

## X-RAY DIFFRACTION DATA ON SOME RADIOACTIVE OXIDE MINERALS\*

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### ABSTRACT

X-ray powder photographs and specific gravity determinations of specimens belonging to the uraninite-thorianite series and the pyrochlore-microlite series gave, for the former,  $a = 5.403\text{--}5.575$  Å (19 specimens),  $G = 6.43\text{--}9.55$  (9), and for pyrochlore-microlite,  $a = 10.296\text{--}10.441$  Å (5). Indexed powder data are given for uraninite and for ignited microlite. The powder pattern of orthorhombic euxenite (ignited at  $1000^\circ$  C), interpreted with the aid of established morphological descriptions, gave for this mineral,  $a = 5.520$ ,  $b = 14.57$ ,  $c = 5.166$  Å, most probable space-group  $Pcmn$ ,  $Z = 4$ ,  $G$  (meas.) = 5.23,  $\rho$  (calc for Y:Er = 2:1) = 5.58. An indexed powder pattern is given. Two specimens of "tanteuxenite" gave patterns of the uraninite type with  $a \sim 5.10$  Å thus casting doubt on their identity with euxenite.

Radioactive minerals are currently of general interest because they frequently contain uranium and related elements, but they hold a special interest mineralogically because they include most of the minerals classed as "metamict." The possession of this characteristic is probably the main reason why certain of these minerals have not previously been studied by x-ray diffraction methods. The author of this paper became interested in radioactive minerals during the summer of 1948 while working in the radioactive laboratory of the Mineralogical Section of the Geological Survey of Canada, at Ottawa. Dr. H. V. Ellsworth, mineralogist in charge of that laboratory, kindly donated a representative collection of these minerals, mostly from Canadian localities, many of which he had analyzed chemically (Ellsworth, 1932). Other specimens of radioactive minerals were obtained from the Mineralogical Museum of the Department of Geology, University of Manitoba, in which Department the present research was carried out under the direction of Dr. R. B. Ferguson, Assistant Professor of Mineralogy, whose guidance is gratefully acknowledged.

This paper deals with the members of three series of radioactive minerals, uraninite-thorianite, pyrochlore-microlite, and euxenite-polycrase. The investigation of representatives of the first two of these groups, both of which are isometric, was confined to indexing the x-ray powder photographs and to tabulating new cell edges with old and new specific gravities for specimens from various localities. In the case of the orthorhombic

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mineral euxenite, however, cell dimensions, possible space-groups, and probable cell content were deduced for the first time from power data.

*The metamict state.* A considerable number of minerals are known which show external crystal form but are amorphous to  $x$ -rays—they are non-crystalline pseudomorphs of originally crystalline material and are termed “metamict.” Although amorphous, these minerals can be restored to crystallinity by heating them until they glow, their original structure presumably being regained. The resultant material, however, is cryptocrystalline and not suitable for single-crystal study.

All minerals that are commonly metamict have fairly complex compositions, involving a large amount of isomorphous substitution. They usually contain, among other elements, metals of the rare-earth group, and uranium and thorium, and it is the presence of these elements which accounts for the characteristic radioactivity of these minerals. There has been some speculation in the past as to the reason for the breakdown of the crystal structure in metamict minerals, but no definite conclusions have been reached. Proposed explanations have attributed it to hydration (Brögger, 1893), radioactivity (Mügge, 1922), the type of lattice and valence-change (Goldschmidt & Thomassen, 1924), and pressure (Vegard, 1927).

*Methods.* Standard  $x$ -ray powder diffraction techniques were employed. All lattice spacings and cell dimensions are given in Ångström units ( $\text{CuK}\alpha_1 = 1.5405 \text{ \AA}$ ) except where stated otherwise. Data obtained from outside sources either are given in kX units ( $\text{CuK}\alpha_1 = 1.5374 \text{ kX}$ ) or have been converted to Å units. Specific gravities were measured on a Berman microbalance. For the heating experiments on euxenite, a rheostat-controlled electric furnace was used and the accuracy is probably about  $\pm 25^\circ\text{C}$ .

#### URANINITE-THORIANITE SERIES

In addition to the two end-members, uraninite  $\text{UO}_2$  and thorianite  $\text{ThO}_2$ , this series includes several varieties, the best known of which is pitchblende, a massive or colloform uraninite. The members of this series are isometric with cell edges of about 5.47 kX for uraninite and 5.57 kX for thorianite (Goldschmidt & Thomassen, 1923). Neither of these minerals has been reported as metamict.

$X$ -ray powder photographs were taken of nineteen specimens belonging to this series. Table 1 gives, for a typical uraninite, the indexed powder data, in Å units, which are in reasonable agreement with those published in the ASTM card index (1945), and Figs. 1 and 2 show powder photographs of two different members of this series. Table 2 gives a list of the specimens examined, the cell edge derived from a powder photograph of each one, and the measured specific gravities for most of them.

TABLE 1. URANINITE—(U,Th)O<sub>2</sub>: X-RAY POWDER PATTERN

Locality: Lot 31, Range 1, Ottawa county, P.Q.

