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A REINFORCED CARBON COMPOSITE MATERIAL
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SURFACE EMISSIVITY OF A REINFORCED CARBON COMPOSITE MATERIAL WITH AN OXIDATION–INHIBITING COATING

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Surface Emissivity of a Reinforced Carbon Composite Material With an Oxidation-Inhibiting Coating

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ABSTRACT

Total effective emissivity and spectral emissivity over the wavelength range of 0.65 to 6.3 microns were determined for temperatures from 1300 to 2250 deg K. A multi-channel radiometer was used in the arcjet and laboratory tests. The "black-body-hole" method was used to independently check radiometer results. The results show the silicon-carbide coated reinforced carbon composite material is a non-gray radiator. The total effective emissivity and the spectral emissivity at 0.65 micron both decreased with increasing temperature, respectively, from approximately 0.8 to 0.6, and from 0.4 to 0.25, over the temperature range. The emissivity values were the same when the sample was viewed normal to the surface or at a 45 deg angle. Recommended emissivity values are presented.

INTRODUCTION

In both study and use of reinforced carbon composite (RCC) as a thermal protection material, there are numerous requirements for knowledge of the surface emissivity. RCC provides entry heating protection principally by radiation of the imposed heating, and therefore the temperature of the RCC surface is strongly influenced by the emissivity of the surface. The surface temperature, in turn, is an important element of the material temperature field that is related to both thermal stresses and the heat conduction within the material. In material experiments, surface optical properties are needed for evaluation of surface temperatures and radiation levels. All these are factors which must be considered in the design of a thermal protection system.

In this investigation of RCC performance, the spectral and total effective emissivity were determined both from measurements performed during tests in an arcjet and also in a laboratory. Some of the spectral emissivity measurements were evaluated by two independent methods to check validity of procedures used. Also, previously published measurements (refs. 1 and 2) have been analyzed for comparison with the results of the present investigation.

TEST MATERIAL

The test material in this investigation was produced by Vought Missiles and Space Company of Dallas, Texas. Fabrication procedures are described in ref. 3. The manufacturer's designations for the test samples were related to specific details of the individual sample fabrication and are therefore also used in this report.

The RCC test samples had a graphitized carbon core with the oxidation-inhibiting coating on all sides and edges. The coating was principally silicon carbide and silicon. When the RCC samples were convectively heated in a stream of arc-heated air, an increase in sample mass was observed during initial exposures of a sample. The increase in mass is believed to result from formation of silicon-oxygen compounds from reaction of the air stream with the coating material. Surface composition of arcjet-tested samples (at room temperature, determined by x-ray diffraction methods) is silicon carbide, silicon and cristobalite.

INSTRUMENTATION AND PROCEDURES

Radiation measurements in the arcjet tests and in the laboratory were performed with a multi-channel radiometer. In the arcjet tests, the radiometer was mounted on the wind tunnel wall and viewed the RCC sample surface by means of a front-surface silver mirror (fig. 1). Energy radiated by the sample surface was measured with a "total radiation" channel that is uniformly sensitive to all radiation in the spectral region from 0.4 to 9 microns. This range encompasses 95 percent or more of the black-body emission at RCC operating temperatures. There are also two filter radiometer channels to measure surface radiation in discrete spectral regions. Spectral radiation data were obtained at 8 wavelengths from 0.62 to 1.62 microns with one radiometer, and at 10 wavelengths from 2.0 to 6.3 microns with the other. The filters in both radiometer channels had approximately uniform transmission over a wavelength interval that was nominally 10 percent of the filter center wavelength and negligible transmission outside this region. The radiometer also has a pyrometer channel for surface temperature measurement that is sensitive to radiation at 0.4 microns. In the temperature range of the present tests, surface radiation at a wavelength of 0.4 microns is such a strong function of temperature that the pyrometer channel indicates surface temperature directly with negligible error due to uncertainty in surface emissivity. Simultaneous measurements were performed by all radiometer channels at a rate of 20 samples per second, and the filter radiometers completed a scan in 0.5 second. The multi-channel radiometer was calibrated over the temperature range of the measurements with a black-body radiation source using an optical pyrometer (a Pyrometer Instrument Co. Micro-Pyrometer) with a calibration traceable to the NBS as a standard.

An automated data system was used to process the test data. Radiometer signals were recorded (during tests) on a magnetic tape analog recorder. Following a test, the analog records were input to a digital converter and tape recorder. The digitized data records were utilized in the data reduction calculations performed on a computer.

RCC spectral emissivity and total effective emissivity were determined from the spectral and total radiation data. Repeatability of emissivity values determined with this system is approximately ±0.05. Spectral emissivity is the ratio of the surface spectral radiation intensity to the spectral intensity of a black-body radiator at the same wavelength and the same temperature. The total effective emissivity (E) is used to calculate radiation from a non-gray body at surface temperature T by the relation

$$\text{Surface radiation} = E \times \text{constant} \times (T/1000)^4.$$

If T is the true temperature in degrees K, the constant is 56.7 and the radiation units are kw/m^2. If T is in degrees R, the constant is 0.483, and the radiation units are Btu/ft^2-sec.

The arcjet tests were conducted in the Aerodynamic Test Facility of the Thermal Protection Branch at NASA Ames Research Center. Test samples were 7.62 cm in diameter, and were tested in a flat disc stagnation point orientation. The test sample holder was fully immersed in a supersonic air stream. Results to be presented were obtained in tests in which convective (cold wall) heating rates to the sample were from 770 to 1180 kw/m^2, stream enthalpy was from 24.8 to 34.2 mj/kg, and sample surface pressures were from 0.014 to 0.018 atm. In these tests, radiation data were taken after the test sample temperature was stabilized. Radiation data were recorded for short periods (nominally 10 seconds) at intermittent intervals for several minutes. When the data were reduced, results for each nominal 10 second period were averaged and considered a separate measurement. In a similar experiment using the multi-channel radiometer (ref. 4), tests were performed that demonstrated there was no interference in the radiation measurements from the arcjet or stream radiation. A polished aluminum reflector was placed in the sample position in the arcjet stream at comparable test conditions. The ambient arcjet radiation intensity was below the detection threshold of the total radiation and both filter radiometer channels. Some radiation was detected by the pyrometer channel sensitive to 0.4 micron radiation, but the effect on indicated temperature was negligible.

In laboratory tests, radiation measurements of several types were made with heated RCC material. The specimens for these tests were cut from RCC samples used in the arcjet tests. Specimens were placed in the graphite cavity of a high temperature radiation source, as shown in fig. 2, and heated in an argon atmosphere. The graphite cavity was heated inductively, and in turn heated the specimen by radiation to the back and circumferential surfaces of the RCC.

The heated RCC specimens were used in tests to determine the spectral emissivity by the classical "black-body-hole" technique. A cylindrical hole was drilled in the specimen surface, and pyrometers were used to measure the apparent temperatures of the surface and the hole. Radiation relations were used to determine the spectral emissivity of the RCC surface at the pyrometer wavelength. The spectral emissivity was obtained for wavelengths of 0.65 and 0.80 microns using measurements made with the same optical pyrometer employed for the radiometer calibration and a monochromatic electronic pyrometer.

The fundamental difference between the black-body-hole method and the method used in the multi-channel radiometer is in the determination of the specimen true temperature. A surface temperature indicated by the 0.4 micron pyrometer channel of the multi-channel radiometer is used as the true temperature in analysis of the radiometer measurements. In the black-body-hole method, the hole in the test specimen is a small, radiating black-body at the true temperature of the specimen.

Multi-channel radiometer measurements were also made in the laboratory using heated specimens. The specimens were as shown in fig. 2, except that the cylindrical hole was omitted.

DISSCUSSION

Arcjet Test Results

In the arcjet tests, the multi-channel radiometer was used to measure surface temperature, spectral and total radiation from the RCC samples. RCC spectral emissivity and total effective emissivity were determined from the measurements. RCC spectral intensity measurements (normalized) are shown as a function of wavelength in fig. 3-a. The spectral intensity does not have any irregularities, band structure, or "windows" resolvable by the multi-channel radiometer. Total radiation obtained by integration of the spectral intensity measurements was 560 kw/m^2, which agreed within 3 percent with the measurement from the total radiation channel. The spectral intensity results have a peak value in the vicinity of 1.6 microns. A black or gray body radiatior with a peak at 1.6 microns would have a true temperature of 1800 deg K, based on Wein's displayment law. However, the measured radiation intensity at 1.62 microns corresponds to radiation from a blackbody at 1817 deg K. The measured radiation intensity in other wavelength regions (Table 1) corresponds to blackbody radiation at temperatures as low as 1720 deg K in three separated spectral regions. Intensity of the total radiation is the same as from a black body at 1775 deg K. RCC cannot be a black body radiator because there are differences between the Wein displacement law temperature and the temperatures corresponding to the intensity of the total radiation and in the various spectral regions. RCC cannot be a gray body radiation because the temperatures corresponding to the spectral radiation intensity match or exceed the Wein law temperature in some regions, and also because the radiation intensity temperatures do not decrease systematically from short to long wavelengths.

