# A SURVEY OF INORGANIC PIEZOELECTRIC MATERIALS

PAUL H. EGLI, *Crystal Section, Naval Research Laboratory, Washington 20, D.C.*

ABSTRACT

An exhaustive survey of inorganic piezoelectric materials was made in an effort to develop improved crystals, particularly for underwater sound gear. The field of water-soluble materials was covered thoroughly enough that further prospecting appears unprofitable. The results of this survey, together with all major surveys by previous investigators, are presented in a single table. Sufficient data are presented, concerning the piezoelectric activity of each of the materials investigated to indicate whether they justify further investigation for various applications.

## INTRODUCTION

This survey was undertaken in an effort to provide improved materials for piezoelectric applications, particularly for underwater sound gear, a goal which influenced both the selection of materials to be investigated and the extent to which each material was studied. The essential properties required for sonar gear are maximum sensitivity, chemical and mechanical stability, and high dielectric breakdown strength.

On this basis, water-soluble inorganic materials represented the most promising field for investigation. In selecting the individual compounds for study, previous surveys were of little value because of obvious errors, discrepancies between different investigations, and lack of quantitative data. Moreover, there were no well established principles by which the piezoelectric activity of a particular compound could be even roughly predicted. Certain generalizations appeared reasonable, but there were no data to confirm them and the possibility of exceptions could not be ignored. For example, it seemed likely that activity would be greatest when there was a large difference in electrochemical potential between constituent ions. It was also suggested that hydrogen bonding, or largely ionic coupling, were necessary; but existing data were not sufficient to confirm these hypotheses.

Attempts were completely unsuccessful to establish firm relationships by which piezoelectric activity could be predicted on the basis of carefully investigating a small series of type compounds. Thus it became necessary to make an exhaustive survey, eliminating from consideration only those compounds which were unsuitable for other reasons, e.g., poor chemical stability.*

* As a result of the survey, the factors which influence piezoelectric activity can be outlined somewhat more confidently and will be discussed in a paper to be released shortly by S. Zerfoss et al.

## Test Procedure

The efficiency and reliability of the investigation depended as much on developing new techniques for detecting and measuring piezoelectricity as on the ability to grow crystals. The general goal was to be able to make tests on as small specimens as possible in order to save growing time.

A "click" test, using a modification of a circuit by Giebe and Scheibe was used for the first indication of activity. In general, well-formed crystals down to 100 mesh can be tested on this device. The *NRL* design of this apparatus has proved highly reliable and free of spurious responses so that a click is positive evidence of piezoelectric activity. Moreover, the loudness of the click is a rough quantitative measure of activity. Several other factors including $Q$ (internal mechanical and electrical losses), dielectric, and elastic constants contribute to the magnitude of the click; but the variability of these factors between most crystals is relatively small so that the piezoelectric coupling is the dominating variable.

Absence of any response is less positive proof of lack of piezoelectric activity because the indication may be swamped out on very weak materials by a low $Q$ or by high conductivity. Usually, however, these difficulties can be easily identified by a characteristic sizzling noise so that for all practical purposes the click test is reliable.**

For more quantitative data, a dynamic test procedure was adopted which depends on accurate measurement of the resonant and antiresonant frequencies of the specimen. A low capacity crystal holder and the associated circuits were perfected to the point where reasonably accurate data can be obtained on well shaped specimens as small as 2 mm. cubed. The results of these tests on small crystals have proved in every case to be within 25% of precise measurements on full sized specimens.†

## Basis for Selecting the Materials Included in Survey

The first step in compiling the list of materials to be investigated was an exhaustive search through the literature for all inorganic compounds which had ever been reported as having a symmetry structure which permits piezoelectric activity. All such compounds were considered even

** A complete report on the important factors in this test procedure and the design of the *NRL* device has been described. See "An Improved Apparatus for Detecting Piezoelectricity" by Ralph G. Stokes, *Am. Mineral.*, **32**, 670–677 (1947).

