NATIONAL BUREAU OF STANDARDS REPORT

7834

STANDARDIZATION OF THERMAL EMITTANCE MEASUREMENTS

PROGRESS REPORT No. 17

October 1 - December 31, 1962

Contract No. DO (33-616) 61-02 Task No. 73603

AERONAUTICAL SYSTEMS DIVISION AIR FORCE SYSTEMS COMMAND UNITED STATES AIR FORCE WRIGHT-PATTERSON AIR FORCE BASE, OHIO



U. S. DEPARTMENT OF COMMERCE NATIONAL BUREAU OF STANDARDS

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NBS PROJECT

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The two phases of this project are conducted under the supervision of the following persons, who have approved this report.

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uson - William N. Harrison - Coordinator Chief. Metallic Building Materials Section, Building Research Division

to

AERONAUTICAL SYSTEMS DIVISION AIR FORCE SYSTEMS COMMAND UNITED STATES AIR FORCE WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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*See footnote on page 1.

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I. SUMMARY *

Most of the work during the report period was concentrated on improvement and overhaul of the data-processing attachment. By the end of the period most of the malfunctions had been corrected, but the equipment was still not functioning correctly in all respects.

A computer code was written to facilitate checking of the performance of the data-processing attachment.

II. INSTRUMENTATION

Spectrometer Maintenance

In order to ensure operation of the spectrometer at peak efficiency, all of the mirrors were removed, carefully cleaned and replaced. The entire optical system was then realigned. After this had been done, it became apparent that a diminution in sensitivity of the vacuum thermocouple detector required its replacement. A new detector was installed, and the removed detector returned to the factory for repair.

As a preliminary step to extending the wavelength range of experimental work to 38 microns, a new thermocouple detector having approximately four times the sensitivity of the one now used was ordered.

III. DATA-PROCESSING ATTACHMENT

The manufacturer had been informed of the deficiencies in the dataprocessing attachment, and sent an engineer to the Bureau to correct them. In the main, the difficulties consisted of unstable circuits which resulted in drift from the calibration settings of potentiometers controlling corrections of the zero and 100-percent lines. The trouble was found to be in the digital portions of the circuits. A number of changes were made to improve these functions. A mechanical difficulty, binding of the gears in in the correcting potentiometer drive mechanism, was also found and corrected.

Following these adjustments, the data-processing equipment operated satisfactorily for a time, after which intermittent trouble developed, which was manifested as unequal response of the stepping motors, to signals calling for change in one direction as compared to the other. This effect was found in both correcting circuits, and was traced to overheating of the motor-drive transistor, indicating excessive current through it. Normally the transistor should be kept at cutoff when it is not in operation, but continuous overheating indicated the cutoff was not effective. The difficulty could arise from leakage from a defect in the power transistor, incorrect bias in the preceding driver stage, improper circuit design, or a combination of causes. Each of these possibilities is being checked.

* The fifteenth quarterly progress report covered the period Jan. 1 -Mar. 31, 1962. Work done during the period April 1 - December 31, 1962 was covered and included in the summary report for the period July 1, 1958 through Oct. 31, 1962, WADC TR 59-510 Pt IV, which constitutes the sixteenth progress report. Some of the difficulties with the data-processing equipment were aggravated by noise in the spectrometer amplifier. Efforts to find a preamplifier with a lower noise level than that now used, have not so far been successful.

During a period of satisfactory operation the equipment was checked by use of the reference blackbody furnace and sector-disc attenuator simulating a graybody specimen having an emittance equal to the known transmission factor of 0.75. Curves were obtained which represented a graybody spectral distribution within \pm 0.01 of the known correct value over the spectral range of 1 to 15 microns.

The data-processing attachment has provision also for making punched-tape records that can be fed into separate computers to obtain various types of information. Use can be made of the punched-tape records to test the functioning of the equipment as follows: In addition to digitized records of the "zero line", the "100% line" and the uncorrected spectral emittance curve of the specimen, a fourth set of values is recorded on the punched tape, representing the emittance curve of the specimen as corrected concurrently with the test, by use of the magnetic tape, and recorded on the strip chart. This operation requires separate tests on the specimen, with and without correction.

During the report period a computer program was designed so that, from the four-channel punched-tape, the computer would: (1) apply corrections to the uncorrected emittance data, based on the "100% line" and "zero line" records, (2) compare the resulting corrected emittance values with the corresponding corrected values recorded on the punched tape during test through functioning of the magnetic tape, and (3) record the algebraic differences between the two sets of independently corrected data.

The computer program was tried, and was found to function, so that it could be used for the intended purpose. Several tapes had been recorded, ready for processing, at the end of the report period.

IV. WORKING STANDARDS OF NORMAL SPECTRAL EMITTANCE

Working standards of normal spectral emittance having low, intermediate and high emittance, respectively, were prepared, calibrated and transmitted to the Physics Laboratory, A.S.D., prior to the start of the current report period.

Detailed instructions for the handling and use of these standards were prepared and transmitted to the Applications Laboratory, A. S. D., during the current report period.

