NBS TECHNICAL NOTE

417

Spectral Emission Properties of NBS Standard Phosphor Samples Under Photo-Excitation

U.S. DEPARTMENT OF COMMERCE
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Carl F. Shelton

Metrology Division
Institute for Basic Standards
National Bureau of Standards
Washington, D.C. 20234

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SPECTRAL EMISSION PROPERTIES OF NBS STANDARD PHOSPHOR SAMPLES UNDER PHOTO-EXCITATION

Carl F. Shelton*

The photo-excitation spectral emission properties of 10 of the 14 NBS standard phosphor samples have been determined. Pressed tablets of the phosphors were excited by radiation from a mercury arc lamp, passing through a narrow band-pass filter to obtain either 2537Å or 3650Å excitation. The measurement system is described, correction of the data is discussed, and the spectral emission data are presented. Relative quantum efficiencies were calculated. The results are compared with measurements reported by two other laboratories.

Key Words: Phosphors, photo-excitation, photoluminescence, spectral emission, spectral radiometry, standard phosphor samples.

1. Introduction

The spectral emission properties of ten NBS standard phosphor samples under ultraviolet excitation have been measured. The phosphors and the exciting radiation used are listed in Table I. The relative quantum efficiencies of the 2537Å excited phosphors were calculated relative to magnesium tungstate from the data obtained.

The purpose of this report is to describe the measurement technique used, to discuss a computer program written to reduce the raw data, and to present the results obtained.

2. Measurement Technique

Measurements of the relative spectral emission of the phosphor samples under photo-excitation were made with the equipment shown in Figure 1. The phosphor powder sample to be measured was placed in a small cup made of aluminum (1.25 inches in diameter and approximately 0.04 inch deep) and pressed level by using a spatula. This phosphor plaque was then placed on a turret sample holder mounted horizontally in front of the monochromator which was mounted vertically.

A 4-watt low-pressure mercury-arc lamp (germicidal) was used as source for 2537Å excitation with a filter (Corning No. 9863) in front of the lamp to block the mercury lines in the visible region. A 100-watt high-pressure mercury-arc lamp with a narrow-band-pass filter centered at 3650Å, in front

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*Research Associate from the International Business Machines Corporation at the National Bureau of Standards, 1967.

TABLE I

NBS Standard Sample Phosphors

Sample No.	Measurement Excitation (Å)	Phosphor Description	Use
1020	3650	Zinc Sulfide ZnS:Ag	Blue Component of P-4 Cathode Ray Tube (CRT) Phosphor
1021	2537	Zinc Silicate Zn_2SiO_4:Mn	P-1 CRT Phosphor
1022	3650	Zinc Sulfide ZnS:Cu	P-2 CRT Phosphor
1023	3650	Zinc-Cadmium Sulfide ZnCdS:Ag	Yellow Component of P-4 CRT Phosphor
1024	3650	Zinc-Cadmium Sulfide ZnCdS:Cu	Orange Component of P-14 CRT Phosphor
1025	----(1)	Zinc Phosphate $Zn_3(PO_4)_2$:Mn	Red Component of P-22 CRT Phosphor
1026	2537	Calcium Tungstate $CaWO_4$:Pb	CRT, Lamps
1027	2537	Magnesium Tungstate $MgWO_4$	CRT, Lamps
1028	2537	Zinc Silicate Zn_2SiO_4:Mn	Lamps
1029	2537	Calcium Silicate $CaSiO_3$:Pb,Mn	Lamps
1030	----(2)	Magnesium Arsenate $(MgO)_x(As_2O_5)_y$:Mn	Lamps
1031	2537	Calcium Halophosphate $3Ca_3(PO_4)\cdot Ca(F,Cl)$:Sb,Mn	Lamps
1032	----(3)	Barium Silicate $BaSi_2O_5$:Pb	Lamps (UV)
1033	----(3)	Calcium Phosphate $Ca_3(PO_4)_2$:Tl	Lamps (UV)

(1) Would not emit under 2537Å or 3650Å excitation

(2) Fine emission structure not resolved with 5Å pass band of monochromator used; results not reported

(3) Not measured.

of the lamp, was used as a source of 3650Å excitation. The output of the monochromator was measured by using a photomultiplier tube (PMT) with an S-20 photocathode (Dumont EM2433), an amplifier or a picoammeter, and a digital voltmeter as shown in Figure 1.

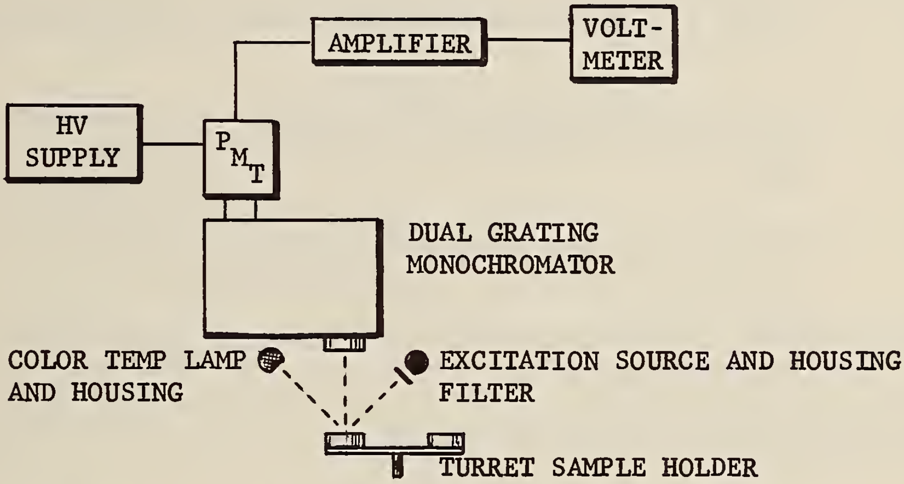

Figure 1 Spectral Measurement Equipment

In order to calibrate the monochromator and PMT combination, its relative spectral sensitivity was measured by using an NBS color temperature standard operated at a color temperature of 2854K. A USP grade barium sulfate (standard reflector) plaque was placed on the turret sample holder so that it could be rotated into position in front of the entrance slit of the monochromator. The spectral radiant flux of the color temperature standard, as diffusely reflected by the plaque, was used to calibrate the equipment.

A measurement of the phosphor sample consisted of setting the monochromator at a particular wavelength (scale readable to three places), and recording the digital voltage reading; first, with the color temperature lamp and the $BaSO_4$ plaque; and second, with the excitation source and the phosphor sample in front of the entrance slit. Both lamps were housed and shuttered such that they could be left on continuously during a data run and used independently. The wavelength scale on the monochromator was verified by using the mercury lines in the low pressure excitation source.

3. Computer Correction of Data

A computer program was used to calculate the relative spectral sensitivity of the instrument for each run and to apply calibration corrections to the data obtained in order to obtain the relative spectral distribution of the phosphor photo-luminescence for each data run. The corrected phosphor relative radiant energy distribution curves for several independent runs were then averaged over the number of runs to provide an average curve for each phosphor measured.

The following quantities are defined:

N ≡ Number of data runs for each phosphor

λ_j ≡ Wavelength value: $j = 1, \ldots, 20$

$S_i(\lambda_j)$ ≡ Relative sensitivity of instrument for the i-th data run $i = 1, \ldots, N$

$C_i(\lambda_j)$ ≡ Digital voltage reading when using color temperature lamp and $BaSO_4$ plaque for the i-th data run at the j-th wavelength value

$L(\lambda_j)$ ≡ Relative spectral luminance of $BaSO_4$ plaque when irradiated by color temperature standard (2854K).

$D_i(\lambda_j)$ ≡ Digital voltage reading when using excitation source and phosphor plaque.

Thus, since $C_1(\lambda_j)$ is by definition

$$C_1(\lambda_j) = S_i(\lambda_j)\, L(\lambda_j), \tag{1}$$

the relative spectral sensitivity for the i-th data run is therefore

$$S_i(\lambda_j) = \frac{C_i(\lambda_j)}{L(\lambda_j)} \tag{2}$$

also by definition,

$$D_i(\lambda_j) = S_i(\lambda_j)\, P_i(\lambda_j) \tag{3}$$

where:

$P_i(\lambda_j)$ ≡ Relative radiant energy distribution of the phosphor for i-th data run.

Therefore,

$$P_i(\lambda_j) = \frac{D_i(\lambda_j)}{S_i(\lambda_j)} = \frac{D_i(\lambda_j)\, L(\lambda_j)}{C_i(\lambda_j)} \tag{4}$$

and the normalized distribution curve is given by,

$$NP_i(\lambda_j) = \frac{P_i(\lambda_j)}{P_{i_{Max}}} \tag{5}$$

where:

$P_{i_{Max}}$ ≡ Maximum value of $P_i(\lambda_j)$ for $j = 1, \ldots, 20$

and the average relative energy distribution over the N data runs for each phosphor is finally

$$P_{ave}(\lambda_j) = \frac{\sum_{i=1}^{N} NP_i(\lambda_j)}{N} \tag{6}$$

3.1. Results

The relative energy distribution curves obtained for the ten phosphors measured are shown in figures 2 to 11. Each figure is followed by its computer output data, in Tables 2 to 11, showing the tabular values for each curve. The average curve for each phosphor is plotted and the tabular values are given on each curve. The tabular values shown are 95% confidence interval estimates of the true mean, calculated as:

$$\bar{x} \pm \tau_n w$$

where: w = range (maximum value minus minimum value)
n = sample size
$\bar{x}$ = computed mean of sample

and values of τ_n are given in Table 8c(1), page 408, of Ref. 5.

