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FINAL REPORT

EMITTANCE OF ABLATIVE MATERIALS

Supplemental Test Program to Contract No. NAS 9-4518

"Study to Determine Thermophysical Properties of Ablative Materials"

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INTRODUCTION

This is the final report for the program, "Emittance of Ablative Materials," a supplementary test program to Contract NAS 9-4158 for a "Study to Determine Thermophysical Properties of Ablative Materials." The object of this test program was to measure the emittance, at a series of temperatures, of five ablative liner materials used in rocket engines.

The emittance is a dimensionless ratio which compares the radiation from the material under consideration with that from an ideal radiator (or black body) at the same temperature. Determination of the emittance of a material as a function of temperature is necessary to the proper definition of its thermophysical properties. The experimental techniques required for this measurement are reasonably well established for solid opaque materials. However, ablative materials which are not opaque present a difficult problem, and special procedures must be used or evolved. These difficulties are accentuated by the oxidation and physical changes of the materials at the higher temperatures required in heat transfer analysis of such surfaces. The accuracy of the prediction of the energy emitted or absorbed by ablators can be critical to the design of rocket engines and the structure viewing the ablation surface.

In this program, measurements were performed on laboratory-prepared test specimens and then on test specimens taken from the fired ablative liners that were tested under the Phase II effort of this contract. No differences in the emittances of the virgin nondecomposed ablative materials, obtained from both the laboratory specimens and the engine specimens, were anticipated. Therefore, emittance measurements were performed only on the virgin laboratory test specimens at temperatures of 25, 100 and 205°C. The charred laboratory-prepared test specimens were prepared in the same manner as the charred specimens that were prepared for the Phase I effort of this contract (16 hours at 800°C), and emittance measurements were performed at temperatures of 25, 100, 300, 500, 750, 1000 and 1120°C. The charred engine test specimens were tested at the same temperatures. From a comparison of the two sets of emittance values, the validity of assuming the emittance values of the charred laboratory-prepared materials to be the same as the actual engine ablative liners can be determined.

EXPERIMENTAL SYSTEM

The experimental system used for the determination of directional emittance at the elevated temperatures of this program consisted of:

1) A blackbody energy source
2) A paraboloid reflectometer
3) A dispersion system (to decompose the radiation into the desired narrow spectral regions)
4) A radiation detector
5) An electrically heated sample holder
6) A temperature measuring device
7) An enclosure and purge system (for controlling the atmospheric environment)

The basis of this system, the paraboloid reflectometer, was an instrument developed by TRW Systems (formerly TRW Space Technology Laboratories) in 1961 to circumvent certain problems (sample emission error and wavelength restrictions) associated with other spectral reflectance measuring instruments. A similar device was recently reported by D. K. Edwards of U.C.L.A. (Reference 1). The instrument utilizes an interrupted blackbody source to irradiate a sample hemispherically via two paraboloid mirrors (see Figure 1). Reflected energy from the sample is collected at an angle of 9 degrees from the normal by conventional source optics for a Model 12C Perkin-Elmer spectrometer.

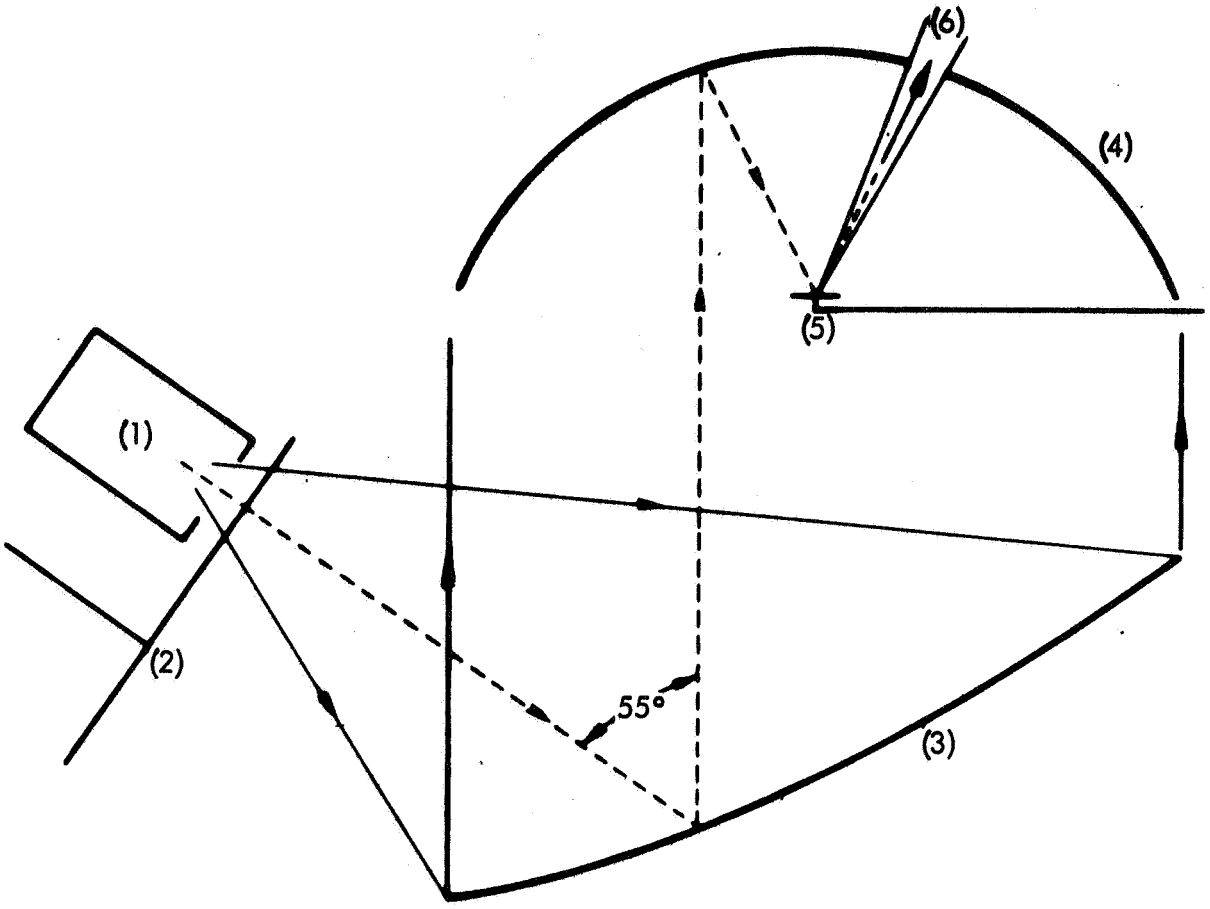
By chopping the energy before it is incident upon the sample, the signal detected by the monochromator is alternating. Thus, with the use of a tuned a.c. amplifying system, only the reflected incident energy is observed. The emitted energy from the sample is not detected and does not influence the measurement. The measured reflectances are read relative to a known reference surface (gold for this program) and are normalized accordingly.

The reference standard is readily obtained for wavelengths less than 25 microns with the heated cavity and integrating sphere reflectometers (References 2 and 3, respectively).

An electrically heated high-temperature sample holder was used to heat the test specimens to the required temperatures. A low voltage high alternating current power supply (manufactured by Gebr. Ruhnstrat Gottingen) was employed to pass current through a conductive inconel sample enclosure (See Figures 3 and 4).

Temperatures were measured by use of Chromel-Alumel thermocouples whose millivolt output was monitored on a Houston Instrument Company D. C. Voltmeter (Model HV-160). Since the monochromatic reflectance is not strongly dependent upon temperature, the temperature measurement could be performed without extreme accuracy restrictions. This is especially important in the measurement of non-opaque materials where the emittance property is volume dependent, not surface dependent. Thus, a temperature gradient through the sample is of less importance than in other schemes.

In order to reduce the atmospheric content of gases which might chemically react with the ablative char samples at high temperatures, the paraboloid reflectometer was housed in a near leak-free aluminum enclosure which included a purging system for maintaining a nearly pure nitrogen gas atmosphere (see Figure 5).



(1) SOURCE (2) CHOPPER (3) OFF-AXIS PARABOLOID

(4) PARABOLOID (5) SAMPLE AND HOLDER (6) EXTERNAL OPTICAL SYSTEM TO MONOCHROMATOR AND DETECTOR

Figure 1. Schematic Representation of Paraboloid Reflectometer

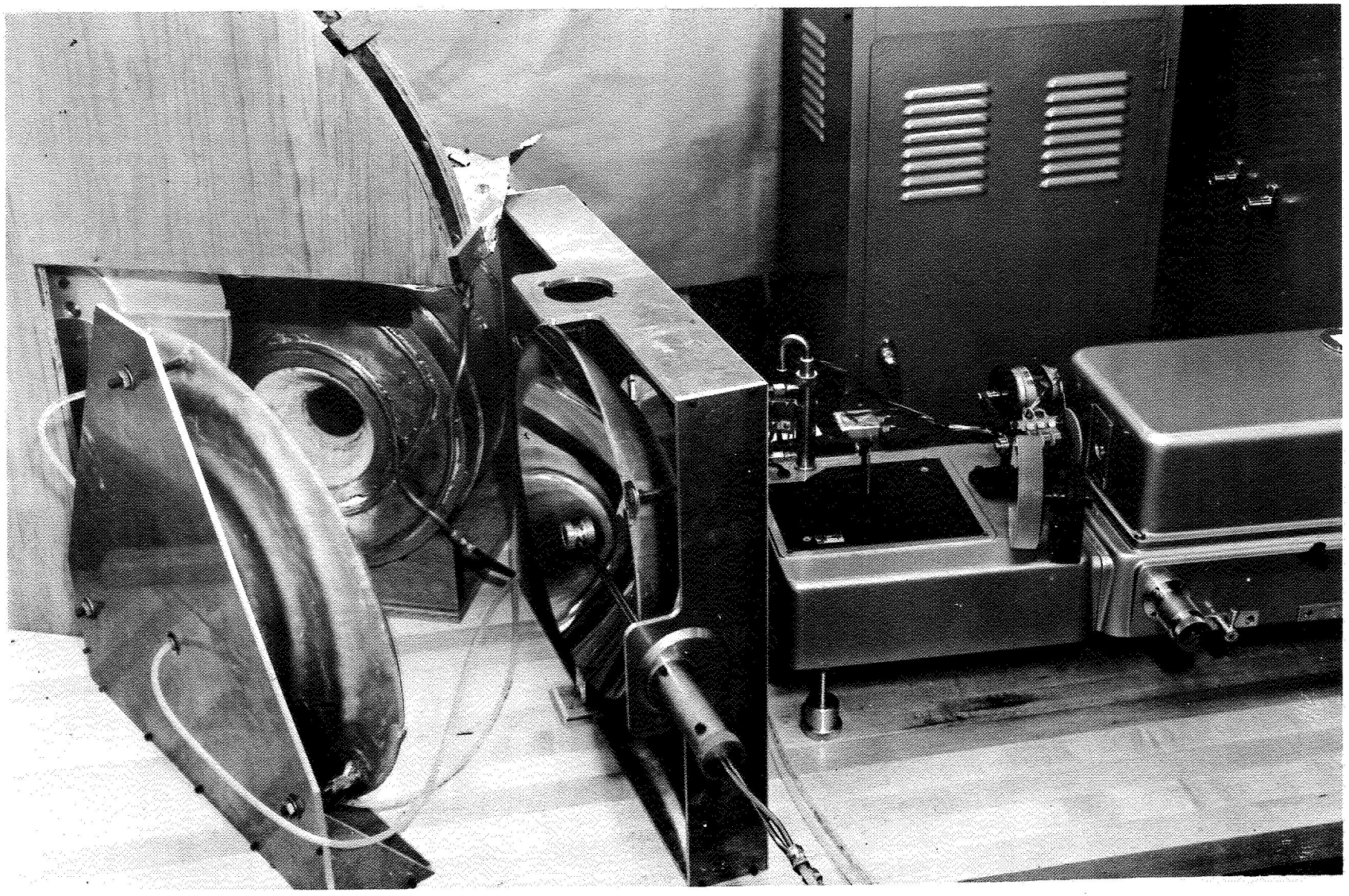


Figure 2. Paraboloid Reflectometer (With Low-Temperature Sample Holder)

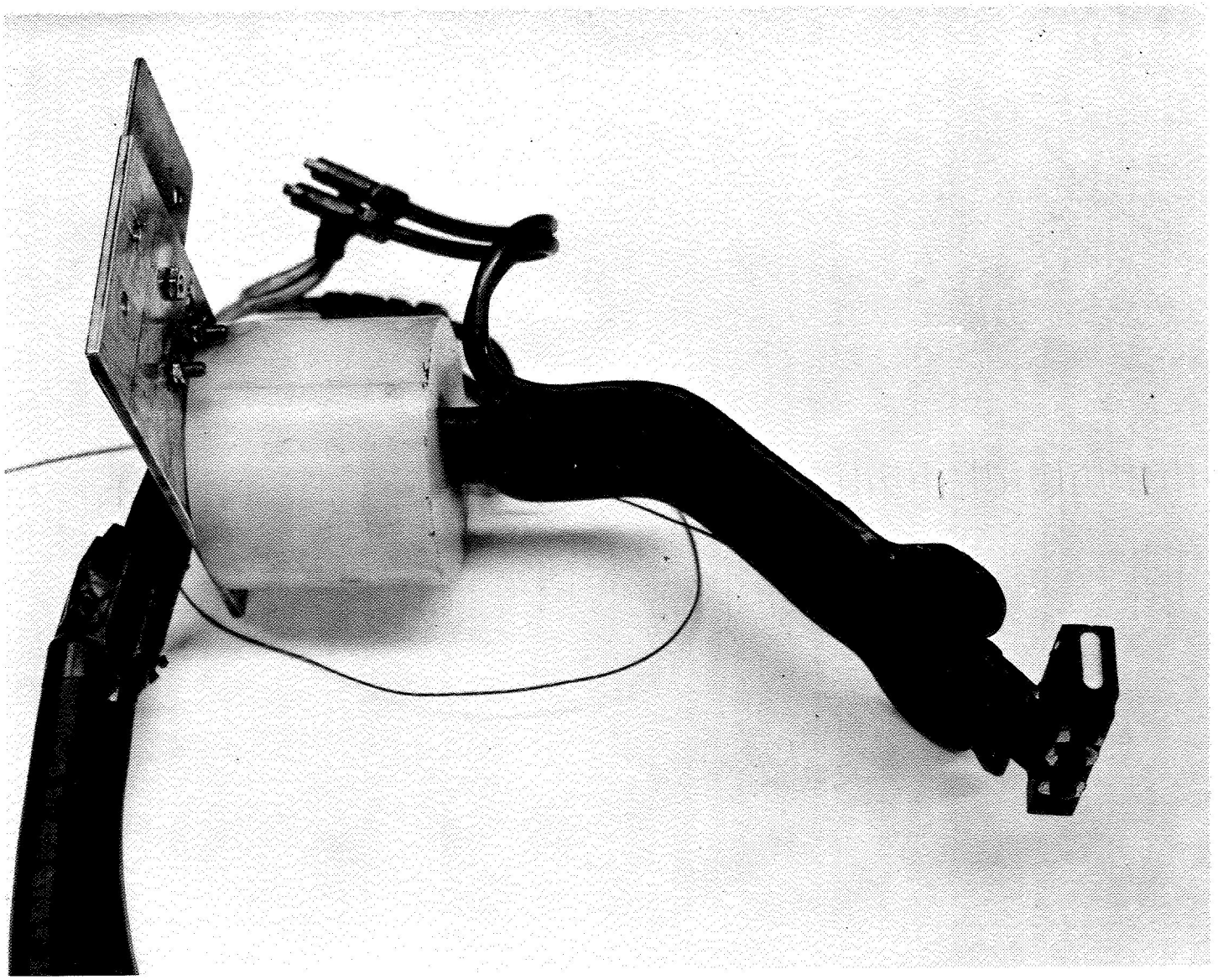


Figure 3. TRW High-Temperature Sample Holder

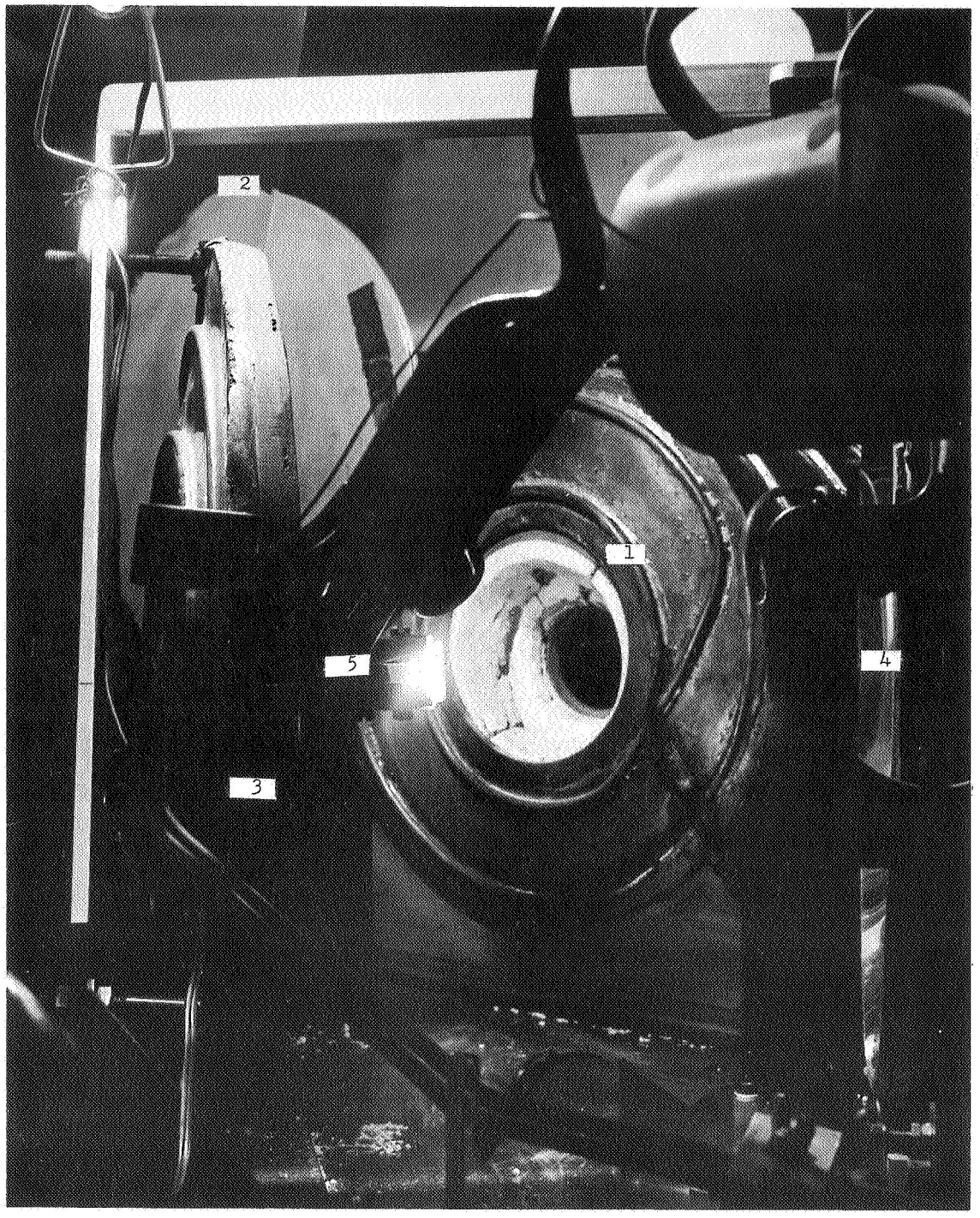


Figure 4. Interior View of Paraboloid Reflectometer (during 1000°C Emittance Test) (See Figure 1 for Number Legend)