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V. EQUATIONS

The formulas for reflectivity were rewritten using new parameters which are combinations of the original parameters. An analysis of the equations indicated that the new parameters are more directly related to the geometric properties of the calculated reflectivity curve, and it is hoped that their use will facilitate the fitting of the observed reflectivity data. Existing programs were modified to permit use of the new parameters, and exploratory calculations were continued.

VI. WAVELENGTHS FOR 100 SELECTED ORDINATE COMPUTATIONS

The rigorous method of computing total normal emittance from spectral data may be expressed mathematically as follows:

$$E_{ts} = \frac{\int_{0}^{\infty} \epsilon_{b\lambda} E_{s\lambda} d\lambda}{\int_{0}^{\infty} \epsilon_{b\lambda} d\lambda}$$
(1)

where $E_{te} = total normal emittance of specimen$

- $s_{b\lambda}$ = rate of energy emission(radiant flux), per unit area, from a blackbody at the temperature of the specimen, within the wave-length interval λ to $(\lambda + d\lambda)$.
- $E_{s\lambda}$ = normal spectral emittance of the specimen at wavelength λ .

All computations from data are based upon finite intervals of wavelength, Δ .

The following equation applies:

$$E_{ts} \approx \frac{\lambda_{2}}{\sum_{\substack{\Sigma \\ \Sigma \\ \Sigma \\ \Sigma \\ \lambda_{1}}}} e_{b\lambda} \Delta \lambda$$
(2)

 λ_1 and λ_3 being selected to include substantially all of the flux emitted by a blackbody radiator at the test temperature.

In the weighted ordinate method, uniform values of $\Delta\lambda$ are used, and each value of $\mathcal{E}_{B\lambda}$ must be weighted by a factor proportional to $\epsilon_{b\lambda}$. This value of $\epsilon_{b\lambda}$ represents the area, within the wavelength interval λ to $(\lambda + \Delta\lambda)$, under the spectral distribution curve of radiant flux, from unit area of a blackbody radiator, at the test temperature.

In the 100-selected-ordinate method, the area under the spectral distribution curve for the radiant flux from a blackbody radiator at the test temperature is divided into 100 equal slices. The 100 selected ordinates are then the 100 median wavelengths for the 100 areas. In this case $\Delta\lambda$ varies, but the quantity $\epsilon_b\lambda\Delta\lambda$ is held constant at 0.01. Under these conditions equation (2) can be rewritten:

$$E_{ts} \approx 0.01 \sum_{\lambda_1}^{\lambda_{100}} E_{s\lambda}$$

In practice, any desired degree of precision in the computation of E_{ts} can be attained by either method by taking a sufficient number of ordinates. With any given number of ordinates, the computation error will be less by the selected ordinate method than by the weighted ordinate method. With solids, whose spectral emittance curves do not normally have sharp peaks or valleys, the 100 selected ordinate method gives values that have no significant computation error from this source.

(3)

The wavelengths representing the 100 selected ordinates were computed for temperatures of 600, 700, 800, 900, 1000, 1100, 1200, 1300 and 1400° K, and are given in Table I.

The 100 selected ordinates for temperatures of 800°, 1100°, 1300° and 1400°K were converted to digital form and punched on paper tape for use with the data-processing attachment to the normal spectral emittance equipment. TABLE I

WAVELENGTHS FOR COMPUTATION OF TOTAL EMITTANCE FROM SPECTRAL DATA BY THE 100-SELECTED ORDINATE METHOD

 λ in Microns at Temperature in ^{O}K of

1				~	~	~	_		~	~	~	~	.+		5	_		~	_	+	5	~	~		0		5
	1400	7 44	1.096	1.187	1.258	1.318	1.371	1.424	1.466	1.508	1.549	1.587	1.624	1.661	1.696	1.731	1.764	1.798	1.831	1.864	1.896	1.927	1.959	1.991	2.022	2.054	2.086
	1300	1.017	1.180	1.278	1.355	1.420	1.477	1.530	1.578	1.624	1.668	1.709	1.749	1.788	1.826	1.864	1.900	1.936	1.972	2.007	2.042	2.075	2.110	2.144	2.178	2.212	2.246
	1200	1.102	1.278	1.385	1.468	1.538	1.600	1.657	1.710	1.759	1.806	1.852	1.895	1.937	1.978	2.019	2.058	2.097	2.136	2.174	2.212	2.248	2.286	2.322	2.359	2.397	2.433
	1100	1.202	1.395	1.511	1.602	1.678	1.745	1.808	1.865	1.919	1.971	2.020	2.067	2.114	2.158	2.203	2.245	2.288	2.330	2.372	2.413 .	2.453	2.494	2.534	2.574	2.615	2.655
	1000	1.322	1.534	1.622	1.762	1.846	1.920	1.989	2.052	2.111	2.168	2.222	2.274	2.325	2.374	2.423	2.470	2.51.7	2.563	2.609	2.654	2.698	2.743	2.787	2.831	2.876	2.920
	006	1.469	1.704	1.847	1.958	2.051	2.133	2.210	2.280	2.346	2.409	2.469	2.527	2.583	2.638	2.692	2.744	2.797		2.899	2.949	2.998	3.048	3.097	3.146	3.196	3.244
	800	1.652	1.918	2.078	2.020	2.308	2.400	2.486	2.565	2.639	2.710	2.778	2.842	2.906	2.968	3.029	3.088	3.146	3.204	3.261	3.318	3.372	3.429	3.484	3.539	3.595	2.650
	700	1.889	2.191	2.374	2.517	2.637	2.743	2.841	2.931	3.016	3.097	3.174	3,249	3.321	3.391	3.461	3.529	3.596	3.662	3.727	3.792	3.854	3.919	3.982	4.044	4.109	4.172
	600	2.203	2.557	2.770	2.937	3.077	3.200	3.315	3.420	3.518	3.613	3.703	3.790	3.875	3.957	4.038	4.117	4.195	4.271	4.348	4.423	4.496	4.571	4.645	4.718	4.793	4.866
ž	°, 1	1322	1534	1662	1762	1846	1920	1989	2052	2111	2168	2222	2274	2325	2374	2423	2470	2517	2563	2609	2654	2698	2743	2787	2831	2876	2920
	₩	· 5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	21.5	2.5	23.5	24.5	25.5