The relative energy distribution curves obtained for Sample Nos. 1020, 1022, 1023 and 1024 with photo-excitation are compared with data obtained with cathode-ray excitation by Bril (Ref. 2). Sample 1022 is a P-2 phosphor and the JEDEC P-2 data (Ref 3) is compared with the results obtained with photo-excitation.

The relative energy distribution curves obtained for Sample Nos. 1021 and 1026 with 2537 Å excitation are compared with results obtained by Bril (Ref 1) also with 2537 Å excitation. While Sample No. 1021 compares very closely with Bril's data, Sample No. 1026 shows some differences. Sample Nos. 1026 and 1029 have been compared with data obtained in 1961 by Dr. Frank J. Studer at the Nela Park Laboratory of the General Electric Company (now at NBS). The two sets of data are in close agreement. Since Sample No. 1021 is a P-1 phosphor, the JEDEC P-1 curve is also plotted from Ref. 3.

The difference shown in comparing the results obtained with photo- and cathode-ray excitation are the same order of magnitude as the differences noted above obtained for Sample No. 1026 from data obtained with only photo-excitation, e.g., compare results for Sample No. 1024 where the results of photo and cathode ray excitation are shown, with Sample No. 1026. One might therefore hypothesize that the spectral emission curves are independent of the excitation used, but this hypothesis requires further investigation.

The tabular results show the repeatability of the measurements. In general, the results obtained with the low-pressure mercury-arc lamp (2537 Å excitation) are more repeatable than those obtained with the high-pressure lamp (3650Å excitation) because of greater fluctuations of the output of the latter lamp.

Other measurement problems and sources of uncertainty include the low resolution of the wavelength scale on the monochromator (readable to only three places), the incomplete blocking of the mercury lines by the filter (preventing accurate readings near 4000 Å with 2537 Å excitation source), and the variations in the physical repositioning of the sample with the turret mount between data points.

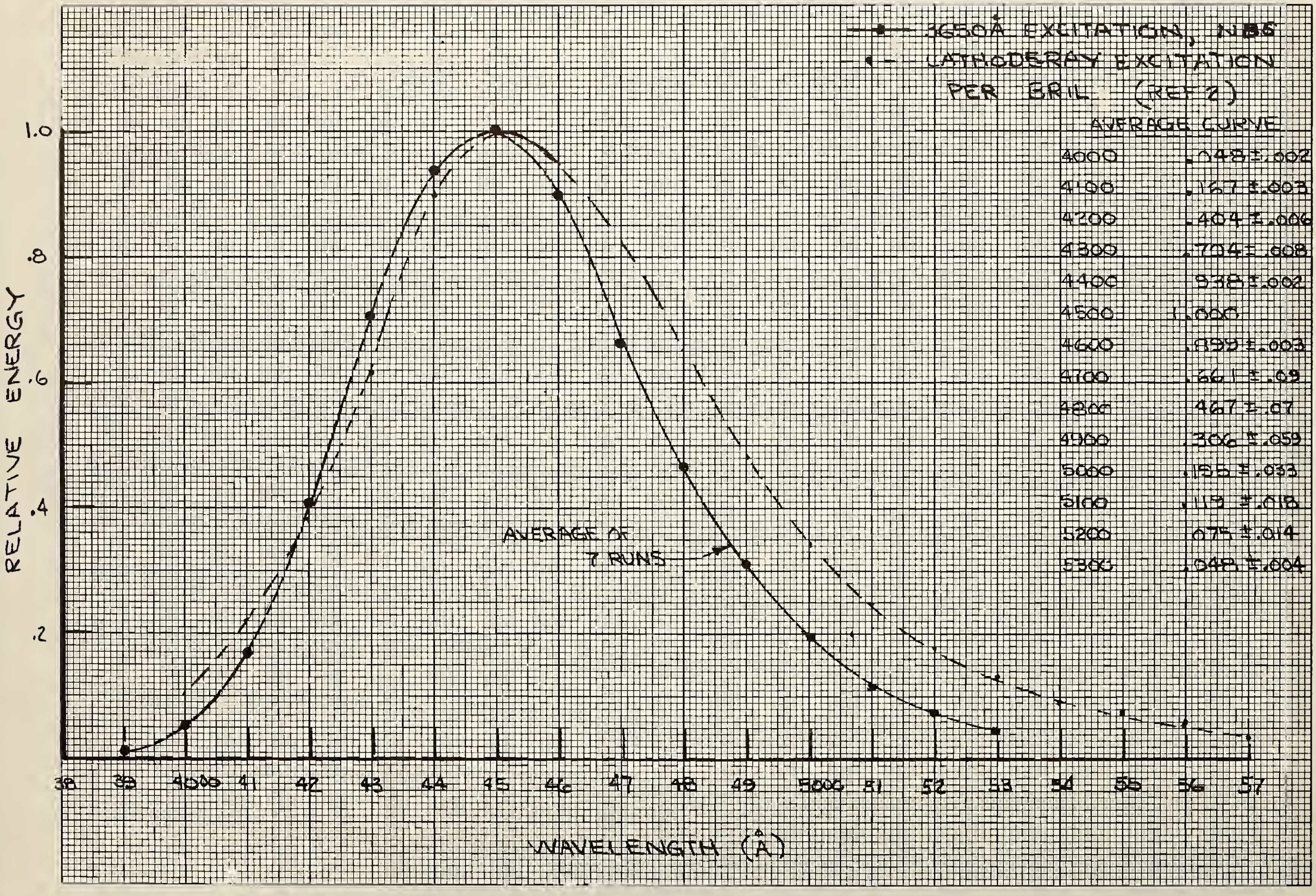

Figure 2. Relative Spectral Energy of Phosphor NBS 1020, Zinc Sulfide, ZnS:Ag

Table 2. Computer Printout of Relative Spectral Energy of Phosphor NBS 1020, Zinc Sulfide, ZnS:Ag

WAVE LENGTH	**NORMALIZED CURVES**							AVERAGE
3800	0.007	0.006	0.007	0.006	0.006	0.006	0.006	0.006
3900	0.011	0.010	0.011	0.012	0.012	0.012	0.012	0.011
4000	0.044	0.045	0.047	0.050	0.050	0.050	0.050	0.048
4100	0.162	0.164	0.163	0.172	0.170	0.171	0.168	0.167
4200	0.399	0.402	0.395	0.405	0.412	0.410	0.406	0.404
4300	0.703	0.690	0.699	0.707	0.713	0.713	0.705	0.704
4400	0.935	0.936	0.936	0.940	0.940	0.941	0.938	0.938
4500	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
4600	0.897	0.897	0.899	0.897	0.907	0.899	0.899	0.899
4700	0.704	0.438	0.709	0.699	0.687	0.694	0.695	0.661
4800	0.491	0.296	0.490	0.489	0.496	0.506	0.498	0.467
4900	0.329	0.158	0.334	0.325	0.336	0.331	0.332	0.306
5000	0.211	0.112	0.209	0.206	0.208	0.209	0.208	0.195
5100	0.124	0.075	0.130	0.129	0.119	0.129	0.130	0.119
5200	0.076	0.044	0.086	0.080	0.079	0.079	0.079	0.075
5300	0.048	0.038	0.051	0.048	0.049	0.049	0.050	0.048

