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# PHYSICAL PROPERTIES OF SALT,

# ANHYDRITE, AND GYPSUM--

# PRELIMINARY REPORT

By Eugene C. Robertson, Richard A. Robie, and Kenneth G. Books

Trace Elements Memorandum Report 1048

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

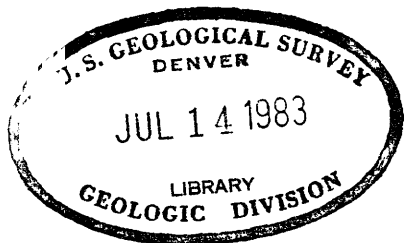UNITED STATES DEPARTMENT OF THE INTERIOR

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August 1958

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# PHYSICAL PROPERTIES OF SALT, ANHYDRITE, AND GYPSUM

By Eugene C. Robertson, Richard A. Robie,

and Kenneth G. Books

## ABSTRACT

This summary is the result of a search of the available literature. Emphasis is placed on the mechanical and calorimetric properties of salt; the measurements of elastic, thermal, magnetic, and mass properties of salt are merely tabulated.

Under hydrostatic pressure < 1,000 $kg/cm^2$ at room temperature, salt deforms plastically to strains > 100 percent at a nearly constant stress difference of about 300 $kg/cm^2$. Similarily, under temperatures > 400°C at one atmosphere, salt deforms plastically to strains > 100 percent under stress differences of about 100 $kg/cm^2$.

Enthalpies were calculated for various temperatures to 2,000°C from the low temperature and high temperature heat capacities and the heats of solution of the following minerals: salt (or halite), $NaCl$; anhydrite, $CaSO_4$; quartz, $SiO_2$; and calcite, $CaCO_3$. Three combinations of these minerals were assumed to represent three possible natural salt beds, and the heats required to raise the temperature of each to 1,500°C and to 2,000°C were calculated. For a half and half mixture of salt and anhydrite, 1,300 cal/gm were required to raise the temperature to 2,000°C. For an evaporite containing 60 percent salt and about equal amounts of anhydrite, calcite, and quartz, 1,100 cal/gm

cal/gm are required to raise the temperature to 2,000°C.

Most of the measurements of the elastic moduli were made on single crystals of salt, anhydrite, and gypsum. For the most part, the measurements of density, magnetic susceptibility, and other properties were made on natural salt samples.

DEFORMATION OF SALT

By Eugene C. Robertson

The deformation of salt, NaCl, has been well studies, especially during the period from 1924 to 1934, when important phenomena and characteristics of salt were established by Joffe, Levitsky, Polanyi, Przibram, Rinne, Schmid, and many others. In the following summary, references have been omitted, but in a more complete treatment to follow, a bibliography will be listed. An excellent review of the studies on salt to 1935 is given in Schmid and Boas (Ch. 7, 1950).

The effects of the following variables on the yielding and fracturing of salt have been studied: temperature, hydrostatic pressure, time, composition (both with regard to sample impurities and to chemical environment during the test), and the previous history of the salt.

Yield strength of a solid may be defined as the maximum stress difference at the beginning of large deformation by plastic flow. This definition is arbitrary, and does not account for time effects. The yield strength varies from 10 to 1,000 $kg/cm^2$, depending on the exper-imental conditions.

To compare the crystal lattice effects with the macroscopic effects of yielding, the start of submicroscopic inelastic strain was observed by change of color of the sample, by the onset of birefringence in the sample under polarized light, and by asterism of X-ray Laue patterns taken during the tests. These internal effects indicated a slightly

lower (10 to 20 percent) yield strength in comparison with external yielding.

The size effect on the yield strength of salt is large; the tensile strength of a circular cylinder in air increases exponentially for cylinder diameters < 0.5 mm (about 1,000 $kg/cm^2$ for d = 0.03 mm).

Some observations were made on yielding by twin or translation gliding in single crystals as a function of orientation. The most important twin-gliding is on the dodecahedron (110) toward [1$\bar{1}$0].

Rupture strength may be arbitrarily defined as the maximum stress difference at the beginning of large deformation by fracturing. Most of the deformation tests that have been reported were in tension, but many were in compression or in torsion. The rupture strengths of salt in air by the three methods are roughly equal, between 10 and 100 $kg/cm^2$.

The origin of the salt specimen is important in determining its rupture strength: melt-grown salt is stronger than compacted salt, which is in turn usually stronger than natural salt; however, natural salt is highly variable. Annealing of a sample of any origin at 400° to 600°C reduces the rupture strength to a common value of about 25 $kg/cm^2$.