TABLE I - continued

 λ in Microns at Temperature in ${}^{\rm O}{\rm K}$ of

2.117 2.149 2.180 2.212 2.576 2.611 2.647 2.684 2.758 2.758 2.758 2.758 2.758 2.874 2.874 2.914 2.244 2.276 2.308 2.341 2.341 2.341 2.406 2.439 2.473 2.507 2.542 1400 2.280 2.314 2.348 2.348 2.382 2.775 2.812 2.851 2.850 2.930 2.970 3.011 3.052 3.052 3.052 3.138 2.416 2.451 2.485 2.551 2.556 2.556 2.556 2.552 2.663 2.663 2.737 2.737 1300 2.507 2.543 2.581 2.617 2.655 2.655 2.692 2.731 2.769 2.807 2.865 2.885 2.925 2.925 2.965 3.006 3.047 3.088 3.131 3.174 3.217 3.217 3.217 3.217 3.252 3.352 3.352 3.359 1200 2.695 2.735 2.775 2.815 2.855 2.937 2.937 3.021 3.021 3.063 3.105 3.147 3.191 3.235 3.279 3.324 3.324 3.415 3.415 3.415 3.415 3.415 3.415 3.415 3.415 3.415 3.415 3.415 3.415 3.415 3.415 3.415 3.510 3.558 3.657 3.667 3.5788 1100 3.141 3.186 3.231 3.277 3.277 3.277 3.277 3.277 3.277 3.277 3.277 3.253 3.558 3.558 3.558 3.607 3.656 3.757 3.757 3.809 3.861 3.914 3.914 3.968 4.023 4.079 2.964 3.008 3.052 3.097 1000 4.008 4.062 4.118 4.174 4.232 4.232 4.232 4.470 4.470 4.532 3.293 3.342 3.391 3.441 3,490 3.540 3.550 3.641 3.641 3.642 3.743 3.743 3.847 3.900 3.953 906 3.705 3.760 3.815 3.871 4.509 4.570 4.570 4.632 4.696 4.826 4.826 4.826 4.826 5.029 5.029 3.926 3.982 4.039 4.036 4.154 4.211 4.269 4.328 4.388 4.448 800 4.234 4.297 4.360 4.424 4.487 4.552 4.616 4.682 4.682 4.747 4.813 4.813 4.813 4.813 4.813 4.813 4.813 5.014 5.014 5.033 5.152 5.294 5.294 5.367 5.441 5.441 5.516 5.669 5.747 5.827 700 4.940 5.013 5.086 5.161 6.011 6.093 6.176 6.261 6.348 6.435 6.435 6.435 6.523 6.613 6.705 6.705 600 3141 3231 3231 3231 3237 3323 3323 3415 3415 3415 3415 3415 3415 3510 3558 2964 3008 3052 3097 3607 3656 37556 3757 3757 3861 3914 3914 3968 3968 4023 4079 NT Por 26.5 27.5 28.5 29.5 30.5 31.5 32.5 33.5 34.5 34.5 336.5 336.5 337.5 338.5 337.5 40.5 41.5 441.5 441.5 444.5 444.5 446.5 447.5 447.5 447.5 447.5 49.5 49.5 17

