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TOURMALINE PRESSURE GAUGES*

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ABSTRACT

Large single-crystals of tourmaline have been in demand in recent years for use in piezoelectric gauges for the measurement of blast pressures in air and under water. Tourmaline is responsive piezoelectrically to hydrostatic pressure and because of this and its high mechanical strength and chemical stability is used in preference to quartz and various water-soluble salts such as ADP and Rochelle-salt. The gauges comprise thin discs of tourmaline from $\frac{1}{4}$ inch up to several inches in diameter cut perpendicular to the *c*-axis and used singly or in stacks. The design and construction of the gauges is described in detail. The piezoelectric response of the tourmaline is amplified and recorded on associated electronic equipment and both the magnitude of the peak pressure and the wave-form deduced thereby.

The sources of supply, price and factors determining the usability of raw tourmaline for the purpose are discussed. Tourmaline for radio oscillator-plates must be entirely free from imperfections, and requires crystals of gem quality, but material for gauges can contain a considerable amount of cracking. The size and shape of the raw crystals are added factors in grading, but the color (composition) is of no consequence. Most of the tourmaline employed is of low-iron, high-alkali types from Madagascar and Brazil.

TOURMALINE PRESSURE GAUGES

During recent years, tourmaline has found an important application in the construction of piezoelectric gauges for the measurement of blast

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* Contribution from the Department of Mineralogy and Petrography, Harvard University, No. 290.

pressures in air and in sea-water. The present paper describes the design of tourmaline gauges and the relevant properties of the mineral but is primarily concerned with the specification and processing of raw tourmaline for the purpose.

FIELD OF APPLICATION OF PIEZOELECTRIC GAUGES

The basic problem in the study of shock-waves emanating from an explosion is the resolution of the wave-form, or pressure versus time curve, the principal points of interest being the shape of the wave-front and the magnitude of the peak pressure. The circumstances of measurement are ordinarily such that the incident pressures range up to a few hundred pounds per square inch in air and from a few thousand up to 30,000 psi or so in water measurements, although much higher pressures have been explored. The time interval over which the transient pressure wave is significant ranges from a few microseconds up to several hundred milliseconds. These conditions impose severe limitations on the type of gauge to be employed. Mechanical gauges, such as the ball-crusher type, are incapable of resolving the pressure-time curve, and are suited only to the measurement of peak pressure at relatively high pressure levels. Electromechanical devices, in which an applied pressure generates an electrical charge, in turn amplified and recorded, are better suited to the purpose primarily because of the continuous and nearly instantaneous nature of the response. In the condenser type of gauge, the applied pressure changes the capacitance of the condenser by effecting a mechanical displacement of the electrode plates. The so-called resistance gauges utilize materials that have a high pressure or strain coefficient of electrical resistance. Electromagnetic and magnetostrictive devices also have been developed for the purpose. Devices of the types mentioned are somewhat objectionable, variously because of non-linearity of response, low signal intensity or lack of ruggedness, and most of the work in recent years has been concerned with the development of gauges similar in principle but utilizing piezoelectric single-crystals.

The interconversion of electrical and mechanical energy effected by certain kinds of crystals immediately suggests their application to the measurement of pressure. Shortly after Pierre and Jacques Curie discovered the phenomenon of piezoelectricity in 1880, the two brothers devised a *manomètre piézoélectrique* that was a forerunner of the gauges described beyond. Their instrument[1] comprised a quartz plate cut perpendicular to a piezoelectric $X=a$-axis with attached electrodes connect-

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[1] Curie, P., Oeuvres de Pierre Curie, Paris (**1908,** p. 38); *Jour. de Phys.,* [2] **8,** 149 (1889).

ing with an electrometer. Pressure applied in the direction of the X axis caused a deflection of the electrometer proportional to the applied force. Various adaptations of this gauge were later applied by others to the measurement of cylinder pressures in internal combustion engines, explosive pressures in firearms and artillery, blood pressures in veins and arteries and varied other problems.

TABLE 1. TYPES OF PIEZOELECTRIC RESPONSE AMONG THE 32 CRYSTAL CLASSES

Class Number	System	Class Name	Hermann-Mauguin Symbol	Piezoelectric	Hydrostatically Sensitive	Not Hydrostatically Sensitive
1	Triclinic	Pedial	1	•	•	
2	"	Pinacoidal	$\bar{1}$			
3	Monoclinic	Domatic	m	•	•	
4	"	Sphenoidal	2	•	•	
5	"	Prismatic	$2/m$			
6	Orthorhombic	Rhombic-pyramidal	$mm2$	•	•	
7	"	Rhombic-disphenoidal	222	•		•
8	"	Rhombic-pyramidal	$2/m\,2/m\,2/m$			
9	Tetragonal	Tetragonal-disphenoidal	$\bar{4}$	•		•
10	"	Tetragonal-pyramidal	4	•	•	
11	"	Tetragonal-dipyramidal	$4/m$			
12	"	Tetragonal-scalenohedral	$\bar{4}2m$	•		•
13	"	Ditetragonal-pyramidal	$4mm$	•	•	
14	"	Tetragonal-trapezohedral	422	•		•
15	"	Ditetragonal-dipyramidal	$4/m\,2/m\,2/m$			
16	Hexagonal-P, R	Trigonal-pyramidal	3	•	•	
17	"	Rhombohedral	$\bar{3}$			
18	"	Ditrigonal-pyramidal	$3m$	•	•	
19	"	Trigonal-trapezohedral	32	•		•
20	"	Hexagonal-scalenohedral	$\bar{3}\,2/m$			
21	Hexagonal-P	Trigonal-dipyramidal	$\bar{6}$	•		•
22	"	Hexagonal-pyramidal	6	•	•	
23	"	Hexagonal-dipyramidal	$6/m$			
24	"	Ditrigonal-dipyramidal	$\bar{6}m2$	•		•
25	"	Dihexagonal-pyramidal	$6mm$	•	•	
26	"	Hexagonal-trapezohedral	622	•		•
27	"	Dihexagonal-dipyramidal	$6/m\,2/m\,2/m$			
28	Isometric	Tetartoidal	23	•		•
29	"	Diploidal	$2/m\,\bar{3}$			
30	"	Hextetrahedral	$\bar{4}3m$	•		•
31	"	Gyroidal	432			
32	"	Hexoctahedral	$4/m\,\bar{3}\,2/m$			