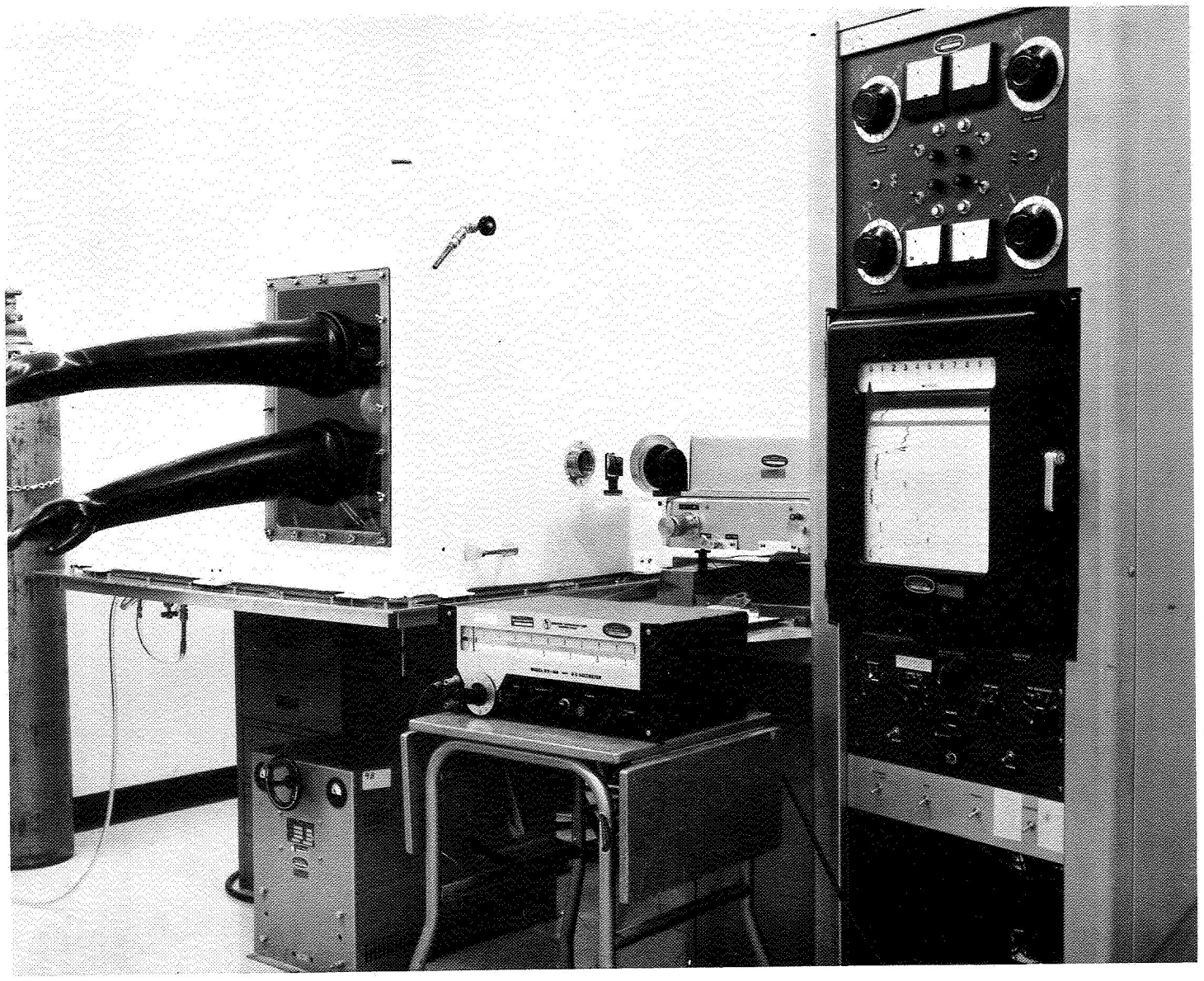


Figure 5. Paraboloid Reflectometer Controlled-Atmosphere/Temperature System

TEST PROCEDURES

The basic test procedures included the following:

A. Preparation of Test Specimens
B. Preparation of Specimen Atmosphere
C. Elevation of Specimen Temperature
D. Measurement of Spectral Reflectance

A. Preparation of Test Specimens

The test specimens were cut from larger sections of laboratory samples (virgin and charred) and sections of the fired rocket engine liners in the vicinity of the nozzle convergent section. Table 4 lists those ablative liner materials which were tested, and the location from which the engine samples were cut is illustrated in Figure 7. The dimensions of the test specimens were 2 cm in length, 1 cm in width, and $\frac{1}{2}$ cm in thickness. It was found from initial reflectance measurements that the most representative results were obtained when the specimens were cut with the edges of the fiberquartz planes oriented at about 45° to the length of the front surface. Also, in order to accommodate a 26 gauge Chromel-Alumel thermocouple, a small hole was drilled in the side of each specimen near the bottom. Post-test examples of test specimens of the five materials tested and the three states (Virgin, laboratory-charred, and engine liner) are illustrated in Figure 6. In turn, each specimen was mounted in the inconel enclosure attached to the high-temperature sample holder (see Figure 3).

B. Preparation of Specimen Atmosphere

Three methods of purging the atmosphere, contained within the aluminum housing of the paraboloid reflectometer, were used successively. The object was to reduce the content of gases (CO_2, H_2O, O_2) which might chemically react with the ablative char at high temperatures. It was found that above $500^{\circ}C$, the quality of the atmosphere (mainly the level of oxygen content) was of major concern. When the oxygen content was too high, it was observed that excessive

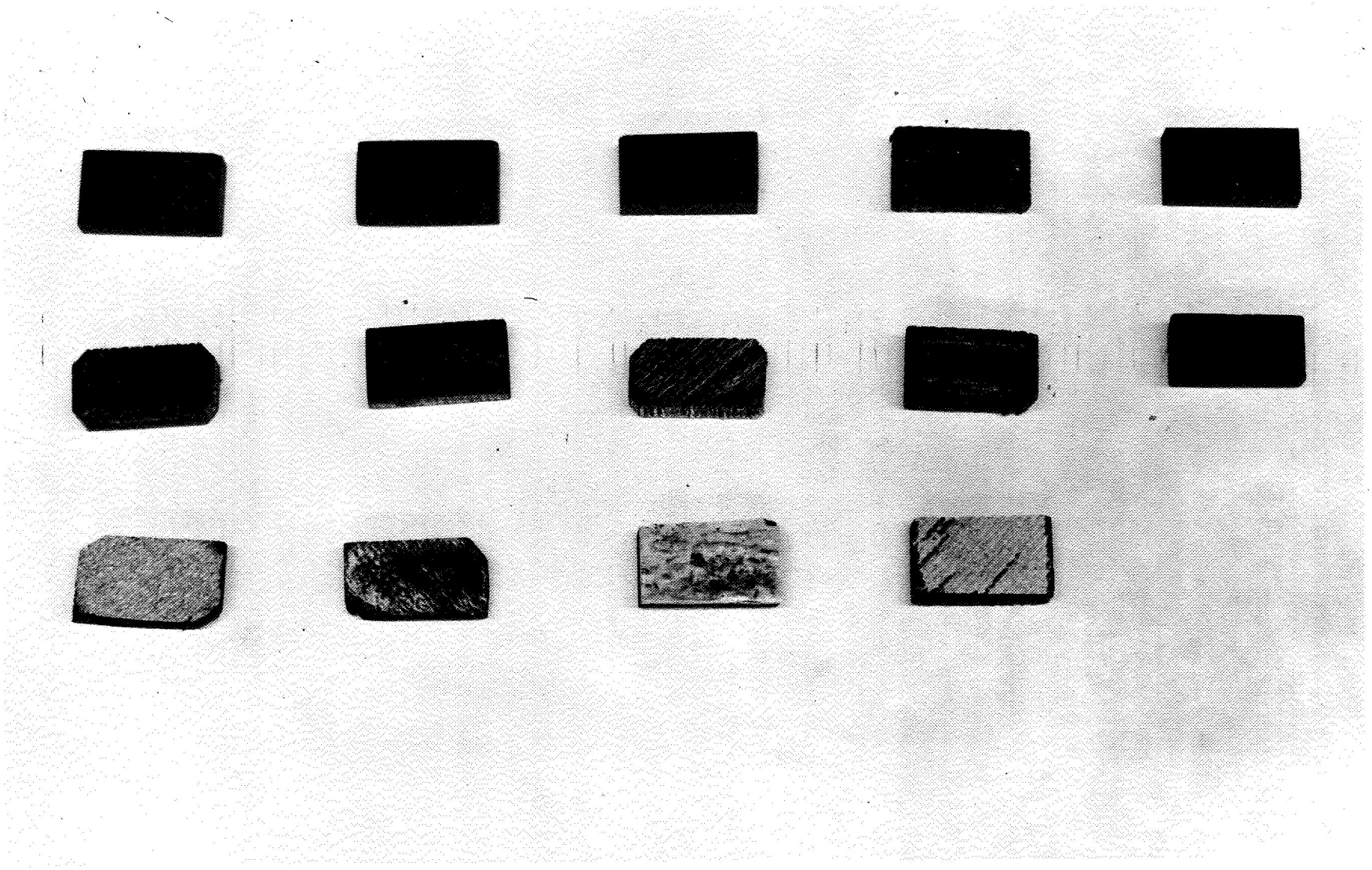
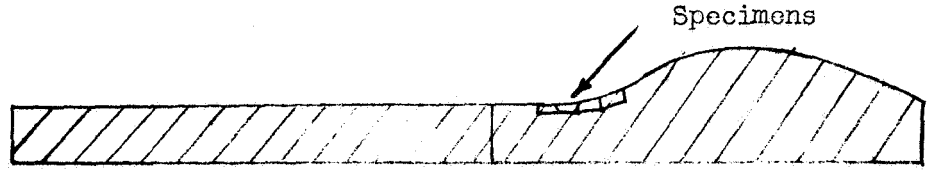


Figure 6. Ablative Material Test Specimens (after emittance tests)
(from left to right: WBC 2234, MX 2600, MX 2646, XR 2015, WBC 5217)
(from top to bottom: Virgin; Laboratory Charred; Engine Charred)

Figure 7. Location of Test Specimens Before Removal from Rocket Engine Liner (Nozzle Convergent Section)



oxidation occurred on the surface of the specimens at the high temperatures. As a result, the spectral reflectance generally rose with time for wavelengths less than 3.0 microns. By developing an effective purge technique (see Method 3, Table 1), oxidation of the specimen surface was minimized, and the stability of the reflectance data was greatly increased.

The method of measuring the oxygen content of the atmosphere around the test specimens involved using a 60 watt incandescent lamp with the glass envelope removed. The length of time that the tungsten filament glowed, with 110 volts applied, indicated the relative level of oxygen content. From information supplied by Vacuum Atmospheres, Inc. of Canoga Park, California, a tungsten filament lifetime of 20 minutes would indicate that the atmosphere had an oxygen content as low as 0.02%.

C. Elevation of Specimen Temperature

When the oxygen content of the atmosphere was judged to be low enough according to the tungsten filament test, the test specimens were heated by use of the high-temperature sample holder. Spectral reflectance data was then taken. The specimen temperatures were measured continuously during the tests by use of two 26 gauge Chromel-Alumel thermocouples, one placed in the hole in the specimen and the other pressed between the front edge of the specimen and the inconel envelope. The difference between the millivolt readings of the two thermocouples was not significant.

Specimen temperatures of 25, 100, 300, 500, 750, 1000, and 1120°C were attained for test specimens of both laboratory-charred and fired engine liner specimens. As the specimens were moved in and out of the incident beam of energy from the heated cavity energy source, the actual temperatures of the test specimens were observed to oscillate about the nominal temperatures. An oscillation of about ± 15°C was typical at low temperatures and less at high temperatures (above 500°C). Since the spectral reflectance of materials is a slow-varrying function of temperature, an effect due to this temperature

TABLE 1: SUCCESSIVE METHODS OF PURGING THE ATMOSPHERE OF REACTIVE GASES

PURGE METHOD	COMPONENTS AND PROCEDURES	COMMENTS
1.	1. Dilution with pure nitrogen gas while forcing the atmosphere out of enclosure with a centrifugal vacuum cleaner pump for 30 minutes. 2. Diluted atmosphere further purged by use of an internal circulation system consisting of columns of Ascarite (removes CO_2) Molecular Sieve (removes H_2O), heated copper wool at 450 to 500°F (removes O_2), and ice-water bath for cooling.	1. Oxygen content of atmosphere remained too high, evidenced by surface oxidation on samples at 750°C. 2. Electric motor brushes eroded due to over heating.
2.	1. Polyvinyl Chloride bag was used inside enclosure to remove 1/2 of initial atmosphere. 2. Dilution with liquid nitrogen while using centrifugal pump to force out atmosphere. 3. Internal circulation system used as in Method 1.	1. Oxygen content much lower than with Method 1. 2. Tungsten filament lasted from 3 to 6 minutes. 3. Motor brushes again eroded due to over heating.
3.	Compression pump, capable of evacuating volume of enclosure one time in 20 minutes, used while continually diluting the atmosphere with liquid nitrogen for 50 minutes.	1. Compression pump (Sears, Roebuck, and Co.) very durable. 2. Tungsten filaments last from 12 to 20 minutes with 50 to 60 minute purge. 3. Stability of sample reflectance at high temperatures markedly increased.

oscillation was not observed.

D. Measurement of Spectral Reflectance

The reflectance measurement program is illustrated by the sample data sheet, Figure 8. As tabulated in Table 2 and justified by the facts presented in Table 3, the reflectance measurements were conducted over the wavelength intervals which include almost all of the black body radiation for each respective temperature. (Twenty-six microns is the long wavelength limit of the potassium bromide prism used in the Model 98 Perkin-Elmer monochromator.)

As was mentioned previously in Section B., the spectral reflectance for wavelengths shorter than 3.0 microns was observed to change (generally increased) with time for the high temperatures of 750, 1000, and 1120°C. (Negligible changes were generally measured for longer wavelengths.) This change, considered to be largely due to oxidation of the surfaces of the specimens, was considerably reduced when the purge method 3 (see Table 1) was adopted. However, a second limitation to stable reflectance values at temperatures above 1000°C was recognized. Since four of the five materials tested contained a large proportion of quartz fibers, devitrification of the quartz might be expected to affect the stability of the reflectance readings during the period of an emittance test. Above 1000°C, fused quartz devitrifies at an increasing rate as temperature increases. When the quartz is in contact with other chemicals, such as phenolic, this rate is increased.

In order to further increase the reproducibility of the short wavelength reflectance data and to simulate the short duration of rocket engine firings, spot measurements at 1.0, 1.5, 2.0, 2.5, 3.1, 4.0, and 5.0 microns were taken within the first ten minutes of each emittance test at 750°C and higher. Then the regular measurement program (in consecutive order) proceeded over all the wavelengths listed on the sample data sheet, Figure 8. (A typical test took $1\frac{1}{2}$ hours to complete.) If the regularly measured data differed significantly ($\pm$ 0.01) from the initial spot check data, then graphs

TABLE 2: WAVELENGTH SPANS OF REFLECTANCE MEASUREMENTS

SAMPLE TEMPERATURE (°C)	WAVELENGTH SPAN (MICRONS)
T < 500	1.0 to 26.0
750	1.0 to 22.0
1000	1.0 to 18.0
1120	0.9 to 15.0

TABLE 3: PER CENT OF TOTAL BLACKBODY RADIATION WHICH EXISTS OUTSIDE OF THE WAVELENGTH SPAN OF EMITTANCE MEASUREMENTS

BLACKBODY TEMPERATURE (°C)	%ENERGY BELOW λ_S		%ENERGY BEYOND λ_L	
	λ_S		λ_L	
25	1.0	0.00	26.0	15.2
100	1.0	0.00	26.0	9.2
205	1.0	0.00	26.0	5.0
300	1.0	0.00	26.0	3.2
500	1.0	0.00	26.0	1.4
750	1.0	0.04	22.0	1.0
1000	1.0	0.36	18.0	1.0
1120	.9	0.28	15.0	1.3

of both sets of data were used to obtain a composite spectral reflectance curve which represented the sample before oxidation and/or devitrification. Figure 9 is an example of such a procedure.

In addition to the high temperature spot check measurements, the spectral reflectance was remeasured at 1.0, 1.5, and 2.0 microns midway through and at the end of each test for all specimens and temperatures, in order to ascertain the stability of the data.

EXPERIMENTAL RESULTS

When the assumption of no transmittance (τ_λ) is made, the spectral reflectance (ρ_λ) data can be converted to a spectral emittance (ε_λ) by subtracting the reflectance from unity:

$$\varepsilon_\lambda = 1 - \rho_\lambda \quad , \text{ for } \tau_\lambda = 0 \ .$$

Integration of the product of spectral emittance and Planck's equation for the material temperature yields the total normal directional emittance.

The calculated values of total normal emittance are tabulated for each material in Tables 5 through 8. In addition, graphs of the spectral reflectance data are shown in Figures 10 to 24.

No attempt was made to reduce the near normal emittance values to hemispherical emittance (ε_H). If hemispherical data is desired, the conversion can be performed by using Figure 13 - 15 of Reference 6.

DISCUSSION OF RESULTS

Some general observations can be made about the total emittance values of these five materials. As shown in Tables 5 to 9, the emittances of the virgin and laboratory-charred materials remained rather constant over the temperature range of measurements. The emittances ranged from 0.88 to 0.96 with most values within 0.93 to 0.95.

On the other hand, the emittance values of the four liner materials tended to decrease with increasing temperature. Also, these values ranged more widely (0.70 to 0.96) and were generally lower than those of the laboratory-prepared materials.

When a visual comparison of the surfaces of the laboratory-charred and engine specimens was made (see Figure 6), it was noticed that the engine specimens had a lighter shade. Much of the phenolic had been burned out or eroded away by the hot engine exhaust (1700°C) leaving a shallow layer of pure quartz fibers above the charred material. Since clear fused quartz is known to have a spectral transmittance in excess of 0.8 for the wavelength span of 0.3 to 3 microns, there was some concern that these ablative materials might become somewhat transparent, especially at the higher temperatures. However, no significant differences were observed when reflectance measurements were made at 1120°C on two test specimens with and without a platinum reflector behind the specimen. It was thus concluded that the transmittance for the specimens tested was zero.

The test conditions, under which the emittance values were measured for the engine liner specimens, differed from that of the rocket engine environment in two ways:

1. The test specimens were uniformly heated during measurements, whereas in the engine environment, the liner experienced a severe thermal gradient from the heat of the exhaust gases.
2. The emittances were measured after the engine firing. These actual emittances of the liners most likely changed with time (probably decreased), while exposed to the hot exhaust gases.

It is surmised that if the actual engine environment could have been exactly duplicated, the measured emittance values at each temperature could be slightly higher.

For the low reflecting materials considered, the paraboloid reflectometer system may be relied upon to yield accurate total emittance values within ± 0.015. Reproducibility of the total emittance results is about ± 0.01 as indicated by duplicate tests on the laboratory chars (see samples 453-66 and 465-66 of Table 5; also samples 398-66 and 432-66 of Table 6.).

In addition, it should be noted that the emittance values of the fired engine liners represent only the vicinity of the convergent section of the nozzles. The scope of this program did not include duplicate measurements at various positions in the nozzle. Even in the convergent section there were significant variations in the reflective qualities of the selected test specimens. The Irish Refrasil test specimens 640-66 and 641-66 (see Table 5) are good examples.

