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PHYSICAL PROPERTIES OF EVAPORITE MINERALS

By E. C. Robertson

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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PHYSICAL PROPERTIES OF EVAPORITE MINERALS

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Introduction

The data in the following tables were abstracted from measurements of physical properties of evaporite minerals or of equivalent synthetic compounds. The compounds considered are the halide and sulfate salts which supposedly precipitated from evaporating ocean water and which form very extensive and thick "rock salt" beds. These beds are composed almost entirely of NaCl. In places where the beds are deeply buried and where fractures occur in the overlying rocks, the salt is plastically extruded upward as in a pipe to form the "salt domes".

Most of the tables are for NaCl, both the natural (halite) and the synthetic salt, polycrystalline and single crystals. These measurements have been collected for use 1) in studies on storage of radioactive wastes in salt domes or beds, 2) in calculations concerned with nuclear tests in salt domes and beds, and 3) in studies of phenomena in salt of geologic interest.

Rather than an exhaustive compilation of physical property measurements, these tables represent a summary of data from accessible sources. As limitations of time have prevented making a more systematic and comprehensive selection, the data given may seem arbitrarily chosen. Some of the data listed are old, and newer, more accurate data are undoubtedly available.

Halite (and synthetic NaCl) has been very thoroughly studied because of its relatively simple and highly symmetrical crystal structure, its easy availability naturally or synthetically, both in single crystals and polycrystalline, its useful and scientifically interesting properties, and its role as a compound of almost purely ionic bonding. The measurements of NaCl in the tables, however, represent only a small part of the total number of observations; discrimination was necessary to keep the size of the tabulations manageable. The physical properties of the evaporite minerals other than halite and sylvite have received only desultory attention from experimentalists, and appear in only a few tables.

The effects of temperature, hydrostatic pressure, stress difference, and other mechanical, electrical, and optical conditions on the physical properties have probably been observed more completely on NaCl than on any other solid substance, which makes it a unique and important substance. Several new and important phenomena have been observed first on it. The mechanical properties of NaCl, for example, depend very strongly on the condition and the composition of the gas or liquid in contact with the sample surface; the data are sparse as yet and are not reported here.

1. Mineralogy, Density, and General Physical Properties

Emphasis has been placed in this section on the oceanic evaporite minerals, as they compose the large bodies of rock salt. The chemical compositions of the lake evaporite deposits are considerably different, and the minerals in them are moderately rare and are not found in salt beds and domes. The chemistry and the mineralogy of the evaporite deposits are important in evaluating the physical properties of the minerals composing them, and the data in this section comprise information helpful to this purpose. Phase equilibria and transitions also are important in interpreting the physical properties of these low-melting, highly soluble minerals, but such data fall more aptly under chemical properties, and reference should be made to appropriate sources for this information.

The chemical analyses given in table 1.2 are the only information given here on the mineralogical compositions of oceanic salt beds; reference should be made to geologic studies of salt domes and layered salt deposits for further data. In general, salt beds contain 95 percent or more NaCl, or halite.

Table 1.1 Theoretical chemical compositions of oceanic evaporite minerals (in weight percent).

Mineral	Chemical Formula	Na	K	Ca	Mg	Sr	Cl	SO_4	CO_3	H_2O
Anhydrite	$CaSO_4$	-	-	29.44	-	-	-	70.56	-	-
Bischofite[1/]	$MgCl_2 \cdot 6H_2O$	-	-	-	11.96	-	34.88	-	-	53.16
Bloedite	$Na_2Mg(SO_4)_2 \cdot 4H_2O$	13.75	-	-	7.27	-	-	57.44	-	21.54
Calcite	$CaCO_3$	-	-	40.04	-	-	-	-	59.96	-
Carnallite	$KMgCl_3 \cdot 6H_2O$	-	14.07	-	8.75	-	38.28	-	-	38.90
Celestite	$SrSO_4$	-	-	-	-	47.70	-	52.30	-	-
Chlorocalcite[1/]	$KCaCl_3$	-	21.07	21.60	-	-	57.33	-	-	-
Chloromagnesite[1/]	$MgCl_2$	-	-	-	25.54	-	74.46	-	-	-
Dolomite	$CaMg(CO_3)_2$	-	-	21.73	13.19	-	-	-	65.08	-
Epsomite	$MgSO_4 \cdot 7H_2O$	-	-	-	9.87	-	-	38.97	-	51.16
Glauberite	$Na_2Ca(SO_4)_2$	16.59	-	14.10	-	-	-	69.31	-	-
Gypsum	$CaSO_4 \cdot 2H_2O$	-	-	23.28	-	-	-	55.79	-	20.93
Halite	NaCl	39.34	-	-	-	-	60.66	-	-	-
Kainite	$KMg(SO_4)Cl \cdot 3H_2O$	-	15.70	-	9.77	-	14.24	38.58	-	21.71
Kieserite	$MgSO_4 \cdot H_2O$	-	-	-	17.57	-	-	69.41	-	13.02
Langbeinite	$K_2Mg_2(SO_4)_3$	-	18.84	-	11.72	-	-	69.44	-	-
Leonite	$K_2Mg(SO_4)_2 \cdot 4H_2O$	-	21.32	-	6.63	-	-	52.39	-	19.65
Loewite	$Na_4Mg_2(SO_4)_4 \cdot 5H_2O$	14.95	-	-	7.91	-	-	62.49	-	14.65

Mineral	Chemical Formula	Na	K	Ca	Mg	Sr	Cl	SO_4	CO_3	H_2O
Picromerite[1]	$K_2Mg(SO_4)_2 \cdot 6H_2O$	-	19.92	-	6.04	-	-	47.70	-	26.84
Polyhalite	$K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$	-	12.97	13.29	4.03	-	-	63.73	-	5.98
Sylvite	KCl	-	52.44	-	-	-	47.56	-	-	-
Syngenite[1]	$K_2Ca(SO_4)_2 \cdot H_2O$	-	23.81	12.20	-	-	-	58.50	-	5.49
Vanthoffite	$Na_6Mg(SO_4)_4$	25.24	-	-	4.45	-	-	70.31	-	-

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[1] Note: This mineral is rare.

Table 1.2 Typical bulk chemical compositions of halite beds in evaporite mineral deposits.

Location	Deposit Type	Compound	Composition (weight percent)	Reference
Avery Island, Louisiana	Dome	NaCl	99.03	Looker, 1954, p. 68
		$CaCl_2$	.01	
		$MgCl_2$	.01	
		$CaSO_4$	.22	
		H_2O	.02	
		water insoluble	.71	
Hutchinson, Kansas	Bedded[1]	NaCl	96.97	do.
		$CaCl_2$	.03	
		$MgCl_2$	.07	
		$CaSO_4$	.85	
		H_2O	.67	
		water insoluble	1.43	
Detroit, Michigan	Bedded[1]	NaCl	98.18	do.
		$CaCl_2$	.06	
		$MgCl_2$	.02	
		$CaSO_4$	.87	
		H_2O	.11	
		water insoluble	.76	
Slanic-Prahova, Rumania	Bedded[1]	NaCl	98.96	Mottled salt; Parker, Hemphill, and Crowell, 1958, table 8.
		$CaCl_2$	.10	
		$MgCl_2$	.08	
		$CaSO_4$	.63	
		H_2O	.18	
		water insoluble	.05	
Winnfield, Louisiana	Dome	NaCl	95.60	Guido and Warner, 1960, table 2
		$CaSO_4$	4.26	
		$FeSO_4$	.01	
		H_2O	.03	
		other	.10	

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[1] Analyses are of salt as mined from beds of high-purity sodium chloride and do not represent the composition of the entire evaporite deposit.

Table 1.3 Minerals in shaly layers in evaporite deposits.

Location	Mineral	Formula	Composition (Weight Percent)	Reference
Stuttgart, Germany	Quartz	SiO_2	25[1]	Fuchtbauer, H. and Goldschmidt, 1959, p. 335
	Muscovite[2]	$KAl_3Si_3O_{10}(OH)_2$	20	
	Chlorite[2]	$FeMg_4Al(AlSi_3O_{10})(OH)_8$	20	
	Calcite and	$CaCO_3$ and		
	Dolomite	$CaCO_3 \cdot MgCO_3$	15	
	Mixed layer clay[3]		10	
	Hematite and	Fe_2O_3 and		
	Pyrite	FeS_2	5	
	Feldspar (albite)	$NaAlSi_3O_8$	5	
Hutchinson, Kansas	Quartz	SiO_2	50	Zen, E., 1961, written communication
	Muscovite[2]	$KAl_3Si_3O_{10}(OH)_2$	30	
	Chlorite[2]	$FeMg_4Al(AlSi_3O_{10})(OH)_8$	10	
	Mixed layer clay[3]		10	

[1] Note: Percentages were arbitrarily assigned according to petrographic descriptions, and anhydrite was deliberately left out because it is associated with the halite rather than the silicate minerals.