TABLE I - continued

 λ in Microns at Temperature in $^{O}\mathrm{K}$ of

3.416 3.469 3.579 5.636 5.636 3.759 3.759 3.889 3.889 3.958 4.029 4.105 4.181 4.263 4.348 4.437 2.954 2.954 3.039 3.039 3.081 3.081 3.171 3.171 3.218 3.266 3.314 3.364 1400 3.182 3.226 3.272 3.318 3.318 3.415 3.415 3.465 3.465 3.465 3.569 3.569 3.569 3.678 3.735 3.735 3.735 3.735 3.735 3.736 3.916 3.916 3.981 4.048 4.116 4.1188 4.1188 4.339 4.419 4.503 4.591 4.682 4.778 1300 3.447 3.495 3.495 3.545 3.545 3.545 3.647 3.754 3.754 3.754 3.867 3.867 3.925 3.985 4.047 4.110 4.175 4.175 4.312 4.312 4.335 4.459 4.536 4.536 4.701 4.787 4.878 4.878 4.923 5.072 5.176 1200 3.750 3.813 3.813 3.867 3.922 3.979 4.036 4.095 4.156 4.218 4.218 4.347 4.415 4.484 4.555 4.628 4.705 4.705 4.784 4.865 4.945 5.037 5.037 5.128 5.223 5.322 5.425 5.533 1100 4.136 4.194 4.254 4.314 4.377 4.377 4.505 4.505 4.572 4.572 4.572 4.572 4.782 4.856 4.856 4.932 5.010 5.091 5.175 5.262 5.262 5.351 5.444 5.444 5.641 5.745 5.854 5.968 6.087 6.212 000 5.313 5.396 5.480 5.480 5.480 5.480 5.480 5.487 5.445 5.945 6.049 6.157 4.596 4.660 4.727 4.793 4.863 4.863 4.933 5.006 5.006 5.156 5.233 6.268 6.383 6.504 6.631 6.763 006 5.170
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TABLE I - continued