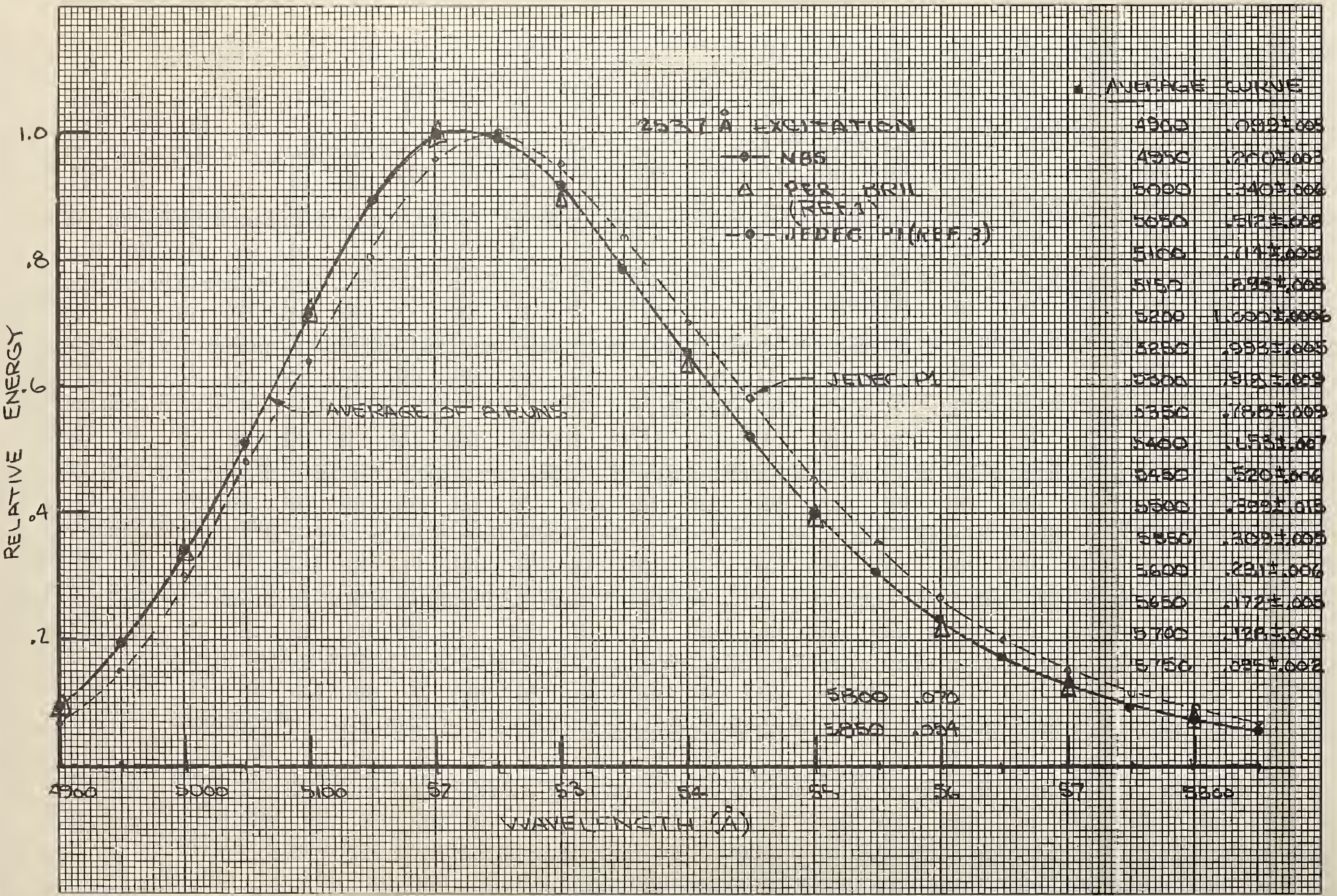

Figure 3. Relative Spectral Energy of Phosphor NBS 1021, Zinc Silicate, $ZnSiO_4$:Mn

Table 3. Computer Printout of Relative Spectral Energy of Phosphor NBS 1021, Zinc Silicate, $ZnSiO_4$:Mn

WAVE LENGTH	**NORMALIZED CURVES**							AVERAGE
4900	0.100	0.098	0.097	0.102	0.104	0.099	0.087	0.105	0.099
4950	0.200	0.203	0.200	0.204	0.198	0.198	0.193	0.202	0.200
5000	0.347	0.342	0.329	0.342	0.345	0.333	0.332	0.349	0.340
5050	0.498	0.515	0.504	0.515	0.526	0.514	0.513	0.515	0.512
5100	0.720	0.709	0.696	0.711	0.729	0.707	0.710	0.725	0.714
5150	0.890	0.899	0.884	0.900	0.899	0.892	0.898	0.901	0.895
5200	1.000	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5250	0.994	1.000	0.982	0.991	0.998	0.994	0.994	0.993	0.993
5300	0.916	0.931	0.903	0.918	0.927	0.934	0.909	0.910	0.918
5350	0.793	0.805	0.772	0.787	0.789	0.805	0.774	0.779	0.788
5400	0.647	0.663	0.644	0.655	0.653	0.670	0.644	0.646	0.653
5450	0.521	0.525	0.518	0.526	0.532	0.524	0.504	0.510	0.520
5500	0.398	0.409	0.388	0.400	0.418	0.415	0.367	0.399	0.399
5550	0.308	0.312	0.303	0.310	0.317	0.315	0.298	0.307	0.309
5600	0.230	0.231	0.230	0.233	0.238	0.236	0.218	0.230	0.231
5650	0.174	0.176	0.171	0.178	0.175	0.174	0.160	0.167	0.172
5700	0.133	0.131	0.125	0.130	0.132	0.132	0.118	0.121	0.128
5750	0.094	0.094	0.094	0.098	0.100	0.091	0.092	0.092	0.095
5800	0.073	0.071	0.067	0.070	0.072	0.071	0.068	0.066	0.070
5850	0.052	0.054	0.055	0.056	0.057	0.057	0.049	0.053	0.054

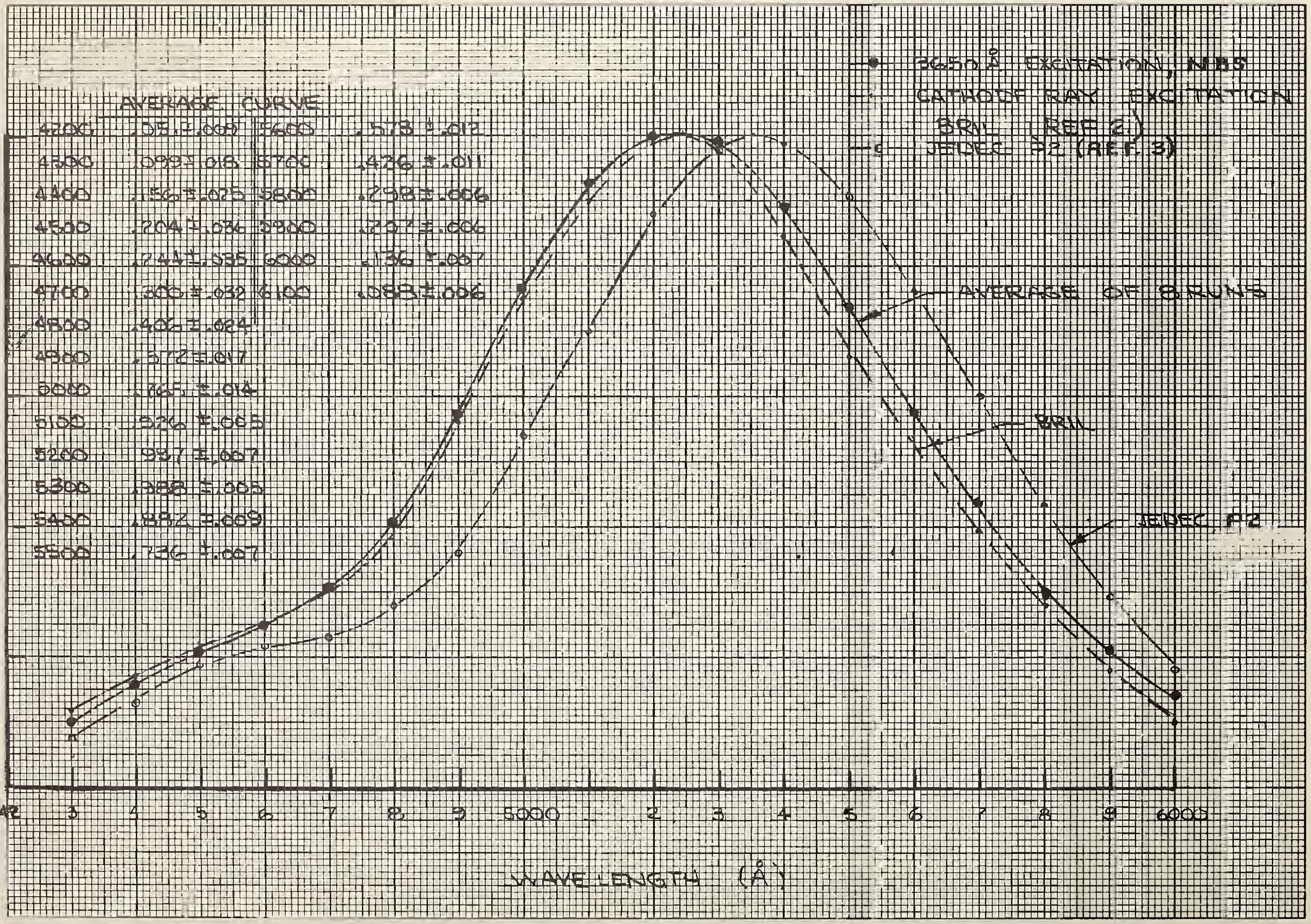

Figure 4. Relative Spectral Energy of Phosphor NBS 1022, Zinc Sulfide, ZnS:Cu

Table 4. Computer Printout of Relative Spectral Energy of Phosphor NBS 1022, Zinc Sulfide, ZnS:Cu

WAVE LENGTH	**NORMALIZED CURVES**							AVERAGE
4200	0.039	0.035	0.038	0.036	0.064	0.065	0.066	0.065	0.051
4300	0.074	0.070	0.068	0.069	0.128	0.129	0.128	0.128	0.099
4400	0.113	0.113	0.114	0.113	0.200	0.200	0.199	0.200	0.156
4500	0.150	0.139	0.150	0.154	0.259	0.263	0.258	0.258	0.204
4600	0.187	0.187	0.183	0.194	0.298	0.303	0.298	0.299	0.244
4700	0.250	0.239	0.260	0.257	0.347	0.351	0.347	0.347	0.300
4800	0.373	0.365	0.366	0.379	0.439	0.447	0.440	0.437	0.406
4900	0.554	0.542	0.543	0.547	0.593	0.602	0.594	0.598	0.572
5000	0.762	0.738	0.739	0.760	0.775	0.786	0.778	0.780	0.765
5100	0.936	0.919	0.919	0.927	0.927	0.933	0.921	0.924	0.926
5200	0.974	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.997
5300	1.000	0.993	0.988	0.996	0.975	0.991	0.981	0.983	0.988
5400	0.873	0.903	0.878	0.900	0.871	0.882	0.876	0.877	0.882
5500	0.747	0.748	0.740	0.741	0.730	0.732	0.723	0.727	0.736
5600	0.592	0.553	0.576	0.594	0.561	0.573	0.564	0.567	0.573
5700	0.451	0.414	0.430	0.433	0.418	0.428	0.417	0.420	0.426
5800	0.310	0.288	0.309	0.287	0.296	0.298	0.298	0.298	0.298
5900	0.205	0.213	0.213	0.219	0.199	0.203	0.200	0.201	0.207
6000	0.150	0.133	0.135	0.125	0.134	0.134	0.141	0.134	0.136
6100	0.097	0.076	0.092	0.085	0.087	0.089	0.087	0.088	0.088

