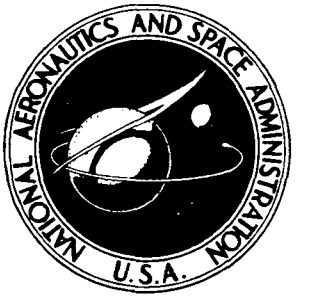
NASA TECHNICAL MEMORANDUM

NASA TM X-3394



NASA TM X-3394

SPECTRAL RADIANCE MEASUREMENTS AND CALCULATED SOOT CONCENTRATIONS ALONG THE LENGTH OF AN EXPERIMENTAL COMBUSTOR

Carl T. Norgren and Robert D. Ingebo

Lewis Research Center
Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1976

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TM X-3394		

4. Title and Subtitle	5. Report Date
SPECTRAL RADIANCE MEASUREMENTS AND CALCULATED SOOT CONCENTRATIONS ALONG THE LENGTH OF AN EXPERIMENTAL COMBUSTOR	April 1976
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Carl T. Norgren and Robert D. Ingebo	E-8630
	10. Work Unit No.
	505-03

9. Performing Organization Name and Address	11. Contract or Grant No.
Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135	
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Radiometric data were obtained over a range of parametric test conditions at three positions along the length of an experimental combustor segment corresponding to the primary, intermediate, and dilution zones. The concentration of soot entrained in the combustion gases was calculated by a technique using spectral radiance measurements. Tests were conducted primarily with Jet A fuel, although limited data were taken with two fuels having higher aromatic content, diesel oil number 2 and a blend of 40 percent tetralin in Jet A fuel. Radiometric observation of the combustion gases indicated that the maximum total radiance peaked at the intermediate zone, which was located immediately upstream of the dilution holes. Soot concentrations calculated from optical measurements in the dilution zone compared favorably with those obtained by in situ gas sampling at the exhaust. The total radiance increased with the higher aromatic content fuels.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Combustion Fuels Pollutants Heat transfer Flame radiance	Unclassified - unlimited STAR Category 07

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	24	$3.25

* For sale by the National Technical Information Service, Springfield, Virginia 22161

SPECTRAL RADIANCE MEASUREMENTS AND CALCULATED SOOT CONCENTRATIONS ALONG THE LENGTH OF AN EXPERIMENTAL COMBUSTOR

by Carl T. Norgren and Robert D. Ingebo

Lewis Research Center

SUMMARY

Radiometric data were obtained over a range of parametric test conditions at three positions along the length of an experimental combustor segment corresponding to the primary, intermediate, and dilution zones. The concentration of soot entrained in the combustion gases was calculated by a technique using spectral radiance measurements. Fuel was injected by means of air-atomizing fuel injectors of an advanced design. Tests were conducted primarily with Jet A fuel, although limited data were taken with two fuels having higher aromatic content, diesel oil number 2 and a blend of 40 percent tetralin in Jet A fuel.

Radiometric observation of the combustion gases indicated that the maximum total radiance peaked at the intermediate zone, which was located immediately upstream of the dilution holes. Typical maximum radiance levels were of the order of 40 watts per square centimeter per steradian for inlet pressures of 100 and 200 newtons per square centimeter and inlet-air temperatures of 589 and 700 K. Soot concentrations within the combustor primary zone were calculated to be approximately 10 to 20 times greater than those at the dilution zone. Soot concentrations calculated from optical measurements at the dilution zone compared favorably with those obtained by in situ gas sampling at the exhaust.

An increase in total radiance was observed when the combustor was operated with fuels with higher aromatic content and decreased hydrogen-carbon ratio as compared with Jet A fuel.

INTRODUCTION

In this study flame radiance and soot concentrations were determined along the length of an experimental combustor segment, with an advanced air-atomizing fuel injector system, over a range of parametric test conditions representative of contemporary high-thrust turbine engines.

Soot formation within the combustor causes two problems: first, the emission of a smoke trail and pollution of the atmosphere, particularly in the vicinity of the airport, and second, combustor cooling problems due to excessive radiation to the liner walls. The mechanisms whereby soot is formed within the combustor have not been clearly defined; however, fuel type, hydrogen-carbon ratio, and fuel preparation (including atomization, vaporization, equivalence ratio, and the degree of mixing of the fuel and air) have a pronounced effect on the smoking tendency of a combustor. Visible exhaust smoke plumes have largely been eliminated in contemporary turbine engines by application of designs that reduce the primary-zone equivalence ratio and improve mixing. The primary-zone equivalence ratio can be reduced somewhat, but the level must not fall below the stability limit. Since the smoke threshold is often just above the stability limit, soot is usually still present in the primary combustion zone. Even so, experimental evidence indicates it is possible to achieve a reduction of visible exhaust smoke by reducing the primary-zone equivalence ratio and improving the fuel and air mixing by means of an air-atomizing fuel injector (ref. 1). Future aviation turbine fuels refined from either petroleum, shale oil, or coal syncrudes may have an even higher tendency for soot formation than currently available fuels (ref. 2). Even when the level of the exhaust smoke has been reduced below visibility, high soot densities are still present within the combustion flame, particularly at high pressure levels. The high soot density increases the total radiance to the combustor walls because the continuum radiation of the soot has a much higher emittance than the select-band emission of the normal products of combustion (carbon dioxide and water).

The most direct approach to determining soot concentration is by sampling the combustion gas. Attempts have been made to take samples within the primary flame zone; however, as combustor pressure and temperature are increased, sampling becomes increasingly more difficult because of the tendency for soot to build up in the sampling probe, as discussed in reference 3. An alternative technique which does not require a sampling probe has been investigated at the NASA Lewis Research Center. In this technique the primary-zone soot concentration is calculated from optical measurements, as reported in reference 4. The continuum radiance from soot is observed in a spectral region where the combustion products are transparent. It is assumed that the soot and combustion products are in thermal equilibrium. The apparent temperature of the combustion products can be obtained from spectral radiance in a region where black-body

emittance can be assumed. Then the spectral emittance of the soot can be calculated. The soot concentration required to achieve this emittance can in turn be calculated from Beer's law and a knowledge of the extinction coefficient of the cloud of soot particles as determined from Mie theory. Previous data were limited to the total and spectral radiance in the primary zone obtained by using pressure-atomizing fuel nozzles.

In the present study a similar optical technique was used; however, both total and spectral radiance measurements were made downstream of the combustor faceplate at three positions within the flame zone corresponding not only to the primary zone but also the intermediate and dilution zones. In addition, an air-atomizing fuel injection system of advanced design was used. The dilution zone was located near the turbine stator and provided a reference point for comparing exhaust soot concentration determined optically with soot concentration inferred from smoke number.

The combustor was similar to that reported in reference 1 and was also equipped with the same advanced air-atomizing fuel injectors. Tests were conducted over a parametric range of test conditions with pressures from 40 to 200 newtons per square centimeter, inlet-air temperatures from 589 to 811 K, and fuel-air ratios from 0.010 to 0.020; Jet A fuel was used. Limited tests were also conducted with a higher boiling point fuel (diesel oil number 2) and a high-molecular-weight aromatic blend (40 percent tetralin in Jet A fuel). These data were compared with those for Jet A fuel. Total flame radiance and calculated soot concentrations for three positions representing the primary, intermediate, and dilution zones are presented in this report. A comparison of calculated soot concentrations and soot concentrations obtained from the smoke number determination by using the correlation of reference 5 is presented for the dilution zone.

APPARATUS AND PROCEDURE

Test Facility

The test combustor was mounted in the closed-duct facility described in reference 1 and shown in figure 1. Tests were conducted at pressures from 40 to 200 newtons per square centimeter. Combustion air drawn from the laboratory high-pressure supply system was indirectly heated to 811 K (1460° R) in a counterflow U-tube heat exchanger. The temperature of the air flowing out of the heat exchanger was automatically controlled by being mixed with varying amounts of cold bypassed air. The airflow through the heat exchanger and bypass flow system and the total pressure of the combustor inlet airflow were regulated by remotely controlled valves.

