THE RELATION BETWEEN THE MECHANICAL
AND PIEZO-ELECTRICAL PROPERTIES
OF A ROCHELLE SALT CRYSTAL

by

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INTRODUCTION.

It was the purpose of this piece of research to investigate the relation between the mechanical and piezo-electrical properties of a Rochelle Salt Crystal, under various temperature conditions and with varying stresses applied.

*Piezo-electricity was discovered in 1880 by the brothers, Jacques and Pierre Curie, while investigating the similar phenomenon of pyro-electricity in various crystals. This latter is the property of a crystal to produce an electric charge on its ends due to a temperature change. While the former, with which this paper deals, is the property of a crystal to produce a charge on its sides or ends due to a stress along the longitudinal axis.

Since the discovery of the piezo-electrical phenomenon many crystals have been found to possess this property to a greater or lesser degree. In all crystals with polar axes, i.e. those of which the opposite ends of an axis are not alike in the grouping of the atoms, there is at least one and usually ^{there are} many directions along which the application of force will produce a charge, either on the planes where the force is applied, or on the

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* Poynting and Thompson, Elect. and Mag. p. 148.

perpendicular
 surface/to this. The accumulation of electrical charges are of opposite signs and on opposite ends or sides. Only in a few crystals is this change very appreciable and in only a very few is it comparatively large. Rochelle Salt crystals are one of these very few. Poynting and Thompson, in their text on Electricity and Magnetism page 148, give the best discussion of the effect of any of the standard works on physics.

Until recently (1917) little work has been done on this subject. But during the Great War, a study of it was again taken up. A number of men in this country have taken an interest in working on the crystal. W.G. Cady¹ of Wesleyan University, Middletown Connecticut, has done considerable work in determining the crystal properties. J. Valasek² of Minnesota, has perhaps done more than any other man. His work has been especially with the application of a potential difference across the surfaces of the crystal. He found that a dilation was produced, also that there is a permanent polarization in the natural state that caused a marked hysteresis effect. He further worked with the optical refraction and temperature effects on the crystal. Anderson³ and Wood⁴ made investigations

- (1) Reports to the National Research Council, May 1918.
- (2) Physical Review, 17 475, 19 478, 20 639.
- (3) Reports to the National Research Council, March and April, 1918.
- (4) Bulletin of the Seismological Society of America, 11, no. 1, March 1921.

with the ideas in view of adapting the crystal to signal and seismographic uses respectively. Taylor and Yoder¹ for their Master's Thesis, in 1922, at the University of Kansas, worked on the correlation of the mechanical and piezo-electrical properties. But, tho they arrived at a value of Young's modulus, for both open and short circuit of the crystal, their results were not definite and their method seemed inaccurate and inconclusive.

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- (1) Thesis Physics Dept. University of Kansas 1922. An Investigation of the Electrical and Mechanical Phenomenon in the Rochelle Salt Crystal.

P R E P A R A T I O N .

In the study of this problem, it was desired to devise a method whereby the stress, strain, and charge could be measured as nearly simultaneously as possible. Also it was necessary to keep the atmospheric conditions fairly constant or variable as desired.

The apparatus used by Taylor and Yoder in 1922 was still available. So the first thought was to use as much as possible of their apparatus and yet change the parts that seemed to be unsteady. With this idea in mind, their apparatus was carefully looked over. It consisted of a solenoid with an iron plunger attached to the crystal for applying the force, and an interferometer arrangement for determining the contraction or strain.

The method of applying the force seemed good so that part was kept but the interferometer method of reading the change ^{in length} was unstable and inaccurate due to the great change in forces applied. This part was changed and an optical extensometer, described later, was used.

After the extensometer was in place and the process of calibrating the solenoid by means of a Jolly balance arrangement was in progress, it was decided that because of the heating effect of the solenoid (which was considerable

for some of the forces desired) that this method of applying the force would also be discarded for a simple lever arm.

Temperature control was thot to be secured easiest by an electric light bulb for heating and a coil of copper pipe for cooling.

For measuring the quantity of the charge a Leeds and Northrup galvanometer with a sensitivity factor of 2241 megohms, was considered adequate. This galvanometer had a critical damping resistance of 8100 ohms, with a resistance of 525 ohms, and a period of 5.85 seconds.