[2] The platey silicates differ widely from the theoretical chemical compositions given.

[3] Note: Mixed-layer clay is principally interlayered muscovite, $KAl_3Si_3O_{10}(OH)_2$ and montmorillonite, $MgAl_5Si_{12}O_{30}(OH)_6$, both with widely varying compositions.

Table 1.4 Densities of evaporite minerals.

Mineral	Physical character	Deposit Type	 Location	Density (g/cm^3)	Reference and Remarks
Anhydrite -	Polycrystalline, impure	Salt dome	Bieinrode, Germany	2.1 - 3.0	Heiland, 1940, p. 79
-	do.	do.	Hockley, Texas	2.2 - 2.8	Peters and Dugan, 1945, p. 376
-	do.	do.	Grand Saline, Texas	2.2 - 3.0	do.
-	do.	do.	-	2.8	Typical value
-	Single crystal	-	-	2.963	Theoretical value[1]
Bloedite	Single crystal	-	-	2.25	Palache and others, 1951, p. 448
-	do.	-	-	2.274	Theoretical
Calcite	Single crystal	-	-	2.712	Theoretical
Carnallite	Single crystal	-	-	1.602	Palache and others, 1951, p. 92
-	do.	-	-	1.598	Theoretical
Celestite	do.	-	-	3.97	Palache and others, 1951, p. 416
-	do.	-	-	3.96	Theoretical

Mineral	Physical character	Deposit		Density	Reference and Remarks
		Type	Location	(g/cm^3)	
Dolomite	Single crystal	-	-	2.85	Palache and others, 1951, p. 210
-	do.	-	-	2.866	Theoretical
Epsomite	Single crystal	Artificial	-	1.677	Palache and others,1951, p. 510
-	do	-	-	1.650	Theoretical
Glauberite	Polycrystalline	-	-	2.75 - 2.85	Palache and others,1951, p. 431
-	Single crystal	-	-	2.81	Theoretical
Gypsum	Polycrystalline impure	Salt dome	Bieinrode, Germany	2.2 - 2.4	Heiland, 1940, p. 79
-	do.	do.	Hockley, Texas	2.2 - 2.6	Jakosky, 1950, p. 266
-	do.	do.	-	2.3	Typical value
-	Single crystal	-	-	2.317	Theoretical
Halite	Polycrystalline impure	Salt dome	Winn Parish, Louisiana	2.17	Allen, et al, 1955, p. 829-840
-	do.	do.	Hockley, Texas	2.0 - 2.2	Peters and Dugan, 1945, p. 376-393
-	do.	Bedded	Eddy County, New Mexico	2.16	Allen, et al, 1955, p. 829-840

Mineral	Physical character	Deposit		Density (g/cm^3)	Reference and Remarks
		Type	Location		
Halite	Polycrystalline	Rock salt	-	2.15	Typical
-	Single crystal	-	-	2.163	Theoretical
Kainite	Single crystal	-	-	2.15	Palache and other, 1951, p. 594
-	do.	-	-	2.24	Theoretical
Kieserite	Single crystal	-	-	2.571	Palache and others, 1951, p. 477
-	do.	-	-	2.571	Theoretical
Langbeinite	Single crystal	-	-	2.83	Palache and others, 1951, p. 434
-	do.	-	-	2.77	Theoretical
Leonite	Single crystal	-	-	2.201	Palache and others, 1951, p. 450
Loewite	Single crystal	-	Ischl, Austria	2.374	Palache and others, 1951, p. 446
-	do.	-	Stassfurt, Germany	2.423	Palache and others, 1951, p. 446
Polyhalite	Single crystal	-	-	2.78	Palache and others, 1951, p. 459

Mineral	Physical character	Deposit Type	 Location	Density (g/cm^3)	Reference and Remarks
Sylvite	Single crystal			1.993	Palache and others, 1951, p. 8
	do.			1.987	Theoretical
Vanthoffite	Single crystal			2.694	Palache and others, 1951, p. 430

[1] Theoretical values were obtained from R. A. Robie, (in press) or from Palache, and others, 1951.

Table 1.5 Miscellaneous physical properties of evaporite minerals[1]

Mineral	Hardness (Moh's scale)	Cleavage	Fracture	Luster	Crystal System	Melting point[2] (°C)
Anhydrite	3-1/2	$\{010\}$ $\{100\}$	Uneven	Pearly	Orthorhombic	1,450°
Bloedite	2-1/2 - 3	none	Conchoidal	Vitreous	Monoclinic	
Calcite	3	$\{10\bar{1}1\}$	Conchoidal	Vitreous	Hexagonal	
Carnallite	2-1/2	none	Conchoidal	Greasy	Orthorhombic	
Celestite	3 - 3-1/2	$\{001\}$ $\{210\}$	Uneven	Vitreous	Orthorhombic	1,605°
Dolomite	3-1/2 - 4	$\{10\bar{1}1\}$	Subconchoidal	Vitreous	Hexagonal	
Epsomite	2 - 2-1/2	$\{010\}$ $\{101\}$	Conchoidal	Vitreous	Orthorhombic	
Glauberite	2-1/2 - 3	$\{001\}$ $\{110\}$	Conchoidal	Vitreous	Monoclinic	
Gypsum	2	$\{010\}$ $\{100\}$	Conchoidal, fibrous	Subvitreous	Monoclinic	
Halite	2	$\{001\}$	Conchoidal	Vitreous	Isometric	800.5°
Kainite	2-1/2 - 3	$\{001\}$	Smooth, splintery	Vitreous	Monoclinic	

Mineral	Hardness (Moh's scale)	Cleavage	Fracture	Luster	Crystal System	Melting point[2] (°C)
Kieserite	3-1/2	{110} {111}	Friable	Vitreous	Monoclinic	
Langbeinite	3-1/2 - 4	none	Conchoidal	Vitreous	Isometric	930°
Leonite	2-1/2 - 3	none	Conchoidal	Waxy	Monoclinic	
Loewite	2-1/2 - 3	none	Conchoidal	Vitreous	Trigonal (?)	
Polyhalite	3-1/2	$\{10\bar{1}\}$	-	Vitreous	Triclinic	
Sylvite	2	{001}	Uneven	Vitreous	Isometric	770°
Vanthoffite	3-1/2	-	Uneven, conchoidal	Vitreous	(Anhedral)	

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[1] Most of this data is from Palache and others, 1951.

[2] Water-bearing minerals decrepitate in air between 100° and 200° C.

Table 1.6 Permeability of rock salt.

(from Reynolds and Gloyna, 1960, tables 4-3, 4-5)

Mean confining stress (10^3 psi)	Permeability (10^{-12} cm^2)[1]		Number of samples	Test period (days)	Fluid used[2]
	Initial[3]	Minimum			
Salt from Grand Saline Dome, Texas[4]					
0.5	10. - 42.	1.1 - 32.	4	3, 4, 6, 9	Kerosene or brine
1.0	1.0 - 4.5	0 - 1.5	4	3, 4, 8, 14	Brine
1.5	0.5 - 2.1	0 - 0.5	2	9, 10	Kerosene or brine
2.3	5.0	0.005 -	1	22	Kerosene
3.0	0.6	0.002 -	1	36	Brine
Salt from Hutchinson salt bed, Kansas[5]					
0.5	0	0	2	2	Helium or kerosene
1.0	0 - 0.072	0	2	7, 9	Brine
1.5	0	0	1	2	Helium
2.0	0.015	0	1	11	Brine
2.3	0.23	0.005	1	23	Kerosene

[1] Conversion: 1 darcy = 9.87×10^{-9} cm^2 (cgs unit).

[2] "Brine" represents NaCl, or NaCl + $CaSO_4$, or NaCl + Al $(NO_3)_3$ solutions.

[3] Initial permeability is also the maximum value. Permeating fluid pressures were 100 to 500 psi.

[4] Grand Saline salt: average density = 2.14 g/cm^3, average porosity = 1.71 percent.

[5] Hutchinson salt: average density = 2.15 g/cm^3, average porosity = 0.59 percent.

2. Thermodynamic Properties

The data in this section are entirely from R. A. Robie's various compilations of thermochemical data. Detailed data are given only for halite, sylvite, anhydrite, and quartz. The heat required to raise the temperature of rock salt to very high temperatures were calculated by Robie for four compositions, arbitrarily chosen to differ from natural rock salt to show the possible spread of values.