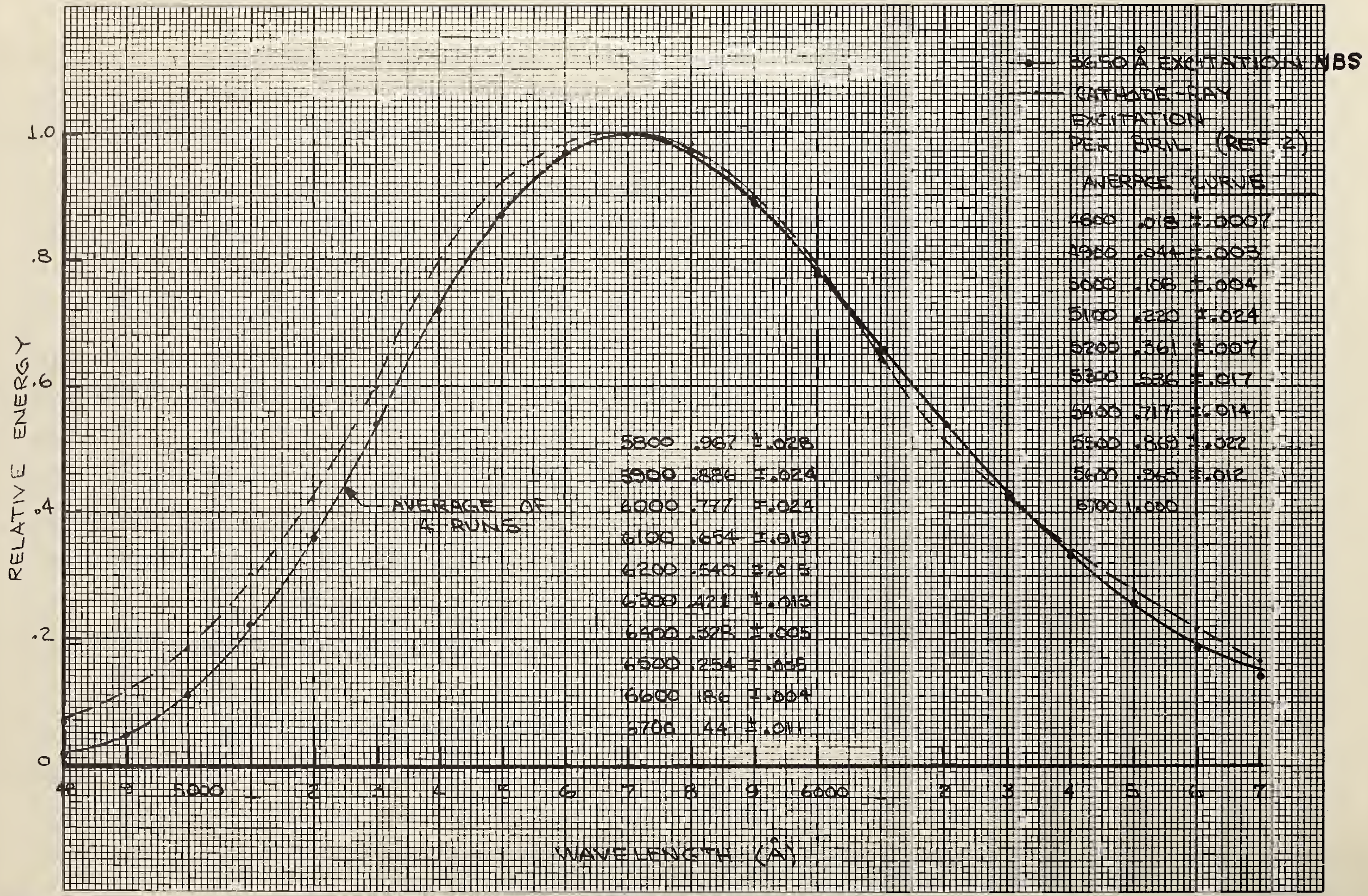

Figure 5. Relative Spectral Energy of Phosphor NBS 1023, Zinc Cadmium Sulfide, ZnCdS:Ag

Table 5. Computer Printout of Relative Spectral Energy of Phosphor NBS 1023, Zinc Cadmium Sulfide, ZnCdS:Ag

WAVE LENGTH	**NORMALIZED CURVES**				AVERAGE
4800	0.017	0.018	0.018	0.018	0.018
4900	0.045	0.045	0.042	0.046	0.044
5000	0.109	0.105	0.109	0.110	0.108
5100	0.244	0.212	0.211	0.212	0.220
5200	0.361	0.356	0.359	0.366	0.361
5300	0.525	0.531	0.540	0.549	0.536
5400	0.713	0.709	0.716	0.729	0.717
5500	0.856	0.868	0.867	0.886	0.869
5600	0.957	0.966	0.964	0.974	0.965
5700	1.000	1.000	1.000	1.000	1.000
5800	0.960	0.953	0.962	0.992	0.967
5900	0.879	0.875	0.881	0.908	0.886
6000	0.760	0.774	0.781	0.794	0.777
6100	0.646	0.642	0.657	0.668	0.654
6200	0.528	0.549	0.540	0.542	0.540
6300	0.408	0.424	0.423	0.426	0.421
6400	0.332	0.325	0.327	0.328	0.328
6500	0.257	0.254	0.256	0.250	0.254
6600	0.185	0.183	0.187	0.189	0.186
6700	0.133	0.146	0.148	0.148	0.144

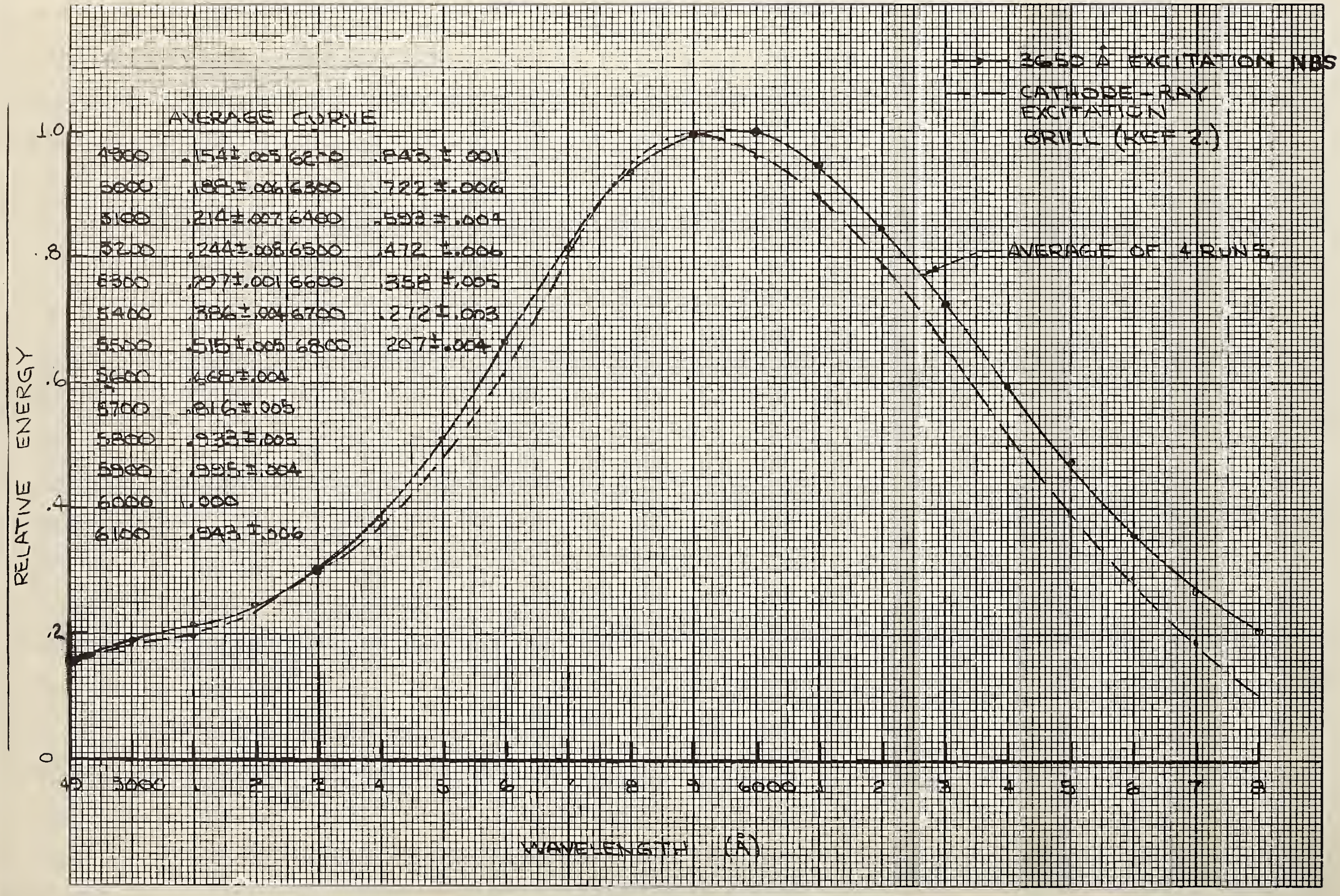

Figure 6. Relative Spectral Energy of Phosphor NBS 1024, Zinc Cadmium Sulfide, ZnCdS:Cu

