0

swirling-recirculating flow structure at the front end (i.e., primary zone), followed by penetrating jets of air to reduce gradually the local fuel-air ratio, and hence gas temperature, to levels acceptable to a turbine. The burner consisted of a dome constructed from a frustrum of a 90-deg cone and six conventional sheet-metal louvers; the overall length was 41.1 cm, with a 12.7-cm i.d. (Fig. 1). A flange on the dome was provided to mount a central fuel injector-swirler combination. A family of pressure atomizers was used. All injectors produced hollow cone sprays with a rated included cone angle of 80 deg. The nozzle size used with each test fuel was determined from the spray characterization data described below.

A single airflow condition was used in this program to simulate high-power operation of a gas turbine engine. Each fuel was tested at the three flow rates required to produce ideal combustor exhaust temperatures of 1247, 1346, or 1473 K. These three temperatures were the ideal temperature levels associated with combusting Jet A at fuel-air ratios of 0.015, 0.018, and 0.022, respectively. The actual flow rates for each fuel were determined from thermochemical calculations using the chemical properties determined from the fuel analyses. The combination of airflow parameters and combustor exit temperatures defined three test conditions indicated in Table 2.

Two transpiration-type radiometers were mounted on the dome of the burner. Each radiometer was a probe-like device constructed from three concentric tubes; it had 1.6-cm o.d. and was approximately 25 cm long. The outer two tubes provided a delivery-return cooling loop to ensure survival of the probe, while the central tube ducted a metered flow of gaseous nitrogen to the probe tip. The tip was covered by a tightly woven steel screen, which permitted the nitrogen to seep out of the probe. It was mounted to place the screen flush with the combustor liner to acquire the full-hemispherical radiative flux.

The screen was the radiative load sensor. It was heated because of heat transfer from the combusting medium and cooled by the convective flow of nitrogen. At steady state, the energy removed by the nitrogen must equal the input energy. Direct measurement of the energy gain of the nitrogen was not possible since it would have required measurement of the nitrogen temperature leaving the screen. However, if the screen was a perfect heat exchanger, the screen temperature would equal the exit gas temperature. All probes were calibrated by the Pratt & Whitney Heat-Transfer Laboratory at elevated pressures to account for the nonideal heat exchanger behavior of the tip screen.

As shown by Moffat,[14] with sufficient nitrogen flow, the gas boundary layer will be blown off the tip, and only radiative transfer would heat the screen. The occurrence of blowoff depends on the flow of the inner, combusting flow; experiments with a flat plate suggest that the mass flux must exceed 8% of freestream value to achieve this condition. During this mode of operation, as the nitrogen flow rate is reduced, the probe temperature rise (screen minus upstream nitrogen temperatures) would increase while the energy input remains constant. Only at low nitrogen flow would the hot gas boundary layer reattach, a situation to be avoided because the input energy would destroy the screen. Data were acquired at various nitrogen flow rates during combustor shakedown tests to confirm measurement of radiative heat transfer only (Fig. 2). As expected, the probe temperature rise did vary, but the input energy remained constant. During combustor testing, a nitrogen mass flux of approximately 6 g/s/cm^2 was used to assure operation in this mode.

Table 2 Test conditions

	Condition 1	Condition 2	Condition 3
Combustor upstream air pressure, MPa	1.32	1.32	1.32
Combustor upstream air temperature, K	700	700	700
Combustor total air flow, Kg/s	1.84	1.84	1.84
Combustor ideal exit temperature, K	1246	1346	1473

Three water-cooled thermopile radiometers were acquired from Medtherm, Inc., to document the changing pattern of radiative heat transfer within the combustor. These devices were mounted on the test section housing to view the combusting medium through the 1.2-cm-diam combustion air holes located in louvers 1, 2, and 3. The radiometers were designed to have a narrow view angle (effectively, 33.43 deg) to allow locating them on the case to view the combusting gas but not the metal liner. These devices provided an indication of the axial distribution of radiative heat transfer and of how this distribution was influenced by fuel chemical properties or test conditions. These radiometers used a thermopile sensor located behind a sapphire window that was continuously purged by nitrogen.