It must be noted that in every piezoelectric substance, except those belonging to the triclinic pedial class, that the crystal plate must be properly oriented in order to obtain a response, and that in some substances the pressure must be properly applied as well. Thus 20 of the 32 crystal classes permit the occurrence of piezoelectricity. In 10 of these classes a piezoelectric response is obtained only if the pressure is applied in certain directions, while in the 10 remaining classes a response is obtained from hydrostatic compression as well. The crystal classes responsive in these ways are indicated in Table 1. Substances in the non-hydrostatically sensitive classes, which include quartz, when used for the measurement of hydrostatic pressures require holders or gauge-bodies which laterally shield the crystal and transmit the applied force by means of a piston to only one face of the crystal plate.

The problem of gauge design is simplified considerably by employing a hydrostatically sensitive substance. It is also desirable that the substance have a high mechanical strength, since it may be subjected to pressures ranging up to many tons per square inch, and that it is insoluble in water and not hygroscopic. Chemical and structural stability over a wide range of temperature also is a desirable feature, partly because of metal plating and soldering techniques used in the assembly operations. A high piezoelectric response also is advantageous because it eases the problem of amplifying the signal or permits a reduction in the size of the gauge. The temperature coefficient of frequency and the frequency-thickness constant are unimportant, but a large pyroelectric response is undesirable. Generally speaking, the artificial piezoelectric substances so far developed are unsuitable, principally because they are water soluble and mechanically weak, although Rochelle-salt, ammonium dihydrogen phosphate (ADP), lithium sulfate monohydrate and certain tartrates have had a limited application. Tourmaline is now in general use for gauge applications, primarily because it is hydrostatically sensitive, mechanically strong and chemically stable. The piezoelectric response of the substance is comparable to that of quartz but is only about a hundredth of that of Rochelle-salt. The principal drawback to tourmaline is the high cost of crystals of suitable size and quality. But for this, tourmaline probably would have a much wider application in piezoelectric devices, especially for supersonic applications, than it presently enjoys. A search among natural piezoelectric substances with desirable properties, however, has not yielded any practical substitute for either quartz or tourmaline for these applications. Some of the more likely or interesting possibilities that have been investigated in this laboratory are pyromorphite, mimetite, heulandite, stibiotantalite-stibiocolumbite, nepheline, boracite, wurtzite, and hemimorphite.

Design of Piezoelectric Gauges

The details of the design of piezoelectric gauges vary considerably with the particular application, especially in the type of housing employed. Basically, all such gauges consist of one or more plates or discs cut from a properly oriented single-crystal. The surfaces of the disc ordinarily are metal-plated and lead wires are attached thereto. The gauge-element is then housed in an appropriate holder which may be water-proofed and electrically shielded. The piezoelectric response of the gauge-element to the transient pressure wave is transmitted via cable to associated amplifying and recording equipment.[2] The size of the plates or discs employed is fixed primarily by the piezoelectric constants of the material, the magnitude of the pressure changes to be measured, and the requirements of the amplifying equipment. An added factor is the transit time of any given element of the shock wave across the gauge relative to the duration of the wave. The smaller the transit time, and hence the smaller the gauge, the more accurate is the representation of the wave form. The charge produced by a gauge is directly proportional to the surface area of the tourmaline disc and is independent of the thickness of the disc. If a large surface area is needed in order to give an adequate signal under a certain set of conditions it is conventional practice, if single-crystals of sufficiently large size are not available, to employ a stack of small, thin discs attached together so that they are electrically parallel (and crystallographically opposite). Relatively large discs are needed especially in the case of air blast gauges in which the relatively

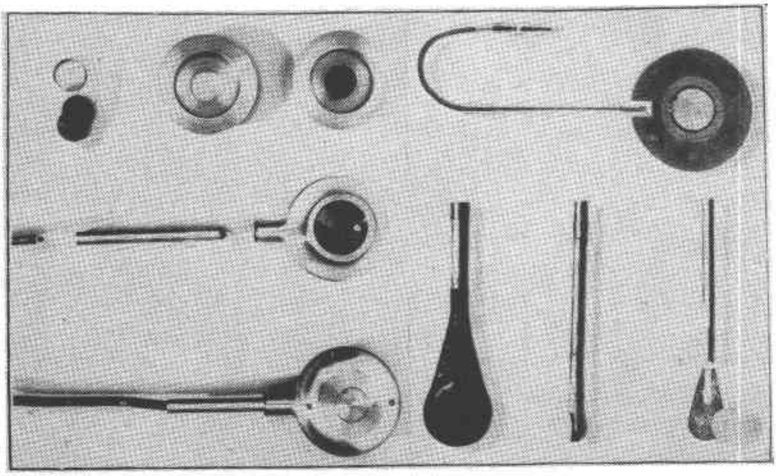

FIG. 1. *Left:* Piston-type air-blast gauge for use with quartz discs. *Right, above:* Air-blast gauge utilizing stacked tourmaline discs; shown without insulation. *Right, below:* Early type of underwater gauge using stacked discs soldered to a supporting metal tab.

