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EFFECT OF CERAMIC COATING OF JT8D COMBUSTOR LINER ON MAXIMUM LINER TEMPERATURES AND OTHER COMBUSTOR PERFORMANCE PARAMETERS

by Helmut F. Butze and Curt H. Liebert
Lewis Research Center
Cleveland, Ohio 44135
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16. Abstract

The effect of ceramic coating of a JT8D combustor liner was investigated at simulated cruise and takeoff conditions with two fuels of widely different aromatic contents. Substantial decreases in maximum liner temperatures and flame radiation values were obtained with the ceramic-coated liner. Small reductions in exhaust-gas smoke concentrations were observed with the ceramic-coated liner. Other performance parameters such as combustion efficiency and emissions of unburned hydrocarbons, CO, and NO_x were not affected significantly. No deterioration of the ceramic coating was observed after about 6 hours of cyclic operation including several startups and shutdowns.

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INTRODUCTION

An experimental investigation was conducted to determine the effect of a ceramic thermal barrier coating on liner temperatures of a single-can JT8D combustor at simulated idle, cruise and takeoff conditions.

The operating conditions of current aircraft gas turbine engines impose severe temperature problems on the hot components such as combustor liners and turbine blades. The trend toward leaner primary zones to reduce smoke formation and emissions of NO_x and the trend toward higher turbine-inlet temperatures reduce the amount of air available for cooling. Increasing engine compression ratios increases the temperature of the air entering the combustor and thus aggravates the liner cooling problem. At the same time, the fuel supply problems which have surfaced during the past few years have made it desirable to relax the specifications of aircraft turbine fuels, especially with respect to aromatic content. However, as shown in reference 1, increases in aromatic content of jet fuels increased liner temperatures; thus, in cases where liner temperatures were marginal with Jet A fuel, small increases in aromatic content could cause durability problems. The use of ceramic thermal barrier coatings to reduce cooling requirements and metal temperatures could produce substantial benefits with regard to combustor durability.

Ceramic coatings to reduce metal temperatures in rockets and aircraft and ground power gas turbine engines have recently been the subject of intensive investigations at the NASA Lewis Research Center. These coatings, to be useful in combustor liner applications, must substantially reduce the metal wall temperature and, at the same time, withstand thousands of hours of cyclic engine operation without cracking, spalling or eroding. A ceramic yttria stabilized zirconia coating, developed at the NASA Lewis Research Center has shown that substantial reductions in turbine blade temperatures can be achieved. At the same time, the coatings were found to be in good condition after many hours of cyclic and steady-state high temperature operation. (Ref. 2, 3, 4, 5).

The success of the turbine blade tests prompted an investigation to determine the effectiveness of this coating in reducing combustor liner temperatures. Tests were conducted with a single-can JT8D combustor at simulated idle, cruise and takeoff conditions with Jet A fuel and with a blend of Jet A and an aromatic fuel (HiSol 3) consisting primarily of alkyl benzenes. The aromatic content of the blend was 65.2 percent by volume and the aromatic content of the Jet A fuel was only 16.8 percent. The principal parameters of interest were coated liner metal temperatures, flame radiation and exhaust smoke concentration. Other performance parameters such as combustion efficiency, pollutant emissions and pattern factor were also investigated. Coating durability was also monitored during the experiment.

APPARATUS AND PROCEDURE

Combustor Installation and Instrumentation

The tests were conducted with a single JT8D combustor liner housed in a closed-duct test facility capable of supplying the required airflow rates with nonvitiated air at the specified combustor-inlet pressures and temperatures.

The JT8D liner, retrofitted to reduce smoke emissions and utilizing a standard Duplex fuel nozzle was installed as shown in figure 1. An existing circular combustor housing was modified to accommodate the JT8D liner. Although this installation did not provide the actual combustor-inlet and exit geometry, it was felt that this expedient would not compromise the combustor performance parameters of interest in this investigation, since the tests were essentially comparisons between an uncoated and a ceramic-coated liner for the two fuels tested.

The combustor instrumentation stations are shown in figure 1. Inlet-air temperatures were measured at station A-A with 5 chromel-alumel thermocouples while exhaust-gas temperatures were measured at station B-B with 8 five-point platinum - 13% rhodium/platinum thermocouple rakes. Combustor-inlet and exit pressures were determined at stations A-A and C-C, respectively.

Exhaust-gas samples for gas analysis were obtained by means of four water-cooled sampling probes located at station C-C. Each probe had 5 sampling ports located at the centers of equal areas; the gases collected from all 20 ports were passed to a common manifold and from there through steam-heated lines to a gas-analysis console. The exhaust gas was analyzed for concentrations of CO_2, CO, unburned hydrocarbons, and oxides of nitrogen in accordance with the recommendations set forth in reference 6.

The smoke measurement technique was in accordance with SAE recommended practice, as described in reference 7. It consists essentially of passing metered volumes of exhaust gas through a filter paper with resultant deposition of the soot particles contained in the gas. The darkness of the stain on the paper, as determined by optical means, serves as a measure of the concentration of soot in the sample.

Liner temperatures were measured by 10 chromel-alumel thermocouples installed on the liner at the locations shown in figure 2. The positions of the thermocouples were selected on the basis of previous experience and as a result of calibration tests with temperature-indicating paints. In all cases, maximum liner temperatures were registered by either one of two thermocouples, as shown in figure 2.

Total flame radiation was measured with a commercially available radiometric microscope using an unimmersed bolometer thermal detector with a sensitivity range from 0.25 to 6 micrometers. The flame was viewed from a single port through an air-cooled sapphire window in the primary combustion zone (figure 1). A complete description of the radiometer including calibration techniques can be found in reference 8.

Test Conditions

Tests were conducted at the combustor-inlet conditions shown in Table I. Although variations may exist among the various engine models, these conditions were considered to be typical of idle, cruise, and takeoff operation of the JT8D engine. At each condition fuel flows were varied over a sufficiently wide range so as to bracket the desired fuel-air ratios.