The test rig was also instrumented to verify achievement of the test conditions and to document the operating characteristics of the burner. Liner temperatures, exhaust gas temperature, and exhaust gas and particulate concentrations were determined. A complete description of these data are presented in Ref. 13.

Fuel Spray Characterization

The principal objective of this study was to determine the influence of fuel *chemical* properties on the operation of a gas turbine combustor. Fuel physical properties were de-emphasized by producing finely atomized and hence rapidly vaporizing sprays for all fuels. Ballal and Lefebvre[15] analytically considered the influence of fuel chemical and physical properties on the combustion efficiency of a gas turbine combustor. Limiting cases were identified where the heat-release rate was dominated by chemical reaction, mixing, or fuel vaporization. A vaporizing fuel spray characterized by a Sauter mean diameter (SMD) droplet was analyzed to determine a critical SMD (SMD_c); for $SMD > SMD_c$, fuel vaporization would control the heat release. Large values of SMD_c indicate that the fuel properties and flow condition were favorable to vaporization—that is, a large SMD could be tolerated without becoming vaporization-controlled. Longer combustion zones or greater residence times would also permit an increased SMD_c.

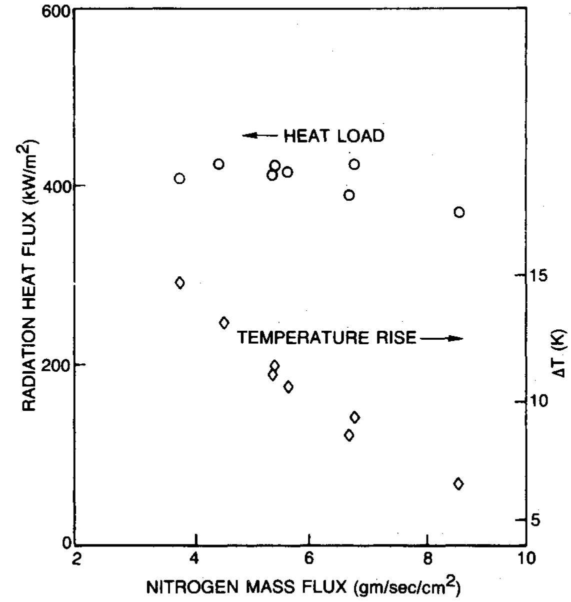

Fig. 2 Radiometer operating characteristics.

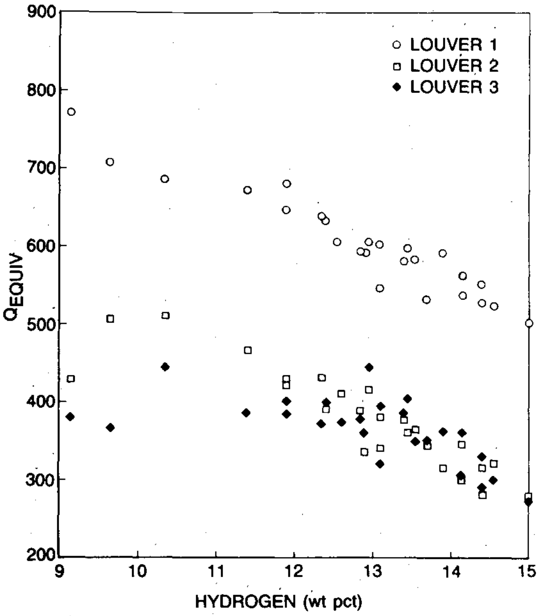

Fig. 3 Axial distribution of radiative heat load.