Table 2.1 Standard state (at 298.15°K) thermodynamic properties of some evaporite minerals.

(from Robie, in press)

Chemical Formula	Gram Formula Weight (gfw)	Molar Volume (cm^3)	Entropy $S^\circ_{298.15}$ (cal/gfw)	Heat of Formation $\Delta H^\circ_{298.15}$ (cal/gfw)	Free Energy of Formation $\Delta F^\circ_{298.15}$ (cal/gfw)	Equilibrium Constant for Formation from Elements ($\log_{10}$)
$NaCl$ (halite)	58.448	27.018 ±.007	17.33 ±.10	-98,230 ±300	-91,812 ±350	67.30
KCl (sylvite)	74.557	37.528 ±.007	19.70 ±.05	-104,180 ±200	-97,521 ±250	71.48
SiO_2 (α-quartz)	60.09	22.690 ±.005	9.88 ±.02	-217,650 ±400	-204,643 ±500	149.59
$CaSO_4$ (anhydrite)	136.146	45.94 ±.05	25.5 ±.4	-343,335 ±1,000	-316,475 ±1,000	231.97
$CaSO_4 \cdot 2H_2O$ (gypsum)	172.178	74.31 ±.16	46.36 ±.3	-484,000 ±1,100	-430,137 ±1,000	315.28
H_2O (water)	18.016	-	45.106 ±.03	-57,798 ±30	-54,636 ±30	-

Table 2.2 Thermodynamic data of NaCl from 400°K to 1, 300°K.[1]
(from Robie, 1959, p. 35)

Temperature (°K)	Heat Content[2] (cal/gfw)	Entropy (cal/gfw)	Free Energy[3] Function (cal/deg gfw)	Formation from Reference[4] State: Heat (cal/gfw)	Formation from Reference[4] State: Free Energy (cal/gfw)
400	1, 240	20.88	17.78	-98, 767	-89, 570
500	2, 510	23.71	18.69	-98, 665	-87, 285
600	3, 830	26.12	19.74	-98, 503	-85, 024
700	5, 190	28.21	20.80	-98, 284	-82, 802
800	6, 590	30.08	21.84	-98, 024	-80, 598
900	8, 020	31.76	22.85	-97, 729	-78, 430
1, 000	9, 480	33.30	23.82	-97, 405	-76, 310
1, 073 crystal	10, 580	34.36	24.50	-97, 141	-74, 474
1, 073 liquid	17, 430	40.74	24.50	-90, 291	-74, 474
1, 100	17, 860	41.14	24.90	-90, 169	-74, 382 [5]
1, 200	19, 460	42.53	26.31	-113, 106	-72, 538
1, 300	21, 060	43.81	27.61	-112, 455	-69, 201

[1] Additional data: gram formula weight (gfw), 58.448 gm; molar volume 27.018 cm^3; melting point 1, 073°K; heat of melting 6, 850 cal; boiling point 1, 738°K; heat of vaporization 40, 808 cal.

[2] Difference in heat content at temperature and at standard temperature, 298.15°K.

[3] Difference in free energy at temperature and heat content at standard temperature, 298.15°K, divided by the temperature, $-(F^\circ - H^\circ_{298.15})/T$.

[4] Heat and free energy of formation calculated from the chemical elements.

[5] Transition: metallic sodium melts at 1, 163°K.

Table 2.3 Thermodynamic data of KCl from 400°K to 1,200°K.[1]
(from Robie, 1959, p. 36)

Temperature (°K)	Heat Content[2] (cal/gfw)	Entropy (cal/gfw)	Free Energy[3] Function (cal/deg gfw)	Formation from Reference State[4] Heat (cal/gfw)	Formation from Reference State[4] Free Energy (cal/gfw)
400	1,260	23.40	20.25	-104,666	-95,176
500	2,520	26.21	21.17	-104,576	-92,810
600	3,810	28.56	22.21	-104,447	-90,470
700	5,150	30.62	23.26	-104,262	-88,150
800	6,550	32.49	24.30	-104,016	-85,860
900	8,000	34.20	25.31	-103,724	-83,615
1,000	9,500	35.78	26.28	-103,392	-81,400 [5]
1,043 crystal	10,150	36.42	26.69	-122,401	-80,441
1,043 liquid	16,250	42.27	26.69	-116,301	-80,441
1,100	17,160	43.12	27.52	-115,931	-78,572
1,200	18,760	44.51	28.88	-115,277	-75,200

[1] Additional data: formula weight (gfw), 74.557 gm; molar volume 37.532 cm^3; melting point 1,043°K; heat of melting 6,100 cal; boiling point 1,680°K; heat of vaporization 38,840 cal.

[2] Difference in heat content at temperature and at standard temperature, 298.15° K.

[3] Difference in free energy at temperature and heat content at standard temperature, 298.15° K, divided by the temperature, $-(F° - H°_{298.15})/T$.

[4] Heat and free energy of formation calculated from the chemical elements.

[5] Transition: metallic potassium boils at 1,039° K.

Table 2.4 Thermodynamic data of $CaSO_4$ from 400°K to 1,400°K.[1]

(from Robie, 1959, p. 42)

Temperature (°K)	Heat Content[2] (cal/gfw)	Entropy (cal/gfw)	Free Energy[3] Function (cal/deg gfw)	Formation from Reference[4] State	
				Heat (cal/gfw)	Free Energy (cal/gfw)
400	2,600	32.99	26.41	-342,868	-306,222
500	5,200	38.78	28.38	-343,326	-297,050
600	8,050	43.97	30.55	-343,550	-287,772
700	11,250	48.90	32.83	-343,636	-278,490 [5]
800	14,850	53.70	35.14	-356,428	-270,306
900	18,800	58.35	37.46	-355,389	-259,602
1,000	22,850	62.61	39.76	-354,339	-249,000
1,100	27,000	66.57	42.02	-353,298	-238,512 [6]
1,200	31,300	70.31	44.23	-354,013	-227,994
1,300	35,800	73.91	46.37	-352,415	-217,595
1,400	40,500	77.39	48.46	-350,633	-207,286

[1] Additional data: gram formula weight (gfw), 136.146 gm; molar volume 45.95 cm^3; melting point 1,723°K; heat of melting 6,700 cal.

[2] Difference in heat content at temperature and at standard temperature, 298.15°K.

[3] Difference in free energy at temperature and heat content at standard temperature, 298.15°K, divided by the temperature, $-(F° - H°_{298.15})/T$.

[4] Heat and free energy of formation calculated from the chemical elements.

[5] Transitions: sulfur boils at 717.75°K, and Ca_I inverts to Ca_{II} at 713°K.

[6] Transition: Ca_{II} melts at 1,123°K.

Table 2.5 Thermodynamic data of SiO_2 (quartz) from 400°K to 1,900°K.[1]

(R. A. Robie, 1962, written communication)

Temperature (°K)	Heat Content[2] (cal/gfw)	Entropy (cal/gfw)	Free Energy[3] Function (cal/deg gfw)	Formation from Reference[4] State	
				Heat (cal/gfw)	Free Energy (cal/gfw)
400	1,200	13.33	10.33	-217,650	-200,129
500	2,560	16.36	11.24	-217,573	-195,759
600	4,040	19.05	12.32	-217,418	-191,407
700	5,630	21.50	13.46	-217,196	-187,089
800	7,320	23.76	14.61	-216,914	-182,817
848 α	8,170	24.79	15.16	-216,729	-180,780
848 β	8,460	25.13	15.16	-216,439	-180,780
900	9,300	26.09	15.76	-216,363	-178,585
1,000	10,920	27.80	16.88	-216,196	-174,389
1,100	12,570	29.37	17.94	-216,024	-170,210
1,140	13,247	29.97	18.35	-215,944	-168,543
1,200	14,250	30.83	18.96	-215,843	-166,057
1,300	15,940	32.18	19.92	-215,669	-161,917
1,400	17,640	33.44	20.84	-215,503	-157,800
1,500	19,360	34.63	21.72	-215,334	-153,694
1,600	21,100	35.76	22.57	-215,161	-149,577[5]
1,700	22,860	36.82	23.37	-226,073	-145,359
1,800	24,630	37.84	24.16	-225,892	-140,641
1,900	26,420	38.81	24.90	-225,697	-135,871

[1] Additional data: gram formula weight (gfw), 60.09 gm; and molar volume 22.692 cm^3.

[2] Difference in heat content at temperature and at standard temperature, 298.15°K.

[3] Difference between free energy at temperature and heat content at standard temperature, 298.15° K, divided by the temperature, $-(F^\circ - H^\circ_{298.15})/T$.