Fuels

The two fuels used in this investigation are listed in Table II. One was a typical Jet A fuel and the other a blend of Jet A and a commercially available fuel consisting primarily of alkyl benzenes. The latter fuel was chosen to give a fuel blend with approximately the same boiling range as Jet A, but with a much higher aromatic content.

Liner Coating

The thermal barrier coating composite consisted of a bond coat of nickel-chromium-aluminum-yttrium alloy (Ni-16Cr-6Al-0.5Y), covered with a ceramic layer of nominal 12 weight percent yttria stabilized zirconia. The nominal thickness of these bond and ceramic layers was 0.010 and 0.025 centimeters, respectively. The liner was made from Hastelloy X and was 0.097 cm thick in the areas where the thermocouples were mounted.

The liner was cut apart at the weld lines shown in figure 3 and rewelded after the coating had been applied. It was necessary to cut the liner to make room for use of the coating apparatus. (If the combustor had not already been assembled, each stacked ring could have been coated before they were welded together to make the liner.) The two liner parts were than degreased for four hours in inhibited 1, 1, 1 trichloroethane at about 330^{o}K. The inner surfaces were grit blasted with commercial, pure, (white) alumina. Use of the white alumina minimized contamination that might occur with less pure grit. The inlet air supply to the equipment was 70 N/cm^2. Grit blasting with impingement nearly normal to the surface cleaned and roughened the metal liner walls. The alumina grit size was 250 micrometers.

Within 30 minutes after grit blasting, the bond coat was plasma sprayed onto the roughened surface. The particle size of the bond powder fed into the spray gun was 77 to 44 micrometers.

Within 30 minutes after bond coat application, the zirconia ceramic was plasma sprayed over the bond coat. The substrate temperature did not exceed $420^{\circ}K$ during the plasma spray operations.

The bond and ceramic coatings were built up to the desired thickness by a succession of spray passes over the surface. The coating thickness was measured during the coating process with micrometer calipers. No coating was deposited into the cooling slots shown in figure 3. Thus the coating did not significantly affect liner cooling airflows.

After coating, the two pieces of combustor liner were tungsten-inert gas welded in argon. The ceramic was not applied over the welds (fig. 3) because the uncoated weld area was small and will negligibly affect the radiative heat transfer. The uncoated area was only 4 percent of the total internal combustor area.

RESULTS AND DISCUSSION

The effect of operating conditions on the various combustion performance parameters is discussed in the following sections. Although tests were conducted at simulated idle, cruise, and takeoff conditions, significant differences between the performance of the uncoated and ceramic-coated liners were observed only at cruise and takeoff conditions. Furthermore, the effect of ceramic coating on liner performance was evidenced primarily in differences in liner temperatures, flame radiation and exhaust smoke numbers. Differences in concentrations of gaseous pollutants and in combustion efficiency were generally small and often within the limits of accuracy of the measurements. As a result, the following discussion will be concerned primarily with the effects on maximum liner temperatures, flame radiation, and exhaust smoke numbers.

Liner Temperatures

Maximum liner temperatures as a function of average exhaust-gas temperature for Jet A fuel are shown in figure 4. For both cruise and takeoff conditions substantial reductions in maximum liner temperatures were achieved with the ceramic-coated liner. At an exhaust-gas temperature of 1325^{O}K, representative of takeoff conditions, the maximum liner temperature was reduced from about 1220^{O}K for the uncoated liner to a value of about 1060^{O}K for the ceramic-coated liner. Similarly, at an exhaust-gas temperature of 1125^{O}K, representative of cruise, the maximum liner temperature was reduced from about 1050^{O}K to about 920^{O}K through the use of the ceramic-coated liner.

Maximum liner temperatures attained with the blend of Jet A and HiSol 3 are shown in figure 5. This fuel blend was selected because, while having roughly the same boiling range as Jet A, it has an aromatic content of 65.2 percent by volume compared to 16.8 percent for Jet A. Figure 5 shows that at an exhaust-gas temperature of 1325^{O}K maximum liner temperatures approached a value of 1265^{O}K with the standard liner while with the ceramic-coated liner the maximum liner temperature was only about 1050^{O}K. Metal temperatures of 1250^{O}K and above could present severe liner durability problems while temperatures of 1050^{O}K should be quite safe. At an exhaust-gas temperature of 1125^{O} K, representative of cruise operation, maximum liner temperatures decreased from 1180^{O} K for the uncoated liner to about 920^{0} K for the ceramic coated liner.

Maximum liner temperatures of the uncoated liner obtained with the high-aromatic fuel blend were higher than those obtained with Jet A while, with the ceramic-coated liner, no significant differences were observed with the two fuels. In reference 1, it was shown that decreases in hydrogen content of the fuel, resulting from increasing aromatic content, produced increases in maximum liner temperatures. Although one would have expected a lesser dependency on aromatic content with the ceramic-coated liner because of its higher reflectance, the fact that no significant differences were observed with the two fuels cannot be explained readily.

Flame Radiation

Flame radiation in watts/cm^2/steradian for Jet A fuel is shown in figure 6. Inasmuch as radiation measurements were made from only one observation port in the combustor primary zone, flame radiances should be considered only as relative values. At both cruise and takeoff conditions, noticeable reductions in flame radiation were obtained with the ceramic-coated liner. Recent experiments at Lewis have shown that the ceramic coating has a reflectance which is 2 to 3 times greater than that of an uncoated Hastelloy X wall. It is believed that the intense radiation from the ceramic-coated walls back to the flame affected the soot concentration in the primary zone, either through reduction of the amount of soot formed initially or through burnup of the soot formed. Since the hot soot particles account for most of the flame radiation, any reduction in soot concentration should reduce flame radiation.