The effects of temperature on salt is shown in figure 1 (after Theile, 1932): the rupture strength is increased by increase of temperature, whereas the yield strength is sharply decreased. Cohesion is enhanced, and so ductility is highly increased by increase of temperature. However, only the maximum stresses at rupture were
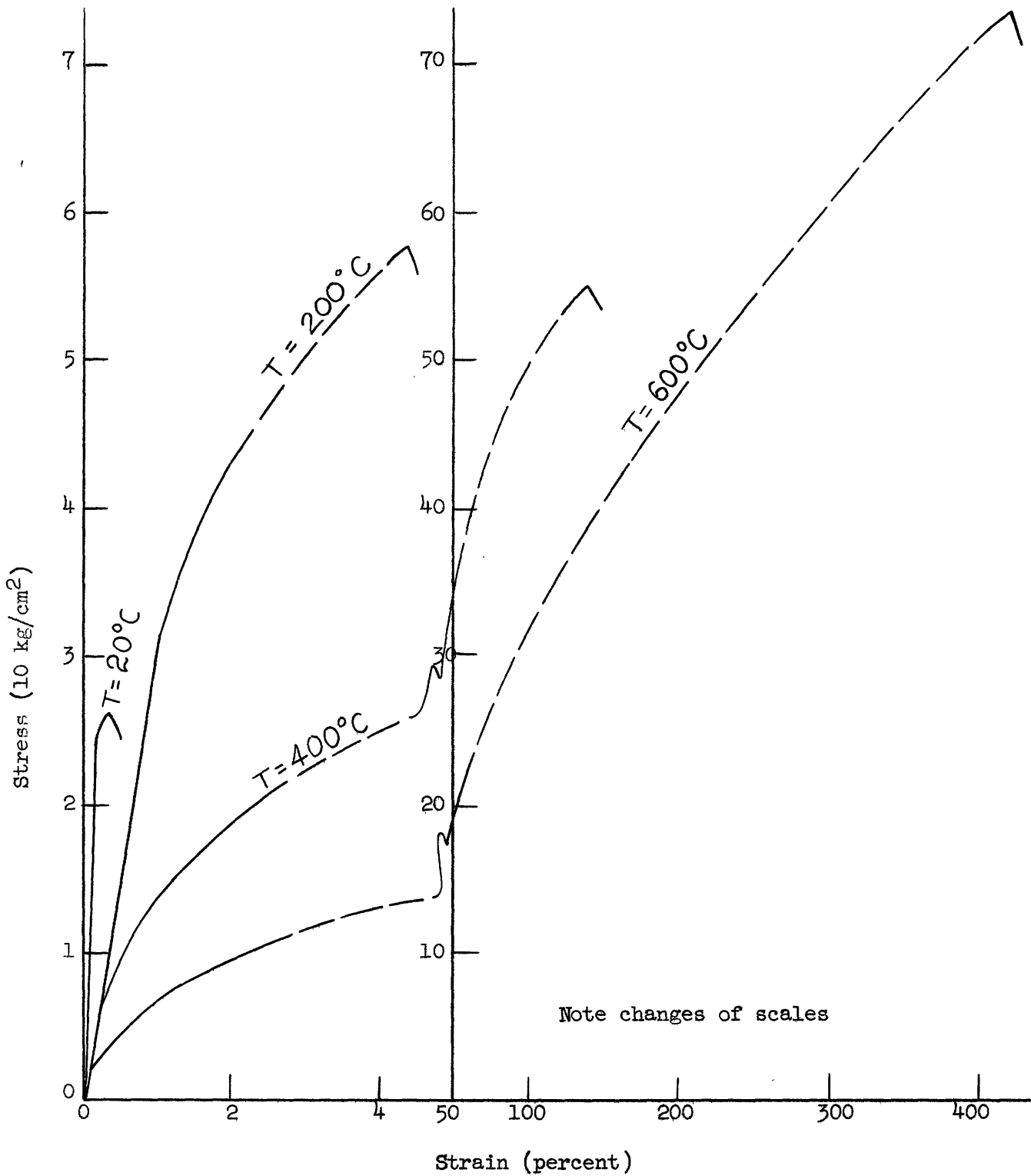
Figure 1.--Effect of temperature on the deformation of salt (after Theile, 1932)

recorded by Theile, so the strains had to be extrapolated, as shown by the dashed lines in figure 1.

Salt under hydrostatic pressure, P, at room temperature, has a maximum yield strength (stress difference) of about 300 $kg/cm^2$, beyond which increase of P has small effect. Although measurements extend only to P = 600 $kg/cm^2$, it is probable that even for very much higher P the maximum compressive yield strength will not be > 500 $kg/cm^2$. These results apply only for slow loading rates; with impact loading under hydrostatic pressure, the strength will probably be 2 to 3 times greater.

With fairly rapid loading in air, salt is brittle, and the strength is about 45 $kg/cm^2$. With very slow loading, the salt is strain strengthened, and the strength may be 10 times higher.

Very few studies have been made of the creep of salt, and no studies have been made of impact loading, either in air or under hydrostatic pressure.

An impurity of about 0.02 mole percent of $CaCl_2$, or of $SrCl_2$, or of $PbCl_2$ increases both the yield and rupture strength of salt as much as 3 times that of pure salt. The startling result of deforming salt in a water bath is to increase its rupture strength 20 times; this has become known as the Joffe effect.

It has been found that the permeable channels in natural salt may be sealed off very effectively, reducing permeability from 1.0 to < 0.01 millidarcies, by subjecting a surface of the salt to a flowing water solution under low pressure. This may have considerable

importance in plans to use natural salt beds or domes as containers of large amounts of fluids.

The salt exposed in salt mines behaves as a brittle solid for the most part, with only slight creep strain. This is probably because all the existing mines are relatively shallow and therefore are at relatively low temperature and low mean pressure. Judging from laboratory tests on the effects of hydrostatic pressure on salt at room temperature, stress differences of 50 to 100 $kg/cm^2$ are enough to cause fracturing in the dry ($<$ 1 percent water) salt in the mines. The fracturing in the mines is exhibited by heaving of the floor and back, and by slabbing of walls, especially of pillars. As an approximation, large plastic flow probably will begin to predominate over fracturing in workings in salt at 3,000 to 4,000 feet depth.

