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THE EFFECT OF HIGH TEMPERATURE UPON THE TRANSMITTANCE AND THE EMISSION SPECTRUM OF INFRARED WINDOW MATERIALS

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THE EFFECT OF HIGH TEMPERATURE UPON THE TRANSMITTANCE AND THE EMISSION SPECTRUM OF INFRARED WINDOW MATERIALS

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The Effect of High Temperature Upon The Transmittance and the Emission Spectrum of Infrared Window Materials

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I. INTRODUCTION

The transmittance of an infrared window material is one of the most important characteristics of that material, and one which can determine immediately whether or not a given material may be suitable for a particular application. Since this information is so important, transmittance curves are readily obtainable for all of the commercially available infrared materials.

A number of infrared applications, however, require utilizing window materials under other than optimum conditions. These conditions may include exposing the window to corrosive contaminants and/or operation at high temperatures. The performance of possible candidate window materials under these severe conditions must be evaluated before their suitability can be determined.

The purpose of this investigation is to determine the effect of high temperatures such as those expected to be encountered in the Pioneer Venus Probe mission upon the transmittance of zinc selenide and cadmium telluride infrared window materials, and to determine the radiation emitted by these materials at high temperatures.

II. ABSORPTION COEFFICIENT

There are actually two values of transmittance which can be associated with an optical material. The most familiar of these is referred to as "external" transmittance, and is represented by

$$T = I/I_0 \tag{1}$$

where I_0 is the intensity of the radiation impinging upon the first surface of an optical body and I is the intensity of the radiation emerging from the final surface of the body.

The second value of transmittance is known as "internal" transmittance, and it is represented by

$$T_i = I_a/I_e \tag{2}$$

where I_e is the intensity of radiation which has just entered the first optical surface and I_a is the intensity arriving at the final optical surface. The distinction between these two values of transmittance is that internal transmittance includes only intrinsic absorption losses while external transmittance measurements also include reflection losses.

The Bouger or Lambert law states that the radiation passing through an optical material will diminish in geometrical progression, and the transmittance of the material can be expressed as

$$T_i = e^{-ax} = I_a/I_e \tag{3}$$

where x is the thickness of the absorbing material and a is the absorption coefficient of that material. The absorption coefficient is usually expressed in units of reciprocal centimeters, and represents the fraction of the energy lost while the radiation is passing through a pathlength of one centimeter in the material. The absorption coefficient is constant, depending upon the nature of the material and the wavelength of radiation.

Absorption coefficients can be evaluated from external transmittance measurements provided the reflection losses can be determined. The theoretical reflection loss r at each uncoated optical surface can be calculated from the formula

$$r = \frac{(n - 1)^2}{(n + 1)^2} \tag{4}$$

where n is the refractive index of the material. Applying this loss to the radiation incident upon the two surfaces of an optical window gives the following relationships:

$$I_e = (1 - r)I_o$$

and

$$I = (1 - r)I_a \tag{5}$$

Substituting the above values for I_e and I_a into (3) gives

$$T = I/I_o = (1 - r)^2 e^{-ax} \tag{6}$$

With this formula, the absorption coefficient of a material can be determined by measuring the external transmittance T of a material of known thickness, provided the refractive index of the material is available.

III. TOTAL LOSSES

While absorption coefficients are useful for determining the energy absorbed as radiation traverses a given pathlength within a material they do not provide complete information concerning the transmission, reflection, and absorption of radiation by an optical component.

In Figure 1 it can be seen that radiation of intensity I_o is incident upon a material of thickness x. Some of this radiation will be reflected as r_1, while that portion not reflected enters the material as $I_1(I_e)$. A portion of I_1 will be absorbed as it traverses the material. The fraction of energy lost is denoted by k, and depends upon the thickness of the material and its absorption coefficient. Intensity $I_2(I_a)$ will reach the second surface of the material, where part will be reflected as r_2 and the rest transmitted as t_1. The reflected component r_2 will be reduced by absorption losses, arriving back at the first surface as I_3. Again, a portion of I_3 will be reflected as r_3 while the remaining radiation will be transmitted and return toward the source of radiation. The reflected r_3 will be reduced by absorption and reach the second surface as I_4. The reflected portion of I_4 will have become insignificantly small and can be neglected. The portion of I_4 which is not reflected will emerge from the material.

From observing Figure 1 it is seen that the total measured transmitted radiation I is composed of t_1 and t_3. Likewise, the total reflected component R consists of r_1 and t_2. The total absorbed energy, K, is the sum of k_1, k_2, and k_3.

Each of the components of Figure 1 could be individually determined by evaluating the reflection loss factor r and the absorption loss factor k. The former is found from Equation (4), while k is calculated as follows:

$$k = \frac{1 - T - 2rm}{1 - 2r + 4r^2} \qquad (7)$$

The factor m is determined by the refractive index of the material, and is found by using the proper formula:

Refractive Index (n)	Factor (m)	
2.0 or less	$(1 - r + r^2)$	
2.0 to 2.5	$(1 - r + r^2 - r^3)$	
2.5 to 3.0	$(1 - r + r^2 - r^3 + r^4)$	(8)

The quantities of primary interest are the total reflected component R and the total absorbed component K. These can be calculated directly from

$$R = r\{1 + (1 - k)^2(1 - r)^2\} \qquad (9)$$

and

$$K = k(1 - kr) \qquad (10)$$

All of the energy incident upon an optical material should be accounted for in the reflected, absorbed, and transmitted components. Any scattering which may occur within the material will be included in the absorption component K. The relationship between these various portions of the incident radiation is

$$R + K + T = 1 \qquad (11)$$

IV. EMITTANCE

The black body spectral energy density for unpolarized radiation is given by Planck's equation

$$W_\lambda = 2\pi C^2 h\lambda^{-5}(e^{hc/\lambda kT} - 1)^{-1} \qquad (12)$$

where W_λ is the radiant flux per unit area per unit increment of wavelength, c is the velocity of light, h is Planck's constant, λ is the wavelength, k is Boltzmann's constant, and T is the absolute temperature.

The wavelength of maximum radiation will vary with the temperature of the black body according to Wein's Displacement Law

$$\lambda_{max} = 2897.9/T \qquad (13)$$

The emission spectrum of a material has the same basis and provides the same type of information as the absorption spectrum. The emission spectrum of a material at temperature T is the same as black body emission at the same temperature T and at wavelength λ multiplied by the percent absorption of the sample.[1] Therefore, if the total absorption of a material at temperature T and wavelength λ is evaluated from Equation (10) the emission spectrum can be obtained by multiplying this factor by the black body radiation calculated from Equation (12).

The relationship of reflectance, transmittance, and emittance can be expressed as[2]

$$\text{Reflectance} + \text{Transmittance} + \text{Emittance} = 1 \qquad (14)$$

V. EXPERIMENTAL RESULTS

The infrared window materials chosen for testing were Irtran-4 (zinc selenide) and Irtran-6 (cadmium telluride) furnished by Eastman Kodak Company. Test windows were placed in the sample beam of a Perkin-Elmer

Model 21 Infrared Spectrophotometer. The test pieces were each placed inside a cylindrical heating element, arranged in such a manner that the test windows could be heated without restricting the passage of the instrument sample beam. The temperature of the window was monitored by a thermocouple in contact with the material.

The transmittance of a test window was measured at room temperature in the conventional manner. The sample was then heated in place to the desired temperature and its transmittance remeasured. The measured transmittance at elevated temperatures, T_H, was usually larger than that measured at room temperature, T_C, due to the presence of radiation being emitted by the window itself and also by the heating element.

To correct the measurements of T_H for the background emission from the window and heater it was necessary to measure this radiation. This was accomplished by blocking the sample beam and allowing only the radiation from the heater and window to enter the instrument. A sum of this emission over the wavelength range of interest and at the test temperature produced the desired background emission spectrum.

The actual transmittance of the test windows at elevated temperatures was obtained by subtracting the background emission from the measured values of T_H at each temperature. Transmittance data for Irtran-4 are shown in Table 1 for temperatures of 25^oC, 200^oC, 300^oC, and 425^oC. The window was 0.32 cm thick (Figure 2).

Similar data for Irtran-6 material, 0.6 cm thick, are shown in Table II. In remeasuring the transmittance of the Irtran-6 window at room temperature, after it had been at 425^oC for approximately 15 minutes it was observed that the material did not return to its original transmittance values. Apparently the heating had an adverse effect upon the transmittance at wavelengths below 6 microns and above 11 microns. Visual inspection of the window showed that the surface of a portion of the window was coated, apparently with an oxide film. The data from Table II suggest that the damage occurred somewhere between 300°C and 425°C (Figures 3 and 4).

A series of measurements were made in an effort to determine the temperature at which the Irtran-6 sample had become damaged, and also to compare the performance of Irtran-4. Two 2 mm-thick windows, one of Irtran-4, the other of Irtran-6, were chosen for these tests.

Initially, the transmittance of each window was measured at room temperature. The windows were then heated to 200°C in an oven and maintained at that temperature for one hour. The windows were then allowed to cool, and their transmittances remeasured.

The windows were then heated to 300°C for 30 minutes, cooled, and their transmittances measured again.

The identical procedures were followed, heating the windows sequentially to 350°C for 30 minutes, 400°C for 30 minutes, and 425°C for five minutes.

The results of these transmittance measurements are shown in Tables III and IV. Measurements in the 200°C columns were obtained after the windows had been at 200°C for one hour. Measurements in the 300°C columns were made after the windows had been at 300°C for 30 minutes and at or above 200°C for a total of two hours. The 350°C measurements were made after the windows had been at 350°C for 30 minutes, at or above 300°C for one hour and 15 minutes, and at or above 200°C for a total of three hours and five minutes.