 λ in Microns at Temperature in $^{\text{O}}K$ of

yuo 1000 1100 1100 1200 1200 1200 7 7 6 6.343 5 7.66 5 286 4.879 7 7.374 6.783 6.166 5.652 5.218 4.986 7.374 6.783 6.166 5.730 5.479 5.7218 7.914 7.123 6.166 5.652 5.218 9.7311 6.475 5.936 5.479 5.749 9.142 8.311 6.646 6.092 5.624 8.591 7.732 7.029 6.443 5.9448 6.166 6.261 6.336 7.732 7.730 8.591 7.732 7.029 6.443 5.9448 7.732 7.371 6.2641 6.130 6.737 8.854 7.723 7.371 8.743 7.371 8.874 7.732 8.748 7.552 <td< th=""><th>NT 0</th><th></th><th></th><th>Cof</th><th></th><th>0000</th><th>0001</th><th>0011</th><th>000 5</th><th>000 1</th><th>1400</th></td<>	NT 0			Cof		0000	0001	0011	000 5	000 1	1400
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7.202 6.482 5.893 5.401 4.986 7.364 6.628 6.025 5.523 5.098 7.537 6.783 6.166 5.5523 5.098 7.514 6.316 5.5365 5.218 7.914 7.123 6.475 5.936 5.479 8.123 7.311 6.6446 6.092 5.479 8.123 7.311 6.6446 6.092 5.479 8.123 7.312 6.6445 6.092 5.479 8.123 7.732 7.029 6.443 5.948 8.591 7.732 7.029 6.443 5.948 8.854 7.969 7.245 6.641 6.130 9.459 8.513 7.729 6.791 5.948 9.459 8.513 7.739 7.094 6.548 9.459 8.513 7.739 7.094 6.548 9.459 8.8213 8.712 7.936 7.371 9.459 8.8213 8.712 7.986 7.371 9.4610 10.203 9.1298 7.371 10.648 9.583 8.712 7.986 7.371 11.752 10.042 9.129 8.316 7.371 11.752 10.042 9.129 8.316 7.371 11.752 10.042 9.129 8.316 7.371 11.752 10.926 11.939 10.021 11.752 10.926 11.932 14.413 12.936 $12.$	10.571 9.062	0.571 9.062	.062	7.9:	59	7.048	6.343	5.766	5.286	4.879	4.531
7.364 6.628 6.025 5.523 5.098 7.537 6.783 6.166 5.5652 5.218 7.914 7.123 6.475 5.936 5.479 8.123 7.311 6.646 6.092 5.479 8.123 7.311 6.646 6.092 5.652 5.218 8.123 7.311 6.646 6.092 5.479 8.123 7.311 6.646 6.092 5.479 8.3291 7.732 7.029 6.443 5.948 8.544 7.906 7.7245 6.641 6.130 9.459 8.513 7.029 6.641 6.130 9.459 8.513 7.732 7.024 6.641 6.130 9.459 8.513 7.739 7.094 6.548 6.548 9.459 8.513 7.739 7.094 6.548 6.731 9.142 8.228 7.739 7.094 6.548 6.731 9.183 8.712 7.986 7.371 7.064 10.203 9.183 8.712 7.986 7.371 11.752 10.042 9.129 8.813 8.136 7.725 11.752 10.0577 9.615 8.813 8.136 7.725 11.752 10.0577 9.129 8.813 8.136 7.725 11.752 10.0577 9.615 8.813 8.136 7.725 12.461 11.275 9.9996 9.9996 9.9926		0.803 9.260	.260	8.1(02	7.202	6.482	5.893	5,401	4.986	4.630
7.537 6.783 6.166 5.652 5.218 7.720 6.948 6.316 5.790 5.345 7.914 7.123 6.475 5.936 5.479 8.123 7.123 6.475 5.936 5.479 8.123 7.311 6.646 6.092 5.624 8.349 7.514 6.831 6.646 6.092 5.624 8.349 7.732 7.029 6.443 5.948 8.591 7.732 7.029 6.641 6.130 8.531 7.732 7.024 6.641 6.130 9.459 8.513 7.739 7.094 6.5329 9.459 8.513 7.739 7.094 6.548 9.459 8.513 7.739 7.094 6.548 9.459 8.026 7.357 6.791 $9.10.203$ 9.183 8.712 7.986 7.725 11.152 10.042 9.129 8.813 8.136 11.152 10.042 9.129 9.345 8.627 11.152 10.042 9.129 9.346 9.228 11.152 10.042 9.129 9.345 8.627 11.152 10.042 9.129 9.345 8.627 11.152 10.042 9.129 9.345 8.627 11.152 10.925 11.939 10.021 12.461 11.939 10.825 9.996 9.281 14.327 11.809 10.825 $14.$	11.046 9.469	1.046 9.469	.469	8.2	85	7.364	.6.628	6.025	5.523	5.098	4.734
7.720 6.948 6.316 5.790 5.345 7.914 7.123 6.475 5.936 5.479 8.123 7.311 6.6466 6.092 5.624 8.349 7.514 6.831 6.261 5.780 8.391 7.732 7.029 6.443 5.948 8.854 7.969 7.245 6.641 6.130 9.142 8.228 7.029 6.641 6.130 9.142 8.228 7.029 6.641 6.130 9.459 8.513 7.739 7.094 6.329 9.142 8.829 8.026 7.371 7.064 9.142 8.823 8.712 7.094 6.5329 9.143 9.583 8.712 7.094 6.548 $9.11.752$ 10.042 9.129 8.348 7.725 11.752 10.042 9.129 8.3136 7.725 11.752 10.042 9.129 8.3136 7.725 11.752 10.977 9.615 8.813 8.136 12.461 11.215 10.0195 9.996 9.228 11.752 10.9724 10.878 9.996 9.228 14.433 12.990 11.809 10.825 9.9925 14.433 12.990 11.809 10.825 9.9925 14.435 19.724 17.931 16.436 15.172 18.105 16.295 14.814 13.579 12.7294 18.105 19.724 <td>11.304 9.690</td> <td>.304 9.690</td> <td>.690</td> <td>8.4</td> <td>79</td> <td>7.537</td> <td>6.783</td> <td>6.166</td> <td>5.652</td> <td>5.218</td> <td>4.845</td>	11.304 9.690	.304 9.690	.690	8.4	79	7.537	6.783	6.166	5.652	5.218	4.845
7.720 6.948 6.316 5.790 5.345 7.914 7.123 6.475 5.936 5.479 8.123 7.311 6.6466 6.092 5.624 8.349 7.514 6.831 6.261 5.780 8.391 7.732 7.029 6.443 5.948 8.591 7.732 7.029 6.443 5.948 8.854 7.969 7.245 6.641 6.130 9.142 8.228 7.029 6.641 6.130 9.459 8.513 7.729 6.743 5.948 9.459 8.513 7.729 6.791 9.142 8.8228 7.739 7.094 6.548 9.459 8.513 7.739 7.094 6.791 9.459 8.513 7.729 7.064 7.725 10.203 9.183 8.712 7.986 7.725 11.752 10.042 9.129 8.813 8.136 11.752 10.0577 9.615 8.813 8.136 11.752 10.577 9.615 8.813 8.136 11.752 10.0577 9.615 8.813 8.136 12.461 11.215 10.195 9.345 8.627 11.752 10.0577 9.615 8.813 8.136 12.461 11.225 9.345 9.996 9.995 12.461 11.225 9.345 9.995 9.995 12.919 14.814 13.779 12.759											