The effects of the Rainier test may be used to predict the effect of a nuclear explosion underground in salt. All the thermal radiation will be emitted so rapidly (most of it in $<$ 1 second) that there will not be time to conduct heat away from the melted and vaporized salt surrounding the test chamber. Some of the thermal radiation (say one-third) will be converted into mechanical energy, which will be added to the shock wave emitted by the device, so that the shock wave train may transmit as much as 65 percent of the total energy outside the melted shell. The mechanical properties of salt therefore take on considerable importance.

As natural salt in most salt beds and domes have a porosity of only about 2 percent, the salt cannot absorb shock energy by large

compression (that is, by large reduction of volume) such as occurred in the Rainier test. In that test the rhyolite tuff, which has a porosity of 35 to 50 percent, was highly compressed. In salt, a large proportion of shock energy will be absorbed by plastic flow and by fracturing, and a moderate proportion will be transmitted beyond the zone of flow and fracturing as elastic energy in the form of a compressional wave. Reflection of the elastic wave at the surface may produce tensile stress greater than the tensile strength, which would cause a crater and additional fracturing.

If the device to be set off in the salt is 10 kilotons (as stated in the newspaper release), the proposed 1,200 foot depth may be deep enough to contain the blast, but probably will not be deep enough to contain the vapor products. Although 200 feet is the approximate limit of large fracturing damage in the tuff of the Rainier device of 1.7 kilotons, the limit in salt may well be 10 times greater in a 10-kiloton blast in salt because salt has a greater capacity for transmitting shock energy than tuff.

It need hardly be mentioned that fractures open to the surface may allow vaporized salt and radioactive products to escape, with $Na^{24}$, $Cl^{38}$, etc. being released into the atmosphere.

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HEATS REQUIRED TO RAISE THE TEMPERATURES OF

THREE EVAPORITE ROCKS TO 1,500° AND TO 2,000° C

By Richard A. Robie

NaCl (Halite)

Sodium chloride melts at 1,073°K and boils to a molecular vapor
of NaCl molecules at 1,738°K. The heat required to raise the tempera-
ture of a mole (58.45 grams) of NaCl to 1,773°K (1,500°C) or 2,273°K
(2,000°C) is given by the relation:

$$H^o_{2273 \atop 1773} - H^o_{298} = \int_{298}^{1073} C_{p_{SOLID}} dT + \Delta H^{1073}_{MELTING} + \int_{1073}^{1738} C_{p_{LIQUID}} dT + \Delta H^{1758}_{VAPOR} + \int_{1738}^{2273 \atop 1773} C_{p_{GAS}} dT$$

Data for the heats of melting and of vaporization, and for the
enthalpy of the solid and liquid phases have been critically reviewed
by Kelley [1], [2] and are adopted here. We have extrapolated the
enthalpy of the liquid from 1,300°K to the normal boiling point, 1,738°K,
and assumed that the diatomic gas is ideal with a heat capacity, Cp,
of 9/2 R, (8.9 cal. deg.$^{-1}$ mole$^{-1}$). In this manner we have constructed
a table of the enthalpy ($H^o_T - H^o_{298}$) for NaCl from 300° to 2,300°K.

The errors at 1,500° and 2,000°C due to (1) the accumulated uncer-
tainties in the heats of melting and vaporization, (2) the extrapolation
of the enthalpy of the liquid, and (3) the estimate of heat capacity
of the gas, are of the order of 4,000 calories per mole (68. cal. gm$^{-1}$).

Using the data in Table 1, the heats required to raise one mole
of NaCl from 25°C to 1,500°C and from 25°C to 2,000°C are 69,200 calories

Table 1.--Enthalpies of NaCl and $CaSo_4$

| | NaCl | | | $CaSO_4$ | |
|---|---|---|---|---|---|
| | $H-H^O_{298}$ | $H-H^O_{298}$ | | $H-H^O_{298}$ | $H-H^O_{298}$ |
| $T\ ^oK$ | cal mole$^{-1}$ | cal gm$^{-1}$ | | cal mole$^{-1}$ | cal gm$^{-1}$ |
| 400 | 1,240 | 21.21 | | 2,600 | 19.10 |
| 600 | 3,830 | 65.52 | | 8,050 | 59.12 |
| 800 | 6,590 | 112.74 | | 14,850 | 109.07 |
| 1000 | 9,480 | 162.18 | | 22,850 | 167.83 |
| 1073 (crystal) | 10,580 | 181.00 | | | |
| 1073 (liquid) | 17,430 | 298.18 | | | |
| 1200 | 19,460 | 332.91 | | 31,300 | 229.89 |
| 1400 | 22,660 | 387.66 | | 40,500 | 297.47 |
| 1600 | 25,860 | 442.40 | | 50,998 | 374.57 |
| 1723 | | | (crystal) | 57,891 | 425.20 |
| 1723 | | | (liquid) | 64,591 | 474.41 |
| 1738 (liquid) | 28,068 | 480.17 | | | |
| 1738 (vapor) | 68,876 | 1178.3 | | | |
| 1773 | 69,200 | 1184.0 | | 67,751 | 497.6 |
| 1900 | 70,318 | 1203.0 | | | |
| 2100 | 72,098 | 1223.4 | | | |
| 2273 | 73,640 | 1259.9 | | 179,143 | 1315.8 |

and 73,640 calories respectively, or 1184.0 ± 40 and 1259.9 ± 50 cal. gram$^{-1}$. The largest portion of this heat is that required to vaporize NaCl, 698 cal. gram$^{-1}$.