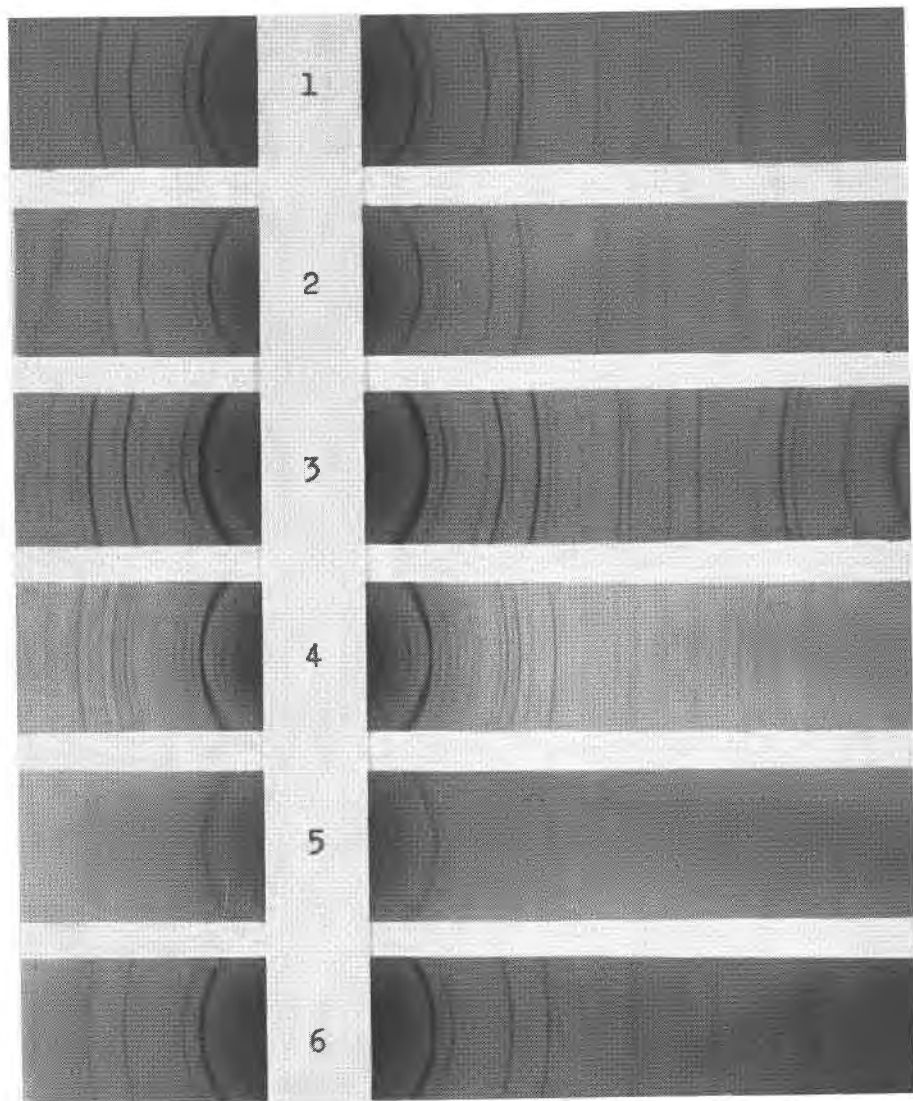
Cubic, *Fm3m*; *a* = 5.468 Å, *Z* = 4

<i>I</i>	$\theta$ (Cu)	<i>d</i> (meas.)	( <i>hkl</i> )	<i>d</i> (calc.)	<i>I</i>	$\theta$ (Cu)	<i>d</i> (meas.)	( <i>hkl</i> )	<i>d</i> (calc.)
10	14.10°	3.16	(111)	3.157	3	47.05°	1.052	{(333)} {(115)}	1.052
5	16.38	2.73	(002)	2.734	1	52.95	0.965	(044)	0.967
8	23.45	1.935	(022)	1.935	4	56.35	0.925	(135)	0.924
8	27.85	1.648	(113)	1.648	2	57.65	0.912	{(006)} {(244)}	0.912
2	29.23	1.576	(222)	1.578	2	63.05	0.864	(026)	0.865
1	34.30	1.366	(004)	1.367	2	67.35	0.835	(335)	0.834
3	37.95	1.252	(133)	1.254	2	69.15	0.824	(226)	0.825
3	39.10	1.221	(024)	1.222	$\frac{1}{4}$	77.85	0.788	(444)	0.790
3	43.65	1.116	(224)	1.116					