Corresponding times for the remaining columns are:

	Temperature	Total Time
$400^{\circ}C$:	$T \geq 200^{\circ}C$	4 hours 25 minutes
	$T \geq 300^{\circ}C$	2 hours 15 minutes
	$T \geq 350^{\circ}C$	1 hour 15 minutes
	$T = 400^{\circ}C$	30 minutes
$425^{\circ}C$	$T \geq 200^{\circ}C$	6 hours
	$T \geq 300^{\circ}C$	3 hours 15 minutes
	$T \geq 350^{\circ}C$	2 hours
	$T \geq 400^{\circ}C$	1 hour
	$T = 425^{\circ}C$	5 minutes

After baking at $400^{\circ}C$, the surface of the Irtran-4 material appeared as if an oxide were forming. This condition appeared slightly worse after baking at $425^{\circ}C$, but had no adverse affects upon the transmittance of the window. In fact, baking at high temperatures apparently improved the short wavelength transmittance of the window appreciably.

A deposit was formed on one side of the Irtran-6 window after baking at $350^{\circ}C$. This deposit is believed to have been the result of a contaminant not completely removed by cleaning prior to these measurements. The transmittance did drop after this deposit formed, but it is believed that this decrease was due mainly to the presence of the deposit and little, if any, was due to thermal damage to the window itself. One side of the Irtran-6 remained unchanged in appearance throughout these tests.

The lack of an oxide film on the Irtran-6 surface such as that observed in obtaining data for Table II and the absence of a dramatic decrease in transmittance at the longer wavelengths indicate that the damage suffered by the 6-mm thick Irtran-6 window during transmittance measurements at 425°C was the result of uneven heating of the window. Apparently, the damaged areas of the window were raised to temperatures above those indicated. For this reason, all of the measurements made for Irtran-6 at 425°C must be considered as extremely pessimistic. In addition, since the identical heating method was used for all measurements listed in Tables I and II, all of these values may be considered as being a possible "worst case".

The absorption coefficients for Irtran-4 and Irtran-6 have been calculated and are listed in Tables V and VI. These values were obtained from Equation (6). Values of theoretical single surface reflection loss, r, were obtained from Equation (4), using the manufacturer's values for refractive index at the various wavelengths.[2] It is conservatively assumed that any loss of transmittance at elevated temperatures was due to changes in the absorption coefficient of the material and not to variations in its reflective properties. Calculated absorption coefficients can vary appreciably with small changes in transmittance, as can be seen in Table V. At 8 microns and 200°C a transmittance of 65.9 percent gives an absorption coefficient of .1228. At the same wavelength but at 300°C an obviously slightly high measurement of 68.9 percent transmittance resulted in a negative absorption coefficient. In Table VI, a number of absorption coefficients for Irtran-6 both at 425°C and after subsequent cooling are greater than unity. If this were true, no radiation at all would be transmitted by one centimeter of this material. Obviously, since radiation is being transmitted, the reflective properties of the material have been altered to some extent by the formation of the oxide coating.

Table VII and VIII list the total reflection losses, R, and the total absorption losses, K, for the two materials at various temperatures. In comparing the absorption losses for Irtran-4 and Irtran-6 it must be noted that the Irtran-6 test window was 6 mm thick, while the Irtran-4 window had a thickness of only 3.2 mm. The values in these tables were calculated from Equations (4), (7), (9), and (10) using transmittance values from Tables I and II (Figures 5 and 6).

Tables IX through XII (Figures 7-10) are calculations of the radiant flux (watts/cm^2/micron) emitted by the two Irtran materials at various temperatures. These figures are the result of multiplying black body radiation at the appropriate temperature, Equation (12), by the emittance or total absorbance from Tables VII and VIII.

VI. THE CHEMICAL EFFECT OF H_2SO_4 UPON IRTRAN WINDOWS

In the report for work performed under NASA Research Grant NGL 04-001-007 dated March 15, 1974, the results of tests were reported in which acids were placed in contact with Irtran-4 and Irtran-6 materials. The following is a continuation of these studies at elevated temperatures.

Some scraps of Irtran material were obtained from the manufacturer for the purpose of destructive testing. The transmittance of a number of these samples was measured over the wavelength range of 2.5 to 15 microns, using a Perkin-Elmer Model 21 IR Spectrophotometer. Concentrated H_2SO_4 was then placed in contact with one polished surface of the materials, and the samples were heated for 30 minutes, after which they were removed from the oven and any remaining H_2SO_4 and water soluble reaction products were removed from the surface. The transmittance of the sample was then re-measured. This procedure was repeated two additional times, resulting in a total time of 1.5 hours in the oven.

Tests conducted with Irtran-4 showed that the transmittance of the material was not affected by concentrated H_2SO_4 at 100°C. The surface was not visibly eroded and there were no reaction products seen. This was true after contact with the acid for periods of 30 minutes, 60 minutes, and 90 minutes.

Those pieces of Irtran-4 material tested at 150°C showed that the concentrated H_2SO_4 caused minimal damage after 30 minutes. The transmittance of the samples dropped to approximately 84 percent of the original value at 2.5 microns, with a slight increase to 98 percent of the original value at 15 microns. A further 30 minute period at 150°C severely damaged the material, with the transmittance of the samples varying in a fairly linear manner from zero at 2.5 microns to approximately 65 percent of the original value at 15 microns. A further 30 minute exposure to the acid at 150°C resulted in more loss of transmittance, from zero at 3.5 microns to approximately 50 percent at 15 microns. In all of the above and following cases, once the transmittance is cited to be zero at a given wavelength, it remains at that value for all values of shorter wavelength radiation.

Those samples tested at 200°C showed a drop to zero transmittance for all wavelengths below 9.5 microns. The transmittance increased to only 7 percent of the original value at a wavelength of 15 microns. A further 30 minute exposure to the acid reduced the transmittance to zero for all wavelengths measurable with the spectrophotometer.

The Irtran-6 materials were affected quite strongly and erratically by the concentrated H_2SO_4. The general trend of the degradation was fairly linear. Transmittance varied from approximately 7 percent of the original value at 2.5 microns to 35-45 percent at 15 microns after 30 minutes of contact with the concentrated H_2SO_4 at 150°C. Further exposure to the acid caused the transmittance to be further reduced, until after a total of 1.5 hours at 150°C the transmittances varied from zero at 2.5 microns to approximately 10 percent of the original value at 15 microns.

Results obtained with concentrated H_2SO_4 on Irtran-6 at 200°C were approximately the same as those obtained at 150^{0}C. Results of tests conducted at 100^{0}C were extremely erratic, in some cases the loss of transmittance was greater than that indicated from the results at higher temperatures.

VII. CONCLUSIONS

The transmittance of Irtran-4 is slightly greater than that of Irtran-6. This variance is due in part to the higher refractive index of Irtran-6 which results in greater reflection losses in air under standard conditions. Comparison of the absorption coefficients in Tables V and VI shows that the cadmium telluride (Irtran-6) material also absorbs more energy per unit length than zinc selenide (Irtran-4).

Total absorption losses from Tables VII and VIII (Figures 4 and 5) should not be directly compared because of the difference in thickness of the Irtran-4 and Irtran-6 test samples. For equal sample thicknesses the Irtran-6 should exhibit the higher absorption loss of the two materials, but the difference is exaggerated in these tables since the Irtran-6 test window was almost twice as thick as the Irtran-4 window.

The emission spectra of the two materials are found in Tables IX through XII (Figures 6 through 9). The difference in sample thickness is also a factor in these tables, since these calculations are performed using total absorption values.

From these tests it would appear that the Irtran-6 material is more severely affected by high temperatures than Irtran-4. However, based upon the data from Tables III and IV, it is doubtful that significant damage would occur to either material in air at the maximum temperature expected (700^{0}K) during the Pioneer Venus Probe mission.

Several obvious discrepancies in the calculated data have been pointed out in the body of this report. In Table V Irtran-4 is shown to have a negative absorption coefficient at 8 microns for a temperature of 300°C. The table below has been prepared to demonstrate how small variations in the measured transmittance of a sample material will affect the calculated absorption coefficient of that material. In the table it is assumed that the sample is an Irtran-4 window 3.2 milimeters thick and that the transmittance is measured at a wavelength of 8 microns. The value of the absorption coefficient is calculated for several possible transmittance measurements.

Transmittance	Absorption Coefficient
.660	.118
.665	.094
.670	.071
.675	.048
.680	.025
.685	.002
.690	-.021

These figures show that in this particular case an error in the measured transmittance of only one-half of one percent will result in a change in the calculated quantity of energy absorbed per centimeter of material of approximately 2.3 percent of the incident energy. It has been observed that measurements made with the particular instrument used in these tests generally have a precision of approximately ±0.5 percent of the full scale reading. However, the particular method used for determining the transmittance of windows at elevated temperatures could introduce several errors which would have an adverse affect upon this precision.

Transmittance values were obtained by measuring the transmittance of the window while the window was being heated in an oven. These values were higher than the actual transmittance, due to the presence of radiation from the oven and the heated window itself. To correct the transmittance measurements it was necessary to subtract the contribution from the oven and window radiation. This value was determined by shutting off the sample beam of the instrument and measuring the emitted radiation of the oven and window as compared to the instrument reference beam. During this measurement the advantage of a double-beam instrument was lost. Any fluctuations in source intensity would be detrimental to the precision of the measurement. In addition, small variations in the temperature of the oven and the window between the transmittance measurement and the background measurement would also affect the precision. Finally, if there were no other errors, the precision of the background run itself would reduce the overall precision by a factor of 2, or ±1 percent.