Flame radiation values obtained with a blend of Jet A and HiSol 3 for both cruise and takeoff conditions are shown in figure 7. Because of the high aromatic content of this fuel, one would expect an intensely yellow flame with high soot concentration. Flame radiation values obtained with this fuel with the standard liner were considerably higher than those obtained with the lower aromatic Jet A fuel. Again, because of increased soot burnup with the ceramic-coated liner, flame radiation values obtained with the coated liner were reduced substantially over those obtained with the uncoated liner. Absolute values obtained with the ceramic-coated liner were approximately the same for both fuels.

As was the case with liner temperatures, flame radiation values with the uncoated liner were considerably higher with the high-aromatic fuel blend than with Jet A, while with the ceramic coated liner no significant differences were observed between the two fuels. It appears that the insulating effect as well as the increased reflectivity of the ceramic coating were responsible for the reduction in heat transfer through the liner walls although it is difficult to tell which effect predominated.

Smoke

SAE smoke numbers obtained with both liners at cruise and takeoff conditions are shown in figure 8. In general, exhaust smoke numbers were decreased slightly with the ceramic-coated liner. This is in accord with previous observations that flame radiation values were lower with the ceramic-coated liner.

It has been shown in reference 8 that soot is the primary source of flame emissivity at high pressures. Thus, decreases in flame radiation could be the direct result of decreases in soot concentrations in the primary zone. Although most of the soot formed in the primary zone of a combustor is burned up as it passes through the flame zone (ref. 8), it seems reasonable to assume that the higher-primary zone soot concentrations will result in higher smoke concentrations in the exhaust gas.

A comparison of the smoke numbers obtained with the two fuels shows that exhaust smoke concentrations obtained with a blend of Jet A and HiSol 3 were considerably higher than those obtained with Jet A. This is a direct result of the substantially higher aromatic content of the Jet A - HiSol 3 fuel blend.

Other Considerations

Other combustor parameters such as combustion efficiency, emissions of gaseous pollutants and pattern factor were not affected significantly by the use of the ceramic-coated liner or by the difference in hydrogen content of the fuels. At cruise and takeoff conditions, emission indices of unburned hydrocarbons and carbon monoxide were less than 1.0 and 5.0 respectively; as a result, combustion efficiency values in all cases were 99.9 percent or above. Emission indices of NO_x varied between 12 and 15 for cruise and between 28 and 40 for takeoff; differences in values between the two liners were small and no consistent trends were observed. Also, no cracking, spalling or eroding of the ceramic coating was observed after about 6 hours of cyclic operation including several startups and shutdowns. The interior of the liner after completion of the runs is shown in figure 9.

SUMMARY OF RESULTS

In an investigation of the effect of ceramic coating of the combustor liner on combustor performance with two fuels of widely differing aromatic content the following results were obtained:

1. Liner temperatures and flame radiation values were reduced substantially, relative to the same combustor with uncoated walls.
2. Slight decreases in exhaust smoke numbers were observed.
3. Other combustor performance parameters, such as combustion efficiency and emissions of unburned hydrocarbons, carbon monoxide, and oxides of nitrogen were not affected significantly.
4. No cracking, spalling, or eroding of the ceramic coating was observed.

A summary of the performance of the two liners is shown in the following table.

Fuel	Test Condition	Average exhaust-gas temp. - ok	Maximum liner temperature-ok		Flame radiation watts/cm^2/steradian		SAE Smoke Number	
			Uncoated liner	Ceramic coated liner	Uncoated liner	Ceramic-coated liner	Uncoated liner	Ceramic-coated liner
Jet A	Takeoff	1325	1223	1058	6.9	6.1	33.2	28.5
	Cruise	1126	1052	922	7.3	6.5	21.8	15.6
Jet A HiSol3 Blend	Takeoff	1325	1264	1051	8.8	5.3	41.9	41.9
	Cruise	1126	1181	924	9.2	6.4	40.2	36.1

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TABLE I - TEST CONDITIONS

Condition	Idle	Cruise	Takeoff
Combustor-inlet pressure, N/cm^2	27.3	71.0	176.5
Combustor-inlet temperature, ^oK	400	621	714
Fuel-air ratio	0.0100	0.0138	0.0182
Airflow, kg/sec	1.84	3.57	7.46

TABLE II - TEST FUELS

Fuel	Percent, by weight, of Jet A	Percent hydrogen by weight	Percent Aromatics, by volume	Boiling range, ^oK	Lower heating value, cal/g	Viscosity at 294 K, $\left(m^2/s\right) \times 10^6$
Jet A	100	13.88	16.8	442 - 544	10,350	1.3
Jet A-HiSol3	36.8	11.76	65.2	446 - 524	10,155	1.4

