

# APPLICATION OF THE RULE OF GLADSTONE AND DALE TO MINERALS\*

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## ABSTRACT

The relation,  $(n-1)/d=K$ , the rule of Gladstone and Dale, holds very well for crystalline substances based upon data for 121 minerals selected from modern literature. The specific refractive energy values of the constituents of minerals, determined by Larsen, need very little revision. New values are given for  $Ce_2O_3$ ,  $La_2O_3$ ,  $Nd_2O_3$ ,  $Pr_2O_3$ ,  $Sm_2O_3$ ,  $Sc_2O_3$ ,  $MoO_3$ ,  $Y_2O_3$ , and  $V_2O_5$  in minerals.

To emphasize the relation between index of refraction, density, and chemical composition, Larsen (1921) suggested that the rule of Gladstone and Dale be applied to crystalline substances. Gladstone and Dale (1864) showed that  $(n-1)/d=K$ , and  $K=(k_1)(p_1/100)+(k_2)(p_2/100)+\text{etc.}$ , where  $K$  is the specific refractive energy of a liquid,  $k_1$ ,  $k_2$  are the specific refractive energies of the components of the liquid, and  $p_1$ ,  $p_2$  are the weight percentages of the components. A table of specific refractive energies ( $k$ ) of the constituents of minerals was published by Larsen (1921 and 1934). Larsen's specific refractive energies are average values calculated from the most reliable mineralogical data available more than 30 years ago. Recently, Prof. Larsen suggested that the author publish a revised set of  $k$  values based upon more recent optical, chemical, and density data. With few exceptions, it was found that Larsen's data did not need revision. The few suggested changes are as given at the top of the next page.

When the rule,  $(n-1)/d=K$ , is applied to minerals, the arithmetical mean index of refraction,  $(\alpha+\beta+\gamma)/3$  or  $(2\omega+\epsilon)/3$ , is used and the relations are stated to hold approximately (Larsen and Berman, 1934).

Mineralogists have made relatively little use of the rule of Gladstone and Dale in the belief that the relations would not hold sufficiently well because of major differences in the manner of combination of the constituents of minerals. Where the optical, chemical, and density data are accurate, the Gladstone and Dale relations hold very well for most minerals, with only slight modifications due to the manner of combination of the constituents. Mineralogists would do well to reexamine their data before deciding that a mineral is an exception to the rule [ $(n-1)/d=K$ ]. This paper was written on the advice of Prof. Larsen and several of the author's colleagues who did not expect that the rule would hold so well for most minerals.

All of the data are presented as a comparison of the calculated mean index of refraction,  $dk+1$ , with the arithmetical mean index of refraction,  $(\alpha+\beta+\gamma)/3$  or  $(2\omega+\epsilon)/3$ , determined experimentally.

\* Publication authorized by the Director, U. S. Geological Survey.

	Larsen and Berman (1934)	Jaffe (1955)
$k$ Ce <sub>2</sub> O <sub>3</sub>	.160	.149 (a)
$k$ La <sub>2</sub> O <sub>3</sub>	.149	.142 (a)
$k$ Nd <sub>2</sub> O <sub>3</sub>	—	.138 (a)
$k$ Pr <sub>2</sub> O <sub>3</sub>	—	.140 (a)
$k$ Sm <sub>2</sub> O <sub>3</sub>	—	.141 (a)
$k$ (Ce, La, Nd, Pr, Sm) <sub>2</sub> O <sub>3</sub>	—	.144 (b)
$k$ Y <sub>2</sub> O <sub>3</sub>	.144	.170 (c)
$k$ Fe <sub>2</sub> O <sub>3</sub>	.308	.290 (d)
		.310 (e)
		.404 (f)
$k$ V <sub>2</sub> O <sub>5</sub>	.430	.340 (g)
$k$ Sc <sub>2</sub> O <sub>3</sub>	—	.248 (h)
$k$ MoO <sub>3</sub>	—	.234 (i)

- (a) derived from artificial inorganic compounds and minerals.  
 (b) derived from numerous minerals.  
 (c) derived from Y<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>·8H<sub>2</sub>O, xenotime and yttrigarnet.  
 (d) derived from silicates.  
 (e) derived from hydrated ferric sulfates.  
 (f) derived from the oxide.  
 (g) derived from rossite and metatyuyamunite.  
 (h) derived from thortveitite.  
 (i) derived from powellite.

In Table 1, the calculated and experimental mean indices of refraction are compared for minerals representative of different silicate structure types.

Regardless of the different linkages of SiO<sub>4</sub> tetrahedra, the silicates in Table 1 show excellent agreement between the calculated and experi-

TABLE 1. COMPARISON OF CALCULATED AND EXPERIMENTAL MEAN INDICES OF REFRACTION FOR MINERALS OF DIFFERENT SILICATE-STRUCTURE TYPES

Mineral	O:Si Ratio	$(\alpha+\beta+\gamma)/3$ or $(2\omega+\epsilon)/3$	$dK+1$	Deviation
Forsterite Mg <sub>2</sub> SiO <sub>4</sub>	4:1	1.652	1.649	-0.003
Pyrope Mg <sub>3</sub> Al <sub>2</sub> (SiO <sub>4</sub> ) <sub>3</sub>	4:1	1.705	1.705	0.000
Akermanite Ca <sub>2</sub> MgSi <sub>2</sub> O <sub>7</sub>	7:2	1.634	1.628	-0.006
Benitoite BaTiSi <sub>3</sub> O <sub>9</sub>	3:1	1.773	1.779	+0.006
Enstatite MgSiO <sub>3</sub>	3:1	1.654	1.649	-0.005
Talc Mg <sub>3</sub> (OH) <sub>2</sub> Si <sub>4</sub> O <sub>10</sub>	5:2	1.572	1.570	-0.002
Quartz SiO <sub>2</sub>	2:1	1.547	1.551	+0.004

mental mean indices of refraction with a maximum deviation of only 0.006. The relations can be shown to hold very well for minerals of extremely complex chemical compositions. This may be demonstrated by a calculation of the mean index of refraction ( $dk+1$ ) of schroeking-  
 erite,  $\text{Ca}_3\text{Na}[\text{UO}_2(\text{CO}_3)_3(\text{SO}_4)\text{F}] \cdot 10\text{H}_2\text{O}$ .

Oxide	$p/100$		$k$		$(k)(p/100)$	
CaO	18.93	×	.225	=	.04259	
Na <sub>2</sub> O	3.49	×	.181	=	.00632	
UO <sub>3</sub>	32.19	×	.134	=	.04313	
CO <sub>2</sub>	14.86	×	.217	=	.03225	
SO <sub>3</sub>	9.01	×	.177	=	.01595	
H <sub>2</sub> O	20.28	×	.340	=	.06895	
F	2.14	×	.043	=	.00092	
	100.90				.21011	
-O=F	.90	×	.203	=	.00183	
	100.00		$K$	=	.20828	$\alpha=1.489$
			$d$	=	2.51	$\beta=1.542$
			$dK$	=	.52278	$\gamma=1.542$

Mean index,  $dk+1=1.523$  ( $n$  calculated).  
 Mean index,  $(\alpha+\beta+\gamma)/3=1.524$  ( $n$  experimental).

Agreement between the calculated and experimental mean index of refraction is not always as good as  $\pm 0.00X$ . Some of the calculated and measured values for various minerals show much greater deviations. In some minerals it is thought that the chemical composition or density values are slightly in error inasmuch as the equation  $(n-1)/d=K$  is very sensitive to small differences in density.

For example, schroeking-  
 erite with  $d=2.51$  and  $K=.20828$  gives  $dK+1=1.523$  and  $(\alpha+\beta+\gamma)/3=1.524$ . The calculated mean index of refraction would vary as follows with errors in density:

$$\begin{aligned} \text{if } d=2.41, dK+1 &= 1.502 \text{ } (-0.022) \\ \text{if } d=2.61, dK+1 &= 1.544 \text{ } (+0.020). \end{aligned}$$

Similarly small errors in chemical analysis may cause differences of as much as  $\pm 0.02$  in the calculated and measured mean indices of refraction. On occasion, however, small chemical errors may balance each other so that they may not be apparent if the constituents involved have similar specific refractive energies. For example,  $k_{\text{Na}_2\text{O}}=.181$  and  $k_{\text{K}_2\text{O}}=.189$  and small errors in their determination may be hidden.