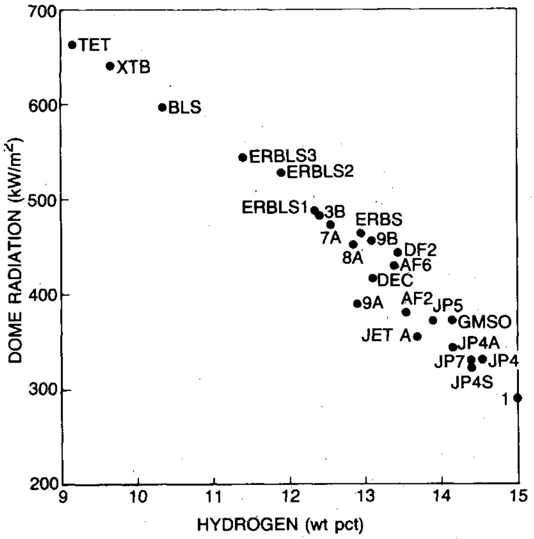

Fig. 4 Dependence of radiative load on fuel hydrogen content.

The critical droplet size to avoid vaporization control was evaluated for the combustor used in this test program. In particular, the SMD_c value sought was to assure rapid vaporization within the combustor primary zone. Calculations indicated that for Jet A fuel, a 20% turbulence intensity, and a droplet lifetime half the primary zone residence time, $SMD_c = 52\ \mu m$; that is, a Jet A spray with an $SMD < 52\ \mu m$ would vaporize fast enough so as not to limit the heat-release rate. The least volatile test fuel to be tested had distillation characteristics similar to a No. 2 oil. For conditions as described above, the critical diameter was calculated to be $SMD_c = 45\ \mu m$.

A second analysis of fuel vaporization was conducted using the UTRC Spray Vaporization Computer Program. Droplet lifetimes (i.e., complete vaporization) for specified initial droplet diameters of Jet A or No. 2 oil were calculated for the same operating condition of the primary zone as for the Ballal analysis. Again, the convective heat and mass transfer were represented by the inability of the droplet to respond to turbulent velocity fluctuations. To achieve complete vaporization within half the primary zone residence time, the SMD of the Jet A spray could approach 65 μm while for No. 2 oil the spray must be limited to $SMD < 56\ \mu m$. These results were similar to those achieved in the preceding analysis and therefore confirmed the approximate level of atomization required to eliminate fuel physical property influences. Recognizing that the atomization level will degrade for reduced fuel flow, a conservative atomization goal was set: $35 < SMD < 45\ \mu m$ for all fuels at the median fuel flow rate.

In order to assure meeting the atomization goal, the fuel spray formed by each of the 25 test fuels was experimentally characterized. Spray SMD and cone angle were determined for all fuels with a single nozzle, with additional tests performed to quantify the influence of nozzle size (capacity). Photographic records of the spray were obtained to determine the included cone angle. A Malvern Model ST1800 particle size analyzer was used to measure the droplet size distribution in a plane 6.4 cm downstream from the injector. Using these data, nozzle sizes designated by nozzle number, NN (defined as volumeric flow, GPH, of No. 2 oil at 100 psid), were selected to produce sprays for *all fuels* with a narrow SMD variation. This selection process is detailed in Ref. 13. Note that the nozzle selection procedure was conservative. First, data suggest that finer sprays will be formed when the liquid is injected into a high-pressure environment. Second, the atomization data used to specify nozzles were obtained from sprays into a quiescent surrounding. Limited tests indicated strong secondary atomization phenomena caused by the swirler airflow. Both of these influences would exist in the combustor tests, promoting finer atomization. Hence, complete rapid spray vaporization was clearly expected for all fuels, assuring minimal effects of both fuel physical properties and spray structure.