CONCLUSIONS

From the emittance values listed in the tables, one can conclude that the emittance of the laboratory-prepared specimens remains rather constant over the temperature range 25 to 1120°C and generally decreases for the engine specimens. In addition, it appears that the comparison between the emittance values for the laboratory-prepared specimens and the engine specimens is only approximate. Apparently, the erosion and devitrification of the quartz plus the higher rocket exhaust temperatures, as experienced by the engine liner , can not be very adequately duplicated by laboratory charred material (800°C for 16 hours), at least as far as the emittance is concerned.

A third conclusion, taken from the tabulated results and from experience in the actual reflectance tests, is that less confidence should be placed on the results at 1000°C and 1120°C as compared to results at the lower temperatures. Devitrification of the quartz fibers plus surface oxidation with time tended to make for less stable short wavelength reflectance data than for the lower temperatures.

Although the specimens tested in this program were apparently thick enough (1/2 cm) to have a zero net transmittance at temperatures below 1120°C, a non-zero value of transmittance for a shallow layer near the surface is probable, especially at the higher temperatures. For this reason, together with the severe temperature gradient caused by the rocket exhaust on the liner, the net energy emitted by the engine liner is not correctly specified by the surface temperature and the emittance at that temperature.

In an accurate radiative transfer analysis in the rocket engine nozzle, the energy transmitted from below the surface (at temperatures lower than at the surface) must be taken into account.

RECOMMENDATIONS

In order to increase the confidence in the emittance values measured in this program, it would be wise to conduct tests on more than one test specimen, especially at the temperatures above 500°C. In addition, it would be desirable to test specimens that are taken from several locations in the charred ablative liner to determine whether different emittance values are obtained from specimens taken from regions of different heating environments.

Lastly, it would be of advantage to conduct transmission experiments to determine the extent of transparency at high temperatures. Measurements could be performed on several thicknesses of the most promising liner materials at the corresponding temperature measured earlier during the engine firings.

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TABLE 4: DESCRIPTION OF ABLATIVE LINER MATERIALS

	MATERIAL	MATERIAL LOT NO.	TRW PART NO.	TRW EMITTANCE SAMPLE NO'S.
I.	Irish Refrasil (WBC 2234)			
	A. Virgin Material	980-1	X110519-3 Item 3	402-66
	B. Laboratory Char	980-1	X110519-1 Item 1	433-66, 453-66, 465-66, 657-66
	C. Engine Liner		E 110502-3 S/N 001	639-66, 640-66, 641-66, 642-66
II.	Fiberite MX 2600			
	A. Virgin Material	B-912-2A	X110519-3 Item 3	405-66
	B. Laboratory Char	B-912-2A	X110519-1 Item 1	398-66, 432-66, 480-66, 481-66, 484-66
	C. Engine Liner		E110502-1 S/N 001	505-66, 506-66, 507-66, 658-66
III.	Fiberite MX 2646			
	A. Virgin Material	B-921-1A	X110519-3 Item 3	406-66
	B. Laboratory Char	B-921-1A	X110519-4 Item 4	431-66, 452-66, 466-66, 476-66
	C. Engine Liner		E110502-4 S/N 001	645-66, 646-66, 647-66, 648-66, 649-66
IV.	Refrasil Cloth/Phenolic Resin (U.S. Polymeric XR 2015)			
	A. Virgin Material	G 4180-1	X110519-3 Item 3	404-66
	B. Laboratory Char	G 4180-1	X110519-1 Item 1	435-66, 474-66, 475-66, 476-66
	C. Engine Liner		E110502-2 S/N 001	651-66, 652-66, 653-66

TABLE 4: DESCRIPTION OF ABLATIVE LINER MATERIALS (Cont.)

	MATERIAL	MATERIAL LOT NO.	TRW PART NO.	TRW EMITTANCE SAMPLE NO'S.
V.	Magnesium Hydroxide (WBC 5217)			
	A. Virgin Material	8674	X110519-2	400-66
	B. Laboratory Char	8674	X110519	434-66, 454-66, 478-66, 479-66
	C. Engine Liner - None available. Liner eroded excessively during engine firing.			

TABLE 5: EMITTANCE OF IRISH REFRASIL (WBC 2234) ABLATIVE MATERIAL

	PHYSICAL STATE	TRW SAMPLE NO.	TEMPERATURE (°C)	NORMAL EMITTANCE $\varepsilon_N(T)$
1)	Virgin, nondecomposed	402- 66	25	0.95
		402- 66	100	0.95
		402- 66	205	0.95
2)	Charred (Laboratory)	433-66	25	0.94
		433-66	100	0.94
		433-66	300	0.94
		433-66	500	0.95
		433-66	750	0.93
		453-66	1000	0.92
		465-66	1000	0.93
		657-66	1120	0.93
3)	Charred (Engine Liner)	639-66	25	0.89
		639-66	100	0.89
		639-66	300	0.86
		639-66	500	0.80
		640-66	750	0.71
		641-66	1000	0.70
		642-66	1120	0.80

TABLE 6: EMITTANCE OF FIBERITE MX 2600 ABLATIVE MATERIAL

	PHYSICAL STATE	TRW SAMPLE NO.	TEMPERATURE (°C)	NORMAL EMITTANCE $\varepsilon_N(T)$
1)	Virgin nondecomposed	405-66	25	0.93
		405-66	100	0.93
		405-66	205	0.94
2)	Charred (Laboratory)	398-66	25	0.95
		432-66	25	0.93
		398-66	100	0.95
		432-66	100	0.93
		432-66	300	0.94
		432-66	500	0.95
		480-66	750	0.95
		481-66	1000	0.94
		484-66	1120	0.94
3)	Charred (Engine Liner)	505-66	25	0.96
		505-66	100	0.96
		505-66	300	0.95
		505-66	500	0.94
		507-66	750	0.89
		658-66	1000	0.89
		506-66	1120	0.92

TABLE 7: EMITTANCE OF FIBERITE MX 2646 ABLATIVE MATERIAL

	PHYSICAL STATE	TRW SAMPLE NO.	TEMPERATURE (°C)	NORMAL EMITTANCE $\varepsilon_N(T)$
1)	Virgin, Nondecomposed	406-66	25	0.92
		406-66	100	0.92
		406-66	205	0.93
2)	Charred (Laboratory)	431-66	25	0.93
		431-66	100	0.93
		431-66	300	0.94
		431-66	500	0.95
		452-66	750	0.95
		466-66	1000	0.94
		476-66	1120	0.88
3)	Charred (Engine Liner)	645-66	25	0.92
		645-66	100	0.92
		645-66	300	0.91
		649-66	500	0.90
		646-66	750	0.81
		647-66	1000	0.88
		648-66	1120	0.87

TABLE 8: EMITTANCE OF REFRASIL CLOTH/PHENOLIC RESIN (U. S. POLYMERIC XR 2015) ABLATIVE MATERIAL

	PHYSICAL STATE	TRW SAMPLE NO.	TEMPERATURE (°C)	NORMAL EMITTANCE $\varepsilon_N(T)$
1)	Virgin, nondecomposed	404-66	25	0.96
		404-66	100	0.96
		404-66	205	0.96
2)	Charred (Laboratory)	435-66	25	0.95
		435-66	100	0.95
		435-66	300	0.96
		435-66	500	0.96
		475-66	750	0.95
		474-66	1000	0.93
		476-66	1120	0.93
3)	Charred (Engine Liner)	651-66	25	0.89
		651-66	100	0.89
		651-66	300	0.88
		651-66	500	0.84
		651-66	750	0.80
		652-66	1000	0.78
		653-66	1120	0.71

TABLE 9: EMITTANCE OF MAGNESIUM HYDROXIDE (WBC 5217) ABLATIVE MATERIAL

	PHYSICAL STATE	TRW SAMPLE NO.	TEMPERATURE (°C)	NORMAL EMITTANCE $\varepsilon_N(T)$
1)	Virgin, nondecomposed	400-66	25	0.92
		400-66	100	0.93
		400-66	205	0.95
2)	Charred (Laboratory)	434-66	25	0.94
		434-66	100	0.94
		434-66	300	0.96
		434-66	500	0.96
		454-66	750	0.96
		478-66	1000	0.92
		479-66	1120	0.94
3)	Charred (Engine Liner)			

None was available for emittance testing. The liner eroded excessively during the engine firing.

Bulb Lasted 12 Min. INFRARED SPECTRAL REFLECTANCE

DATE: 1-6-67 OPERATOR: P.E.7 SAMPLE NO: 651-66 INSTRUMENT: Parab.

DESCRIPTION: XR 2015 (Engine Sample)

Part No. E 110502-2, S/N 001 SAMPLE TEMP. 750°C (1380°F)

.349 after test, .346 after NaCl Run

ΔD	DRUM NO.	SLIT (M.M.)	λ MICRONS	ρ	$\frac{W_{\Delta\lambda}}{W_o - \infty}$	SOLAR ρ_{96}	SOLAR ρ_{98}
		NaCl Prism		ρ300°K			
MIRROR	19.09	.23	2.0	.331	(.337)		
	19.03	.23	2.1	.334			
	18.98	.22	2.2	.331			
	18.94	.20	2.3	.333	(.333)		
	18.89	.19	2.4	.334		.200	
	18.85	.21	2.5	.327		.225	
	18.78	.22	2.65	.310		.225	
	18.71	.25	2.8	.249		.185	
	18.64	.27	2.95	.308		.165	
	18.58	.27	3.10	.317	(.320)	.115	
	18.50	.27	3.25	.327	.0001	.110	
	18.43	.28	3.4	.325	.0002	.080	
	18.35	.28	3.55	.312	.0003	.080	
	18.27	.29	3.7	.300	.0004	.065	
	18.19	.30	3.85	.292	.0006	.060	(.271)
	18.11	.33	4.0	.270	.0009	.055	
	18.00	.40	4.2	.247	.0012	.050	
	17.89	.45	4.4	.171	.0020	.055	
	17.77	.54	4.6	.165	.0024	.040	(.046)
	17.65	.61	4.8	.108	.0030	.030	
	17.52	.68	5.0	.045	.0039	.035	
	17.36	.73	5.25	.026	.0056	.030	
	17.19	.78	5.50	.022	.0066	.030	(.020)
SCATTER PLATE	17.02	.85	5.75	.023	.0079	.025	
	16.83	.90	6.0	.020	.0086	.020	
	16.63	.95	6.25*	.016	.0100	.020	
	16.43	1.0	6.50	.015	.0109	.015	
	16.22	1.05	6.75	.011	.0119	.010	(.008)
	16.00	1.10	7.0	.008	.0170	.015	
	15.64	1.60	7.4	.007	.0226	.015	
	15.25	1.80	7.8	.037	.0240	.010	
	14.83	1.90	8.2*	.126	.0254	.010	
	14.40	1.95	8.6	.215	.0265	.010	(.269)
	13.95	2.00	9.0	.270	.0269	.010	
	13.49		9.4	.231	.0272	.005	
	13.00		9.8 *	.160	.0271		
	12.49		10.2	.111	.0270		
	11.97		10.6	.085	.0265		
	11.41		11.0 *	.070	.0294		
	10.69		11.5	.055	.0318		
	9.95		12	.045	.0307		
	9.19		12.5	.052	.0295		
	8.24		13 *	.053	.0281		
	7.30		13.5	.051			
	6.47		14				
	5.53		14.5				
	4.57	2.00	15				

1.0μ = .303
1.1 = .312
1.2 = .315
1.3 = .321
1.4 = .327
1.5 = .326
1.6 = .328
1.7 = .330
1.8 = .333
1.9 = .334

1.5μ = .338 after NaCl run
.341 after test

2.5μ = .340 after NaCl run
.342 after test

(.303), .323 after NaCl Run, .323 after test

ΔD	DRUM NO.	SLIT (M.M.)	λ MICRONS	ρ	Σρ $\frac{W_{\Delta\lambda}}{W_o - \infty}$
		KBr PRISM			
SCATTER PLATE	17.59	1.10	13	.055	
	17.30	1.15	13.5	.052	.0268
	16.99	1.20	14	.050	.0253
	16.68	1.25	14.5	.045	.0244
	16.37	1.30	15 *	.042	.0227
	16.03	1.35	15.5	.037	.0217
	15.67	1.40	16	.036	.0203
	15.31	1.50	16.5	.033	.0192
	14.93	1.53	17 *	.029	.0184
	14.54	1.60	17.5	.029	.0171
	14.13	1.65	18	.028	.0161
	13.68	1.70	18.5	.030	.0153
	13.28	1.75	19	.040	.0141
	12.83	1.80	19.5	.082	.0136
	12.37	1.85	20	.160	.0129
	11.89	1.90	20.5*	.243	.0125
	11.40	1.95	21	.285	.0112
	10.89	2.00	21.5	.273	.0103
	10.36		22	.240	.0100
	9.81		22.5	.200	.0093
	9.27		23	.190	.0091
	8.73		23.5	.180	.0086
	8.18		24	.170	.0080
	7.60		24.5		.0075
	7.00		25		.0072
	6.38		25.5		.0068
	5.73	2.00	26 *		.0064
			26-∞*	.170	.1489

(.330)

204805/

$\Sigma\rho \frac{W_{\Delta\lambda}}{W_o - \infty}$ $\bar{\rho}$ = .205

$(1 - \bar{\rho}) = \epsilon_N$ ~~300°K~~ 750°C = .795+

$\epsilon_N(\epsilon_H)/(\epsilon_n) = \epsilon_H$ 300°K =

QED ϵ_Q =

ρ_{49} (2%) ρ_{96} =

ρ_{50} (2%) ρ_{98} =

ρ_{25} (4%) Av =

$\Sigma\rho^* = \bar{\rho}$(10%) =

Figure 8. Sample Data Sheet for Directional Reflectance Measurements made with the TRW Paraboloid Reflectometer

Figure 9. EXAMPLE OF GRAPH OF SPECTRAL DIRECTIONAL REFLECTANCE BEFORE AND AFTER OXIDATION OF TEST SPECIMEN

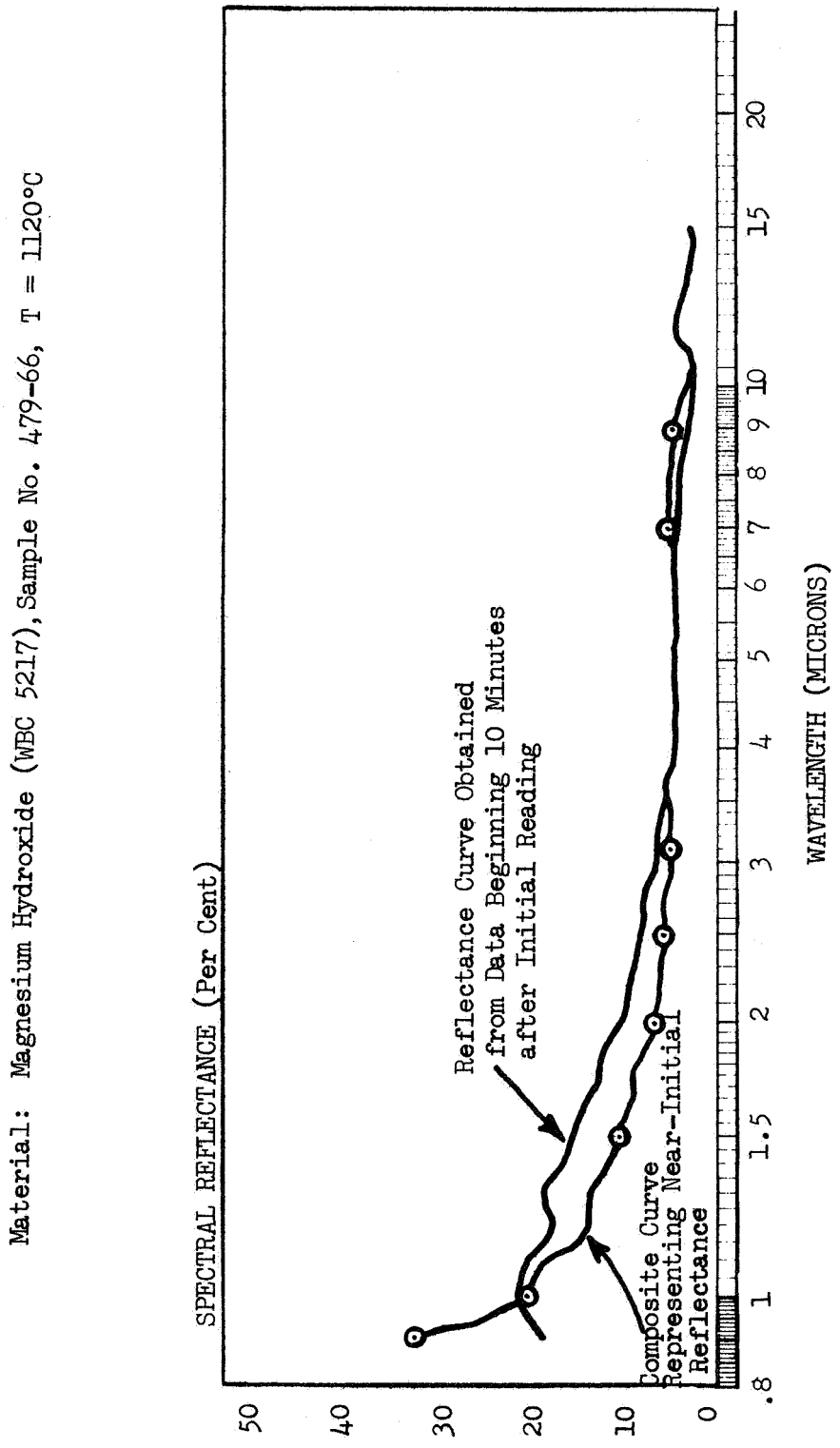


Figure 10

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS
TEMPERATURE OF IRISH REFRASIL (WBC 2234) VIRGIN ABLATIVE MATERIAL

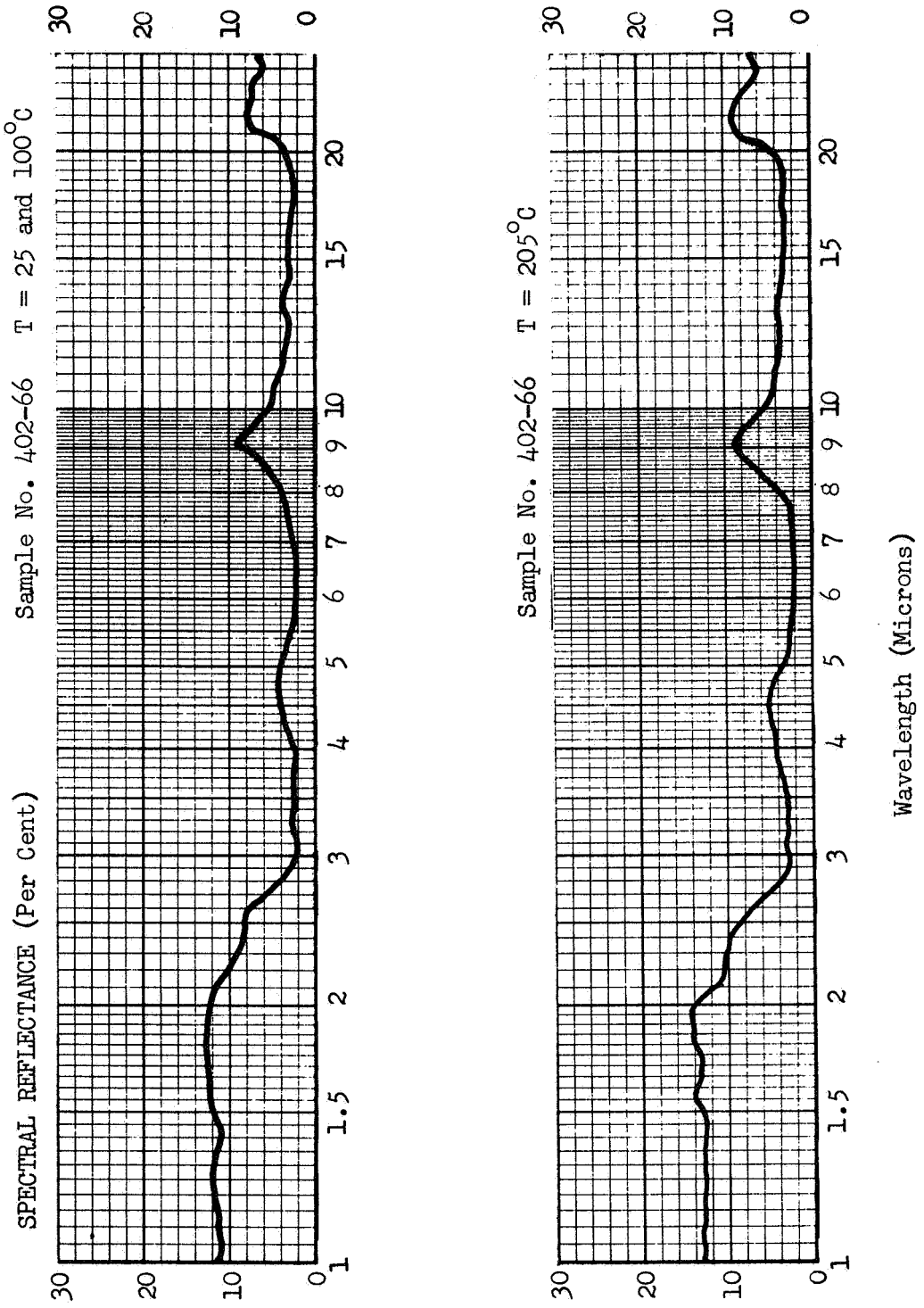


Figure 11

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS
TEMPERATURE OF IRISH REFRASIL (WBC 2234) LABORATORY-CHARRED ABLATIVE MATERIAL