Differences in the manner of combination may be expected to modify the relations (Barth, 1930) but the effects are not as pronounced as might

be expected. For example, the relations in calcite and aragonite are illustrative, as follows:

$$\begin{aligned} \text{calcite } dK+1 &= 1.602 (2\omega + \epsilon)/3 = 1.601 (+0.001) \\ \text{aragonite } dK+1 &= 1.652 (\alpha + \beta + \gamma)/3 = 1.632 (+0.020). \end{aligned}$$

Assuming that the density and optical data are correct for aragonite<sup>7</sup> the deviation of 0.020 for the calculated mean index of aragonite must be a function of the different manner of combination of the constituents. In general, it can be expected that, regardless of the manner of combination of the mineral constituents, a deviation of not more than  $\pm 0.020$  in the mean index of refraction calculation can be obtained for most minerals from accurate chemical and density data. In most minerals studied by the author the calculated and experimental mean indices of refraction agree within  $\pm 0.009$  where the data are known to be reliable. If the relation  $[(n-1)/d = K]$  holds so well for pure minerals, what would be the effect of isomorphism in a complex silicate series? There are too few complex mineral groups for which density and index of refraction

TABLE 2. COMPARISON OF THE CALCULATED AND EXPERIMENTAL MEAN INDICES OF REFRACTION FOR 7 MEMBERS OF THE ANTHOPHYLLITE SERIES

	1	8	9	14	17	29	30
SiO <sub>2</sub>	42.90	45.47	46.06	48.38	50.32	57.16	57.05
TiO <sub>2</sub>	0.49	0.44	0.53	0.41	0.43	None	None
Al <sub>2</sub> O <sub>3</sub>	17.82	15.86	14.95	13.23	8.05	1.40	1.94
Fe <sub>2</sub> O <sub>3</sub>	1.03	2.94	0.62	1.28	2.18	None	None
FeO	18.36	15.34	17.45	14.56	18.34	8.73	11.10
MnO	0.14	0.07	0.04	None	None	0.09	0.11
MgO	15.58	17.62	18.30	20.51	17.55	28.88	26.78
CaO	None	0.14	0.07	0.04	0.74	1.48	0.64
Na <sub>2</sub> O	1.52	0.28	0.47	0.11	0.70	0.66	0.27
K <sub>2</sub> O	0.03	None	None	None	None	None	0.06
F	0.31	None	None	None	None	None	None
H <sub>2</sub> O+	1.95	1.84	1.51	1.48	1.69	1.60	2.05
	100.13						
-O=F	0.13						
	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Density	3.277	3.261	3.245	3.259	3.279	3.106	3.102
$(\alpha + \beta + \gamma)/3$	1.667	1.663	1.661	1.655	1.660	1.630	1.628
$dK+1$	1.666	1.672	1.660	1.667	1.670	1.637	1.633
Difference	-0.001	+0.009	-0.001	+0.012	+0.010	+0.007	+0.005

Chemical analyses by F. A. Gonyer (Rabbitt, 1948) after recalculation to 100.00 per cent.

Density and optical data determined by J. C. Rabbitt (Rabbitt, 1948).

measurements were made on analyzed material. Usually the density or indices of refraction are given as a range covering several chemical analyses. One good example of complete data is given by Rabbitt (1948) for a series of seven anthophyllites from Montana. Calculation of the mean index of refraction  $(dK+1)$  for each anthophyllite is compared with the experimental mean index of refraction,  $[(\alpha+\beta+\gamma)/3]$  in Table 2. In calculating the mean index of refraction, all of the minor constituents were included and the analyses were recalculated to 100 per cent. Inasmuch as the analytical totals range from 99.77 to 100.23, the effects of the recalculations to 100.00 are negligible. The recalculation must be made because the relation,  $[(n-1)/d=K]$ , obviously requires that the specific refractive energy of the compound,  $K$ , be based upon 100 per cent. The agreement between the calculated and experimental mean  $n$  for each anthophyllite is excellent although the analyses show major variations in silica, alumina, and iron. Thus, if the chemical, optical, and density data are reliable, large-scale isomorphism will not seriously affect the relation  $[(n-1)/d=K]$ .

In Table 3, the calculated and experimental mean indices of refraction are compared for 121 minerals of widely different chemical composition for which the data seemed most reliable. Several minerals were rejected on the basis of (1) large differences in the calculated and measured density, (2) large amounts of material designated "remainder" in chemical analyses, and (3) poor analytical summations. For example, the measured density of cordylite and that calculated from  $x$ -ray data are given as 4.31 and 5.61, respectively (Palache, Berman, and Frondel, 1951). Obviously one of the values is in error for material of a given composition. Application of the rule of Gladstone and Dale suggests the density of cordylite should be near 4.76, assuming that the indices of refraction and chemical composition are correct. Table 3 includes the chemical composition, density, and indices of refraction for each of 121 minerals from which the  $n$  values  $(dK+1)$  were calculated. All of the analyses in Table 3 were recalculated to 100.00 per cent as required by the law of Gladstone and Dale.

Differences of the calculated from the experimental mean indices of refraction are less than  $\pm 0.020$  for 92.6 per cent of the entries (Table 3) of which 64.5 per cent are less than  $\pm 0.009$ . The differences of  $dK+1$  from  $(\alpha+\beta+\gamma)/3$  or  $(2\omega+\epsilon)/3$  are graphically represented in Fig. 1. Some of the 7.4 per cent (9 in 121) of the entries for which  $dk+1$  deviates by greater than  $\pm 0.020$  obviously result from poor data; others apparently reflect failure of the rule,  $[(n-1)/d=K]$ , to hold because of marked differences in polarizabilities of the constituents. For example, the data for 16 amphiboles in Table 3 show good agreement between the

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TABLE 3. COMPARISON OF EXPERIMENTAL AND CALCULATED MEAN INDICES OF REFRACTION,  $[(\alpha+\beta+\omega)]$  OR  $[(2\omega+\epsilon)/3]$  WITH  $dk+1$  FOR 121 MINERALS

Mineral data	$(\alpha+\beta+\gamma)/3$ or $(2\omega+\epsilon)/3$	$dK+1$	Deviation
<i>Oxides</i>			
1. Periclase, MgO MgO 94.03, FeO 5.97 $d$ 5.72, $n$ 1.745	1.745	1.732	-0.013
2. Bromellite, BeO BeO 97.89, CaO 1.03, BaO 0.55, MgO 0.07, Sb <sub>2</sub> O <sub>3</sub> 0.29, Al <sub>2</sub> O <sub>3</sub> 0.17 $d$ 3.017, $\omega$ 1.719, $\epsilon$ 1.733	1.724	1.715	-0.009
3. Gahnite, ZnAl <sub>2</sub> O <sub>4</sub> FeO 1.70, MnO 0.50, ZnO 41.31, Al <sub>2</sub> O <sub>3</sub> 53.28, Fe <sub>2</sub> O <sub>3</sub> 2.51, SiO <sub>2</sub> 0.70 $d$ 4.57, $n$ 1.818	1.818	1.816	-0.002
4. Zincite, ZnO ZnO 99.64, MnO 0.27, FeO 0.01, SiO <sub>2</sub> 0.08 $d$ 5.66, $\omega$ 2.013, $\epsilon$ 2.029	2.018	2.036	+0.018
5. Sassolite, B(OH) <sub>3</sub> B <sub>2</sub> O <sub>3</sub> 56.39, H <sub>2</sub> O 43.61 $d$ 1.48, $\alpha$ 1.340, $\beta$ 1.456, $\gamma$ 1.459	1.418	1.403	-0.015
6. Corundum, Al <sub>2</sub> O <sub>3</sub> Al <sub>2</sub> O <sub>3</sub> 99.09, Fe <sub>2</sub> O <sub>3</sub> 0.91 $d$ 4.0, $\omega$ 1.769, $\epsilon$ 1.760	1.766	1.775	+0.009
7. Baddelyite, ZrO <sub>2</sub> ZrO <sub>2</sub> 98.93, Fe <sub>2</sub> O <sub>3</sub> 0.82, CaO 0.06, SiO <sub>2</sub> 0.19 $d$ 5.72, $\alpha$ 2.13, $\beta$ 2.19, $\gamma$ 2.20	2.173	2.154	-0.019
8. Quartz, SiO <sub>2</sub> SiO <sub>2</sub> 100.00 $d$ 2.66, $\omega$ 1.544, $\epsilon$ 1.553	1.547	1.551	+0.004
9. Tridymite, SiO <sub>2</sub> SiO <sub>2</sub> 100.00 $d$ 2.30, $\alpha$ 1.469, $\beta$ 1.470, $\gamma$ 1.473	1.471	1.476	+0.005
10. Cristobalite, SiO <sub>2</sub> SiO <sub>2</sub> 100.00 $d$ 2.3, $n$ 1.486	1.486	1.476	-0.010
11. Rutile, TiO <sub>2</sub> TiO <sub>2</sub> 100.00 $d$ 4.23, $\omega$ 2.612, $\epsilon$ 2.899	2.708	2.691	+0.017
12. Anatase, TiO <sub>2</sub> TiO <sub>2</sub> 100.00 $d$ 3.90, $\omega$ 2.561, $\epsilon$ 2.488	2.537	2.548	+0.011
13. Brookite, TiO <sub>2</sub> TiO <sub>2</sub> 100.00 $d$ 4.14, $\alpha$ 2.583, $\beta$ 2.584, $\gamma$ 2.700	2.622	2.643	+0.021

TABLE 3—(continued)