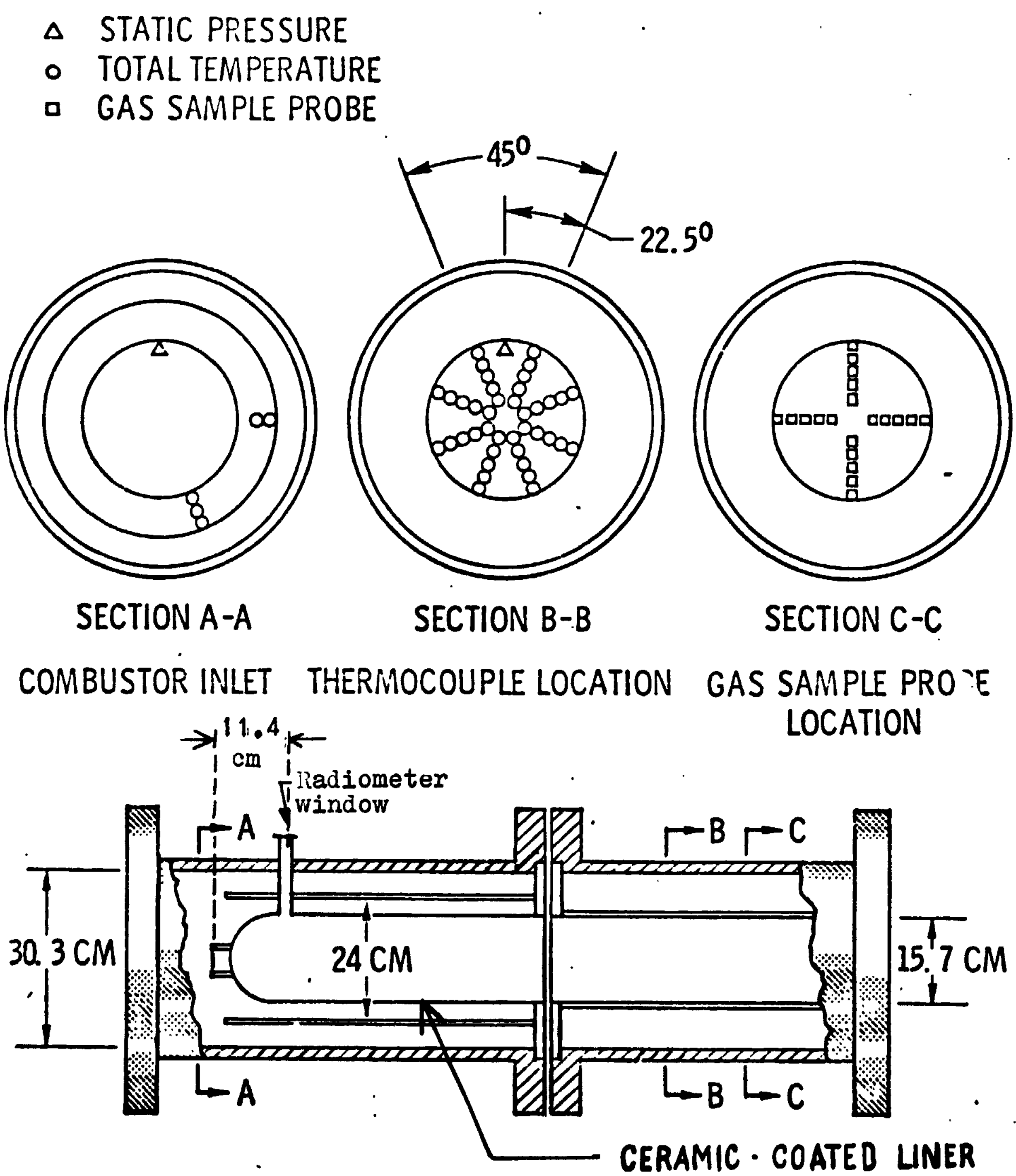

Figure 1. - Combustor assembly and instrumentation sections.

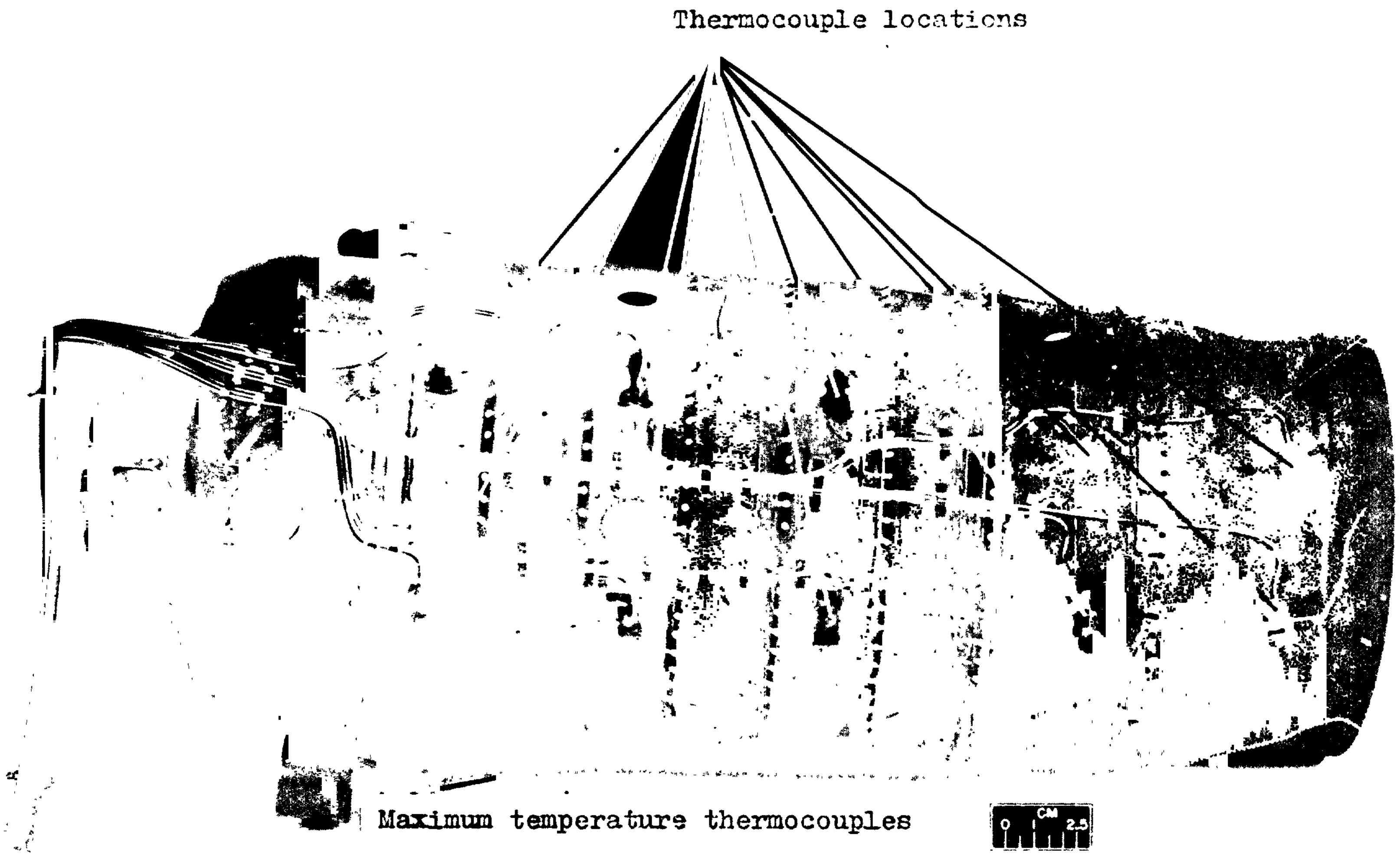

Figure 2.- Location of thermocouples on liner.