It has been concluded that the precision of measurements made at room temperature is approximately ±0.5 percent. Precision at elevated temperatures is estimated to be generally 2.5 percent or better.

Table VI contains a number of absorption coefficients for Irtran-6 which are greater than unity. These occur at wavelengths where the transmittance of the window has been greatly affected by heating. In Equation (2) any scattering losses which might be introduced either within the material or upon its surface will be lumped with the absorption losses. Scattering from the surface of the material will result in less radiation entering the material than expected, resulting in high values for the calculated absorption losses.

Irtran-4 appears to withstand contact with concentrated H_2SO_4 at 100^oC much better than Irtran-6. At other temperatures both materials are severely affected. The behavior of individual samples was quite erratic, permitting only generalizations to be made concerning material performance. This was due in part to the unpredictable nature of surface reactions of this type, and possibly due to individual variations within the scrap materials used for the tests.

VIII. REFERENCES

1. Introduction to Infrared Spectrometry, The Perkin-Elmer Corporation, Norwalk, Connecticut, 1, 8, (1952).

2. Kodak Publication U-72, "Kodak Irtran Infrared Optical Materials," Eastman Kodak Company, 1971.

TABLE I

Transmittance of Irtran-4 Material at Various Temperatures (3.2 mm Sample)

	Percent Transmittance of Irtran-4 (3.2 mm Thick)			
Wavelength (microns)	25°C	200°C	300°C	425°C
2	56.1	56.1	56.1	56.4
3	56.3	55.5	55.5	56.6
4	60.5	62.5	60.5	55.6
5	64.6	64.0	64.9	59.8
6	66.0	65.7	66.6	62.3
7	65.7	66.0	67.8	62.7
8	66.5	65.9	68.9	64.1
9	65.4	65.4	66.4	61.5
10	67.0	67.6	68.3	63.1
11	67.1	66.5	67.1	62.0
12	67.3	65.8	65.5	60.2
13	67.8	65.8	65.5	58.9
14	67.2	63.8	63.4	55.7
15	64.5	56.5	62.5	57.6

TABLE II

Transmittance of Irtran-6 Material at Various Temperatures (6 mm Sample)

	Percent Transmittance of Irtran-6 (6 mm Thick)				
Wavelength (microns)	25°C	200°C	300°C	425°C	After Heating 25°C
2	39.9	39.9	39.9	27.4	28.9
3	46.2	44.9	44.6	30.3	38.8
4	48.5	47.2	48.3	36.8	38.2
5	50.2	50.2	44.5	40.5	42.4
6	50.7	51.4	46.5	43.9	48.4
7	50.0	50.3	44.7	42.8	49.2
8	49.7	50.4	43.7	41.4	50.0
9	50.1	46.6	44.6	39.3	48.2
10	52.2	43.3	42.2	28.9	48.5
11	51.9	44.2	43.3	25.8	47.3
12	52.0	43.1	42.2	25.0	45.5
13	51.3	42.8	41.1	20.0	34.1
14	50.3	43.5	40.1	14.4	20.1
15	49.3	41.9	38.6	9.5	16.7

TABLE III

Transmittance of Irtran-4 After Heating to Elevated Temperatures (2.1 mm Sample)

Wavelength (microns)	Percent Transmittance of Irtran-4 (2.1 mm Thick) After Being Heated to the Following Temperatures:					
	25°C	200°C	300°C	350°C	400°C	425°C
2	59.9	59.9	61.2	62.0	65.8	73.6
3	60.1	60.1	61.4	62.8	64.0	66.9
4	63.0	63.0	64.6	65.9	65.9	68.2
5	65.8	65.8	67.4	68.4	67.8	69.5
6	66.8	66.4	68.3	69.6	68.0	69.3
7	66.6	66.2	68.1	69.3	67.9	68.4
8	67.2	66.6	68.3	69.8	68.3	68.7
9	66.5	66.2	67.6	68.8	67.4	67.8
10	67.6	67.1	68.6	69.5	67.9	68.6
11	67.7	67.7	69.2	69.8	68.1	68.2
12	67.9	67.9	69.5	70.4	68.9	67.9
13	68.3	67.9	69.8	70.7	69.4	69.1
14	68.0	68.0	69.6	70.6	69.2	69.2
15	66.2	65.9	67.7	66.5	68.0	68.8

TABLE IV

Transmittance of Irtran-6 After Heating to Elevated Temperatures (2.1 mm Sample)

	Percent Transmittance of Irtran-6 (2.1 mm Thick) After Being Raised to the Following Temperatures:					
Wavelength (microns)	25°C	200°C	300°C	350°C	400°C	425°C
2	49.3	47.6	47.6	44.5	44.5	47.6
3	53.5	52.1	53.3	49.8	49.2	52.0
4	54.8	53.4	54.8	50.8	49.7	52.4
5	55.9	54.6	55.9	51.3	49.5	51.5
6	56.9	55.9	56.9	51.7	49.9	50.8
7	57.0	55.3	57.0	51.5	49.1	49.5
8	57.3	55.8	57.3	51.3	48.8	49.2
9	57.5	56.0	56.9	51.1	48.5	48.5
10	58.7	56.9	58.2	51.6	48.7	48.7
11	58.7	57.1	58.1	51.8	48.9	48.5
12	58.9	57.6	58.9	52.0	47.0	48.3
13	58.8	57.2	58.4	51.7	46.7	48.0
14	57.9	56.4	57.1	50.7	46.1	46.8
15	56.2	54.4	53.7	48.4	44.4	43.7

TABLE V

Absorption Coefficients of Irtran-4

			Absorption Coefficient a			
Wavelength (microns)	Refractive Index	r	$25^\circ C$	$200^\circ C$	$300^\circ C$	$425^\circ C$
2	2.447	.176	.594	.594	.594	.578
3	2.440	.175	.591	.636	.636	.574
4	2.435	.174	.371	.270	.371	.635
5	2.432	.174	.170	.199	.155	.411
6	2.428	.173	.107	.121	.079	.287
7	2.423	.172	.127	.112	.028	.273
8	2.418	.172	.094	.122	-.016	.209
9	2.413	.171	.151	.151	.104	.344
10	2.407	.170	.083	.055	.023	.270
11	2.401	.169	.084	.112	.084	.331
12	2.394	.168	.082	.153	.167	.431
13	2.386	.167	.067	.161	.175	.507
14	2.378	.166	.104	.266	.286	.691
15	2.370	.165	.241	.654	.339	.594

$$T = (1 - r)^2 e^{-ax}$$

TABLE VI

Absorption Coefficients of Irtran-6

Wavelength (microns)	Refractive Index	r	Absorption Coefficient a				
			25°C	200°C	300°C	425°C	25°C After Heating
2	2.714	.213	.732	.732	.732	1.359	1.270
3	2.695	.210	.499	.547	.558	1.203	.790
4	2.688	.209	.422	.467	.429	.882	.820
5	2.684	.209	.367	.367	.567	.724	.648
6	2.681	.208	.352	.329	.496	.592	.430
7	2.679	.208	.376	.366	.563	.635	.403
8	2.677	.208	.388	.364	.602	.692	.377
9	2.674	.207	.376	.497	.570	.780	.440
10	2.672	.207	.309	.620	.663	1.294	.431
11	2.669	.206	.320	.588	.622	1.485	.475
12	2.666	.206	.318	.631	.666	1.540	.541
13	2.663	.206	.343	.645	.712	1.913	1.024
14	2.660	.205	.377	.619	.755	2.462	1.906
15	2.657	.205	.412	.683	.820	3.157	2.217

$$T = (1 - r)^2 e^{-ax}$$

TABLE VII

Total Reflection and Absorption Losses for Irtran-4 (3.2 mm Thick)

	Total Reflection Loss R				Total Absorption Loss K			
Wavelength (microns)	25°C	200°C	300°C	425°C	25°C	200°C	300°C	425°C
2	.256	.256	.256	.257	.172	.172	.172	.169
3	.255	.272	.272	.256	.172	.181	.181	.168
4	.265	.271	.265	.252	.121	.097	.121	.181
5	.276	.274	.277	.263	.071	.079	.067	.131
6	.279	.278	.281	.268	.054	.058	.047	.101
7	.277	.278	.283	.268	.059	.056	.033	.097
8	.278	.276	.285	.271	.050	.058	.020	.081
9	.273	.273	.276	.263	.066	.066	.053	.114
10	.276	.278	.280	.265	.047	.039	.031	.0992
11	.275	.274	.275	.261	.047	.055	.047	.111
12	.274	.270	.269	.255	.047	.066	.069	.135
13	.273	.268	.267	.250	.042	.068	.071	.153
14	.270	.260	.259	.240	.052	.095	.100	.194
15	.260	.240	.255	.243	.088	.186	.113	.173

$$R = r\left[1 + (1 - k)^2(1 - r)^2\right]$$

$$K = k(1 - kr)$$

$$k = \frac{1 - T - 2r(1 - r + r^2)}{1 - 2r + 4r^2}$$

TABLE VIII

Total Reflection and Absorption Losses for Irtran-6
(6.0 mm Thick)