[4] Heat and free energy of formation calculated from the chemical elements.

[5] Transition: metallic silicon melts at 1,683°K.

Table 2.6 Heat required to raise the temperature of rock salt to 1,500° C and to 2,000° C.

(from Robertson, Robie, and Books, 1958, table 4)

	Assumed composition		Heat required[1]	
Minerals	(vol. percent)	(wt. percent)	$H_{1500^\circ C}$ (cal/gm)	$H_{2000^\circ C}$ (cal/gm)
Composition I				
Halite	95	95	1,125	1,197
Anhydrite	5	5	25	66
			1,150 ±50	1,263 ±100
Composition II				
Halite	50	42	497	529
Anhydrite	50	58	289	763
			786 ±50	1,292 ±100
Composition III				
Halite	50	43	503	536
Anhydrite	40	46	233	617
Calcite	8	9	68	80
Quartz	2	2	8	12
			812 ±50	1,245 ±100
Composition IV				
Halite	60	54	640	682
Anhydrite	10	12	62	164
Calcite	15	17	134	158
Quartz	15	17	67	98
			903 ±50	1,102 ±100

---

[1] Calculated from thermochemical data on pure chemical compounds: NaCl, $CaSO_4$, $CaCO_3$, and SiO_2.

3. Thermal Properties

The thermal conductivity, diffusivity, and expansion of NaCl and KCl have been measured fairly precisely only recently; in fact, some of the data given in this section has not been published as yet. No information seems to be available for anhydrite and other evaporite minerals. The good agreement between the values from Schneider and from Birch and Clark in table 3.1, may actually be coincidental due to compensating errors in Schneider's results, because the thermal conductivities should differ much more than is evident here between compacted, granular NaCl and single crystal NaCl.

Table 3.1 Thermal conductivity and diffusivity of NaCl at high temperatures.

Temperature (°C)	Thermal Conductivity (10^{-3} cal/cm sec deg C)		Diffusivity (10^{-3} cm^{2}/sec)
0	14.65[1]	14.6[2]	32.7[3]
100	9.80	10.05	21.5
200	7.55	7.45	16.3
300	6.00	5.95	12.8
400	4.95	4.98	10.4
500	4.20		8.8
600	3.65		7.6
700	3.20		6.7
800[4]	(2.80)		(6.0)

---

[1] Data from unpublished thesis, W. A. Schneider, 1961, figure 25, on compacted granular NaCl.

[2] Data from Birch and Clark, 1940, table 6, on single crystal NaCl.

[3] Calculated from Schneider's measurements, heat capacities from Kelley, 1949, p. 166, and thermal expansions from McKinstry, 1960.

[4] Values are from extrapolated curves.

Table 3.2 Thermal conductivity of NaCl and KCl
single crystals from -40°C to 100°C.
(from McCarthy and Ballard, 1960)

Temperature (°C)	Conductivity (10^{-3} cal/cm sec deg C)	
	NaCl	KCl
-40°	18.9	19.9
0°	15.5	17.2
50°	13.3	15.7
100°	12.4	15.0

Table 3.3 Thermal expansions of NaCl and KCl single crystals.[1]

(from McKinstry, 1960, tables 11, 30)

Temperature	Volumetric Thermal Expansion	
	NaCl	KCl
(°C)	(10^{-6} deg^{-1})	(10^{-6} deg^{-1})
0	115.8	106.4
100	120.8	111.4
200	125.9	116.4
300	130.9	121.4
400	136.0	126.5
500	141.0	131.5
600	146.0	136.5
700	151.1	-

---

[1] Expansions were determined by calculating the increase from 20°C in unit-cell edge from measurements of four back reflections with an X-ray diffractometer. Volumetric expansions are three times the linear expansions.

4. Elastic Moduli and Internal Friction

The variation of the elastic moduli in NaCl and KCl with pressure and with temperature have been measured recently with fairly high precision. The interrelations of changes of conditions on physical properties has received considerable interest in recent years, especially in these simple compounds, mostly due to the usefulness of the data in theoretical computations. The attenuation of acoustic energy in NaCl and KCl also has been studied extensively recently for the same reason. The fact that very much improved apparatus has become available has given impetus to all these investigations.

Table 4.1 Adiabatic elastic constants of NaCl and KCl from 1 to 10,000 bars pressure at room temperature.

(from Lazarus, 1949)

Elastic stiffnesses (10^{11} dynes/cm^2)

Symbols	Pressure (bars) 1	2000	4000	6000	8000	10,000
			NaCl			
C_{11}	4.91	5.16	5.40	5.65	5.89	6.14
C_{12}	1.23	1.28	1.34	1.39	1.45	1.50
C_{44}	1.28	1.29	1.29	1.30	1.30	1.31
			KCl			
C_{11}	4.10	4.35	4.59	4.84	5.08	5.33
C_{12}	0.70	0.72	0.74	0.76	0.78	0.80
C_{44}	0.63	0.62	0.61	0.60	0.59	0.58

Relative compression $(V_o-V_p)/V_o$

	1	2000	4000	6000	8000	10,000
NaCl	0	0.0084	0.0165	0.0241	0.0313	0.0381
KCl	0	0.0085	0.0216	0.0315	0.0408	0.0496

Table 4.2 Temperature effect on dynamic elastic constants of NaCl and KCl single crystals. (from Rose, 1936, table 1; and Durand, 1936, tables 1 and 2)

Temperature (°K)	Elastic stiffnesses (10^{11} dynes/cm^2) NaCl C_{11}	NaCl C_{12}	NaCl C_{44}	KCl C_{11}	KCl C_{12}	KCl C_{44}
80	5.76	1.17	1.332	4.81	0.6	0.664
150	5.52	1.23	1.315	4.59	0.6	0.656
200	5.33	1.26	1.301	4.40	0.6	0.648
250	5.14	1.29	1.285	4.20	0.6	0.639
270	5.06	1.30	1.278	4.12	0.6	0.636
300	4.96	1.31	1.268			
350	4.77	1.33	1.251			
400	4.58	1.36	1.234			
480	4.28	1.39	1.203			

Table 4.3 Dynamic elastic moduli and specific heat of KCl for the temperature range 25° to 760°C. (from Enck, 1960)

Temperature (°C)	Adiabatic Stiffnesses[1] (10^{11} dynes/cm^2)			Adiabatic Compressibility $10^{-13}\frac{\text{cm}^2}{\text{dyne}}$	Specific Heat $\frac{\text{cal}}{\text{mole deg}}$	Gruneisen's Ratio
	C_{11}	C_{12}	C_{44}			
25°	3.95	.487	.631			
100	3.76	.555	.617			
200	3.46	.621	.601			
300	3.17	.667	.584	66.60	13.125	1.393
400	2.87	.711	.568	69.84	13.635	1.447
500	2.57	.712	.551	75.00	14.113	1.397
600	2.30	.723	.534	80.16	14.572	1.371
700	2.05	.701	.517	87.00	15.028	1.329
760	1.90	.697	.504	91.20	15.30	1.310

---

[1] Measured with a composite quartz oscillator.

Table 4.4 Internal friction of single crystals of NaCl from 20°K to 220° K. (from Taylor, 1961)

Temperature	Internal Friction (10^{-3} log decrement)[1]	
(°K)	Annealed Crystal[2]	Deformed Crystal[3]
20	-	1.5
60	1.3	2.6
100	1.9	7.5
140	2.5	5.7
180	2.2	5.0
220	2.5	5.7

---

[1] Composite oscillator method using a quartz crystal driving NaCl at 40 kcyc/sec at strains of about 10^{-6} cm/cm.

[2] Annealed at 650° C and furnace cooled.

[3] Deformed only until slightly birefringent.

Table 4.5 Acoustic velocities and dynamic elastic moduli of rock salt in place.

	Bedded Salt Deposit		Salt Dome
	Potash Ore[1] Pillar	Rock salt[1] Pillar	Rock salt[2] Floor
Compressional velocity (ft/sec)	13,300	13,200	14,350
Shear velocity (ft/sec)	7,160	7,650	8,380
Elastic moduli (calculated):			
Poisson's ratio	0.30	0.25	0.24
Young's modulus (10^6 psi)	3.7	4.2	5.1
Shear modulus (10^6 psi)	1.4	1.7	2.1
Bulk modulus (10^6 psi)	3.0	2.8	3.3

[1] Acoustic pulses were produced underground (Roller, and others, 1959, table 5) in the U. S. Potash Company mine, Carlsbad, New Mexico, by hitting a steel plate (directly for longitudinal waves and on the edge for shear waves) with a steel hammer. Times of arrivals were determined from accelerometer responses displayed on an oscilloscope.