† The complete procedure and a description of the equipment were presented in an article entitled "The Approximate Determination of Piezoelectric Properties by Measurements on Small Crystals" by Elias Burstein, published in *The Review of Scientific Instruments*, **18**, 317–327 (1947).

if the more recent structure investigations indicated a non-piezoelectric class.

To this list were added all the compounds that had previously been tested by anyone regardless of their reported results. On the basis of modern symmetry data, many of these compounds would not be considered, but they were included in order that all available information be available from one source.

Finally, to complete the list, it was realized that errors in symmetry classification had caused omissions just as it had caused many non-piezoelectric materials to be included. In the course of the investigation as generalizations were developed concerning the type of chemical formulas which were likely to be piezoelectric, all available compounds of these types were considered, regardless of symmetry data.

Before a material was investigated, a search was made for all available information concerning its properties. On the basis of this information, many compounds were eliminated because of some factor which prevented their having any possible practical application. For example, a long list of sulfides and oxides was eliminated because of high conductivity, and another large group was eliminated because they were chemically unstable at temperatures within usual operating ranges. Many insoluble materials, particularly if naturally occurring, were eliminated because several recent surveys of minerals have failed to discover any compound of value, and synthesis would be excessively expensive.

If, however, a compound was of possible help in confirming some general principle in relating activity to composition and structure, it was investigated regardless of possible practical value. Thus, it seems unlikely that any further prospecting among water-soluble inorganic materials would be profitable.

## Description of Results

All compounds which it was thought reasonable to consider are listed alphabetically in Table 1. The first column lists the reported symmetry classifications. No effort was made to check the classifications which are from many sources, and wherever the symmetry listed conflicts with the test for piezoelectricity, it seems certain that the symmetry class is incorrect. In cases where more than one classification is shown, the order in which they are listed is not intended to infer which is most likely. When two classes are listed which differ only by a center of symmetry, the test for piezoelectricity indicates which is more likely correct. The principal reason for including the reported symmetry is for convenience in considering possible applications. For example, the modes of vibration of certain classes are not suitable for high frequency oscillator applica-

tions even though some of the crystals in that class may be strongly piezoelectric.

The second column indicates the results of previous investigators by number as listed in the bibliography. Only the six principal surveys by previous investigators are listed, but these cover essentially all past work. Less than a dozen other references were located, each of which referred to a single compound. The remaining compounds were new to *NRL* with the exception of the well known developments of $BaTiO_3$ and the isomorphs of *ADP*.*

The third column lists the results of *NRL* tests. An adjective description is the result of click tests. A $k$ value refers to the piezoelectric coupling coefficient. This is a measure of the interaction between the electrical and mechanical behavior of the crystal, and forms a useful "figure of merit" for most applications. In a few cases, the $k$ given is an approximate value obtained by test of a small specimen of unknown orientation, but for the most part, it represents confirmed data for the strongest activity along the various axes. Repeated observations on many materials indicated that a material classified as "moderate" by the click test had a coupling coefficient of approximately 0.1, which it is generally agreed is the minimum necessary to be usable for any application. Thus, any material with less than a moderate response can confidently be regarded as having no practical value, and a response of "moderate" or better indicates that further consideration is justified. The data included are not intended to be sufficient for evaluating possible applications but do narrow the list which must be more thoroughly investigated. For example, a material with a $k$ of less than 0.2 could offer no advantage over the present crystals used for underwater sound gear. Materials with $k$ as low as 0.1 can be considered for high frequency oscillator control, providing they are in symmetry classes having desirable modes of vibration.

A number of materials are listed which were not investigated at *NRL*. Some of these compounds are obviously not piezoelectric—by well confirmed symmetry data—but are included so that no material considered in previous surveys is omitted. Other compounds are included which are reported to be in a symmetry class that allows piezoelectricity but have not been tested at *NRL* or by previous investigators. The reason for this lack of attention is described in the final column. Comments are also included for some of the materials tested to indicate a limiting factor in

* It was later found that a number of these compounds had also been tested by H. Jaffe of the Brush Development Company. For example, $LiSO_4 \cdot H_2O$, valuable for its strong hydrostatic response, was being developed under the company code name *LH*.