Wavelength (microns)	Total Reflection Loss R					Total Absorption Loss K				
	25°C	200°C	300°C	425°C	After Heating 25°C	25°C	200°C	300°C	425°C	After Heating 25°C
2	.272	.272	.272	.246	.249	.307	.307	.307	.443	.427
3	.283	.280	.279	.248	.265	.238	.253	.257	.416	.323
4	.288	.285	.288	.260	.263	.212	.227	.214	.347	.331
5	.292	.292	.277	.267	.272	.192	.192	.260	.306	.284
6	.293	.295	.281	.275	.286	.187	.178	.237	.268	.215
7	.290	.291	.276	.272	.288	.196	.192	.259	.281	.205
8	.289	.291	.274	.268	.290	.200	.191	.271	.297	.196
9	.290	.280	.275	.263	.284	.196	.237	.261	.322	.218
10	.295	.272	.269	.241	.285	.171	.277	.289	.436	.215
11	.293	.273	.271	.236	.281	.175	.267	.277	.469	.230
12	.293	.270	.268	.234	.276	.174	.280	.290	.478	.252
13	.291	.269	.265	.226	.250	.183	.284	.304	.529	.382
14	.287	.270	.262	.219	.226	.196	.277	.316	.584	.528
15	.284	.265	.258	.213	.221	.209	.296	.333	.630	.562

$$R = r\left[1 + (1 - k)^2(1 - r)^2\right]$$

$$K = k(1 - kr)$$

$$k = \frac{1 - T - 2r(1 - r + r^2 - r^3)}{1 - 2r + 4r^2}$$

TABLE IX

Emission Spectra of Irtran-4 and Irtran-6 at 25°C

	Radiant Flux Per Unit Area Per Unit Increment of Wavelength at 25°C W_λ (watts/cm^2/micron)		
Wavelength (microns)	Black Body	Irtran-4	Irtran-6
2	4.5×10^{-8}	7.8×10^{-9}	1.4×10^{-8}
3	1.8×10^{-5}	3.1×10^{-6}	4.3×10^{-6}
4	2.1×10^{-4}	2.6×10^{-5}	4.5×10^{-5}
5	7.8×10^{-4}	5.6×10^{-5}	1.5×10^{-4}
6	1.6×10^{-3}	8.8×10^{-5}	3.0×10^{-4}
7	2.3×10^{-3}	1.4×10^{-4}	4.5×10^{-4}
8	2.7×10^{-3}	1.4×10^{-4}	5.4×10^{-4}
9	3.0×10^{-3}	2.0×10^{-4}	5.9×10^{-4}
10	3.0×10^{-3}	1.4×10^{-4}	5.1×10^{-4}
11	2.9×10^{-3}	1.4×10^{-4}	5.1×10^{-4}
12	2.7×10^{-3}	1.3×10^{-4}	4.7×10^{-4}
13	2.5×10^{-3}	1.1×10^{-4}	4.6×10^{-4}
14	2.3×10^{-3}	1.2×10^{-4}	4.5×10^{-4}
15	2.0×10^{-3}	1.8×10^{-4}	4.2×10^{-4}

$$W_\lambda \text{ (black body)} = 2\pi C^2 h\lambda^{-5}(e^{hc/\lambda kT} - 1)^{-1}$$

$$W_\lambda \text{ (non-black body)} = \text{Emittance} \times W_\lambda \text{ (black body)}$$
$$= KW_\lambda \text{ (black body)}$$

TABLE X

Emission Spectra of Irtran-4 and Irtran-6 at 200°C

Wavelength (microns)	Radiant Flux Per Unit Area Per Unit Increment of Wavelength at 200°C W_λ (watts/cm^2/micron)		
	Black Body	Irtran-4	Irtran-6
2	3.0×10^{-4}	5.2×10^{-5}	9.2×10^{-5}
3	6.3×10^{-3}	1.1×10^{-3}	1.6×10^{-3}
4	1.9×10^{-2}	1.8×10^{-3}	4.3×10^{-3}
5	2.7×10^{-2}	2.1×10^{-3}	5.2×10^{-3}
6	3.0×10^{-2}	1.8×10^{-3}	5.4×10^{-3}
7	2.9×10^{-2}	1.6×10^{-3}	5.6×10^{-3}
8	2.6×10^{-2}	1.5×10^{-3}	5.0×10^{-3}
9	2.2×10^{-2}	1.5×10^{-3}	5.2×10^{-3}
10	1.8×10^{-2}	7.2×10^{-4}	5.0×10^{-3}
11	1.5×10^{-2}	8.3×10^{-4}	4.0×10^{-3}
12	1.3×10^{-2}	8.6×10^{-4}	3.6×10^{-3}
13	1.0×10^{-2}	6.8×10^{-4}	2.8×10^{-3}
14	8.7×10^{-3}	8.3×10^{-4}	2.4×10^{-3}
15	7.2×10^{-3}	1.3×10^{-3}	2.1×10^{-3}

TABLE XI

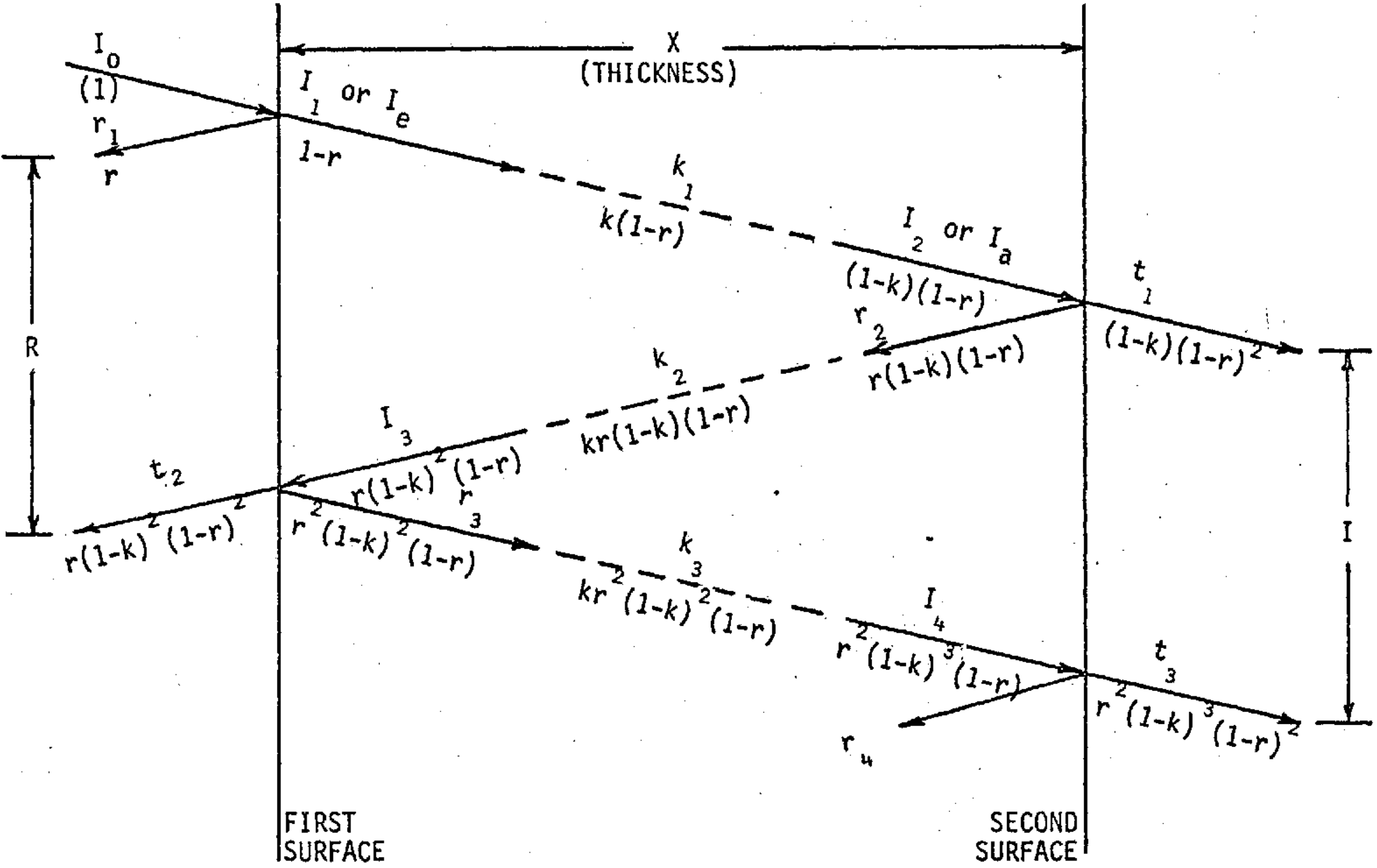
Emission Spectra of Irtran-4 and Irtran-6 at 300^{o}C

	Radiant Flux Per Unit Area Per Unit Increment of Wavelength at 300^{o}C W_{λ} (watts/cm^{2}/micron)		
Wavelength (microns)	Black Body	Irtran-4	Irtran-6
2	4.3×10^{-3}	7.5×10^{-4}	1.3×10^{-3}
3	3.6×10^{-2}	6.5×10^{-3}	9.3×10^{-3}
4	6.9×10^{-2}	6.7×10^{-3}	1.5×10^{-2}
5	7.9×10^{-2}	5.3×10^{-3}	2.1×10^{-2}
6	7.3×10^{-2}	3.4×10^{-3}	1.7×10^{-2}
7	6.2×10^{-2}	2.1×10^{-3}	1.6×10^{-2}
8	5.1×10^{-2}	1.0×10^{-3}	1.4×10^{-2}
9	4.1×10^{-2}	2.2×10^{-3}	1.1×10^{-2}
10	3.2×10^{-2}	9.9×10^{-4}	9.3×10^{-3}
11	2.6×10^{-2}	1.2×10^{-3}	7.2×10^{-3}
12	2.1×10^{-2}	1.5×10^{-3}	6.1×10^{-3}
13	1.7×10^{-2}	1.2×10^{-3}	5.2×10^{-3}
14	1.4×10^{-2}	1.4×10^{-3}	4.4×10^{-3}
15	1.1×10^{-2}	1.2×10^{-3}	3.7×10^{-3}