Mineral data	$(\alpha+\beta+\gamma)/3$ or $(2\omega+\epsilon)/3$	$dK+1$	Deviation
14. Portlandite, $\text{Ca}(\text{OH})_2$ CaO 75.64, $\text{H}_2\text{O}$ 24.31 $d$ 2.230, $\omega$ 1.574, $\epsilon$ 1.547	1.565	1.564	-0.001
<i>Carbonates</i>			
15. Calcite, $\text{CaCO}_3$ CaO 56.03, $\text{CO}_2$ 43.97 $d$ 2.710, $\omega$ 1.658, $\epsilon$ 1.486	1.601	1.602	+0.001
16. Aragonite, $\text{CaCO}_3$ CaO 56.03, $\text{CO}_2$ 43.97 $d$ 2.947, $\alpha$ 1.531, $\beta$ 1.681, $\gamma$ 1.685	1.632	1.652	+0.020
17. Magnesite, $\text{MgCO}_3$ MgO 47.81, $\text{CO}_2$ 52.19 $d$ 3.00, $\omega$ 1.700, $\epsilon$ 1.509	1.636	1.627	-0.009
18. Siderite, $\text{FeCO}_3$ FeO 62.01, $\text{CO}_2$ 37.99 $d$ 3.96, $\omega$ 1.875, $\epsilon$ 1.633	1.794	1.786	-0.008
19. Rhodochrosite, $\text{MnCO}_3$ MnO 61.71, $\text{CO}_2$ 38.29 $d$ 3.70, $\omega$ 1.816, $\epsilon$ 1.597	1.744	1.743	-0.001
20. Smithsonite, $\text{ZnCO}_3$ ZnO 64.90, $\text{CO}_2$ 35.10 $d$ 4.43, $\omega$ 1.848, $\epsilon$ 1.621	1.772	1.777	+0.005
21. Strontianite, $\text{SrCO}_3$ SrO 62.55, CaO 6.10, $\text{CO}_2$ 31.35 $d$ 3.628, $\alpha$ 1.520, $\beta$ 1.667, $\gamma$ 1.669	1.618	1.621	+0.003
22. Alstonite, $\text{CaBa}(\text{CO}_3)_2$ CaO 17.64, BaO 48.64, SrO 4.25, $\text{CO}_2$ 29.47 $d$ 3.707, $\alpha$ 1.526, $\beta$ 1.671, $\gamma$ 1.672	1.623	1.636	+0.013
23. Barytocalcite, $\text{CaBa}(\text{CO}_3)_2$ BaO 51.56, CaO 18.85, $\text{CO}_2$ 29.59 $d$ 3.66, $\alpha$ 1.525, $\beta$ 1.684, $\gamma$ 1.696	1.632	1.630	-0.002
24. Shortite, $\text{Na}_2\text{Ca}_2(\text{CO}_3)_2$ $\text{Na}_2\text{O}$ 20.25, CaO 36.63, $\text{CO}_2$ 43.12 $d$ 2.605, $\alpha$ 1.531, $\beta$ 1.555, $\gamma$ 1.570	1.552	1.554	+0.002
25. Thermonatrite, $\text{Na}_2\text{CO}_3 \cdot \text{H}_2\text{O}$ $\text{Na}_2\text{O}$ 50.03, $\text{CO}_2$ 35.45, $\text{H}_2\text{O}$ 14.52 $d$ 2.255, $\alpha$ 1.420, $\beta$ 1.509, $\gamma$ 1.525	1.485	1.489	+0.004
26. Nesquehonite, $\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$ MgO 29.11, $\text{CO}_2$ 31.65, $\text{H}_2\text{O}$ 39.24 $d$ 1.842, $\alpha$ 1.417, $\beta$ 1.503, $\gamma$ 1.527	1.482	1.480	-0.002
27. Lansfordite, $\text{MgCO}_3 \cdot 5\text{H}_2\text{O}$ MgO 23.25, $\text{CO}_2$ 25.06, $\text{H}_2\text{O}$ 51.69 $d$ 1.694, $\alpha$ 1.456, $\beta$ 1.469, $\gamma$ 1.508	1.478	1.469	-0.009

TABLE 3—(continued)

Mineral data	$(\alpha + \beta + \gamma)/3$ or $(2\omega + \epsilon)/3$	$dK+1$	Deviation
28. Natron, $\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$ $\text{Na}_2\text{O}$ 21.66, $\text{CO}_2$ 15.38, $\text{H}_2\text{O}$ 62.96 $d$ 1.478, $\alpha$ 1.405, $\beta$ 1.425, $\gamma$ 1.440	1.423	1.424	+0.001
29. Pirssonite, $\text{Na}_2\text{Ca}(\text{CO}_3)_2 \cdot 2\text{H}_2\text{O}$ $\text{Na}_2\text{O}$ 25.73, $\text{CaO}$ 23.41, $\text{CO}_2$ 36.11, $\text{H}_2\text{O}$ 14.75 $d$ 2.352, $\alpha$ 1.504, $\beta$ 1.509, $\gamma$ 1.575	1.529	1.536	+0.007
30. Gaylussite, $\text{Na}_2\text{Ca}(\text{CO}_3)_2 \cdot 5\text{H}_2\text{O}$ $\text{Na}_2\text{O}$ 20.42, $\text{CaO}$ 19.03, $\text{CO}_2$ 30.05, $\text{H}_2\text{O}$ 30.50 $d$ 1.991, $\alpha$ 1.443, $\beta$ 1.516, $\gamma$ 1.523	1.494	1.495	+0.001
31. Lanthanite, $(\text{Ce}, \text{La})_2(\text{CO}_3)_3 \cdot 8\text{H}_2\text{O}$ $(\text{Ce}, \text{La})_2\text{O}_3$ 55.03, $\text{CO}_2$ 21.95, $\text{H}_2\text{O}$ 24.21 $d$ 2.84, $\alpha$ 1.520, $\beta$ 1.587, $\gamma$ 1.613	1.573	1.587	+0.014
32. Artinite, $\text{Mg}_2(\text{CO}_3)(\text{OH})_2 \cdot 3\text{H}_2\text{O}$ $\text{MgO}$ 40.99, $\text{CO}_2$ 22.37, $\text{H}_2\text{O}$ 36.64 $d$ 2.02, $\alpha$ 1.488, $\beta$ 1.534, $\gamma$ 1.556	1.526	1.515	-0.011
33. Hydrocerussite, $\text{Pb}_3(\text{CO}_3)_2(\text{OH})_2$ $\text{PbO}$ 86.33, $\text{CO}_2$ 11.35, $\text{H}_2\text{O}$ 2.32 $d$ 6.94, $\omega$ 2.09, $\epsilon$ 1.94	2.040	2.046	+0.006
34. Dawsonite, $\text{NaAl}(\text{CO}_3)(\text{OH})_2$ $\text{Na}_2\text{O}$ 21.81, $\text{Al}_2\text{O}_3$ 36.01, $\text{CO}_2$ 30.51, $\text{H}_2\text{O}$ 11.61 $d$ 2.44, $\alpha$ 1.466, $\beta$ 1.542, $\gamma$ 1.596	1.535	1.524	-0.011
35. Bastnaesite, $(\text{Ce}, \text{La})(\text{CO}_3)\text{F}$ $\text{Ce}_2\text{O}_3$ 38.23, $\text{La}_2\text{O}_3$ 36.79, $\text{CO}_2$ 20.30, $\text{F}$ 7.94, $\text{H}_2\text{O}$ 0.08 $d$ 5.12, $\omega$ 1.717, $\epsilon$ 1.818	1.751	1.763	+0.012
36. Ancyrite, $(\text{Ce}, \text{La})_4(\text{Sr}, \text{Ca})_3(\text{CO}_3)_7(\text{OH})_4 \cdot 3\text{H}_2\text{O}$ $\text{CaO}$ 1.54, $\text{SrO}$ 21.25, $\text{FeO}$ 0.35, $\text{Ce}_2\text{O}_3$ 22.45, $\text{La}_2\text{O}_3$ 24.29, $\text{CO}_2$ 23.53, $\text{H}_2\text{O}$ 6.59 $d$ 3.95, $\alpha$ 1.625, $\beta$ 1.700, $\gamma$ 1.735	1.687	1.692	+0.005
37. Tychite, $\text{Na}_4\text{Mg}_2(\text{SO}_4)(\text{CO}_3)_4$ $\text{Na}_2\text{O}$ 35.58, $\text{MgO}$ 15.42, $\text{SO}_3$ 15.32, $\text{CO}_2$ 33.68 $d$ 2.588, $n=1.510$	1.510	1.506	-0.004
38. Roentgenite, $\text{Ca}_2(\text{Ce}, \text{La})_3(\text{CO}_3)_6\text{F}_3$ $\text{CaO}$ 13.11, $(\text{Ce}, \text{La})_2\text{O}_3$ 57.32, $\text{CO}_2$ 25.71, $\text{F}$ 6.66 $d$ 4.19 (calc.), $\omega$ 1.662, $\epsilon$ 1.756	1.693	1.694	+0.001
39. Parisite, $(\text{Ce}, \text{La})_2\text{Ca}(\text{CO}_3)_3\text{F}_2$ $\text{CaO}$ 10.10, $\text{BaO}$ 0.33, $(\text{Ce}, \text{La})_2\text{O}_3$ 61.57, $\text{CO}_2$ 23.95, $\text{F}$ 7.00 $d$ 4.32, $\omega$ 1.667, $\epsilon$ 1.760	1.698	1.695	-0.003
40. Sahamalite, $(\text{Ce}, \text{La})_2(\text{Mg}, \text{Fe})(\text{CO}_3)_4$ $(\text{Ce}, \text{La})_2\text{O}_3$ 59.8, $\text{MgO}$ 6.2, $\text{FeO}$ 2.0, $\text{CO}_2$ 32.0 $d$ 4.30, $\alpha$ 1.679, $\beta$ 1.776, $\gamma$ 1.807	1.754	1.738	-0.016
41. Andersonite, $\text{Na}_2\text{Ca}(\text{UO}_2)(\text{CO}_3)_3 \cdot 6\text{H}_2\text{O}$ $\text{MgO}$ 0.5, $\text{CaO}$ 8.1, $\text{Na}_2\text{O}$ 9.6, $\text{UO}_3$ 44.9, $\text{CO}_2$ 20.3, $\text{H}_2\text{O}$ 16.0 $d$ 2.8, $\omega$ 1.520, $\epsilon$ 1.540	1.527	1.552	+0.025