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[2] The general problem of the recording and interpretation of blast pressure measurements by the piezoelectric method is described in detail by Arons and Cole: *NDRC Rpt.* No. **A-361,** March (1946).

low incident pressures, usually only a few psi, must be compensated by increased surface area. Mosaic gauge-elements also have been employed, particularly in quartz and ADP underwater signaling devices. Stacking techniques are restricted insofar as a low ratio of width to thickness of the gauge-element is desirable in order to minimize the Bernoulli effect and turbulence as the pressure wave passes the gauge.

The tourmaline discs currently used in air-blast gauges range from an inch or so up to about 2 inches in diameter, although much larger plates, usually as irregular slabs cut directly from the raw crystal, have been employed. Underwater gauges in general employ discs from $\frac{1}{4}$ to $1\frac{1}{4}$ inches in diameter, although four-pile gauges as small as 1/16 inch in diameter have been constructed. Some representative types of gauges used in air-blast and underwater measurements are shown in Fig. 1.

SOME RELEVANT PROPERTIES OF TOURMALINE

Tourmaline crystallizes in the ditrigonal class (3 *m*) of the rhombohedral system. The space group[3] is *R* 3 *m*. The axial ratio obtained from morphological measurements[4] is $a:c=1:0.4477$, $\alpha=113°57\frac{1}{2}'$, in the orientation and unit of the structural cell.[3] The morphological unit and the unit cell dimensions vary measurably as the chemical composition varies, as noted beyond, and the value given is close to the average of the observed range. Some crystals of typical habit are shown in Fig. 2. The orientation of the discs cut therefrom for gauge applications and the connection between the morphology and the principal electrical and physical properties are shown in Fig. 3.

The principal crystallographic problems for the technician engaged in cutting tourmaline discs and assembling them into gauges are the recognition of the piezoelectric axes of reference, X, Y and Z, specifically the Z-axis, and the separate identification of the ends of the polar Z-axis. The crystallographic and piezoelectric axes are so related that $Z=c$, $X=a$ and Y is perpendicular to the ZX plane and hence in a vertical plane of symmetry (see Fig. 3). The Z axis is the polar, piezoelectric, axis and the plates or discs are cut perpendicular thereto. Z can be recognized in faced crystals by a three-fold distribution of faces when the crystal is viewed along Z (see the upper and lower projections in Fig. 2, in which Z is perpendicular to the paper). Further, the crystals are ordinarily (but not always) more or less elongated parallel to Z, and the side or prism faces are always striated parallel thereto. Z can be located approxi-

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[3] Buerger and Parrish: *Am. Mineral.*, **22**, 1139 (1937), on an Etta Mine, South Dakota, crystal with $a_0=15.928$, $c_0=7.151$ Å in the hexagonal unit.

[4] From an unpublished critical curvey of the morphology of tourmaline by J. D. H. Donnay (priv. comm., 1947).

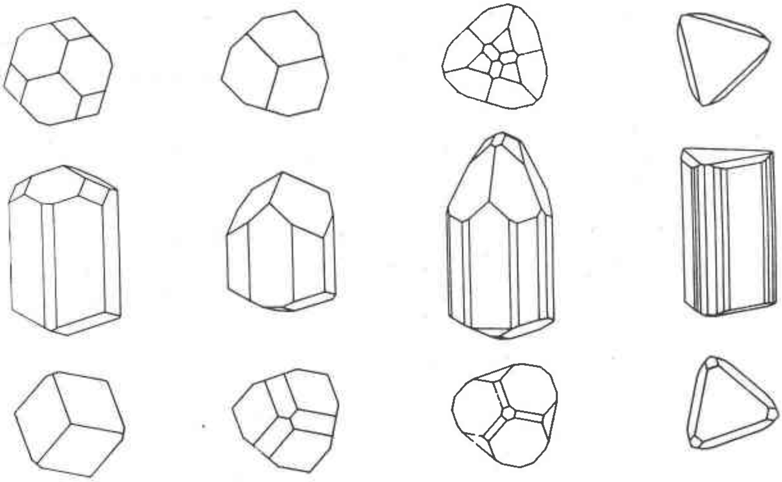

Fig. 2. Some typical habits of tourmaline crystals. Basal projections are given of the antilogous (above) and analogous (below) poles.

mately in unfaced crystals by the electrical tests described beyond; and precisely, provided that the crystal or section is transparent, by viewing the crystal or section in a conoscope or polarizing microscope and locating the optic axis, coincident with Z.