Combustor instrumentation stations are also shown in figure 1. The inlet-air temperature was measured at station A with eight Chromel-Alumel thermocouples. Inlet

total pressures were measured at the same station by four stationary rakes consisting of three total-pressure tubes each. The total-pressure tubes were connected to differential pressure strain-gage transducers that were balanced by wall static-pressure taps located at the top and bottom of the duct. The three radiometer locations were at stations B1, B2, and B3, and the exhaust gas sampling probe was at station C.

Combustor

The combustor liner used in this investigation was similar to the combustor of reference 1. A schematic of the combustor is shown in figure 2. The combustor had an inlet snout area which was 40 percent of the combustor inlet area. The main portion of the airflow entering the snout passed through air swirlers. A small portion, approximately 6 percent of the total flow, was used to film cool the sides of the combustor. The combustor liner walls were film cooled by means of continuous slots. The dilution air was admitted by means of external scoops. Also shown in figure 2 are the radiometer locations (stations B1, B2, and B3) corresponding to the combustor primary, intermediate, and dilution zones 0.051, 0.114, and 0.254 meter (2, 4.5, and 10 in.), respectively, downstream of the fuel nozzle faceplate.

Fuel Injectors

The fuel injectors used in this study were similar to the splash-groove air-atomizing fuel injectors described in reference 1. The splash-groove fuel injector assembly and detail are shown in figure 3. Four fuel injectors were used, and all the primary air was ducted into the shrouds surrounding each injector so that swirl would stabilize the flame. There were 42 orifices 0.051 centimeter in diameter in each fuel nozzle. The fuel pressure drop for Jet A fuel was of the order of 10 newtons per square centimeter for a flow rate of 0.015 kilogram per second.

Radiometric System

The basic radiometer unit consisted of an indium antimonide detector, maintained at 78 K and equipped with four narrow-band filters (± 0.03 μm) centered at 2.01, 2.70, 4.05, and 4.30 micrometers, and a bolometer with an unimmersed detector with a sensitivity range of 0.25 to 6 micrometers. A schematic of the infrared measuring system is shown in figure 4. A pair of sapphire window 0.64 centimeter thick was mounted on

each side of the combustor pressure housing for viewing the flame. The system was calibrated by means of two black-body sources, a resistance source heated to 1273 K and an induction source capable of 3000 K operation. All optical paths and the radiometer unit were purged continually with nitrogen gas.

The radiometric system used in this study is described in reference 4. Details of the detector, optics, filtering, and calibration procedure may be found in reference 4.

Test Conditions

The combustor was operated over a range of parametric test conditions based on takeoff and cruise of high-thrust contemporary turbine engines. The test conditions are given in table I. Test conditions B and D are typical of cruise and takeoff, respectively, for high-bypass-ratio turbofan engines, while test condition G is typical of supersonic cruise. In general, each test condition included a range of fuel-air ratios with Jet A fuel for each of the three radiometer locations. The radiometer was positioned at the locations shown in figure 2, defined as the primary, intermediate, and dilution zones. In addition, limited data were also obtained with alternative fuels at test conditions E, F, and G: with diesel oil number 2 the radiometer was positioned at the primary zone, and with the blend of 40 percent tetralin in Jet A fuel the radiometer was positioned at the dilution zone. Fuel properties are listed in table II.

CALCULATIONS

Radiometry

The calculation procedure is briefly summarized in this section. More details, including assumptions, limitations, and background material, are given in reference 4. The total radiance was determined from the bolometer indication by means of calibration curves. The soot concentration was calculated from spectral radiance measurements.

The soot concentration within a radiating cloud can be related to its emittance by means of Beer's law:

$$\epsilon_\lambda = 1 - \exp(-c l K_{t,\lambda}) \tag{1}$$

where ϵ_λ is the spectral emittance of the soot, c is the concentration of the soot, l is the optical path length, and $K_{t,\lambda}$ is the total extinction coefficient. All measurements and values refer to a single wavelength λ. A more convenient form of equation (1) used to determine the soot concentration is

$$c = \frac{-\ln(1 - \epsilon_\lambda)}{l K_{t,\lambda}} \tag{1a}$$

The spectral emittance of the soot for a given wavelength λ is defined as

$$\epsilon_\lambda = \frac{L_\lambda}{L_{b,\lambda}} \tag{2}$$

where L_λ is the spectral radiance of the soot, and $L_{b,\lambda}$ is the blackbody spectral radiance evaluated at the temperature of the soot.

The following assumptions were made in the determination of the soot emittance from equation (2):

(1) The combustion products can be represented by a single value of temperature (i.e., there is a uniform temperature profile in the line of sight).

(2) The soot is in thermodynamic equilibrium with the surrounding combustion products (ref. 6).

(3) The spectral radiance of the soot can be measured in a flame over a wavelength interval where the radiation from the combustion products (water vapor and carbon dioxide) is transparent. (A narrow-band filter centered at 4.05 μm was selected for viewing the soot radiance.)

(4) The temperature of the combustion products can be determined over a wavelength interval where their emittance can be assumed to be unity. (A narrow-band filter centered at 2.70 μm was selected for viewing the normal products of combustion.)

Thus, on the basis of assumption (4), the temperature of the combustion products was calculated from the 2.70-micrometer spectral radiance by using black-body radiation functions. The value of $L_{b,\lambda}$ for equation (2) was then calculated by using blackbody functions at this combustion temperature and 4.05 micrometers, in accordance with assumption (2). Finally, L_λ was determined from the 4.05-micrometer radiometer readings, on the basis of assumption (3).

For calculations of soot concentrations from equation (1a), the total extinction coefficient $K_{t,\lambda}$ and beam length l are required. Because the average soot particle is small with respect to the measurement wavelengths, scattering is negligible, and the extinction coefficient is equal to the fraction of radiation absorbed. Furthermore, the extinction coefficient is assumed independent of temperature, soot composition, and particle size and is a function of wavelength only. The bases of these assumptions are discussed in references 6 and 7. A value of 4.3×10^{-6} cubic meter per milligram per centimeter at a wavelength of 4.05 micrometers was used (from the data of Foster, refs. 7 and 8). A mean path length l equivalent to the combustor width of 30.48 centimeters was used.

Smoke-Number Determination

The exhaust particulate sample was withdrawn through an exhaust probe located at station C (see fig. 1). The probe had a four-port sampling head to obtain a representative sample across the duct. The probe was positioned 0.92 meter downstream of the dilution-zone radiometric station. The sample line was heated by means of steam tracing, and the smoke number was determined with the smoke meter shown in figure 5. The smoke number was determined from the sample collected on a filter paper according to the procedure recommended in reference 9 and described in reference 5.

RESULTS AND DISCUSSION

An experimental rectangular combustor segment was operated with splash-groove fuel injectors over the range of parametric test conditions shown in table I. Data were obtained with Jet A fuel at all test conditions and with diesel oil number 2 and a tetralin blend at test conditions E, F, and G. Total flame radiance and calculated soot concentrations are presented for Jet A fuel at three locations downstream of the fuel injectors corresponding to the primary, intermediate, and dilution zones. Soot concentrations at the dilution zone are compared by different methods: (1) remote optical measurement and (2) in situ gas sampling. Data are presented for the primary zone and diesel oil number 2 and for the dilution zone and the tetralin blend.

Total Flame Radiance

The total flame radiance for test conditions A, B, C, and D over a range of fuel-air ratios is shown in figure 6 at each of the three radiometer locations. (The term "total flame radiance" in all cases refers to directional total flame radiance.) Qualitatively, it can be noted that the total radiance increased with fuel-air ratio. There were exceptions; in particular, at the intermediate position the total radiance decreased at the highest fuel-air ratio investigated. It is possible, for example, that recirculation patterns were intensified at the higher fuel-air ratio because of the close proximity of the dilution holes, and a decrease in the combustion gas temperature resulted. Because of the complex nature of the combustion process it is not surprising that there were exceptions to apparent trends. Fuel-flow distribution and internal airflow patterns were affected by changes in reaction-zone volume due to test conditions and heat loading requirements. It was beyond the scope of this program to control independently all variables to establish meaningful trends for each segment of the combustion process.