TABLE 3—(continued)

Mineral data	$(\alpha+\beta+\gamma)/3$ or $(2\omega+\epsilon)/3$	$dK+1$	Deviation
42. Bayleyite, $Mg_2(VO_2)(CO_3)_3 \cdot 18H_2O$ MgO 9.76, $Na_2O$ 0.21, $K_2O$ 0.10, $UO_3$ 35.29, $CO_2$ 16.72, $H_2O$ 37.92 $d$ 2.05, $\alpha$ 1.455, $\beta$ 1.490, $\gamma$ 1.500	1.482	1.477	-0.005
43. Swartzite, $CaMg(VO_2)(CO_3)_3 \cdot 12H_2O$ CaO 7.32, MgO 5.47, $Na_2O$ 0.26, $K_2O$ 0.49, $UO_3$ 38.85, $CO_2$ 17.92, $H_2O$ 29.69 $d$ 2.3, $\alpha$ 1.465, $\beta$ 1.51, $\gamma$ 1.540	1.505	1.508	+0.003
44. Leadhillite, $Pb_4(SO_4)(CO_3)_2(OH)_2$ PbO 82.78, $SO_3$ 7.36, $CO_2$ 8.17, $H_2O$ 1.690 $d$ 6.55, $\alpha$ 1.87, $\beta$ 2.00, $\gamma$ 2.01	1.960	1.982	+0.022
<i>Nitrates</i>			
45. Darapskite, $Na_3(NO_3)(SO_4) \cdot H_2O$ $Na_2O$ 38.00, $N_2O_5$ 22.10, $SO_3$ 32.65, $H_2O$ 7.25 $d$ 2.20, $\alpha$ 1.391, $\beta$ 1.481, $\gamma$ 1.486	1.453	1.449	-0.004
46. Gerhardtite, $Cu_2(NO_2)(OH)_3$ CuO 66.12, $N_2O_5$ 22.67, $H_2O$ 11.21 $d$ 3.43, $\alpha$ 1.703, $\beta$ 1.713, $\gamma$ 1.722	1.713	1.750	+0.037
47. Nitrobarite, $Ba(NO_2)_2$ BaO 58.67, $N_2O_5$ 41.33 $d$ 3.250, $n$ 1.571	1.571	1.564	-0.007
48. Niter, $KNO_3$ $K_2O$ 46.58, $N_2O_5$ 53.42 $d$ 2.109, $\alpha$ 1.332, $\beta$ 1.504, $\gamma$ 1.504	1.447	1.456	+0.009
49. Soda-Niter, $NaNO_3$ $Na_2O$ 36.46, $N_2O_5$ 63.54 $d$ 2.266, $\omega$ 1.587, $\epsilon$ 1.336	1.503	1.495	-0.008
50. Nitrocalcite, $Ca(NO_3)_2 \cdot 4H_2O$ CaO 23.75, $N_2O_5$ 45.75, $H_2O$ 30.50 $d$ 1.90, $\alpha$ 1.465, $\beta$ 1.498, $\gamma$ 1.504	1.489	1.507	+0.018
<i>Iodate</i>			
51. Lautarite, $Ca(IO_3)_2$ CaO 14.95, $I_2O_5$ 85.04 $d$ 4.59, $\alpha$ 1.792, $\beta$ 1.840, $\gamma$ 1.888	1.840	1.845	+0.005
<i>Borates</i>			
52. Kernite, $Na_2B_4O_7 \cdot 2H_2O$ $Na_2O$ 22.65, $B_2O_3$ 50.80, $H_2O$ 26.55 $d$ 1.93, $\alpha$ 1.455, $\beta$ 1.472, $\gamma$ 1.487	1.471	1.469	-0.002
53. Probertite, $NaCaB_5O_9 \cdot 5H_2O$ $Na_2O$ 8.53, CaO 15.45, $B_2O_3$ 50.44, $H_2O$ 25.58 $d$ 2.141, $\alpha$ 1.514, $\beta$ 1.524, $\gamma$ 1.543	1.527	1.531	+0.004

TABLE 3—(continued)

Mineral data	$(\alpha + \beta + \gamma)/3$ or $(2\omega + \epsilon)/3$	$dK+1$	Deviation
54. Colemanite, $\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 5\text{H}_2\text{O}$ CaO 27.84, $\text{B}_2\text{O}_3$ 49.61, $\text{H}_2\text{O}$ 22.55 $d$ 2.423, $\alpha$ 1.568, $\beta$ 1.592, $\gamma$ 1.614	1.591	1.602	+0.011
55. Tincalconite, $\text{Na}_2\text{B}_4\text{O}_7 \cdot 5\text{H}_2\text{O}$ $\text{Na}_2\text{O}$ 21.47, $\text{B}_2\text{O}_3$ 47.42, $\text{H}_2\text{O}$ 31.11 $d$ 1.880, $\omega$ 1.461, $\epsilon$ 1.474	1.465	1.468	+0.003
56. Borax, $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ $\text{Na}_2\text{O}$ 16.26, $\text{B}_2\text{O}_3$ 36.51, $\text{H}_2\text{O}$ 47.23 $d$ 1.715, $\alpha$ 1.447, $\beta$ 1.469, $\gamma$ 1.472	1.463	1.463	0.000
57. Inyoite, $\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 13\text{H}_2\text{O}$ CaO 20.5, $\text{B}_2\text{O}_3$ 37.2, $\text{H}_2\text{O}$ +26.1, $\text{H}_2\text{O}$ -16.2 $d$ 1.875, $\alpha$ 1.495, $\beta$ 1.510, $\gamma$ 1.520	1.508	1.510	+0.002
<i>Sulfates</i>			
58. Barite, $\text{BaSO}_4$ BaO 65.70, $\text{SO}_3$ 34.30 $d$ 4.50, $\alpha$ 1.636, $\beta$ 1.637, $\gamma$ 1.648	1.641	1.649	+0.008
59. Celestite, $\text{SrSO}_4$ SrO 56.42, $\text{SO}_3$ 43.58 $d$ 3.97, $\alpha$ 1.621, $\beta$ 1.624, $\gamma$ 1.631	1.625	1.625	0.000
60. Anhydrite, $\text{CaSO}_4$ CaO 41.19, $\text{SO}_3$ 58.81 $d$ 2.98, $\alpha$ 1.570, $\beta$ 1.575, $\gamma$ 1.614	1.586	1.586	0.000
61. Alunite, $\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$ $\text{K}_2\text{O}$ 10.02, $\text{Al}_2\text{O}_3$ 39.65, $\text{SO}_3$ 35.50, $\text{H}_2\text{O}$ 14.83 $d$ 2.752, $\omega$ 1.572, $\epsilon$ 1.592	1.579	1.574	-0.005
62. Boussingaultite, $(\text{NH}_4)_2\text{Mg}(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$ $(\text{NH}_4)_2\text{O}$ 14.44, MgO 11.18, $\text{SO}_3$ 44.40, $\text{H}_2\text{O}$ 29.98 $d$ 1.722, $\alpha$ 1.472, $\beta$ 1.473, $\gamma$ 1.479	1.475	1.474	-0.001
63. Ilesite, $\text{MnSO}_4 \cdot 4\text{H}_2\text{O}$ MnO 31.82, $\text{SO}_3$ 35.88, $\text{H}_2\text{O}$ 32.30 $d$ 2.25, $\alpha$ 1.511, $\beta$ 1.519, $\gamma$ 1.521	1.517	1.527	+0.010
<i>Phosphates, Arsenates, Vanadates, Tungstates</i>			
64. Moraesite, $\text{Be}_2\text{PO}_4(\text{OH}) \cdot 4\text{H}_2\text{O}$ BeO 25.32, $\text{P}_2\text{O}_5$ 34.82, $\text{H}_2\text{O}$ 39.86 $d$ 1.805, $\alpha$ 1.462, $\beta$ 1.482, $\gamma$ 1.490	1.478	1.473	-0.005
65. Svanbergite, $\text{SrAl}_3(\text{PO}_4)(\text{SO}_4)(\text{OH})_6$ $\text{Al}_2\text{O}_3$ 36.98, $\text{Fe}_2\text{O}_3$ 0.24, CaO 3.25, SrO 12.87, $\text{P}_2\text{O}_5$ 16.74, $\text{SO}_3$ 17.38, $\text{H}_2\text{O}$ 12.54 $d$ 3.22, $\omega$ 1.635, $\epsilon$ 1.649	1.640	1.654	+0.014