The RCC spectral emissivity deduced from the radiation intensity is also shown in fig. 3-a. The surface temperature of 2014 deg K was based on simultaneous measurements by the radiometer pyrometer channel and a radiation pyrometer sensitive to radiation at 0.8 microns. The two independent values of temperature agreed within ± 1.5 percent. Variation in the spectral emissivity shows that RCC is a non-gray radiator. The reason for the low values of emissivity at the shorter wavelengths has not been determined, but this result was confirmed by other tests in the present investigation. The total effective emissivity, determined from the independent total radiation measurement, was 0.59. Over much of the spectral range of the surface radiation, the spectral emissivity is on the same order as the total effective emissivity.

A second set of RCC radiation measurements is shown in fig. 3-b. When these data were obtained, the test sample had 115 minutes accumulative test time, or 50 minutes more than when the data in fig. 3-a were taken. The surface temperature is this test was 2010 deg K. The spectral intensity peak again occurs near 1.6 microns, and the total radiation intensity was 564 kw/m^2. (The value obtained by integrating the spectral intensity data and the total radiation measurement agreed within 4 percent.) The surface temperature in this test was 2010 deg K ± 1 percent. Spectral emissivity results in figs. 3-a and 3-b are virtually identical at wavelengths below 3 microns. At longer wavelengths, the emissivity values in fig. 3-b range from 0.07 to 0.14 higher. The differences may indicate slight changes in surface properties or may result from experimental uncertainty.

In either case, the differences in spectral emissivity occur at long wavelength and do not significantly affect the total radiation from the RCC surface.

The results of radiation measurements in RCC tests shown in fig. 3 are consistent and mutually supporting. However, published data on silicon carbide surfaces is in accord with these results in some cases and in disagreement in others. Data presented in ref. 5 for silicon carbide spectral emissivity show levels and trends that match results in fig. 3 and results to be presented later herein. Also in ref. 5 are total effective emissivity and spectral emissivity data at 0.66 microns completely unlike the present results. The effective total emissivity reported in ref. 1 and the effective emissivity and spectral emissivity at 0.65 micron reported in ref. 2 are all appreciably different from the present results. The applicability of the information in ref. 5 is uncertain because the test material surface was not specifically RCC. The results in refs. 1 and 2 were for RCC and will be discussed later herein.

Laboratory Measurements

Measurements With Black-Body-Hole Specimens

An independent check of the multi-channel radiometer results was obtained by use of heated RCC specimens with cylindrical holes to determine spectral emissivity. Samples and heating method have been described in a previous section. The method used was the classical "black-body-hole" approach, by which spectral emissivity was determined from measurements of the apparent temperatures of a sample surface and the aperture of a hole in the sample. Optical pyrometer measurements of true and surface brightness (or apparent) temperature for the RCC specimens are shown in fig. 4. The true temperature was consistently higher than the brightness temperature, and temperature difference increased with increasing temperature. Differences in the true and brightness temperatures indicate RCC surface emissivity is significantly lower than the apparent emissivity of the black-body hole. The black-body-hole method was used to determine spectral emissivity for specimens from five RCC arcjet-tested samples. Results for a wavelength of 0.65 microns are shown as a function of temperature in fig. 5 and are listed in Table 2. All these results fall within a band with a width at any temperature of approximately 0.1, if the results from the sample with the 0.38 mm hole are excluded. (These data, represented with square symbols, were a limiting case that will be discussed later.) The band of results is tending to decrease with increasing temperature, from approximate mean values of 0.4 at 1300 deg K to 0.25 above 2000 deg K. Also, at temperatures of approximately 2000 deg K, the values are in agreement with results from the arcjet tests. The range of results at a single temperature is probably the combination of uncertainty in the measurements and possibly some variation in sample properties. The errors cannot be quantitatively evaluated, but the width of the band is comparable to the uncertainty of ± 0.05 in the multi-channel radiometer results. However, at a sample temperature of 1800 deg K, an emissivity variation of 0.25 to 0.35 indicates a range in measured surface brightness temperature from 1660 to 1620 deg K.

The potential errors in the black-body-hole method have been considered in order to ascertain the quality of the results. One possible source of error concerns the extent to which the cylindrical hole approaches a black-body radiator. If the simulation is not satisfactory, the apparent temperature of the hole will be lower than the true temperature of the specimen and the deduced emissivity values will be erroneously high. This is related to the apparent emissivity of the hole, which is a function of the hole geometry. The analysis discussed in ref. 6 indicates that if a hole is more than 2.7 diameters deep, the apparent emissivity is 0.95 or greater even if the actual emissivity of the material's surface is as low as 0.3. The hole depth, in diameters, is listed in fig. 5 for each specimen. In all cases, the apparent emissivity of the holes equaled or exceeded 0.95, which could contribute a maximum of a 5 percent error in the deduced emissivity values. A second possible error is the reflection of extraneous radiation from the test specimen surface into the measurement instrument. Such reflections would increase the indicated brightness temperatures of the surface, but would not affect the indicated true temperature (because the black-body hole is non-reflecting). In such a case, the deduced surface emissivity values would be higher than the actual values. In the present tests, surface reflections were prevented by placing the test specimen at the edge of the radiation source cavity. There was negligible radiation incident to the viewed surface of the specimen, and consequently there could not be sufficient reflected radiation to affect the measurements. A third potential source of error is temperature gradients in the specimen over the length of the cylindrical hole. For specimens heated from the sides and back and radiating from the front surface, the internal temperature was undoubtedly somewhat higher than the surface temperature. Errors could be introduced if the apparent temperature of the hole was significantly weighted in the direction of the higher internal temperatures. Results within the band of data were obtained with various RCC specimens having hole depths ranging from 1.8 to 4.0 mm (hole diameters between 0.66 and 1.50 mm). In particular, the results for specimen W19-(11-1)-2 were essentially the same with a minimum depth hole (2.7 dia), and after the hole was drilled to almost twice the original depth. Consequently, it is believed that temperature gradients in the RCC samples were not significant enough to influence the sample true temperature measurements or the resulting emissivity values. The results for the specimen with the 0.38 mm hole are shown because the hole depth was on the order of the thickness of the silicon carbide layer. Thus the deduced emissivity results are the least subject to temperature gradient effects. However, a different factor is believed to have influenced the results for this specimen. The hole was on the threshold of resolution in the pyrometer because the hole, when viewed through the pyrometer telescope, was only slightly larger than the pyrometer filament. As a consequence, it was difficult to perform the pyrometer filament match to the hole brightness and exclude the influence of the lower brightness surface. In this case, any error in the pyrometer setting resulted in a lower reading for the true temperature and thus a higher deduced value for the emissivity. The problem in the true temperature measurement quite possibly results in values that are somewhat high, but due to this and the minimum hole depth, the values represent an upper limit for the RCC spectral emissivity at 0.65 microns. It is believed that the black-body-hole test were performed properly, and that the test results (excluding the results from the specimen with the 0.38 mm hole) are correct.

The black-body-hole method was also used to determine RCC spectral emissivity at 0.8 microns. For these measurements, an electronic pyrometer sensitive to radiation at 0.8 microns was employed. Results of these measurements are shown in fig. 6 and listed in Table 2. The RCC spectral emissivity at 0.8 microns is not appreciably different from the values for 0.65 microns. The level of the emissivity again decreases with increasing temperature, from approximately 0.4 at 1400 deg K to 0.33 above 1750 deg K, and the results coincide with the arcjet results.

Measurements With the Multi-Channel Radiometer

Further laboratory tests were conducted using heated RCC specimens and the multi-channel radiometer to extend the temperature range of the results. The test specimen was identical to the one shown in fig. 2, except without a cylindrical hole. The radiometer viewed the specimen normal to the surface. At the time these tests were performed, the pyrometer channel of the radiometer was inoperative and therefore surface temperatures were determined from optical pyrometer readings. Correction of the indicated surface temperature to true temperature was based on data in fig. 4.

Measurements were made on an RCC specimen over a range of temperatures, and representative results are shown in fig. 7.

The absolute spectral intensity is shown as a function of wavelength for three RCC specimen temperatures. The results are ordered with temperature, as would be expected, and the curves are smooth. Integration of the spectral intensity curves to obtain total radiation yields values in close agreement with the total radiation measurement. (The maximum discrepancy in all the laboratory and arcjet tests with the radiometer was 5 percent, in the 2170 deg K case shown.)

The spectral emissivity values determined from the intensity measurements are shown in fig. 8. These results have a non-gray characteristic, or the variation of the spectral emissivity with wavelength, similar to that observed in the arcjet results. Also in all the results for wavelengths less than 2.5 microns, there is a trend of decreasing emissivity with increasing temperature. The combination of the non-gray surface and the changes in spectral emissivity with temperature result in a temperature dependence of the total effective emissivity which will be seen later.

Correlation of Total Effective Emissivity Results

Results from Present Tests

Total radiation data taken with the multi-channel radiometer in the laboratory and arcjet tests show both the level and trends in the total effective emissivity. The results determined in the laboratory tests discussed in the previous section are in the temperature range from 1685 deg K to 2170 deg K. Arcjet results had a temperature range from approximately 1750 deg K to 2000 deg K, including the results discussed in the first section. The total effective emissivity results from the present tests are shown as a function of temperature in fig. 9 and listed in Table 3. There is reasonable agreement between the arcjet and laboratory results. The trend in the results is for the effective total emissivity to decrease with increasing temperature, as would be expected from the results for spectral emissivity shown earlier. There also is no detectable difference between results from measurements made viewing normal to the surface in the laboratory tests and at a 45 deg angle in the arcjet tests. Thus, it is reasonable to conclude that the RCC surface emissivity is relatively independent of angle effects, at least over the important central solid angle.