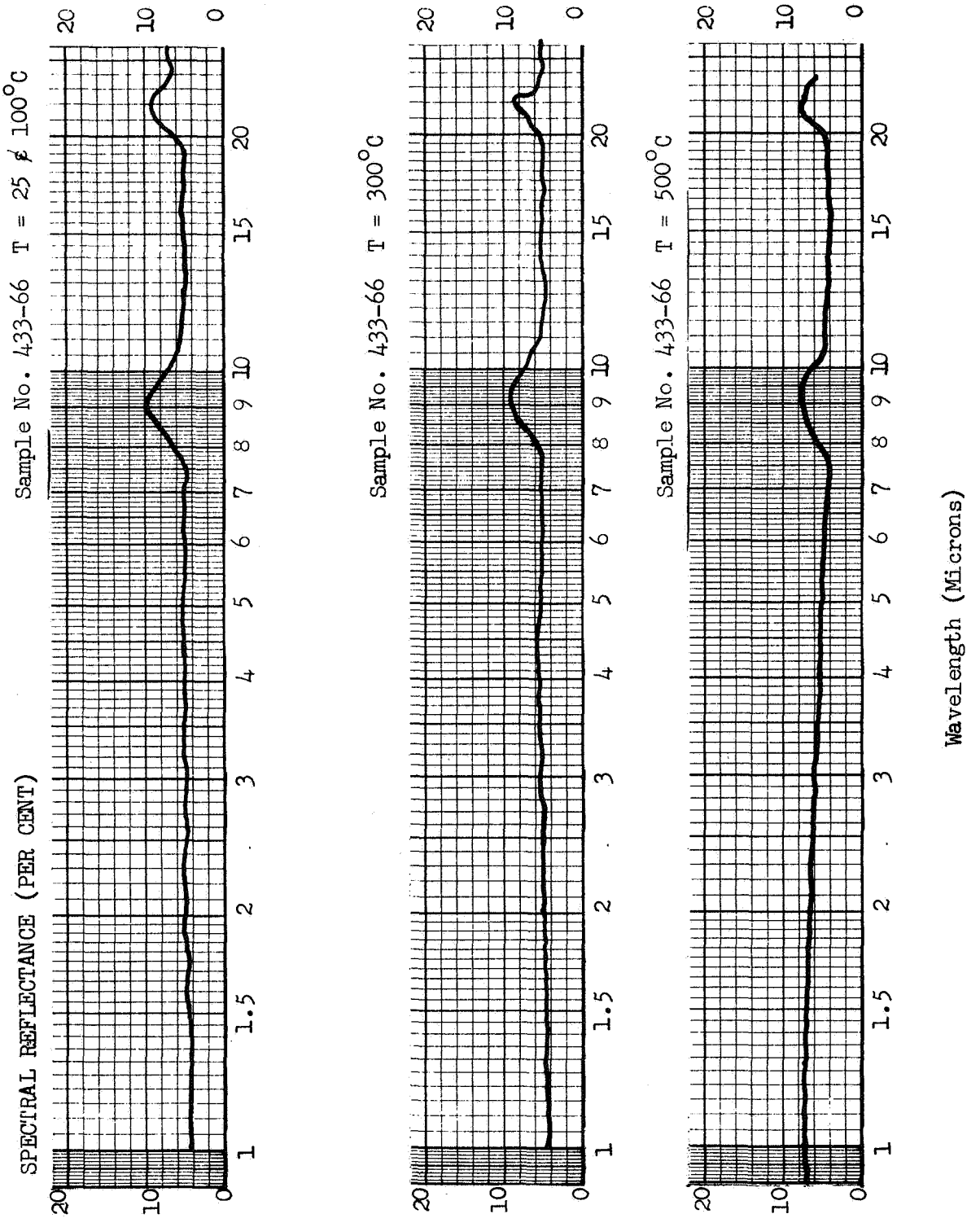


Figure 11 (Continued)

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS
TEMPERATURE OF IRISH REFRASIL (WBC 2234) LABORATORY-CHARRED ABLATIVE MATERIAL

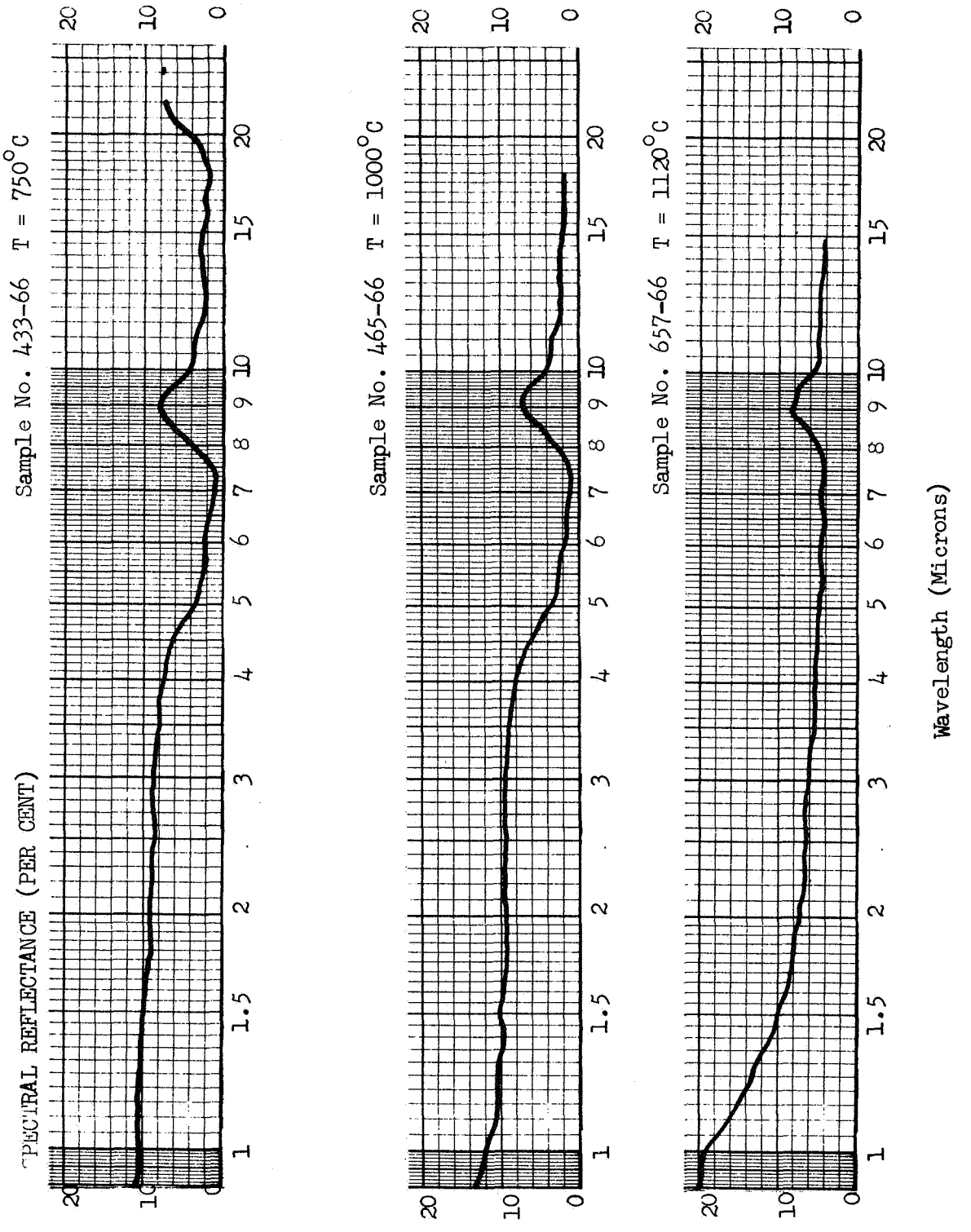


Figure 12

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS
TEMPERATURE OF IRISH REFRASIL (WBC 2234) ENGINE-CHARRED ABLATIVE MATERIAL

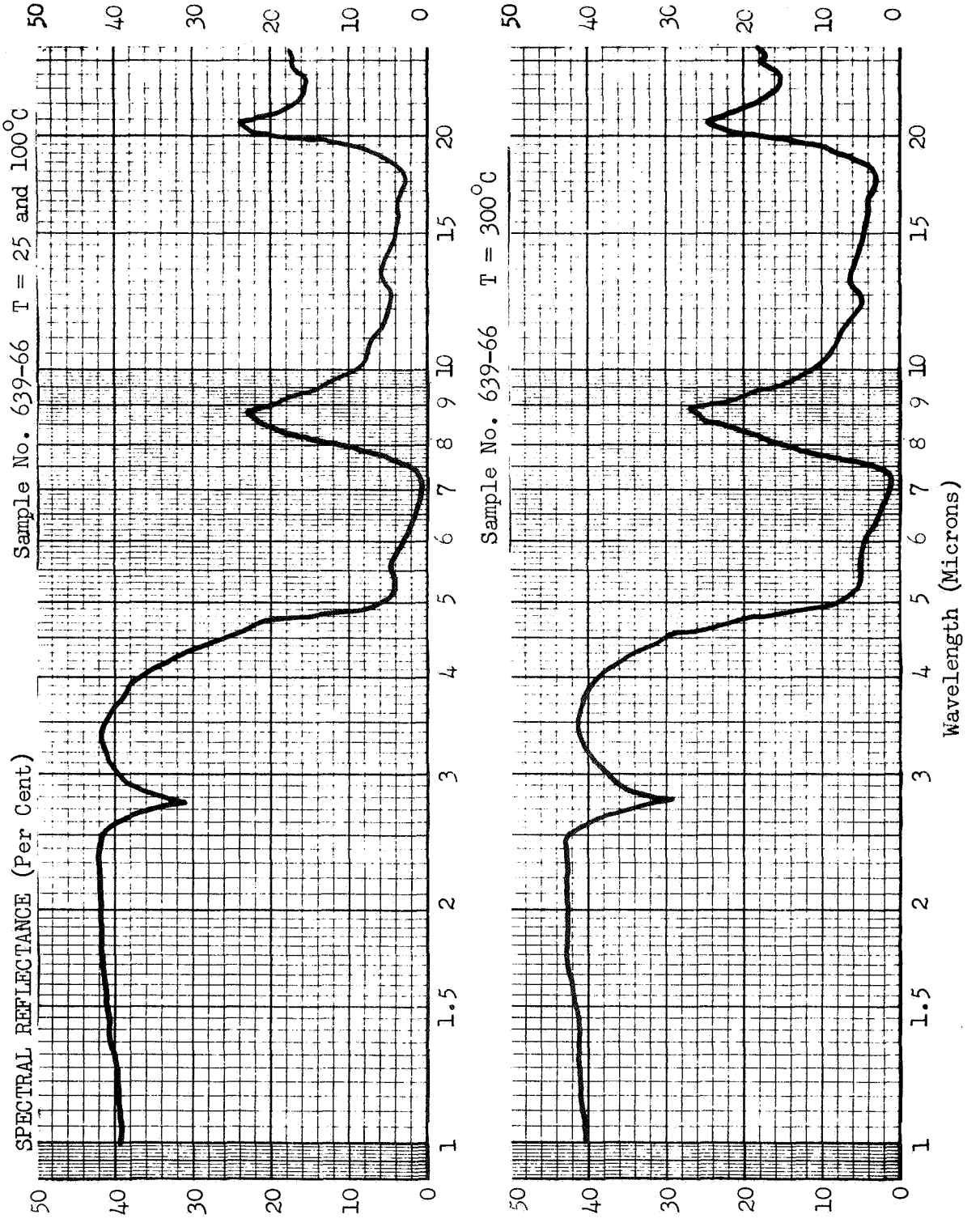


Figure 12 (Continued)

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS
TEMPERATURE OF IRISH REFRASIL (WBC 2234) ENGINE-CHARRED ABLATIVE MATERIAL

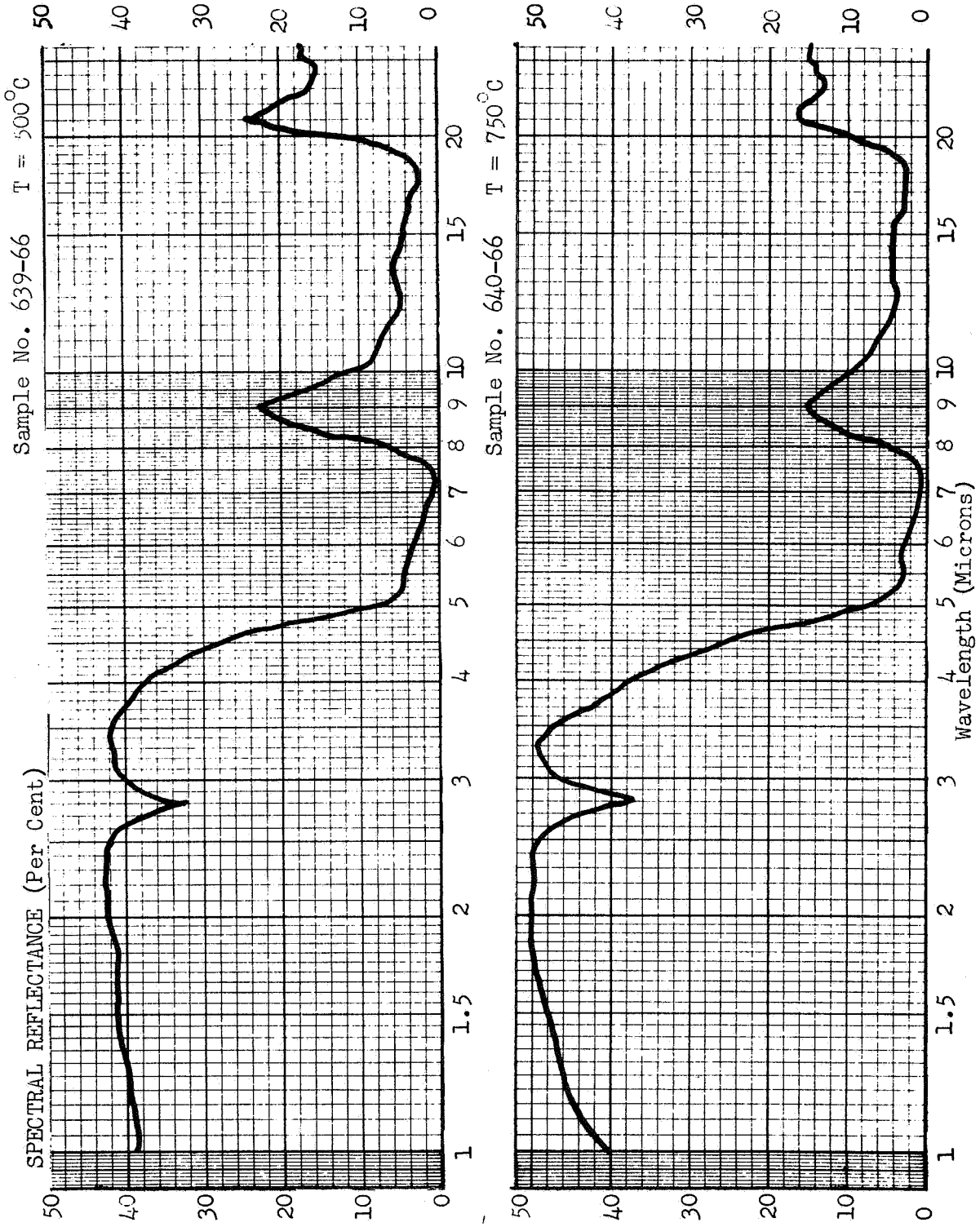


Figure 12 (Continued)

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS TEMPERATURE OF IRISH REFRASIL (WBC 2234) ENGINE-CHARRED ABLATIVE MATERIAL

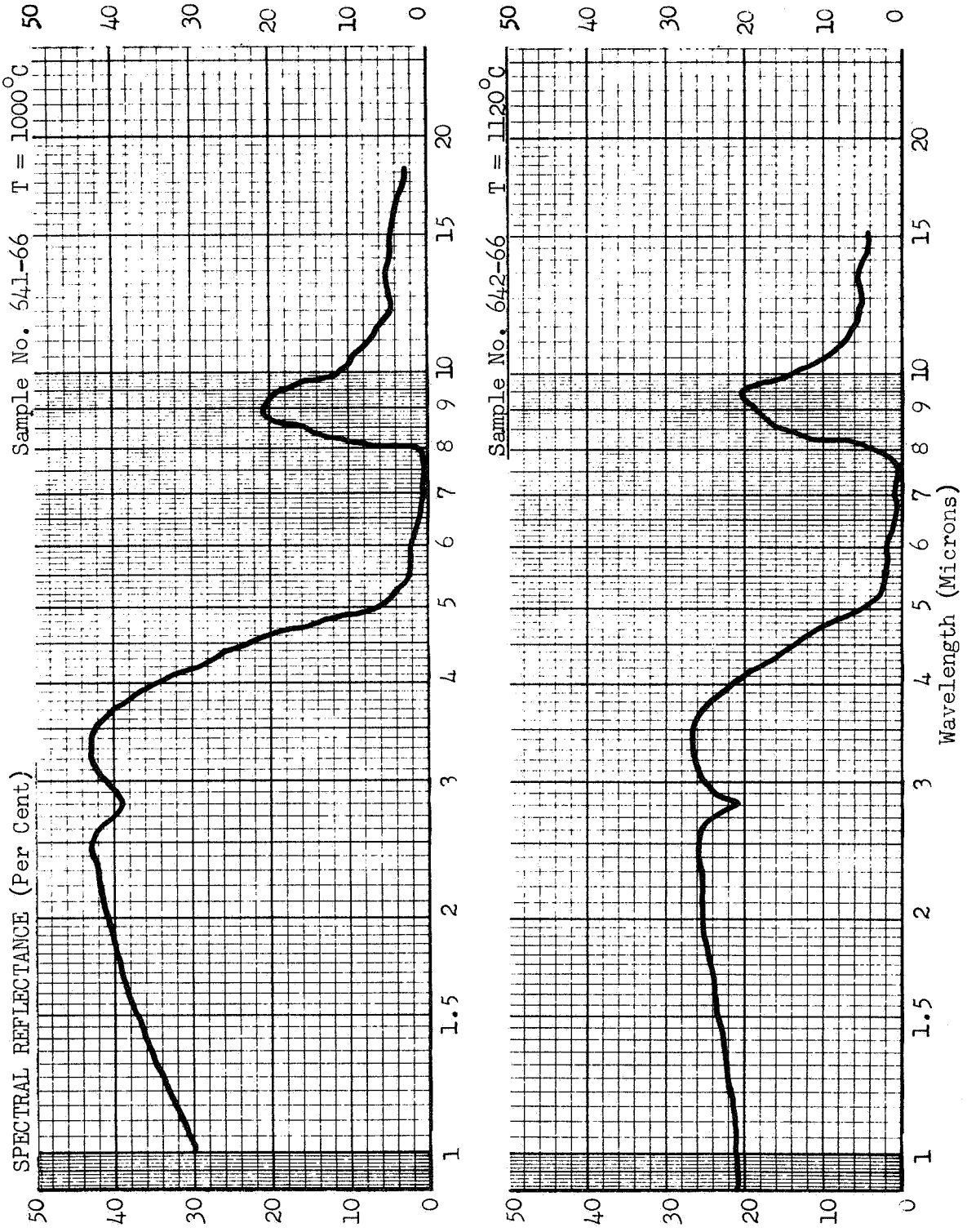


Figure 13. Directional Spectral Reflectance Versus Temperature Of Fiberite MX 2600 Virgin Ablative Material