Radiant heat transfer to the combustion liner is of most interest at the higher fuel

flows. In figure 7 the total radiance levels are cross plotted for a fuel-air ratio of 0.018 at the three radiometer positions along the length of the combustor. The maximum radiance was 36, 41, 38, and 41 watts per square centimeter per steradian at test conditions A, B, C, and D, respectively. Note that 1 watt per square centimeter per steradian is equal to 3174 Btu per square foot per steradian or 9971 Btu per hour per square foot, for a total hemispherical radiance of approximately 10 000 Btu per hour per square foot. The peak radiance observed at the intermediate zone was similar to that which could be expected on the basis of black-body emittance at an adiabatic flame temperature corresponding to the design equivalence ratio of approximately 0.75 at a fuel-air ratio of 0.018. The total radiance peaked at the intermediate position at a level approximately twice that of the primary zone. The high total radiance at the intermediate position was unexpected. It had been previously noted from experimental data reported in reference 4 that the maximum total radiance was observed approximately 5 centimeters downstream of the pressure-atomizing fuel nozzles. Although data were not reported for additional longitudinal positions, a preliminary axial survey had been taken to determine the maximum radiance. At the position equivalent to the intermediate zone of this report the total radiance had decreased approximately 25 percent as compared with that of the primary zone. All data reported in reference 4 were therefore obtained at the position of peak total radiance, the primary zone of this report.

Total flame radiance is dependent on the soot concentration within the flame, the normal products of combustion, and the temperature. Any parameter which affects the flow characteristics affects total radiance. One of the major differences between the combustion in the present study and that of reference 4 was the preparation of the fuel prior to combustion. In the previous study a simplex pressure-atomizing fuel nozzle was used, and most of the primary air was introduced at the faceplate by means of swirlers (to stabilize the flame) concentric with the fuel nozzles. In the present study an air-atomizing splash-groove fuel injector of advanced design was used. Fuel at low pressure was distributed onto a series of splash grooves (see fig. 3). The fuel was picked up as a film and atomized by means of high-velocity air obtained by a venturi restriction at the point of fuel injection. It is possible that mixing and associated fuel preparation changed the recirculation zones and shifted the peak radiance. At the present time there are not sufficient data to generalize about where along the length of the primary combustion zone the peak radiance will occur for different types of combustor configurations.

Soot Concentration

The calculated soot concentrations for the four test conditions over a range of fuel-air ratios are shown in figure 8. For the primary zone the soot concentration was of the order of 20 to 50 milligrams per cubic meter for test conditions A and B and 50 to

180 milligrams per cubic meter for test conditions C and D over a range of fuel-air ratios of 0.010 to 0.020. At the exhaust (dilution zone) the soot concentration ranges were 2 to 6 and 3 to 16 milligrams per cubic meter for test conditions A and B and test conditions C and D, respectively.

Also shown in figure 8 are the soot concentrations obtained from reference 4. Up to a fuel-air ratio of 0.013 the primary-zone soot concentrations obtained with the pressure-atomizing fuel nozzles of reference 4 were higher by a factor of 15 to 30 than the soot concentrations obtained with the air-atomizing injectors of the present study.

The calculations of soot concentration at the intermediate position gave inconsistent results, and these are omitted from figure 8. As already noted, total radiance peaked at this position. Nevertheless, calculations from the spectral radiometer measurements indicated a flame temperature lower than expected. Two extreme possibilities are considered which could account for the apparent discrepancy between the total and spectral radiance measurements: (1) the soot particles were at a higher temperature than the surrounding gas because of surface phenomena, and (2) strong thermal gas gradients existed in the flame.

The excess particle temperature is conceivable because of surface oxidation by oxygen recirculation from the combustor dilution holes. Evidence of intense mixing was seen in oscillations of the radiometer indications (approximately ±12 percent about the average at the intermediate position). A nonequilibrium of gases and soot in flames has been reported in a previous investigation (ref. 10), where soot temperatures were 200 K higher than the combustion gas environment.

The second possibility lies in low apparent flame temperature indication due to strong thermal gradients. All the dilution air was admitted to the combustor downstream of the intermediate-zone observation window. The assumption of uniform temperature in the radiometer line of sight was most severely strained at this location. It has been shown in reference 11 that erroneous measurements may be caused by locally strong absorbing gases when thermal gradients are present. In the test runs of this study, the 200-newton-per-square-centimeter pressure (test conditions C and D) indicated lower apparent flame temperatures than the 100-newton-per-square-centimeter pressure (test conditions A and B). If similar thermal gradients and mixing were assumed, a lower temperature indication would be expected because of doubling the pressure (increasing the density) of the absorbing media.

Where the assumptions necessary for the calculation of the soot concentration discussed in the section CALCULATIONS are valid, as at the primary and dilution zones, the soot particle concentration is calculated with reasonable accuracy. The complex flow field existing in the intermediate zone cannot be adequately approximated by this method.

Comparison of Exhaust Measurements

In figure 9 the smoke numbers obtained from sampling at the exhaust sampling station are compared with the soot (carbon) concentrations obtained optically at the dilution station for test conditions A, B, C, and D. Also shown in figure 9 is the correlation relating smoke number and carbon concentration from reference 5. The carbon concentration from reference 5 was obtained from soot collected on a fiberglass filter and quantitatively analyzed for carbon.

Comparison of the data from the present investigation with the correlation from reference 5 indicates similar trends of increasing carbon concentration with smoke number. Comparison of the carbon concentration determined by the optical technique indicated a concentration of 5 milligrams per cubic meter for a smoke number of 20 as compared with 2 milligrams per cubic meter indicated by the previous correlation of reference 5.

The optical method is expected to give soot concentrations somewhat higher than those indicated by gas sampling for the following reasons: (1) soot particles may contain up to 8 percent or more noncarbonaceous constituents (ref. 6) ignored in the smoke sample analysis of reference 5; (2) boundary layer and vena contracta effects can produce a small inefficiency in sampling resulting in a lowering of the smoke number; and (3) while reactions are nominally frozen at the exhaust equilibrium temperature, some surface oxidation of soot particles may continue in unquenched hot zones. The gas sampling probe was located 0.92 meter downstream of the optical viewing station at the dilution zone in an expanded rectangular exhaust section (fivefold area increase, see fig. 1).

Nevertheless, the agreement between soot concentration as determined from optical measurement and from in situ gas sampling is within an order of magnitude. This provides a good check of the accuracy of spectral data at the dilution position, where the temperature profiles are relatively uniform. It should be noted that the accuracy of the quantitative method used to determine carbon content at low carbon concentrations (i.e., of the order of 1 mg/m^3) is within a factor of 2 if the complexities of sampling are neglected. The soot concentration calculated from optical measurement was high by a factor of 2.5. At the primary position, near the multiple fuel injection points, the optical soot concentration measurements may have less accuracy because of nonuniform temperature zones but should still provide a reasonable representation of the particle concentration.

Effect of Fuel Properties on Total Radiance

Limited data with alternative fuels were obtained at test conditions E, F, and G (inlet pressure of 40 N/cm^2; reference velocity of 21.3 m/sec; inlet-air temperatures

from 589 to 811 K; and a range of fuel-air ratios of 0.010 to 0.020). Figure 10 shows test data for diesel oil number 2 and Jet A fuel with the radiometer located at the primary zone, and figure 11 shows test data for a blend of 40 percent tetralin in Jet A fuel and Jet A fuel with the radiometer located at the dilution zone. The fuels were originally evaluated to determine the exhaust emission characteristics of oxides of nitrogen, carbon monoxide, and unburned hydrocarbons with the air-atomizing injector (ref. 1). Radiometric measurements were made at the same time; however, because of the limited quantity of fuel available only a single radiometer location could be selected. The data from figures 10 and 11 are cross plotted in figure 12 for a constant fuel-air ratio of 0.018 for a range of inlet-air temperatures.

The total radiance obtained with Jet A fuel shown in figure 12 varied from 5.5 to 10 and from 3 to 5 watts per square centimeter per steradian for the primary and dilution zones, respectively. The data obtained with diesel oil number 2 with the radiometer at the primary location indicate a total radiance range of 6.5 to 18 watts per square centimeter per steradian or an increase in radiance from 18 percent at 589 K to 75 percent at 811 K as compared with values for Jet A fuel in this experimental combustor. The data obtained at the dilution zone location with 40 percent tetralin in Jet A fuel indicate a total radiance range of 5.2 to 8.6 watts per square centimeter per steradian or an increase in radiance from 58 percent at 589 K to 65 percent at 811 K as compared with values for Jet A fuel in the experimental combustor.