[2] Seismic waves were produced underground (Nicholls and others, 1960, table 14) in the Carey Salt Company mine, Winnfield, Louisiana, by detonating electric blasting caps in 1 to 6 ounces of high explosive; the whole wave train was recorded.

Table 4.6 Internal friction of single crystals of NaCl and KCl at high ultrasonic frequency, the effect of temperature, and the calculated velocities and elastic constants.

(from Merkulov, 1959)

(A) Absorption coefficient per cycle, α/f (10^{-10} sec/cm cyc)

Frequency (10^6 cyc/sec)	Wave type		NaCl			KCl	
	Longitudinal	Transverse	Natural crystal	Synthetic ∥ [100]	Crystal ∥ [110]	Natural crystal	Temperature range (°C)
50 [1]	x	-	9	3.5	3	5	-
	-	x	5	1.5	-	4.5	-
100 [1]	x	-	10	6.5	5	11	-
	-	x	6	2.5	-	8.5	-
150 [1]	x	-	-	10	7.5	16	-
17 [2]	x	-	-	2.5	-	-	-120° to +270°
85 [2]	x	-	-	6.5	-	-	0° to +290°
17 [2]	x	-	8.0	-	-	-	-120° to +20°

[1] Absorption coefficient is proportional to the frequency squared in the range 5×10^6 to 200×10^6 cyc/sec.

[2] Absorption coefficient is constant.

(B) Calculated velocities and elastic constants.

Crystal	Crystal Direction	Velocity (km/sec)		Elastic stiffnesses (10^{11} dynes/cm^2)		
		Longitudinal	Transverse	C_{11}	C_{12}	C_{44}
NaCl	∥ [100]	4.79	2.44	4.96	1.24	1.29
	∥ [110]	4.50	2.92	-	-	-
KCl	∥ [100]	4.52	1.77	4.04	0.70	0.62
	∥ [110]	3.89	2.90	-	-	-

Table 4.7 Variation of internal friction according to dynamic strain of single crystal NaCl with prior compressive strain and with annealing temperature.[1]

(from Whitworth, 1960)

A. After prior static compression.

Maximum stress (kg/cm^2)	Maximum strain (percent)	Internal friction (10^{-3} log decrement)			
		Maximum dynamic strain	10^{-7}	5×10^{-6}	10^{-5}
6.2	0.2		0.09	2.5	13.5
8.7	1.1		0.54	11	-
40.0	6.7		6.2	32	-

B. After annealing[2]

Maximum strain (percent)	Annealing temperature (°C)	Internal friction (10^{-3} log decrement)			
			Before annealing	After annealing	
		Maximum dynamic strain	10^{-5}	10^{-5}	1.5×10^{-5}
0.2	102°		31.5	3.1	-
0.2	127°		16.5	1.4	6.1
0.2	146°		13.5	0.6	1.1
0.2	167°		35	<.1	0.3

---

[1] Specimens were 0.5 x 0.5 x 2.52 cm in size. Internal friction was measured by a resonance technique.

[2] Annealing was done before resonance measurements but after compression.

Table 4.8 Effect of friction reducer and gage type on static Young's modulus for rock salt.

(from Serata and Gloyna, 1959, tables 7-2)

Friction reducer[1]	Strain gage type	Number of samples tested	Range of stress (10^3 psi)	Static Young's modulus (10^5 psi) Range	Average
Not used	SR-4	3	0 - 2.0	5 - 10	8
Not used	Dial	4	0 - 3.0	3 - 4	3.5
Used	Dial	10	0 - 1.5	1.0-3.0	1.4

---

[1] Friction reducers at the sample ends were made of several layers of aluminum foil and one of plastic, each separated by a vaseline coating. Samples were tested in compression.

5. Electrical and Magnetic Properties

Most of the data in this section are quite old, but more recent measurements were not obtained; for example, the data in table 5.2 are inconsistent. The data in table 5.4 are from a study of a new and interesting, although complex phenomenon.

Table 5.1 Electrical resistivity as a function of temperature of NaCl and KCl single crystals.

Compound	Temperature (°C)	Resistivity (ohm cm)	Reference
NaCl	20°	4.60×10^{16}	Seelen, 1924
	100°	1.38×10^{13}	
	400°	8.27×10^{7}	
	750°	4.28×10^{3}	
NaCl	580°	1.95×10^{5}	Tammann and Veszi, 1926
	700°	1.42×10^{4}	
	790°	2.0×10^{3}	
KCl	520°	4.37×10^{6}	Tammann and Veszi, 1926
	600°	5.58×10^{5}	
	760°	8.7×10^{3}	

Table 5.2 Electrical conductivity on NaCl near the melting point (800.5° C).

Temperature (°C)	Conductivity ($ohm^{-1}cm^{-1}$)	Reference
720°	2.87	Poincare, 1890
740°	3.22	do.
750°	3.40	do.
770°	3.77	do.
780°	4.09	do.
850°	3.50	Arndt, 1906
900°	3.66	do.
950°	3.82	do.

Table 5.3 Dielectric strength of NaCl and KCl single crystals as a function of temperature.
(from Cooper, and others, 1960)

Compound	Dielectric strength (10^6 volts/cm)					
	Temperature (°C)	-200°	-100°	0°	+100°	+200°
NaCl		0.80	0.78	0.75	0.72	0.61
KCl		0.62	0.69	0.77	0.87	0.43

Note: Measurements were made with pulses of 50 microseconds length.

Table 5.4 Transient currents induced by cyclic loading of NaCl single crystal. (from Fischbach and Nowick, 1955)

Cycle number	Current (10^{-15} amp)[1]			
	At loading, at 0 sec[2]	After loading, at 20 sec[2]	At unloading, at 35 sec[2]	After unloading, at 60 sec[2]
1	(150)[3]	35	23	2
2	50	12	12	1
3	25	6	8	0.5
4	15	5	6	0.2

[1] A transient, decaying current was observed to flow between opposite faces of slightly unequal area, 1 mm apart, as the crystal was loaded from 6 to 7 bars and when unloaded from 7 to 6 bars (estimated stresses). Negative charge flowed from the high stress side, in the same direction at loading and at unloading. The current is equal both in normal and in parallel directions to the stress axis, and is the same in the presence of electric fields to 1,000 volts/cm. A total charge of 3×10^{-11} coulomb of transient current flowed as the current decayed from 150×10^{-15} amp to 3×10^{-15} amp in 4 minutes. Resistivity of the crystal used was about 10^{17} ohm cm.

[2] Time is from the initial loading in a cycle.

[3] Estimated by extrapolation of curve.

Table 5.5 Magnetic susceptibility of NaCl, KCl, and $CaSO_4$.
(from Ishiwari, 1914)

Compound	Temperature (°C)	Susceptibility (10^{-6} cgs units)
NaCl	-150°	0.501
	18°	0.499
	362°	0.499
	933°	0.508
KCl	22°	0.516
$CaSO_4$	17°	0.54

6. Optical Properties

This section comprises very old and very new data, some of the latter being observations of rarely studied phenomena in unusual combinations. The effects of radioactivity on the properties of rock salt are given emphasis because of their interest to many users of these tables.

Table 6.1 Spectral absorption of light by NaCl.

Wavelength (microns)	Absorption (cm^{-1})	Reference
0.186	0.36	Pfluger, 1904
0.210	0.26	do.
0.231	0.15	do.
0.280	0.046	do.
6-8	<0.001	Rubens and Nichols, 1897
9-11	0.005	do.
12	0.007	do.
13	0.024	do.
14	0.071	do.
15	0.167	do.
16	0.41	do.
17	0.66	do.
18	1.29	do.
19	2.34	do.
20.7	5.1	do.
24	10.7	Rubens and Aschkinass, 1898
52	>16	do.
61	>16	do.

Table 6.2 Luminescence activation energies in NaCl and KCl as a function of temperature.[1] (from Halperin, and others, 1960)

NaCl		KCl	
Temperature (°K)	Activation Energy (electron volts)	Temperature (°K)	Activation Energy (electron volts)
178°	0.44	126	0.24
241	0.67	142	0.38
298	0.93	262	0.72
339	1.12	362	1.20
491	1.45	392	0.9

---

[1] Single crystals were under X-radiation for 30 minutes, and luminescence was measured at glow peak temperatures shown.