The opposite ends of the polar Z axis can be identified with certainty only by electrical tests, the antilogous pole—conventionally shown upper-

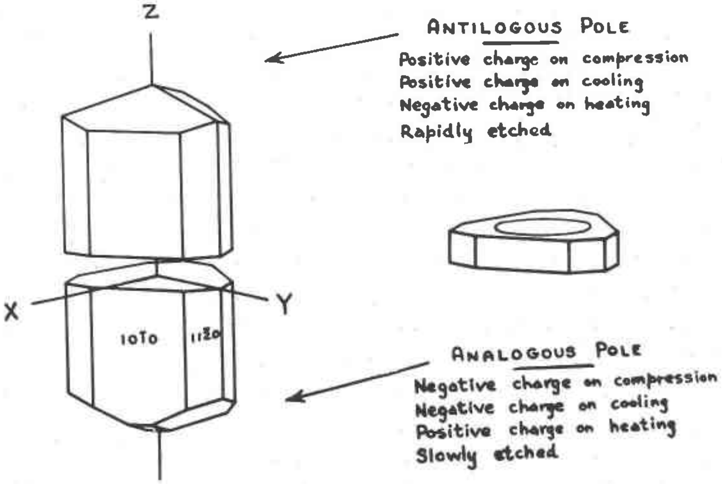

Fig. 3. Correlation between the principal physical and electrical properties of tourmaline and the morphology.

most in crystal drawings—developing a positive electrostatic charge on decrease of temperature or on compression. The opposite, or analogous, pole develops an equal negative charge under the same conditions. A quick and certain electrical method to identify the positive and negative surfaces of sawn slabs and discs is to place the piece in firm contact between two metal plates, one plate being connected to the input post of a sensitive cathode-ray oscilloscope such as the DuMont 208. The other plate is grounded. The horizontal sweep is then synchronized at about 60 cycles/sec. A gentle tapping of the upper plate produces a superimposed signal whose inclination reveals the polarity of the upper surface (input side) of the disc (see Fig. 4). Turning the plate over reverses the signal. In testing for piezoelectricity by this method care must be taken to distinguish effects due to contact potentials and frictional electricity. The polarity also can be determined with a piezometer, in which the voltage produced by squeezing the disc under a small lever arm is impressed on the grid of a high gain amplifier tube such as the 6*J*7. A negative charge impressed on the grid will decrease, and a positive charge increase, the plate current. A milliameter in the plate circuit of the tube permits visual observation of the polarity. Thin discs or fragile materials are not best tested by this method.

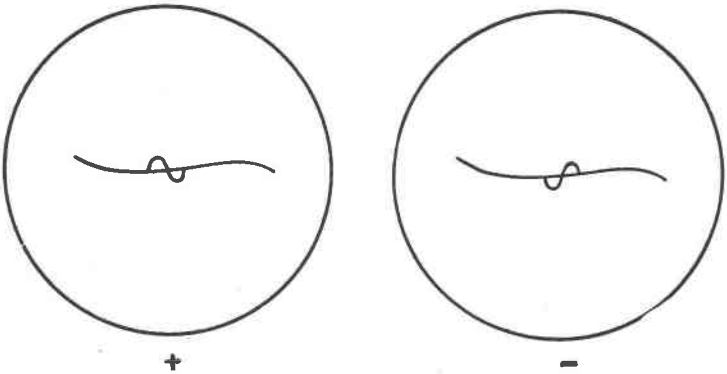

FIG. 4. The drawings represent the screen of a cathode-ray oscilloscope, and show the nature of the superposed signal produced when the antilogous (positive) or analogous (negative) surfaces of the test piece are connected with the input post, and are compressed.

The polar nature of the $Z=c$-axis is well illustrated by differences in the rate of solution and the rate of growth therein. Spheres of tourmaline when dissolved in a solvent develop a bee-hive shape due to a relatively large rate of solution along *Z toward* the analogous pole.[5] Similarly, when

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[5] Kulaszewski, *Akad. Wiss. Leipzig, Sitzber.*, **72**, 48 (1920); and Frondel, *Am. Mineral.*, **20**, 855 (1935).

sawn Z-cut slabs are etched in a solvent, such as fused KOH containing 5 or 10 per cent H_2O, the surface at the antilogous pole is very much more deeply attacked than the opposite, parallel surface. Etching tests may usefully serve to identify the two poles, but are destructive of the test piece. Study of the color bands within single-crystals often reveals a relatively large rate of growth along Z in the direction toward the antilogous pole,[6] and the secondary overgrowths on rounded detrital grains of tourmaline always are located on the antilogous pole only.[7]

As shown in the figures, the opposite ends of the $Z=c$-axis of individual crystals are always or probably always terminated by geometrically different faces or combinations of faces. There are no trustworthy morphological criteria, however, by which the separate poles can be recognized. Several observers have proposed such rules but a recent study[8] has shown that while they may apply to crystals from a particular locality or type of occurrence they are not true in general.

Chemically, tourmaline is a complex borosilicate conforming to the general formula $XY_3ZB_3Si_6O_{27}(O,OH,F)_4$. In this formula, X is Na or Ca with both usually present and Na dominant; Z is Al with some Fe^3 usually present, especially in black tourmaline; Y is one or more of the following: Mg, Fe^2, Fe^3, Al, Li, Mn, Cr; with Mg dominant in the brown tourmaline from crystalline limestones; Fe^2 and Fe^3 present especially in black, pegmatitic tourmaline; Li often present, especially in the light colored varieties. The precise mechanisms by which these varied isomorphous substitutions are effected, particularly those requiring coupled valence compensations, are not clearly understood. The optical properties, specific gravity, color, cell dimensions and other characters of the mineral vary concomitantly with variation in composition. The color banding commonly seen in sawn sections of tourmaline (see Fig. 7) reflects changes in the chemical composition of the crystallizing solution during the growth of the crystal.