TABLE XII

Emission Spectra of Irtran-4 and Irtran-6 at 425°C

Wavelength (microns)	Radiant Flux Per Unit Area Per Unit Increment of Wavelength at 425°C W_{λ} (watts/cm^2/micron)		
	Black Body	Irtran-4	Irtran-6
2	4.0×10^{-2}	6.8×10^{-3}	1.8×10^{-2}
3	1.6×10^{-1}	2.7×10^{-2}	6.7×10^{-2}
4	2.1×10^{-1}	3.8×10^{-2}	7.3×10^{-2}
5	1.9×10^{-1}	2.5×10^{-2}	5.8×10^{-2}
6	1.6×10^{-1}	1.6×10^{-2}	4.3×10^{-2}
7	1.2×10^{-1}	1.2×10^{-2}	3.4×10^{-2}
8	9.2×10^{-2}	7.5×10^{-3}	2.7×10^{-2}
9	6.9×10^{-2}	7.9×10^{-3}	2.2×10^{-2}
10	5.3×10^{-2}	5.3×10^{-3}	2.3×10^{-2}
11	4.1×10^{-2}	4.6×10^{-3}	1.9×10^{-2}
12	3.4×10^{-2}	4.6×10^{-3}	1.6×10^{-2}
13	2.6×10^{-2}	4.0×10^{-3}	1.4×10^{-2}
14	2.1×10^{-2}	4.1×10^{-3}	1.2×10^{-2}
15	1.7×10^{-2}	2.9×10^{-3}	1.1×10^{-2}



$$R = r_1 + t_2 = r\left[1 + (1 - k)^2(1 - r)^2\right]$$

$$K = k_1 + k_2 + k_3 = k(1 - kr)$$

FIGURE 1

REFLECTED, TRANSMITTED, AND ABSORBED COMPONENTS OF INCIDENT RADIATION

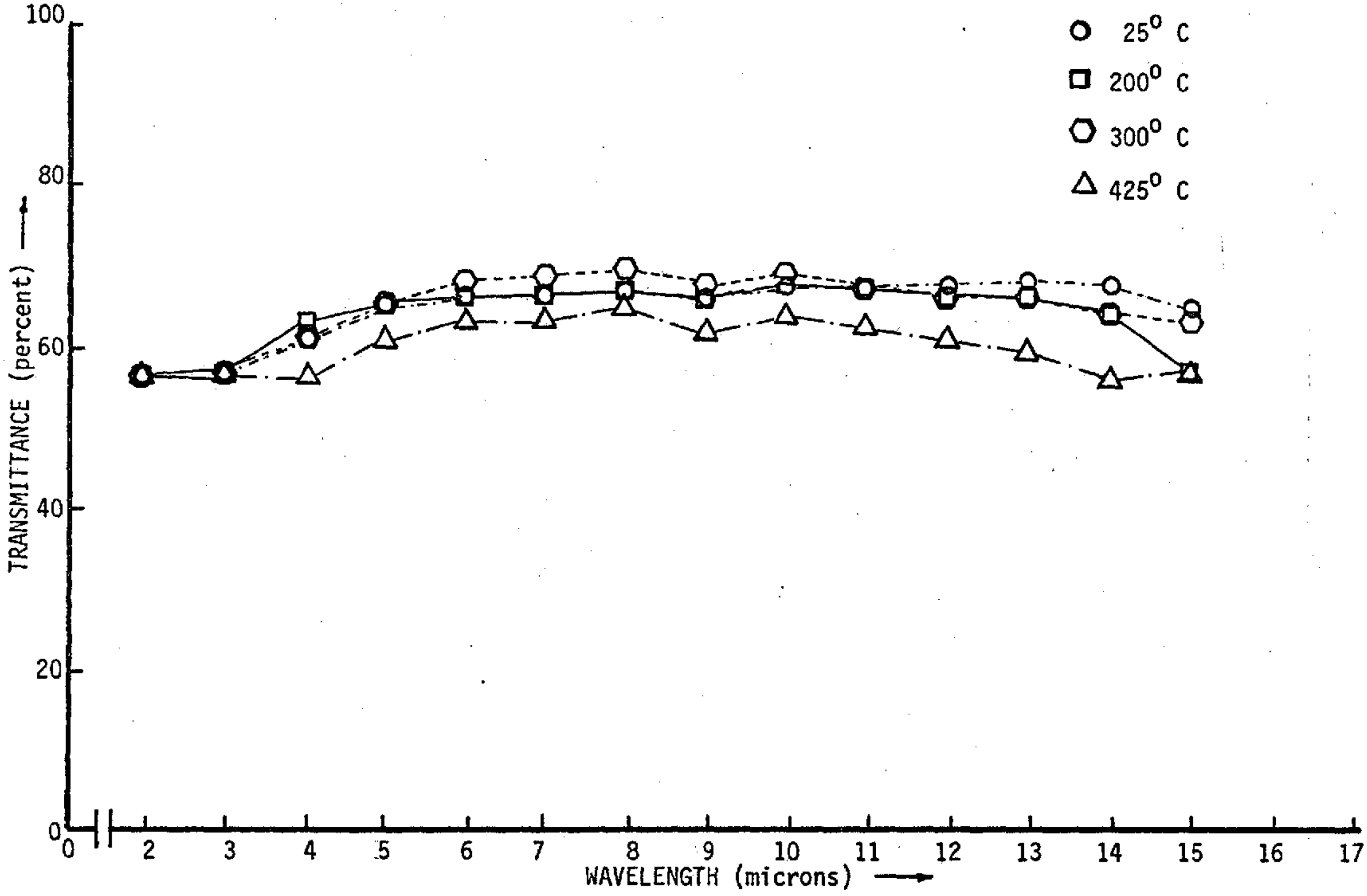


FIGURE 2

TRANSMITTANCE OF AN IRTRAN-4 WINDOW AT VARIOUS TEMPERATURES (3.2 mm THICK)

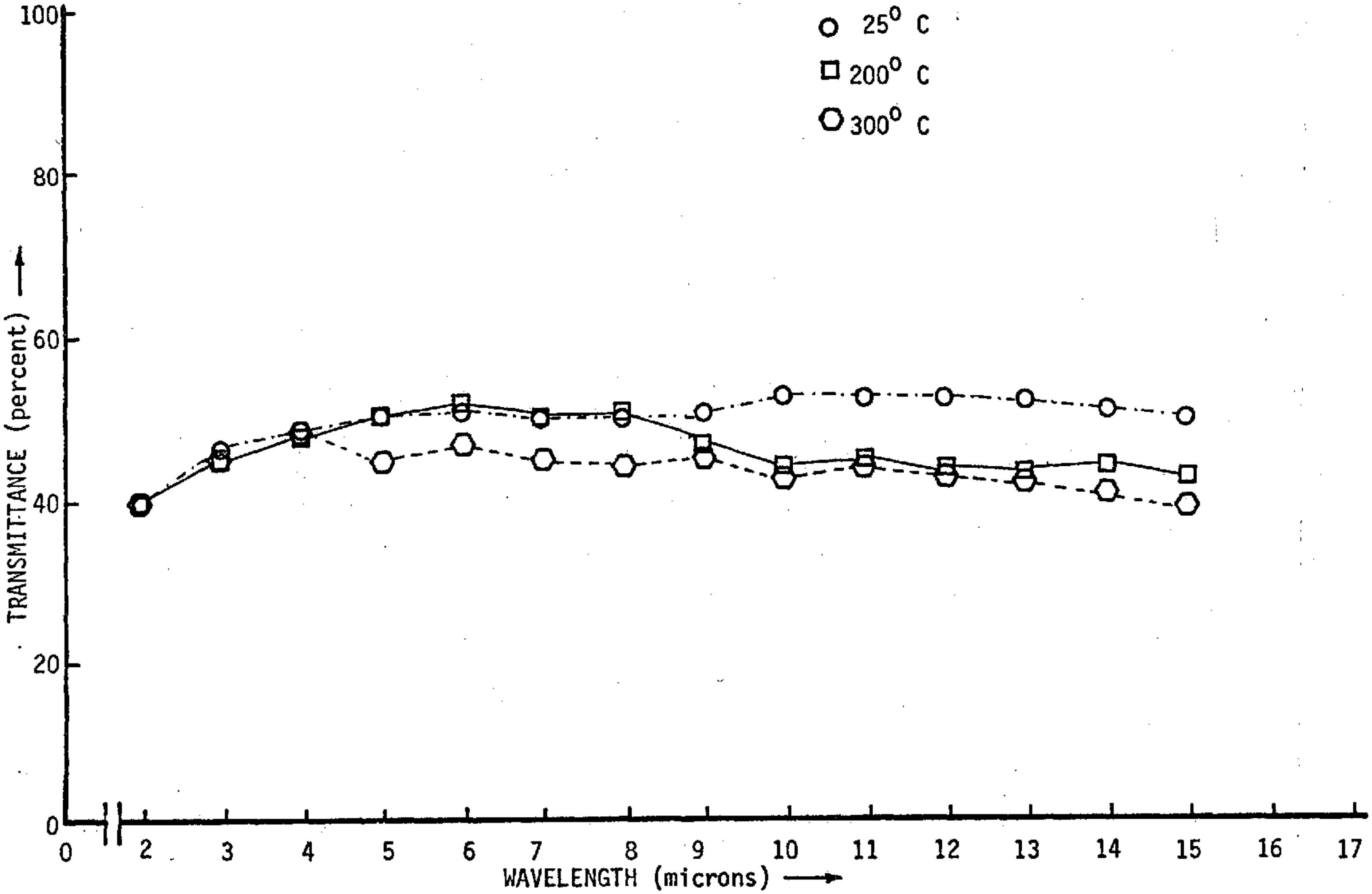


FIGURE 3

TRANSMITTANCE OF AN IRTRAN-6 WINDOW AT VARIOUS TEMPERATURES (6.0 mm THICK)