TABLE I. CRYSTALS INVESTIGATED FOR PIEZOELECTRICITY

| Chemical Compound | Schoenfliess Symbol for Reported Structure | Previous Investigation | NRL Investigation | Practical Limitations |
|---|---|---|---|---|
| $Ag_3AsO_3$ | $T_d$ | | V. Weak | Unstable |
| $Ag_3AsO_4$ | $T_d$ | | | Unstable |
| $Ag_3AsS_3$ | $C_{6v}$ | +1 | | Insol.-Decomp. |
| $AgBrO_3$ | $D_{4h}$, $V_d$ | | Neg. | |
| AgCl | $O_h$ | −5 | Neg. | |
| AgCN | $C_{3v}$ | | Mod. | Hygroscopic |
| $AgClO_3$ | $V_d$ | | Neg. | |
| $AgClO_4$ | $T_d$ < 208° C. | | | |
| $Ag_2HgI_4$ | $V_d$ | | Neg. | |
| AgI | $T_d$, $C_{6v}$ | +5, −3 | Neg. | |
| $AgIO_3$ | Rhomb? | +5 | Mod. | Insol.-Decomp. |
| $AgK(CN)_2$ | $D_3d$ | −4, −5 | | |
| $AgNO_2$ | $D_{2h}$ | | V. Weak | Hygroscopic |
| $AgNO_3$ | V, $C_{2v}$ | −3, −4 | Neg. | |
| $Ag_3PO_4$ | $O_h$, $T_d$ | | V. Weak | |
| $AgTl(NO_3)_2$ | | | Neg. | |
| $AlAsO_4$ | $V_d$ | | | Req. hydrothermal synthesis |
| $AlCl_3$ | $D_3$ | | | Deliquescent |
| $AlF_3$ | $D_3$ | | | Hygroscopic |
| $Al(PO_3)_3$ | $T_d$ | | | |
| $AlPO_4$ | $D_3$ | | Mod. | |
| $AuI_3$ | $C_3$ | | | Unstable |
| $BAsO_4$ | $S_4$, $V_d$, $D_{6h}$ | | | Non piezo. symmetry most likely |
| $BPO_4$ | $S_4$, $V_d$, $D_{6h}$ | | | Non piezo. symmetry most likely |
| $BaBr_2 \cdot 2H_2O$ | $C_{2h}$ | −5 | Neg. | |
| $Ba(BrO_3)_2 \cdot H_2O$ | $C_{2h}$ | | Neg. | |
| $BaCdCl_4 \cdot 4H_2O$ | $C_i$ | −5 | | |
| $BaCl_2 \cdot 2H_2O$ | $C_{2h}$ | −5 | Neg. | |
| $Ba(ClO_3)_2 \cdot H_2O$ | | −5 | Neg. | |
| $Ba(CNS)_2$ | | | Neg. | |
| $BaFe(CN)_6 \cdot 6H_2O$ | | −5 | Neg. | |
| $Ba(NO_2)_2 \cdot H_2O$ | | +5 | Weak | Unstable |
| $Ba(NO_3)_2$ | T, $T_h$ | −1 | Neg. | |
| $BaPt(CN)_4 \cdot 4H_2O$ | $C_{2h}$ | −5 | | |
| $BaSO_4$ | $V_h$ | −5 | | |
| $BaS_2O_6 \cdot 2H_2O$ | | +6 | Mod. | |