## $CaSO_4$ (Anhydrite)

When heated, anhydrous calcium sulfate undergoes a transformation at 1,466°K and melts with a small amount of decomposition at about 1,723°K. The total vapor pressure at the melting point is only 0.012 atmospheres, Kelley [3] gives a somewhat lower melting point and calculates a heat of melting of 6,700 calories mole$^{-1}$. We have neglected the heat of transition at 1,466°K (probably less than 500 calories) and have extrapolated the table in Kelley [1] to the melting point.

We have assumed that the heat capacity of the liquid is 1.1 times that of the solid at the melting point (1,723°K) and that it does not change with temperature. We have neglected the small amount of decomposition of the liquid. The data are listed in Table 1; the heat required at 1,500°C is 497.6 calories per gram.

The heat necessary to raise anhydrite and its decomposition products to 2,273°K is obtained by a different method. We assume that $CaSO_4$ is completely dissociated at 2,273°K according to the reaction:

$$CaSO_4 = CaO + SO_2 + 1/2 \ O_2 \tag{1}$$

Note that the stable gases are $SO_2$ and $O_2$ and not sulfur trioxide. This is because the equilibrium:

$$SO_3 = SO_2 + 1/2 \ O_2 \tag{2}$$

is shifted very far to the right above 1,400°K (Evans and Wagman [4]).

The heat required to go from the initial state, anhydrite crystals at 298°K, to the final state, $CaO + SO_2 + 1/2\ O_2$ at 2,273°K is given by

$$H^{\circ}_{2273} - H^{\circ}_{298} = \Delta H^{\circ}_{298}(1) + \int_{298}^{2273} C_{p\ CaO}\,dT + \int_{298}^{2273} C_{p\ SO_2}\,dT + \frac{1}{2}\int_{298}^{2273} C_{p\ O_2}\,dT$$

the enthalpy change is the same whether or not the actual process followed this path or not.

The heat of reaction (1) was obtained from data in Rossini [5] and Huber and Holley [6]. The enthalpies were taken from the tables of Kelley [1], making a small extrapolation for CaO. The results are:

Table 2.--Heat required to raise $CaSO_4$ to 2,000°C

| | |
|---|---|
| $\Delta H_{298}\ (1)$ | + 119,460 |
| $H_{2273} - H^{\circ}_{298}\ (CaO)$ | + 25,955 |
| $H_{2273} - H^{\circ}_{298}\ (SO_2)$ | + 25,400 |
| $H_{2273} - H^{\circ}_{298}\ (1/2\ O_2)$ | + 8,328 |
| | 179,143 cal mole$^{-1}$ |
| | or 1315.8 cal gram$^{-1}$ |

The uncertainty in these figures is of the order of 50 cal gm$^{-1}$.

## $SiO_2$ (Quartz)

Quartz is used here to provide an average figure for siliceous impurities (such as shale) found in natural salt deposits. Upon heating, $\alpha$-quartz undergoes a transition to $\beta$-quartz at 848°K, with an associated heat of transition of about 290 calories. $\beta$-quartz changes to tridymite at 1,143°K and tridymite inverts to cristobalite at 1,743°K. Cristobalite melts at 1,986°K, and the heat of fusion is 1,835 calories mole$^{-1}$, Kracek [7] .

The required enthalpy data is obtained from Kelley's tables [1]; an extrapolation to 2,273°K is made by assuming the heat capacity of liquid $SiO_2$ is 1.1 times that of cristobalite at its melting point. The results are:  $H^\circ_{1773}-H^\circ_{298}$     24,150 cal mole$^{-1}$ or 401.9 cal gm$^{-1}$

$\qquad\qquad\qquad\quad H^\circ_{2273}-H^\circ_{298}$     27,970 cal mole$^{-1}$ or 592.0 cal gm$^{-1}$

The uncertainty is about 20 cal gm$^{-1}$.

## $CaCO_3$ (Calcite)

Calcite decomposes upon heating according to the following reaction:

$$CaCO_3 = CaO + CO_2 \qquad\qquad\qquad (3)$$

At 894°C (1,167°K) the partial pressure of $CO_2$ in equilibrium with calcite is 1 atmosphere.

We obtain the required heat value as in the case of anhydrite. The heat of reaction (3) is + 42,500 calories, to which we add the enthalpies of CaO and $CO_2$ from 298°K to 1,773°K or to 2,273°K. The

results are summarized in Table 3.

Table 3.--Enthalpies of $CaCO_3$ at 1,500°C and at 2,000°C

| Temp 1773°K | | Temp 2273°K | |
|---|---|---|---|
| $\Delta H^o_{298}$ (3) | + 42,500 | $\Delta H^o_{298}$ | + 42,500 |
| $H^o_{1773}-H^o_{298}$ (CaO) | + 18,420 | $H^o_{2273}-H^o_{298}$ (CaO) | + 25,955 |
| $H^o_{1773}-H^o_{298}$ ($CO_2$) | + 18,650 | $H^o_{2273}-H^o_{298}$ ($CO_2$) | + 25,200 |
| heat required | 79,570 cal mole$^{-1}$ | | 93,655 cal mole$^{-1}$ |
| | 795.0 cal gm$^{-1}$ | | 935.7 cal gm$^{-1}$ |

In Table 4 we have calculated the heat required to raise the temperature of three evaporite rocks of assumed mineral compositions to 1,500° and to 2,000°C.