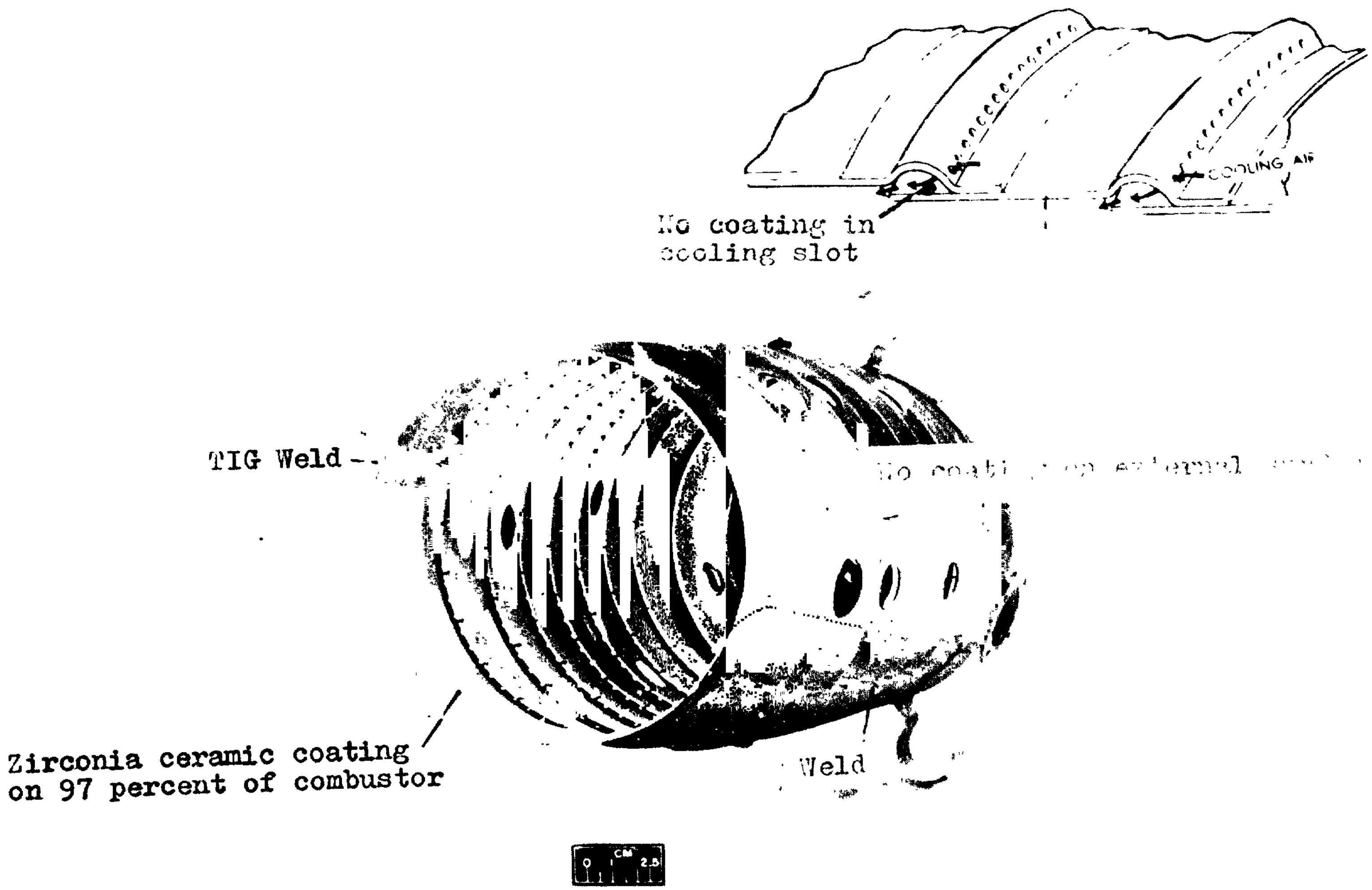

Figure 3.- Thermal barrier coated combustor before tests.