Results From Other Tests

RCC effective total emissivity results have been published by Battelle (Columbus Laboratories) in ref. 1, and effective total emissivity and spectral emissivity at 0.65 micron have been reported by Southern Research Institute (SRI) in ref. 2. A comparison of the results is as follows:

Battelle: Effective total emissivity range from 0.80 to 0.87 at temperatures between 533 deg K and 1530 deg K.

SRI: Effective total emissivity and spectral emissivity at 0.65 micron range from 0.85 to 0.94 at temperatures from 520 deg K to 1950 deg K.

Present Tests: Effective total emissivity range from 0.80 to 0.56 and spectral emissivity at 0.65 micron range from 0.30 to 0.25 at temperatures from 1680 deg K to 2170 deg K.

Both Battelle and SRI made measurements of the radiation from heated RCC specimens using techniques similar in most respects to the total radiation measurements in the present tests. The reasons for the differences are not definitely known. However, there are features of the tests described in refs. 1 and 2 that may have produced in erronous values of RCC emissivity.

The experimental approach used by Battelle (ref. 1) may have resulted in an error in the RCC emissivity. The sample and a sample holder were heated by a surrounding radiant heater in their tests and equilibrium temperature throughout the sample and sample holder was assumed. Radiation from the sample surface was measured, and the surface temperature was taken as the temperature of the sample holder measured by a thermocouple. If the sample viewed by the radiometer also was subjected to radiation from the heater during the radiation measurement, radiation from the heater could have been reflected into the radiometer. An investigation of effects of reflection on emissivity determination was conducted with an RCC specimen of the type shown in fig. 2. The specimen was rotated so that the viewed face of the sample was approximately at a 45 deg angle with the cavity centerline. In this orientation, there was radiation from the cavity wall incident on the viewed surface of the RCC. An optical pyrometer was used to measure the apparent temperatures of the RCC surface and black body hole. Spectral emissivity values of 0.55 to 0.90 deduced from the indicated temperatures were inconsistent with the results shown in fig. 5. The reason is that RCC surface surface brightness temperatures were in error due to reflection of the radiation from the cavity sidewall into the pyrometer. The possible influence of reflection emissivity measurements was shown in this demonstration although the apparatus differed from the Battelle test. From the description of the Battelle experiment in ref. 1, it appears that reflection problems could have resulted in errors in the emissivity values reported therein.

The data analysis used by SRI (ref. 2), rather than the test procedures, may have resulted in incorrect values of RCC emissivity. The RCC test specimen was heated inductively, and surface reflections were avoided. An optical pyrometer was used to measure the specimen surface temperature. Analysis consisted of determing a common emissivity value that corrected pyrometer brightness temperature to the true temperature for a radiometer reading in the same ratio to the radiometer measurement as the emissivity. The resulting spectral emissivity and total emissivity values are therefore identical. This is a critical presumption of gray-body radiation from test surfaces in the analysis and such an analysis cannot provide correct emissivity values for a significantly non-gray material. Validation of this analysis for RCC is claimed on the basis of results of tests in which sample temperatures were determined by thermocouples. In some SRI tests at temperatures in the 1300 deg K range, thermocouples were placed in the RCC samples for comparison with the optical pyrometer results. Reasonable agreement between the thermocouple measurements and the corrected temperatures from the pyrometer measurements was cited in ref. 2 as validation of the data analysis. However, samples in the SRI tests were heated by an induction coil, and a thermocouple in an induction-coil field can yield erronous results because the field imposes an AC signal on the thermocouple DC output. The presence of an AC signal is not apparent when the thermocouple output is measured with a slow time-response potentiometer of the type used by SRI. When a thermocouple is placed in the graphite cavity of the source shown in fig. 2, the AC component may be up to an order of magnitude larger than the DC signal. The AC signal can produce as much as a 35 deg K change in the temperature indicated by a chromel-alumel thermocouple. An uncertainty of 35 deg K in the RCC sample temperature results in a significant effect in effective emissivity, as will be seen later. The possibility of similar pickup and comparable errors in the SRI thermocouple measurements make the claim of validation of the data analysis suspect.

The SRI measurements listed in ref. 4 have been re-analyzed, using results of the present investigation. This was accomplished by correcting the SRI brightness temperatures from optical pyrometer readings to true temperatures by use of the results in fig. 4. The corrected values for total effective emissivity from the SRI measurements, with the arcjet and laboratory results from the present investigation, are shown in fig. 10. All these results are in reasonable agreement. Also, the previously noted trend of the total effective emissivity to decrease with increasing temperature is apparent over a greater temperature range. The SRI result at a temperature of 1343 deg K (0.77 effective emissivity) was from a test in which both thermocouple and pyrometer measurements were made. An emissivity of 0.93-0.96, based on a true temperature of 1270-1276 deg K from the thermocouple data, was reported. A change of 35 deg K in the thermocouple reading would have changed SRI's deduced emissivity to 0.84-0.86. (This is the only SRI test with both thermocouple and optical pyrometer data in the temperature range of the data in fig. 5.)

RECOMMENDED RCC EMISSIVITY VALUES

The aggregrate results for total effective emissivity and spectral emissivity at 0.65 and 0.80 micron have been faired to develop recommended values. These are shown as a function of temperature in fig. 11. Also, there may be advantages to using a monochromatic pyrometer that is sensitive in the 2.0 micron range for RCC test measurements, and therefore spectral emissivity for 2.0 microns is also shown.

CONCLUDING REMARKS

The surface emissivity of a silicon carbide coated reinforced carbon composite material has been determined. The material is significantly non-gray. Spectral emissivity at wavelengths shorter than one micron was much lower than spectral emissivity at longer wavelengths or the total effective emissivity. The spectral emissivity levels also generally decreased with increasing temperature. Consequently, the total effective emissivity also decreases with increasing temperature. There was no detectable variation in emissivity when the surface was viewed at 45 deg or near the surface normal.

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Table 1. - Black-body temperatures for spectral radiation intensity corresponding to measured values.

Wavelength, micron	0.62	0.79	0.88	1.00	1.12	1.26	1.42	1.62	2.00
Temperature, deg K	1717	1732	1759	1763	1771	1795	1802	1815	1726
Wavelength, micron	2.25	2.42	2.83	3.18	3.56	3.90	4.50	5.00	6.30
Temperature, deg K	1716	1733	1742	1669	1776	1799	1807	1755	1721

Table 2. - RCC spectral emissivity at wavelengths of 0.65 and 0.80 micron from laboratory and arcjet test measurements.

W19-(11-1)-5 Hole: 0.96 mm dia.

Temperature, deg K	1280	1300	1370	1390	1550	1560	1725	1935
Emissivity, 0.65 micron	0.45	0.40	0.43	0.37	0.35	0.35	0.35	0.30

Temperature, deg K	2025	2045	2170
Emissivity, 0.65 micron	0.30	0.25	0.25

W19-(11-1)-4 Hole: 1.50 mm dia.

Temperature, deg K	1440	1810	2000
Emissivity, 0.65 micron	0.35	0.25	0.25
Emissivity, 0.80 micron	0.42	0.35	0.32

W19-(11-1)-6 Hole: 1.50 mm dia.

Temperature, deg K	1475	1560	1670	1745	1820
Emissivity, 0.65 micron	0.29	0.26	0.28	0.21	0.24
Emissivity, 0.80 micron	0.38	0.36	0.30	0.30	0.30

W19-(11-1)-2 Hole: 0.66 mm dia. (2.7 dia deep).

Temperature, deg K	1410	1435	1595	1755
Emissivity, 0.65 micron	0.41	0.35	0.33	0.32

W19-11-1)-2 Hole: 0.66 mm dia. (5.0 dia deep).

Temperature, deg K	1450	1475	1620	1805
Emissivity, 0.65 micron	0.32	0.30	0.28	0.24

M195 3-3 Hole: 1.50 mm dia.

Temperature, deg K	1460	1460	1625	1750	1850	1940
Emissivity, 0.65 micron	0.37	0.33	0.30	0.28	0.27	0.27

W19-(11-1)-5 Arcjet Test

Temperature, deg K	2010	2014
Emissivity, 0.65 micron	0.29	0.25
Emissivity, 0.80 micron	0.25	0.31

Table 3. - RCC effective total emissivity from laboratory and arcjet test measurements.