TABLE 2. URANINITE-THORIANITE SERIES: DENSITY AND CELL EDGE OF SPECIMENS FROM VARIOUS LOCALITIES

Mineral	Locality	Measured Sp. Gr.	<i>a</i> (Å)
Thorianite	Artificial ThO <sub>2</sub>	9.87*	5.62*
Thorianite	Galle, Ceylon	9.43	5.575
Thorianite	Ceylon	—	5.563
Thorianite	Sherrer Quarry, Eastern Penn.	—	5.505
Uraninite	Artificial UO <sub>2</sub>	10.95*	5.48*
Uraninite	Branchville, Conn.	9.73*	5.486
Uraninite	Raade, Norway ( <i>var.</i> Bröggerite)	—	5.485
Uraninite	Wilberforce, Ontario	7.05	5.469
Uraninite	Lot 31, Range 1, Ottawa Co., P.Q.	6.50	5.468
Uraninite	Belgian Congo	—	5.458
Uraninite	Besner Mine, Henvey twp., Ont.	—	5.454
Uraninite	Yancey Co., North Carolina	9.55	5.449
Uraninite	Deer Park Mine, N. Carolina	6.52	5.446
Uraninite	Lanark Co., Ontario	—	5.436
Uraninite	Lot 9, Range 2, Mattawan twp., Ont.	8.64	5.433
Uraninite	Reboleira property, Portugal	—	5.409
Pitchblende	Various	6.5–8.5*	5.43–5.46*
Pitchblende	Great Bear Lake, N.W.T.	6.43	5.475
Pitchblende	Great Bear Lake, N.W.T.	6.51	5.472
Pitchblende	Great Bear Lake, N.W.T.	—	5.461
Pitchblende	Hottah Lake, N.W.T.	6.46	5.441
Pitchblende	Black Lake, Sask.	—	5.403

\* From Palache, Berman & Frondel (1944). *a* values have been converted from kX to Å units.



FIGS. 1-6. X-ray powder photographs with Cu/Ni radiation; camera radius  $360/4\pi$  mm. (1 mm. on film =  $1^\circ\theta$ ); full size reproductions of double-printed negatives. FIG. 1. Pitchblende, Great Bear Lake, Northwest Territories,  $a=5.472$  A. FIG. 2. Thorianite, Galle, Ceylon,  $a=5.575$  A. FIG. 3. Microlite, Amelia Court House, Virginia,  $a=10.424$  A. FIG. 4. Euxenite, Mattawan twp., Ontario, heated at  $1000^\circ$  C. for 100 hours. FIG. 5. Euxenite, Sabine twp., Ontario, heated at  $400^\circ$  C. for 5 minutes. FIG. 6. "Tanteuxenite," Eleys, West Australia,  $a=5.10$  A.

Several of the specimens were largely altered, and fragments suitable for specific gravity determinations could not be obtained from them. Where the specific gravities were measured, a range of values was obtained for each sample. In all cases, the specific gravity quoted is the largest, since the variation is due to different degrees of alteration, and the unaltered mineral has the greatest specific gravity.

Table 2 shows that apparently no correlation exists between cell edge and specific gravity, nor between the latter and the mineral variety. The range of cell edges for thorianite (5.505 to 5.62 Å), however, is above the range for uraninite-pitchblende (5.403 to 5.486 Å) so that these two members of the series can be distinguished by powder photographs. The table also shows a wider range of cell edges for pitchblende (5.403 to 5.475 Å) than that given by Palache, Berman & Frondel (1944), 5.43 to 5.46 Å.

#### PYROCHLORE-MICROLITE SERIES

Although many elements are found in small amount in these minerals, the essential composition of pyrochlore may be expressed as  $\text{NaCaCb}_2\text{O}_6\text{F}$ , and of microlite as  $(\text{Na,Ca})_2\text{Ta}_2\text{O}_6(\text{O,OH,F})$ . The variable composition has given rise to numerous varietal names according to the predominant replacing element. The members of this series are cubic with symmetry of the space-group  $Fd\bar{3}m$ , and with cell edges of about 10.37 Å for pyrochlore and about 10.40 Å for microlite. Almost all specimens of pyrochlore and microlite are metamict, this characteristic varying from slight to complete.

X-ray powder diffraction photographs were taken of one specimen of microlite, one of pyrochlore, and two of "ellsworthite" (uranian pyrochlore). All of these were metamict, and were ignited and rephotographed, although the microlite gave an indistinct pattern without heating indicating that it was only partially metamict. The patterns obtained in this manner were read and indexed using the cubic crystal analyzer. The indexed powder data for microlite (ignited) from Amelia Court House, Virginia, are given in Table 3 and the photograph appears as Fig. 3.

The cell edges obtained from the five photographs are in good agreement with those in Palache, Berman & Frondel (1944), and are as follows: microlite from Amelia Court House, Virginia, before ignition 10.441 Å, after ignition 10.424 Å; ignited pyrochlore from Brevik, Norway, 10.404 Å; ignited ellsworthite from Hybla, Ontario 10.318 Å, and from Cardiff township, Ontario 10.296 Å.

#### EUXENITE-POLYCRASE SERIES

In addition to euxenite and polycrase, this series includes lyndochite, which is a member having less than one per cent uranium (Ellsworth,

TABLE 3. MICROLITE (IGNITED)—(Na,Ca)<sub>2</sub>Ta<sub>2</sub>O<sub>6</sub>(O,OH,F): X-RAY POWDER PATTERN  
 Locality: Amelia Court House, Virginia  
 Cubic, *Fd3m*; *a*=10.424 Å; *Z*=8