Table 6. Computer Printout of Relative Spectral Energy of Phosphor NBS 1024, Zinc Cadmium Sulfide, ZnCdS:Cu

WAVE LENGTH	**NORMALIZED CURVES**				AVERAGE
4900	0.158	0.151	0.153	0.154	0.154
5000	0.192	0.183	0.188	0.188	0.188
5100	0.218	0.208	0.215	0.216	0.214
5200	0.247	0.236	0.246	0.246	0.244
5300	0.298	0.296	0.298	0.297	0.297
5400	0.389	0.385	0.384	0.384	0.386
5500	0.515	0.518	0.511	0.515	0.515
5600	0.667	0.672	0.667	0.667	0.668
5700	0.817	0.817	0.812	0.819	0.816
5800	0.932	0.933	0.930	0.936	0.933
5900	0.994	0.998	0.992	0.998	0.995
6000	1.000	1.000	1.000	1.000	1.000
6100	0.939	0.945	0.939	0.948	0.943
6200	0.843	0.842	0.843	0.844	0.843
6300	0.717	0.723	0.725	0.722	0.722
6400	0.590	0.596	0.591	0.593	0.593
6500	0.473	0.474	0.467	0.476	0.472
6600	0.354	0.360	0.356	0.361	0.358
6700	0.273	0.272	0.270	0.274	0.272
6800	0.206	0.209	0.204	0.208	0.207

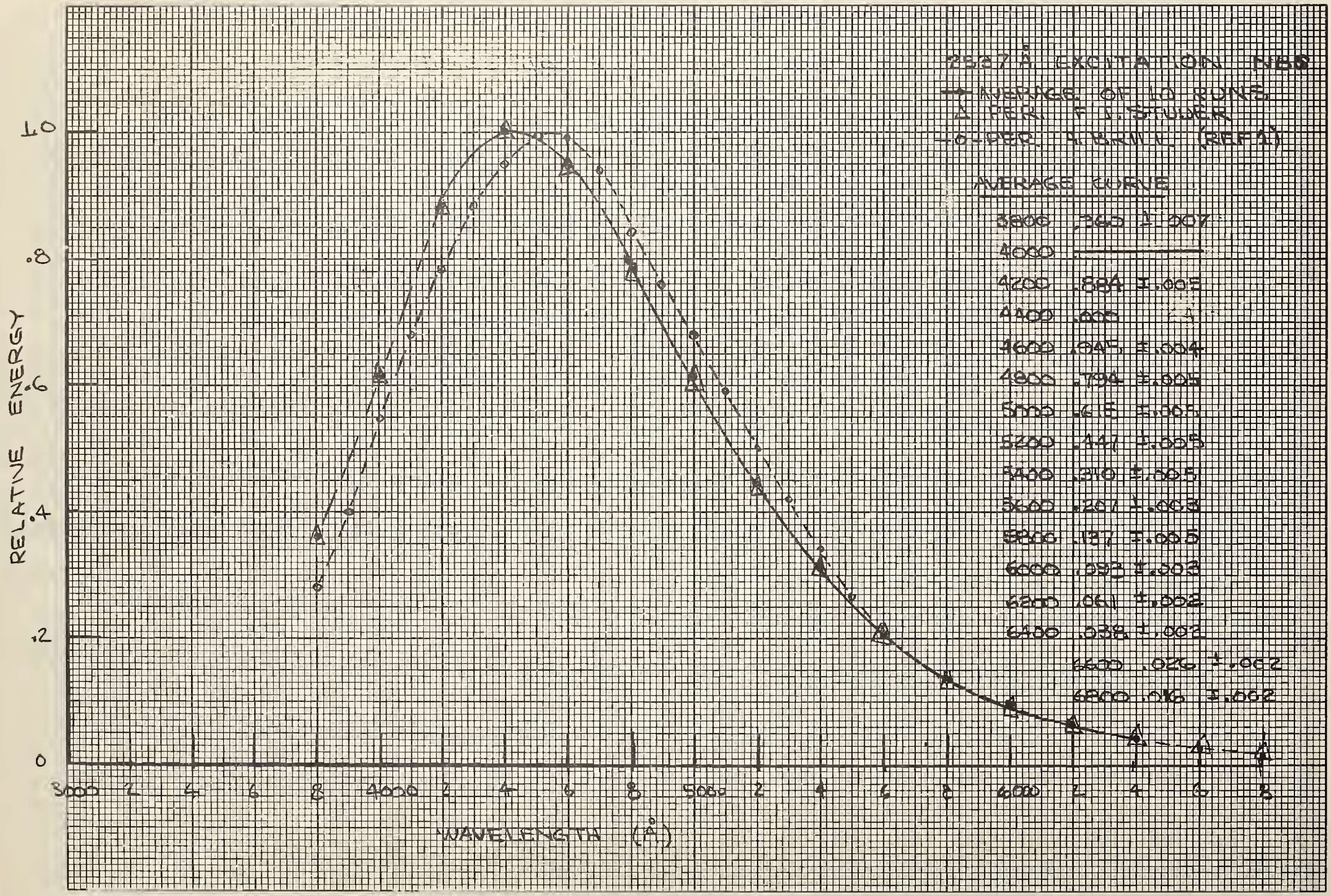

Figure 7. Relative Spectral Energy of Phosphor NBS 1026, Calcium Tungstate, $CaWO_4$:Pb

Table 7. Computer Printout of Relative Spectral Energy of Phosphor NBS 1026, Calcium Tungstate, $CaWO_4:Pb$, (Average energy at 4000 A is interpolated because of interference of nearby mercury lines in measurements)

NORMALIZED CURVES

WAVE LENGTH											AVERAGE
380C	0.355	0.382	0.371	0.368	0.355	0.352	0.356	0.355	0.354	0.354	0.360
400C	~~0.681~~	~~0.860~~	~~0.704~~	~~0.688~~	~~0.694~~	~~0.689~~	~~0.689~~	~~0.686~~	~~0.691~~	~~0.698~~	≈0.620 ~~0.700~~
420C	0.892	0.895	0.887	0.882	0.887	0.886	0.880	0.878	0.880	0.875	0.884
440C	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
460C	0.935	0.947	0.945	0.949	0.947	0.940	0.949	0.951	0.944	0.946	0.945
480C	0.782	0.795	0.780	0.802	0.792	0.802	0.794	0.799	0.802	0.795	0.794
500C	0.606	0.606	0.604	0.617	0.613	0.622	0.617	0.621	0.616	0.624	0.615
520C	0.440	0.441	0.431	0.446	0.447	0.459	0.447	0.451	0.453	0.452	0.447
540C	0.306	0.302	0.295	0.311	0.306	0.311	0.314	0.316	0.317	0.317	0.310
560C	0.202	0.2C4	0.201	0.209	0.207	0.207	0.209	0.210	0.212	0.212	0.207
580C	0.135	0.135	0.125	0.138	0.139	0.146	0.146	0.130	0.149	0.130	0.137
6C0C	0.088	0.089	0.085	0.089	0.091	0.098	0.096	0.097	0.097	0.098	0.093
620C	0.057	0.056	0.058	0.056	0.063	0.062	0.063	0.064	0.064	0.064	0.061
640C	0.037	0.039	0.037	0.039	0.040						0.038
660C	0.024	0.028	0.026	0.027	0.024						0.026
680C	0.015	0.018	0.015	0.015	0.018						0.016

Table 8. Computer Printout of Relative Spectral Energy of Phosphor NBS 1027, Magnesium Tungstate, $MgWO_4$ (Average energy at 4000 Å is interpolated because of interference of nearby mercury lines in measurements)

WAVE LENGTH	**NORMALIZED CURVES**									AVERAGE
380C	0.092	0.099	0.106	0.104	0.093	0.094	0.097	0.096	0.097	0.098
400C	~~0.292~~	~~0.328~~	~~0.318~~	~~0.317~~	~~0.302~~	~~0.310~~	~~0.286~~	~~0.306~~	~~0.340~~	≈0.250 ~~0.311~~
420C	0.500	0.490	0.490	0.487	0.496	0.474	0.481	0.479	0.484	0.487
440C	0.761	0.754	0.753	0.749	0.772	0.744	0.750	0.745	0.744	0.752
460C	0.947	0.944	0.938	0.941	0.957	0.934	0.934	0.938	0.943	0.942
480C	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5000	0.941	0.944	0.934	0.936	0.933	0.927	0.952	0.940	0.933	0.938
520C	0.802	0.802	0.801	0.802	0.797	0.802	0.805	0.805	0.806	0.803
540C	0.643	0.634	0.644	0.630	0.621	0.652	0.649	0.655	0.637	0.641
560C	0.474	0.486	0.474	0.472	0.465	0.480	0.491	0.490	0.496	0.481
5800	0.341	0.350	0.346	0.339	0.332	0.344	0.344	0.344	0.347	0.343
600C	0.239	0.245	0.245	0.242	0.227	0.250	0.250	0.249	0.253	0.244
620C	0.160	0.167	0.166	0.162	0.152	0.163	0.164	0.163	0.166	0.163
640C	0.112	0.105	0.111	0.111	0.089	0.135	0.136	0.136	0.137	0.119
660C	0.072	0.071	0.072	0.074	0.057	0.077	0.076	0.077	0.077	0.073
680C	0.047	0.050	0.050	0.051	0.038					0.049