Variation in the composition of tourmaline is of interest in the present connection because of the presumed accompanying variation in the piezoelectric properties. The property of interest in gauge construction is the

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[6] Frondel, *Am. Mineral.*, **21,** 782 (1936).

[7] Krynine, *Jour. Geol.*, **54,** 65 (1946).

[8] J. D. H. Donnay (priv. comm., 1947). The common forms at the antilogous pole are $o\{02\bar{2}1\}$, $r\{10\bar{1}1\}$, $u\{32\bar{5}1\}$, $y\{40\bar{4}1\}$ and $x\{12\bar{3}1\}$; at the analogous pole $\bar{r}\{10\bar{1}1\}$, $\bar{e}\{01\bar{1}2\}$, $\bar{o}\{02\bar{2}1\}$ and $\bar{c}\{000\bar{1}\}$. Very broadly, the forms at the antilogous pole tend to be more numerous and steeper than those at the analogous pole. Also, $\bar{c}\{000\bar{1}\}$ (analogous) is generally large and dull, while $c\{0001\}$ (antilogous) is small and brilliant and often absent. Striations on $r\{10\bar{1}1\}$ run parallel the opposing edge (or edge between $\bar{r}$ and *o;* the short face diagonal); but $\bar{r}\{10\bar{1}1\}$ is always striated parallel the adjacent edges (or edge between $\bar{r}$ and $\bar{e}$).

amount of electrostatic charge developed per unit area of a Z-cut plate per unit change of pressure. Determinations of this constant, designated K, and representing averaged measurements of numerous tourmaline discs regardless of their composition, have been made as follows:

K = 10.9 micromicrocoulombs per lb. per sq. in. (on *ca.* 100 four-pile airblast gauges[2])
= 11.08 micromicrocoulombs per lb. per sq. in. (on 8 four-pile underwater gauges[2])
= 10.8 micromicrocoulombs per lb. per sq. in. (on 45 four-pile underwater gauges[9])

Numerous determinations on individual discs also have been reported.[2] These show a wide variation, but unfortunately in no case has the chemical composition of the tourmaline been stated so that the significance of the variation is unknown. From a study now in progress, the ordinary range of variation in K in commercially available tourmaline, including both pale colored and black opaque varieties, appears to be about 4 per cent.

The elastic properties of tourmaline have been summed up by Cady.[10]

SPECIFICATIONS OF RAW TOURMALINE

Size and Shape of Raw Crystals

SIZE. The range of sizes of raw tourmaline needed for gauges and most other electronic applications is from 1 to 4 inches as measured in the minimum dimension at right angles to the $Z = c$-axis. Only rarely are crystals needed in sizes up to 6 or 7 inches in diameter. The length of the crystal along the Z axis is not critical, but in small sizes at least the length should not be less than the diameter and in general the longer the crystal the better. If raw tourmaline was abundant and cheap, so that a selection of material could be effected, it would be desirable to use only the largest sizes available. This is true because of cracks and other defects invariably present in the material which cause a relatively small yield of large discs, so that the supply of these usually is inadequate. In large crystals a considerable amount of trim material becomes available which can be salvaged for discs of a range of smaller sizes. In small crystals, however, the trim pieces ordinarily are not salvageable insofar as discs over about $\frac{3}{8}$ inch diameter are concerned. The practice of purchasing large crystals would apply particularly to applications in which a large range of disc sizes is needed. Under present conditions of scant supply and high prices, it is largely a question of taking what is available. Since the small sizes greatly predominate, it is general practice to use the

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[9] Anderson, R. H., Cambridge Thermionic Corp., Cambridge, Mass. The value 11.08 is considered to be the best of those reported here, since the major experimental errors all tend to give low values.

[10] Cady, Piezoelectricity, New York (**1946,** p. 156).

smallest raw crystal that will cut discs of the size immediately needed. A tolerance of 25% or so is added to the minimum dimension needed so that some leeway is had in avoiding cracks when the sawn slabs are diced.

The yield of slabs to be obtained from a raw crystal of known length can be calculated approximately from a knowledge of the thickness of the slabs and saw-blade used. The breakage during the sawing of tourmaline of average quality is only a few per cent. The yield of discs from irregular sawn slabs depends on a variety of geometrical and other factors: some representative data are given in Table 2, beyond. The loss of discs due to breakage during the dicing and machine lapping operations should run less than 10 per cent.

SHAPE. The efficiency of utilization of a crystal depends considerably on the shape. Very short crystals, as measured along the $Z=c$-axis, are undesirable since the broken ends, or much of the termination if the crystal is faced, must be discarded as waste and this may be a large proportion of the whole. In small sizes at least the crystals should be as long as they are wide. Crystals that are bounded externally or internally by fractures making small angles with Z are particularly wasteful, and productive of relatively small discs. Well rounded or barrel-shaped crystals are better suited geometrically to cutting discs than are sharply triangular or prismatically flattened crystals. These factors may seem of minor importance but can not be overlooked since a raw crystal weighing only a few pounds may cost a hundred dollars or more and the yield of thin discs therefrom may be only 25 per cent or so by weight at best.