EXPERIMENTAL WORK.

Rochelle Salt, $\text{NaKC}_4\text{H}_4\text{O}_6 \cdot 4\text{H}_2\text{O}$, crystallizes in the hemihedral form as distinguished from the hemimorphic class of the orthorhombic system. It is in a class in which the crystal forms are referred to the three axes at right angles to each other, but in which the planes of the simplest prismatic bounding surfaces intercept these axes at different distances from the common center of the crystal. Fig. (1). Further the class has no center of symmetry and consequently the ends of the axes, or any other direction thru the crystal, have different physical characteristics. Therefore each axis is a piezo-electric axis.

All of the principle axes are polar and therefore many ways would present themselves for cutting the crystal into a slab that would yield the piezo-electric effect. The best way, however, is considered as follows: A thin plate of given thickness t , Figure (2), was cut from the bc plane and from the central portion of the crystal. From this plate a slab of length l , and width w , was cut so that its sides were inclined at an angle of 45° with the edge of the original crystal.

The cutting of the crystal had to be undertaken with great care for any uneven strain would cause the crystal to crack and break. The method of cutting is one that has been used by most of those working with this

(7)

Fig. 1.

(8)

Fig. 2.

type of crystal. Figure (3) shows the apparatus. It consists of a platform on which the crystal rests and to which is fastened four pulley wheels. Two of which are under water so that an endless thread, driven by a motor, passes thru the water, over the pulleys, and against the crystal. The crystal was thus dissolved away by the water.

The slab that was left was in a rough and uneven condition. It was ground to a perfect rectangular form with emery and water on a glass plate and later polished by water on a piece of ground glass.

In order to eliminate any change in vapor tension of the crystal and to minimize the change in the crystal due to any change in humidity, it was coated with an asphaltum cement. This cement was made by dissolving powdered asphaltum gum in Benzine (C_6H_6) and was used both because of its tenacity and rapidly drying property and also because neither the asphaltum nor the benzine had any harmful effects on the crystallographic structure.

To each side of the crystal was cemented, with the same cement, a piece of tinfoil, the tinfoil coming within a few millimeters of the edge of the crystal.

The crystal, thus prepared, was cemented to a brass base and supported by two sets of glass rods, wedges being placed between the rods and the crystal. After the cement had hardened the wedges were removed leaving the crystal free to move up and down without any friction.

Fig.3.

Figures (5) and (6) show the crystal in place.

Construction and Calibration of Extensometer.

The instrument used in measuring the change in length of the crystal was an optical extensometer, made according to a description of such an instrument by S.R. Williams* of Oberlin. It was made in the machine shop of the physics department, with the exception of the jewelers work on the pivot and bearings.

Figure (4) shows the construction of the piece. The lever arm was made eighteen centimeters long, with three centimeters as the distance from pivot to the groove in which the stirrup rested. The pivot of the lever arm was made of a fine cambric needle and rested in a "V" groove. At the end of the lever arm a fine phosphor-bronze wire was fastened. This wire passed around another small pivot and to a weight, which held it tight to the pivot. This latter pivot was made of highly tempered steel and was perhaps two millimeters in diameter, except where the fine wire passed around it. At this point it had been cut to a diameter of about one millimeter. The bearings were jewels. The stirrup was made with the lower part of steel in order to make as keen a knife edge as possible for the lever arm to rest on. The mirror was a small galvanometer mirror and fastened to the pivot by wax.

* An Extensometer Amplifier. Journal of the Optical Society of America. 7, no 11 Nov. 1923 p. 1011.

Fig. 4.

it was counterbalanced so that there would be no tendency of the mirror to creep.

In the calibration of the instrument, a wire from the stirrup was fastened to the micrometer screw of a cathetometer. A telescope was focused on the mirror image of a scale. The micrometer screw was then turned so as to give the mirror an even number of complete rotations. From the micrometer movement and number of rotations, the distance the stirrup moved for one complete revolution could be calculated. From this value the movement of the stirrup for a centimeters movement of the mirror at any scale distance could be computed. With a scale three meters distant a movement of less than a twentieth of the wave length of sodium light could be detected. This was thought to be fine enough, as a matter of fact the scale was used at a distance of only two meters.