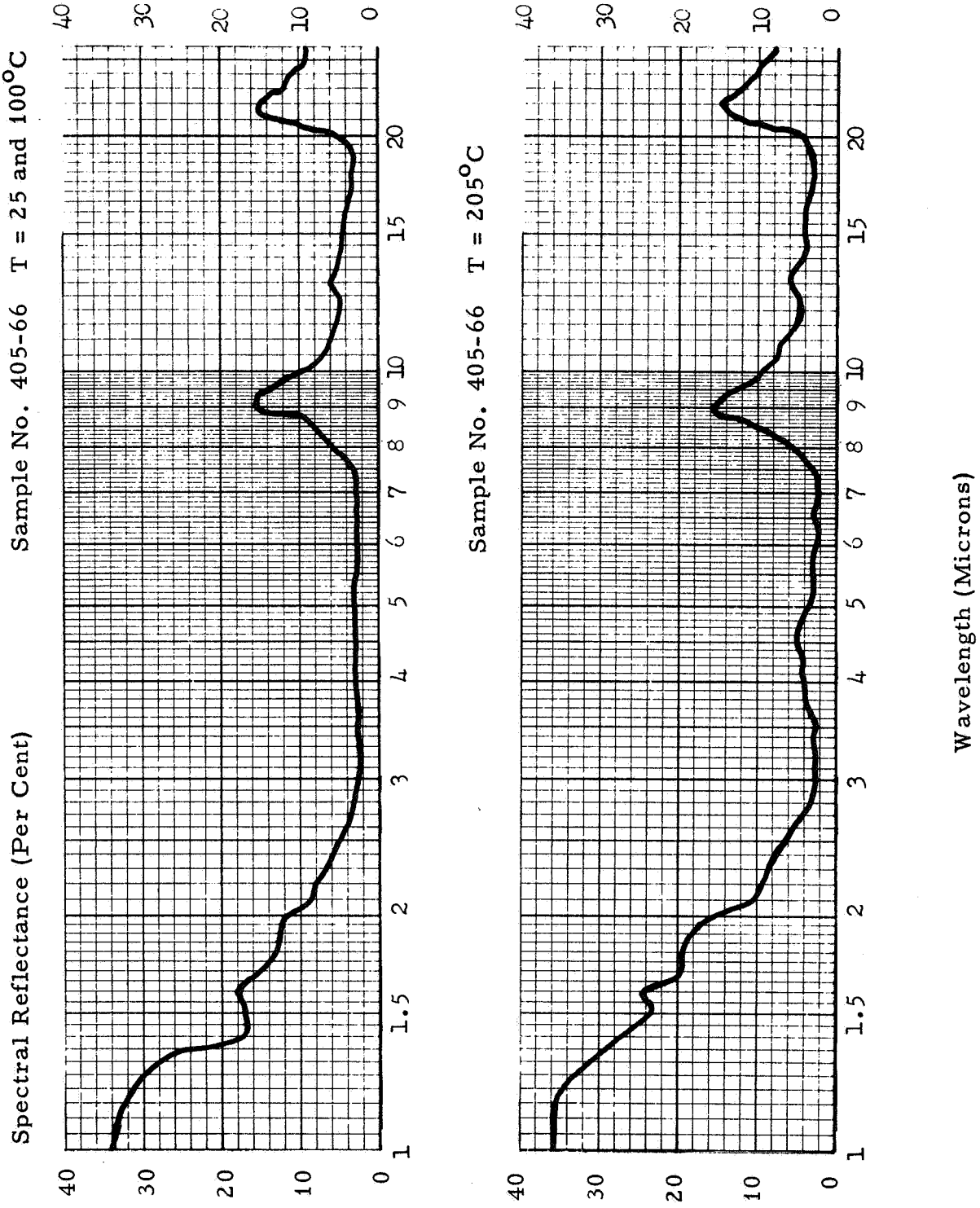


Figure 14. Directional Spectral Reflectance Versus Temperature Of Fiberite MX 2600 Laboratory-Charred Ablative Material

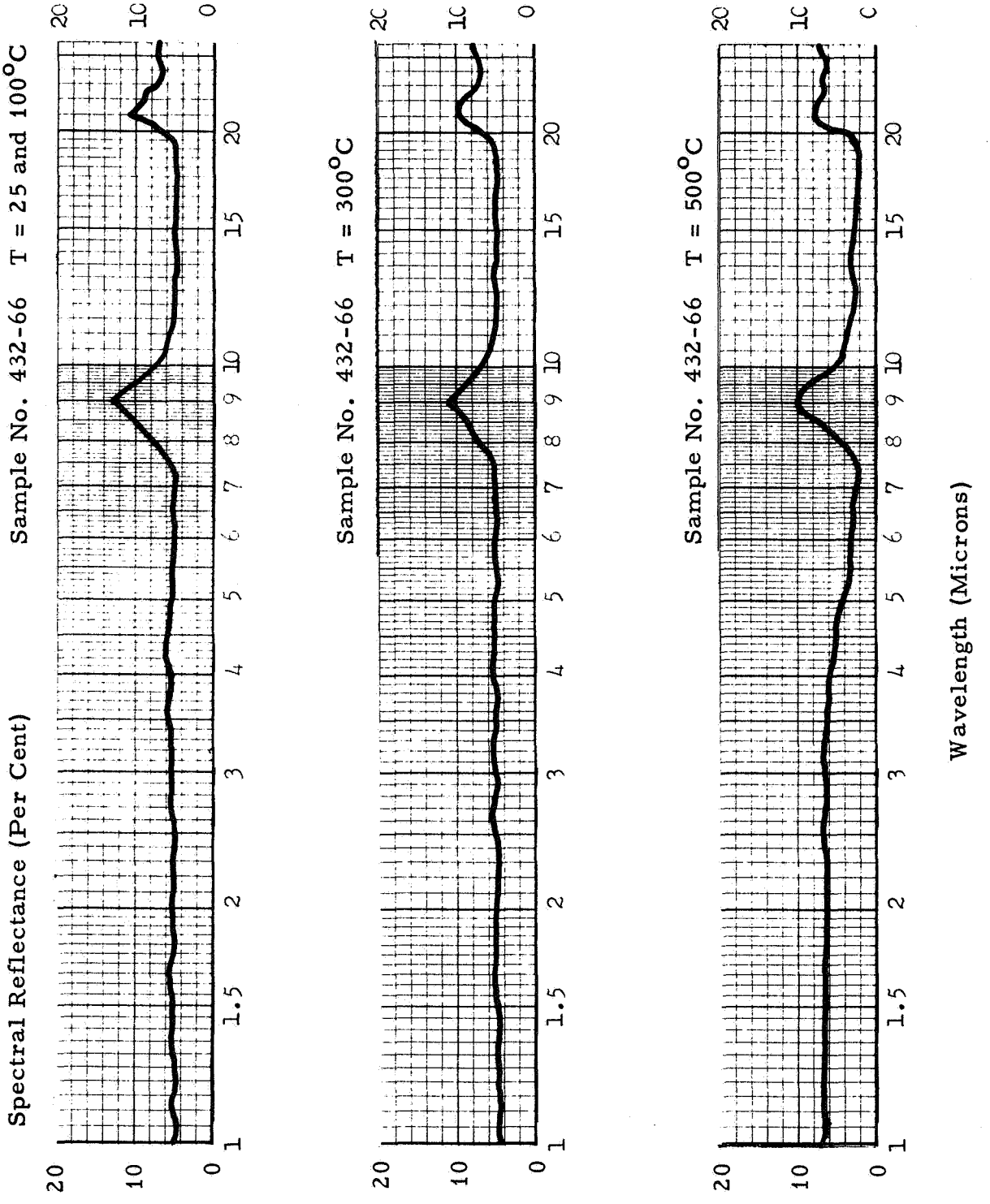


Figure 14. Directional Spectral Reflectance Versus Temperature Of Fiberite MX 2600 Laboratory-Charred Ablative Material (continued)

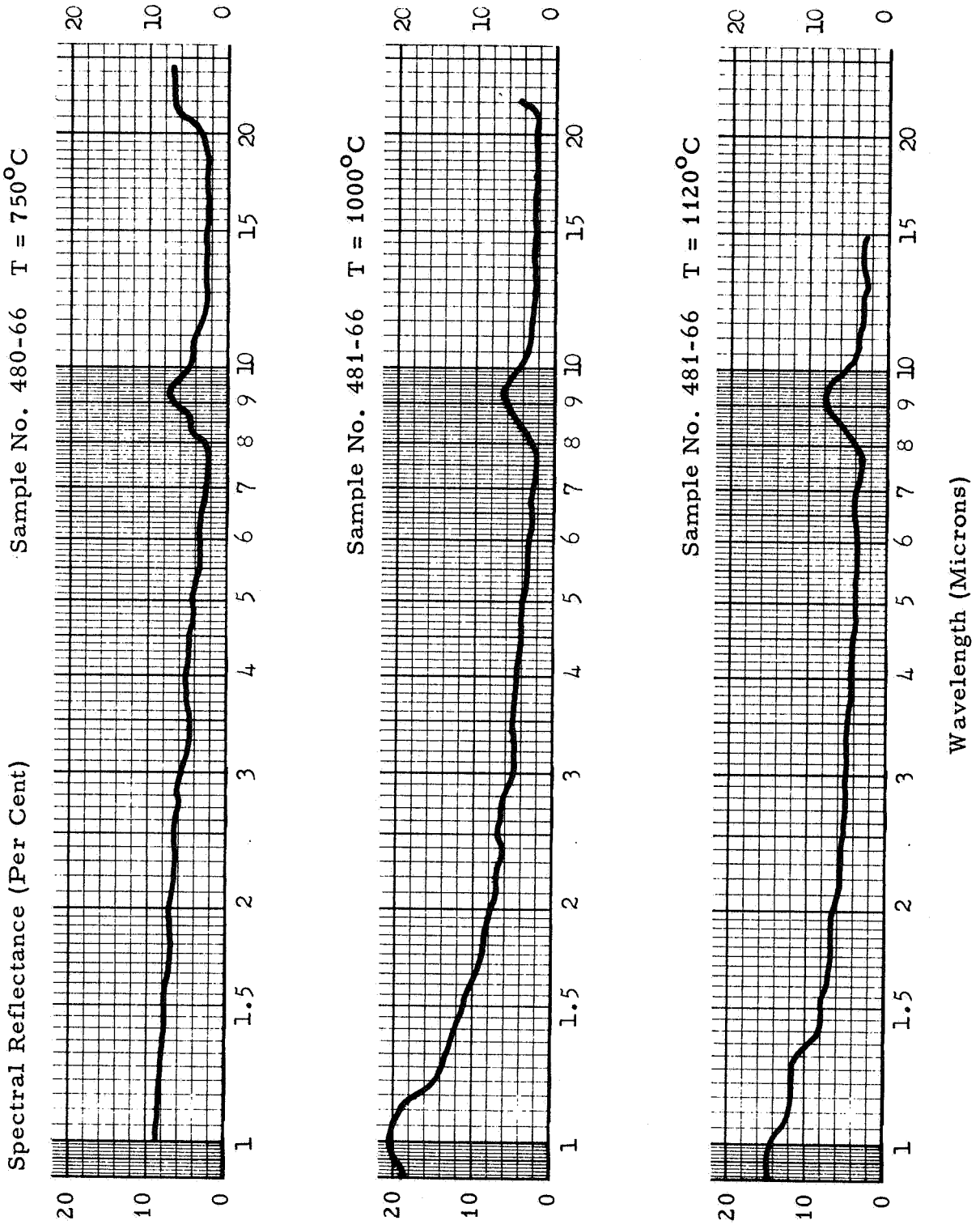


Figure 15. Directional Spectral Reflectance Versus Temperature Of Fiberite MX 2600 Engine-Charred Ablative Material

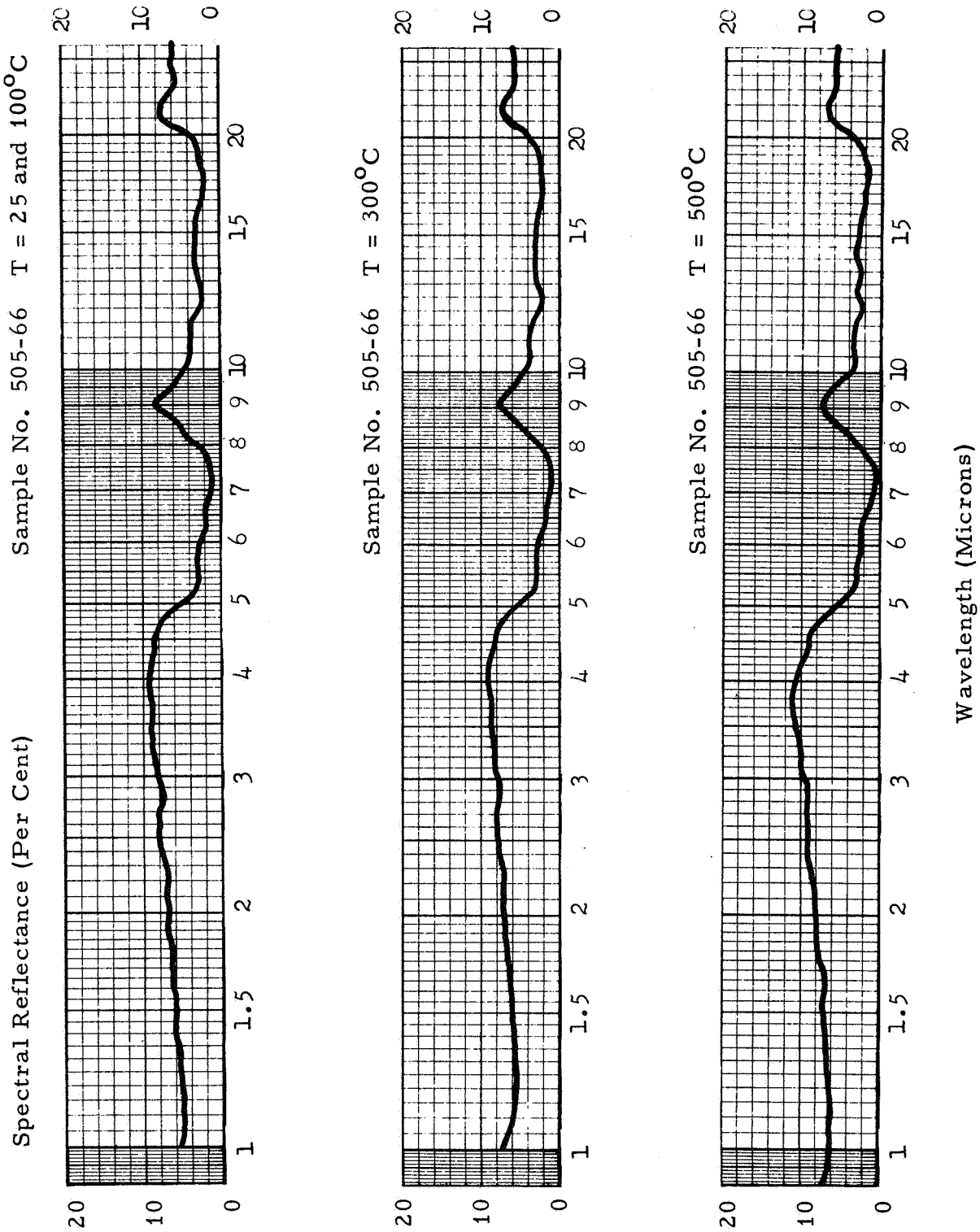


Figure 15. Directional Spectral Reflectance Versus Temperature Of Fiberite MX 2600 Engine-Charred Ablative Material (continued)