<i>I</i>	$\theta$ (Cu)	<i>d</i> (meas.)	( <i>hkl</i> )	<i>d</i> (calc.)	<i>I</i>	$\theta$ (Cu)	<i>d</i> (meas.)	( <i>hkl</i> )	<i>d</i> (calc.)
6	7.40°	5.98	(111)	6.01	$\frac{1}{2}$	49.15°	1.018	{(0.2.10) (268)}	1.022
$\frac{1}{4}$	12.05	3.69	(022)	3.69	$\frac{1}{2}$	49.75	1.009	{(377) (159)}	1.008
4	14.35	3.11	(113)	3.14	3	50.20	1.003	(666)	1.003
10	15.00	2.98	(222)	3.00	$\frac{1}{2}$	52.40	0.972	(359)	0.972
3	17.38	2.58	(004)	2.61	1	55.15	0.939	{(1.1.11) (577)}	0.938
1	18.85	2.38	(133)	2.39	2	56.75	0.921	(088)	0.921
$\frac{1}{4}$	21.45	2.11	(224)	2.13	2	57.75	0.911	{(1.3.11) (179) (559)}	0.911
2	22.65	1.999	{(333) (115)}	2.01	4	60.90	0.881	{(2.6.10) (668)}	0.881
8	24.80	1.836	(044)	1.843	3	62.45	0.869	{(0.0.12) (488)}	0.869
2	26.00	1.757	(135)	1.762	1	63.75	0.859	{(1.5.11) (777)}	0.860
$\frac{1}{2}$	26.85	1.705	(244)	1.735	$\frac{1}{4}$	65.25	0.848	{(2.2.12) (4.6.10)}	0.846
$\frac{1}{4}$	29.05	1.585	(335)	1.589	2	66.95	0.837	{(3.5.11) (579)}	0.837
8	29.50	1.563	(226)	1.571	3	69.20	0.824	(0.4.12)	0.824
2	30.88	1.500	(444)	1.504	1	69.55	0.822	(199)	0.817
2	31.95	1.455	{(117) (155) (137)}	1.460	1	75.15	0.797	{(1.1.13) (1.7.11) (5.5.11) (399)}	0.798
2	34.70	1.352	{(355)}	1.357	3	75.70	0.795	(6.6.10)	0.795
2	36.25	1.302	(008)	1.303	2	78.85	0.785	(4.4.12)	0.786
$\frac{1}{2}$	37.25	1.272	(337)	1.274	1	81.75	0.778	{(1.3.13) (3.7.11) (779)}	0.779
$\frac{1}{4}$	38.95	1.225	{(066) (228)}	1.228	1	82.45	0.777	{(0.6.12) (4.8.10)}	0.777
$\frac{1}{4}$	39.85	1.202	(555)	1.203					
3	40.15	1.194	(266)	1.195					
3	41.35	1.165	(048)	1.165					
1	42.45	1.141	{(119) (357)}	1.144					
$\frac{1}{4}$	42.95	1.130	(248)	1.137					
$\frac{1}{2}$	43.85	1.112	(466)	1.111					
1	44.80	1.093	(139)	1.093					
3	46.35	1.064	(448)	1.064					
1	47.35	1.047	{(177) (339) (557)}	1.047					

1932, p. 49). Tanteuxenite, a supposed high-tantalum member of this series, is discussed briefly at the end of this paper. The composition of these minerals may be expressed as AB<sub>2</sub>O<sub>6</sub> where A = Y, Ce, Ca, U, Th; and B = Ti, Cb, Ta, and Fe<sup>III</sup>. The high-Ti end-member is polycrase and the high-(Cb+Ta) member is euxenite.

According to morphological evidence, these minerals crystallize in the

dipyramidal class of the orthorhombic system and have an axial ratio of  $a:b:c=0.3789:1:0.3527$  (Palache, Berman & Frondel, 1944). They are all metamict and, to date, their unit cell dimensions and space-group have not been published.

It was possible to obtain  $x$ -ray diffraction patterns from these minerals by igniting them but since the ignited fragments were cryptocrystalline, it was not possible to use them for single-crystal  $x$ -ray analysis. Attempts were made, however, to produce single crystals sufficiently large for this purpose by heating the fragments for long periods at high temperatures.