FACES. It is very desirable that the raw crystals have one or more large and even prism faces present. These are needed to mount and orient the crystal preliminary to sawing. {0001} faces can be used for the purpose as well, and also rhombohedral faces if the position of the Z axis can be established by inspection. Unfaced material is difficult to handle since the crystals ordinarily do not transmit enough light to be oriented by optical methods. Color bands parallel to the terminating rhombohedral faces are frequently present in tourmaline and can be used as a guide in orienting unfaced material.

Internal Quality

CRACKS. The amount of cracking present in the raw crystal is the most important factor determining its usability. A considerable and often surprisingly large amount of cracking can be tolerated provided that the cracks are discontinuous. The degree of cracking that is permissible is difficult to estimate, however, and shipments of raw material should be tested by trial sawing and dicing in order to determine usability. Through-going cracks, especially when associated with parallel growths in the crystal, usually cause failure. The nature of the fracture surfaces in tourmaline is a useful guide to quality. The best material has a glassy, conchoidal fracture, and non-usable material generally has a very uneven to coaly fracture. Examples of usable and non-usable tourmaline are shown in Figs. 5 and 6. Tourmaline used for oscillator-plate applications must be flawless—gem-grade tourmaline is best for the purpose—and that for ultrasonic generators should be nearly or entirely flawless.

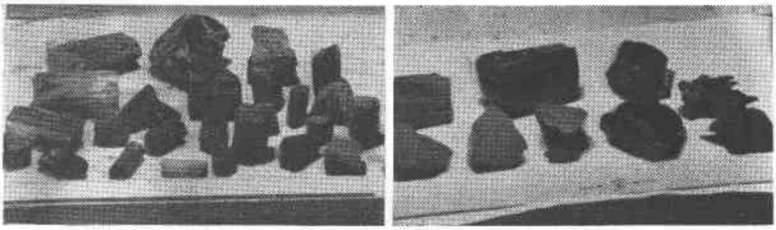

FIG. 5. *Right:* Badly cracked, non-usable black tourmaline from New England. *Left:* Selection of black Brazilian tourmaline of usable grade.

PARALLEL GROWTHS AND POROSITY. Some tourmaline crystals are aggregates of parallely grown, pencil-like, small crystals, such as shown in Fig. 6. The composite part may be only an overgrowth on an earlier-formed, relatively perfect crystal. Parallel growth is very undesirable in industrial tourmaline, since the crystals when sawn tend to break apart along the surfaces of juncture of the separate individuals. Other crystals have a related defect, consisting of threadlike openings and channels running parallel to Z. This sometimes grades into a parallel fibrosity.

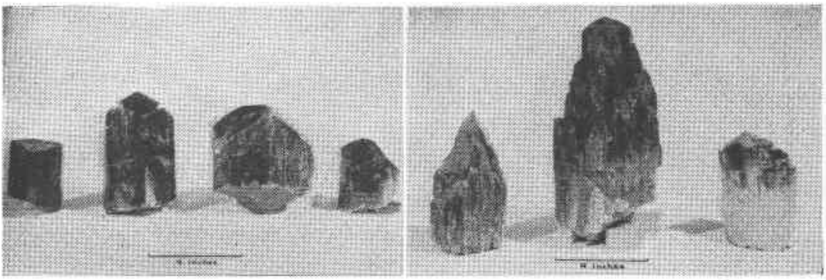

FIG. 6. *Left:* Usable, faced crystals of tourmaline from Madagascar. *Right:* Un-usable crystals of tourmaline, showing parallel-growth. The crystal on the right is from Mt. Mica, Maine, the others from Brazil.

Porosity of this nature is objectionable because discs containing throughgoing holes short out when metal-plated on the opposite sides.

COLOR. The color (or chemical composition) is not of consequence in itself in specifying tourmaline. Black, iron-rich types of tourmaline, however, usually are too badly cracked and friable to be useful. This is due to the early period of formation of such tourmaline in pegmatites, causing it to be solidly embedded in the matrix and then susceptible to fracture by mechanical stress. Black tourmaline from open cavities in some Brazilian occurrences proved to be of very high grade. Zoned Madagascar tourmaline often shows intense cracking confined to the colorless or pale pink zones, due presumably to differential thermal contraction.

TWINNING. Tourmaline, in distinction to quartz, is very rarely twinned and this feature is of no importance in specifying and grading the raw material. Only a few instances of twinning were observed in approximately 50 slabs of Madagascar and Brazilian tourmaline that had been etched in molten KOH. These comprised small isolated areas, amounting to only a few per cent of the total area of the slab, twinned apparently in all instances on $\{10\bar{1}1\}$.