Combustor Test Results

General Combustor Operation

The combustor always operated in a consistent manner. The combustion efficiency (determined from exhaust gas analyses) was always 99.9% or greater. Often the unburned hydrocarbons and carbon monoxide were below the threshold detection level of the analyzers. The NO_x emissions were relatively constant at a level EINOX = 12–14. The combustor exit temperature pattern factor was typically 0.12 ± 0.01 at test condition 1, increasing slightly to 0.14 ± 0.02 at test condition 3. The combustion test data were acquired from a repetitive test cycle. Each test condition was established three times, with three data points obtained for each setup to develop a set of nine data points available for statistical analysis. A high degree of test condition repeatability was achieved; that is, the standard error for the nine data point set was typically less than 0.8% of the mean value of inlet air pressure and temperature, airflow, and fuel flow. As a result of this care in repeating test conditions, the combustor performance parameters were also very consistent, with a standard error on radiation heat transfer of 2%.

Three case-mounted radiometers were used to sense changes in the axial distribution of the combusting gas radiation. One device was aligned with a large combustion air hole in each of louvers 1, 2, and 3 (hence referred to as liner radiation measurements). It is important to note that these devices did not measure the total radiation to the liner at the measurement point. The narrow view angle limited the accepted radiation to only 2.2% of the potential hemispheric solid angle source. Typical liner radiation levels obtained for all test fuels are compared in Fig. 3 for test condition 1. Clear trends in the radiation levels are evident. It is important that these data confirm that the combusting flow structure was not significantly altered by any of the test fuels; that is, for condition 1 (Fig. 3), the radiation in louver 1 was always greater than in louvers 2 and 3. Similar distinctive trends were evident for other test conditions. This feature affirmed that for each condition, every fuel was similarly atomized and distributed within the burner.

Chemical Property Influences

Data acquired to determine the influences of fuel chemical properties on the combustor radiative heat load indicated that the principal variation was the quantity of soot formed in the front end of the combustor. Fuels with a high indicated propensity to soot (i.e., lower smoke point) produced high radiation heat loads. Data analysis indicated that the influences determined at one test condition were similar to those determined at the other two conditions. Therefore, the following detailed discussions of data will focus on the dome radiation as documented at test condition 2.

Data Analysis Methodology

The chemical property influences were discerned from analysis of two sets of data—data from limited tests, which provide parametric variations in fuel properties, and data from all tests to include the widest range of chemical properties. This latter data set was analyzed by use of multivariable regressions. The limits of this approach were recognized; in performing regression analyses, attempts were made to determine the best functional relationship between the dependent variables (combustor performance parameters such as dome radiation) and the independent variables (fuel properties such as hydrogen content, smoke point, etc.). Unfortunately, since regression analyses do not derive from first-principle considerations, no general guide is available for their formulation, and poor representations of the data can result solely from assuming improper functions. The quality of the data representation was evaluated by the square of the correlation coefficient, R^2. This term indicates the fraction of the total variation in the data that is represented by the function; $R^2 = 1$ would denote a relation that perfectly tracks the observed data. The functional expressions developed during this effort were good to excellent representations of the data, with $R^2 > 0.7$ always achieved and values greater than 0.9 often encountered. Hence, reasonable functional forms were evaluated, especially for cases that achieved $R^2 > 0.9$. The fuel property regression equation was limited to include exponential functions of fuel properties, such as

$$\text{combustor parameter} \sim H^{C1} A^{C2} N^{C3}$$

where H, A, N represented the percent hydrogen, total aromatics, and naphthalene contents, respectively, and $C1$, $C2$, $C3$ were constants optimized during the regression process. Several fuels had total aromatic or naphthalene contents near or equal to zero. The above exponential form could not be used in regression analyses for fuels with zero concentration and, for fuels with low concentrations, was susceptible to large error because of the uncertainties in the property analysis. For such instances, the fuel property was expressed as the difference from total concentration (e.g., 100-N). Several fuel property functions were evaluated in an attempt both to represent globally the combustor parameter response to chemical property variations and to discern particular fuel property influences.