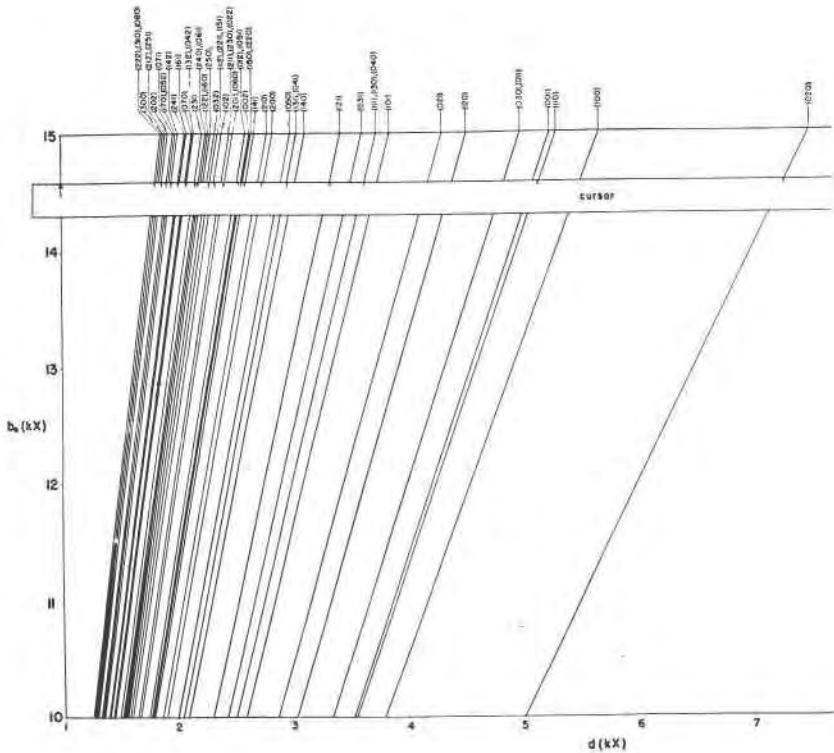
*Heating Experiments and Variations in the Powder Pattern.* To investigate this possibility, a sample of euxenite (from Lot 28, Con. 1, Sabine twp., Nipissing District, Ontario) was selected, and portions of it were heated for varying lengths of time at different temperatures. The first sample was heated at 400° C. for 5 minutes, the second at 800° C. for 10 minutes, the third at 800° C. for 6 hours, and others at 1000° C. for 1, 2, 13, 26, 32, 40, and 100 hours. Although a slight increase in crystal size was noted with the first three samples, all those heated to 1000° C. appeared cryptocrystalline under the petrographic microscope and work along this line was discontinued.

Powder pictures were taken of all fragments ignited and it was noted that, whereas all the powder patterns were generally similar, only those of samples which had been heated to 1000° C. were identical. Those samples heated to 400° and 800° C. showed considerable variations, chiefly in the presence or absence of certain lines. This same type of variation was found in a set of six powder pictures of euxenites from different Canadian localities, these specimens having been heated over a Tyrrel burner to render them crystalline.

The work of Faessler (1942) on gadolinite seems relevant to the present problem. He found that the crystalline structure of that mineral is regained rapidly by heating to 800° C. (the recovery is accompanied by glowing), and is regained more slowly by heating to lower temperatures. This suggests a possible explanation of the variations with heat treatment of the euxenite powder pattern. If, as the constancy of the 1000° C. pattern suggests, the temperature of rapid recovery of the crystal structure lies between 800° C. and 1000° C., then these variations could be the result of incomplete recovery of the crystalline structure when the sample is heated to only 800° C. or less. The variations in the patterns of euxenites from different localities is probably also due to this, since these specimens were heated for about one minute in a Tyrrel burner which gives a range of temperatures up to 1000° C. Fig. 4 reproduces the powder pattern which is believed to be the "true" euxenite pattern (sample heated at 1000° C. for 100 hours), and Fig. 5 reproduces, for

comparison, one of the variable euxenite patterns which illustrates the chief difference from the true pattern—a doubling of the strongest line.

*The "Euxenite Analyzer" and Extraction of Cell Dimensions.* In an effort to index the powder patterns, an analyzer of the type used for cubic crystals was constructed for euxenite. To take account of the three orthorhombic cell dimensions, the axial ratio  $a:b:c=0.3789:1:0.3527$  was used to calculate 40 or so of the largest "spacings" with  $b=1$ . These values and a corresponding set for  $b=10$  provided the data necessary for plotting the curves of  $d$  against  $b$  for numerous lattice planes. The completed analyzer appears as Fig. 7.





Mattawan township, Ontario) was chosen for detailed analysis. It was examined for a series of spacings which might represent the various orders of reflection from one set of lattice planes. One such series was readily found, being 7.30, 3.66, 2.43, 1.823, 1.457, and 1.216 Å. Since the 7.30 Å spacing is that of the innermost line on the film, this was assumed to be a pinakoidal spacing and, adopting the accepted orthorhombic orientation  $c < a < b$ , this was further assumed to be the first order of the side pinakoidal reflection, i.e.  $d(010)$ . On these assumptions, the smaller values above would be the second to sixth order reflections of  $(0k0)$ . When applied to the analyzer, this value of 7.30 Å for  $b$  left many strong lines not indexed. However, when double this value of  $b$  was used (14.60 Å), it was found that all but a few very weak lines could be satisfactorily indexed. In this way, the approximate cell dimensions were deduced as  $a = 5.53$ ,  $b = 14.60$ ,  $c = 5.17$  Å.

*Derivation of the Space-Group.* Using the above values for the unit cell dimensions, the spacings of all possible planes were calculated down to a spacing of 2.00 Å. By comparing these possible reflections with those actually observed in the powder pattern, a set of possible space-groups for euxenite was derived. The method was as follows:  $(110)$  and  $(001)$  are the only planes which would give the second line on the powder pattern, and these reflections would be extinguished by all  $(hkl)$  conditions except  $(hkl)$  present only with  $(h+k) = 2n$  and  $(hkl)$  present only with  $(h+k+l) = 2n$ . Of these, the former is excluded by the unique reflection  $(121)$  and the latter by another unique reflection  $(102)$ . Thus, no condition is possible in  $(hkl)$  which must therefore be present in all orders, and euxenite must have a primitive lattice. By similar reasoning applied to a number of reflections given by unique special planes, the space-group of euxenite was reduced to the possibilities  $P(mnc)$  ( $mc$ ) ( $mnab$ ).