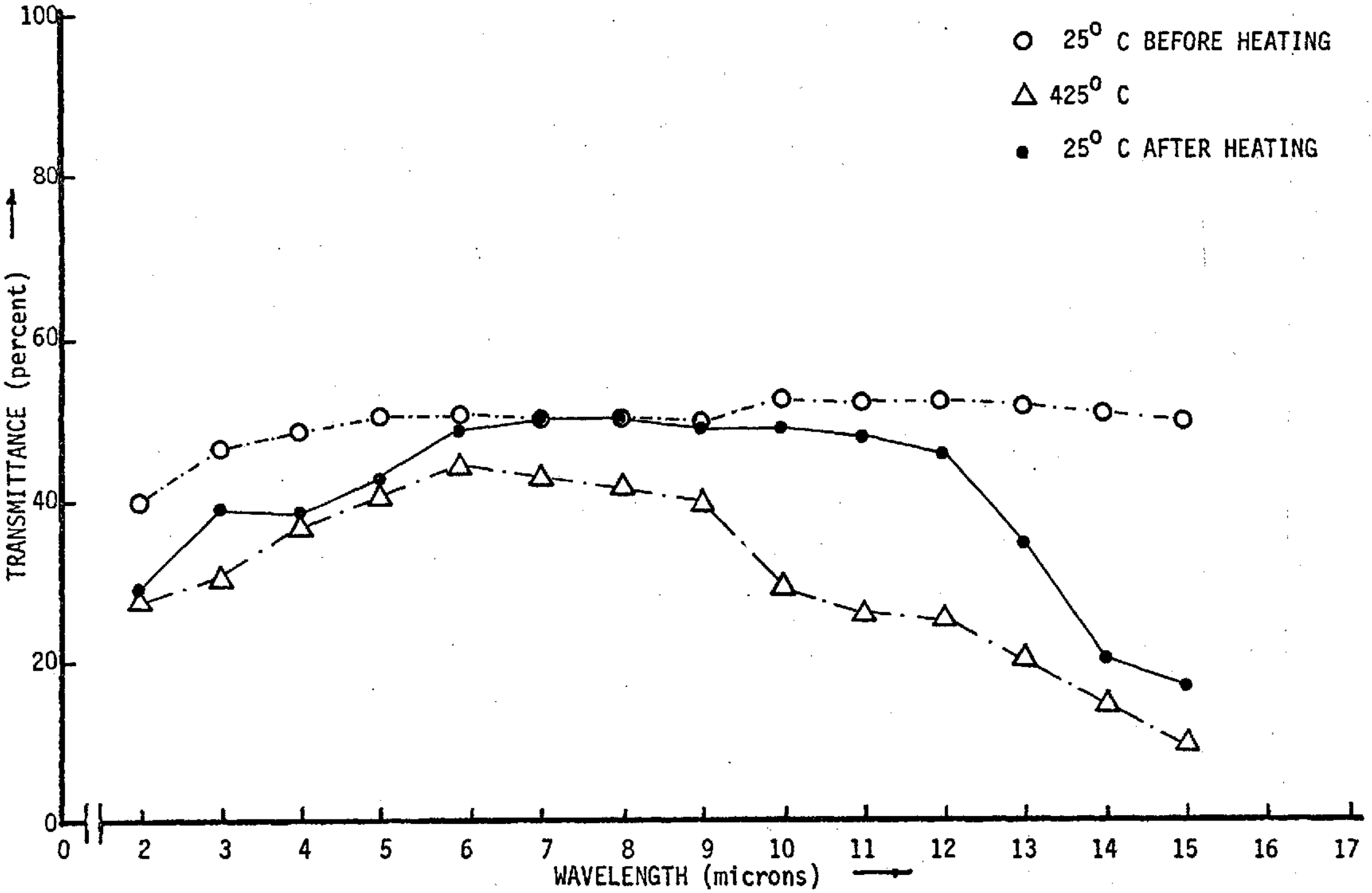


FIGURE 4

TRANSMITTANCE OF AN IRTRAN-6 WINDOW BEFORE, DURING, AND AFTER HEATING TO 425° C (6.0 mm THICK)

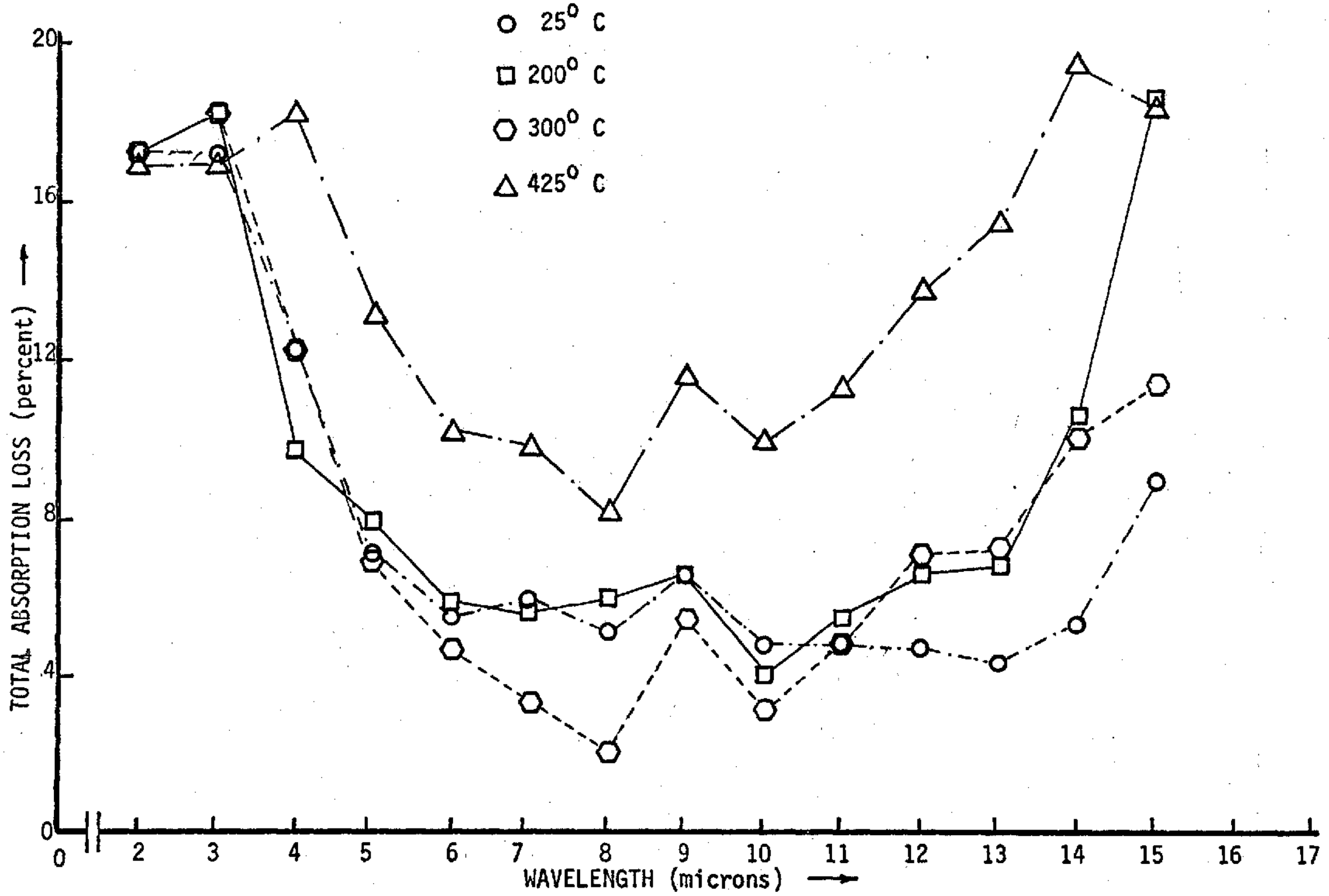


FIGURE 5

TOTAL ABSORPTION LOSS FOR AN IRTRAN-4 WINDOW (3.2 mm THICK)