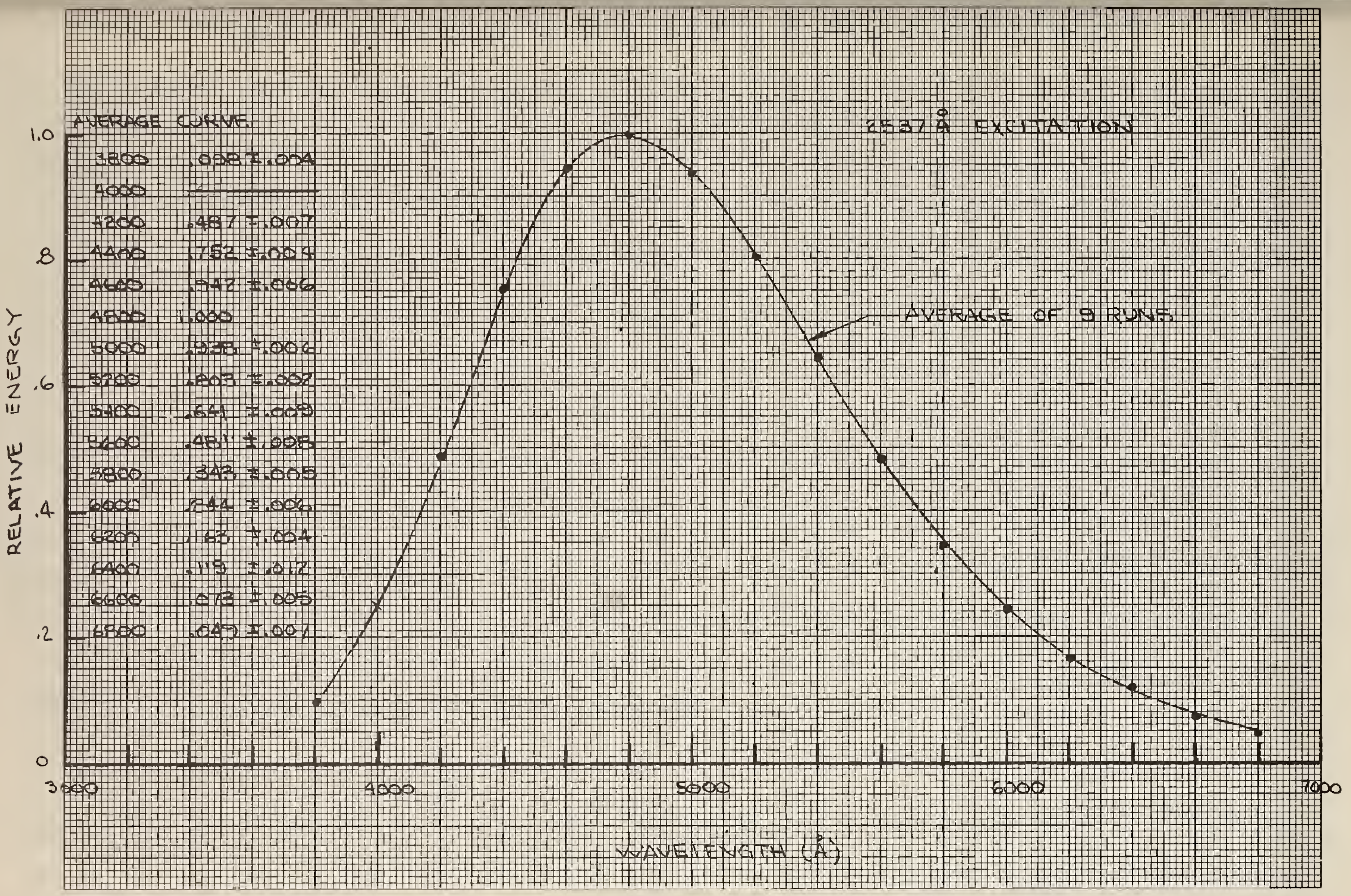

Figure 8. Relative Spectral Energy of Phosphor NBS 1027, Magnesium Tungstate, $MgWO_4$

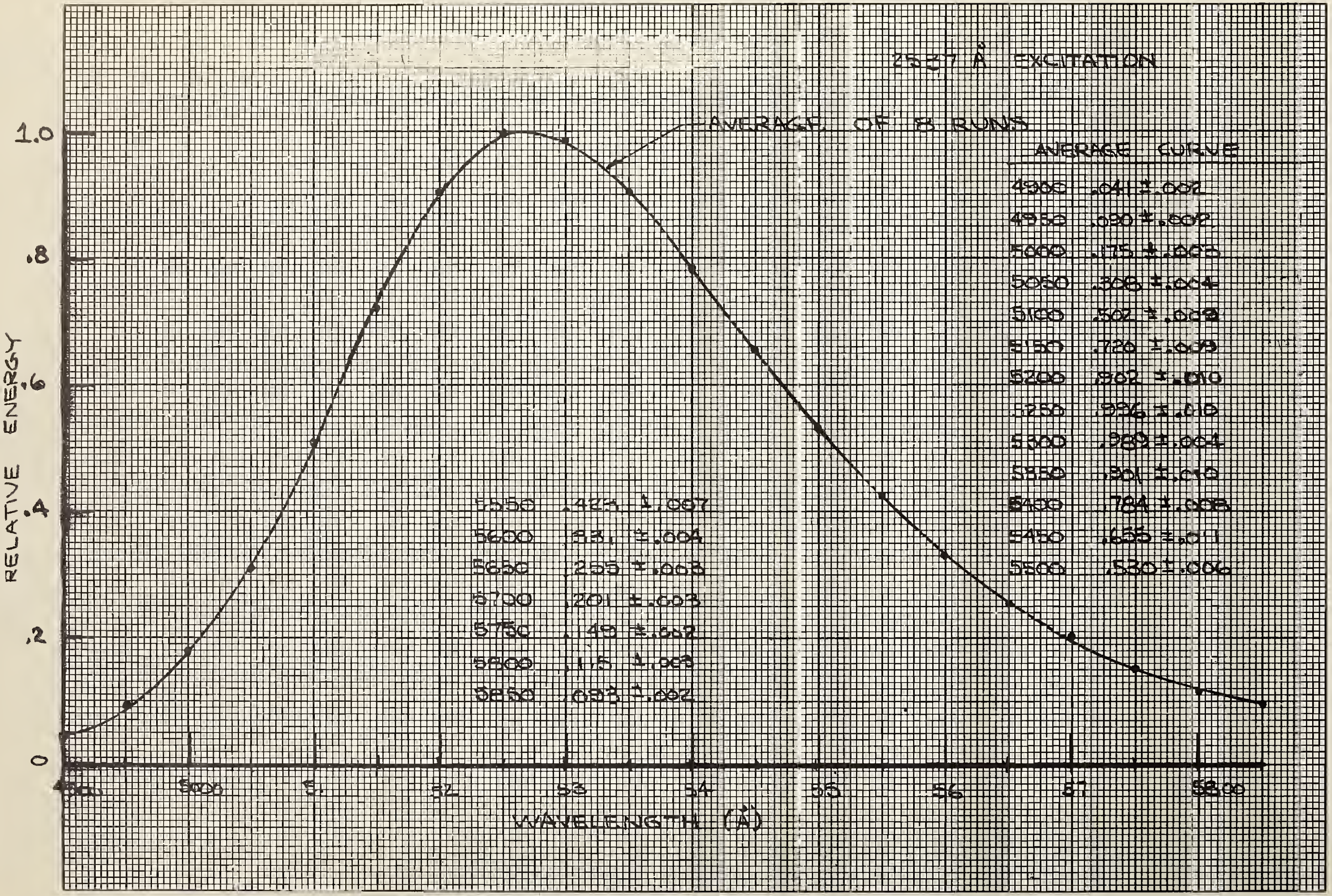

Figure 9. Relative Spectral Energy of Phosphor NBS 1028, Zinc Silicate, Zn_2SiO_4:Mn

Table 9. Computer Printout of Relative Spectral Energy of Phosphor NBS 1028, Zinc Silicate, Zn_2SiO_4:Mn