The cross plots for Jet A fuel and the tetralin blend from figure 12 are repeated in figure 13 with the addition of theoretical black-body radiance. The theoretical black-body radiance was based on the theoretical flame temperature as determined by the fuel type and overall equivalence ratio with the emittance assumed to be unity.

The observed total radiance for Jet A fuel was less than the theoretical radiance; however, the total radiance observed with the tetralin blend was similar to that associated with black-body theoretical radiance. At the low inlet-air temperature (test condition E) the observed radiance was higher than expected. Some stratification of hot gas may have existed near the wall at low fuel flows and could have accounted for the increased apparent total radiance.

A systematic evaluation of the radiation characteristics of alternative fuels was not included in the scope of this investigation. Even though only limited data were obtained, significant trends were noted. Both of the alternative fuels have properties which are known to affect overall performance adversely as compared with the current aviation fuel, Jet A fuel. Diesel oil number 2 has a lower vapor pressure and higher aromatic content, and the 40 percent tetralin blend has a greater high-molecular-weight aromatic content than Jet A fuel (see table II). The increase in soot concentration and hence radiance was probably due to decreased hydrogen content associated with aromatic fuels. Observed total radiance, which was similar to that which could be expected because of

black-body radiance, indicated that at severe conditions liner cooling problems could arise with alternative fuels which would not arise with Jet A fuel. This may become a problem if changes in fuel specifications are necessitated (see also ref. 2).

SUMMARY OF RESULTS

Radiometric measurements of the flame in an experimental combustor segment burning Jet A fuel injected with splash-groove air-atomizing fuel nozzles were obtained at three axial positions corresponding to the primary, intermediate, and dilution zones. Total flame radiance, calculated soot concentrations from spectral radiance measurements, and gas samples at the exhaust were obtained at four test conditions (condition A, pressure equal to 100 N/cm^2 and inlet-air temperature equal to 589 K; B, 100 N/cm^2 and 700 K; C, 200 N/cm^2 and 589 K; and D, 200 N/cm^2 and 700 K). In addition, limited tests were conducted with two alternative fuels, diesel oil number 2 and a blend of 40 percent tetralin in Jet A fuel. These fuels were compared with Jet A fuel at a combustor pressure of 40 newtons per square centimeter and inlet-air temperatures of 589, 700, and 811 K. The constant reference velocity was 21.3 meters per second. The following results were obtained:

1. The total radiance from the soot peaked in the intermediate zone within the combustor at a value approximately twice that observed in the primary zone. The maximum total radiance was approximately 40 watts per square centimeter per steradian for test conditions A, B, C, and D at a fuel-air ratio of 0.018.

2. The calculated soot concentrations within the combustor primary zone were approximately 15 to 30 times lower with the air-atomizing injectors than those previously determined with pressure-atomizing nozzles for a fuel-air ratio of 0.010.

3. Soot concentrations within the combustor primary zone were calculated to be approximately 10 to 20 times greater than those at the dilution zone.

4. The soot concentration determined optically at the dilution zone was in good agreement with the soot concentration determined by gas sampling at the exhaust.

5. An increase in total radiance was observed when the combustor was operated with a fuel having an increased distillation temperature and aromatic content as compared with Jet A fuel (diesel oil number 2) and a fuel blend composed of approximately 50 percent aromatics (40 percent tetralin in Jet A fuel).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 10, 1976,
505-03.

REFERENCES

1. Ingebo, Robert D.; and Norgren, Carl T.: Combustor Exhaust Emissions With Air-Atomizing Splash-Groove Fuel Injectors Burning Jet A and Diesel Number 2 Fuels. NASA TM X-3255, 1975.

2. Butze, Helmut F.; and Ehlers, Robert C.: Effect of Fuel Properties on Combustion Performance of a Single Aircraft Turbojet Combustor. TM X-71789, 1975.

3. Toone, B.: A Review of Aero Engine Smoke Emission. Combustion in Advanced Gas Turbine Systems. I. E. Smith, ed., Pergamon Press, 1967, pp. 271-293.

4. Norgren, Carl T.: Determination of Primary-Zone Smoke Concentrations From Spectral Radiance Measurements in Gas Turbine Combustors. NASA TN D-6410, 1971.

5. Norgren, Carl T.; and Ingebo, Robert D.: Particulate Exhaust Emissions From an Experimental Combustor. NASA TM X-3254, 1975.

6. Millikan, Roger C.: Sizes, Optical Properties, and Temperature of Soot Particles. Temperature: Its Measurement and Control in Science and Industry. Vol. III, Part 2, Applied Methods and Instruments. A. I. Dahl, ed., Rienhold Publishing Co., 1962, pp. 497-507.

7. Liebert, Curt H.; and Hibbard, Robert R.: Spectral Radiance of Soot. NASA TN D-5647, 1970.

8. Foster, P. J.: Calculation of the Optical Properties of Dispersed Phases. Comb. and Flame, vol. 7, no. 3, Sept. 1963, pp. 277-282.

9. Control of Air Pollution From Aircraft and Aircraft Engines - Emission Standards and Test Procedures From Aircraft. Federal Register, vol. 38, no. 136, pt. 2, Tues., July 17, 1973, pp. 19088-19103.

10. Behrens, H.; and Rossler, F.: Temperature Measurements on Soot Jets in Flames. Z. Elektrochem., vol. 61, no. 5, 1957, pp. 610-613.

11. Hornbeck, George A.; and Olsen, Lief O.: Emission and Absorption Studies of Jet Engine Hydrocarbon Combustion Products. Nat. Bureau of Standards (WADC TR 57-516; AD-2037911), 1958.

TABLE I. - COMBUSTOR TEST CONDITIONS

[Combustor reference velocity, 21.3 m/sec (70 ft/sec).]

Test condition	Inlet pressure		Inlet-air temperature		Radiometer position (a)	Fuel	Flight condition simulated
	N/cm^2	atm	K	^oR			
A	100	10	589	1060	P, I, D	Jet A	
B	100	10	700	1260	P, I, D	Jet A	Subsonic cruise
C	200	20	589	1060	P, I, D	Jet A	
D	200	20	700	1260	P, I, D	Jet A	Subsonic takeoff
E	40	4	589	1060	P, I, D	Jet A	----------
					P	Diesel oil number 2	
					D	Tetralin blend	
F	40	4	700	1260	P, I, D	Jet A	----------
					P	Diesel oil number 2	
					D	Tetralin blend	
G	40	4	811	1460	P, I, D	Jet A	Supersonic cruise
					P	Diesel oil number 2	
					D	Tetralin blend	

[a]Primary zone, P; intermediate zone, I; dilution zone, D (see fig. 2).

TABLE II. - PHYSICAL AND CHEMICAL PROPERTIES OF TEST FUELS

Property	Fuel		
	Jet A	Diesel number 2	40 Percent tetralin in Jet A fuel
Boiling point, K (^oR)			
Initial	442 (796)	450 (810)	<466 (<838)
Final	544 (980)	607 (1094)	529 (952)
Distillation point (10 percent), K (^oR)	460 (829)	490 (882)	471 (848)
Lower heating value, J/g (Btu/lb)	43 000 (18 600)	42 600 (18 464)	41 843 (18 114)
Hydrogen-carbon ratio	0.160	0.150	0.135
Aromatics, vol.%	16.8	30.5	51.7
Viscosity, m^2/sec (cS)			
At 294 K (70° F)	1.3×10^{-6} (1.3)	4.0×10^{-6} (4.0)	2.0×10^{-6} (2.0)
At 239 K (-30° F)	9.2×10^{-6} (9.2)	----------	----------