Temperature, deg-K	1680	1750	1765	1855	1975	1985	2010	2015	2070	2170
Emissivity,-Total	0.78	0.77	0.72	0.82	0.74	0.67	0.58	0.59	0.67	0.57

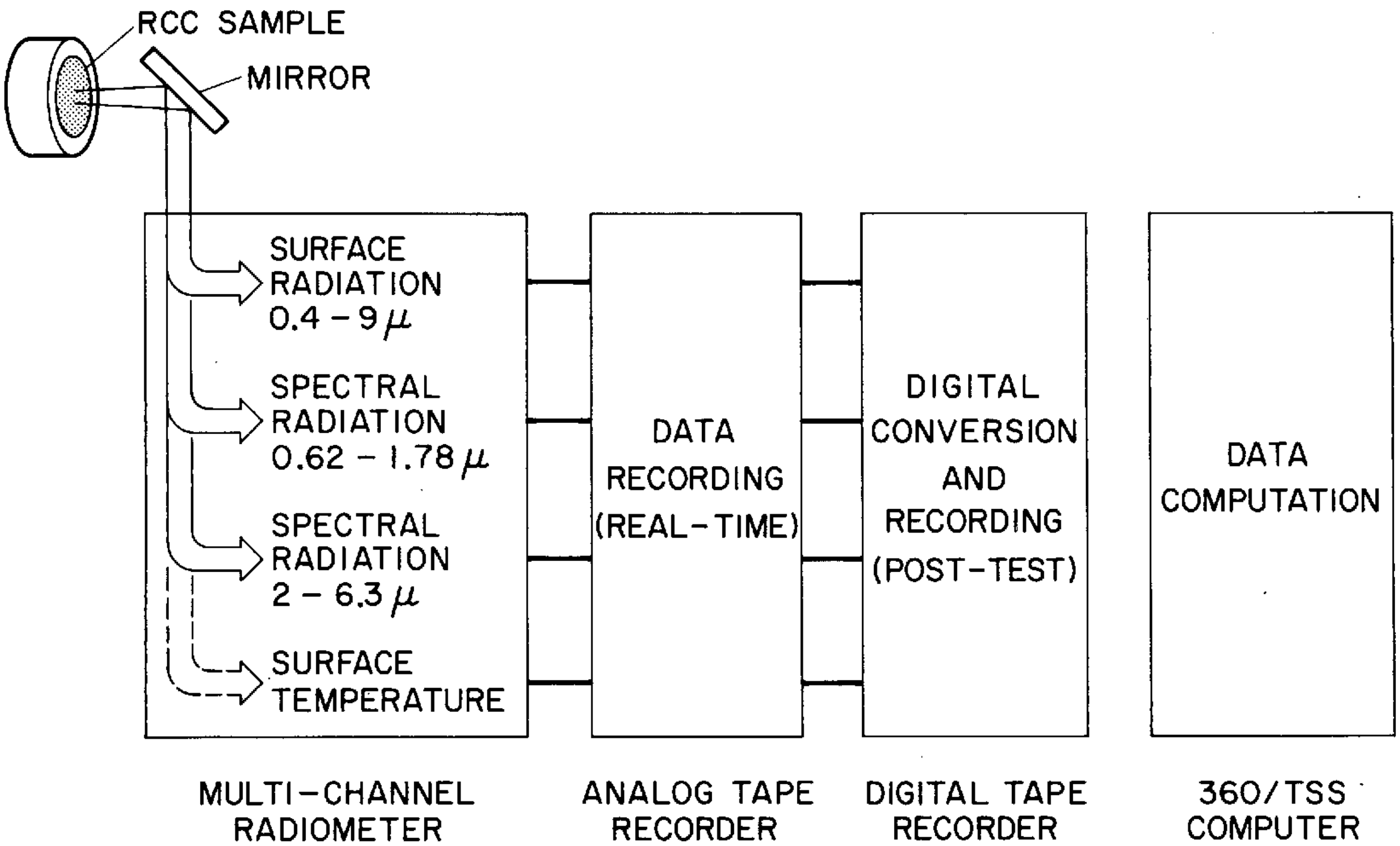


Fig. 1- Schematic of multi-channel radiometr and data processing system.

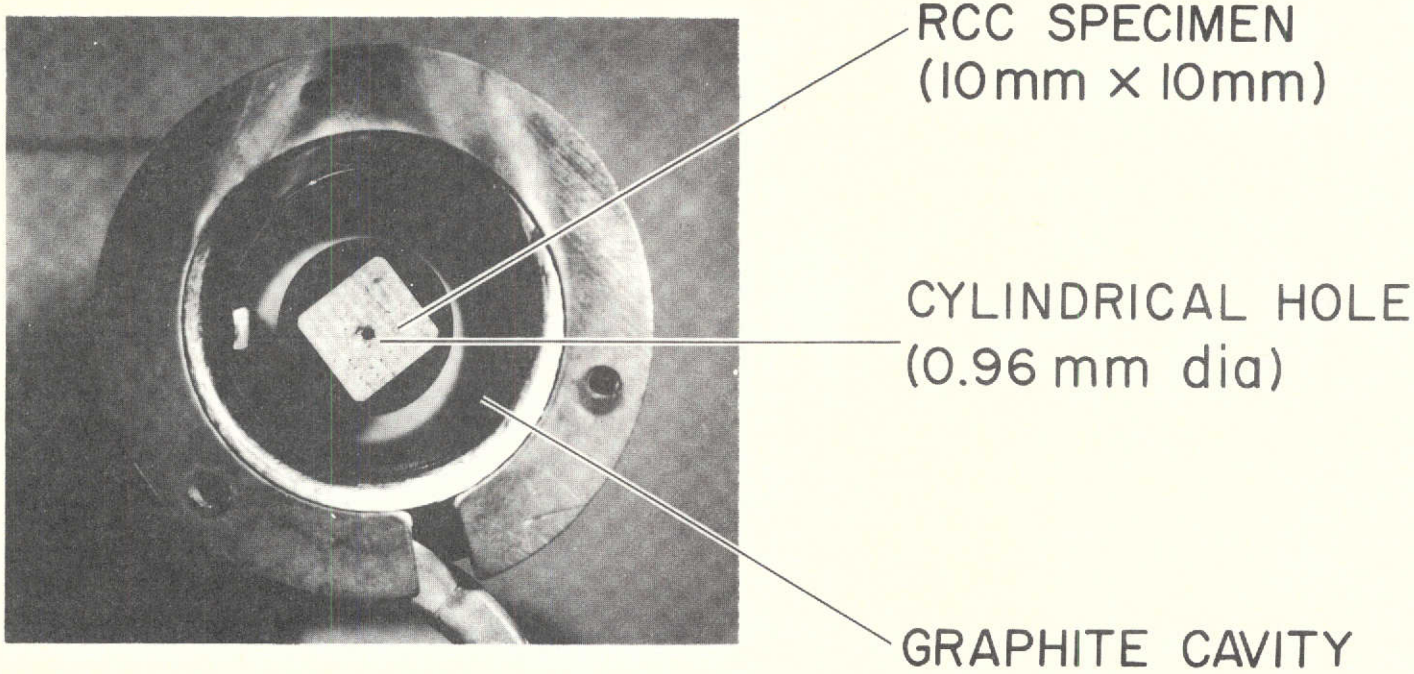


Fig. 2- RCC specimen in graphite cavity in laboratory tests.