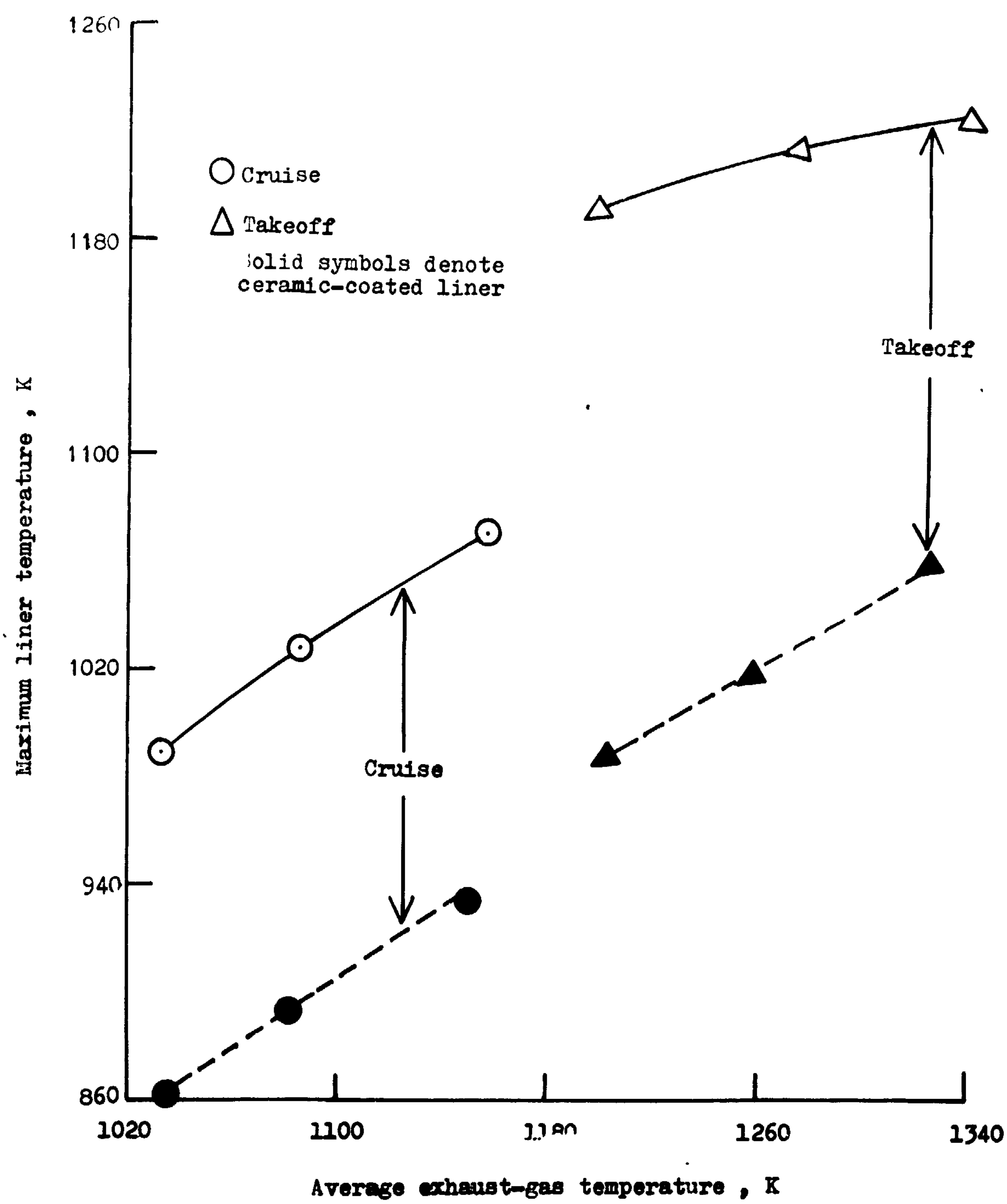

Figure 4. - Effect of ceramic coating on maximum liner temperatures; fuel, Jet A.

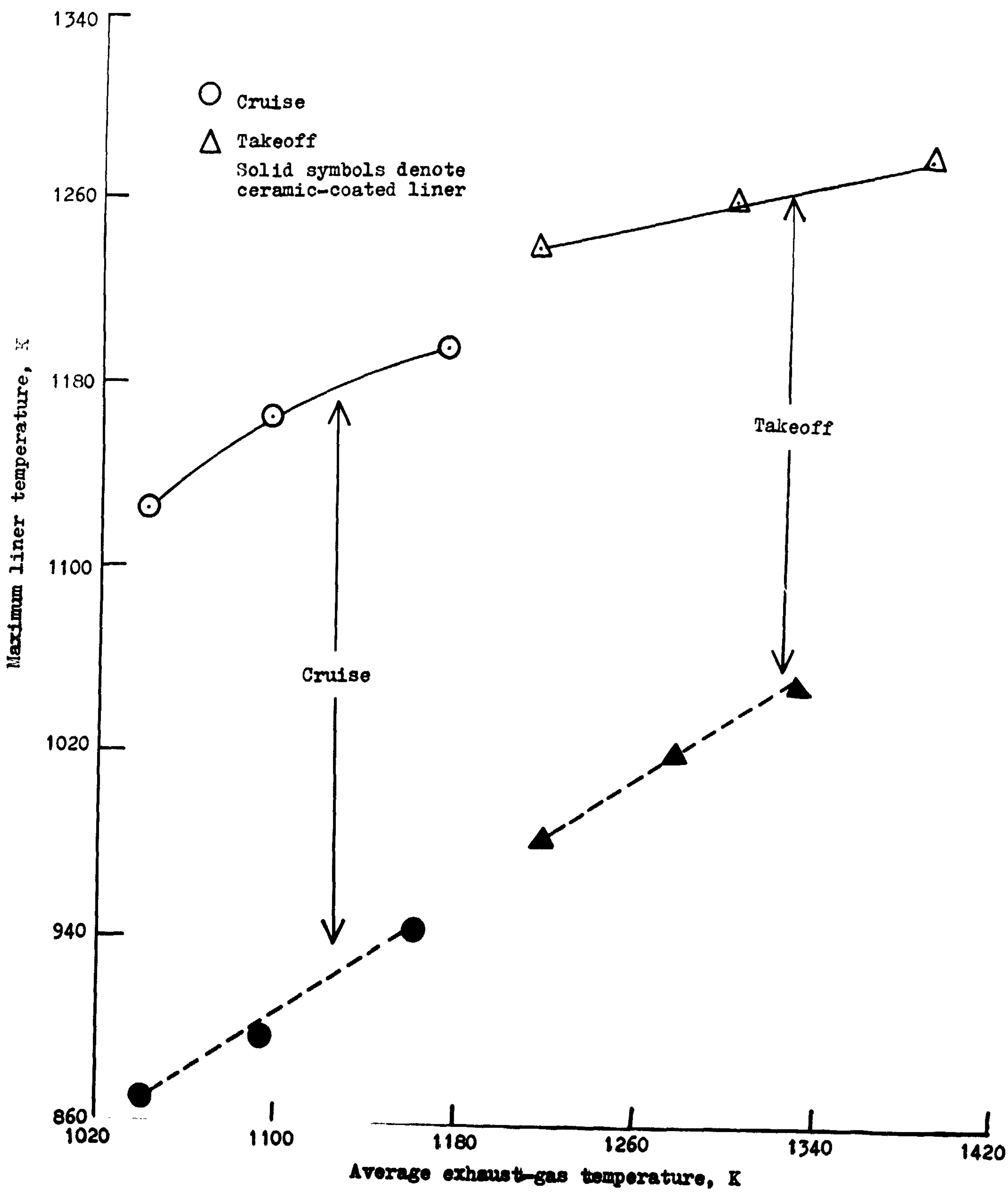

Figure 5. - Effect of ceramic coating on maximum liner temperatures; fuel, blend of HiSol 3 and Jet A.