WAVE LENGTH	**NORMALIZED CURVES**								AVERAGE
4900	0.038	0.042	0.039	0.045	0.041	0.042	0.043	0.038	0.041
4950	0.088	0.093	0.093	0.091	0.091	0.085	0.094	0.088	0.090
5000	0.174	0.175	0.172	0.180	0.180	0.172	0.179	0.170	0.175
5050	0.306	0.309	0.305	0.316	0.316	0.306	0.308	0.301	0.308
5100	0.513	0.501	0.504	0.519	0.496	0.504	0.488	0.487	0.502
5150	0.716	0.723	0.721	0.725	0.725	0.727	0.723	0.696	0.720
5200	0.910	0.902	0.900	0.913	0.906	0.915	0.894	0.874	0.902
5250	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.965	0.996
5300	0.989	0.991	0.992	0.981	0.982	0.990	0.987	1.000	0.989
5350	0.909	0.910	0.907	0.892	0.895	0.911	0.905	0.878	0.901
5400	0.791	0.789	0.795	0.773	0.781	0.786	0.787	0.766	0.784
5450	0.652	0.671	0.656	0.634	0.656	0.659	0.662	0.647	0.655
5500	0.525	0.537	0.539	0.523	0.527	0.529	0.537	0.518	0.530
5550	0.423	0.421	0.434	0.411	0.420	0.430	0.426	0.415	0.423
5600	0.331	0.338	0.335	0.321	0.333	0.331	0.334	0.326	0.331
5650	0.255	0.257	0.258	0.246	0.258	0.259	0.256	0.250	0.255
5700	0.201	0.203	0.203	0.197	0.200	0.205	0.201	0.196	0.201
5750	0.153	0.148	0.148	0.148	0.152	0.149	0.151	0.147	0.149
5800	0.116	0.117	0.117	0.108	0.115	0.118	0.112	0.116	0.115
5850	0.095	0.088	0.096	0.088	0.094	0.097	0.090	0.095	0.093

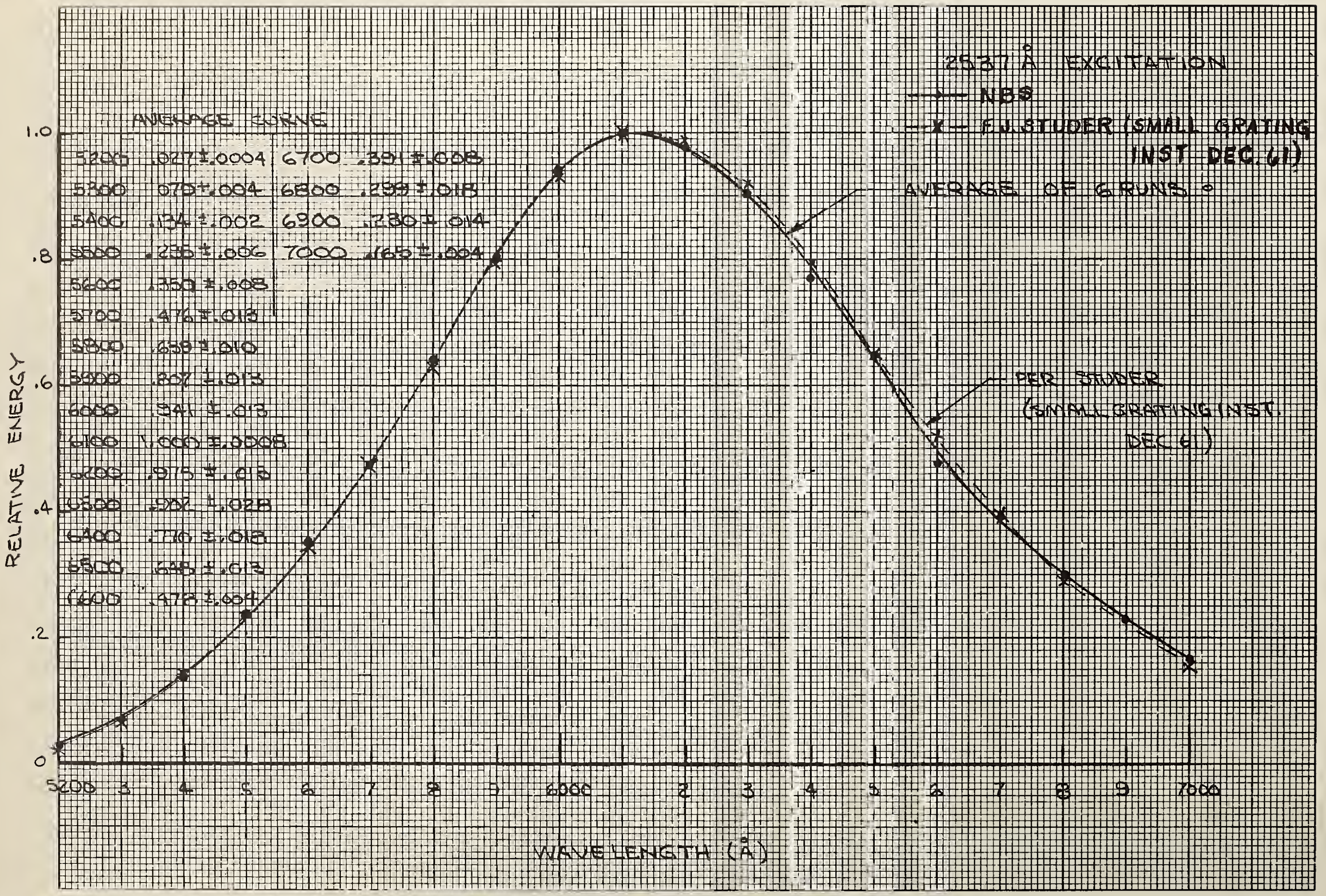

Figure 10. Relative Spectral Energy of Phosphor NBS 1029, Calcium Silicate, $CaSiO_3$:Pb,Mn

Table 10. Computer Printout of Relative Spectral Energy of Phosphor NBS 1029, Calcium Silicate, $CaSiO_3$:Pb,Mn

WAVE LENGTH	**NORMALIZED CURVES**						AVERAGE
5200	0.026	0.027	0.027	0.027	0.027	0.027	0.027
5300	0.071	0.074	0.074	0.063	0.074	0.063	0.070
5400	0.130	0.135	0.135	0.135	0.135	0.135	0.134
5500	0.233	0.241	0.241	0.243	0.227	0.227	0.235
5600	0.348	0.360	0.362	0.345	0.344	0.342	0.350
5700	0.454	0.487	0.487	0.470	0.470	0.486	0.476
5800	0.642	0.648	0.648	0.648	0.625	0.624	0.639
5900	0.811	0.816	0.819	0.819	0.787	0.792	0.807
6000	0.929	0.961	0.961	0.932	0.931	0.934	0.941
6100	0.998	1.000	1.000	1.000	1.000	1.000	1.000
6200	1.000	0.998	0.961	0.965	0.962	0.962	0.975
6300	0.871	0.940	0.901	0.901	0.900	0.901	0.902
6400	0.736	0.766	0.780	0.779	0.778	0.780	0.770
6500	0.627	0.657	0.660	0.657	0.633	0.653	0.648
6600	0.476	0.479	0.475	0.475	0.485	0.479	0.478
6700	0.377	0.396	0.393	0.393	0.395	0.395	0.391
6800	0.298	0.307	0.308	0.264	0.310	0.308	0.299
6900	0.234	0.240	0.210	0.241	0.244	0.213	0.230
7000	0.158	0.165	0.167	0.167	0.166	0.164	0.165
7100	0.0	0.0	0.0	0.0	0.111	0.164	0.046