Now, if the intensity effect of the structure factor is disregarded, and it is assumed that possible planes which are *not* represented by observed lines have been cancelled by some extinction condition, the number of possible space-groups can be reduced much further. For instance, the line  $(021)$  does not appear, and therefore either of the extinction conditions  $(0kl)$  present only with  $(k+l) = 2n$ , or  $(0kl)$  present with  $l = 2n$  must hold since only these will extinguish reflections from this plane. Carried further, this method will reduce the number of probable space-groups for euxenite to only one,  $Pccn$ . However,  $Pcmn$  is eliminated by the condition  $(h0l)$  present only with  $l = 2n$  based solely on the absence of the  $(101)$  reflection, and the occurrence of both  $(101)$  and  $(201)$  as common crystal forms, as explained in the next paragraph, makes it appear more likely that  $Pcmn$  is a possibility. Thus we arrive at the most probable space-group of euxenite as either  $Pccn$  or  $Pcmn$ .

At this point it was found profitable to consider by application of the Donnay-Harker law, which of these two space-groups, if either, is favored by the morphology of the mineral. Donnay and Harker (1937) give as their modification of the Bravais law:

“The morphological importance of a crystal face is inversely proportional to its reticular area  $S$  if the lattice is of the hexahedral mode (no centering) and the space group symmetry does not contain any screw axis or glide plane. The effect of lattice centering, screw axes, and glide planes is corrected for if the face indices are replaced, in the  $S$  formula, by the “multiple indices” of the lowest order of  $x$ -ray reflection compatible with the space group symmetry.”

Since the reticular area of a lattice plane is inversely proportional to the

TABLE 4. EUXENITE: COMPARISON OF THEORETICAL AND ACTUAL FORM IMPORTANCE

$d(hkl)$ A	<i>Pccn</i>	<i>Pcmn</i>	Observed
7.28	(020)	(020)	(010)
5.16	(110)	(110)	(101)
3.77	—	(101)*	(110)
3.65	(130)	(130)	—
3.65	(111)	(111)	(111)
3.36	(121)	(121)	(121)†
2.98	(131)	(131)	(131)†
2.77	(200)	(200)	(100)
2.62	(141)	(141)	—
2.58	(002)	(002)	(001)†
2.57	(150)	(150)	—
2.54	(012)	(012)	—
2.44	(022)	(022)	(011)†
2.44	—	(201)*	(201)†

\* Not observed on powder pattern.

† Infrequent forms whose order of importance cannot be given.

spacing of its set of planes, the Donnay-Harker principle implies that the decreasing order of importance of the faces on a crystal is exactly that of the order of appearance of the lines on the  $x$ -ray powder pattern of that crystal, provided none of the possible lines is extinguished by a very low structure factor value. Consequently, the presence or absence of certain crystal forms can be used as an aid in deducing the space-group of a given crystal. Donnay and his students have, in fact, used the morphology alone to deduce the unique space-group of certain well-developed crystals such as scheelite (Donnay, 1942), but with euxenite the comparatively poor face development can only assist in determining the space-group. Dana's *System of Mineralogy* (Palache, Berman & Frondel,

1944) gives, as the commonest crystal forms for the euxenite-polycrase series, (010), (101), (110), (111), and (100); and, as other forms, (001), (011), (201), (121), and (131). Since good crystals of these minerals are uncommon, the above order which is approximately that of decreasing importance, may not be too reliable. Table 4 shows the order of appearance of the lines on an  $x$ -ray powder pattern of euxenite which would be given by each of the two possible space-groups deduced above, and in comparison, the observed order of form importance. In this table, the

TABLE 5. EUXENITE—(Y, Ce, Ca, U, Th) (Cb, Ta, Ti)<sub>2</sub>O<sub>6</sub>:  
X-RAY POWDER PATTERN

Locality: Lot 29, Con. 3, Mattawan twp., Nippissing dist., Ont.