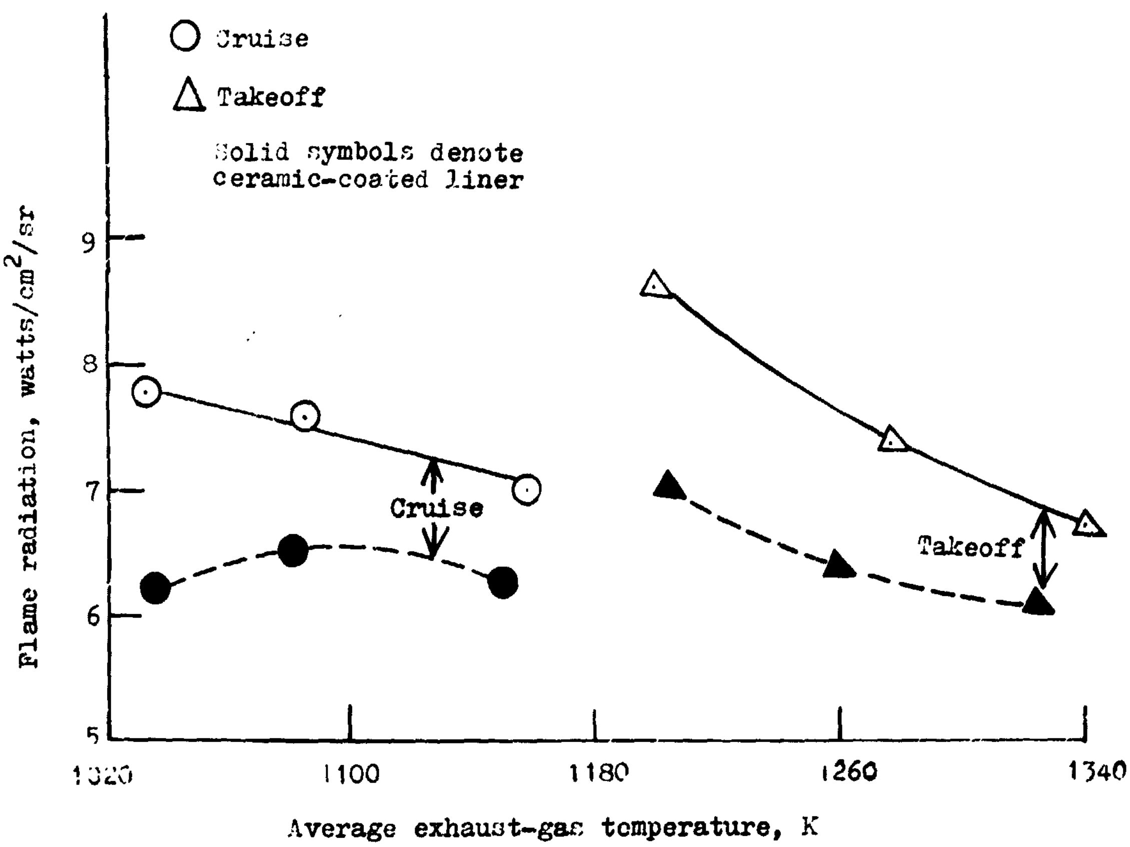

Figure 6. - Effect of ceramic coating on flame radiation; fuel, Jet A.