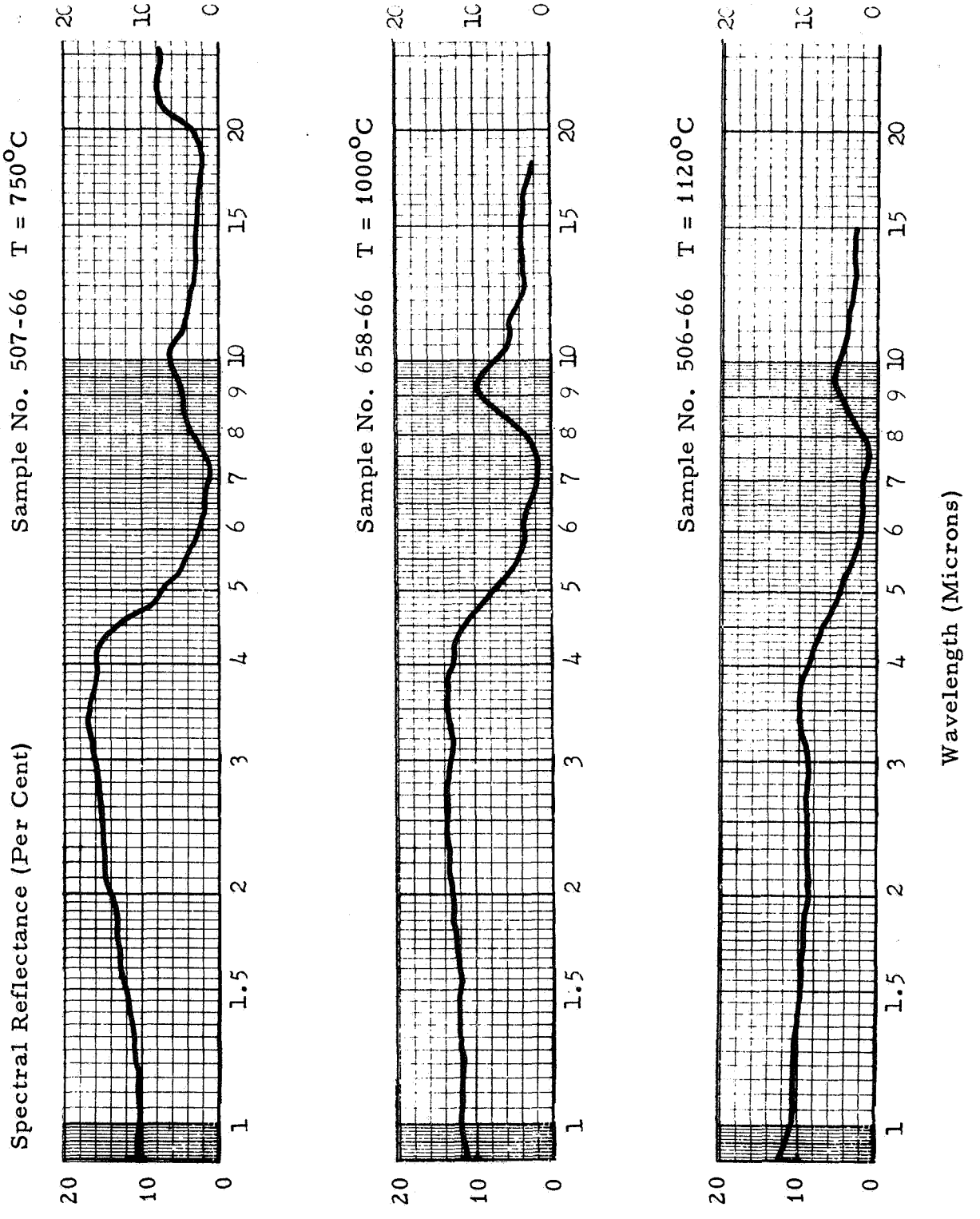


Figure 16

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS TEMPERATURE OF FIBERITE MX 2646 VIRGIN ABLATIVE MATERIAL

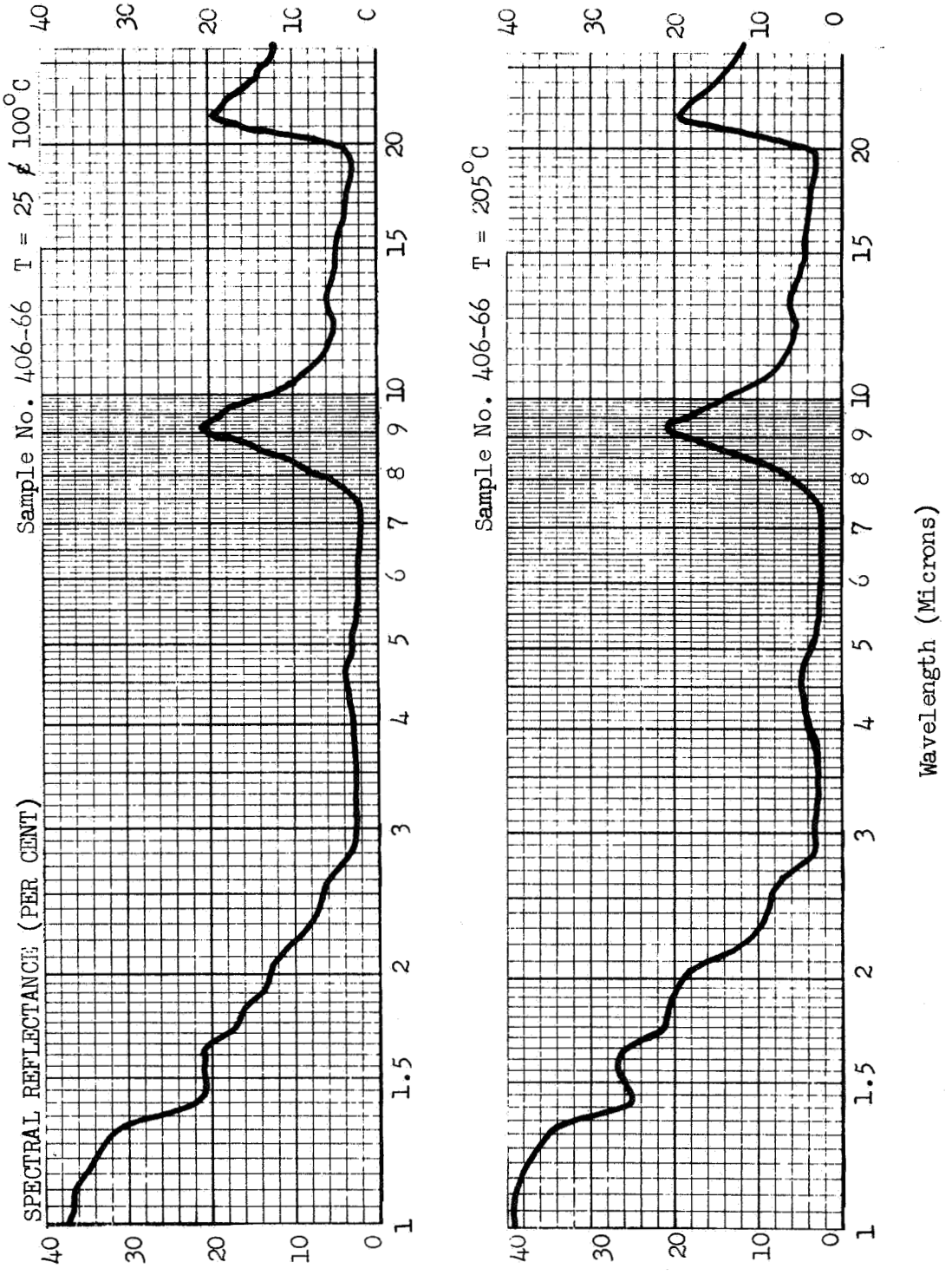


Figure 17

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS
TEMPERATURE OF FIBERITE MX 2646 LABORATORY-CHARRED ABLATIVE MATERIAL

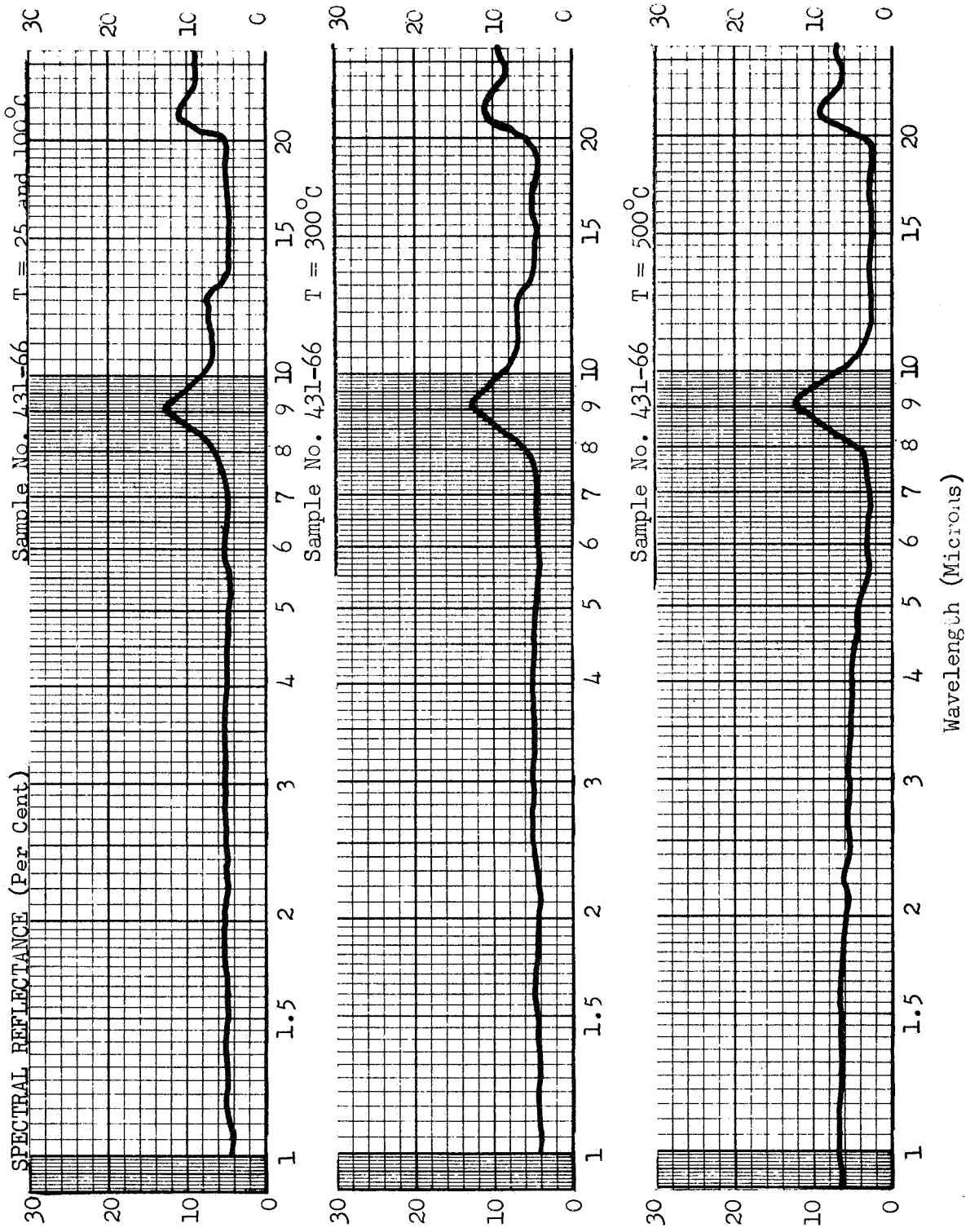


Figure 17 (Continued)
DIRECTIONAL SPECTRAL REFLECTANCE VERSUS
TEMPERATURE OF FIBERITE MX 2646 LABORATORY-CHARRED ABLATIVE MATERIAL

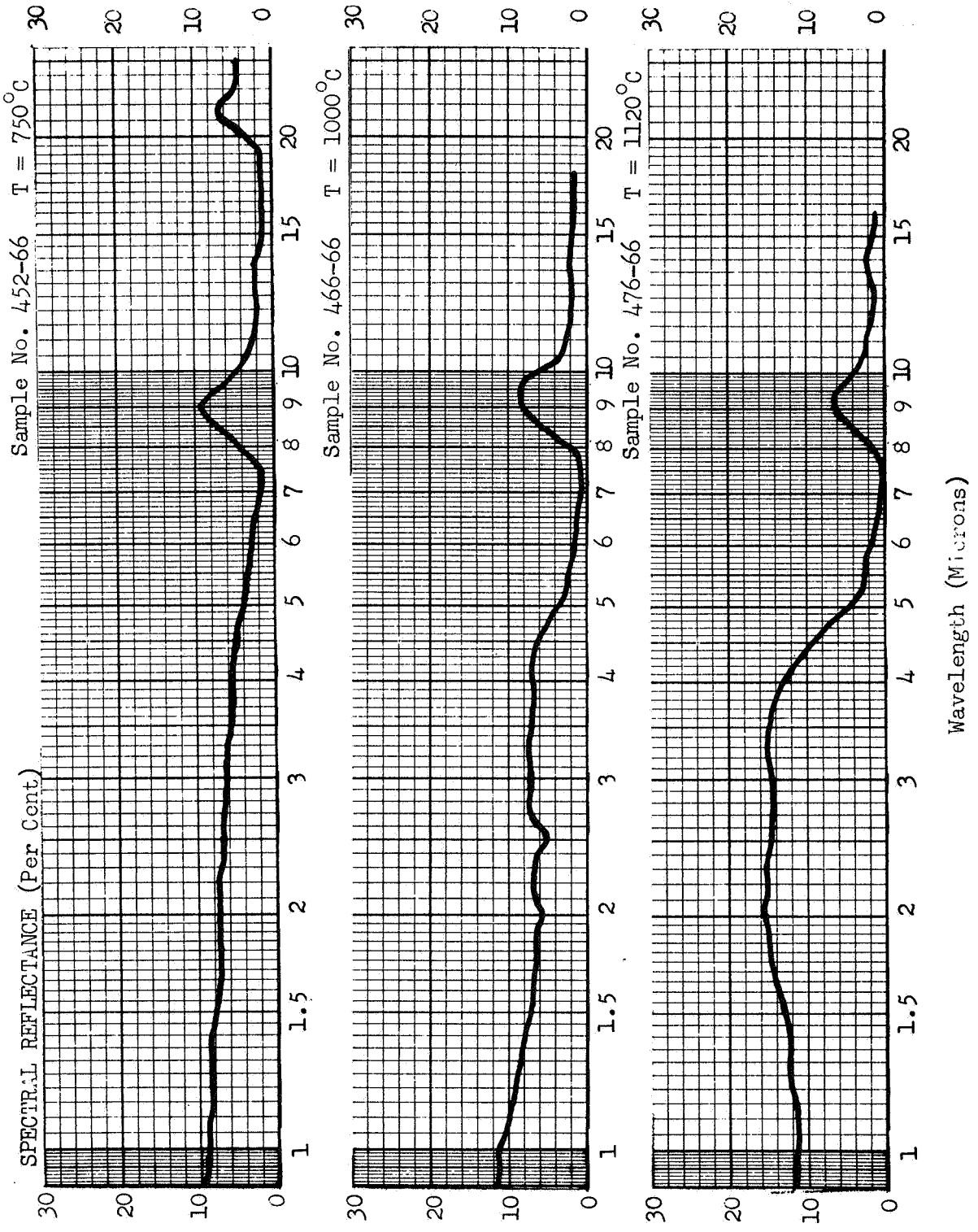


Figure 18

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS
TEMPERATURE OF FIBERITE MX 2646 ENGINE CHARRED ABLATIVE MATERIAL

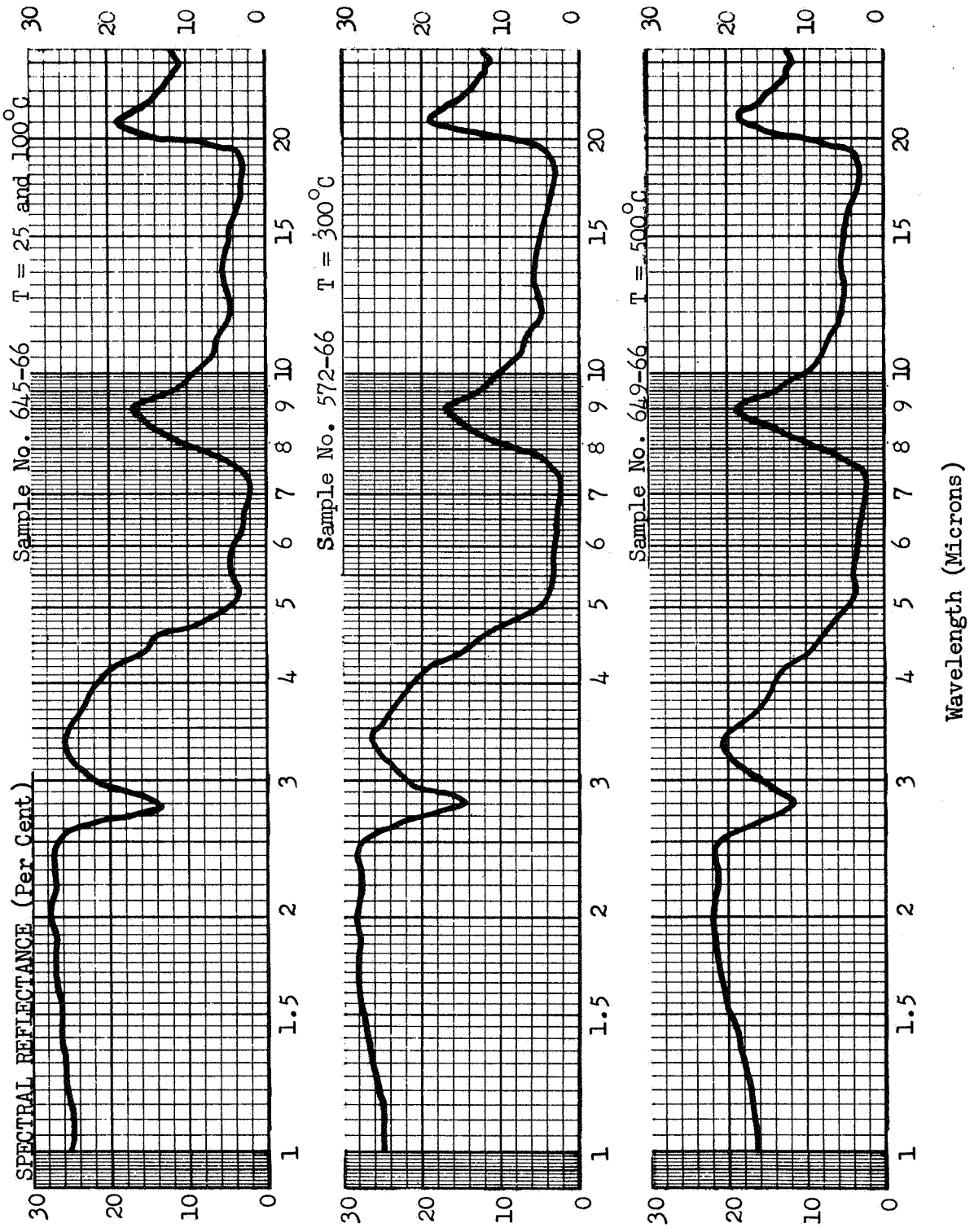


Figure 18 (Continued)

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS
TEMPERATURE OF FIBERITE MX 2646 ENGINE CHARRED ABLATIVE MATERIAL

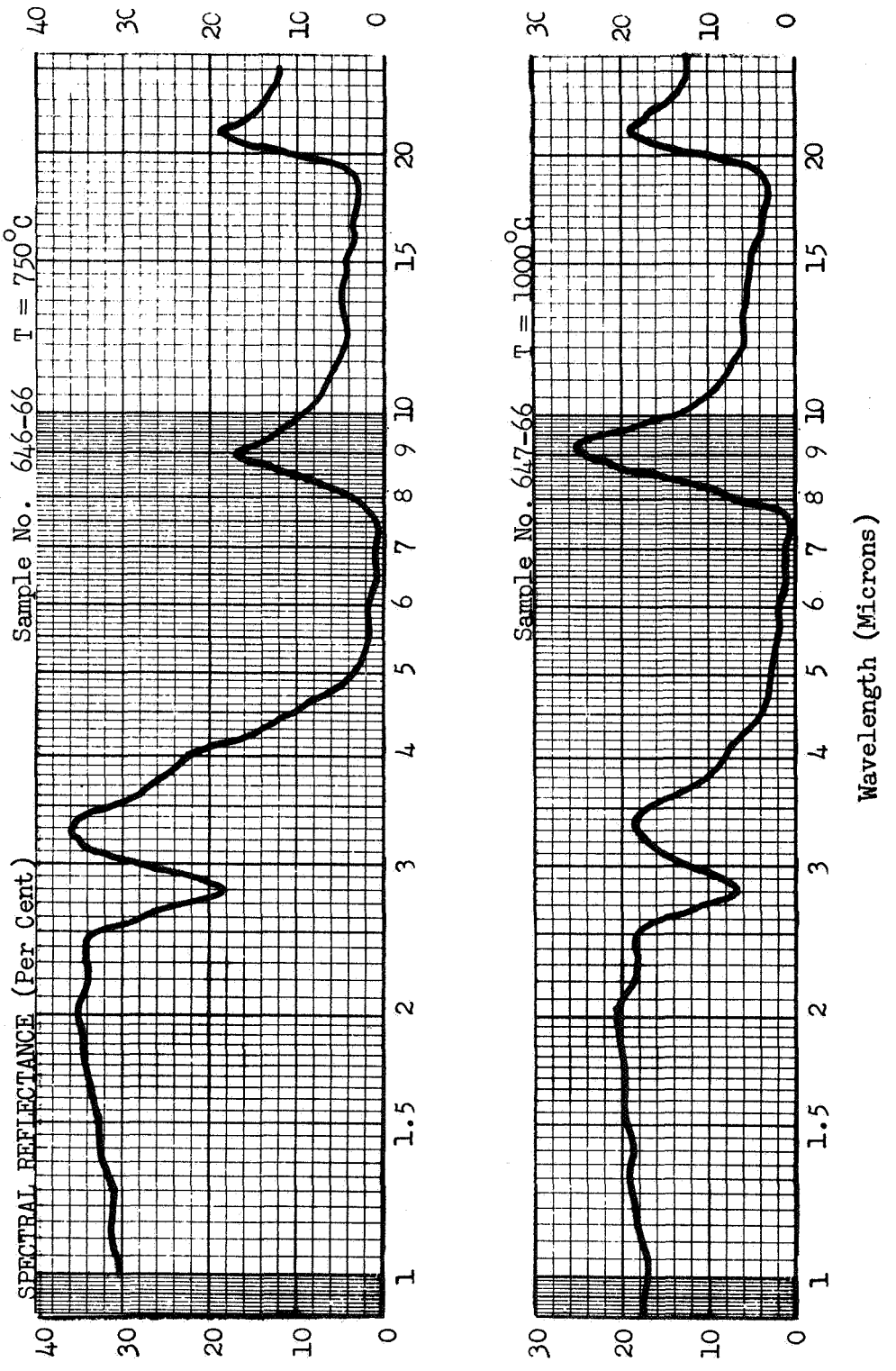


Figure 18 (Continued)