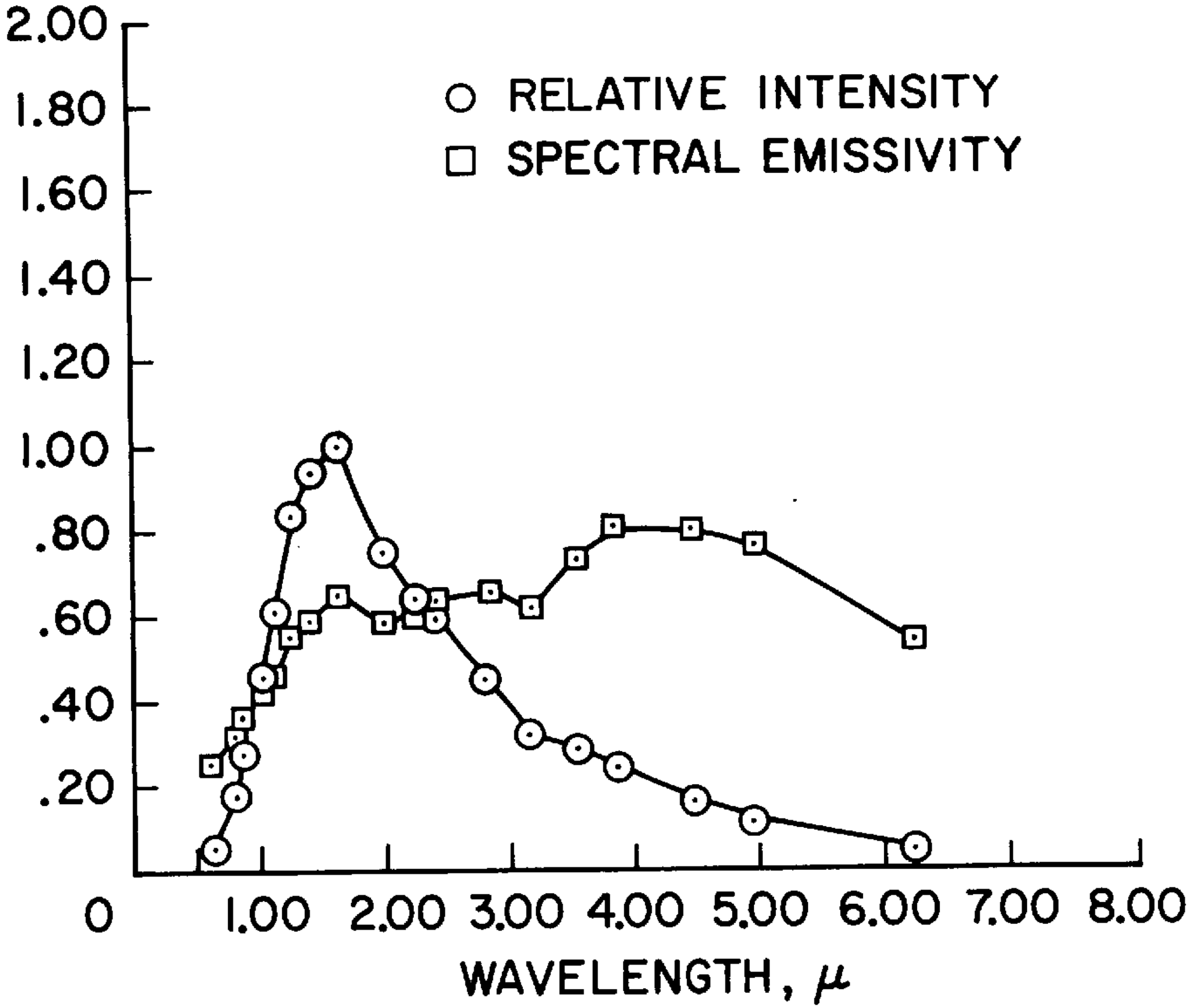


Fig. 3- RCC relative spectral intensity and spectral emissivity determined from arcjet test data (sample W19-(11-1)-5).

(a)- after 65 minutes exposure to convective heating (surface temperature 2014 deg K).

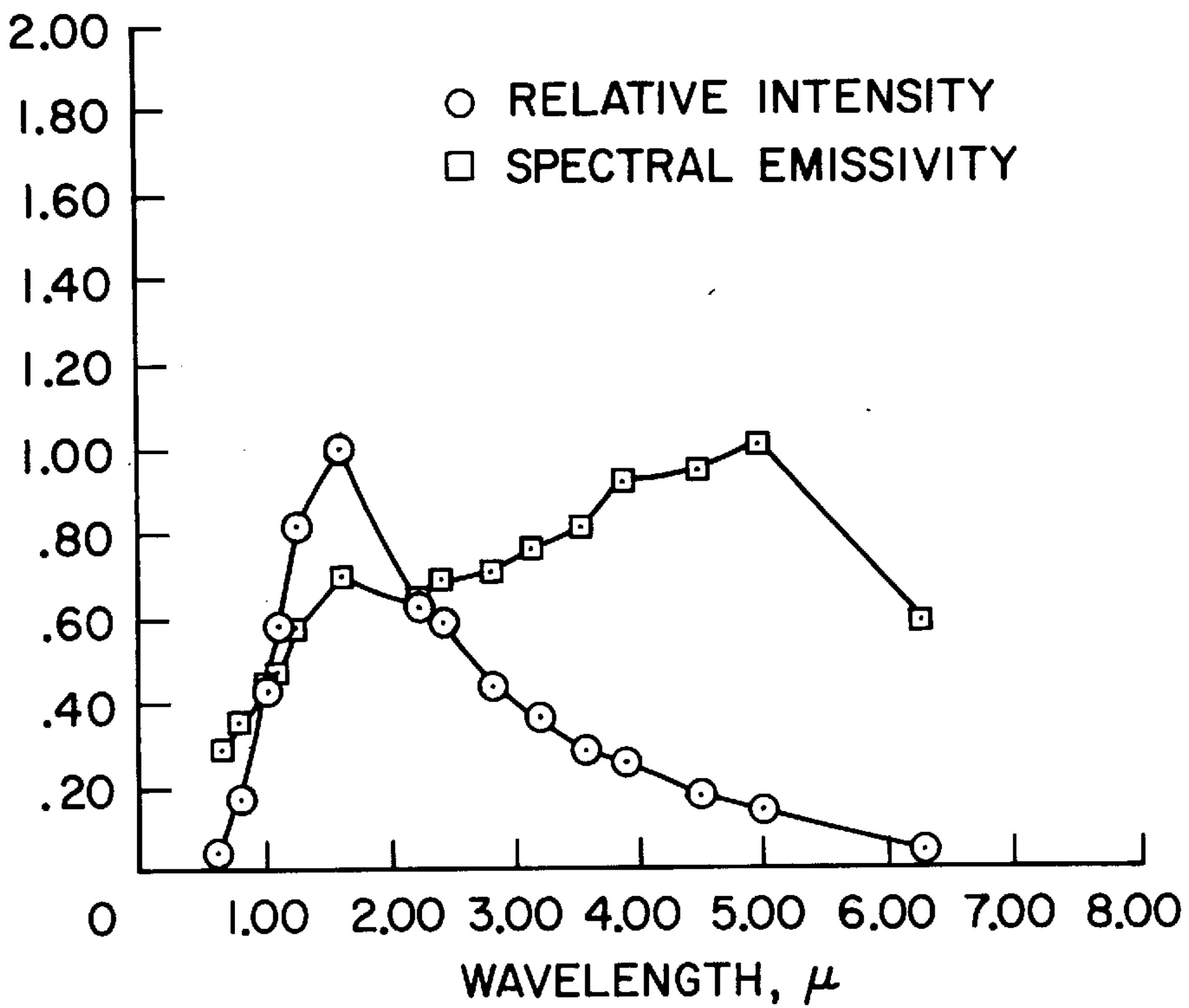


Fig. 3(b)- after 115 minutes exposure to convective heating (surface temperature 2010 deg K).

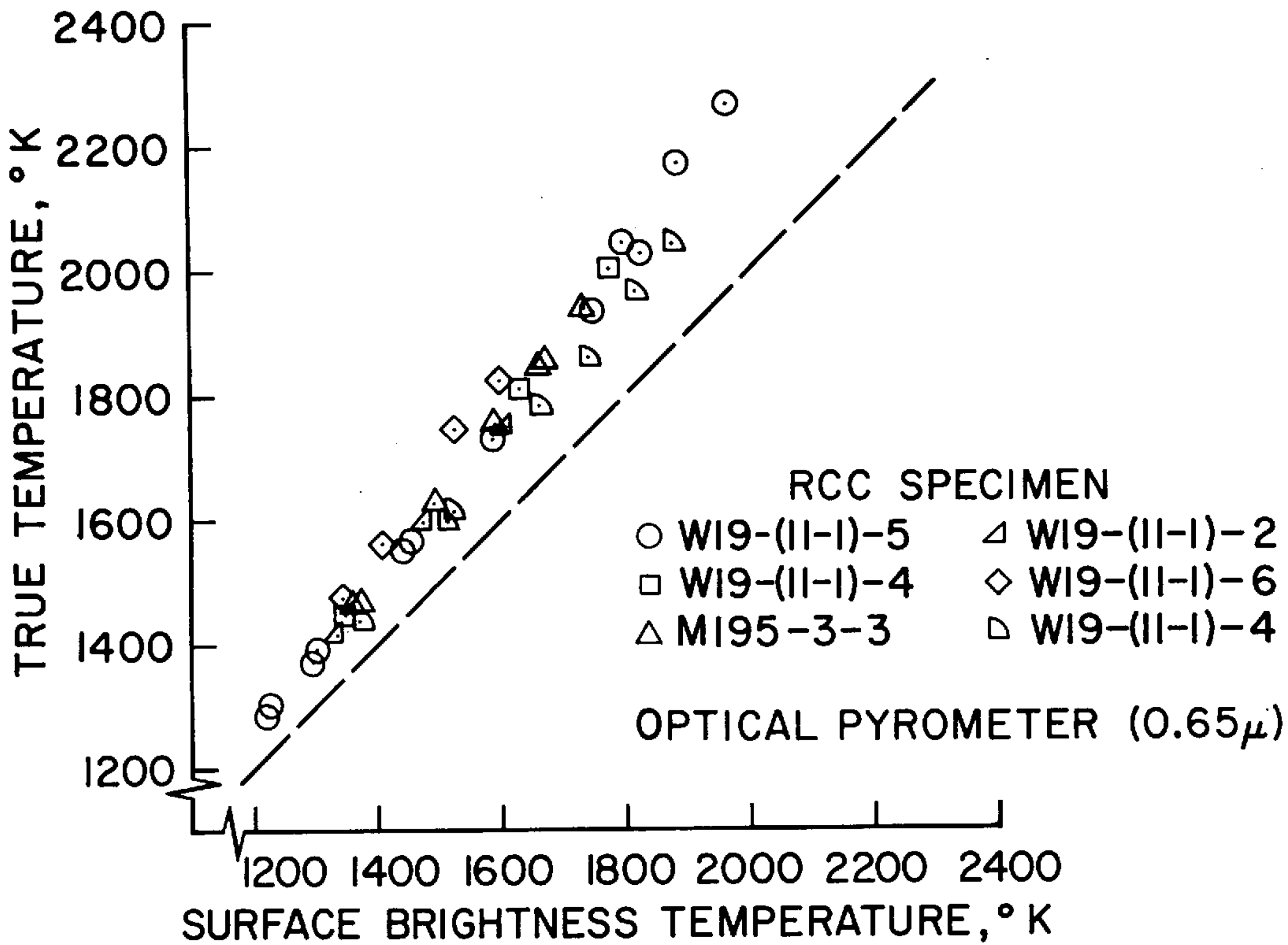


Fig. 4- Temperature measurements in laboratory tests of RCC specimens with cylindrical holes.