TABLE I—*Continued*

| Chemical Compound | Schoenfliess Symbol for Reported Structure | Previous Investigation | NRL Investigation | Practical Limitations |
|---|---|---|---|---|
| $BaTiO_3$ | | | Active | |
| BeO | $C_{6v}$ | | | |
| BeS | $T_d$, $V_{4h}$, $V_d$ | | | Decomposes |
| $BeSO_4 \cdot 4H_2O$ | $V_d$ | | k~0.1 | |
| $Bi(CNS)_3$ | $C_{6v}$ | | Neg. | |
| $BiCl_3 \cdot 3SC(NH_2)_2$ | $C_3$ | | V. Weak | |
| $BiI_3$ | $C_3$ | | | Insol.-Decomp. |
| $BiKF_4$ | | | Neg. | |
| $BiKI_4$ | | | Neg. | |
| $Bi_2O_3$ | $V_d$, T, $C_2$ | | | Insol.-Inverts |
| $CaF_2$ | $O_h$ | −5 | Neg. | |
| $CaPd(CN)_4 \cdot 5H_2O$ | $D_2$ | −5 | | |
| $CaPt(CN)_4 \cdot 5H_2O$ | $D_2$ | −5 | | |
| $CaSO_4 \cdot 2H_2O$ | $C_{2h}$ | −5 | Neg. | |
| $CdF_2$ | $O_h$ | −5 | | |
| $CdI_2$ | $D_{3d}$, $C_{6v}$ | −5 | Neg. | |
| $CdKI_3$ | | | Neg. | |
| CdS, Se, Te | $C_{6v}$, $T_d$ | | | Conductivity |
| $CdSO_4 \cdot xH_2O$ | $C_{2h}$ | | Neg. | |
| $CeF_3$ | $D_{6m}$, $D_6$ | | | Insol. |
| $Ce_2O_3$ | $D_3$ | | | |
| $Ce_2(SO_4)_3 \cdot 8H_2O$ | $C_i$ | | Neg. | |
| $Ce(NH_4)_2(NO_3)_5 \cdot 4H_2O$ | | | Strong | Conducts-Deliquescent |
| $Co(CNS)_2 \cdot 3H_2O$ | $C_{2h}$, $C_{2v}$ | | Neg. | |
| $CoCl_2$ | $C_{3v}$ | | | Deliquescent |
| $Co(NH_3)_w(NO_3)_x(NO_2)_y(SO_4)_z$ | $D_2$, $D_{2h}$ | | Neg., V. Weak | Large series of complexes, all relatively unstable |
| CoS, Se | $D_{6h}$, $C_{6v}$ | | | Conductivity |
| $CoSO_3 \cdot 6H_2O$ | $C_3$ | | Mod. | Unstable |
| $Cr_2(SO_4)_3$ | | | Neg. | |
| $CsNO_3$ | $C_{3v}$ | | Weak | |
| $Cs_2S_2O_6$ | $D_6$ | | V. Weak | |
| CuBr | $T_d$ | | | Unstable |

TABLE I—*Continued*

| Chemical Compound | Schoenfliess Symbol for Reported Structure | Previous Investigation | NRL Investigation | Practical Limitations |
|---|---|---|---|---|
| CuCl | $T_d$ | +3 | k=0.12 | Unstable |
| CuF | $T_d$ | | | Hydrolyses |
| $Cu_2HgI_4$ | $D_{2d}$ | | Neg. | |
| CuI | $T_d$ | | | Unstable |
| $CuK_2Cl_4 \cdot 2H_2O$ | $D_{4h}$ | | Neg. | |
| $CuNaCl_3 \cdot xH_2O$ | | | Neg. | |
| $CuSO_4 \cdot 3H_2O$ | $C_s$ | | Weak | Hygroscopic |
| $CuSeO_3 \cdot 2H_2O$ | $D_2$ | | Neg. | |
| $CuSeO_4 \cdot 5H_2O$ | $C_i$ | | Neg. | |
| $CuSO_4 \cdot 5H_2O$ | $C_i$ | | Neg. | |
| $FeNH_4Cl_4$ | | | Neg. | |
| $Fe(NH_4)_3F_6$ | T, $T_d$, $O_h$, $C_{2v}$ | | | Hygroscopic |
| $Fe(NH_4)_2(SO_4)_2$ | $D_3$ | | Neg. | |
| $FeSO_4 \cdot (NH_4)_2SO_4 \cdot 6H_2O$ | $C_{2h}$ | −5 | | |
| $FePO_4$ | $D_3$ | | | Req. hydrothermal synthesis |
| FeS | $C_{6v}$ | | | Conductivity |
| $GeO_2$ | $D_3$ | | | |
| $GeS_2$ | $C_{2v}$ | | | |
| $HIO_3$ | V | +2 | k=0.3 | Hygroscopic |
| $HgBr_2$ | $C_{2v}$ | | Neg. | |
| HgCN | $V_d$ | | | Unstable |
| $Hg(CN)_2$ | $V_d$ | +2, +3 | Weak | |
| $Hg(CNO)_2$ | | +3 | | Unstable |
| $HgI_2$ | $C_{2v}$, $C_{4h}$ | −5 | Mod. | |
| HgS | $T_d$ | +2, +3 | | Conductivity |
| ICN | $D_{3d}$, $D_3$, $C_3$, $C_{3v}$, $C_{3i}$ | +3, +5 | | |
| $In_2O_3$ | $D_3$ | | | |
| $IrCl_4$ | | −5 | | |
| $KAl(SO_4)_2 \cdot 12H_2O$ | $T_h$ | −3 | | |
| KBr | $O_h$ | −3 | Neg. | |
| $KBrO_3$ | $C_{3v}$, $D_3$ | +2, +3 | $k=0.23$ | |
| $KB_5O_8 \cdot 4H_2O$ | $C_{2v}$ | | Mod. | |
| $KClCrO_3$ | $C_{2h}$ | | Neg. | |