Table 6.3 Temperature effect on the infrared reflection by NaCl single crystals.[1]

(from Hass, 1960, Table 1)

Temperature (°K)	Reflectance[2] (percent)
300	89
460	81
640	70
820	57
985	52

---

[1] Major absorption peak is at 190 cm^{-1}, a sideband at 263 cm^{-1} and a shoulder at 235 cm^{-1}. Angle of incidence of beam was 10°.

[2] Reflectance is in percent of a reflectivity standard, which was an aluminum mirror with 98 percent reflection.

Table 6.4 Removal by annealing of density change in NaCl single crystals produced by proton irradiation.

(from Kobayashi, 1957)

Annealing Temperature (°C)	Remaining Density Change[1/] (10^{-4}g/cc)
25	-6.3
100	-6.3
200	-6.0
300	-1.8
400	0

[1/] Mean values for two runs at 7.1×10^{15} and 8.1×10^{15} protons/cm^2 by irradiation from 350 Mev protons.

Table 6.5 Gamma-ray coloration of plastically deformed NaCl single crystals.[1]

(from Nowick, 1958, Table 2)

Condition of crystal	Coloration[2] (10^{17} F-centers/cm^3)	
	After 20 min. irradiation	Estimated saturation coloration due to irradiation
As received	0.375	0.92
	0.370	0.91
Annealed without deformation		
1 hour at 600°C	0.430	1.05
	0.445	1.09
After compression strain of		
3.7 %	0.412	1.01
4.3 %	0.436	1.08
8.5 %	0.540	1.34
Compressed 3.7 % and annealed at		
1 hour at 175°C	0.392	0.96

---

[1] Plastic deformation was uniaxial and was done on a large crystal in air at room temperature (estimated strain rate of 10^{-3} sec^{-1}); then the sample was cleaved from the large crystal.

[2] Radiation source was cobalt -60 of constant intensity.

Table 6.6 Effect of X-radiation on internal friction of NaCl single crystals.[1]

(from Frank and Read, 1953)

Temperature	Maximum Strain	Internal Friction (10^{-3} log decrement)			
(°C)	(10^{-5} in/in)	Unirradiated	X-radiated	Bleached	Annealed
25°	0.5	0.65	0.45	0.35	0.50
25°	1.0	(>5)	0.45	0.35	1.10
25°	1.5	-	0.45	0.35	2.10
25°	5.0	-	0.50	0.60	-
-196°	0.5	0.25	-	0.31[2]	-
-196°	1.0	1.30	-	2.20[2]	-
-196°	1.5	(>10)	-	(>5)[2]	-

---

[1] X-radiation was applied for 20 minutes, then bleaching was done with daylight, and then annealing was done for 30 minutes at 200° C. A resonance method was used to measure the internal friction.

[2] Samples were X-radiated and then bleached in liquid nitrogen.

Table 6.7 Linear expansion of NaCl and KCl single crystals due to X-radiation.[1]
(from Lin, 1956, figs. 5, 6)

Density of F-centers (10^{16} cm^{-3})	Relative linear expansion (10^{-7} cm/cm)	
	NaCl	KCl
1	1.5	2.1
2	3.0	4.2
4	6.1	8.2
6	9.2	12.3

---

[1] X-ray treatment was 3 hours long. Dimension change was measured electrically by capacitance change. Expansion relation is not valid for coloration > 10^{17} F-centers/cm^3.

Table 6.8 Refractive indices of certain evaporite minerals.
(from Palache, and others, 1951)

Mineral	Crystal System	Optic Angle(2V)	Refractive Indices[1]			Orientation of Indices to crystal axes[2]		
			α	β	γ	α	β	γ
Anhydrite	Orthorhombic	43°41'	1.5698	1.5754	1.6136	b	a	c
Gypsum	Monoclinic	58°	1.5207	1.5230	1.5299		b	c∧51°52'
Halite	Isometric		1.5446					
Sylvite	Isometric		1.4838					

[1] Indices were measured in sodium light.

[2] Index directions are parallel or at the angle shown to the crystal axes.

7. Mechanical Properties

The relative ease with which NaCl can be deformed elastically and plastically has resulted in many studies of its mechanical properties; the data given in this section are only a tiny portion of all the work done, although many of the older studies were duplicative and not very well controlled. A reasonably complete review of work up to 1935 is given in Schmid and Boas (1950, chap. 7);the review covers the early studies of the effect of temperature, pressure, and impurities, of the Joffe effect (strengthening due to enclosing the sample in a water bath), and of optical effects due to strain. A brief summary of deformation of salt is given by Robertson and others (1958).

A large number of recent tests on rock salt under various conditions have been made by Gloyna and his coworkers of the Sanitary Engineering Research Laboratory, Civil Engineering Department, University of Texas. These studies were made to explore the mechanical problems of disposing of radioactive waste in salt domes or beds. Results have been issued as internal reports for the A.E.C. (Serata and Gloyna, 1959, and Reynolds and Gloyna, 1960).

Table 7.1 Translation and twin gliding of certain evaporite minerals. (from Palache, and others, 1951)

	Translation Gliding		
Mineral	Plane	Direction	
Halite	{001}	[110]	
	{011}	[$\bar{1}$10]	
	{111} ?		
Sylvite	{011}	[011]	
	{001}	[011]	
Gypsum	{010}	[001]	
	{010}	[001]	In torsion
	{010}	[010]	In bending
Anhydrite	{010}	[100]	
	{120}	[001]	
Calcite	{01$\bar{1}$2}	[12$\bar{3}$1]	

	Twin Gliding	
	Plane	Plane of Second Circular Section
Anhydrite	(011)	(0$\bar{1}$1)
Calcite	(01$\bar{1}$2)	(0$\bar{1}$11)

Table 7.2 Stress-strain data for NaCl[1] single crystals at various temperatures and pressures. (from Handin and Hager, 1958, figures 7 and 8)

Type of test	Temperature (°C)	Confining pressure (bars)	Stress difference required (bars)						
		Strain (percent)	0.2	0.5	1.0	2.0	5.0	10.0	20.0
Compression	24°	1,000	65	80	115	145	215	315	480
do.	24°	2,000	115	122	140	160	235	335	520
do.	150°	1,000	50	75	85	105	145	180	240
do.	150°	2,000	50	75	90	110	150	190	270
do.	300°	2,000	30	65	80	95	90	90	100
Extension	24°	1,000	25	70	105	135	210	295	420
do.	24°	2,000	45	85	115	145	220	310	435
do.	150°	2,000	30	70	105	120	145	165	185
do.	300°	2,000	30	70	95	100	105	105	60

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[1] Single crystals were cut into right cylinders with one axis normal to $\{001\}$.

Table 7.3 Stress-strain data for rock salt at room temperature under moderate confining pressure. (from Handin, 1953, figs. 22, 23, 24)

Position of curve	Stress Difference (bars)					
Strain (percent)	0.5	1	2	5	10	20
Extension Tests[1]						
Minimum	230	300	400	580	720	920
Maximum	410	460	550	670	840	1,150
Special[2]	620	800	880	940	980	1,080
Compression Tests I[3]						
Minimum	150	250	400	550	660	740
Maximum	380	540	680	850	1,050	1,230
Low pressure[4]	30	50	100	230	390	430
Compression Tests II[5]						
Minimum	90	180	290	450	470	470
Maximum	170	260	370	540	570	570

[1] Nine jacketed, cylindrical specimens from the Hockley mine, Texas, were subjected to confining pressures from 1,000 bars to 5,100 bars; stress difference was produced by reducing the axial stress. Stress-strain curves cross and are irregular with regard to confining pressure; data are from a superimposed plot of the 9 curves.

[2] Special sample was previously compressed 10 percent before being subjected to extension under 2,700 bars confining pressure.

[3] Nine jacketed, cylindrical specimens were compressed axially under confining pressures from 100 to 2,800 bars. Minimum values are for specimens under confining pressures of 100, 200, and 500 bars; maximum values are for confining pressures of 1,200, 2,000, and 2,800 bars.

[4] Low pressure tests were under confining pressures of 1 and 25 bars.

[5] Five cylindrical specimens, unjacketed and exposed to the kerosene pressure fluid, were compressed axially under confining pressures of 240 to 930 bars. Curves are irregular with respect to confining pressure.

Table 7.4 Yield point and tensile strength at room temperature and pressure of NaCl single crystals from various sources.
(from Theile, 1932, table 1)

Single Crystal Source	Yield Point (bars)	Tensile Strength (bars)
Melt grown	15	22 ±1
Wieliczka, Poland Small crystal	9	16 ±2
Wieliczka, Poland Large crystal	21	24 ±2
Heilbronn, Germany	31	35 ±1
Stassfurt, Germany	112	125 ±10

Table 7.5 Temperature effect on tensile strength of NaCl single crystals.[1]
(from Theile, 1932, table 4)

Crystal source	Tensile strength (bars)					
Temperature (°C)	20°	200°	300°	400°	500°	600°
Melt grown	25	58	-	543	-	776
Wieliczka, Poland						
small crystal	26	64	88	-	965	1,030
large crystal	26	49	77	340	-	671
Heilbronn, Germany	37	52	55	104	-	630

---

[1] Tests were made in air at one atmosphere pressure.