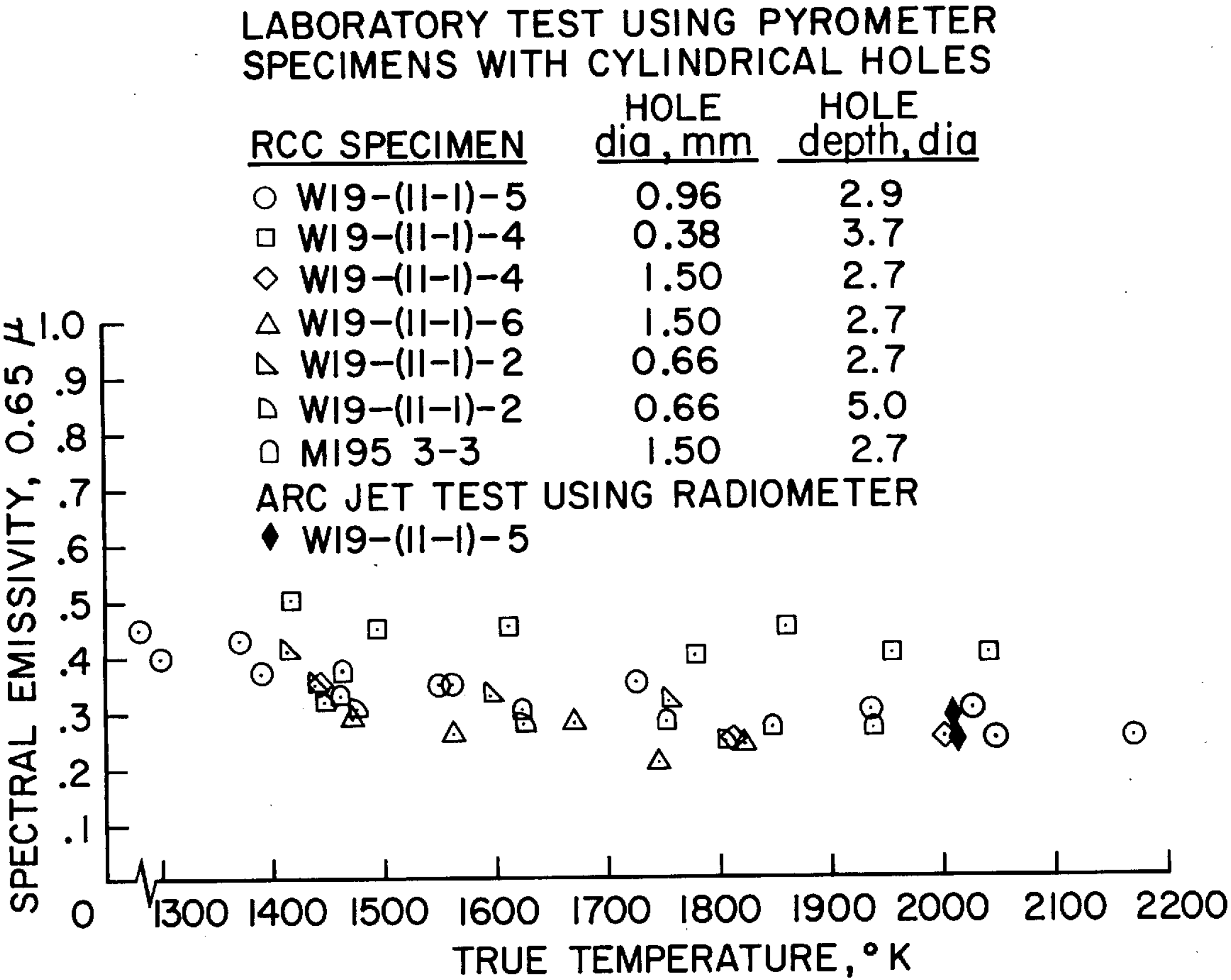


Fig. 5- RCC spectral emissivity at 0.65 micron determined by two independent methods.

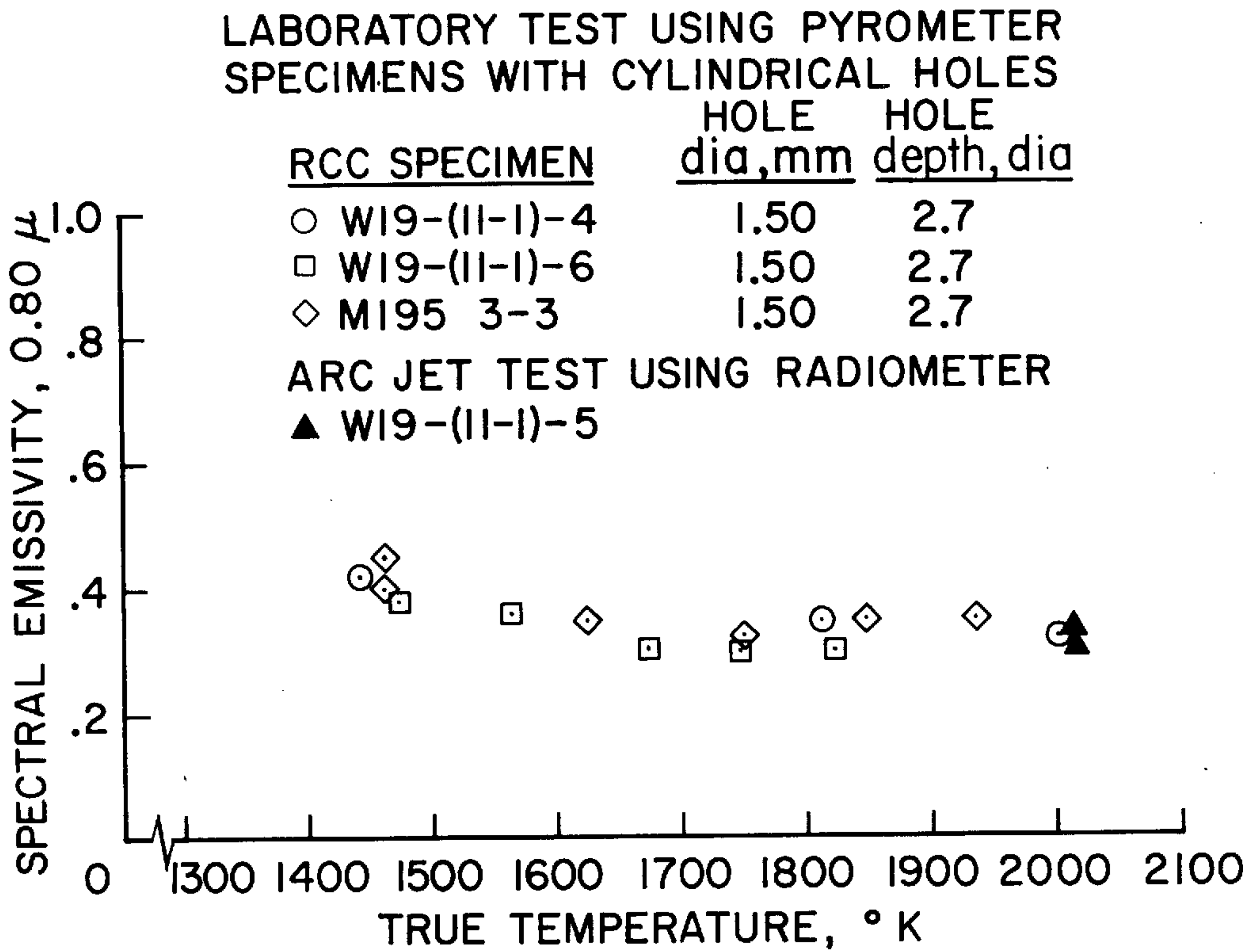


Fig. 6- RCC spectral emissivity at 0.8 micron determined by two independent methods.