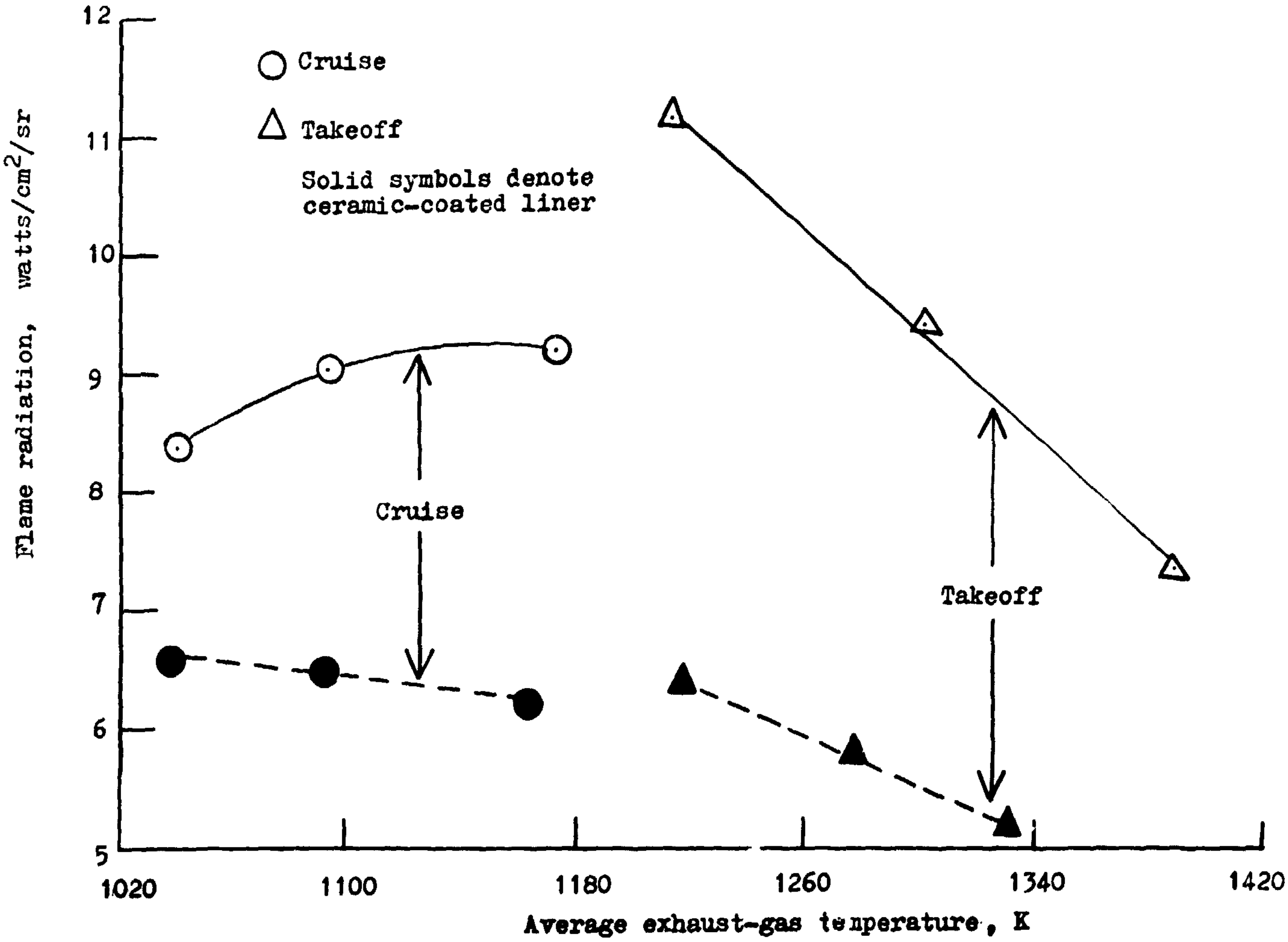

Figure 7. - Effect of ceramic coating on flame radiation; fuel, blend of HiSol 3 and Jet A.

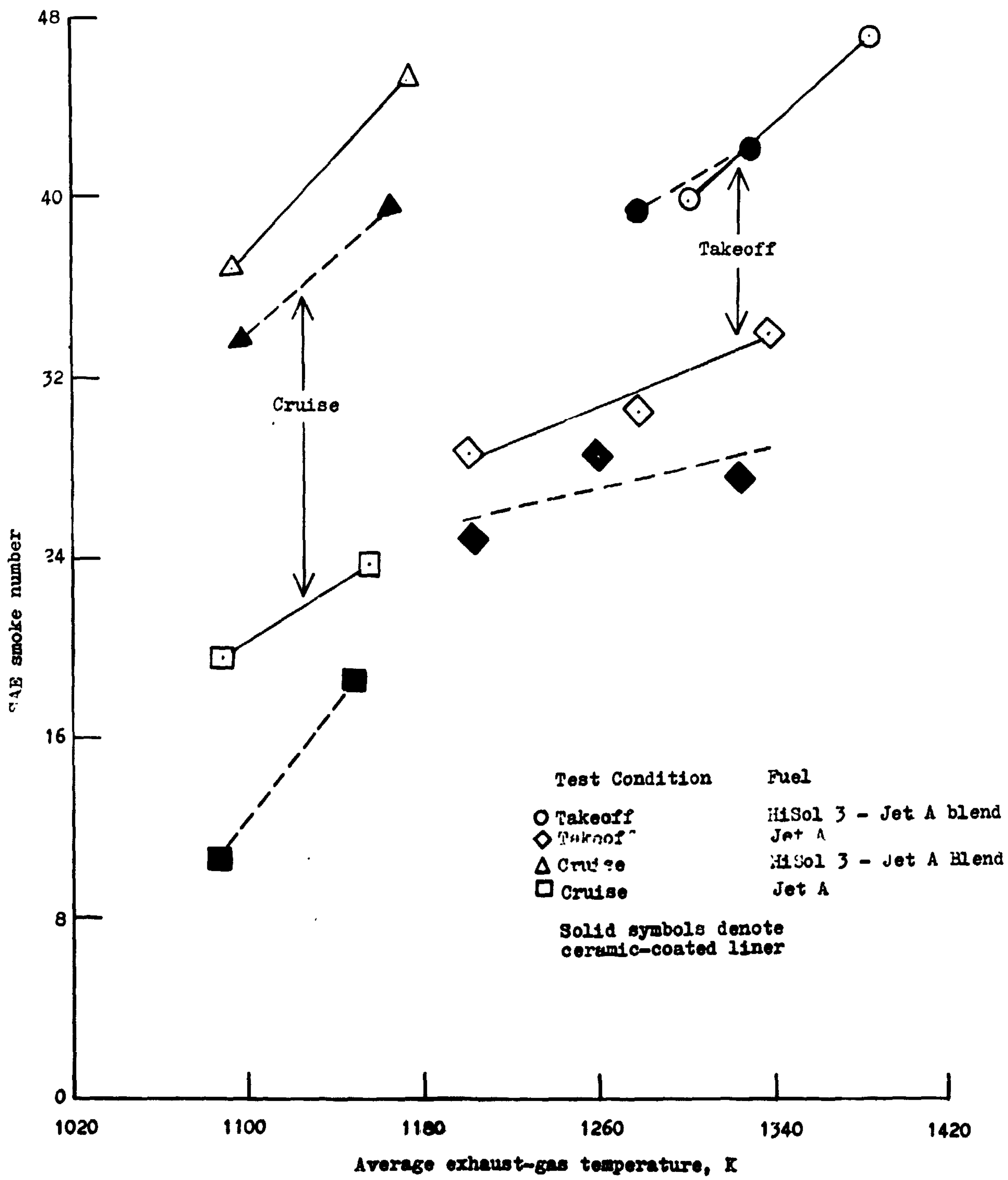

Figure 8. - Effect of ceramic coating on SAE smoke number