TABLE I—*Continued*

| Chemical Compound | Schoenfliess Symbol for Reported Structure | Previous Investigation | NRL Investigation | Practical Limitations |
|---|---|---|---|---|
| KCN | $T, O_h$ | | Neg. | |
| KCNO | $D_{4h}$ | −5 | Neg. | |
| $KCe(NO_3)_5 \cdot 1\frac{1}{2}H_2O$ | $C_{2v}$ | | Neg. | |
| $KCd(NO_2)_3$ | | +5 | | Unstable |
| $K_2Cd(NO_2)_4$ | $V_h$ | −5 | | |
| $KClO_3$ | $C_{2h}$ | | Neg. | |
| $KClO_4$ | $V_h, T_d$ | | Neg. | |
| $K_3Cu(CN)_4$ | $D_3$ | | Quest. | |
| $K_2CrO_4$ | $V_h$ | −3 | Neg. | |
| $K_2Cr_2O_7$ | $C_i$ | −2, −4, −3, −5 | Neg. | |
| $KD_2PO_4$ | $V_d$ | + | | |
| $K_3Fe(CN)_6$ | $C_{2h}$ | −3 | Neg. | |
| $K_4Fe(CN)_6 \cdot 3H_2O$ | $C_{2h}$ | −3 | Neg. | |
| $KHF_2$ | $D_{4h}$ | | | Unstable |
| $KH_2AsO_4$ | $V_d$ | +1, +2 | $k \sim 0.1$ | |
| $KH_2PO_4$ | $V_d$ | +1 | $k = 0.11$ | |
| $K_2Hg(CN)_4$ | $O_h$ | −5 | | |
| $K_3Hg(NO_2)_5 \cdot H_2O$ | $V_h$ | −5 | | |
| $KIO_3$ | Perov. | | Mod. | |
| $KIO_4$ | $C_{4h}$ | | Neg. | |
| $K_2La(NO_3)_5 \cdot 1\frac{1}{2}H_2O$ | $C_{2v}$ | | Weak | |
| $KLiSO_4$ | $C_6$ | +2 | $k = 0.04$ | |
| $KLiSeO_4$ | $C_6$ | +6 | | |
| $KMgPO_4 \cdot 6H_2O$ | $C_{2v}$ | | | Insol.-Decomp. |
| $K_3Na(SO_4)_2$ | $D_{3d}$ | | Neg. | |
| $K_3Na(CrO_4)_2$ | | | Neg. | |
| $KNH_4SO_4$ | | | Neg. | |
| $K_2Ni(SO_4)_2 \cdot 6H_2O$ | | | Neg. | |
| $KNO_2$ | $C_3$ | | V. Weak | |
| $KNO_3$ | $V_h, C_{3v}$ | −3 | Neg. | |
| $K_2PdCl_4$ | $V_d$ | | | Symmetry quest. |
| $K_2S_2O_3 \cdot 1\frac{2}{3}H_2O$ | $C_{2v}$ | | V. Weak | |
| $K_2SO_4$ | $V_h$ | −3 | | |
| $K_2S_2O_6$ | $D_3$ | +6 | Mod. | |
| $K_2S_4O_6$ | $C_s$ | | Slight | |
| $K_2S_2O_8$ | $C_i$ | | | Unstable |
| $K_2SnCl_6$ | $O_h$ | | Neg. | |
| $K_2TeO_3$ | | | Neg. | |
| $K_2TeO_4$ | $V_h$ | | Neg. | |
| $K_2TlCl_6(?)$ | | −5 | | |
| $K_2Zn(CN)_4$ | $O_h$ | +5 | | Inactive structure proven |