It might be pointed out that for temperatures above 1,500°C large volumes of gaseous $NaCl$, $SO_2$, $O_2$, and $CO_2$ will be released.

Table 4.--Heat required to raise the temperature of 100 grams of
three rocks to 1500°C and to 2000°C

| Rock | Minerals | Assumed Composition (vol.%) | (wt. %) | $H_{1500°C}$ (cal/100 gm) | $H_{2000°C}$ (cal/100 gm) |
|------|----------|------------------------------|---------|----------------------------|----------------------------|
| I | Halite | 50 | 42.0 | 49,700 | 52,900 |
| | Anhydrite | 50 | 58.0 | 28,900 | 76,300 |
| | | | | 78,600 | 129,200 |
| | | | | ± 5,000 cal | ± 10,000 cal |
| II | Halite | 50 | 42.51 | 50,300 | 53,600 |
| | Anhydrite | 40 | 46.90 | 23,300 | 61,700 |
| | Calcite | 8 | 8.50 | 6,800 | 8,000 |
| | Quartz | 2 | 2.09 | 840 | 1,200 |
| | | | | 81,240 | 124,500 |
| | | | | ± 5,000 cal | ± 10,000 cal |
| III | Halite | 60 | 54.10 | 64,000 | 68,200 |
| | Anhydrite | 10 | 12.43 | 6,200 | 16,400 |
| | Calcite | 15 | 16.91 | 13,400 | 15,800 |
| | Quartz | 15 | 16.56 | 6,700 | 9,800 |
| | | | | 90,300 | 110,200 |
| | | | | ± 5,000 cal | ± 10,000 cal |

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TABLES OF PHYSICAL PROPERTIES
Compiled by Kenneth G. Books

Table 5.--Density of anhydrite, gypsum, and halite rocks at ordinary
temperature and pressure

| Character of deposit | Location | Density, gm/cm$^3$ | Reference |
|---|---|---|---|
| anhydrite | Bieinrode salt dome, Germany | 2.9-3.0 | 2 |
| do | Brazoria Co., Texas | 2.47-2.93 | 4 |
| do | Hockley salt dome, Harris Co., Texas | 2.2-2.8 | 4 |
| do | Grand Saline salt dome, Texas | 2.37-2.64 | 4 |
| do | | 2.9 | 5 |
| do | | 2.9 | 1 |
| do | | 2.95 | 6 |
| do | | 2.89 | 6 |
| gypsum | | 2.2 | 1 |
| do | | 2.6 | 1 |
| do | Bieinrode salt dome, Germany | 2.2 | 2 |
| do | | 2.2-2.4 | 2 |
| do | Gulf Coast | 2.2-2.4 | 4 |
| do | Hockley salt dome, Harris Co., Texas | 2.2 | 4 |
| do | | 2.2-2.6 | 5 |
| rock salt | | 2.1 | 1 |
| salt | Gulf Coast | 2.16-2.22 | 2 |
| impure salt | Malagash, Nova Scotia | 2.16-2.21 | 2 |
| salt | do | 2.14-2.24 | 2 |
| rock salt | | 2.1-2.2 | 2 |
| older rock salt | Bieinrode salt dome, Germany | 2.1 | 2 |
| younger rock salt | do | 2.1 | 2 |
| clear salt | Winnfield salt dome, Winn Parish, La. | 2.17 | 3 |
| do | Hockley salt dome, Harris Co., Texas | 2.20-2.21 | 3 |
| do | do | 2.19-2.20 | 3 |
| do | do | 2.15-2.18 | 3 |
| clear salt | Potash Co. of Am. Mine Eddy Co., New Mex. | 2.16 | 3 |
| salt | Hockley salt dome, Harris Co., Texas | 2.0-2.2 | 4 |
| clear salt | Grand Saline salt dome, Texas | 2.13-2.6 | 4 |

Table 5.--Continued

| Character of deposit | Location | Density, $gm/cm^3$ | Reference |
|---|---|---|---|
| dark salt | Grand Saline salt dome, Texas | 2.22-2.25 | 4 |
| rock salt | | 2.1-2.4 | 5, 7 |
| anhydrite | | range | |
| | | 2.2-3.0 | |
| | | average | |
| | | 2.79 | |
| gypsum | | range | |
| | | 2.2-2.6 | |
| | | average | |
| | | 2.31 | |
| rock salt | | range | |
| | | 2.0-2.4 | |
| | | average | |
| | | 2.16 | |

Table 6.--Density of anhydrite, gypsum, and halite minerals at ordinary
temperature and pressure

| Mineral | Density, gm/cm$^3$ | Reference |
|---------|--------------------|-----------|
| CaSO$_4$ (anhydrite) | 2.957- .02 | 1 |
| do | 2.899-2.985 | 2 |
| do | 2.9 | 15 |
| CaSO$_4$.2H$_2$O (gypsum) | 2.31-2.33 | 1 |
| do | 2.314-2.328 | 2 |
| do | 2.31-2.33 | 11 |
| do | 2.32 | 15 |
| NaCl (halite) | 2.135 | 1 |
| do | 2.165 | 2, 8 |
| do | 2.164 | 9 |
| do | 2.161 | 10 |
| do | 2.164 | 12 |
| do | 2.163 | 11 |
| do | 2.164 | 13 |
| do | 2.15 | 14 |
| do | 2.163 | 15 |
| anhydrite | range 2.90-2.999 average 2.93 | |
| gypsum | range 2.31-2.33 average 2.32 | |
| halite | range 2.135-2.165 average 2.159 | |