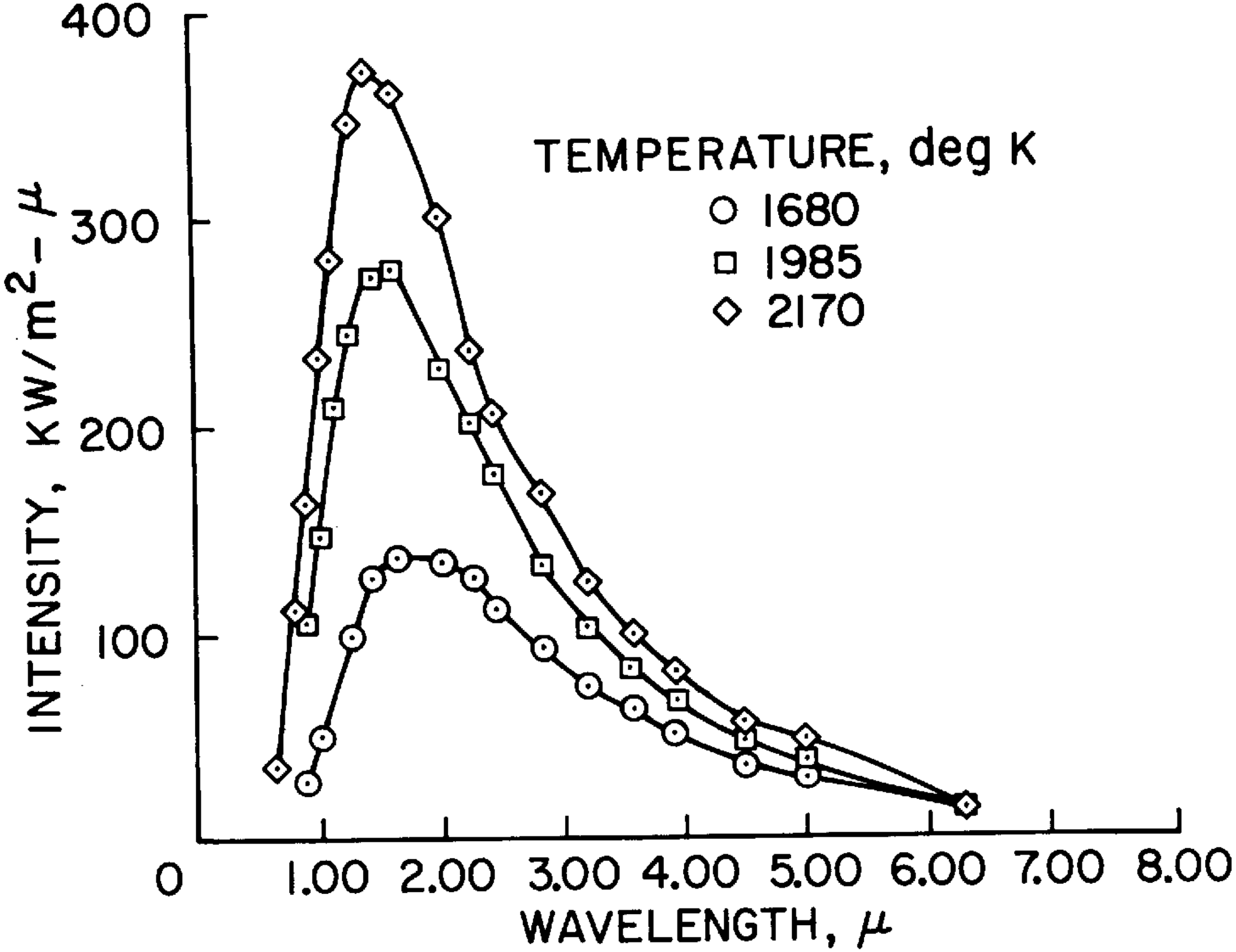


Fig. 7- RCC spectral radiation intesity measured in laboratory tests (specimen from sample W19-(11-1)-5).

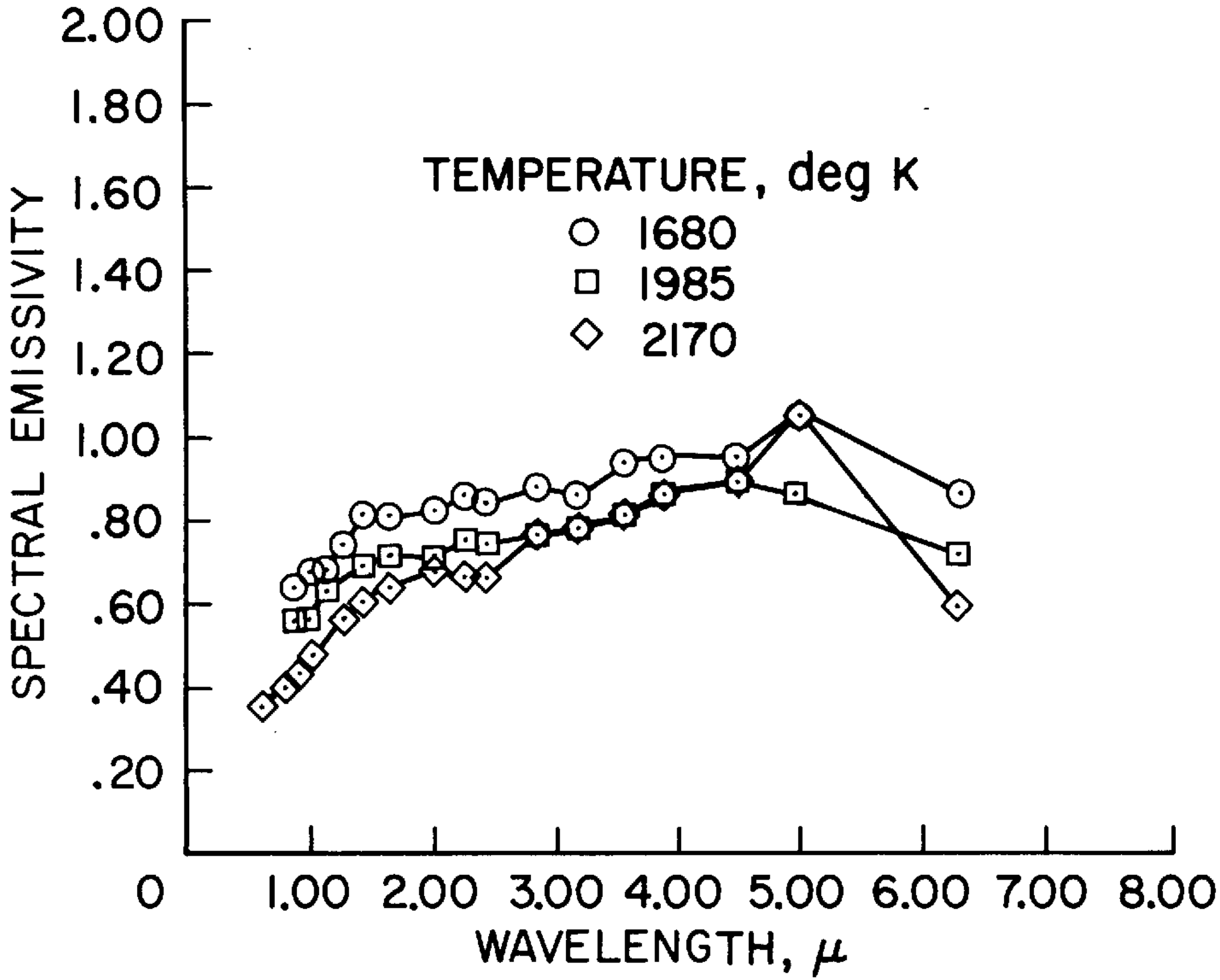


Fig. 8- RCC spectral emissivity determined from laboratory tests (specimen from sample W19-(11-1)-5).