After the calibration of the extensometer, which is shown in Table I, it was securely fastened upside down to the same base that supported the crystal. This is clearly shown in Figures (5) and (6).

On top of the crystal a small block was placed. Through this block a hole was cut so that a small brass rod could pass through. This rod was the top part of a saddle that surrounded the crystal. In the center of this rod a small needle was fastened so that its point rested in a small conical hole in the block. Thus any movement of the crystal

TABLE I

Calibration of Extensometer.

Feb. 7, 1924.

Micrometer Reading.	Micrometer Movement.	No. of Turns made by Mirror.	Movement per turn.
103 25.4			
101 15.2	.5230	1	.5230 mm.
101 16.2	.5282	1	.5282
103 27.8			
103 28.5			
101 20.5	.5200	1	.5200
101 20.5			
99 14.9	.5140	1	.5140
99 14.9			
101 25.1	.5248	1	.5248
101 25.1			
103 36.0	.5272	1	.5272
103 36.0			
105 44.5	.5262	1	.5262
105 43.9			
103 35.8	.5203	1	.5203
103 35.8			
101 26.9	.5223	1	<u>.5223</u>
Average			.5229 mm.

Feb. 8, 1924

Average of nine readings .5230 mm.
 (with various number of complete turns
 made by the mirror)

Feb. 9, 1924

Average of five readings .5227

Final average of three sets of data
 .52287 mm for each complete turn of mirror.

With scale distant two meters, one cm. deflection records a movement of $.315 \times 10^{-4}$ cm.

TABLE II

Crystal Dimensions. Feb. 22, 1924

Length	Width	Thickness
1.575"	.795"	.089"
1.560	.788	.088
1.580	.782	.089
	.791	.088
	.792	.087
		.084
		.090
Average		
1.5716"	.7895"	.0883"
Converted to metric system.		
<u>3.992</u> cm.	<u>2.005</u> cm.	<u>.224</u> cm.

Tinfoil Dimensions.

Length	Width
3.5 cm.	1.39 cm.

Area = length x width = 4.889 square cm.

Fig. 6.

gave, thru the block, a movement to the saddle, which in turn transferred this movement to the extensometer.

Compressing Apparatus.

This apparatus was a simple lever arm. The arm was made of ^Asteel rod less than a centimeter in diameter and nearly thirty centimeters long. It was pivoted at one end by a long needle mounted in conical steel bearings. The blocks composing the bearings were fastened together and clamped to a stand. At the other end a small hook was fastened to the arm, on which the weights were to be hung. At the center of the arm, a threaded hole for a machine screw was made. This screw had a sharpened end that was made to rest in a small hole in the brass block that was placed on the crystal. Thus the force could be applied directly to the crystal. Of course the force applied was twice the value of the weights applied at the lever arm.

The apparatus as thus made gave an initial stress to the crystal. In order to overcome this, a spring was fastened by means of two wires to the brass block as shown in Figure (6) . The spring was stretched enough just to overcome the initial weight on the crystal.

Temperature Control.

In order to keep the conditions of the crystal fairly constant a tin case was made to surround the crystal and to rest on the hard rubber base. A glass top was made to go over the case, it having a small hole in its center for the spring to pass thru.

This tin case was actually a double walled case forming a circular trough. Thus, water could be poured into the trough to regulate the temperature. This method of temperature control was not satisfactory so that a coil of copper tubing was placed in the trough of water and water passed thru the tubing. In this way the temperature could be lowered and kept at any point between room temperature and a minimum of 16° centigrade.

In order to raise the temperature a nitrogen mazda lamp was placed above the glass case, care being taken to keep the light from shining directly on the crystal.

A hole was made near the top of the inner tin case so that a thermometer, divided tenths of degrees, could be inserted into the case and the bulb placed in intimate contact with the lower edge of the crystal.

Calibration of Galvanometer.

The electricity produced by the crystal is a charge so that the galvanometer had to be calibrated for this charge. The method of calibration was the standard condenser method.

Table III shows this data and Figure (7) shows the graph of these values.

From the time the instrument was calibrated until after (the after) the final data was taken, the suspension was not changed. All these circuits were mounted on plate glass in order to reduce leakage to a minimum.