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS TEMPERATURE OF FIBERITE MX 2646 ENGINE CHARRED ABLATIVE MATERIAL

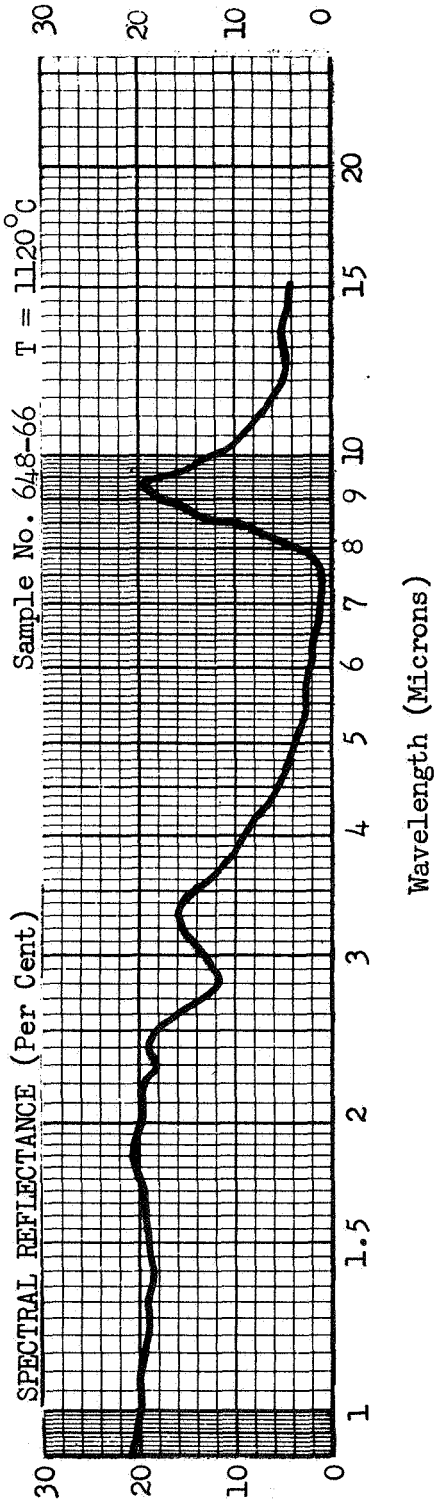


Figure 19

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS
TEMPERATURE OF REFRASIL CLOTH/PHENOLIC RESIN (U.S. POLYMERIC XR 2015)
VIRGIN ABLATIVE MATERIAL

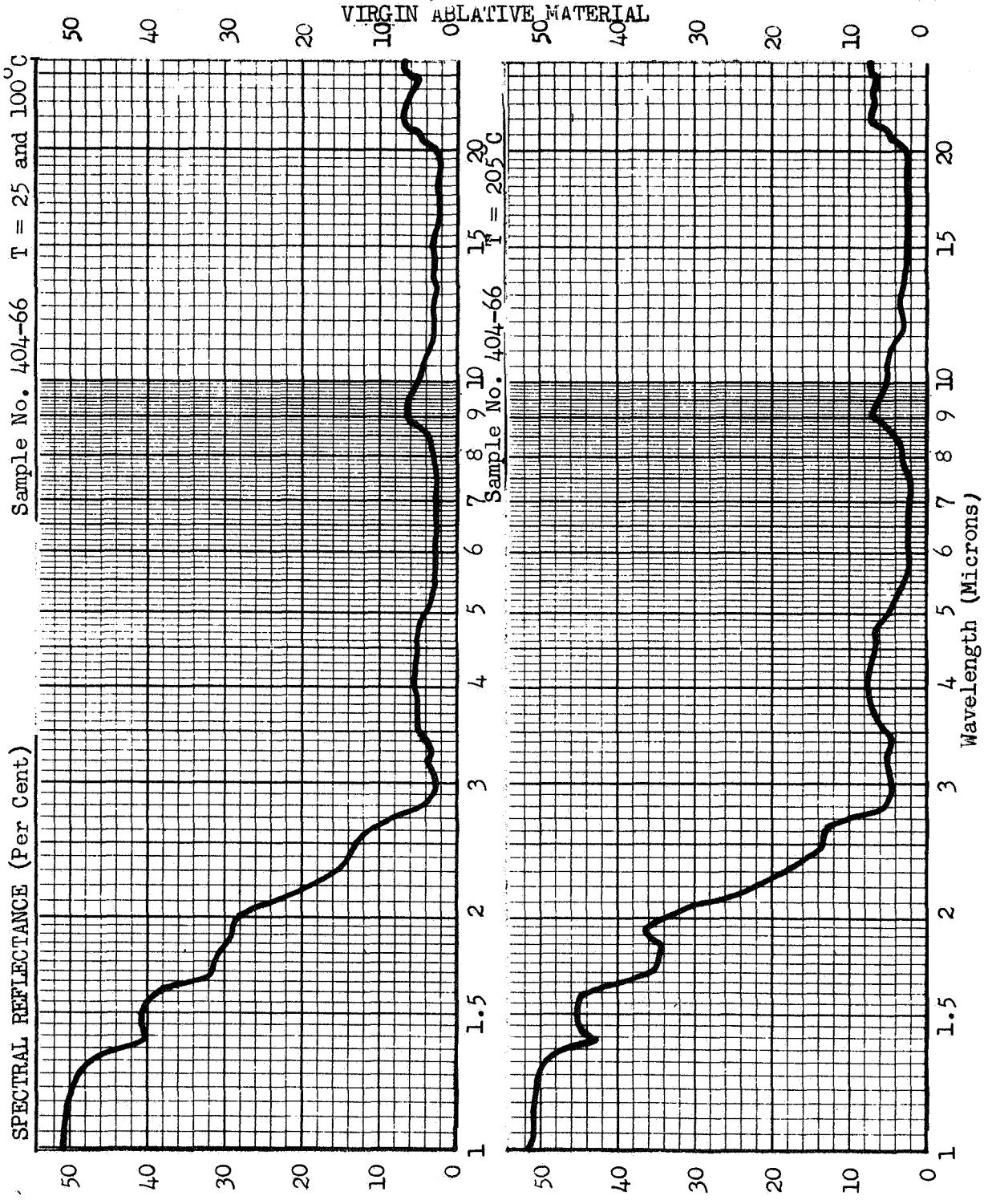


Figure 20

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS TEMPERATURE OF REFRASIL CLOTH/ PHENOLIC RESIN (U.S. POLYMERIC XR 2015) LABORATORY-CHARRED ABLATIVE MATERIAL

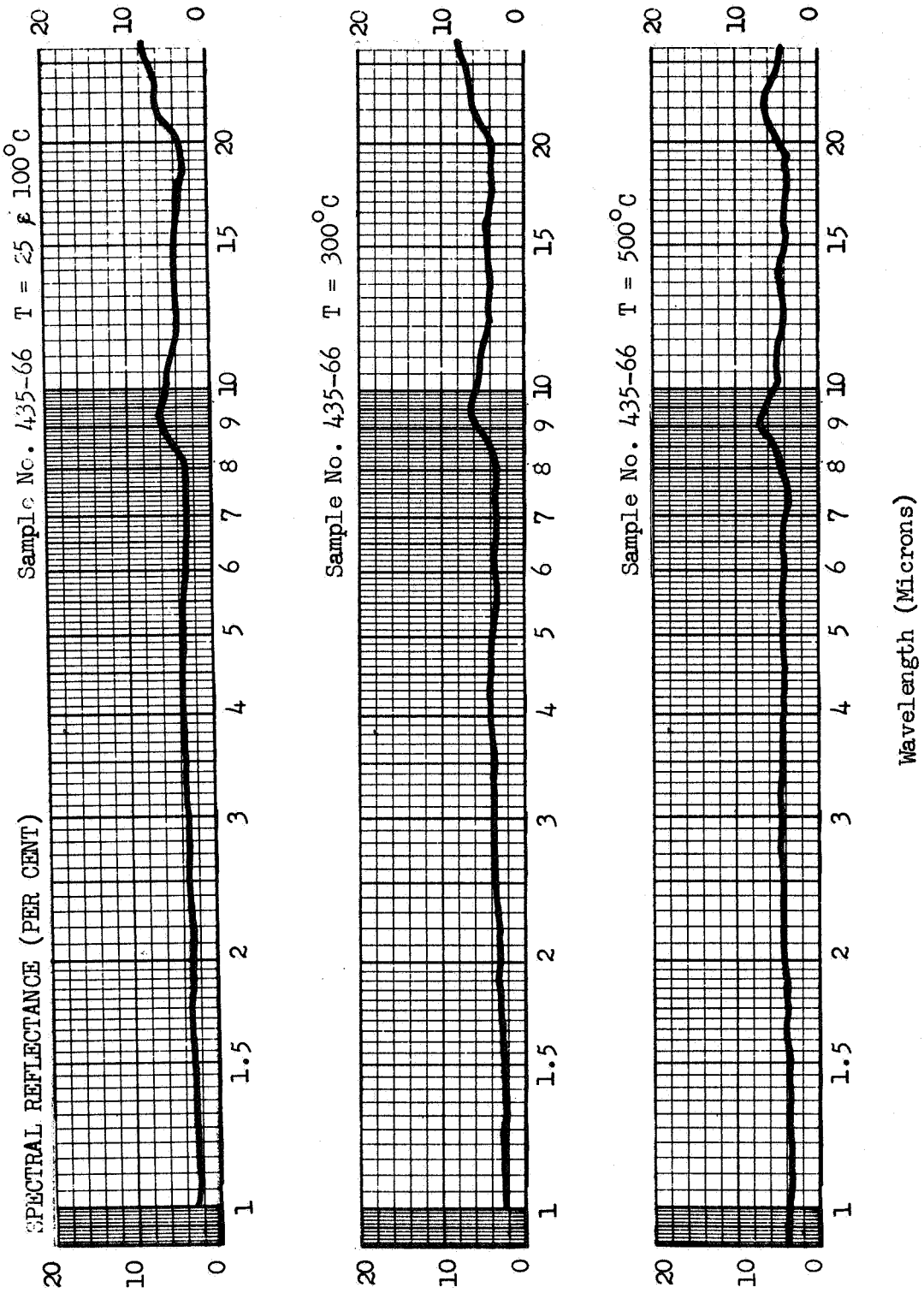


Figure 20 (Continued)

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS TEMPERATURE OF REFRASIL CLOTH/PHENOLIC RESIN (U.S.POLYMERIC XR 2015) LABORATORY-CHARRED ABLATIVE MATERIAL

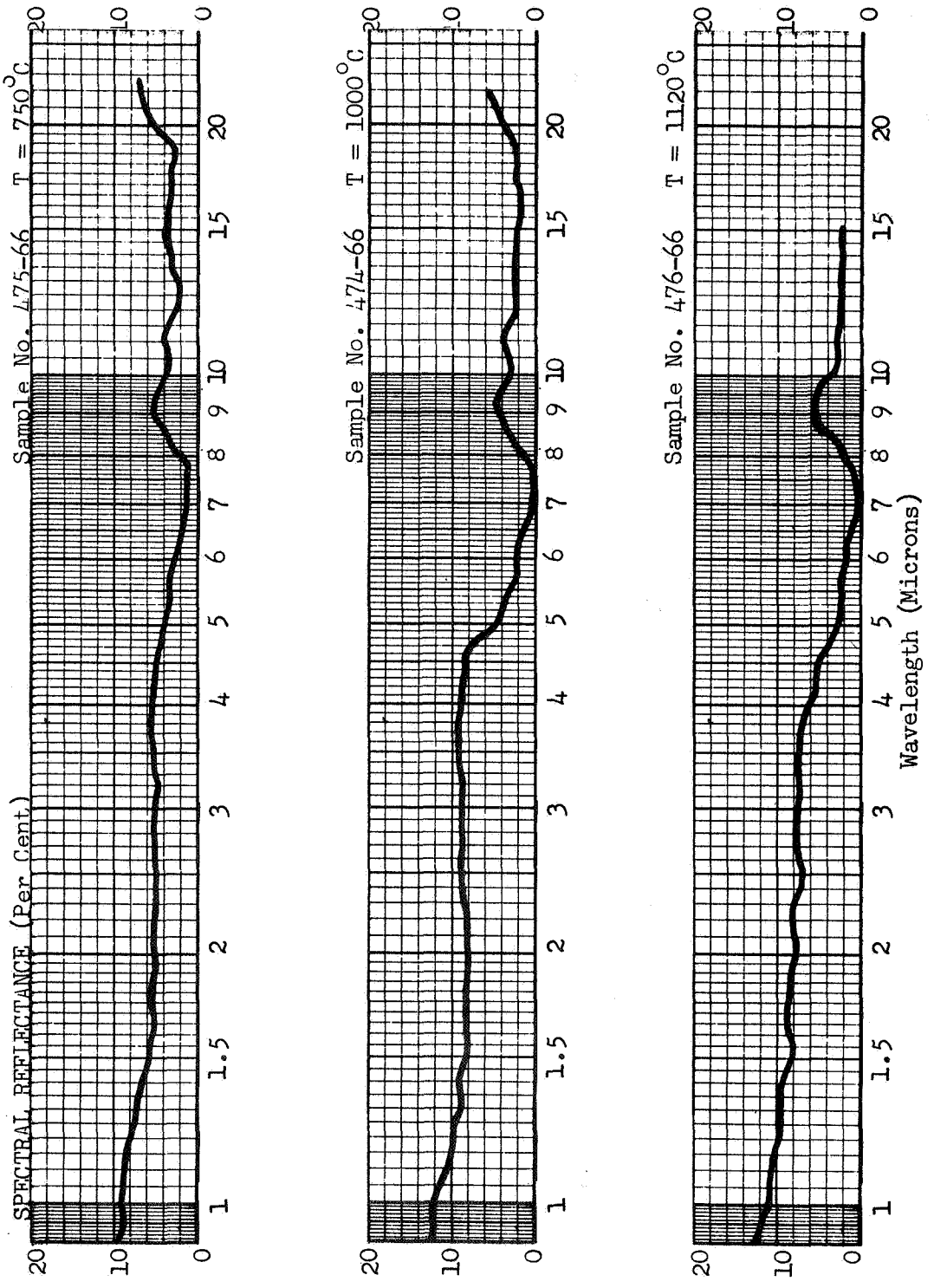


Figure 21 DIRECTIONAL SPECTRAL REFLECTANCE VERSUS TEMPERATURE OF REFRASIL CLOTH/PHENOLIC RESIN (U.S. POLYMERIC XR 2015) ENGINE-CHARRED ABLATIVE MATERIAL

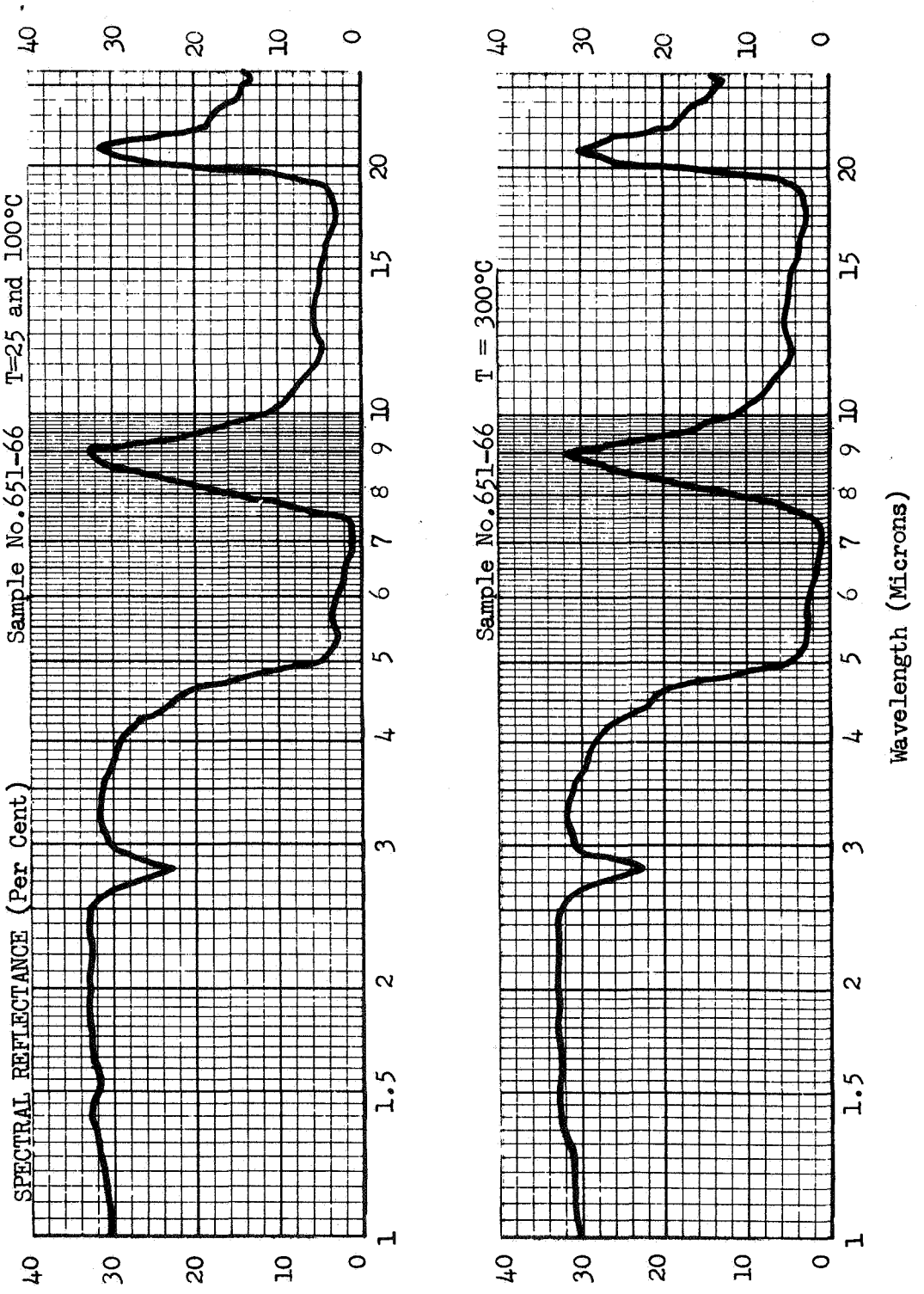


Figure 21 (Continued)

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS TEMPERATURE OF REFRASIL CLOTH/PHENOLIC RESIN (U.S. POLYMERIC XR 2015) ENGINE-CHARRED ABLATIVE MATERIAL