Table 7.6 Compressive strength of rock salt at room temperature and pressure.
(from Serata and Gloyna, 1959, table 7-1)

Source of Salt	Grain size (mm)	Strength (10^3 psi)
Grand Saline Dome, Texas	0.1 - 0.5	2.3
Salt dome, Louisiana	1.0 - 1.7	5.0
Salt mine, New Mexico	0.5 - 1.2	4.2
Hockley Dome, Texas	0.05- 0.1	3.7
Salt domes, west Texas		2.6 - 4.0
Salt mine, Rumania		4.7 - 5.3
Grand Saline Dome, Texas, and Harshaw Chemical Company		4.0 - 4.2[1/]

[1/] These tests were made on single crystals loaded normal to $\{001\}$.

Table 7.7 Reproducibility of strain of NaCl after given times of creep.[1]
(from LeComte, 1960, figures 2 and 3)

Number of Samples	Axial stress difference (bars)	Confining pressure (bars)	Temperature (°C)	Time (sec)	Strain Range (percent)	Strain Average[2] (percent)
5	70	1	29°	10^3	.02 - .27	.14
				10^4	.13 - .44	.27
				10^5	.28 - .65	.46
				3×10^5	.38 .82	.60
6	70	1,000	105°	10^3	(.60 - .95)	(.80)[3]
				10^4	.68 - 1.03	.94
				10^5	.98 - 1.67	1.37
				3×10^5	1.38 - 2.39	1.96

---

[1] Samples were cylinders made by compacting NaCl powder under 5,000 bars, and annealing for one day at 300° C. Porosity was about 2 percent.

[2] Average was taken from a computed average curve.

[3] Data in parentheses represent estimates.

Table 7.8 Strain-time data on NaCl[1] as a function of confining pressure, temperature, and stress difference.
(from LeComte, 1960, figures 4 thru 9)

Sample number	Axial stress difference (bars)	Confining pressure (bars)	Temperature (°C)	Strain (percent)				
			Time[2] (sec)	10^3	10^4	10^5	5×10^5	10^6
14	70	1	29°	0.07	0.15	0.34	0.69	-
15	70	200	29°	0.06	0.14	0.31	0.54	-
16	70	1,000	29°	0.21	0.25	0.33	0.56	-
18	140	1,000	29°	-	0.61	1.58	3.13	4.28
22	35	1,000	105°	-	0.82	0.84	0.93	1.01
43	35	1,000	105°	-	0.75	0.78	0.87	(.95)[3]
54	70	1	105°	(0.60)	1.40	3.45	7.2	-
20	60	1,000	105°	-	0.73	1.06	1.38	1.52
17	70	1,000	105°	-	0.72	1.00	1.85	2.48
47	70	1,000	105°	(0.90)	0.98	1.31	2.36	-
65	70	1,000	105°	-	0.60	0.87	(1.3)	-
55	70	1,000	198°	(0.25)	1.03	3.54	(8.6)	-
48[4]	70	1,000	105°	-	0.28	0.41	(0.63	-
56[5]	70	1,000	105°	-	0.52	1.70	(3.6)	-
S-23[6]	70°	1,000	105°	-	5.22	7.26	8.20	8.54

[1] Samples were cylinders made by compacting NaCl powder under 5,000 bars, and annealing for one day at 300° C. Porosity was about 2 percent.

[2] Time elapsed after initial loading.

[3] Data in parentheses represent extrapolated values.

[4] Sample contained 2 percent $CaSO_4$.

[5] Sample contained 5 percent $CaSO_4$.

[6] Single crystal cut with cylinder axis perpendicular to $\{001\}$; specimen fractured badly during run.

Table 7.9 Density decrease of NaCl with single stage compressive loading and with cyclic compressive loading and unloading (from Davidge and others, 1959).

Method of loading	Density decrease (10^{-4} g/cm^3)			
Maximum strain (percent)	2.5	5.0	7.5	10.0
Single stage compression	0	0.10	0.75	1.35
Fatigue test (after 2 x 10^5 cycles of compression)	0.15	0.90	1.50	1.85

Table 7.10 Density and hardness changes in plastically deformed KCl single crystals.[1]
(from Vaughan and others, 1958)

Strain (percent)	Density decrease (10^{-5} g/cm^3)	Hardness by indentation length[2] (microns)
0	0	91
5	0	
10	0	
15	0.05	
20	0.12	
22	0.16	77
22		78 (after heating to 750° C)

---

[1] Uniaxial loading on crystals cleaved and deformed in 1-3 dibromopropane, at room temperature (estimated strain rate of 10^{-3} sec^{-1}).

[2] Diamond Tukon hardness machine used.

Table 7.11 Quench hardening[1] in single crystals of NaCl. (from Kear and Pratt, 1958)

(A) Quenching Rate Tests[2]

Quenching Medium	Flow Stress (kg/cm^2)	Flow Strain (percent)	Stress at 2.5 percent Strain (kg/cm^2)
Furnace cooled	5	0.1	27
Still air	13	0.25	40
Controlled air	15	0.2	60
Liquid air	55	0.5	100
Carbon tetrachloride	71	0.4	120
Silicone oil	85	0.3	142
Concentrated brine	126	0.6	171

---

[1] Quench hardening is measured in terms of flow stress, or the plastic yield stress, in uniaxial compression; flow stress and flow strain are taken at the knee of the stress-strain curve.

[2] Crystals of NaCl were annealed at 650° C, furnace cooled, heated to 750° C, and quenched, and then tested in compression.

(B) Cross-sectional area tests[3]

Quenching Medium	Sample Area (mm^2)	Flow Stress (kg/cm^2)
Silicone oil	1.0	102
do.	2.0	99
do.	5.0	89
do.	10.0	76
do.	15.0	62

---

[3] Crystals of NaCl were annealed at 650° C, furnace cooled, heated to 750° C, and quenched, and then tested in compression. Tests were made to study the effect on plastic flow of increasing the sample cross-sectional area.

(C) Quenching Temperature Tests[4]

Quenching medium	Quench temperature (°C)	Flow stress (kg/cm^2) Sample area $1.56\ mm^2$	Flow stress (kg/cm^2) Sample area $6.25\ mm^2$
Silicone oil	200	-	28
Concentrated brine	200	-	55
do.	200	55	-
Silicone oil	400	-	60
Concentrated brine	400	-	110
do.	400	124	-
Silicone oil	600	-	67
Concentrated brine	600	-	127
do.	600	143	-
Silicone oil	750	-	76
Concentrated brine	750	-	137
do.	750	163	-

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[4] The effect of different quenching rates at different temperatures was observed on NaCl crystals of two cross sections: 1.25 mm square and 2.5 mm square.

(D) Post-Quench Annealing Tests[5]

Quenching Medium			Sample Area 1.56 mm^2		Sample Area 6.25 mm^2	
	Quench Temp. (°C)	Annealing Temp. (°C)	Flow stress at annealing temp. (kg/cm^2)	Flow stress, furnace cooled (kg/cm^2)	Flow stress at annealing temp. (kg/cm^2)	Flow stress, furnace cooled (kg/cm^2)
Concentrated brine	750	20	158	158		
do.	750	100	138	154		
do.	750	200	116	148		
do.	750	400	60	78		
do.	750	600	34	50		
do.	750	740	16	16		
Silicone oil	750	20			75	130
Concentrated brine	750	20			75	130
Silicone oil	750	100			69	112
Concentrated brine	750	100			75	128
Silicone oil	750	200			62	73
Concentrated brine	750	200			89	122
Silicone oil	750	400			33	48
Concentrated brine	750	400			50	65
Silicone oil	750	600			20	20
Concentrated brine	750	600			26	37

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[5] Two crystals in each set, both quenched at 750°C, were annealed at various temperatures; one crystal was deformed in compression at the annealing temperature, and the other was compressed after cooling slowly to room temperature in the furnace.