TABLE III

Calibration of Galvanometer.

March 27, 1924

E in volts.	C in farads	Q in coulombs	Reading in cms.	Def. in cms.
.1	$.05 \times 10^{-6}$	$.5 \times 10^{-6}$	25.5	.5
.2	.05	1.0	26.17	1.17
.4	.05	2.0	27.1	2.1
.5	.05	2.5	27.58	2.58
.1	.10	1.0	25.9	.9
.2	.1	2.0	27.1	2.1
.4	.1	4.0	28.95	3.95
.5	.1	5.0	30.0	5.0
.8	.1	8.0	33.1	8.1
1.0	.1	10.0	35.1	10.1
1.3	.1	13.0	38.5	13.5
1.5	.1	15.0	40.35	15.35
2.0	.1	20.0	46.0	20.0
.1	.2	2.0	26.85	1.85
.2	.2	4.0	28.7	3.7
.3	.2	8.0	33.1	8.1
.5	.2	10.0	35.0	10.0
.7	.2	14.0	39.25	14.25
1.0	.2	20.0	45.7	20.7
1.1	.2	22.0	48.0	23.0
1.2	.2	24.0	50.2	25.2
.1	.3	3.0	27.7	2.2
.2	.3	6.0	30.7	5.7
.4	.3	12.0	37.4	12.4
.5	.3	15.0	40.3	15.3
.6	.3	18.0	43.95	18.95
.7	.3	21.0	46.4	21.4
.8	.3	24.0	50.2	25.2
.1	.5	5.0	30.6	5.6
.2	.5	10.0	35.1	10.1
.4	.5	20.0	45.9	20.9

(22)

Fig.7.

Calibration Curve
of
Galvanometer

Procedure .

With the apparatus completed an initial stress-strain run was taken. In this run it was found that there was an initial change in crystal length and also that there was a creep in this change for a short period of time. When the load was removed there was an equal initial movement in reversed direction and a creep until the extensometer reading was back at the original.

When the brass block on top of the crystal was moved, even very slightly, the initial reading as well as time effect was changed. One point was found to give a minimum change as well as a minimum of time effect. It was decided that the minimum condition was that in which the stress was being applied to the crystal as nearly as possible along the line "F" of Figure (2). At other points a bending of the crystal was obtained, which did not give the desired results. The time effect in this central position was a very small one compared to that at any other point.

With this minimum point of deflection secured, a series of runs was taken finding the stress-strain relations for the crystal under various fixed temperatures with various loads. This stress went as high as 2325 gr./sq. cm. starting with the smallest as 222.5 gr./sq. cm. and going up in ten even steps.

These runs were taken on both open and short circuit

and at the same time the charge produced on each short circuit run was taken from the galvanometer reading.

The maximum charge showed at 22.25° so that at that temperature an open circuit run was made giving initial and final values of extensometer reading.

Another run was taken with a constant stress of 2225 gr./sq.cm. at various temperatures from 35° to 16° finding both the strain and piezo-electric charge.

RESULTS .

Only typical sets of data are given in the following tables and in the accompanying graphs.

Table IV gives the complete calculations of the Stress and strain values on both open and short circuit for a temperature of 20° centigrade.

Table V gives the end results for stress and strain at temperatures of 20° , 25° , and 30° . These values are shown graphically in Figure (8). It is to be noted that at the temperature of 30° the short and open circuit values are the same and that at this temperature the strain is greatest. At the temperature of 20° there is a difference between open and short circuit values, the open circuit having the less strain.

Tables VI and VII give the stress-charge relations for the same set of runs in which the stress-strain data was taken. The graphs of Figure (9) show these values very well. It will be noted that at 20° (as shown from these runs) the greatest piezo-electric charge is given off while a change in either direction will reduce this charge. As is shown later this maximum charge really comes at 22.25° .

A correlation of Figures (8) and (9) show that at the temperature of least piezo-electric charge there is the greatest strain, the stress being the same. Also that at the temperature where there is considerable charge

TABLE IV

Stress Strain Values.