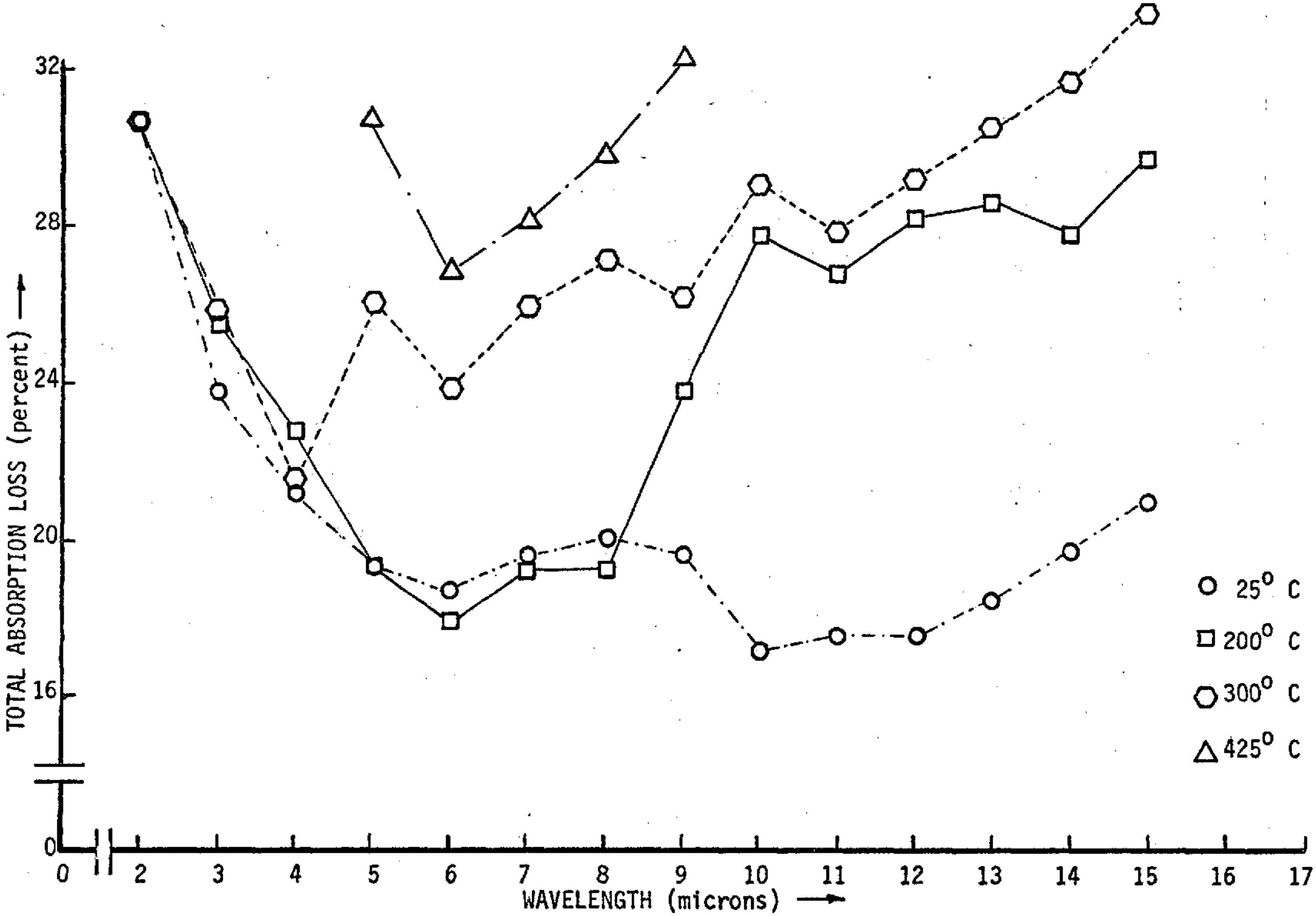


FIGURE 6

TOTAL ABSORPTION LOSS FOR AN IRTRAN-6 WINDOW (6.0 mm THICK)