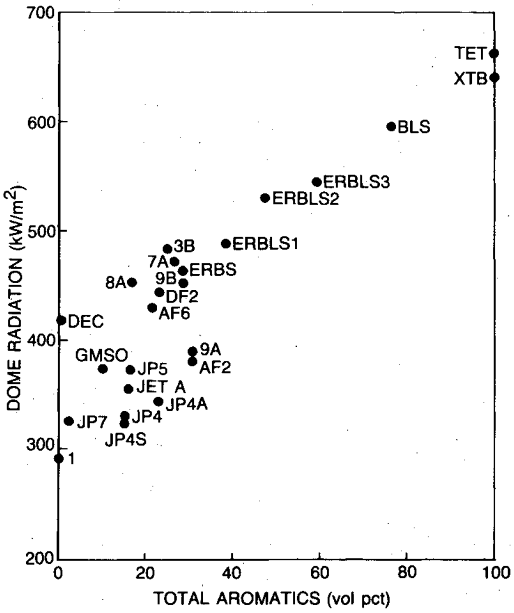

Fig. 5 Dependence of radiative load on fuel total aromatic content.

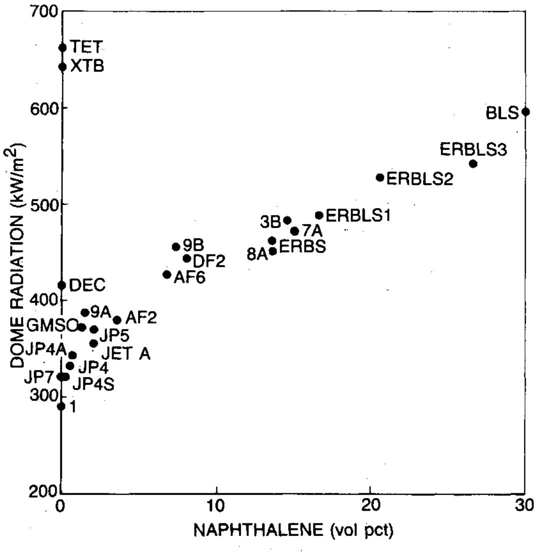

Fig. 6 Dependence of radiative load on fuel naphthalene content.

Detailed Analysis of Dome Radiation Data

The variations of dome radiation for the several test fuels are represented in Figs. 4–6, which display the data in terms of fuel hydrogen, total aromatics, or naphthalene content, respectively. Clear and expected trends are observable in each figure, with increased radiation levels obtained with lower chemical quality fuel. Used in this manner, each of these properties is treated as a global indicator of the fuel property influence. The depicted hydrogen content dependence (Fig. 4) also reflects variations in both total aromatics and naphthalenes; it does not represent the influence of hydrogen content alone. Similarly, the total aromatics and naphthalene representations include the influence of all other chemical property variations. Of these three, the hydrogen content representation correlated the data better than either total aromatics or naphthalene content. Significant scatter is observed in Fig. 5, indicating the total aromatic content does not properly represent the chemical property influences. Naphthalene content correlated the data well except for two low-naphthalenic fuels—tetralin and xylene tower bottoms (XTB). Tetralin is a double-ring molecule produced by saturating one ring of naphthalene. A principal pyrolysis product of tetralin is naphthalene[16] and, therefore, in the diffusive burning environment of the combustor, tetralin probably behaves as a high naphthalene content fuel. Indeed, the radiation level measured for tetralin was slightly greater than obtained for BLS, a fuel with a naphthalene content of 30%. The XTB fuel consisted of 100% benzene-type hydrocarbons. High sooting rates were to be expected and, based on acquired data, were achieved. Thus, while the tetralin behavior can be rationalized with respect to naphthalene content, XTB cannot. Naphthalene content alone could not be expected to correlate fully all data.