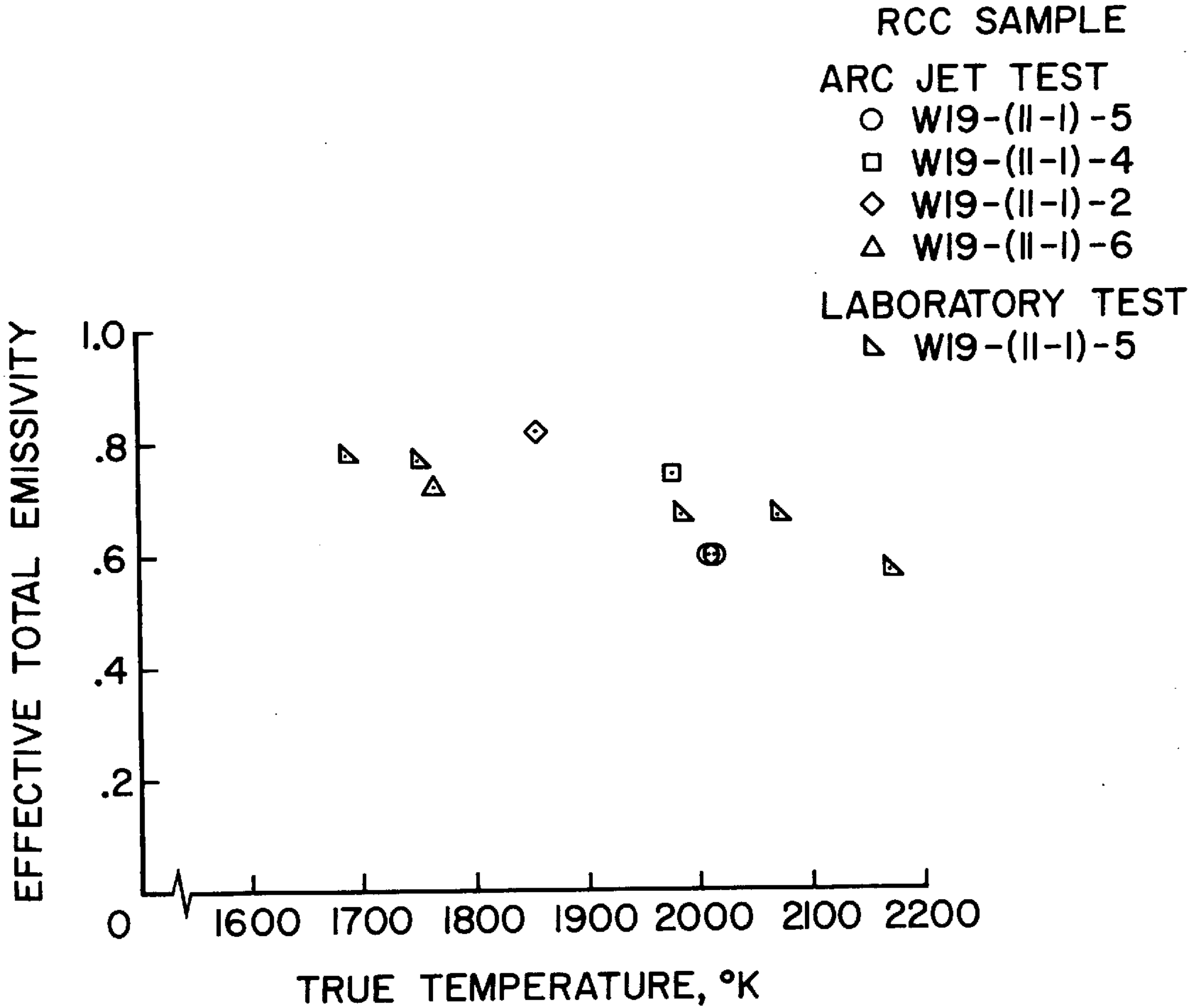
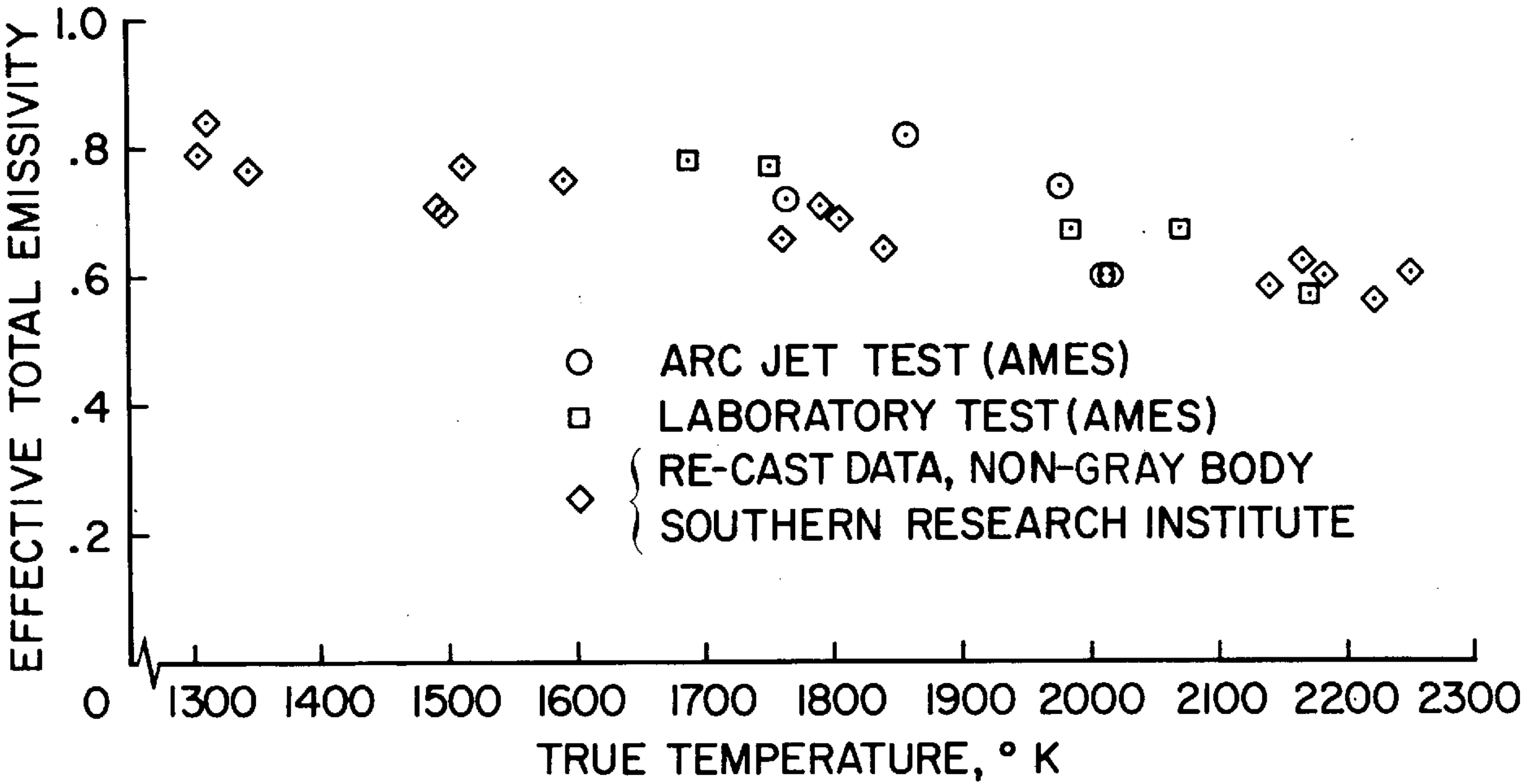


Fig. 9- RCC effective total emissivity determined from arcjet and laboratory tests.



Fiq. 10- RCC effective total emissivity determined from contractor tests and present tests.

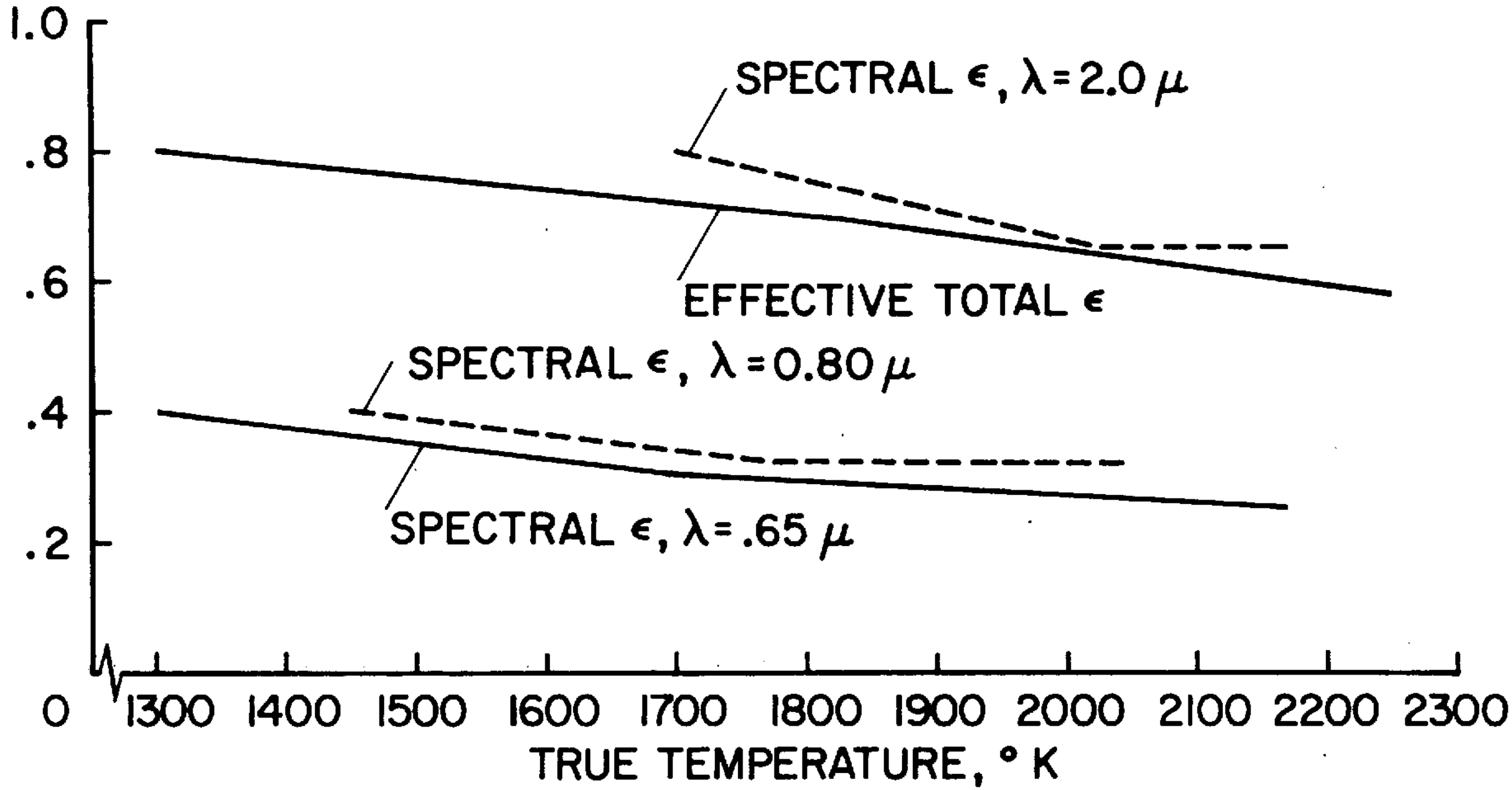


Fig. 11- Recommended RCC emissivity values.