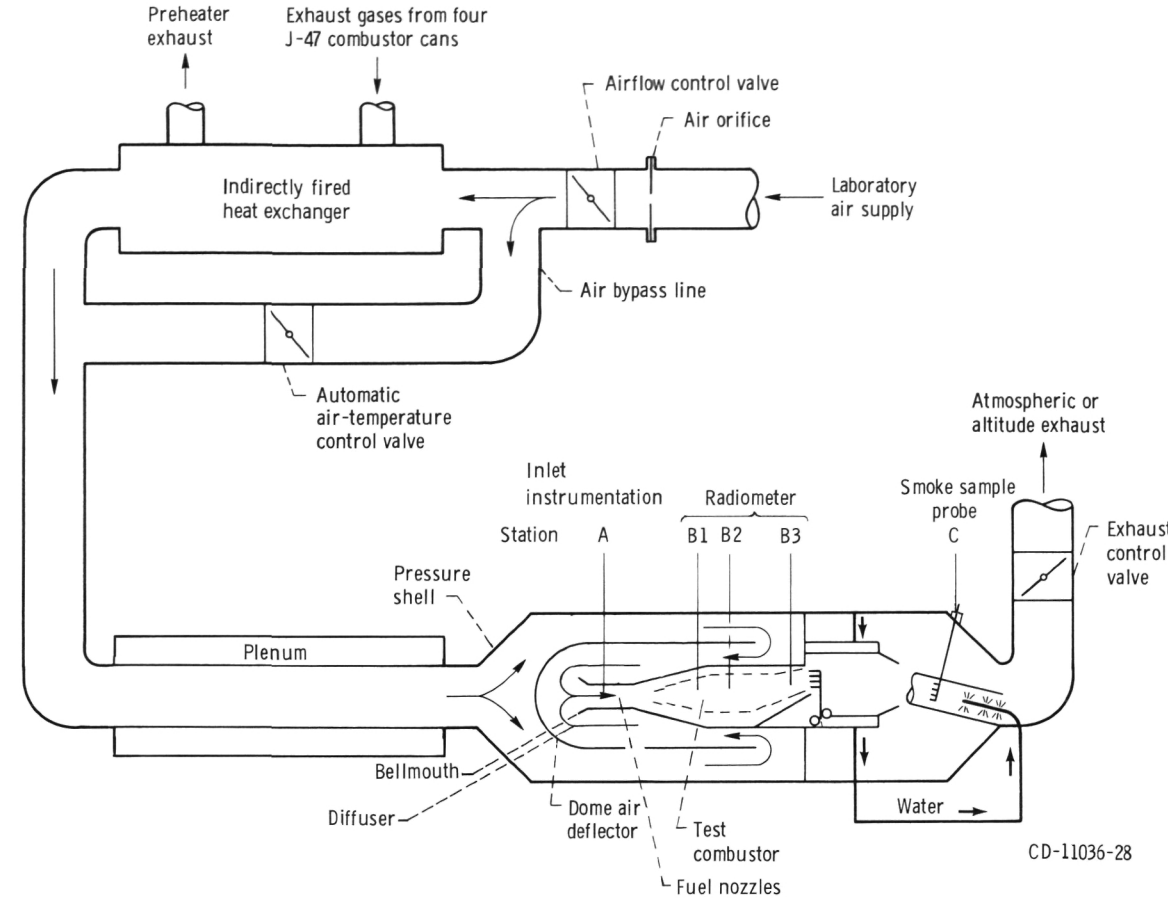


Figure 1. - Test facility.

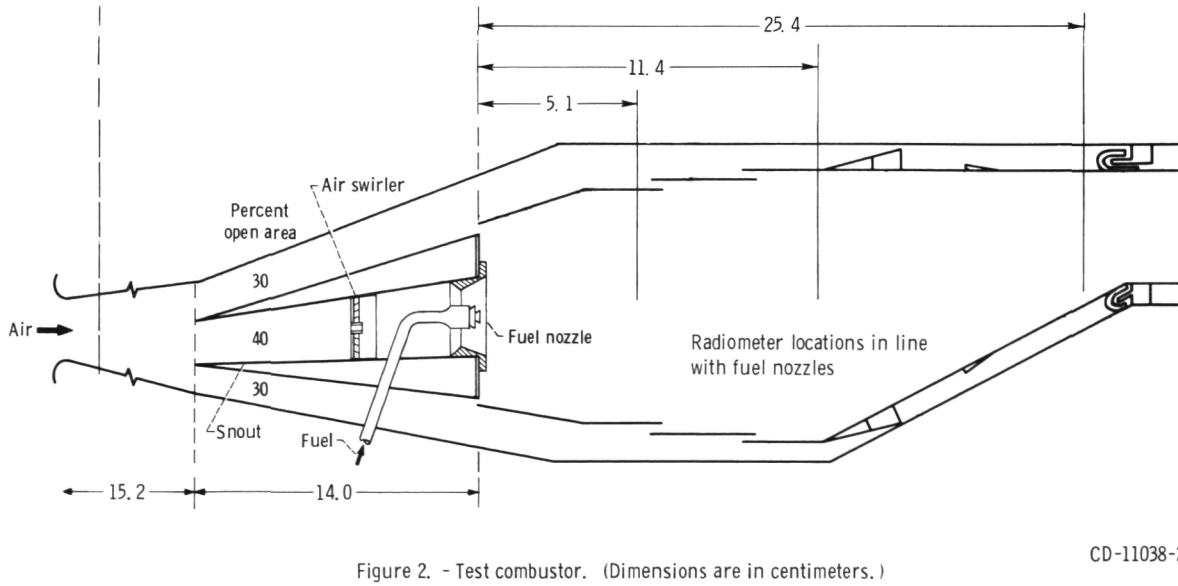
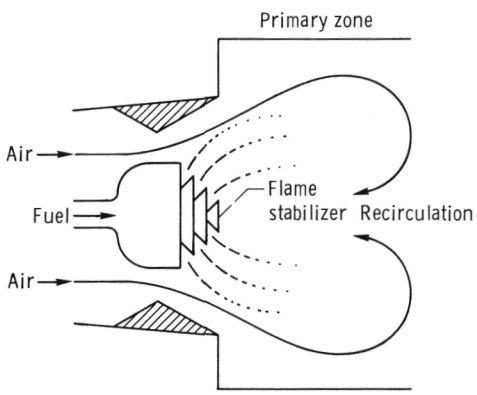
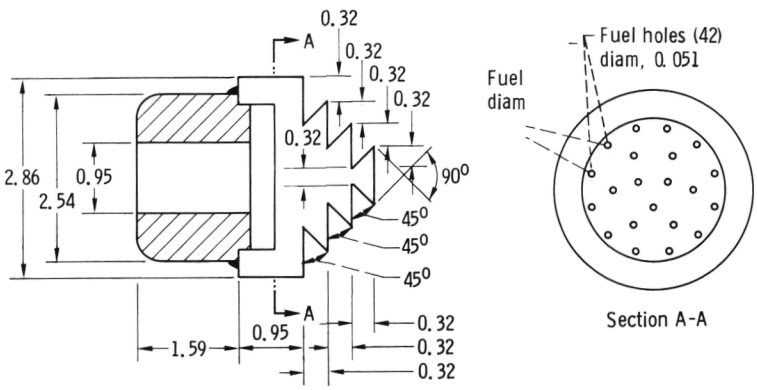


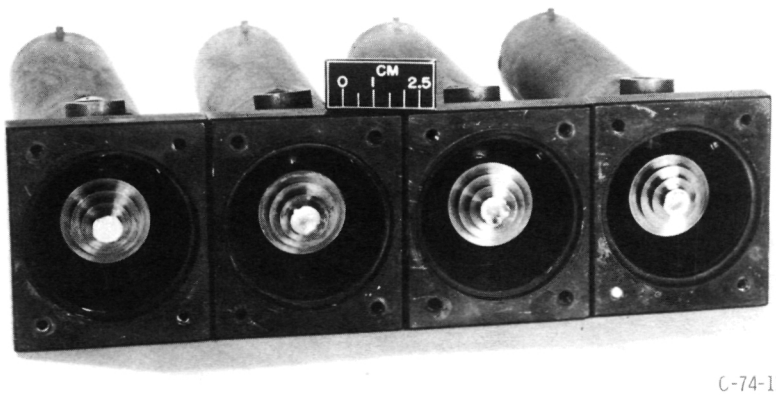
Figure 2. - Test combustor. (Dimensions are in centimeters.)



(a) Schematic of injector mounted in combustor.



(b) Dimensioned detail of fuel injector.



(c) Photograph of combustor snout with fuel injectors.

Figure 3. - Splash-groove air-atomizing fuel injector.