Sources of Supply, and Price

The supply of raw material has in general been inadequate and at times critical. This has lent impetus to efforts to synthesize tourmaline.* The tourmaline imported into the United States in recent years has come from Madagascar and Brazil. About 2000 pounds were obtained from Madagascar via France during the war under exceptionally difficult circumstances. The cost of this material is not known. Recently small amounts have been obtained at $15 a pound. The Madagascar tourmaline in general is usable, but little so far seen is of above-average quality. It is notable for the occurrence of relatively large crystals, some individuals weighing 30 to 50 pounds apiece. The Brazilian tourmaline appears to originate entirely in Minas Geraes, particularly good material coming from the Governador Valladares district. It varies erratically in both quality and price, due to uncertainties as to specifications and how badly it is needed in the United States. The total amount of industrial grade tourmaline imported from Brazil since 1942 is not definitely known but probably is about 3000 pounds. During 1942 small amounts were sold at prices of $15 to $50 a pound. Later, in face of a recognized urgent need, prices are said to have been asked and paid of about $1000 a pound. The usual asking price has been in the neighborhood of $100 a pound, with no enthusiasm shown by buyers, but recently some material has become

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* Frondel, C., Hurlbut, C. S., Jr., Collette, R. C., *Am. Mineral.*, **32**, 680–681 (1947).

available at about $15 a pound. The latter price appears reasonable, and probably will be met or bettered by suppliers from non-Brazilian sources. Crystals over about 4 inches in size generally sell at a premium. Very large crystals, over about 7 inches in diameter, are not needed for gauge applications and are too large to be handled by conventional sawing equipment.

Tourmaline occurs widely in the United States but intensive search so far has not developed any large supply of usable material. Black tourmaline from pegmatites in Colorado, California, the Black Hills and numerous localities in New England when sawn and tested almost invariably proved too badly cracked and friable for use. A few usable crystals were obtained from pegmatites at Mt. Mica and Topsham, Maine. The pink tourmaline from Pala, California, is usable but the available crystals are too small in size. About 500 pounds of black tourmaline was obtained from a pegmatite near Overlook, New York, during the war and sold in the United Kingdom at prices of $1 to $5 a pound. Some of the individual crystals were as much as 10 inches in diameter. This material is believed to have been used as extremely thick slabs and is too badly cracked for use in ordinary gauges.

Manufacture of Tourmaline Discs

The methods and equipment used in sawing raw tourmaline crystals preparatory to cutting discs are essentially those used with quartz. The raw crystal is cemented down by a prism face to a supporting plate. It is then mounted on the bed of a diamond saw and slabs are cut at right angles to the $Z=c$-axis as shown in Fig. 7. The piezoelectric response of Z sections is not very sensitive to small angular deviations from perpendicularity and an angular tolerance of 2° or so, easily attained by mechanical alignment procedures, is permissible. Experience has shown that there is a minimum thickness of the sawn slab in relation to its width (and similarly in the final thickness of the discs cut and lapped thereform, as noted beyond) at which breakage during sawing and subsequent operations is reduced to a practical minimum. The data given below refer to tourmaline of average quality, and the thicknesses in the larger sizes can be reduced somewhat in material of high quality.

Cross-dimension of the raw crystal (width of slab)	Minimum thickness of sawn slab
1 inch	0.035–0.040 inch
$1\frac{1}{2}$	0.040–0.045
2	0.050–0.060
3	0.070–0.090
6	0.100–0.140

It is assumed that a superior type of sawing machine is employed,[11] with a true-running diamond-edged blade. In view of the high cost of the raw material it is essential to use as thin a saw blade as practical. The minimum blade thicknesses are comparable to the slab thicknesses, or

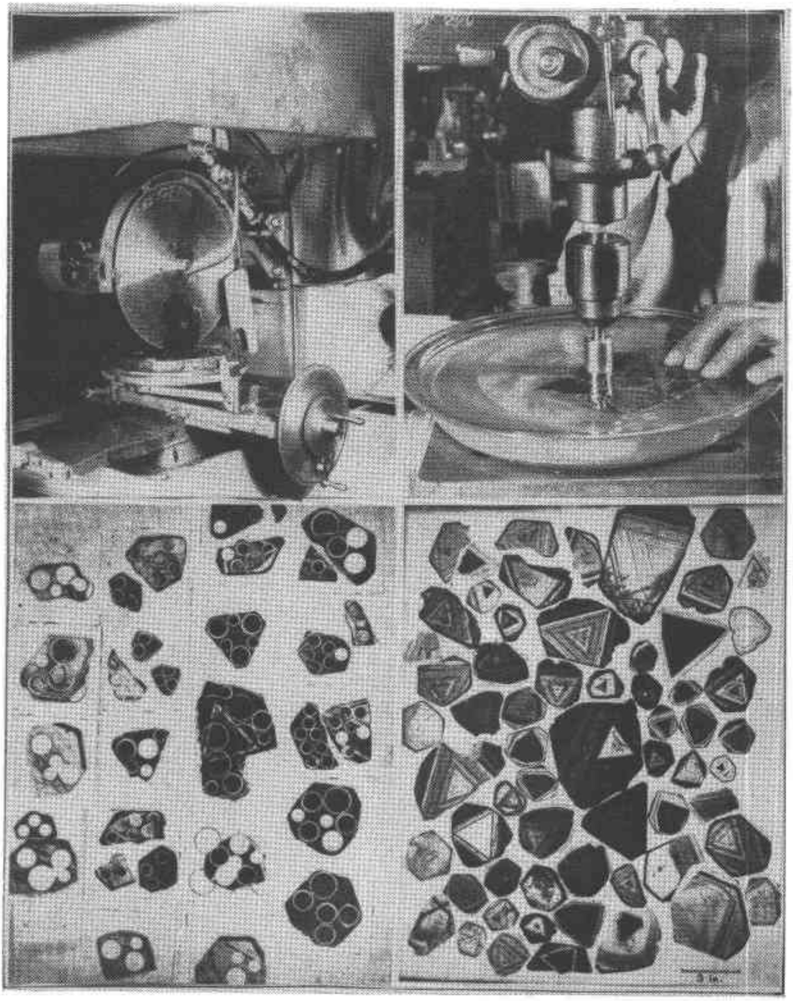

FIG. 7. *Upper, left:* Large tourmaline crystal being sawn with a diamond-edged blade. *Upper, right:* cutting discs with a diamond-edged rotary tool. *Lower, left:* Diced-out slabs of tourmaline. *Lower, right:* Color banding in *Z*-cut (basal) slabs of Madagascar tourmaline.