It is noted that the chemical properties of tetralin and XTB were exceptional. Both were from the specialty products class of fuels, with each composed entirely of a single hydrocarbon-type molecule. Further, each of these hydrocarbons had a high propensity for sooting. Twenty-one test fuels had compositions that included mixtures of single-ring and multiring aromatics (two other specialty product fuels were purely paraffinic—decalin, and UTRC1), which spanned the ranges: total aromatics, 2.5–76% (vol) and naphthalenes, 0–29.7% (vol). Data from tests with these fuels dominate the trends depicted in Figs. 4–6. It is apparent that for these 21 fuels the naphthalene content was a stronger influence on the radiative heat load (and hence on the soot formation) than the total aromatic (or by difference, the single-ring aromatic) content of the fuel. The dominance of naphthalene content was established even though its content was a minor portion of the total aromatics. Again, radiation levels for ERBLS3 with 30% naphthalene content (76% total aromatics) were comparable to a 100% single-ring aromatic fuel (XTB).

As stated above, considering all fuels tested, hydrogen content was a better global indicator of the chemical property influence than total aromatics or naphthalene content alone. Figure 7 depicts the variation in dome radiation with an acknowledged global fuel specification parameter, smoke point. The data were well correlated by this parameter. In fact, regression analyses indicated that smoke point correlated the data better than hydrogen content:

$$\text{radiation} \sim H^{-1.65} \qquad R^2 = 0.87$$

$$\text{radiation} \sim SP^{-0.6} \qquad R^2 = 0.93$$

The latter regression is depicted in Fig. 8. As discussed by others (e.g., Ref. 17), the smoke point is a good indicator of the sooting tendency of a fuel. Hence, the quality of the data fit is consistent with the premise of changing chemical properties principally affecting soot formation.

The influence of specific chemical properties was pursued by examining the results of the parametric variation tests and of further regression analyses of all data. Results from the parametric variation tests are presented in Fig. 9 (which is an enlarged section of Fig. 4). Mean values of the nine-point data set are depicted with brackets indicating the extent of the data set standard error. The values in parentheses are the hydrogen, total aromatics, and naphthalene contents, respectively. The following fuel combinations comprised the property variations: hydrogen—ERBS and 7A; total aromatics—ERBS and 8A; naphthalene—ERBS, 9A, and 9B.

A relatively minor change in dome radiation was attained for the hydrogen content variation. The mean value did increase with reduced hydrogen content, but the overlapping limits of standard error prohibit precise definition of the influence. Indeed, the error limits allow the possibility of no influence of hydrogen content on radiation. While the variation of hydrogen content might appear to be small (0.75% point), it does represent 70% of the difference in hydrogen contents of Jet A and ERBS. Hence, these results indicate that despite a significant variation of hydrogen content (at constant single- and multiring aromatic content), no statistically significant change in radiation would be expected. This result is consistent with the actual fuel composition variation achieved in these tests; that is, the hydrogen variation arose from exchange of normal and cycloparaffins. Both these saturates have low sooting tendencies and, hence, no significant combustor influence would be expected. This observed independence of radiation on purely hydrogen content emphasizes the global character of representations like that depicted in Fig. 4. Used in this manner, hydrogen content variation represents a variation of species more fundamental to the sooting process.

The dome radiation level also did not vary significantly for tests performed with fuels offering a parametric variation of total aromatic hydrocarbons; despite a substantial reduction in this property, the mean value of radiation reduced only slightly, with the limits of standard error overlapping. The total aromatic variation was achieved by exchanging saturated hydrocarbons for single-ring aromatics. Hence, the data indicate that benzene-like structures did not strongly contribute to the radiation load. This result is in contrast to the high radiation levels indicated earlier (Fig. 6) for XTB and to the well-established sooting propensity of benzene-type molecules. The difference in these results may be due to the naphthalene content in the fuels; the variation in total aromatics was achieved at a constant naphthalene content of 13.5%. As discussed previously, it appears that naphthalenic hydrocarbons present a dominant influence on the sooting process. At the 13.5% level, these structures may have overridden the single-ring variation. Another total aromatic parametric variation was achieved in tests performed with fuels ERBLS1 and UTRC3B, both of which possessed a naphthalene content of approximately 15%. Again, no significant influence of total aromatics was observed. Further definition of the influence of these hydrocarbons was sought via regression analyses of data acquired for all fuels; these results are discussed below.