35

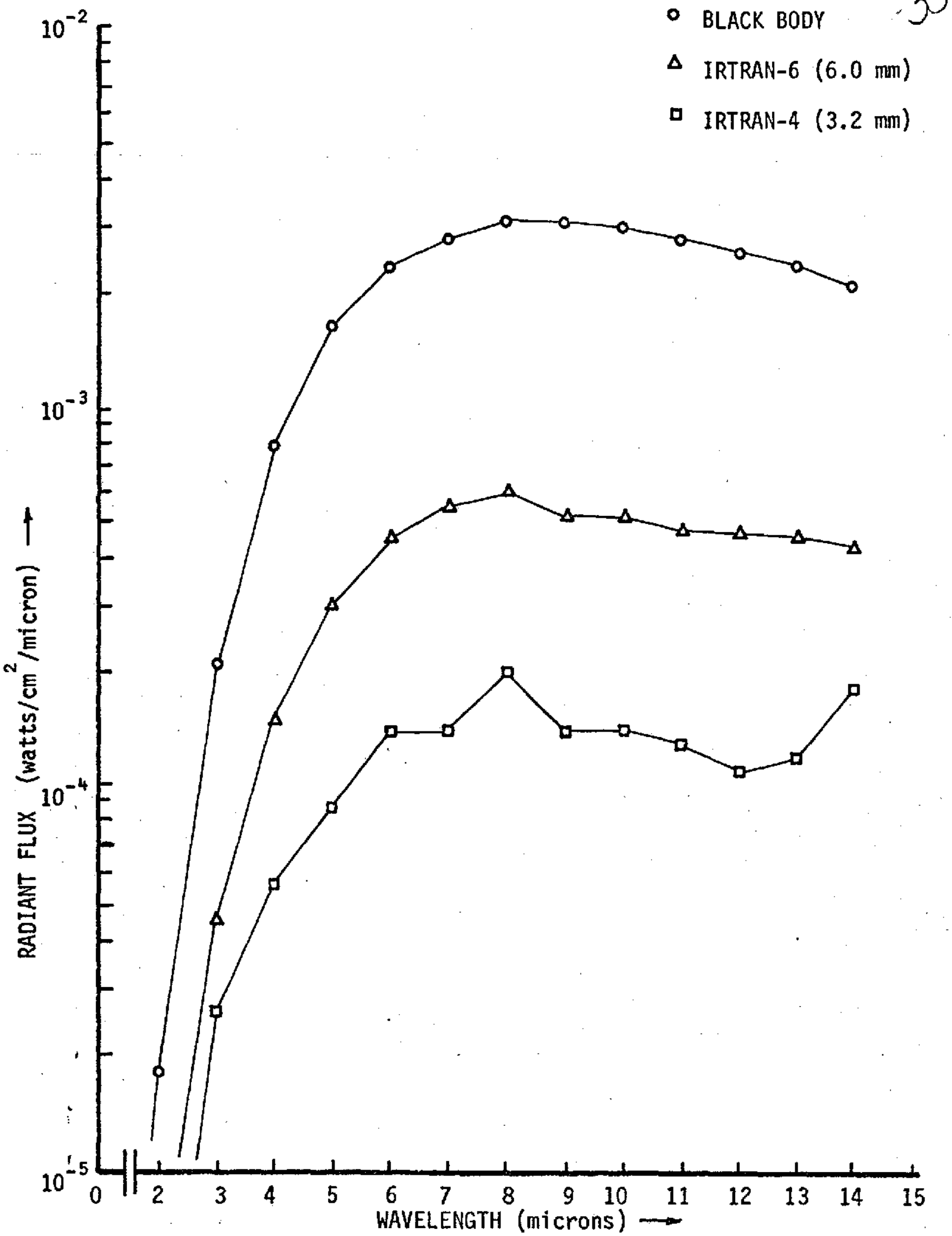


FIGURE 7

RADIANT FLUX AT 25° C

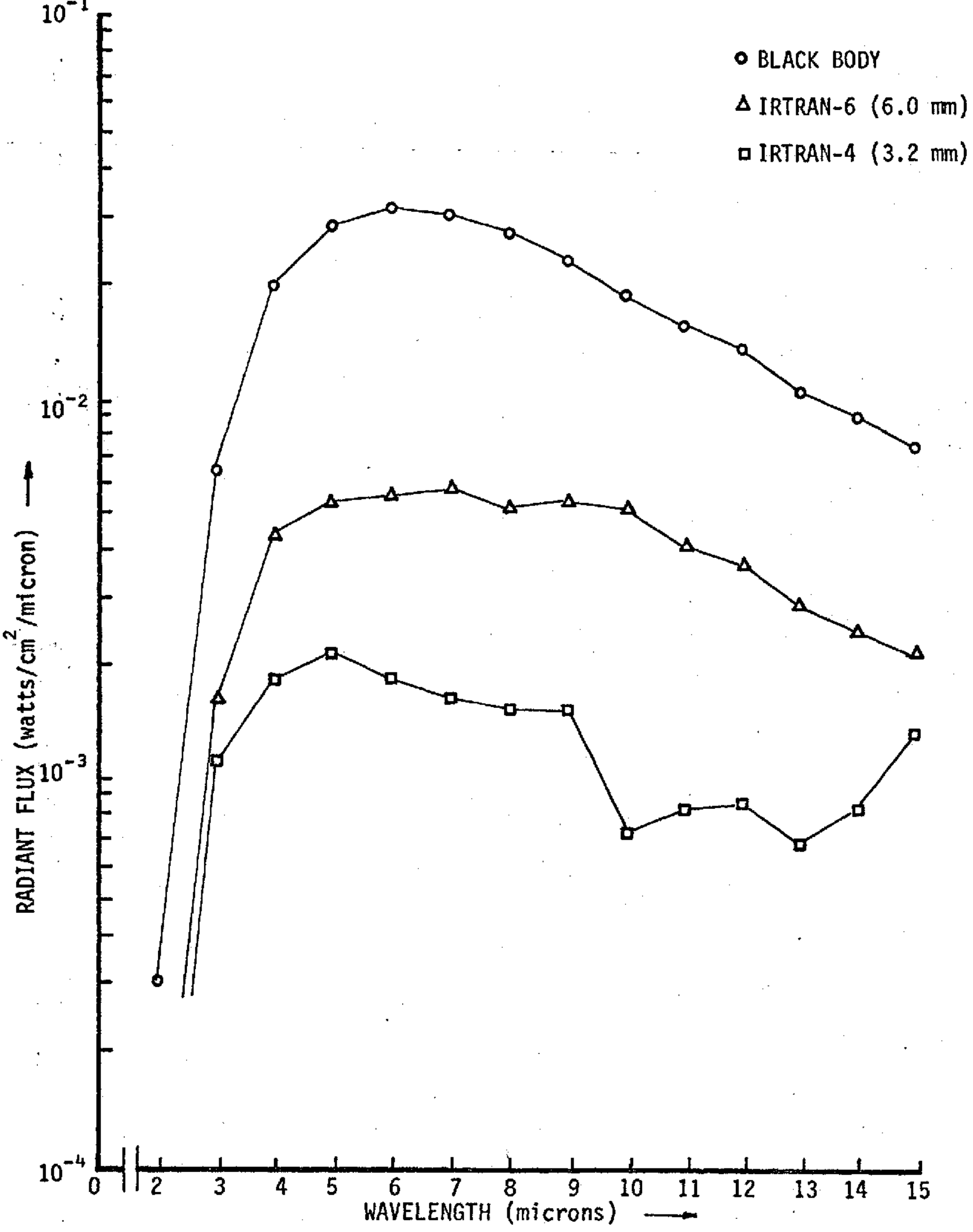


FIGURE 8

RADIANT FLUX AT 200° C

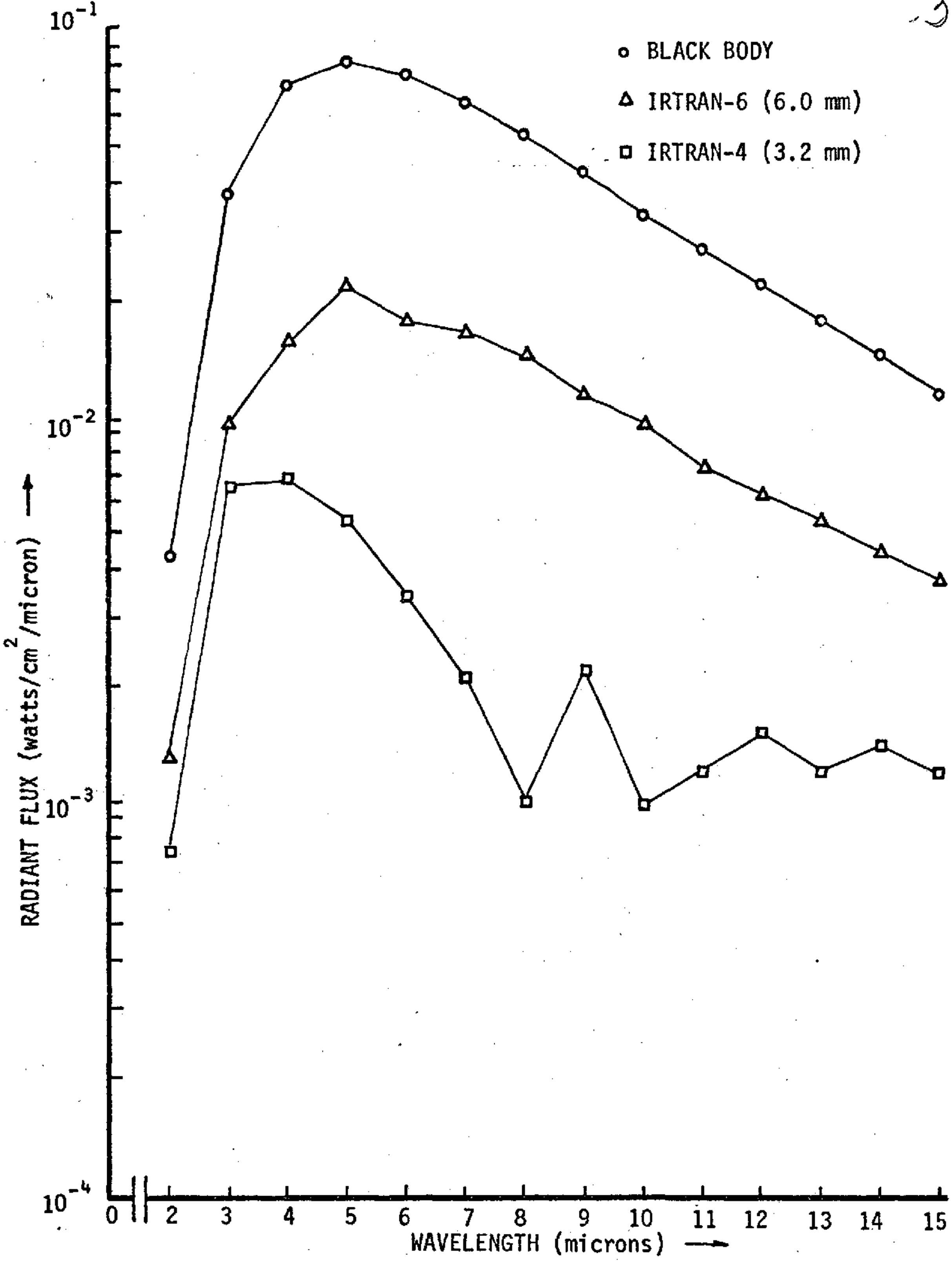


FIGURE 9

RADIANT FLUX AT 300° C

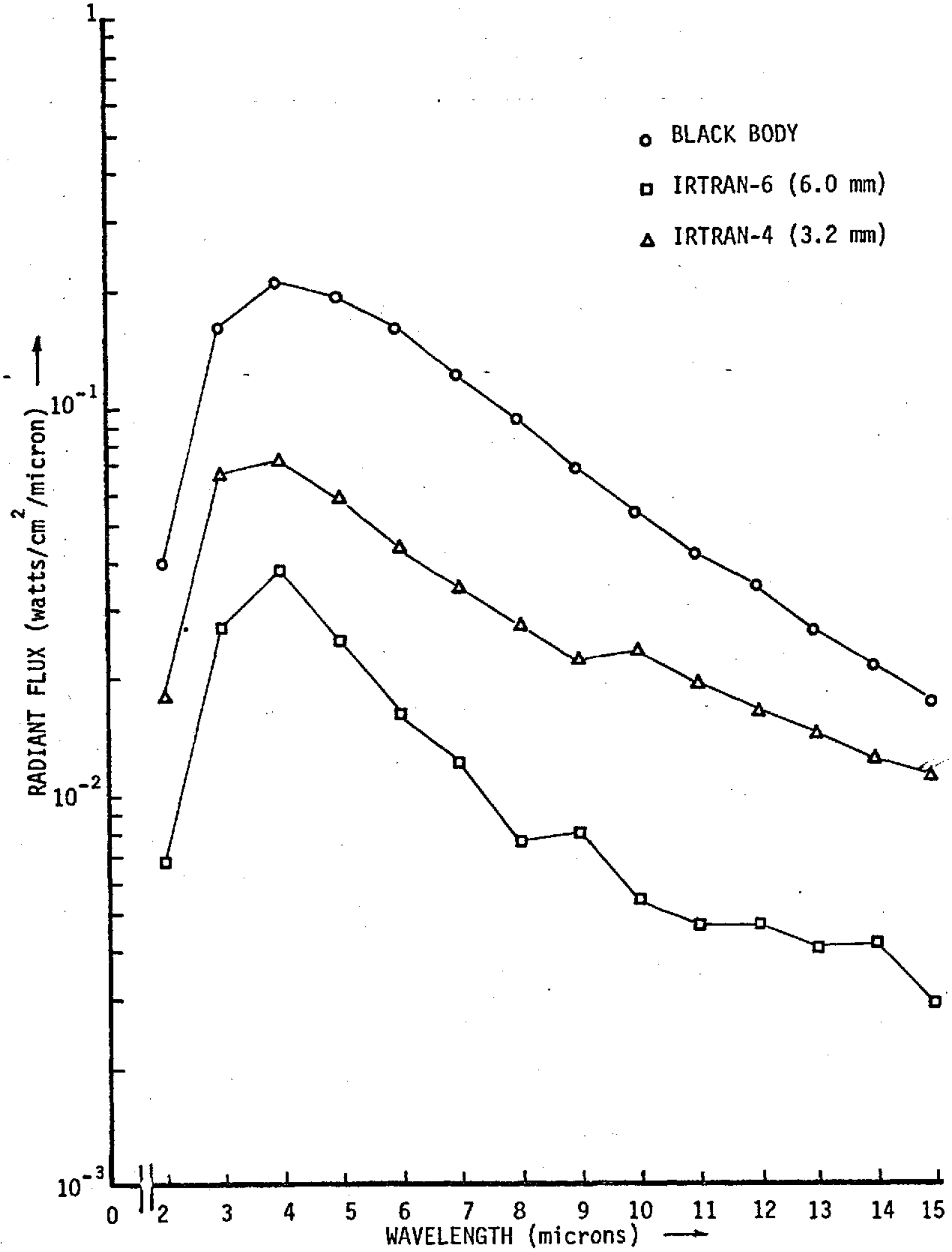


FIGURE 10

RADIANT FLUX AT 425° C

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August 28, 1974

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Gentlemen:

Five copies of a Technical Report of work performed on NASA Grant NGL 04-001-007 concerning that portion of the work associated with a "Study of the Effects of Condensation on the Performance of Pioneer Venus Probe Windows" are enclosed. This report is entitled "The Effect of High Temperature Upon the Transmittance and the Emission Spectrum of Infrared Window Materials."

Sincerely yours,

M K Testerman

M. K. Testerman
Principal Investigator
NGL 04-001-007

N74-32109
Case file