TABLE 3—(continued)

Mineral data	$(\alpha + \beta + \gamma)/3$ or $(2\omega + \epsilon)/3$	$dK+1$	Deviation
66. Arrojadite, $(\text{Na}, \text{K})_5(\text{Fe}, \text{Mn}, \text{Ca})_{16}(\text{PO}_4)_{12}(\text{F}, \text{OH}) \cdot \text{H}_2\text{O}$ P <sub>2</sub> O <sub>5</sub> 40.10, Al <sub>2</sub> O <sub>3</sub> 2.67, FeO 28.29, MnO 15.82, MgO 1.04, CaO 2.47, Li <sub>2</sub> O 0.09, Na <sub>2</sub> O 6.41, K <sub>2</sub> O 1.74, H <sub>2</sub> O 0.91, F 0.80 $d$ 3.553, $\alpha$ 1.664, $\beta$ 1.670, $\gamma$ 1.675	1.670	1.675	+0.005
67. Graftonite, $(\text{Fe}, \text{Mn}, \text{Ca})_3(\text{PO}_4)_2$ P <sub>2</sub> O <sub>5</sub> 39.85, Al <sub>2</sub> O <sub>3</sub> 0.20, FeO 30.85, MnO 21.92, MgO 0.10, Li <sub>2</sub> O 0.05, Na <sub>2</sub> O 0.28, CaO 6.03, H <sub>2</sub> O 0.60, F 0.20 $d$ 3.775, $\alpha$ 1.709, $\beta$ 1.714, $\gamma$ 1.736	1.720	1.725	+0.005
68. Lazulite, $\text{MgAl}_2(\text{PO}_4)_2(\text{OH})_2$ MgO 11.96, FeO 2.80, CaO 0.08, Al <sub>2</sub> O <sub>3</sub> 32.53, Fe <sub>2</sub> O <sub>3</sub> 0.49, TiO <sub>2</sub> 0.16, P <sub>2</sub> O <sub>5</sub> 46.08, H <sub>2</sub> O 5.90 $d$ 3.118, $\alpha$ 1.610, $\beta$ 1.634, $\gamma$ 1.644	1.629	1.629	0.000
69. Scorzalite, $\text{FeAl}_2(\text{PO}_4)(\text{OH})_2$ MgO 2.93, FeO 17.07, MnO 0.10, CaO 0.03, Al <sub>2</sub> O <sub>3</sub> 30.83, Fe <sub>2</sub> O <sub>3</sub> 0.13, TiO <sub>2</sub> 0.10, P <sub>2</sub> O <sub>5</sub> 42.71 H <sub>2</sub> O 6.10 $d$ 3.327, $\alpha$ 1.636, $\beta$ 1.666, $\gamma$ 1.676	1.659	1.666	+0.007
70. Zincian rockbridgeite, $(\text{Fe}''', \text{Mn})(\text{Fe}''_{4-y}, \text{Zn}_y)(\text{PO}_4)_3(\text{OH})_{5-y} \cdot y\text{H}_2\text{O}$ P <sub>2</sub> O <sub>5</sub> 33.74, FeO 10.86, MnO 2.11, Li <sub>2</sub> O 0.01, Na <sub>2</sub> O 0.13, ZnO 5.20, Fe <sub>2</sub> O <sub>3</sub> 41.20, H <sub>2</sub> O 6.75 $d$ 3.51, $\alpha$ 1.82, $\beta$ 1.83, $\gamma$ 1.88	1.843	1.839	-0.004
71. Montebrasite, $(\text{Li}, \text{Na})\text{Al}(\text{PO}_4)(\text{OH}, \text{F})$ Li <sub>2</sub> O 9.68, Na <sub>2</sub> O 0.43, Al <sub>2</sub> O <sub>3</sub> 35.31, P <sub>2</sub> O <sub>5</sub> 47.70, F 5.42, K <sub>2</sub> O 0.10, MgO 0.33, H <sub>2</sub> O 3.31 $d$ 3.085, $\alpha$ 1.594, $\beta$ 1.608, $\gamma$ 1.616	1.606	1.615	+0.009
72. Adamite, $\text{Zn}_2(\text{AsO}_4)(\text{OH})$ ZnO 57.05, As <sub>2</sub> O <sub>5</sub> 39.15, H <sub>2</sub> O 3.54, SiO <sub>2</sub> 0.26 $d$ 4.435, $\alpha$ 1.722, $\beta$ 1.742, $\gamma$ 1.763	1.742	1.736	-0.006
73. Brazilianite, $\text{NaAl}_3(\text{PO}_4)_2(\text{OH})_4$ Na <sub>2</sub> O 8.29, K <sub>2</sub> O 0.20, Al <sub>2</sub> O <sub>3</sub> 42.77, Fe <sub>2</sub> O <sub>3</sub> 0.03, TiO <sub>2</sub> 0.05, P <sub>2</sub> O <sub>5</sub> 38.71, H <sub>2</sub> O 9.95 $d$ 2.985, $\alpha$ 1.602, $\beta$ 1.609, $\gamma$ 1.623	1.611	1.614	+0.003
74. Ludlamite, $\text{Fe}_3(\text{PO}_4)_2 \cdot 4\text{H}_2\text{O}$ FeO 49.59, MgO 0.97, P <sub>2</sub> O <sub>5</sub> 33.20, H <sub>2</sub> O 16.24 $d$ 3.14, $\beta$ 1.650, $\beta$ 1.667, $\gamma$ 1.688	1.668	1.669	+0.001
75. Monazite, $(\text{Ce}, \text{La})\text{PO}_4$ $(\text{Ce}, \text{La})_2\text{O}_3$ 67.23, ThO <sub>2</sub> 2.98, SiO <sub>2</sub> 0.70, P <sub>2</sub> O <sub>5</sub> 28.97, PbO 0.12 $d$ 4.98, $\alpha$ 1.779, $\beta$ 1.782, $\gamma$ 1.833	1.798	1.781	-0.017

TABLE 3—(continued)

Mineral data	$(\alpha+\beta+\gamma)/3$ or $(2\omega+\epsilon)/3$	$dK+1$	Deviation
76. Monazite (Ca, La) <sub>2</sub> O <sub>3</sub> 65.28, Y <sub>2</sub> O <sub>3</sub> 5.13, P <sub>2</sub> O <sub>5</sub> 29.59 $d$ 5.173, $\alpha$ 1.785, $\beta$ 1.787, $\gamma$ 1.840	1.804	1.822	+0.018
77. Variscite, AlPO <sub>4</sub> ·2H <sub>2</sub> O Al <sub>2</sub> O <sub>3</sub> 32.38, Fe <sub>2</sub> O <sub>3</sub> 0.06, Cr <sub>2</sub> O <sub>3</sub> 0.18, P <sub>2</sub> O <sub>5</sub> 44.71, H <sub>2</sub> O 22.67 $d$ 2.53, $\alpha$ 1.563, $\beta$ 1.588, $\gamma$ 1.594	1.582	1.570	-0.012
78. Scorodite, Fe <sup>III</sup> (AsO <sub>4</sub> )·2H <sub>2</sub> O Fe <sub>2</sub> O <sub>3</sub> 34.75, As <sub>2</sub> O <sub>5</sub> 49.45, TiO <sub>2</sub> 0.02, Sb <sub>2</sub> O <sub>5</sub> 0.06, SiO <sub>2</sub> 0.30, H <sub>2</sub> O 15.42 $d$ 3.278, $\alpha$ 1.784, $\beta$ 1.795, $\gamma$ 1.814	1.798	1.779	-0.019
79. Mansfieldite, Al(AsO <sub>4</sub> )·2H <sub>2</sub> O Fe <sub>2</sub> O <sub>3</sub> 0.88, Al <sub>2</sub> O <sub>3</sub> 23.30, As <sub>2</sub> O <sub>5</sub> 56.43, P <sub>2</sub> O <sub>5</sub> 0.59, Sb <sub>2</sub> O <sub>5</sub> 0.12, TiO <sub>2</sub> 0.91, H <sub>2</sub> O 17.77 $d$ 3.031, $\alpha$ 1.622, $\beta$ 1.624, $\gamma$ 1.642	1.629	1.628	-0.001
80. Hurlbutite, CaBe <sub>2</sub> (PO <sub>4</sub> ) <sub>2</sub> CaO 21.99, BeO 21.44, P <sub>2</sub> O <sub>5</sub> 56.57 $d$ 2.877, $\alpha$ 1.595, $\beta$ 1.601, $\gamma$ 1.604	1.600	1.598	-0.002
81. Fluorapatite, Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> F CaO 55.59, P <sub>2</sub> O <sub>5</sub> 42.22, F 3.78 $d$ 3.18, $\omega$ 1.6325, $\epsilon$ 1.630	1.632	1.648	+0.016
82. Chlorapatite, Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> Cl CaO 53.85, P <sub>2</sub> O <sub>5</sub> 40.88, Cl 6.81 $d$ 3.17, $\omega$ 1.6684, $\epsilon$ 1.6675	1.669	1.686	+0.017
83. Rossite, CaV <sub>2</sub> O <sub>6</sub> ·4H <sub>2</sub> O CaO 18.09, V <sub>2</sub> O <sub>5</sub> 58.67, H <sub>2</sub> O 23.24 $d$ 2.45, $\alpha$ 1.710, $\beta$ 1.770, $\gamma$ 1.840	1.773	1.782	+0.009
84. Scheelite, CaWO <sub>4</sub> CaO 19.47, WO <sub>3</sub> 80.53 $d$ 6.10, $\omega$ 1.920, $\epsilon$ 1.936	1.925	1.921	-0.004
<i>Silicates</i>			
85. Anthophyllite, (Mg, Fe, Al) <sub>7</sub> (Si, Al) <sub>8</sub> O <sub>22</sub> (OH, F) <sub>2</sub> SiO <sub>2</sub> 42.90, TiO <sub>2</sub> 0.49, Al <sub>2</sub> O <sub>3</sub> 17.82, Fe <sub>2</sub> O <sub>3</sub> 1.03, FeO 18.36, MnO 0.14, MgO 15.58, Na <sub>2</sub> O 1.52, K <sub>2</sub> O 0.03, F 0.31, H <sub>2</sub> O 1.95 $d$ 3.277, $\alpha$ 1.656, $\beta$ 1.667, $\gamma$ 1.678	1.667	1.666	-0.001
86. Anthophyllite SiO <sub>2</sub> 45.47, TiO <sub>2</sub> 0.44, Al <sub>2</sub> O <sub>3</sub> 15.86, Fe <sub>2</sub> O <sub>3</sub> 2.94, FeO 15.34, MnO 0.07, MgO 17.62, CaO 0.14, Na <sub>2</sub> O 0.28, H <sub>2</sub> O 1.84 $d$ 3.216, $\alpha$ 1.655, $\beta$ 1.663, $\gamma$ 1.672	1.663	1.672	+0.009