Substantial increases in the dome radiation were observed for parametric increases in the fuel naphthalene content over a range comparable to the difference in this property for Jet A

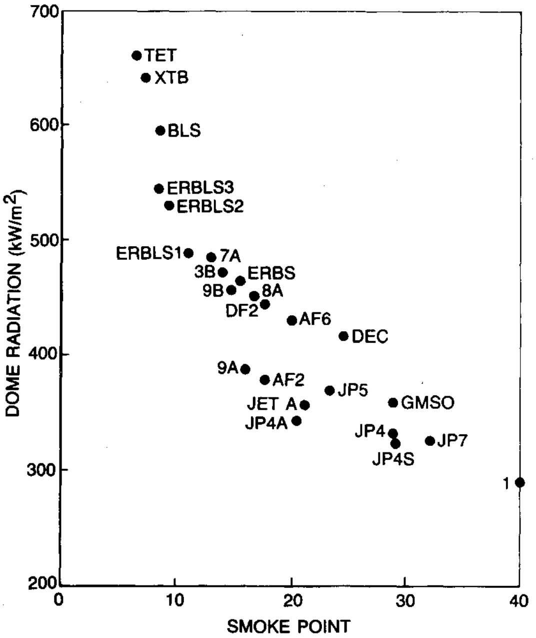

Fig. 7 Dependence of radiative load on fuel smoke point.

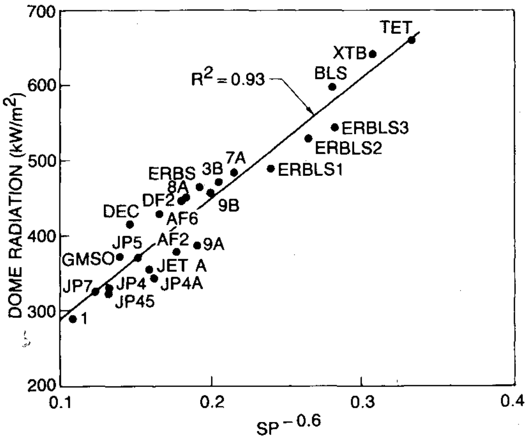

Fig. 8 Correlation of radiative load with smoke point.

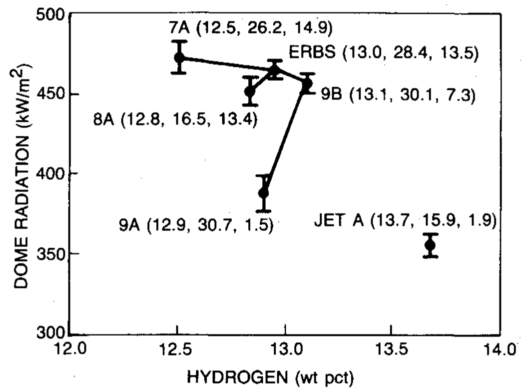

Fig. 9 Influence of parametric fuel property variations on radiative load.

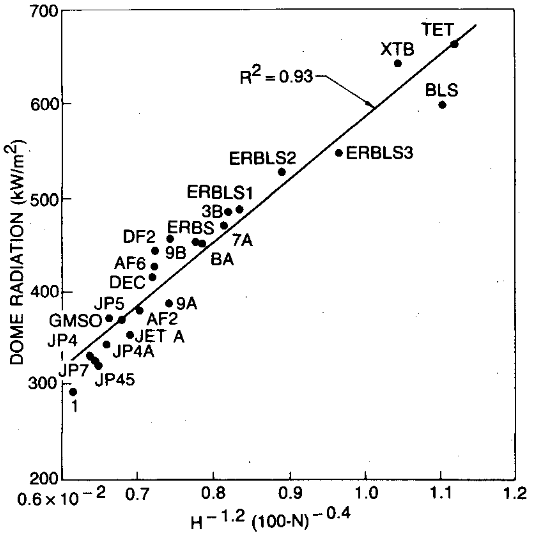

Fig. 10 Correlation of radiative load with fuel chemical properties.