Orthorhombic, *Pcmn*;  $a=5.520$ ,  $b=14.57$ ,  $c=5.166$  Å,  $Z=4$

<i>I</i>	$\theta$ (Cu)	<i>d</i> (meas.)	( <i>hkl</i> )	<i>d</i> (calc.)	<i>I</i>	$\theta$ (Cu)	<i>d</i> (meas.)	( <i>hkl</i> )	<i>d</i> (calc.)
1	6.05°	7.30	(020)	7.28				(222)	1.826
2	8.58	5.16	(110)	5.16				(310)	1.826
			(130)	3.65				(152)	1.825
3	12.15	3.66	(111)	3.65	4	24.98°	1.823	(260)	1.823
			(040)	3.65				(171)	1.823
2	13.28	3.36	(121)	3.36				(080)	1.822
10	15.00	2.98	(131)	2.98	3	25.80	1.769	(062)	1.770
2	16.18	2.77	(200)	2.77				(311)	1.721
$\frac{1}{4}$	17.15	2.61	(141)	2.62	4	26.55	1.723	(330)	1.720
			(002)	2.58				(261)	1.719
2	17.35	2.58	(220)	2.58	$\frac{1}{2}$	27.30	1.679	(242)	1.675
			(150)	2.57				(181)	1.640
$\frac{1}{2}$	17.63	2.54	(012)	2.54	3	28.08	1.635	(113)	1.633
			(022)	2.44				(331)	1.632
3	18.48	2.43	(201)	2.44	1	28.65	1.605	(123)	1.604
			(060)	2.43				(252)	1.583
			(112)	2.31	$\frac{1}{2}$	29.10	1.583	(271)	1.582
1	19.53	2.30	(221)	2.31	1	29.55	1.560	(341)	1.565
			(151)	2.31				(133)	1.557
$\frac{1}{4}$	20.00	2.252	(032)	2.280	$\frac{1}{4}$	30.38	1.522	(280)	1.520
			(122)	2.227	$\frac{1}{4}$	30.85	1.501	(302)	1.499
1	20.50	2.199	(240)	2.200				(143)	1.498
1	20.68	2.182	(231)	2.176				(312)	1.490
2	21.45	2.106	(132)	2.108				(351)	1.490
$\frac{1}{4}$	21.83	2.071	(161)	2.042	4	31.18	1.487	(262)	1.490
$\frac{1}{2}$	22.35	2.025	(241)	2.024				(082)	1.489
$\frac{1}{2}$	23.00	1.970	(142)	1.969				(191)	1.488
			(170)	1.948				(322)	1.462
1	23.45	1.935	(052)	1.933	1	31.90	1.457	(203)	1.461
2	24.05	1.889	(202)	1.886				(281)	1.458
								(0.10.0)	1.457

TABLE 5—continued

<i>I</i>	$\theta(\text{Cu})$	<i>d</i> (meas.)	<i>I</i>	$\theta(\text{Cu})$	<i>d</i> (meas.)	<i>I</i>	$\theta(\text{Cu})$	<i>d</i> (meas.)	<i>I</i>	$\theta(\text{Cu})$	<i>d</i> (meas.)
2	32.43°	1.436	1	39.80°	1.203	$\frac{1}{2}$	48.40°	1.030	1	58.80°	0.901
$\frac{1}{2}$	33.35	1.400	2	40.65	1.182	2	48.90	1.024	1	59.95	0.890
$\frac{1}{2}$	33.60	1.391	2	41.05	1.173	1	49.35	1.015	1	60.95	0.881
1	34.50	1.359	3	41.75	1.156	$\frac{1}{2}$	49.80	1.008	1	63.10	0.864
2	35.20	1.336	$\frac{1}{2}$	42.35	1.143	1	50.65	0.996	1	64.00	0.857
1	35.95	1.311	$\frac{1}{2}$	43.50	1.119	1	51.35	0.986	$\frac{1}{2}$	64.70	0.852
1	36.55	1.292	1	43.95	1.110	$\frac{1}{2}$	51.75	0.981	1	65.35	0.848
$\frac{1}{2}$	37.20	1.273	1	44.45	1.100	$\frac{1}{2}$	52.75	0.968	2	66.70	0.839
$\frac{1}{4}$	37.80	1.256	$\frac{1}{2}$	44.90	1.091	1	53.15	0.963	1	69.85	0.820
$\frac{1}{2}$	38.35	1.241	2	45.50	1.080	1	53.35	0.960	2	72.35	0.808
2	39.05	1.222	1	46.80	1.057	2	54.90	0.941	$\frac{1}{2}$	74.75	0.798
1	39.30	1.216	1	47.40	1.046	3	57.25	0.916	1	80.05	0.782

least important form (100), of those whose order of importance is given in Dana, has been placed after (121) and (131) whose order is not given. With this minor change, the table shows very good agreement between the actual order of importance and those orders predicted by the two space-groups, especially by *Pcmm*. The order given by *Pccn* is the same as that given by *Pcmm* apart from the omission of (101) and (201) both of which are observed forms. This difference suggests strongly that *Pccn* is the less likely of the two, and consequently, the *most probable* space-group for euxenite is *Pcmm* (or *Pc2n* if euxenite is hemihedral).

The cell dimensions were finally recalculated from the indexed powder pattern using only those lines which index uniquely. This was done for two euxenite specimens. Euxenite from Mattawan twp., Nippissing District, Ontario gave the values:

$$a=5.520, b=14.57, c=5.166 \text{ \AA.}$$

This *x*-ray axial ratio,  $a:b:c=0.3789:1:0.3546$ , is in excellent agreement with the morphological ratio,  $a:b:c=0.3789:1:0.3527$ . Table 5 gives the powder data for euxenite indexed to  $d=1.457 \text{ \AA}$  on the above cell dimensions. Euxenite from Sabine twp., Nippissing district, Ontario, gave  $a=5.552, b=14.16, c=5.194 \text{ \AA}$ , and the ratio  $a:b:c=0.3800:1:0.3556$ .