TABLE I—*Continued*

| Chemical Compound | Schoenfliess Symbol for Reported Structure | Previous Investigation | NRL Investigation | Practical Limitations |
|---|---|---|---|---|
| $LaF_3$ | $D_6$ | | | |
| $La_2O_3$ | $D_3$ | | | |
| $Li_2BeF_4 \cdot H_2O$ | $C_{3i}$ | −4 | | |
| $LiClO_3$ | | | Neg. | |
| $LiClO_4 \cdot 3H_2O$ | $C_{6v}$ | | Mod. | |
| $LiI \cdot 3H_2O$ | $C_{6v}$ | | Quest. | |
| $LiIO_3$ | $D_6$ | | Mod. | |
| $LiKSO_4 \cdot CrO_4$(?) | $C_6$ | +6 | | |
| $LiKSO_4 \cdot MoO_4$(?) | $C_6$ | +6 | | |
| $LiNH_4SO_4$ | $V_h$ | | Neg. | |
| $LiNaCO_3$ | $D_{3h}$ | | Mod. | |
| $LiNaSO_4$ | $C_{3v}$ | +6 | $k=0.04$ | |
| $LiNa_3(CrO_4)_2 \cdot 6H_2O$ | $C_{3v}$ | | | |
| $LiNa_3(MoO_4)_2 \cdot 6H_2O$ | $C_{3v}$ | +6 | | |
| $LiNa_3(SO_4)_2 \cdot 6H_2O$ | $C_{3v}$ | | | |
| $LiNa_3(SeO_4)_2 \cdot 6H_2O$ | $C_{3v}$ | +6 | | |
| $LiRbSO_4$ | $C_6$ | | | |
| $Li_2SO_4 \cdot H_2O$ | $C_2$ | +1 | $k=0.35$ | |
| $Li_2SeO_4 \cdot H_2O$ | $C_2$ | +6 | Weak | |
| $Mg(NH_4)_2(SO_4)_2 \cdot 6H_2O$ | $C_{2h}$ | | Neg. | |
| $Mg(ClO_4)_2 \cdot 6H_2O$ | $C_{2v}$ | | | Hygroscopic |
| $MgCrO_4 \cdot 7H_2O$ | V | | V. Weak | |
| $MgSO_3 \cdot 3H_2O$ | $C_{3v}$ | | Weak | |
| $MgSO_3 \cdot 6H_2O$ | $C_3$ | | $k=0.06$ | |
| $MgSO_4 \cdot 7H_2O$ | V | +1 | $k=0.06$ | |
| $NaBrO_3$ | T | +2, +3 | $k=0.04$ | |
| $Na_2Ca(CO_3)_2 \cdot 2H_2O$ | $C_{2v}$ | +6 | V. Weak | |
| $Na_2CO_3 \cdot H_2O$ | $C_{2v}$ | | Mod. | |
| NaCN | $C_{2v}$ | | V. Weak | |
| NaCNO | $C_{3v}$ | | | Unstable |
| $NaClO_2$ | $T_h$ | +1 | $k=0.03$ | |
| $NaClO_4$ | $T_h$, $T_d$ | | Neg. | |
| $Na_4Fe(CN)_6 \cdot 12H_2O$(?) | | −5 | | |
| $Na_2Fe(CN)_5NO \cdot 2H_2O$ | | −5 | Neg. | |
| $NaH_2AsO_4 \cdot H_2O$ | $D_2$ | | | |
| $Na_2HAsO_4 \cdot 7H_2O$ | | | Neg. | |
| $NaH_2PO_4 \cdot H_2O$ | $D_2$ | | $k=0.05$ | |
| $NaIO_3$ | $V_h$ | −5 | Neg. | |
| $NaIO_4$ | $C_{4h}$ | +6, −5 | Neg. | |
| $NaIO_4 \cdot 3H_2O$ | $C_3$ | −5 | Neg. | |