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Table 7.--Density of NaCl at high temperature

| Composition | Temperature °C | Density crystal | Density liquid | Density difference percent | Thermal expansion of liquid | Reference |
|---|---|---|---|---|---|---|
| NaCl | 804(m.p.) | 1.904 | 1.549 | 18.6 | $367 \times 10^{-6}$ | 1 |

Table 8.--Density of fused NaCl

| Composition | Weight, percent | Temperature, °C | Density | Temperature limits for which relation holds | Reference |
|---|---|---|---|---|---|
| Fused NaCl | 100 | 800 | 1.56 | 810° - 1000° | 2 |
| | | 830 | 1.53 | do | 2 |
| | | 884 | 1.50 | do | 2 |
| | | 900 | 1.49 | | 3 |
| | | 910 | 1.49 | 810° - 1000° | 2 |
| | | 968 | 1.46 | do | 2 |
| | | 1100 | 1.40 | | 3 |

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Table 9.--Compressibility of anhydrite and halite at ordinary
temperature and pressure

| Compound | Compressibility $10^{-12}cm^2/dyne$ | Reference |
|---|---|---|
| anhydrite | 1.55 | 10 |
| do | 1.55 | 10 |
| do | 1.70 | 10 |
| halite | 4.07 | 9 |
| do | 4.30 | 11 |
| do | 4.13 | 11 |
| do | 4.12 | 11 |
| do | 4.20 | 5 |
| do | 4.19 | 12 |
| anhydrite | range 1.55-1.70 average 1.60 | |
| halite | range 4.07-4.30 average 4.17 | |

Table 10.--Compressibility of anhydrite, gypsum, and halite
at various temperatures*(P is in bars ($10^6$ dyne/$cm^2$)
and Vo is the volume at 1 atmosphere and room
temperature. a and b are constants.)

* $-\Delta V/Vo-aP-bP^2$ from Birch et al., 1942, Geol. Soc. America Spec. Papers, 36, p. 40

| Compound | 0°C $10^6a$ | 20°C $10^6a$ | 30°C | | 75°C | | Maximum pressure, bars | Reference |
|---|---|---|---|---|---|---|---|---|
| | | | $10^6a$ | $10^{12}b$ | $10^6a$ | $10^{12}b$ | | |
| anhydrite | 1.84 | | | | | | 200 | 8, 11 |
| gypsum | 2.50 | | | | | | 200 | 8, 11 |
| halite | | 4.23 | 4.26 | 5.23 | 4.43 | 5.38 | 12,000 | 1 |
| | | 4.17 | 4.20 | 4.60 | 4.33 | 4.74 | 12,000 | 6 |
| | | 4.12 | | | | | 12,000 | 7 |
| | | 4.14 | | | | | 12,000 | 11 |

Table 11.--Compressibility of NaCl at temperatures from 27° to 804°C

| Temperature (°C) | Compressibility, $10^{-12}cm^2$/dyne | Reference |
|---|---|---|
| 27 | 4.14 | 11 |
| 127 | 4.31 | |
| 227 | 4.56 | |
| 327 | 5.01 | |
| 427 | 5.48 | |
| 527 | 5.93 | |
| 627 | 6.31 | |
| 727 | 6.57 | |
| 777 | 6.68 | |
| 782 | 6.69 | |
| 787 | 6.69 | |
| 792 | 6.71 | |
| 794 | 6.71 | |
| 797 | 6.72 | |
| 799 | 6.72 | |
| 800 | 6.70 | |
| 801 | 6.68 | |
| 802 | 6.65 | |
| 803 | 6.58 | |
| 804 (melting point) | 6.37 | |

Table 12.--Relative volumes of NaCl at 25°C

| Pressure, kg/cm$^2$ | Relative volume | Reference |
|---|---|---|
| 1 | 1.000 | 2, 3, 4 |
| 10,000 | 0.962 | |
| 20,000 | 0.932 | |
| 30,000 | 0.907 | |
| 40,000 | 0.885 | |
| 50,000 | 0.865 | |
| 60,000 | 0.848 | |
| 70,000 | 0.832 | |
| 80,000 | 0.817 | |
| 90,000 | 0.803 | |
| 100,000 | 0.790 | |

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The following table shows thermal expansion data for gypsum and halite.

Data for anhydrite are lacking. Expansion is given for the temperature range 20° to 100° C for both gypsum and halite, and near the melting point for NaCl.

The linear thermal expansion of $CaSO_4.2H_2O$ depends upon orientation with respect to the crystallographic axis, that of NaCl does not. Orientations are given in the second column. Values for volumetric expansion are marked "vol." in this column.

Table 13.--Thermal expansion of single crystals of halite and gypsum

| | | Expansion from 20°C to indicated temperature, in percent | | | | | Refer-ence |
|---|---|---|---|---|---|---|---|
| | | Temperature, °C | | | | | |
| Elements | Orientation | 100 | 200 | 400 | 600 | | |
| NaCl, halite | | .32 | .74 | 1.71 | 2.82 | | 1 |
| CaSO₄.2H₂O, gypsum | //b | .34 | | | | | 1 |
| | -51°12' to c | .01 | | | | | |
| | 38°48' to c | .24 | | | | | |
| | vol. | .58 | | | | | |