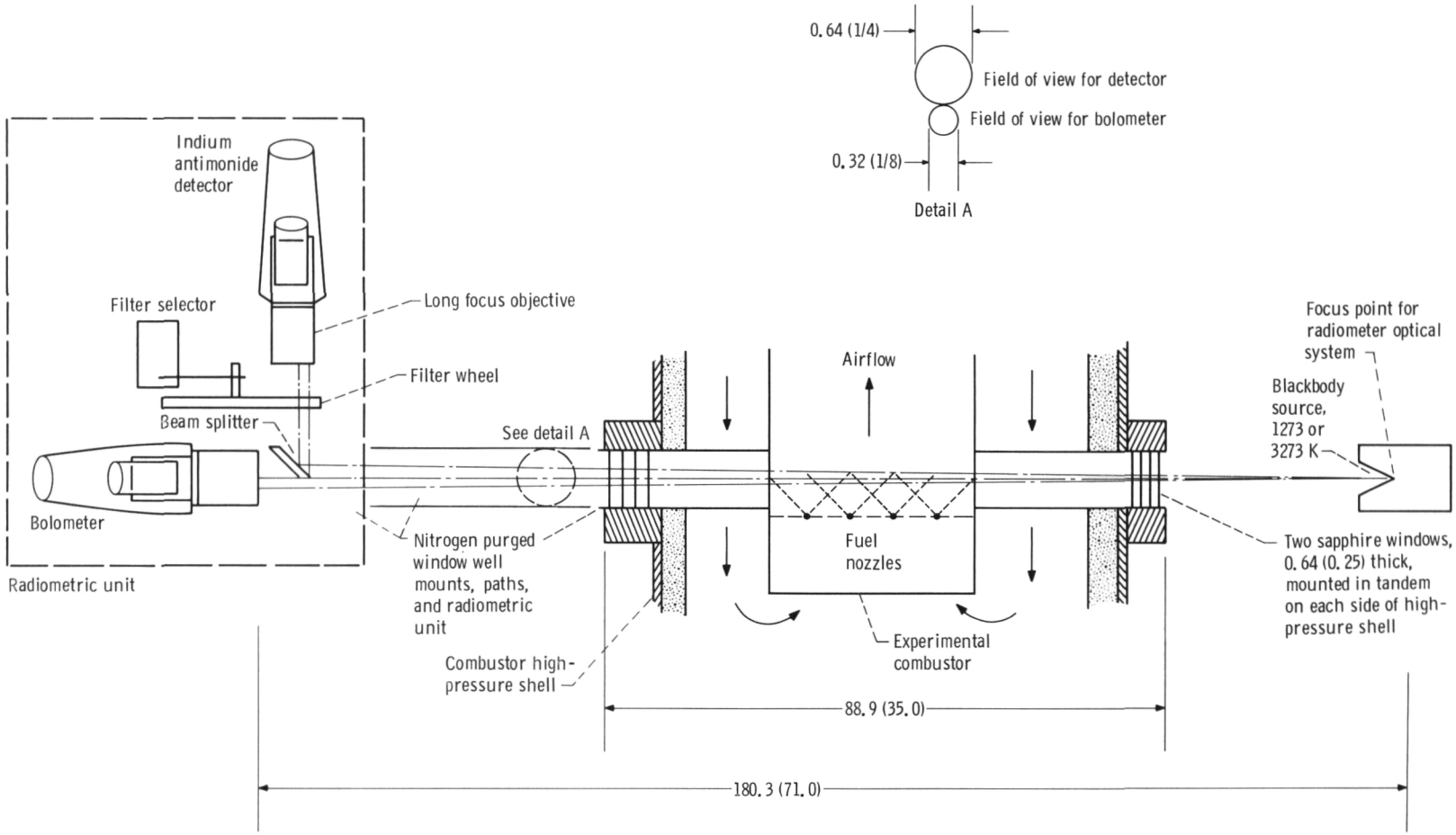
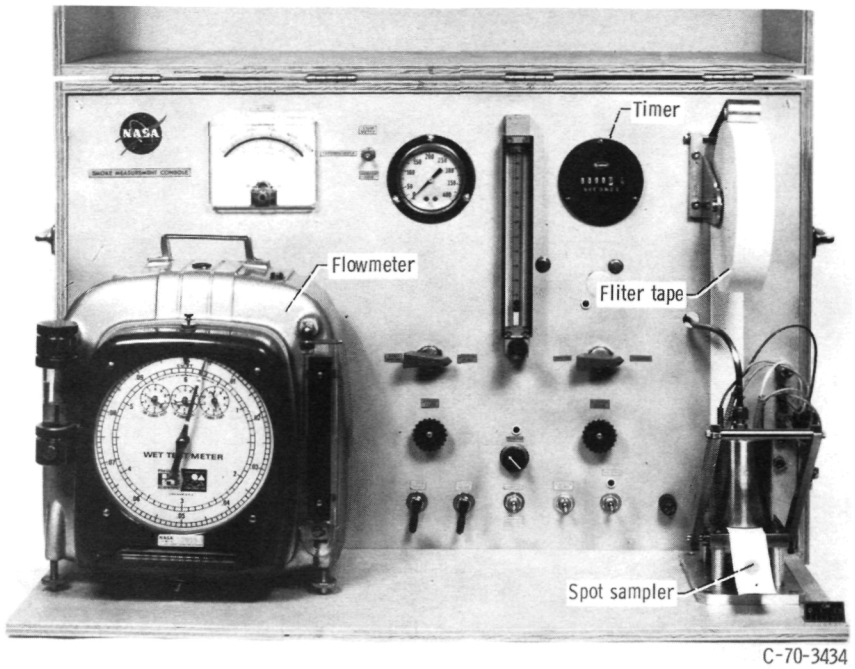
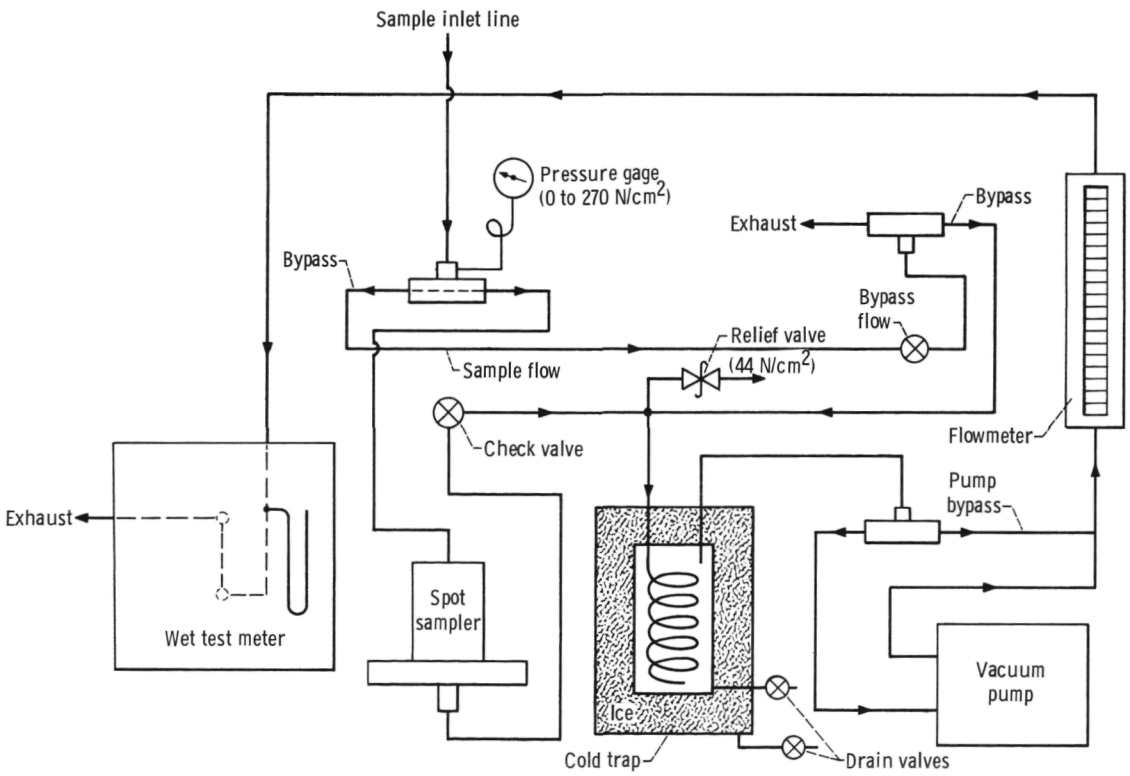


Figure 4. - Infrared measuring system for determination of smoke concentration and total radiance. (Dimensions are in centimeters (in.).)