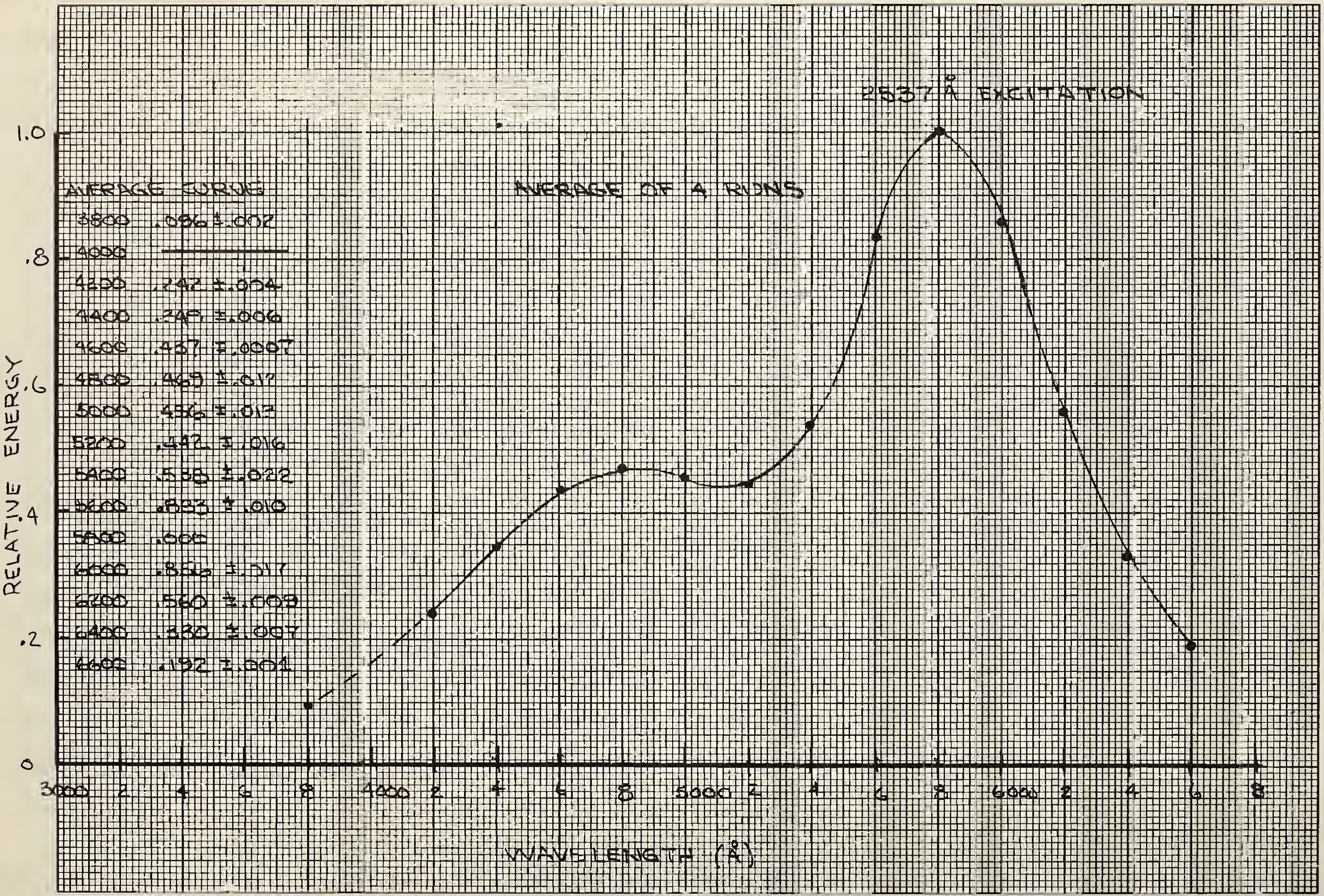

Figure 11. Relative Spectral Energy of Phosphor NBS 1031, Calcium Halophosphate, $3Ca_3(PO_4)_2.Ca(F,Cl):Pb,Mn$

Table 11. Computer Printout of Relative Spectral Energy of Phosphor NBS 1031, Calcium Halophosphate, $3Ca_3(PO_4)_2 \cdot C_a(F,Cl):Pb,Mn$ (Average energy at 4000 A is interpolated because of interference of nearby mercury lines in measurements)

WAVE LENGTH	**NORMALIZED CURVES**				AVERAGE
380C	0.097	0.096	0.094	0.097	0.C96
4000	~~0.237~~	~~0.264~~	~~0.256~~	~~0.243~~	≈0.169 ~~0.250~~
4200	0.244	0.244	0.238	0.242	0.242
440C	0.350	C.35C	0.343	C.352	0.349
460C	0.437	0.438	0.437	0.437	0.437
4800	0.471	0.472	0.459	0.476	0.469
500C	0.449	C.467	0.450	0.458	0.456
5200	0.448	C.450	0.428	0.441	0.442
5400	0.526	0.557	0.528	0.540	0.538
560C	0.829	0.832	0.829	0.843	0.833
5800	1.000	1.0C0	1.CCC	1.000	1.C00
6000	0.851	0.853	0.849	0.873	0.856
620C	0.556	0.557	0.559	0.569	0.560
640C	0.327	C.328	0.328	0.337	0.330
6600	0.191	0.193	0.192	0.193	0.192

The 45°-0° spectral reflectance factor of the $BaSO_4$ plaque was assumed constant over the wavelength range of interest for each phosphor and the relative spectral emission for a blackbody at 2854°K was used for $L(\lambda_j)$ in all calculations involved in correcting the data. The absolute spectral reflectance of USP grade (unpublished data) $BaSO_4$ is shown in Figure 12. The 45°-0° spectral reflectance factor of the plaque was assumed to be equal to its spectral reflectance.

4. Relative Quantum Efficiency

The relative quantum efficiencies of the 2537 Å excited phosphor samples have been calculated from the scale factors used with a picoammeter during the measurements. The method of calculation is as follows: define

$$f \equiv \text{scale factor}$$

then the calibrated spectral energy distribution is

$$E(\lambda) = f\, P(\lambda)$$

where $P(\lambda)$ is the average curve obtained for each phosphor. Thus, since

$$E = h\upsilon = \frac{hc}{\lambda},$$

the number of quanta of luminescence is given by,

$$Q = f \int \frac{P(\lambda)}{\frac{hc}{\lambda}}\, d\lambda = \frac{f}{hc} \int \lambda P(\lambda)\, d\lambda .$$

Since the calculated quantum efficiencies of the samples will be referred to $MgWO_4$, we compute the number of quanta emitted by it as

$$Q_{MgWO_4} = \frac{f_{MgWO_4}}{hc} \int \lambda\, P_{MgWO_4}(\lambda)\, d\lambda .$$

Finally the relative quantum efficiency of each sample is given by,

$$\epsilon \equiv \text{Relative Q.E.} = \frac{Q}{Q_{MgWO_4}} = \frac{f \int \lambda P(\lambda)\, d\lambda}{f_{MgWO_4} \int \lambda P(\lambda)\, d\lambda}$$

or for ease of calculation from the data,

$$\epsilon = \frac{f \sum_{j=1}^{20} \lambda_j\, P(\lambda_j)}{f_{MgWO_4} \sum_{j=1}^{20} \lambda_j P(\lambda_j)}$$

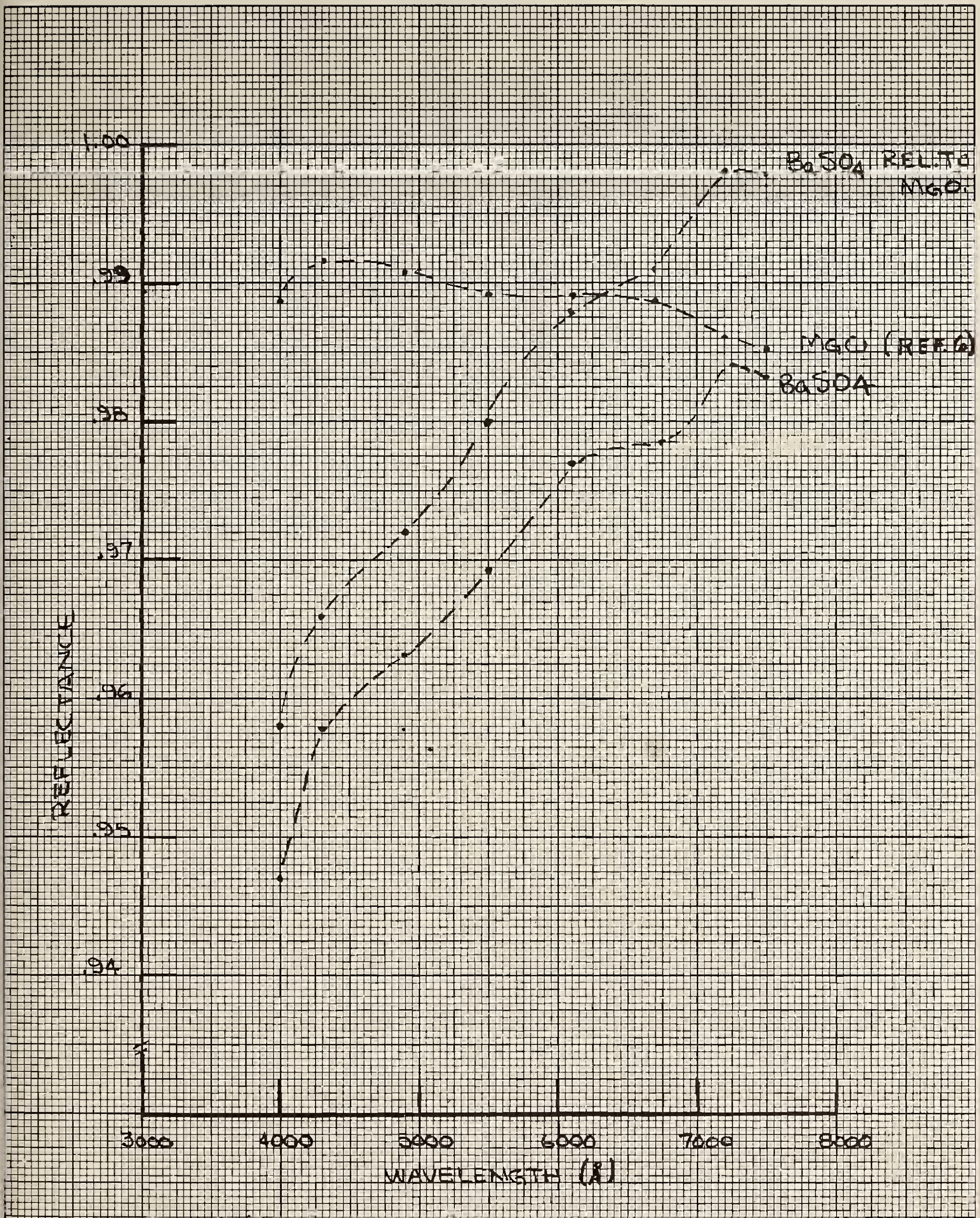

Figure 12. Spectral Reflectance of Barium Sulfate

The following results were obtained with the quantum efficiency of $MgWO_4$ normalized to unity.

RELATIVE QUANTUM EFFICIENCIES
OF 2537Å EXCITED SAMPLES

Sample No.	ϵ	Per Bril (Ref 1)
1021	.66	.83
1026	.86	.89
1027 (M_gWO_4)	1.00	1.00
1028	.86	.81
1029	.85	.81
1031	.82	.84

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