TABLE—*Continued*

| Chemical Compound | Schoenfliess Symbol for Reported Structure | Previous Investigation | NRL Investigation | Practical Limitations |
|---|---|---|---|---|
| $Na_2Mg(CO_3)_2$ | $C_3$ | | Slight | |
| $NaNH_4HPO_4 \cdot 4H_2O$ | $C_{2h}$ | −5 | Neg. | |
| $NaNO_2$ | $C_{2v}$ | | Weak | Deliquescent |
| $NaNO_3$ | $D_{3d}$ | +6 | Neg. | |
| $Na_2S_2O_8$ | | | Neg. | |
| $Na_2S_2O_3 \cdot 5H_2O$ | $C_{2h}$ | | Neg. | |
| $Na_3SbS_4 \cdot 9H_2O$ | T | +1 | | Conductivity |
| $Na_2SeO_3$ | | | Neg. | |
| $Na_2SeO_4$ | $V_h$ | | Neg. | |
| $NaSiO_3 \cdot 5H_2O$ | | | Slight | |
| $Na_2WO_4 \cdot 2H_2O$ | $V_h$ | | Neg. | |
| | | | | |
| $Nd(BrO_3)_3 \cdot 9H_2O$ | $C_{6v}$ | −5 | | |
| $NdF_3$ | $D_6$ | | | |
| $Nd_2O_3$ | $D_3$, $D_{3d}$ | | | |
| | | | | |
| $(NH_4)_3AlF_6$ | T | | | Unstable |
| $NH_4B_5O_8 \cdot 4H_2O$ | $V_h$ | | Weak | |
| $NH_4Br$ | $O_h$ | | Neg. | |
| $NH_4CdCl_3$ | $D_{2h}$ | | Neg. | |
| $NH_4CdBr_3$ | | | Neg. | |
| $NH_4CdI_3$ | | | Neg. | |
| $NH_4Cl$ | $O_h$ | −3 | Neg. | |
| $2NH_4Cl \cdot CuCl_2 \cdot 2H_2O$ | $D_{4h}$ | −5 | | |
| $NH_4ClO_2$ | $C_{4v}$ | | | Unstable |
| $NH_4ClO_4$ | $V_h$, $T_d$ | −5 | Neg. | |
| $(NH_4)_2CrO_4$ | $C_6$, $C_{6h}$ | −5 | Neg. | |
| $(NH_4)_2Cr_2O_7$ | $C_{2h}$ | | Neg. | |
| $NH_4F$ | $C_{6v}$ | +5 | | Hydrolyses |
| $NH_4H_2AsO_4$ | $V_d$ | | $k=0.24$ | |
| $NH_4H_2PO_4$ | $V_d$ | | $k=0.30$ | ADP |
| $(NH_4)_5H_7(MoO_4)_6$ | $C_{2h}$ | −5 | Neg. | |
| $NH_4IO_3$ | $C_{4h}$ | +5 | Neg. | |
| $NH_4MgAsO_4 \cdot 6H_2O$ | $C_{2v}$ | | | Vap. Pres. |
| $NH_4MgPO_4 \cdot 6H_2O$ | $C_{2v}$ | | | Vap. Pres. |
| $NH_4NO_3$ | T, $V_d$, $V_h$ | | Neg. | |
| $(NH_4)_2PtCl_6$ | $O_h$ | −5 | | |
| $(NH_4)_2SnCl_6$ | $O_h$ | | Neg. | |
| $(NH_4)_2SiF_6$ | $O_h$ | −5 | | |
| | | | | |
| $NiCa(CN)_4 \cdot 5H_2O$ | $D_2$ | | | |
| $Ni(NH_4)_2(SO_4)_2 \cdot 6H_2O$ | $C_{2h}$ | | Neg. | |
| $NiNO_3 \cdot 6H_2O$ | $C_{2h}$ | −5 | | |