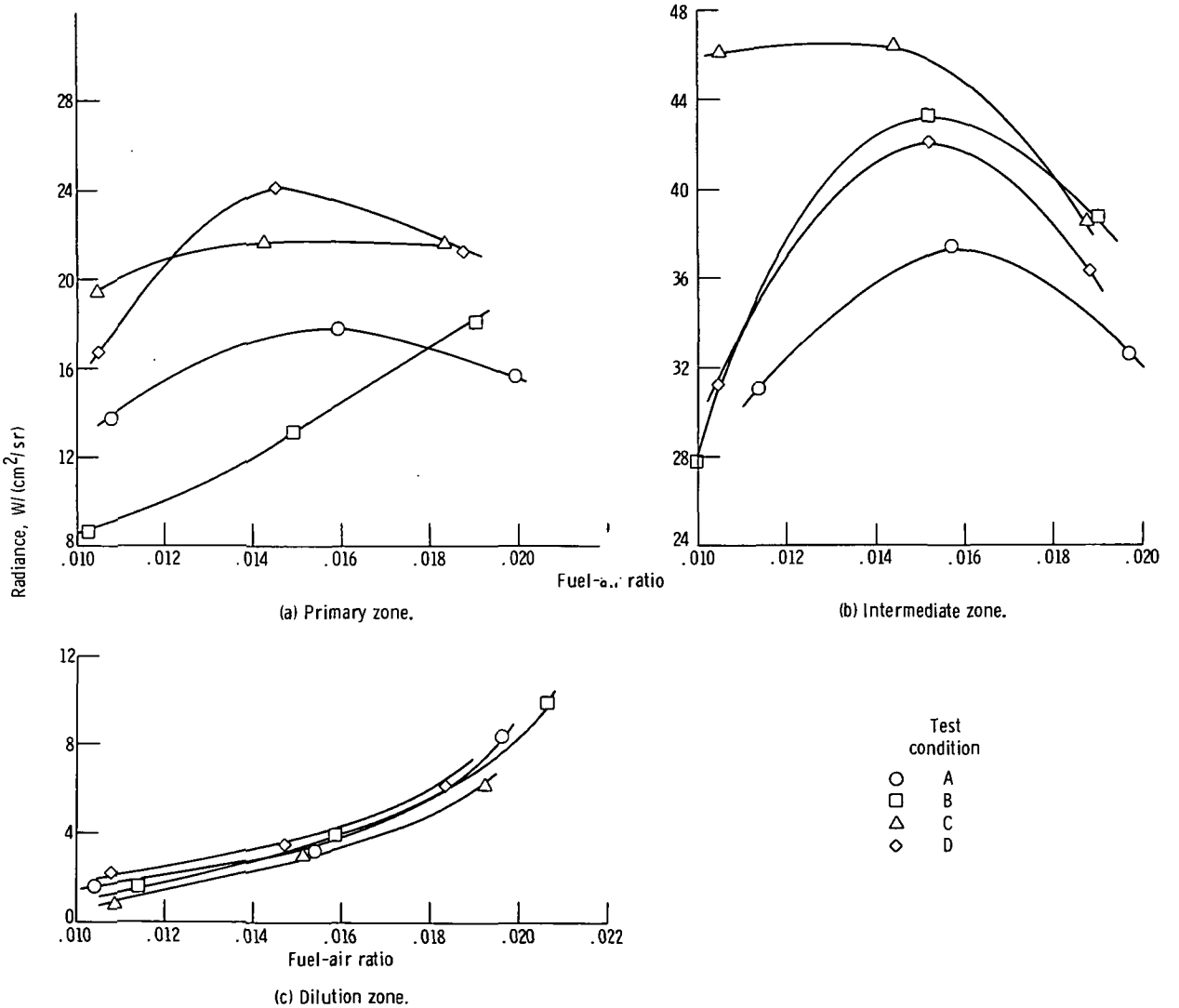


(a) Control panel.



(b) Schematic diagram.

Figure 5. - Smoke meter.



(a) Primary zone.

(b) Intermediate zone.

(c) Dilution zone.

Figure 6. - Directional total flame radiance.

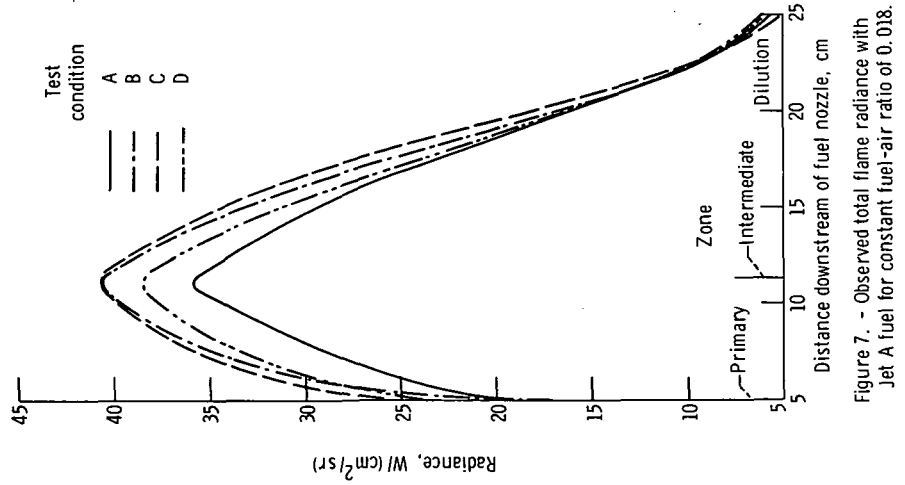


Figure 7. - Observed total flame radiance with Jet A fuel for constant fuel-air ratio of 0.018.

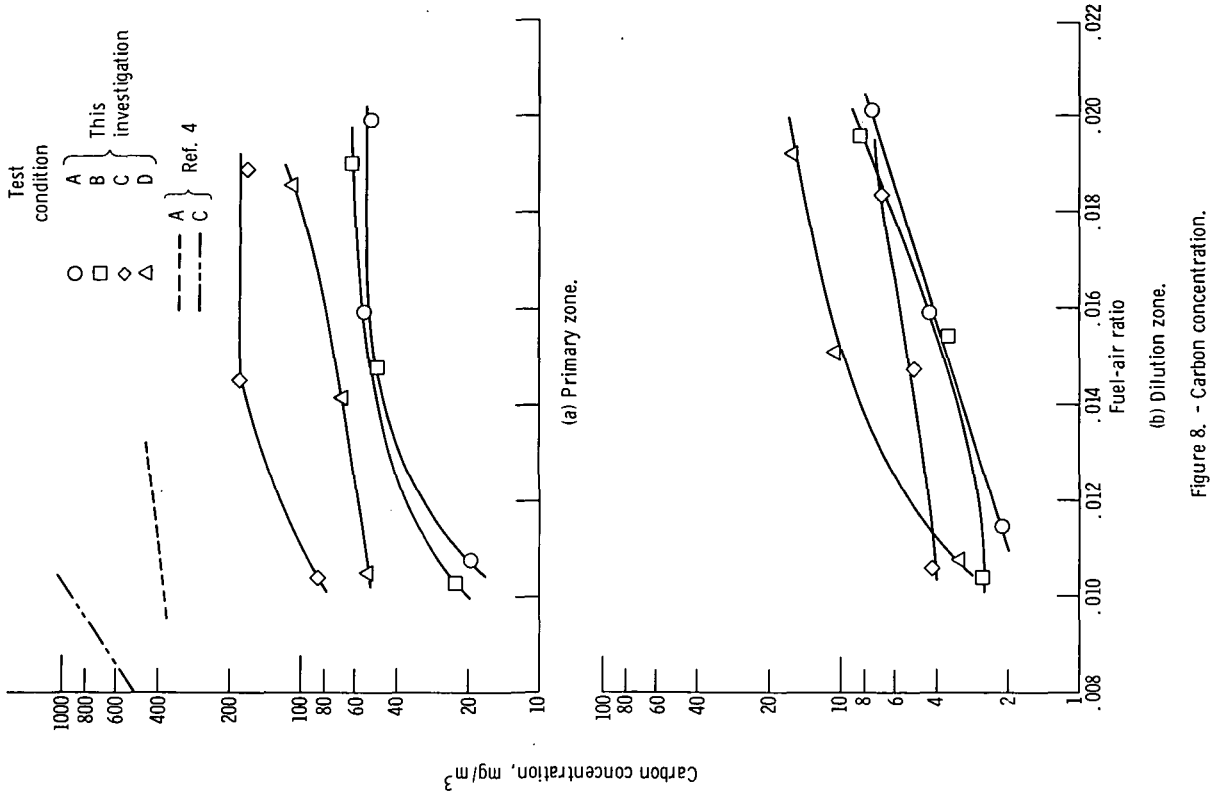


Figure 8. - Carbon concentration.