[11] Cf. Parrish, *Am. Mineral.*, **30,** 371, 389 (1945).

somewhat less in the larger sizes, so that roughly half of the raw material is lost as saw dust in the first operation. Tourmaline saws and laps more readily than quartz, although of the same hardness. An idea of the number and size distribution of discs to be obtained from tourmaline of average quality can be had from Table 2, taken from actual production records. The disproportionally small yield of $1\frac{1}{2}$ inch discs from large crystals shown by this table reflects the fact that slabs not sufficiently free from cracks to afford $1\frac{3}{4}$ inch discs, the first size cut, generally do not yield any immediately smaller sizes but only discs of very much smaller size, usually $\frac{1}{2}$ inch or less. The proportion of $1\frac{1}{2}$ inch relative to $1\frac{3}{4}$ inch discs increases with decreasing size of the raw crystal since the size of the slab then becomes a relatively important yield-determining factor.

TABLE 2. YIELD OF DISCS FROM AVERAGE QUALITY MADAGASCAR TOURMALINE

Approximate diameter of raw crystal	Number of crystals	Total weight	Number of slabs obtained, .065″ thick	Number of discs obtained (cut in order of decreasing size)						
				$1\frac{3}{4}''$	$1\frac{1}{2}''$	$1\frac{1}{4}''$	1″	$\frac{3}{4}''$	$\frac{1}{2}''$	$\frac{1}{4}''$
$3\frac{1}{4}''$–$3\frac{3}{4}''$	9	23 lb. 3 oz.	247	181	35	74	201	167	383	
2″–$3\frac{1}{4}''$	13	14 11	272	92	63	69	93	106	353	
1″–2″	32	11 8	355*	22	36	67	48	70	444**	
Totals	54	49 lb. 6 oz.	874	295	134	210	342	343	1180	>2000 (est.)

* Includes 91 slabs cut 0.130″ thick.

** Includes 160 discs cut 0.130″ thick.

The next step in manufacture is in dicing out discs or rectangular plates from the sawn slabs. The slabs are first cemented down with a beeswax-rosin mixture to a thick glass plate. Discs are cut out to dimension with a tubular, diamond-edged tool mounted on a high speed drill press (see Fig. 7). The tool should be cooled during use, such as by immersing the mounted slab in kerosene or water-soluble oil. The slabs should be carefully inspected before dicing, so that discs of various sizes can be accommodated to the cracks or other defects that may be present. Rectangular plates can be cut by means of dicing saws, described elsewhere.[11]

Usually the discs as cut are at the thickness desired for use in gauges, but sometimes it may be necessary to further reduce the thickness. This can be done by conventional quartz-working techniques on drill-press laps.[11] An assortment of lapped discs is shown in Fig. 8. In general it is desirable to use the thinnest discs practical in order to give a minimum thicknesss to width ratio in the finished gauge. The minimum thickness ordinarily is set by the quality of the raw material available and in part by the method of edge-insulation employed in the gauge. Experience has shown that the values given below are practical with tourmaline of average quality. With flawless tourmaline it is possible to work down to thicknesses of a few thousandths of an inch, or even less, in discs up to $\frac{1}{2}$ inch or so in diameter.

Disc diameter	Minimum disc thickness
$\frac{1}{2}$ inch	0.020–0.025 inch
1	0.025–0.035
$1\frac{1}{2}$	0.040–0.050
2	0.055–0.070
3	0.080–0.120

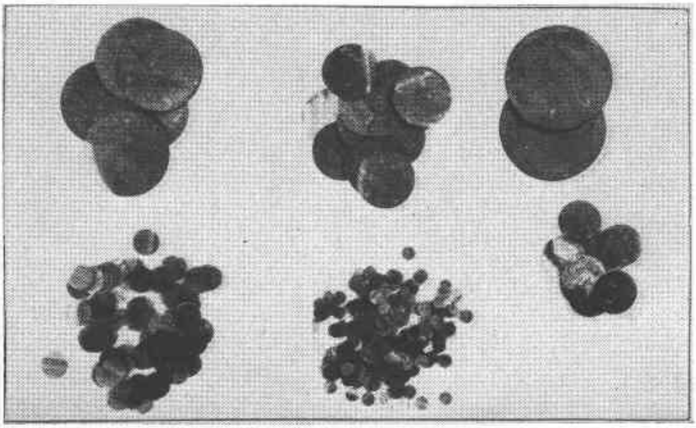

FIG. 8. Selection of lapped tourmaline discs, ranging in thickness from 0.015 inch in the smallest size ($\frac{1}{4}$ inch diameter) to about 0.070 inch in the largest ($1\frac{7}{8}$ inch diameter).