TABLE 3—(continued)

Mineral data	$(\alpha+\beta+\gamma)/3$ or $(2\omega+\epsilon)/3$	$dK+1$	Deviation
87. Anthophyllite SiO <sub>2</sub> 46.06, TiO <sub>2</sub> 0.53, Al <sub>2</sub> O <sub>3</sub> 14.95, Fe <sub>2</sub> O <sub>3</sub> 0.62, FeO 17.45, MnO 0.04, MgO 18.30, CaO 0.07, Na <sub>2</sub> O 0.47, H <sub>2</sub> O 1.51 $d$ 3.245, $\alpha$ 1.652, $\beta$ 1.660, $\gamma$ 1.669	1.661	1.660	-0.001
88. Anthophyllite SiO <sub>2</sub> 48.38, TiO <sub>2</sub> 0.41, Al <sub>2</sub> O <sub>3</sub> 13.23, Fe <sub>2</sub> O <sub>3</sub> 1.28, FeO 14.56, MgO 20.51, CaO 0.04, Na <sub>2</sub> O 0.11, H <sub>2</sub> O 1.48 $d$ 3.259, $\alpha$ 1.648, $\beta$ 1.654, $\gamma$ 1.662	1.655	1.667	+0.012
89. Anthophyllite SiO <sub>2</sub> 50.32, TiO <sub>2</sub> 0.43, Al <sub>2</sub> O <sub>3</sub> 8.05, Fe <sub>2</sub> O <sub>3</sub> 2.18, FeO 18.34, MgO 17.55, CaO 0.74, Na <sub>2</sub> O 0.70, H <sub>2</sub> O 1.69 $d$ 3.279, $\alpha$ 1.654, $\beta$ 1.659, $\gamma$ 1.667	1.660	1.670	+0.010
90. Anthophyllite SiO <sub>2</sub> 57.16, Al <sub>2</sub> O <sub>3</sub> 1.40, FeO 8.73, MnO 0.09, MgO 28.88, CaO 1.48, Na <sub>2</sub> O 0.66, H <sub>2</sub> O 1.60 $d$ 3.106, $\alpha$ 1.618, $\beta$ 1.637, $\gamma$ 1.635	1.630	1.637	+0.007
91. Anthophyllite SiO <sub>2</sub> 57.05, Al <sub>2</sub> O <sub>3</sub> 1.94, FeO 11.10, MnO 0.11 MgO 26.78, CaO 0.64, Na <sub>2</sub> O 0.27, K <sub>2</sub> O 0.06, H <sub>2</sub> O 2.05 $d$ 3.102, $\alpha$ 1.616, $\beta$ 1.628, $\gamma$ 1.641	1.628	1.633	+0.005
92. Amphibole, NaCa <sub>2</sub> (Mg, Fe) <sub>5</sub> (Al, Si) <sub>7</sub> O <sub>22</sub> (OH, F) <sub>2</sub> SiO <sub>2</sub> 44.61, TiO <sub>2</sub> 0.63, Al <sub>2</sub> O <sub>3</sub> 16.72, Fe <sub>2</sub> O <sub>3</sub> 0.72, FeO 8.20, MnO 0.11, CaO 10.36, MgO 15.26, Na <sub>2</sub> O 1.72, K <sub>2</sub> O 0.11, H <sub>2</sub> O 1.51, F 0.08 $d$ 3.17, $\alpha$ 1.646, $\beta$ 1.653, $\gamma$ 1.668	1.656	1.656	0.000
93. Amphibole SiO <sub>2</sub> 45.10, TiO <sub>2</sub> 2.05, Al <sub>2</sub> O <sub>3</sub> 13.39, Fe <sub>2</sub> O <sub>3</sub> 1.58, FeO 9.60, MnO 0.09, MgO 13.69, CaO 11.15, Na <sub>2</sub> O 1.55, K <sub>2</sub> O 0.21, H <sub>2</sub> O 1.49, F 0.18 $d$ 3.17, $\alpha$ 1.661, $\beta$ 1.669, $\gamma$ 1.678	1.669	1.668	-0.001
94. Amphibole SiO <sub>2</sub> 48.07, TiO <sub>2</sub> 0.57, Al <sub>2</sub> O <sub>3</sub> 11.16, Fe <sub>2</sub> O <sub>3</sub> 0.61, FeO 11.31, MnO 0.08, MgO 13.34, CaO 11.67, Na <sub>2</sub> O 0.91, K <sub>2</sub> O 0.14, H <sub>2</sub> O 2.05, F 0.16 $d$ 3.15, $\alpha$ 1.648, $\beta$ 1.664, $\gamma$ 1.678	1.663	1.676	+0.013
95. Amphibole SiO <sub>2</sub> 45.12, TiO <sub>2</sub> 1.70, Al <sub>2</sub> O <sub>3</sub> 9.47, Fe <sub>2</sub> O <sub>3</sub> 3.45, FeO 14.48, MnO 0.07, MgO 10.46, CaO 11.50, Na <sub>2</sub> O 1.45, K <sub>2</sub> O 0.79, H <sub>2</sub> O 1.37, F 0.23 $d$ 3.51, $\alpha$ 1.667, $\beta$ 1.678, $\gamma$ 1.685	1.677	1.741	+0.064

TABLE 3—(continued)