7.9147.123 6.475 5.936 5.479 8.1237.311 6.6466 6.092 5.624 8.3497.514 6.831 6.261 5.780 8.5917.7327.029 6.443 5.948 8.5917.7327.029 6.443 5.948 9.4598.5137.029 6.443 5.948 9.4598.5137.7397.094 6.791 9.4598.5137.7397.094 6.548 9.4598.829 8.026 7.357 6.791 9.4598.813 8.712 7.9867.3719.142 8.829 8.026 7.357 6.791 9.183 8.712 7.9867.37110.2039.183 8.712 7.9867.75511.15810.0429.129 8.336 7.72511.15210.09579.0615 8.813 8.136 11.75210.05779.0129 8.336 7.72512.46111.21510.1959.345 9.996 12.46111.21510.1959.345 9.996 12.46111.21510.1959.345 9.996 12.46111.21510.1959.345 9.996 12.46111.21510.1959.345 9.996 12.46111.93910.8789.99613.32914.43312.99011.80914.43314.32713.02514.47615.91914.32713.02514.47618.105 <td< td=""><td>11.580 9.926</td><td>.580 9.926</td><td>.926</td><td>8</td><td>685</td><td>7.720</td><td>6.948</td><td>6.316</td><td>5.790</td><td>5.345</td><td>4.963</td></td<>	11.580 9.926	.580 9.926	.926	8	685	7.720	6.948	6.316	5.790	5.345	4.963
8.123 7.311 6.646 6.092 5.624 8.591 7.514 6.831 6.261 5.780 8.591 7.732 7.029 6.443 5.948 8.591 7.732 7.029 6.441 6.130 8.591 7.732 7.029 6.443 5.948 8.854 7.969 7.245 6.641 6.130 9.459 8.513 7.739 7.094 6.548 9.459 8.513 7.739 7.094 6.548 9.459 8.026 7.357 6.791 9.10.203 9.183 8.712 7.986 7.371 10.203 9.183 8.712 7.986 7.725 11.158 10.042 9.129 8.386 7.725 11.152 10.042 9.129 8.386 7.725 11.155 10.042 9.129 8.3136 7.725 11.155 10.042 9.129 8.3136 7.725 12.461 11.215 10.042 9.129 9.345 8.627 12.461	11.871 10.176	1.871 10.176	0.176	0	904	7.914	7.123	6.475	5.936	5.479	5.088
8.349 7.514 6.831 6.261 5.780 8.591 7.732 7.029 6.443 5.948 8.854 7.969 7.245 6.641 6.130 9.142 8.513 7.245 6.641 6.130 9.459 8.513 7.245 6.641 6.130 9.459 8.513 7.739 7.094 6.548 9.459 8.513 7.739 7.094 6.548 9.459 8.829 8.026 7.357 6.791 10.203 9.183 8.712 7.986 7.371 10.204 9.583 8.712 7.952 7.064 11.158 10.042 9.129 8.386 7.725 11.152 10.042 9.129 8.313 8.136 11.152 10.042 9.129 8.813 8.627 11.152 10.042 9.129 8.813 8.627 12.461 11.296 10.1955 9.345 8.627 13.329 11.996 10.878 9.9996 9.228 14.433	12.185 10.444	2.185 10.444.	0.444	9.1	39	8.123	7.311	6.646	6.092	5.624	5.222
8.591 7.732 7.029 6.443 5.948 8.854 7.969 7.245 6.641 6.130 9.142 8.228 7.480 6.856 6.329 9.459 8.513 7.739 7.094 6.548 9.459 8.513 7.739 7.094 6.548 9.459 8.813 8.026 7.357 6.791 9.459 8.513 7.739 7.094 6.548 9.459 8.026 7.357 6.791 10.203 9.183 8.026 7.357 6.791 10.203 9.183 8.712 7.986 7.371 11.158 10.042 9.129 8.336 7.371 11.158 10.042 9.129 8.3136 7.725 11.752 10.0577 9.615 8.813 8.627 11.752 10.0577 9.615 8.813 8.627 11.752 10.0577 9.615 8.813 8.627 12.461 11.215 10.1955 9.345 8.627 12.461 11.215 10.1955 9.345 9.996 14.433 12.990 11.809 10.825 9.9956 14.433 12.990 11.809 10.825 9.9956 14.433 12.990 11.809 10.825 9.9956 14.433 16.295 14.814 13.579 12.535 15.915 19.724 17.931 16.476 22.594 21.915 19.724 $17.$	735	2.523 10.735	0.735	9.3	92	8.349	7.514	6.831	6.261	5.780	5.367
8.854 7.969 7.245 6.641 6.130 9.142 8.513 7.739 7.094 6.329 9.459 8.513 7.739 7.094 6.548 9.459 8.513 7.739 7.094 6.548 9.459 8.829 8.026 7.357 6.791 9.810 8.829 8.026 7.357 6.791 10.203 9.183 8.712 7.986 7.371 11.158 10.042 9.129 8.386 7.7725 11.152 10.042 9.129 8.813 8.136 11.152 10.042 9.129 8.813 8.136 11.152 10.0577 9.615 8.813 8.136 11.152 10.0577 9.129 8.336 7.725 12.461 11.215 10.195 9.5615 8.238 12.461 11.215 10.195 9.345 8.627 13.329 11.996 10.878 9.9966 9.228 14.433 12.990 11.809 10.825 9.9995 1	12.886 11.046	2.886 11.046	1.046	9.6	65	8.591	7.732	7.029	6.443	5.948	5.523
9.142 8.228 7.480 6.856 6.329 9.459 8.513 7.739 7.094 6.548 9.459 8.513 7.739 7.094 6.548 9.459 8.513 7.739 7.357 6.791 9.459 8.813 8.712 7.357 6.791 10.203 9.183 8.712 7.357 6.791 10.203 9.583 8.712 7.352 7.371 11.158 10.042 9.129 8.386 7.725 11.152 10.042 9.129 8.336 7.725 11.752 10.042 9.129 8.336 7.725 11.752 10.042 9.129 8.336 7.725 12.461 11.215 10.195 9.345 8.627 12.461 11.215 10.195 9.345 8.627 13.329 11.996 11.809 10.825 9.992 14.433 12.990 11.809 10.825 9.9925	13.281 11.385	3.281 11.385	1.385	9.6	61	8.854	7.969	7.245	6.641	6.130	5.692