TABLE I—*Continued*

| Chemical Compound | Schoenfliess Symbol for Reported Structure | Previous Investigation | NRL Investigation | Practical Limitations |
|---|---|---|---|---|
| NiS | $C_{3v}$ | | | Conducts |
| $NiSO_3 \cdot 6H_2O$ | $C_3$ | | Mod. | |
| $NiSO_4 \cdot 6H_2O$ | $D_4$ | +1 | $k=0.06$ | |
| $NSO_4 \cdot 7H_2O$ | V | +2 | Weak | |
| NiSbS | T | | | |
| $PbBr_2$ | $V_h$ | −5 | | |
| $PbCl_2$ | $V_h$ | | Neg. | |
| $Pb(CNS)_2$ | | −5 | | |
| $Pb_3(Fe(CN)_6)_2 \cdot xH_2O$ | | | Neg. | |
| $PbMoO_4$ | $C_4$, $C_{4m}$, $C_6$ | −2, −4, −3 | | Insol. |
| $Pb(NO_3)_2$ | T, $T_h$ | −1 | Neg. | |
| $PbS_2O_6 \cdot 4H_2O$ | $D_3$ | | | |
| $RbB_5O_8 \cdot 4H_2O$ | | | Mod. | |
| $RbClO_4$ | $V_h$, $T_d$ | | | |
| $Rb_4Fe(CN)_6 \cdot 2H_2O$ | $C_1$ | | | |
| $RbNO_3$ | $C_{3v}$ | +5 | Weak | |
| $Rb_2S_2O_6$ | $D_3$ | | V. Weak | |
| $SbI_3$ | $C_3$ | | | Hydrolyses |
| $Sb_2O_3$ | $O_h$ | −5 | | |
| $ScF_3$ | $D_3$ | | | |
| SiC | T, $C_{3v}$ | −2, −3 | | |
| $SiO_2$ | $D_3$ | | $k=0.1$ | Quartz |
| $Sr(ClO_3)_2$ | $D_{2h}$, $C_{2v}$ | | V. Weak | |
| $Sr(IO_3)_2$ | | | Neg. | |
| $Sr(NO_3)_2$ | T, $T_h$ | −1 | Neg. | |
| $SrS_2O_6 \cdot 4H_2O$ | $D_3$ | | Weak | |
| $SrS_2O_6$ | $D_3$ | +6 | Mod. | Deliquescent |
| $TlClO_4$ | $V_h$, $T_d$ | | | |
| TlF | $V_{2h}$ | | | Hydrolyses |
| $V_2O_5$ | $C_{2v}$ | | | Deliquescent |
| $ZnBeF_4 \cdot 7H_2O$ | | −3 | | |
| $ZnK_2(SO_4)_2 \cdot 6H_2O$ | $C_{2h}$ | | Neg. | |
| $Zn(NH_4)_2(SO_4)_2 \cdot 6H_2O$ | $C_{2h}$ | | Neg. | |

TABLE I—*Continued*

| Chemical Compound | Schoenfliess Symbol for Reported Structure | Previous Investigation | NRL Investigation | Practical Limitations |
|---|---|---|---|---|
| ZnO | $C_{6v}$ | −2 | | |
| $Zn(OH)_2$ | V | | | Gelatinous |
| $Zn_3(PO_4)_2 \cdot 4H_2O$ | $D_2$ | | | Insol.-Inverts |
| ZnS | $T_d$ | +2, +3 | $k=0.02$ | |
| $ZnSO_4 \cdot 7H_2O$ | V | +1, +2 | $k=0.07$ | |

their value even though the piezoelectric activity is strong enough to be of interest.

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Note: The first five references and a list of earlier works which they incorporate are available in a Scheibe, "Piezoelectrizität des Quarzes", Edwards Brothers, Inc., Ann Arbor, Mich. (**1945**).