and ERBS. Since *total* aromatic content was held constant, reductions of naphthalene content resulted from substitution of single-ring aromatics for double-ring naphthalenes. Thus, the lowest naphthalene content fuel, UTRC 9A, had the highest concentration of benzenes in this fuel sequence, while ERBS had the highest naphthalenes and lowest benzenes. The radiation level followed the naphthalene trend, and hence decreased for increasing single-ring aromatics. This behavior again demonstrated the importance of naphthalene content, reaffirming them to be more influential than the benzenes. These data also indicate that the naphthalene influence was nonlinear. That is, most of the total increase in radiation occurred for the first half of the total naphthalene content change. Therefore slight increases in a low naphthalene content fuel could result in disproportionate increases in sooting tendency, and consequently in the radiation load.

Regression analyses were performed to discern specific chemical property influences. Generally, data from tests with all fuels were used to cover the widest range of fuel property variation. Results from analyses using a three-property parameter [i.e., $H^{C1}A^{C2}(100\text{-}N)^{C3}$] indicated that total aromatic content was not a significant correlating term; the data were tracked equally well with or without its inclusion. The following two-property parameter, which embodied both hydrogen and naphthalene content, was the best representation of the data (Fig. 10):

$$\text{radiation} \sim H^{-1.2}(100\text{-}N)^{-0.4}, \; R^2 = 0.93$$

Four important features of this correlation were noted. First, both fuel property terms contribute significantly to the predicted change of radiation. For example, for the property changes associated with Jet A and ERBS fuels, half of the predicted radiation increase is attributed to the hydrogen content decrease and half to naphthalene content increase. Second, this correlation does not fully prescribe the influence of specific chemical properties. As previously discussed, the change in hydrogen content is a global indication of a more fundamental hydrocarbon-type change. Its presence in this correlation compensates for many unknown chemical features such as the apparent interactive influence of benzenes and naphthalenes. The regression analyses did, however, discern the important influence of naphthalenic hydrocarbons. Third, the quality of this correlation was equal to that for a smoke point correlation, both of which were superior to a solely hydrogen content correlation. Hence, while naphthalenes are recognized as an important chemical property class, smoke point—an existing fuel specification parameter—appears to prescribe properly the influence of fuel chemical properties. Fourth, none of the correlations was a perfect fit to the data. Hence, for any two fuels the three functional relationships—hydrogen, smoke point, hydrogen and naphthalene—may overpredict, underpredict, or perfectly predict the changes evidenced by data. For example, the parametric property variation test results indicated that naphthalene content variation was principally responsible for the difference in radiation for Jet A and ERBS. None of these three correlations reflects such a strong influence and hence all underpredict the change in radiation. A user of regression analysis results ought to recognize the implicit assumption that the trends established by a large data set (e.g., twenty-five fuels) are more reliable than trends indicated by a subset (e.g., two fuels) of the data. For a perfect correlation ($R^2 = 1$), this issue is academic; for nonperfect (i.e., realistic correlations) this issue magnifies as the departure from $R^2 = 1$ grows.

Conclusions

Based upon the data acquired in the combustion test program, the following conclusions have been made:

1) The principal influence of the fuel *chemical* properties on a gas turbine combustor is to alter the soot levels in the primary zone.

2) The fuel chemical property influence is properly represented by changes in the fuel smoke point, a specification parameter.

3) Fuel naphthalene content is a strong contributor to gas turbine combustor radiative heat load. It can dominate the influence of single-ring aromatics.

4) The influence of fuel naphthalene content is nonlinear. For low naphthalene content fuel, small increases can produce a large growth of soot concentration and hence radiative heat load.

5) For high naphthalene content fuel, added levels of this type of hydrocarbon result in small increases because the combustion zone has approached a uniform, highly radiating state.

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