Reference

1. Birch, and others, 1942, Geol. Soc. Am., Special Papers, No. 36, p. 30, 32.

Table 14.--Viscosity of NaCl

| Material | t°C | Viscosity, poises | Reference |
|----------|-----|-------------------|-----------|
| NaCl | 18 | $6.2 \times 10^{16}$ | 1 |
| do | 18 | $1.8-2.3 \times 10^{18}$ | 1 |
| do | 181 | $2.6 \times 10^{17}$ | 1 |
| rock salt | 80 | $10^{17}$ | 2 |
| do | 18 | $10^{18}$ | 2 |

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Table 15.--Elastic moduli of anhydrite, gypsum, and
halite at ordinary temperature and pressure

| Rock | Young's modulus $10^{11}$ dynes/cm$^2$ | Shear modulus $10^{11}$ dynes/cm$^2$ | Poisson's ratio | Refer-ence |
|---|---|---|---|---|
| anhydrite | 7.2-7.4 | 2.81 [1]/ | 0.295 | 1 |
| do | 7.19 | | 0.27 | 12 |
| do | 8.10 | | 0.27 | 12 |
| do | 5.36 | 1.96 | 0.360 | 13 |
| do | 6.01 | 2.07 | 0.333 | 13 |
| do | 6.10 | 2.20 | 0.340 | 13 |
| gypsum & anhydrite | 5.64 | | 0.20 | 12 |
| do | 5.43 | | 0.18 | 12 |
| gypsum | 3.53 | 1.24 | 0.338 | 2 |
| rock salt | 3.35 | 1.23 | 0.366 | 2 |
| do | 2.8 | 1.04 | 0.33 | 13 |
| anhydrite | range 5.36-7.4 average 6.77 | range 1.96-2.81 average 2.52 | range 0.270-0.360 average 3.11 | |
| gypsum ** | 3.53 | 1.24 | 0.338 | |
| rock salt ** | range 2.80-3.35 average 3.08 | range 1.04-1.23 average 1.13 | range 0.330-0.366 average 0.347 | |

1/  Derived from measurements by the use of the connecting equations for
    isotropic materials.

**  Based on meager data.

Table 16.--Elastic constants of NaCl at ordinary temperature and pressure
Units of $10^{11}$ dynes/cm$^2$

| $C_{11}$ | $C_{12}$ | $C_{44}$ | References |
|---|---|---|---|
| 4.91 | 1.23 | 1.28 | 4 |
| 4.87 | 1.24 | 1.26 | 5 |
| 4.85 | 1.23 | 1.26 | 6 |
| 4.99 | 1.31 | 1.27 | 5 |
| 4.94 | | | 7 |
| 4.83 | 1.28 | 1.27 | 8 |
| 4.97 | 1.27 | 1.27 | 9 |
| Range | Range | Range | |
| 4.83-4.99 | 1.23-1.31 | 1.26-1.28 | |
| Average value | Average value | Average value | |
| 4.89 | 1.26 | 1.27 | |

Table 17.--Elastic coefficients of NaCl at ordinary temperature and pressure
Units of $10^{-13}$cm$^2$/dynes

| $S_{11}$ | $S_{12}$ | $S_{44}$ | References |
|---|---|---|---|
| 21.6 | | | 10 |
| 20.9 | | | 10 |
| 21.2 | | | 10 |
| 23.0 | | 74.2 | 10 |
| 23.2 | | | 10 |
| 23.0 | 5.0 | 78.0 | 10 |
| 24.3 | 5.27 | 78.8 | 4 |
| 22.8 | 4.5 | 78.09 | 3 |
| 22.9 | | 78.41 | 11 |
| range 20.9-24.3 | range 4.5-5.3 | range 74.2-78.8 | |
| average 22.6 | average 4.9 | average 77.5 | |
| most probable | most probable | most probable | |
| value 23.0 | value 5.0 | value 78.0 | 10 |

Table 18.--Variation of elastic constants of NaCl with temperature
Units of $10^{11}$ dynes/cm$^2$

| Temperature ($^\circ$C) | $C_{44}$ | $C_{11}-C_{12}$ | Reference |
|---|---|---|---|
| 27 | 1.281 | 3.663 | 3 |
| 127 | 1.248 | 3.258 | |
| 227 | 1.214 | 2.884 | |
| 327 | 1.178 | 2.536 | |
| 427 | 1.139 | 2.232 | |
| 527 | 1.098 | 1.930 | |
| 627 | 1.056 | 1.632 | |
| 727 | 1.000 | 1.359 | |
| 777 | 0.966 | 1.230 | |
| 782 | 0.961 | 1.218 | |
| 787 | 0.956 | 1.206 | |
| 792 | 0.952 | 1.193 | |
| 794 | 0.950 | 1.188 | |
| 797 | 0.947 | 1.181 | |
| 799 | 0.945 | 1.175 | |
| 800 | 0.943 | 1.172 | |
| 801 | 0.942 | 1.167 | |
| 802 | 0.940 | 1.163 | |
| 803 | 0.938 | 1.157 | |
| 804 (melting point) | 0.934 | 1.134 | |