*Specific Gravity and Cell Content.* In order to study the effects of heating on the density of euxenite, the Berman microbalance was used to measure the specific gravity of several fragments of the unheated euxenite from Sabine township, Nippissing district, Ontario, and of several fragments from each sample of the same euxenite specimen which had been ignited at 1000° C. for varying lengths of time. The specific gravity varied considerably for different fragments of the same sample and in

each case the highest value is the one reported. The results, given in Table 6, show that the specific gravity increases with heating to a maximum at about two hours, and decreases with longer heating. Since

TABLE 6. EUXENITE: VARIATION IN SPECIFIC GRAVITY WITH HEAT TREATMENT

Treatment	Specific Gravity	Treatment	Specific Gravity
Unheated	4.98	25 hrs. at 1000° C.	5.15
1 hr. at 1000° C.	5.18	32 hrs. at 1000° C.	5.02
2 hrs. at 1000° C.	5.23	40 hrs. at 1000° C.	5.07
13 hrs. at 1000° C.	5.14	100 hrs. at 1000° C.	4.98

alteration lowers the specific gravity, the highest values are considered the best. From the above table, these are: before heating,  $G=4.98$ ; after heating,  $G=5.23$ . These results agree well with the range of values given in Palache, Berman & Frondel (1944, p. 788): " $G. 5.00 \pm 0.10$  (for  $Cb:Ta > 2:1, \dots$ );  $\dots$  the  $G$ . decreases with alteration and increases after ignition."

Using the value 5.23 for the measured specific gravity of euxenite, the molecular weight  $M$  of the unit cell was calculated to be 1327. Table 7 gives, for euxenite from Sabine township, the analysis by Ellsworth (1932), and the number of the various types of atoms in the unit cell,

TABLE 7. EUXENITE: ANALYSIS AND CELL CONTENT

	1	2	3	4
TiO <sub>2</sub>	22.96	—	3.985	7.969
Fe <sub>2</sub> O <sub>3</sub>	2.07	—	0.359	0.539
Cb <sub>2</sub> O <sub>5</sub>	28.62	—	2.986	7.465
Ta <sub>2</sub> O <sub>5</sub>	2.65	—	0.166	0.416
CaO	1.92	0.475	—	0.475
UO <sub>2</sub>	8.61	0.442	—	0.884
UO <sub>3</sub>	0.20	0.010	—	0.019
ThO <sub>2</sub>	3.94	0.207	—	0.414
(Y, Er) <sub>2</sub> O <sub>3</sub>	24.31	2.985	—	4.478
(Ce, etc.) <sub>2</sub> O <sub>3</sub>	0.44	0.037	—	0.056
	95.72	4.156	7.496	22.715

1. Euxenite, Sabine twp., Nipissing Dist., Ont.; anal. Ellsworth (1932).
2. Atoms of type A in the unit cell.
3. Atoms of type B in the unit cell.
4. Oxygen atoms in the unit cell.

calculated for the above value of  $M$ . The letters  $A$  and  $B$  in the table have the same meaning as in the formula for euxenite,  $AB_2O_6$ , where  $A = (Y, Er, Ce, \text{etc.}), Ca, U, Th$ ; and  $B = Cb, Ta, Ti, Fe'''$ . From this table it will be seen that the cell content of euxenite is  $A_{4.16}B_{7.50}O_{22.72}$ , which is close to  $A_4B_8O_{24}$ . Therefore,  $Z$  is probably 4. The value of  $Z$  for the  $A$  part of the molecule (4.16) is close to this figure but, since the proportional values for the  $B$  elements (3.75) and the oxygen atoms (3.78) check well between themselves, it is likely that their proportions represent the true relative value of  $Z$  and that the density should be increased to bring them to 4. The consequent error in the  $A$  part of the molecule probably arises from the calculation of the number of  $Y + Er$  atoms in the unit cell, which was done on the assumption that this combination is all yttrium. If part of this is erbium, the number of these combined atoms in the unit cell will be lower, since the atomic weight of erbium, 167.2, is nearly double that of yttrium, 88.92. The  $Y:Er$  ratio necessary to give  $Z$  for the  $A$  part of the molecule a value of 3.75 calculates to about 2:1. The low value of  $Z$  (3.75 instead of 4) obtained above is probably due to a low measured specific gravity. Evidently the density of euxenite is not completely regained on heating. Assuming the value of  $Z$  to be 4, the molecular weight of the unit cell was recalculated to be 1416, giving a calculated density of 5.58.

*Tanteuxenite.* During the investigation of euxenite,  $x$ -ray powder photographs were taken of two specimens donated by Dr. Ellsworth, labelled "tanteuxenite," one from Woodstock, West Australia, and the other from Eleys, West Australia. Both specimens lack crystal form and both have low densities (4.9), but otherwise they correspond to the physical description of tanteuxenite given in Palache, Berman & Frondel (1944, p. 791): "Fracture subconchoidal. H. 5-6. G. 5.4-5.9. Luster resinous with brownish black color." Both specimens are metamict but on ignition they gave patterns which are similar to those of the uraninite-thorianite series. They were readily indexed on a cubic lattice, the cell edge of the specimen from Woodstock being 5.12 Å and of the specimen from Eleys 5.10 Å. The powder photograph of the specimen from Eleys is reproduced as Fig. 6. In addition to the strong pattern described above, this specimen gave a considerable number of very weak lines which could not be indexed on the above cell edge. These two photographs suggest that "tanteuxenite" is not a member of the euxenite-polycrase series as presently assumed, and that a more detailed investigation is necessary to identify it correctly.

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