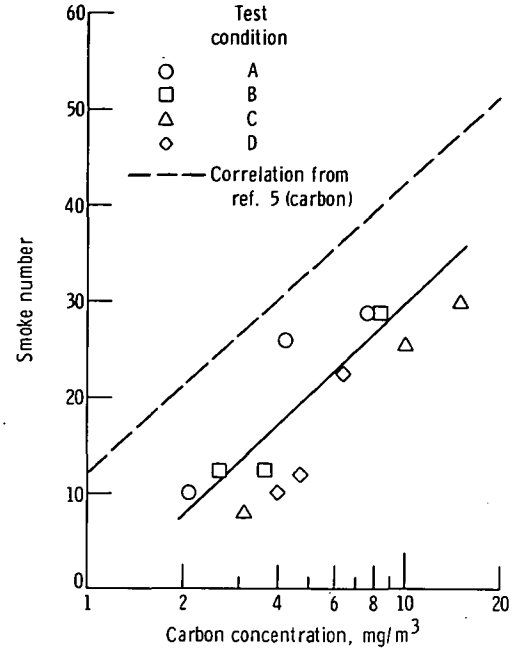


Figure 9. - Comparison of calculated carbon (soot) concentration with smoke number over range of fuel-air ratios of 0.010 to 0.018.

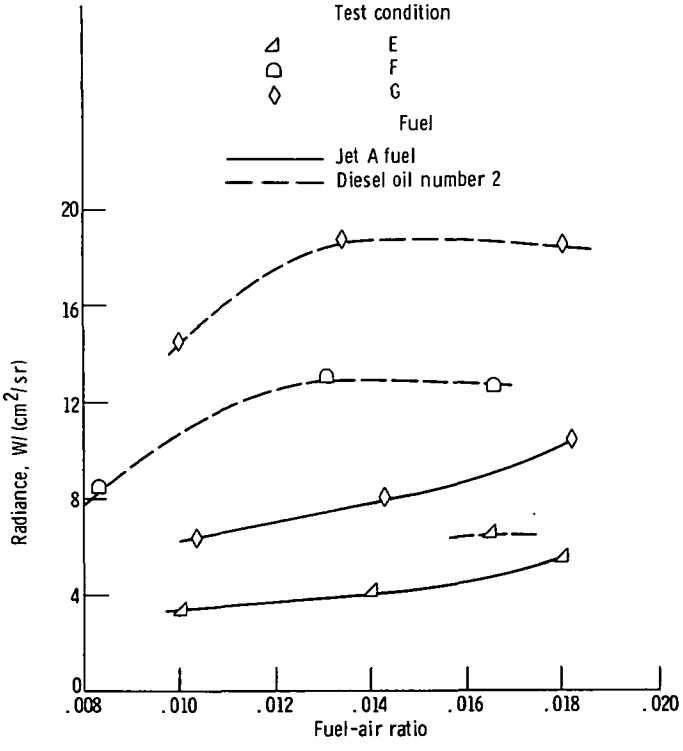


Figure 10. - Comparison of total radiance obtained with diesel oil number 2 and with Jet A fuel at primary zone.

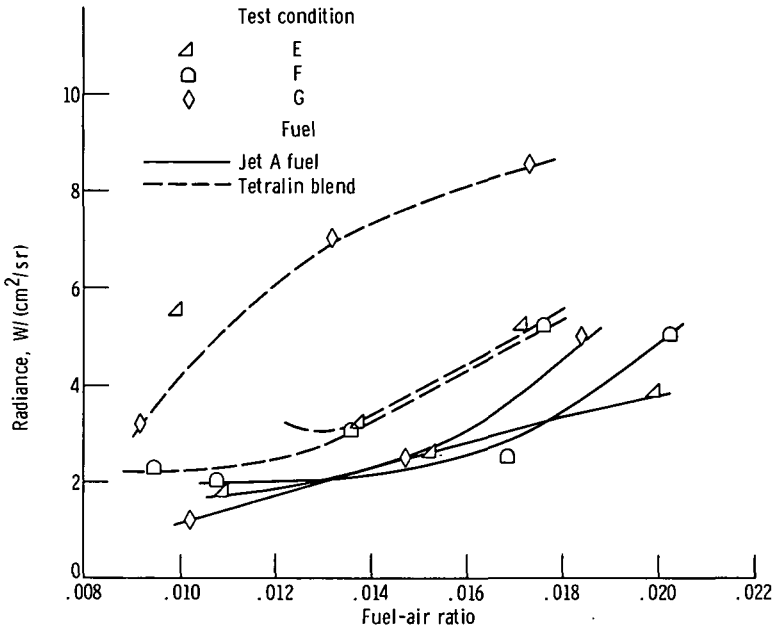


Figure 11. - Comparison of total radiance obtained with 40 percent tetralin in Jet A fuel and with Jet A fuel at dilution zone.

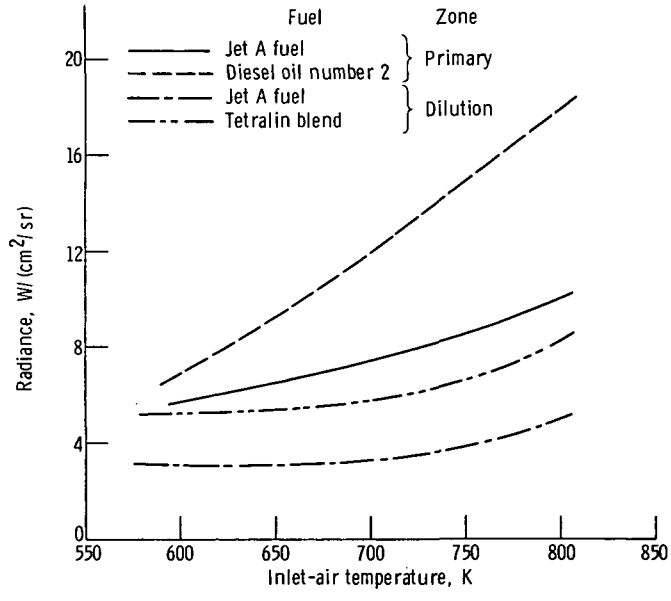


Figure 12. - Comparison of effects of inlet-air temperature on total radiance for three fuels at two radiometric stations. Pressure, 40 newtons per square centimeter; reference velocity, 21.3 meters per second; fuel-air ratio, 0.018.

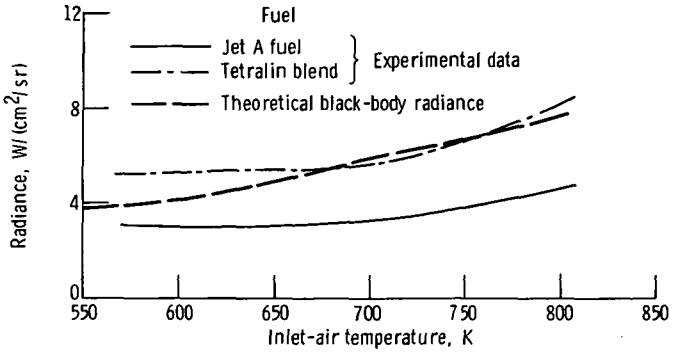


Figure 13. - Comparison of theoretical black-body radiance at dilution zone with data obtained with blend of 40 percent tetralin in Jet A fuel and with Jet A fuel at dilution zone.