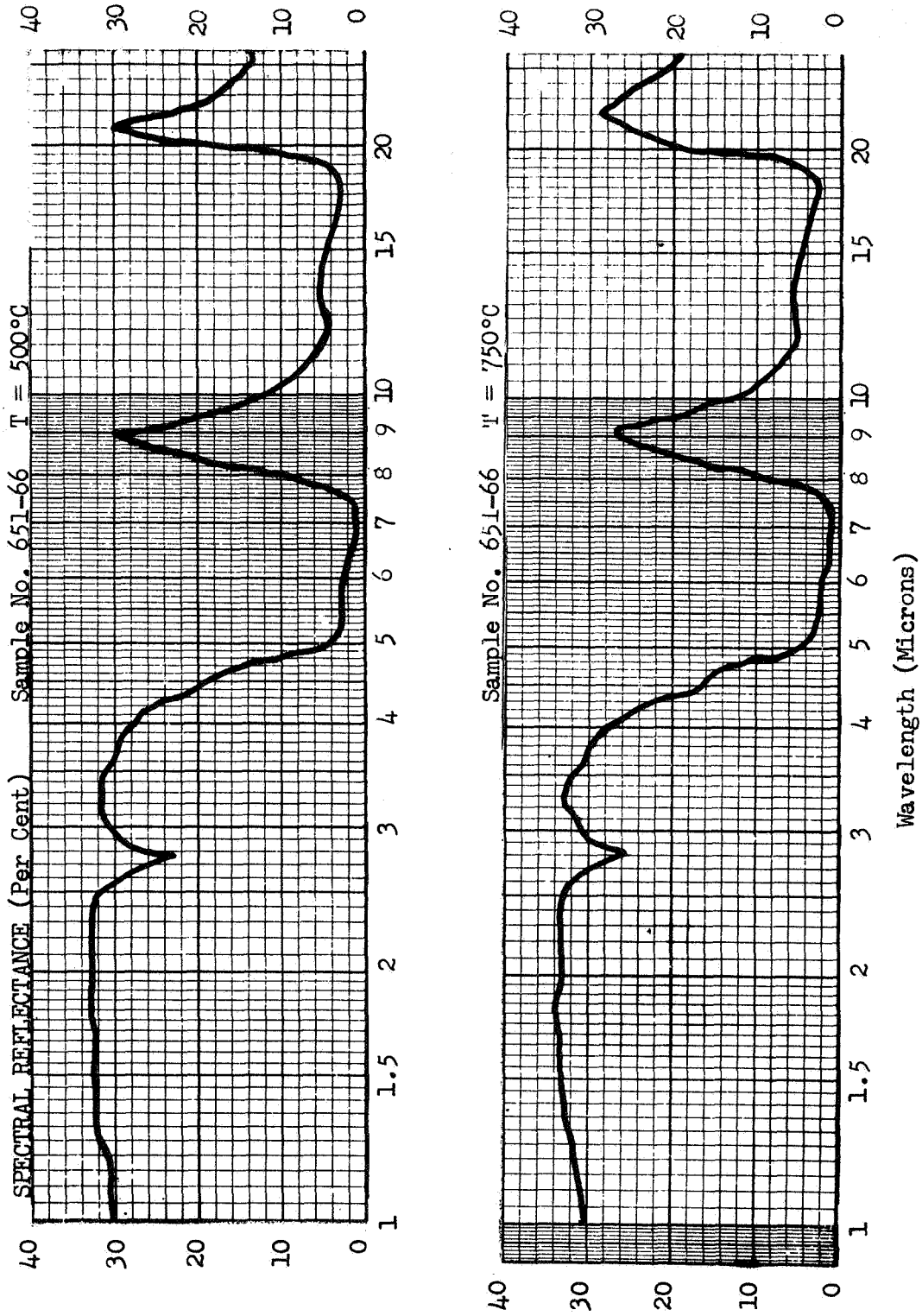


Figure 21 (Continued)

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS TEMPERATURE OF REFRASIL CLOTH/PHENOLIC RESIN (U.S. POLYMERIC XR 2015) ENGINE-CHARRED ABLATIVE MATERIAL.

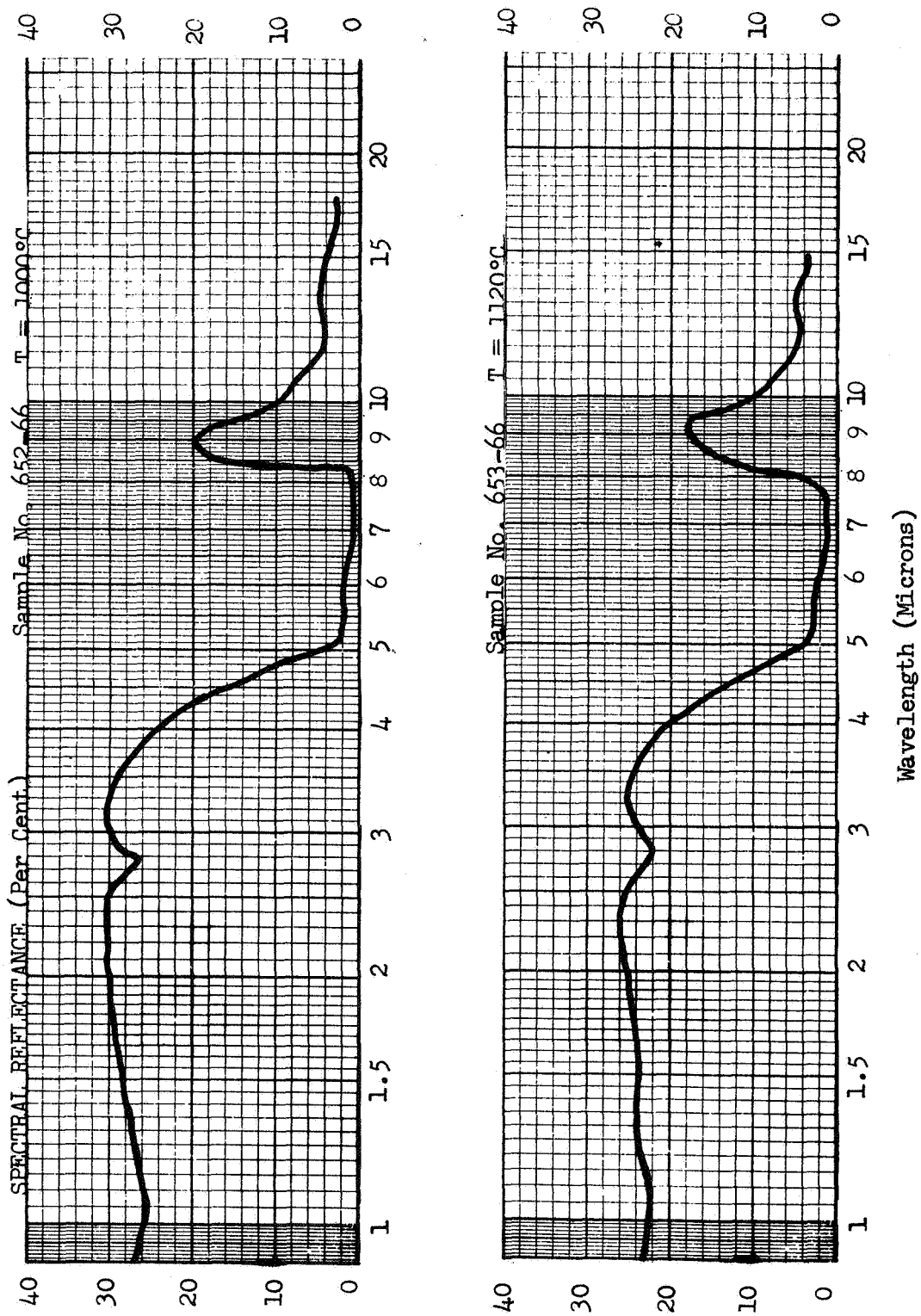


Figure 22 DIRECTIONAL SPECTRAL REFLECTANCE VERSUS TEMPERATURE OF MAGNESIUM HYDROXIDE (WBC 5217) VIRGIN ABLATIVE MATERIAL

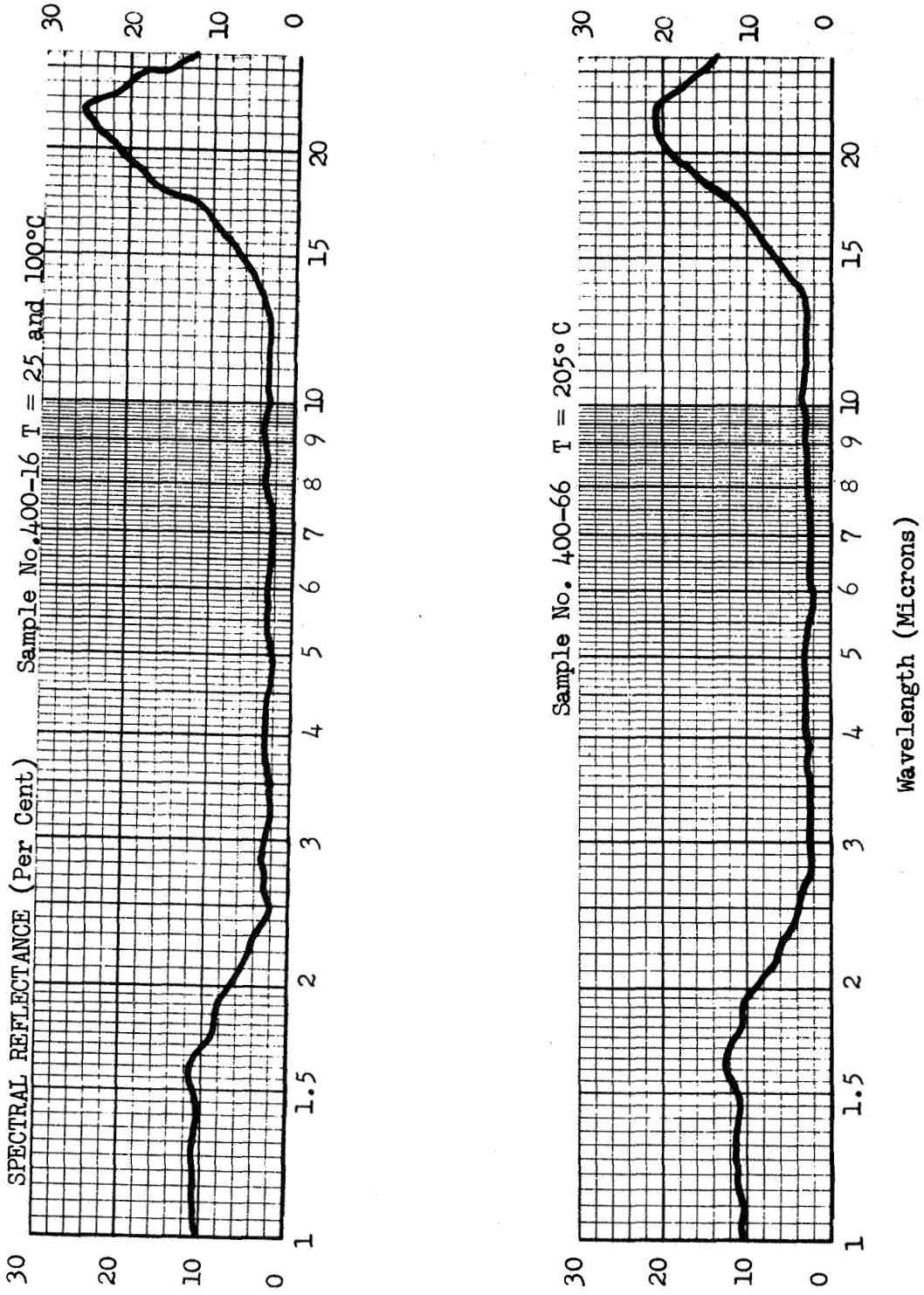


Figure 23

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS TEMPERATURE OF MAGNESIUM HYDROXIDE (WBC 5217) LABORATORY-CHARRED MATERIAL

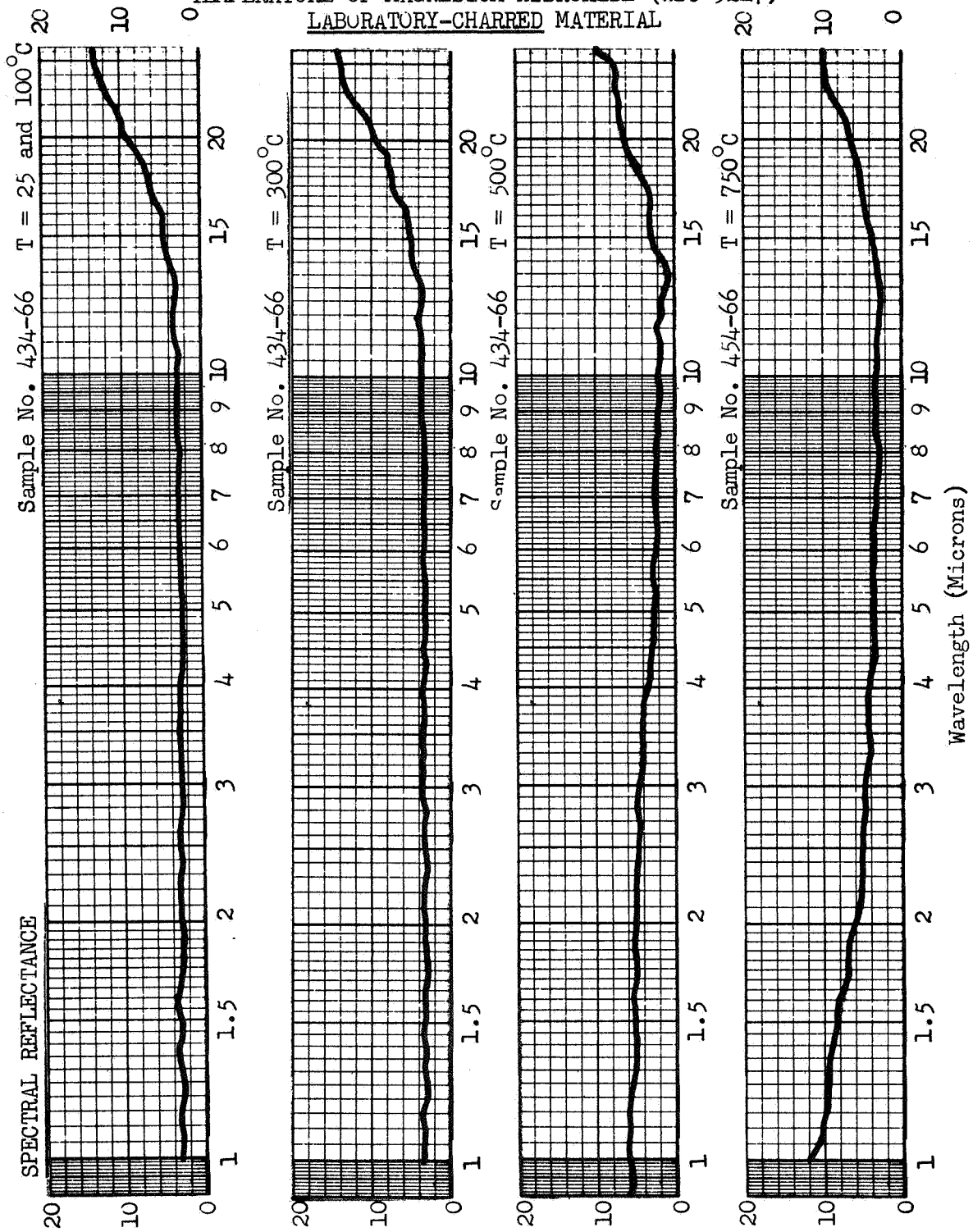
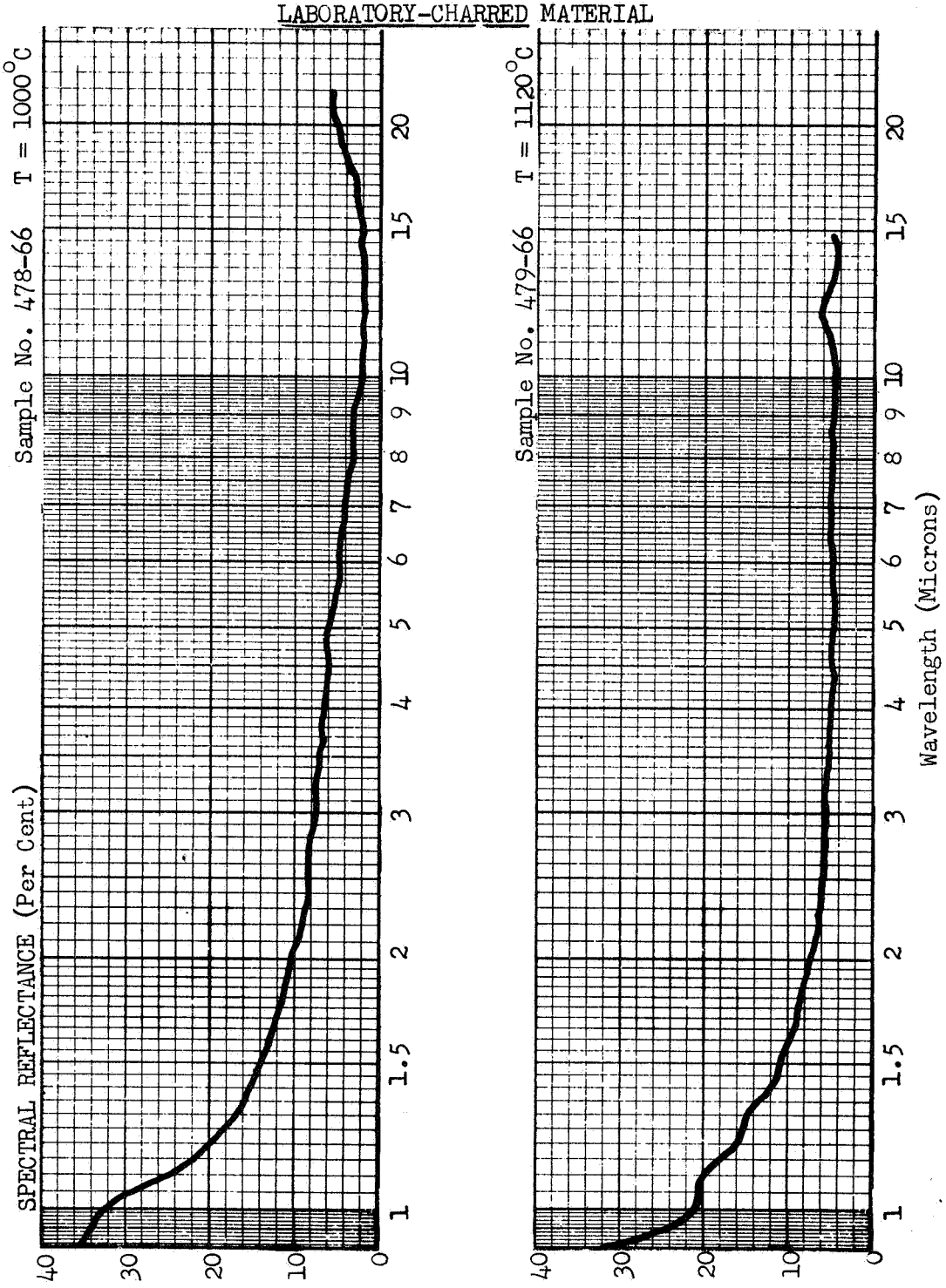


Figure 23 (Continued)

DIRECTIONAL SPECTRAL REFLECTANCE VERSUS
TEMPERATURE OF MAGNESIUM HYDROXIDE (WBC 5217)
LABORATORY-CHARRED MATERIAL