9.459 8.513 7.739 7.094 6.548 9.810 8.829 8.026 7.357 6.791 10.203 9.183 8.348 7.652 7.064 10.203 9.183 8.712 7.986 7.371 11.158 10.042 9.1129 8.813 8.136 11.158 10.042 9.129 8.813 8.136 11.752 10.0577 9.615 8.813 8.136 11.752 10.042 9.129 8.813 8.136 11.752 10.0577 9.615 8.813 8.136 12.461 11.215 10.195 9.345 8.627 13.329 11.996 10.878 9.345 8.627 13.329 11.809 10.878 9.395 9.228 14.433 12.990 11.809 10.825 9.9955 15.919 14.327 13.025 11.939 10.021 18.105 16.295 14.814 13.579 12.535 21.915 19.724 17.931 16.436 15.172 <t< td=""><td>13.712 11.755</td><td>3.712 11.755</td><td>1.755</td><td>10.2</td><td>85</td><td>9.142</td><td>8.228</td><td>7.480</td><td>6.856</td><td>6.329</td><td>5.877</td></t<>	13.712 11.755	3.712 11.755	1.755	10.2	85	9.142	8.228	7.480	6.856	6.329	5.877
9.810 8.829 8.026 7.357 6.791 10.203 9.183 8.348 7.652 7.064 10.203 9.183 8.712 7.986 7.371 11.158 10.042 9.129 8.386 7.371 11.158 10.042 9.129 8.813 8.136 11.752 10.042 9.129 8.813 8.136 11.752 10.042 9.129 8.813 8.136 11.752 10.0577 9.615 8.813 8.136 11.752 10.0577 9.615 8.813 8.136 12.461 11.215 10.195 9.345 8.627 13.329 11.996 10.878 9.996 9.228 14.433 12.990 11.809 10.825 9.9956 9.228 15.919 14.327 13.025 11.939 10.021 18.105 16.295 14.814 13.579 12.535 21.915 19.724 17.931 16.436 15.172 32.635 29.372 26.702 24.476 22.5	14.188 12.162	4.188 12.162	2.162	10.6	41	9.459	8.513	7.739	7.094	6.548	6.081
10.203 9.183 8.348 7.652 7.064 10.648 9.583 8.712 7.986 7.371 11.158 10.042 9.129 8.386 7.725 11.158 10.042 9.129 8.386 7.725 11.752 10.042 9.129 8.386 7.725 11.752 10.0577 9.615 8.813 8.136 12.461 11.215 10.195 9.345 8.627 13.329 11.996 10.878 9.996 9.228 13.329 11.996 10.878 9.9966 9.228 14.433 12.990 11.809 10.825 9.9922 15.919 14.327 13.025 11.939 10.021 18.105 16.295 14.814 13.579 12.535 21.915 19.724 17.931 16.436 15.172 32.635 29.372 26.702 24.476 22.594	14.714 12.613	4.714 12.613	2.613	11.0	36	9.810	8.829	8.026	7.357	6.791	6.306
10.648 9.583 8.712 7.986 7.371 11.158 10.042 9.129 8.336 7.725 11.158 10.042 9.129 8.336 7.725 11.752 10.0577 9.615 8.813 8.136 11.752 10.0577 9.615 8.813 8.136 12.461 11.215 10.195 9.345 8.627 13.329 11.996 10.878 9.3956 9.228 14.433 12.990 11.809 10.825 9.9956 9.228 14.433 12.990 11.809 10.825 9.9995 9.9925 15.919 14.327 13.025 11.939 10.021 18.105 16.295 14.814 13.579 12.535 21.915 19.724 17.931 16.436 15.172 32.635 29.372 26.702 24.476 22.594	15.304 13.119	5.304 13.119	3.119	11.4	19	10.203	9.183	8.348	7.652	7.064	6.559
$\begin{array}{cccccccccccccccccccccccccccccccccccc$									-		
11.158 10.042 9.129 8.386 7.725 11.752 10.577 9.615 8.813 8.136 12.461 11.215 10.195 9.345 8.627 13.329 11.996 10.878 9.996 9.228 14.433 12.990 11.809 10.825 9.992 14.433 12.990 11.809 10.825 9.992 14.433 12.990 11.809 10.825 9.992 15.919 14.327 13.025 11.939 10.021 18.105 16.295 14.814 13.579 12.535 21.915 19.724 17.931 16.436 15.172 32.635 29.372 26.702 24.476 22.594	15.971 13.690	.971 13.690	.690	11.0	979	10.648	9.583	8.712	7.986	7.371	6.845
11.752 10.577 9.615 8.813 8.136 12.461 11.215 10.195 9.345 8.627 13.329 11.996 10.878 9.996 9.228 14.433 12.990 11.809 10.825 9.992 14.433 12.990 11.809 10.825 9.992 15.919 14.327 13.025 11.939 10.021 18.105 16.295 14.814 13.579 12.535 21.915 19.724 17.931 16.436 15.172 32.635 29.372 26.702 24.476 22.594	16.736 14.346	.736 14.346	.346	12.5	52	11.158	10.042	9.129	8.386	7.725	7.173
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	10577 17.628 15.110 13.3	.628 15.110	.110	13.	221	11.752	10.577	9.615	8.813	8.136	7.555
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	18.524 16.022	.524 16.022	.022	14.0	119	12.461	11.215	10.195	9.345	8.627	8.011
14.433 12.990 11.809 10.825 9.992 15.919 14.327 13.025 11.939 10.021 15.919 14.327 13.025 11.939 10.021 18.105 16.295 14.814 13.579 12.535 21.915 19.724 17.931 16.436 15.172 32.635 29.372 26.702 24.476 22.594	19.993 17.137	.993 17.137	.137	14.9	95	13.329	11.996	10.878	966.6	9.228	8.569
15.919 14.327 13.025 11.939 10.021 18.105 16.295 14.814 13.579 12.535 21.915 19.724 17.931 16.436 15.172 32.635 29.372 26.702 24.476 22.594	21.649 18.558	.649 18.558	.558	16.2	38	14.433	12.990	11.809	10.825	9.992	9.278
18.105 16.295 14.814 13.579 12.535 21.915 19.724 17.931 16.436 15.172 32.635 29.372 26.702 24.476 22.594	23.877 20.468	.877 20.468	.468	17.9	60	15.919	14.327	13.025	11.939	10.021	10.233
21.915 19.724 17.931 16.436 15.172 32.635 29.372 26.702 24.476 22.594	27.157 23.279	.157 23.279	.279	20.3	369	18.105	16.295	14.814	13.579	12.535	11.639
32.635 29.372 26.702 24.476 22.594	.872 28.178	.872 28.178	.178	24.	655	21.915	19.724	17.931	16.436	15.172	14.088
	48.951 41.961	.951 41.961	.961	36.	715	32.635	29.372	26.702	24.476	22.594	20.980