Mineral data	$(\alpha+\beta+\gamma)/3$ or $(2\omega+\epsilon)/3$	$dK+1$	Deviation
96. Amphibole SiO <sub>2</sub> 39.51, TiO <sub>2</sub> 1.46, Al <sub>2</sub> O <sub>3</sub> 12.16, Fe <sub>2</sub> O <sub>3</sub> 4.10, FeO 23.15, MnO 0.09, MgO 4.42, CaO 9.97, Na <sub>2</sub> O 1.81, K <sub>2</sub> O 1.38, H <sub>2</sub> O 1.26, F 1.20 $d$ 3.42, $\alpha$ 1.690, $\beta$ 1.702, $\gamma$ 1.711	1.701	1.709	+0.008
97. Muscovite, KAl <sub>2</sub> Si <sub>4</sub> O <sub>10</sub> (OH, F) <sub>2</sub> SiO <sub>2</sub> 46.75, Al <sub>2</sub> O <sub>3</sub> 34.73, Fe <sub>2</sub> O <sub>3</sub> 0.71, FeO 0.77, MgO 0.92, TiO <sub>2</sub> 0.21, CaO 0.13, Na <sub>2</sub> O 0.47, K <sub>2</sub> O 10.61, BaO 0.13, F 0.16, H <sub>2</sub> O 4.48 $d$ 2.82, $\alpha$ 1.555, $\beta$ 1.589, $\gamma$ 1.590	1.578	1.582	+0.004
98. Dalyite, K <sub>2</sub> ZrSi <sub>6</sub> O <sub>15</sub> SiO <sub>2</sub> 61.91, ZrO <sub>2</sub> 21.72, K <sub>2</sub> O 14.62, Na <sub>2</sub> O 1.75 $d$ 2.84, $\alpha$ 1.575, $\beta$ 1.590, $\gamma$ 1.601	1.589	1.575	-0.014
99. Biotite, K(Mg, Fe) <sub>3</sub> (Si, Al) <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub> SiO <sub>2</sub> 34.95, Al <sub>2</sub> O <sub>3</sub> 19.15, TiO <sub>2</sub> 2.86, Fe <sub>2</sub> O <sub>3</sub> 0.88, FeO 20.81, MnO 0.10, MgO 8.42, CaO 0.26, Na <sub>2</sub> O 0.24, K <sub>2</sub> O 8.54, H <sub>2</sub> O 3.79 $d$ 3.06, $\alpha$ 1.595, $\beta$ 1.649, $\gamma$ 1.649	1.631	1.640	+0.009
100. Kaersutite, Ca <sub>4</sub> (Na, K) <sub>2</sub> (Mg, Fe) <sub>7</sub> Al <sub>6</sub> TiSi <sub>12</sub> O <sub>46</sub> (OH, F) <sub>2</sub> SiO <sub>2</sub> 41.39, TiO <sub>2</sub> 5.69, Al <sub>2</sub> O <sub>3</sub> 14.21, Fe <sub>2</sub> O <sub>3</sub> 3.32, FeO 5.69, MnO 0.08, MgO 13.64, CaO 11.60, Na <sub>2</sub> O 2.29, K <sub>2</sub> O 1.72, H <sub>2</sub> O 0.12, F 0.42 $d$ 3.215, $\alpha$ 1.670, $\beta$ 1.692, $\gamma$ 1.701	1.688	1.698	+0.010
101. Searlesite, Na <sub>2</sub> B <sub>2</sub> Si <sub>4</sub> O <sub>12</sub> ·2H <sub>2</sub> O SiO <sub>2</sub> 58.79, B <sub>2</sub> O <sub>3</sub> 16.92, Na <sub>2</sub> O 15.29, H <sub>2</sub> O 8.89, Al <sub>2</sub> O <sub>3</sub> 0.04, Fe <sub>2</sub> O <sub>3</sub> 0.04, MgO 0.03 $d$ 2.46, $\alpha$ 1.516, $\beta$ 1.531, $\gamma$ 1.535	1.527	1.534	+0.007
102. Hornblende, W <sub>2-3</sub> (XY) <sub>5</sub> (Z <sub>4</sub> O <sub>11</sub> ) <sub>2</sub> (OH, F, Cl) <sub>2</sub> SiO <sub>2</sub> 39.80, Al <sub>2</sub> O <sub>3</sub> 11.39, Fe <sub>2</sub> O <sub>3</sub> 5.93, FeO 14.22, MgO 9.62, CaO 9.68, Na <sub>2</sub> O 1.57, K <sub>2</sub> O 1.60, H <sub>2</sub> O+ 2.59, H <sub>2</sub> O- 0.25, TiO <sub>2</sub> 1.47, F 1.29, Cl 0.58, MnO 0.68 $d$ 3.211, $\alpha$ 1.666, $\beta$ 1.689, $\gamma$ 1.693	1.683	1.683	0.000
103. Hornblende SiO <sub>2</sub> 38.38, Al <sub>2</sub> O <sub>3</sub> 11.01, Fe <sub>2</sub> O <sub>3</sub> 5.79, FeO 24.63, MgO 1.97, CaO 9.54, Na <sub>2</sub> O 1.81, K <sub>2</sub> O 1.72, H <sub>2</sub> O 1.28, TiO <sub>2</sub> 2.37, F 0.96, Cl 0.60, MnO 0.48 $d$ 3.445, $\alpha$ 1.694, $\beta$ 1.717, $\gamma$ 1.723	1.711	1.728	+0.017
104. Hornblende SiO <sub>2</sub> 41.37, Al <sub>2</sub> O <sub>3</sub> 10.43, Fe <sub>2</sub> O <sub>3</sub> 3.86, FeO 16.33, MgO 8.05, CaO 10.29, Na <sub>2</sub> O 1.59, K <sub>2</sub> O 1.46, H <sub>2</sub> O 1.80, TiO <sub>2</sub> 2.91, F 1.17, Cl 0.60, MnO 0.76 $d$ 3.258, $\alpha$ 1.680, $\beta$ 1.692, $\gamma$ 1.696	1.689	1.693	+0.004

TABLE 3—(continued)

Mineral data	$(\alpha + \beta + \gamma)/3$ or $dK+1$ $(2\omega + \epsilon)/3$	$dK+1$	Deviation
105. Pyroxene, $\text{Ca}(\text{Mg, Fe})\text{Si}_2\text{O}_6$ SiO <sub>2</sub> 52.49, Al <sub>2</sub> O <sub>3</sub> 2.72, Fe <sub>2</sub> O <sub>3</sub> 2.59, FeO 12.66, MgO 8.73, CaO 16.76, Na <sub>2</sub> O 0.78, K <sub>2</sub> O 0.28, H <sub>2</sub> O 0.94, TiO <sub>2</sub> 1.33, MnO 0.72 $d$ 3.315, $\alpha$ 1.689, $\beta$ 1.695, $\gamma$ 1.716	1.700	1.700	0.000
106. Augite, $\text{Ca}(\text{Mg, Fe})\text{Si}_2\text{O}_6$ SiO <sub>2</sub> 50.13, Al <sub>2</sub> O <sub>3</sub> 4.31, Fe <sub>2</sub> O <sub>3</sub> 1.97, FeO 8.90, MgO 12.04, CaO 20.50, Na <sub>2</sub> O 0.52, H <sub>2</sub> O 0.74 $d$ 3.315, $\alpha$ 1.689, $\beta$ 1.695, $\gamma$ 1.716	1.700	1.700	0.000
107. Ferrosalite, $\text{CaFeSi}_2\text{O}_6$ SiO <sub>2</sub> 50.73, Al <sub>2</sub> O <sub>3</sub> 1.06, Fe <sub>2</sub> O <sub>3</sub> 0.53, FeO 18.57, MgO 5.70, CaO 22.86, Na <sub>2</sub> O 0.16, K <sub>2</sub> O 0.02, H <sub>2</sub> O 0.12, TiO <sub>2</sub> 0.07, MnO 0.18 $d$ 3.413, $\alpha$ 1.708, $\beta$ 1.714, $\gamma$ 1.736	1.719	1.708	-0.011
108. Hedenbergite, $\text{CaFeSi}_2\text{O}_6$ SiO <sub>2</sub> 48.41, Al <sub>2</sub> O <sub>3</sub> 0.30, Fe <sub>2</sub> O <sub>3</sub> 1.50, FeO 22.97, MgO 1.06, CaO 21.33, Na <sub>2</sub> O 0.14, K <sub>2</sub> O 0.03, H <sub>2</sub> O 0.46, TiO <sub>2</sub> 0.08, MnO 3.72 $d$ 3.535, $\alpha$ 1.722, $\beta$ 1.730, $\gamma$ 1.750	1.734	1.734	0.000
109. Antigorite, $\text{Mg}_6\text{Si}_4\text{O}_{10}(\text{OH})_8$ SiO <sub>2</sub> 43.64, Al <sub>2</sub> O <sub>3</sub> 1.03, Cr <sub>2</sub> O <sub>3</sub> 0.02, Fe <sub>2</sub> O <sub>3</sub> 0.90, FeO 0.81, MnO 0.04, MgO 41.03, NiO 0.16, CaO 0.05, Na <sub>2</sub> O 0.01, K <sub>2</sub> O 0.03, H <sub>2</sub> O 12.27 $d$ 2.603, $\alpha$ 1.561, $\beta$ 1.566, $\gamma$ 1.567	1.565	1.575	+0.010
110. Kornerupine, $\text{R}_{40}(\text{Si, B})_{18}\text{O}_{88}$ SiO <sub>2</sub> , 30.28, B <sub>2</sub> O <sub>3</sub> 3.51, Al <sub>2</sub> O <sub>3</sub> 40.92, Fe <sub>2</sub> O <sub>3</sub> 0.42, FeO 8.53, MgO 14.89, CaO 0.06, Na <sub>2</sub> O 0.08, H <sub>2</sub> O 0.97, TiO <sub>2</sub> 0.19, P <sub>2</sub> O <sub>5</sub> 0.09, Cr <sub>2</sub> O <sub>3</sub> 0.06 $d$ 3.37, $\alpha$ 1.681, $\beta$ 1.694, $\gamma$ 1.695	1.690	1.677	-0.013
111. Kornerupine SiO <sub>2</sub> 30.6, B <sub>2</sub> O <sub>3</sub> 2.8, Al <sub>2</sub> O <sub>3</sub> 37.7, Fe <sub>2</sub> O <sub>3</sub> 3.3, FeO 4.8, MgO 20.8 $d$ 3.335, $\alpha$ 1.669, $\beta$ 1.681, $\gamma$ 1.682	1.677	1.675	-0.002
112. Chloritoid, $(\text{Fe, Mg})_2(\text{Al, Fe})_2(\text{Al, Si})_4\text{O}_{10}(\text{OH})_4$ SiO <sub>2</sub> 25.12, Al <sub>2</sub> O <sub>3</sub> 40.25, Fe <sub>2</sub> O <sub>3</sub> 3.22, FeO 19.62, MnO 1.05, MgO 3.89, K <sub>2</sub> O 0.09, H <sub>2</sub> O 6.76 $d$ 3.52, $\alpha$ 1.719, $\beta$ 1.721, $\gamma$ 1.725	1.722	1.734	+0.012
113. Ferrocarpholite, $\text{H}_4(\text{Fe, Mg})\text{Al}_2\text{Si}_2\text{O}_{10}$ SiO <sub>2</sub> 37.59, Al <sub>2</sub> O <sub>3</sub> 29.39, Fe <sub>2</sub> O <sub>3</sub> 2.07, TiO <sub>2</sub> 0.22, MgO 2.52, MnO 0.14, FeO 17.98, H <sub>2</sub> O 10.08 $d$ 3.04, $\alpha$ 1.628, $\beta$ 1.644, $\gamma$ 1.647	1.640	1.652	+0.012