 $\theta = 20^\circ$

April 14, 1924

Force gr.	Stress gr./sq.cm.	Contraction $.315 \times 10^{-4}$ cm.	Strain 10^{-5}
Open Circuit			
100	222.5	1.5	1.183
200	445.0	2.5	1.97
300	667.5	4.8	3.78
400	840.0	6.5	5.125
500	1112.5	7.5	5.92
600	1335.0	8.5	6.7
700	1557.5	9.0	7.1
800	1780.0	9.5	7.5
900	2002.5	10.0	7.88
1000	2225.0	10.5	8.28

Short Circuit			
100	222.5	2.0	1.575
200	445.0	4.0	3.15
300	667.5	5.5	4.33
400	840.0	7.5	5.92
500	1112.5	9.0	7.1
600	1335.0	10.0	7.88
700	1557.5	11.0	8.67
800	1780.0	11.5	9.07
900	2002.5	12.0	9.46
1000	2225.0	13.0	10.25

TABLE V
Stress Strain Values.

April 14, 1924

Stress gr./sq.cm.	Strain 10^{-5}		
	$\theta=30^\circ$	$\theta=25^\circ$	$\theta=20^\circ$
Open Circuit			
222.5	1.97	1.77	1.185
445.0	3.5	3.31	1.97
667.5	4.73	4.33	3.78
890.0	6.7	5.52	5.125
1112.5	7.88	6.7	5.92
1335.0	9.1	7.1	6.7
1557.5	9.86	7.88	7.1
1780.0	11.5	8.67	7.5
2002.5	12.22	9.86	7.88
2225.0	13.0	11.1	8.28
Short Circuit			
222.5	1.97	1.97	1.575
445.0	3.5	3.47	3.15
667.5	4.73	4.73	4.33
890.0	6.7	6.3	5.92
1112.5	7.88	7.42	7.1
1335.0	9.1	7.88	7.83
1557.5	9.86	8.67	8.67
1780.0	11.5	9.86	9.07
2002.5	12.22	10.65	9.47
2225.0	13.0	11.85	10.25

TABLE VI

Force Charge Values.

 $\theta = 20^\circ$

April 14, 1924.

Force gr.	Stress gr./sq.cm.	Charge 10^{-8}	Charge/cm ² Coulombs.
100	222.5	2.2	.565
200	445.0	4.5	1.156
300	667.5	6.8	1.75
400	890.0	9.0	2.31
500	1112.5	11.0	2.83
600	1335.0	12.7	3.36
700	1557.5	14.5	3.72
800	1780.0	16.0	4.12
900	2002.5	17.0	4.37
1000	2225.0	18.0	4.62

TABLE VII

Stress Charge/sq.cm. Values.

April 14, 1924

Stress gr./sq.cm.		Charge /sq.cm. in 10^{-8} Coulombs.				
$\theta=35^\circ$		$\theta=30^\circ$	$\theta=25^\circ$	$\theta=20^\circ$	$\theta=16^\circ$	
222.5	.0514	.077	.2055	.565	.463	
445.0	.103	.154	.462	1.156	1.53	
667.5	.154	.231	.693	1.75	1.94	
890.0	.206	.321	.937	2.31	2.13	
1112.5	.257	.411	1.155	2.83	2.49	
1335.0	.308	.478	1.388	3.36	2.88	
1557.5	.36	.521	1.645	3.72	3.21	
1780.0	.412	.668	1.825	4.12	3.49	
2002.5	.463	.745	2.055	4.62	4.12	

(29)

Fig. 8.

Stress-strain
Curves

Fig. 9.

Stress-Charge
Curves

the short circuit values of strain differ, the open circuit strain being the less.

The stress-strain graphs are all curved, the less so at the higher temperature, where there is the least piezo-electric charge. The stress-charge graphs are curved only where a large charge is obtained.

Figure (10) shows a direct correlation between these two sets of graphs. No special conclusion appears from them, though it does seem as if there were a break in each curve at about the same value of strain.

Table VIII and Figure (11) show another set of stress-strain values for the temperature of 22.25° near the maximum value of charge. Both instantaneous strain and final strain are shown. This final value was taken after the change in crystal length had come to a complete stop. It was secured about fifteen seconds after the initial value. Both of these curves were taken on short circuit.