Table 19.--Variation of elastic coefficients of NaCl with temperature

| Temperature (°C) | $S_{11}$ | $S_{12}$ | $S_{44}$ | Reference |
|---|---|---|---|---|
| -3 | 22.08 | 4.49 | 78.26 | 1 |
| 27 | 22.80 | 4.50 | 78.09 | 3 |
| 27 | 22.90 | | 78.41 | 11 |
| 77 | 23.95 | 4.98 | 79.08 | 3 |
| 77 | 24.01 | | 79.38 | 11 |
| 97 | 24.40 | 5.43 | 80.36 | 1 |
| 127 | 25.23 | 5.46 | 80.14 | 3 |
| 127 | 25.30 | | 80.45 | 11 |
| 177 | 26.63 | 5.96 | 81.22 | 3 |
| 177 | 26.71 | | 81.57 | 11 |
| 197 | 27.33 | 6.62 | 82.85 | 1 |
| 227 | 28.18 | 6.49 | 82.37 | 3 |
| 227 | 28.23 | | 82.75 | 11 |
| 277 | 29.92 | 7.03 | 83.61 | 3 |
| 277 | 30.00 | | 84.01 | 11 |
| 327 | 31.85 | 7.58 | 84.87 | 3 |
| 377 | 33.84 | 8.18 | 86.32 | |
| 427 | 35.95 | 8.85 | 87.79 | |
| 527 | 41.14 | 10.68 | 91.08 | |
| 627 | 47.86 | 13.42 | 94.74 | |
| 727 | 56.37 | 17.24 | 100.0 | |
| 777 | 61.60 | 19.67 | 103.5 | |
| 787 | 62.71 | 20.20 | 104.6 | |
| 797 | 63.92 | 20.76 | 105.6 | |
| 801 | 64.53 | 21.13 | 106.2 | |
| 804 (Melting point) | 65.18 | 21.98 | 107.1 | |

Note for Table 19

Adiabatic elastic moduli of NaCl

The cubic salt crystal has three independent elastic moduli $S_{11}$, $S_{12}$, and $S_{44}$ which are defined by the following set of equations:

$$1/_{E_{(100)}} = S_{11}$$

$$1/_{E_{(110)}} = 1/2 \, (S_{11} + S_{12} + 1/2 \, S_{44})$$

$$1/_{G_{(100)}} = S_{44}$$

$$1/_{G_{(110)}} = S_{11} + S_{12} + 1/2 \, S_{44}$$

where $E_{(100)}$ and $E_{(110)}$ are Young's Modulus measured along the (100) and (110) axes of the salt crystal and $G_{(100)}$ and $G_{(110)}$ are the modulus of rigidity measured along the (100) and (110) axes. For reference 3, values of $S_{11}$, $S_{12}$, and $S_{44}$ are reliable, respectively, to 0.3 percent, 2.0 percent, and 0.3 percent, except near the melting point, where the accuracy is 0.1 percent, 0.4 percent, and 0.1 percent, respectively.

References for Tables 15 through 19

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## Magnetic susceptibility

Magnetic susceptibilities of anhydrite, gypsum, and halite are given

in c.g.s. units in Table 20. All values found are lumped together in the

one table. It may be possible that the more reliable values for anhydrite,

gypsum, and halite are the values for the pure substances given the

International Critical Tables. These are (in $10^{-6}$ c.g.s. units)

respectively, $CaSO_4$: -0.364, $CaSO_4 \cdot 2H_2O$: -0.86, NaCl: -0.50.

Table 20.--Magnetic susceptibilities of anhydrite, gypsum, and halite

| Material | Range, c.g.s. units | Average, c.g.s. units | Reference |
|---|---|---|---|
| anhydrite | -10.0 to $1.0 \times 10^{-6}$ | $-5.5 \times 10^{-6}$ | 2 |
| do | -1.1 | -1.1 | 1 |
| do | -.36 | -.36 | 4 |
| do | -.36 | -.36 | 6 |
| gypsum | -.38 | -.38 | 4 |
| do | -.86 | -.86 | 6 |
| halite | -0.4 | -0.4 | 1 |
| do | -1.3 to -3.0 | -2.2 | 2 |
| do | -0.9 to -1.3 | -1.1 | 1 |
| do | -.51 to -.65 | -.56 | 3 |
| do | -.71 | -.71 | 3 |
| do | -.50 | -.50 | 5 |
| do | -.50 | -.50 | 4 |
| do | -.50 | -.50 | 6 |
| | averages | | |
| anhydrite | -.183 | | |
| gypsum | -.62 | | |
| halite | -.81 prob. around -.50 for pure NaCl | | |
| | range | | |
| anhydrite | -.10.0 to -.36 | | |
| gypsum | -.86 to -.38 | | |
| halite | -3.0 to -.50 | | |

References for Table 20

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     p. 360, 364.

Table 21.--Miscellaneous physical properties of salt

| | Reference |
|---|---|
| **Rock salt** | |
| Permeability, average, 0.05 to 0.3 millidarcy | 1 |
| maximum, 7 millidarcies | |
| Porosity, range, 0.5 to 1.5 percent | |
| Electrical resistivity, pure, $10^6$ to $10^7$ ohm-cm | 2 |
| impure, $10^6$ ohm-cm | 2 |
| Thermal conductivity (Holford), 72 watt-$cm^{-1}$-$deg^{-1}$ | 2 |
| Dielectric constant, 5.6-6.3 | 2 |

**Halite (single crystals)**
Thermal conductivity

| Temperature °C | Conductivity watt $cm^{-1}$ $deg^{-1}$ | |
|---|---|---|
| -190 | 267 | 2 |
| 0 | 69.7 | 2 |
| 100 | 42.0 | 2 |
| 400 | 20.8 | 2 |

References for Table 21

1. Anonymous

2. Birch, F., Schairer, J. F., and Spicer, H. C., 1942, Handbook of physical constants: Geol. Soc. Am., Special papers No. 36, p. 246, 258, 311, 318.