TABLE 3—(continued)

Mineral data	$(\alpha+\beta+\gamma)/3$ or $(2\omega+\epsilon)/3$	$dK+1$	Deviation
114. Allanite, $X_2Y_3Z_3O_{12}OH$ SiO <sub>2</sub> 28.66, Al <sub>2</sub> O <sub>3</sub> 9.95, Fe <sub>2</sub> O <sub>3</sub> 10.20, FeO 7.29, TiO <sub>2</sub> 2.00, MgO 0.58, MnO 6.71, CaO 10.03, ThO <sub>2</sub> 0.95, UO <sub>2</sub> 0.01, (Ce, La) <sub>2</sub> O <sub>3</sub> 22.30, H <sub>2</sub> O 1.32 $d$ 3.95, $\alpha$ 1.791, $\beta$ 1.815, $\gamma$ 1.822	1.809	1.806	-0.003
115. Manganpyrosomalite, (Mn, Fe) <sub>8</sub> (Si <sub>6</sub> O <sub>16</sub> )(OH, Cl) <sub>10</sub> MnO 39.25, FeO 12.48, MgO 0.74, ZnO 1.95, SiO <sub>2</sub> 34.27, As <sub>2</sub> O <sub>5</sub> 0.13, Cl 3.82, H <sub>2</sub> O 8.22 $d$ 3.13, $\omega$ 1.669, $\epsilon$ 1.631	1.656	1.663	+0.007
116. Wollastonite, CaSiO <sub>3</sub> CaO 48.29, SiO <sub>2</sub> 51.71 $d$ 2.915, $\alpha$ 1.616, $\beta$ 1.629, $\gamma$ 1.631	1.625	1.629	+0.004
117. Pseudowollastonite, CaSiO <sub>3</sub> CaO 48.29, SiO <sub>2</sub> 51.71 $d$ 2.905, $\alpha$ 1.610, $\beta$ 1.610, $\gamma$ 1.654	1.625	1.627	+0.002
118. Phenacite, Be <sub>2</sub> SiO <sub>4</sub> SiO <sub>2</sub> 54.45, BeO 45.55 $d$ 3.00, $\omega$ 1.654, $\epsilon$ 1.668	1.659	1.663	+0.004
119. Fayalite, Fe <sub>2</sub> SiO <sub>4</sub> SiO <sub>2</sub> 29.48, FeO 70.52 $d$ 4.34, $\alpha$ 1.835, $\beta$ 1.877, $\gamma$ 1.886	1.866	1.837	-0.029
120. Tremolite, Ca <sub>2</sub> Mg <sub>5</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub> SiO <sub>2</sub> 59.15, CaO 13.81, MgO 24.82, H <sub>2</sub> O 2.22 $d$ 2.9, $\alpha$ 1.599, $\beta$ 1.613, $\gamma$ 1.625	1.612	1.611	-0.001
121. Actinite, NaFeSi <sub>2</sub> O <sub>6</sub> SiO <sub>2</sub> 52.01, Fe <sub>2</sub> O <sub>3</sub> 34.57, Na <sub>2</sub> O 13.42 $d$ 3.55, $\alpha$ 1.776, $\beta$ 1.819, $\gamma$ 1.836	1.810	1.824	+0.014

## INDEX TO DATA OF TABLE 3

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(Continued from page 761)

calculated and experimental  $n$  values for all but one entry, #95, where  $dK+1$  deviates from  $(\alpha+\beta+\gamma)/3$  by  $+0.064$ . The chemical composition of this amphibole, #95, suggests that the density of 3.51 is in error on the high side. Amphibole #96, for example, contains much more combined iron and titanium than amphibole #95 and has a lower density of 3.42.

The density of amphibole #95 calculated from  $(n-1)/d=K$  is 3.21 and suggests that the measured value 3.51 is either a typographical or experimental error. On the other hand, the deviations of the calculated from the measured mean  $n$  values for rutile, anatase, and brookite (nos. 11, 12, 13, Table 3) are +0.029, +0.011, and +0.021 and must result from differences in bonding in the 3 different structures of the poly-

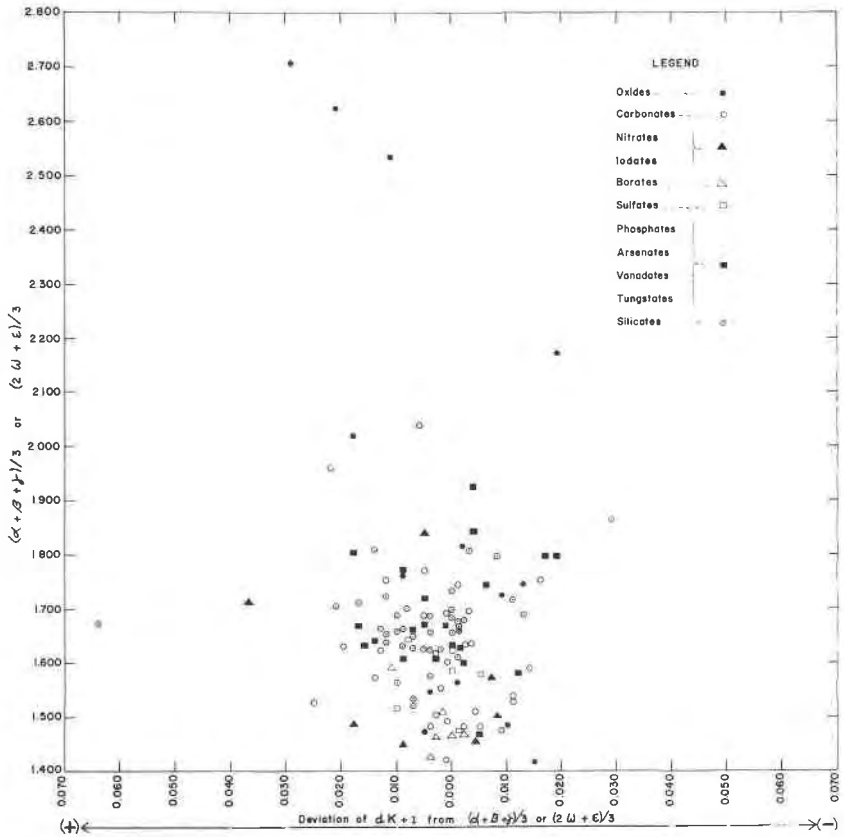


FIG. 1.  $\pm$  Deviation of  $dK+1$  from  $(\alpha+\beta+\gamma)/3$  or  $(2\omega+\epsilon)/3$  for 121 minerals.

morphs. Inasmuch as all 3 polymorphs show a positive deviation of  $dk+1$ , there is good possibility that Larsen's value,  $k_{TiO_2} = .397$ , is slightly on the high side.

The writer concludes that, on the basis of data for 121 minerals from the modern literature, the rule of Gladstone and Dale,  $[(n-1)/d=K]$ , holds surprisingly well for most minerals. Here is a rapid, workable method for (1) evaluating much of the old mineralogical data in the

literature, (2) checking new data before publication, (3) calculating a reasonably reliable approximation of the mean index of refraction or density where one or the other cannot be measured, and (4) locating an inaccurate chemical determination where the density, indices of refraction, and analytical determinations are otherwise accurate, e.g. use of the rule,  $[(n-1)/d=K]$ , revealed that an 88 per cent summation for a preliminary analysis of sahamalite,  $(Mg, Fe)(Ce, La)_2(CO_3)_4$ , resulted from an error in the  $CO_2$  determination. This was accomplished by determining that the specific refractive energy ( $k$ ) of the missing 12 per cent was approximately that of  $CO_2$  (Jaffe, Meyrowitz, and Evans, 1953).

If this paper encourages more widespread use of the neglected rule of Gladstone and Dale, it will have served its purpose.

#### ACKNOWLEDGMENTS

The author is indebted to E. S. Larsen, Jr., for suggesting the study and indicating where old data might be inaccurate for particular minerals. Thanks are due to J. D. H. Donnay and J. C. Rabbitt for suggesting methods of presenting the data and improving the manuscript.

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*Manuscript received Jan 19, 1956.*