 $\underline{1}$ The wavelength λ is chosen so that the indicated percentage of blackbody radiation occurs at wavelengths shorter than the indicated wavelength. Expressed mathematically

 $\int_{0}^{\lambda} E_{B\lambda} d\lambda \quad X \quad 100 =$

20

NATIONAL BUREAU OF STANDARDS

A. V. Astin, Director



THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its major laboratories in Washington, D.C., and Boulder, Colorado, is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside of the front cover.

WASHINGTON, D.C.

Electricity. Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. Dielectrics. High Voltage.

Metrology. Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. Mass and Scale. Volumetry and Densimetry.

Heat. Temperature Physics. Heat Measurements. Cryogenic Physics. Equation of State. Statistical Physics. Radiation Physics. X-ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. Nucleonic Instrumentation. Neutron Physics.

Analytical and Inorganic Chemistry. Pure Substances. Spectrochemistry. Solution Chemistry. Standard Reference Materials. Applied Analytical Research. Crystal Chemistry.

Mechanics, Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Rheology. Combustion Controls.

Polymers. Macromolecules: Synthesis and Structure. Polymer Chemistry. Polymer Physics. Polymer Characterization. Polymer Evaluation and Testing. Applied Polymer Standards and Research. Dental Research.

Metallurgy. Engineering Metallurgy. Microscopy and Diffraction. Metal Reactions. Metal Physics. Electrolysis and Metal Deposition.

Inorganic Solids. Engineering Ceramics. Glass. Solid State Chemistry. Crystal Growth. Physical Properties. Crystallography.

Building Research. Structural Engineering. Fire Research. Mechanical Systems. Organic Building Materials. Codes and Safety Standards. Heat Transfer. Inorganic Building Materials. Metallic Building Materials.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics. Operations Research.

Data Processing Systems. Components and Techniques. Computer Technology. Measurements Automation. Engineering Applications. Systems Analysis.

Atomic Physics. Spectroscopy. Infrared Spectroscopy. Far Ultraviolet Physics. Solid State Physics. Electron Physics. Atomic Physics. Plasma Spectroscopy.

Instrumentation. Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instruments. Basic Instrumentation.

Physical Chemistry. Thermochemistry. Surface Chemistry. Organic Chemistry. Molecular Spectroscopy. Elementary Processes. Mass Spectrometry. Photochemistry and Radiation Chemistry.

Office of Weights and Measures.

BOULDER, COLO.

Cryogenic Engineering Laboratory. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Cryogenic Technical Services.

CENTRAL RADIO PROPAGATION LABORATORY

Ionosphere Research and Propagation. Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services. Vertical Soundings Research.

Radio Propagation Engineering. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.

Radio Systems. Applied Electromagnetic Theory. High Frequency and Very High Frequency Research. Frequency Utilization. Modulation Research. Antenna Research. Radiodetermination.

Upper Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics. High Latitude Ionosphere Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

RADIO STANDARDS LABORATORY

Radio Physics. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time-Interval Standards. Radio Plasma. Millimeter-Wave Research.

Circuit Standards. High Frequency Electrical Standards. High Frequency Calibration Services. High Frequency Impedance Standards. Microwave Calibration Services. Microwave Circuit Standards. Low Frequency Calibration Services.