Tables IX and X and Figure (12) show values of temperature-charge and temperature-contraction for a given stress of 2225 gr./sq.cm. The lower curve shows that there is a maximum charge given off at 22.25° . As the temperature is increased the charge falls off, very rapidly while if it is decreased it falls off, but not so quickly. The upper curve shows that at the point of maximum charge there is a minimum instantaneous strain while the maximum instantaneous strain comes at the temperature where the charge is negligible. It also shows the

TABLE VIII

Stress Strain Values.

 $\theta = 22.5^\circ$

April 15, 1924

Force	Stress	Contraction	Strain	Contraction	Strain
gr.	gr./sq.cm.	(initial) $.315 \times 10^{-4}$ cm.	10^{-5}	(final) $.315 \times 10^{-4}$ cm.	10^{-5}
200	445	3.7	2.92	4.7	3.7
400	890	6.3	4.97	8.5	6.7
600	1335	9.3	7.33	11.8	8.67
800	1780	11.5	9.07	14.1	11.1
1000	2225	13.4	10.58	17.0	13.4

(32)

TABLE IX

Temperature Charge Values

April 17, 1924

Temp.	<u>Q.cooling</u> Q/sq.cm. ---10 ⁻⁸ farads---		<u>Q.heating</u> Q/sq.cm. ---10 ⁻⁸ farads---	
35.0	2	.504		
32.5	2.5	.642		
30.0	3.2	.823		
27.5	5.1	1.31		
25.0	9.0	2.31	9.0	2.31
24.5	10.4	2.67	10.5	2.7
24.0	12.6	3.24	12.5	3.21
23.5	14.8	3.85	14.8	3.83
23.0	17.6	4.52	17.5	4.5
22.5	21.2	5.44	21.0	5.4
22.25	21.3	5.47	21.3	5.47
22.0	20.0	5.14	21.0	5.14
21.5	19.3	4.96	19.2	4.93
21.0	18.4	4.73	18.5	4.75
20.5	18.0	4.63	18.0	4.63
20.0	17.0	4.37	17.2	4.42
17.5	16.4	4.22		
16.0	16.0	4.12		

TABLE X

Temperature Contraction Values .

Temp.	<u>Contraction</u> Strain (initial) .315x10 ⁻² cm. 10 ⁻⁵		<u>Contraction</u> Strain (final) .315x10 ⁻² cm 10 ⁻⁵	
35.0	17.1	13.5	17.1	13.5
32.5	16.8	13.25	16.8	13.25
30.0	16.5	13.0	17.2	13.55
27.5	16.0	12.6	17.0	13.4
25.0	15.0	11.83	16.9	13.31
22.5	12.0	9.46	17.1	13.49
20.0	13.0	10.25	17.0	13.4
17.5	13.3	10.5	17.1	13.49
16.0	13.5	10.65	----	----

(34)

Fig 12

final strain to be a horizontal line with a value the same as that of the maximum instantaneous strain.

Figure (13) shows a correlation of the two curves of Figure (12). It shows a straight line relation between charge and strain, except at low values of charge, where the curve seems to change direction slightly.

All of these curves show conclusively that the strain and consequently the value of Young's modulus for the crystal depends definitely on the charge of the crystal.

Since this is true, the reason for a difference in open and short circuit strain values (Figure 8) can easily be seen. On short circuit the charge goes off practically instantaneously, while on open circuit it is held for a greater length of time depending on the quality of insulation. There is a small amount of charge on open circuit that is not given up immediately this is the reason for the upper curve of Figure (12). As the charge increases there is a greater amount that is not given off immediately; this charge will then tend to keep the crystal from contracting.

The value of Young's modulus obtained from the final value of strain as shown in Figure (12) for 2225 gr. per sq.cm. is 1.62×10^{10} . 2.31×10^{10} being the value at point of minimum strain. The value of the modulus may be found at any point for the crystal by taking the tangent to the stress-strain curve at the stress desired.

(36)

Fig. 13

It will be noted from the curves of Figures (8) and (9) that where the stress-charge curves approach a straight line the stress-strain curves are also more nearly a straight line. Since it is when there is a minimum of charge that the stress-charge curves do become straight lines, it would seem that when there is no charge these lines would become absolutely straight and also the corresponding stress-strain curves would assume that form, which would be expected were there no charge on the crystal for with most substances (where there is no charge present) the stress-strain curve is a straight line.

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