Table 7.12 Effects of radiation on the compressive strength of rock salt.[1]

(from Gunter and Parker, 1961, figs. 7 thru 13)

Sample treatment	Stress (10^3 psi)									Young's modulus
Strain (percent)	0.5	1	2	4	6	10	20	Yield point	Rupture	(10^3 psi)
				Bedded Salt (loaded parallel to bedding)						
Unirradiated										
at 25° C	1.68	2.68	3.68	4.15	3.90	-	-	2.5	4.2	350
at 200° C	-	.91	1.57	2.12	2.39	2.90	3.86	1.6	3.9	90
Irradiated at 10^6 r										
at 25° C	1.58	2.57	3.70	4.50	4.27	-	-	2.5	4.5	320
Irradiated at 5 x 10^8 r										
at 25° C	1.83	2.78	3.45	3.27	-	-	-	2.7	3.5	390
at 200° C	-	1.14	1.96	2.45	2.68	3.00	3.43	1.9	3.4	120
				Bedded Salt (loaded perpendicular to bedding)						
Unirradiated										
at 25° C	1.54	2.38	3.13	3.90	4.00	-	-	2.3	4.0	360
at 200° C	-	1.09	1.74	2.26	2.59	3.07	3.65	1.6	3.6	110
Irradiated at 10^6 r										
at 25° C	1.37	2.07	2.93	3.72	3.75	-	-	1.8	3.8	350

Sample treatment	Stress (10^3 psi)									Young's modulus (10^3 psi)
Strain (percent)	0.5	1	2	4	6	10	20	Yield point	Rupture	
Bedded Salt (loaded perpendicular to bedding)										
Irradiated at 5 x 10^8 r										
at 25° C	1.60	2.66	3.32	3.32	2.6	-	-	2.4	3.5	370
at 200° C	-	2.38	2.19	2.58	2.80	3.12	3.22	2.1	3.3	130
Dome Salt										
Unirradiated										
at 25° C	2.12	3.15	4.34	5.51	5.19	-	-	2.9	5.6	500
at 200° C	-	1.23	1.73	2.22	2.51	2.97	3.64	1.9	3.6	140
Irradiated at 10^6 r										
at 25° C	2.16	3.19	4.33	5.33	4.93	-	-	2.9	5.3	510
Irradiated at 5 x 10^8 r										
at 25° C	2.31	3.03	3.53	2.92	(<1.5)	-	-	2.6	3.6	590
at 200° C	-	1.60	2.23	2.60	2.81	3.03	3.13	2.3	3.1	160

1/ Measurements were made on two-inch cubes of polycrystalline, unannealed salt, in air, at a strain rate estimated to be about 10^{-3} sec $^{-1}$. Bedded salt was from Hutchinson, Kansas, and dome salt was from Grand Saline, Texas. Radiation from a cobalt -60 source was done at Oak Ridge National Laboratory, Tennessee. (r = roentgen)

Table 7.13 Effect of radiation on creep of rock salt.[1]
(from Gunter and Parker, 1961, figs. 16, 17, 18)

Salt Type	Loading	Amount of Irradiation (r = roentgen)	Time (sec)	Creep Strain (percent)			
				10	100	1,000	5,000
Bedded	(Parallel to bedding)	Unirradiated		(0.1)[2]	1.03	1.38	1.49
		After 5×10^8 r		(0.1)	1.32	1.46	1.55
Bedded	(Perpendicular to bedding)	Unirradiated		(0.2)	1.18	1.60	1.73
		After 5×10^8 r		(0.2)	1.07	1.19	1.27
Dome		Unirradiated		(0.4)	0.95	1.16	1.23
		After 5×10^8 r		(0.4)	0.86	1.01	1.09

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[1] Two-inch unannealed, polycrystalline cubes of salt were compressed in air at room temperature under 2,500 psi. Bedded salt was from Hutchinson, Kansas, and dome salt was from Grand Saline, Texas. Radiation from cobalt-60 source was done at Oak Ridge National Laboratory, Tennessee.

[2] Approximate values are given in parentheses.

8. High Pressure Effects on Physical Properties

The data on the high pressure and high temperature effects on the molar volume of NaCl in table 8.1 were obtained by recalculation from the original data of the references given. An interesting result in this table is that pressure greater than 40 kilobars reverses the effect of thermal expansion.

Table 8.1 Molar volumes of NaCl at high pressures and high temperatures.[1]

Pressure (10^3 bars)	Molar volume (cm^3)							
Temperature (°C)	0°	100°	200°	400°	600°	800°	1000°	Reference[1]
0	27.0	27.3	27.7	28.7	29.6	32.0	-	H
	27.7	28.0	28.3	29.2	30.2	31.8	34.3	D-T
	27.0	-	-	-	-	-	-	B
10	26.0	26.3	26.5	26.8	27.6	28.4	-	H
	26.7	27.0	27.2	27.9	28.5	29.4	30.6	D-T
	26.0	-	-	-	-	-	-	B
20	25.3	25.5	25.5	25.6	26.1	26.5	-	H
	25.9	26.2	26.4	26.9	27.4	28.0	28.7	D-T
	25.2	-	-	-	-	-	-	B
30	24.7	24.9	24.9	24.6	25.0	25.2	-	H
	-	25.4	25.7	26.0	26.5	27.0	27.5	D-T
	24.5	-	-	-	-	-	-	B
40	24.2	24.4	24.3	23.9	24.2	24.3	-	H
	-	-	-	-	25.6	26.2	26.7	D-T
	23.9	-	-	-	-	-	-	B
50	23.9	23.9	23.8	23.3	23.5	23.7	-	H
	-	-	-	-	-	-	25.9	D-T
	23.5	-	-	-	-	-	-	B

		Molar volume (cm^3)							
Pressure (10^3 bars)	Temperature (°C)	0°	100°	200°	400°	600°	800°	1000°	Reference[1]
60		23.6	23.6	23.5	22.8	23.0	23.6	-	H
70		23.3	23.3	23.1	22.4	22.6	22.8	-	H
80		23.1	23.1	22.9	22.1	22.2	22.4	-	H
90		22.9	22.9	22.6	21.8	21.9	22.1	-	H
100		22.8	22.7	22.4	21.6	21.7	21.8	-	H

---

[1] Experimental data from Bridgman (1940), B, were extrapolated by use of theoretical equations of state by Hughes (1959), H, and by Dayal and Tolpadi (1959), D-T. Bridgman's measurements were made at 20° C, although listed here under 0° C.

Table 8.2 High pressure transition of KCl single crystal for temperature range 0° to 200° C.[1]

(from Bridgman, 1935, fig. 11)

Temperature (°C)	Pressure (10^3 kg/cm^2)	Volume change (10^{-2} cm^3/g)
0	20.0	-5.7
100	20.4	-5.1
200	20.7	-4.4

---

[1] Measurements on NaCl single crystal revealed no transitions to 50,000 kg/cm^2. Latent heat of KCl transition is 1.97 cal/gm.

Table 8.3 Effect of pressure on the melting points of NaCl and KCl (from Clark, 1959).

Pressure	Melting Temperature	
(10^3 bars)	NaCl (°C)	KCl (°C)
0	801	770
1	824	793
2	849	819
5	910	875
10	1005	946
15	1089	1005
20	1169	1068

Table 8.4 Dynamic volume changes of rock salt under shock pressure, computed from shock and particle velocities by the Hugoniot equation of state.

(from Lombard, 1961, appendix)

Pressure (10^5 bars)	V/Vo[1]
0.89	0.81
1.26	0.77
1.61	0.74
1.62	0.76
1.66	0.75
2.20	0.70
2.26	0.70
2.58	0.67
2.60	0.68
2.62	0.67
4.37	0.59
4.36	0.60
4.57	0.59
4.79	0.60
6.20	0.58
7.09	0.54
7.35	0.55
8.56	0.51
8.65	0.50
8.82	0.50

---

[1] V/Vo is the ratio of the new to the original volume and is equal to the fractional difference between shock U and particle u velocities: $V/Vo = (U-u)/U$.

Table 8.5 Dynamic compressibility and electrical conductivity of sodium chloride at high pressures and temperatures.

(Al'tshuler, Kuleshova, and Pavlovskii, 1960, table 3)

Test number	Relative compression[1/] (V_o/V)	Temperature (°K)	Shock pressure (10^4 bars)	Electrical conductivity ($ohm^{-1} cm^{-1}$)
1	1.26	440	10.0	2.0×10^{-5}
2	1.31	530	13.7	1.9×10^{-4}
3	1.39	760	18.2	5.7×10^{-4}
4	1.43	940	20.9	2.0×10^{-4}
5	1.45	1020	23.6	1.9×10^{-3}
6	1.50	1320	27.6	2.5×10^{-3}
7	1.39	760	18.2	4.4×10^{-4}
8	1.45	1020	23.6	3.5×10^{-3}
9	1.45	1020	23.6	2.6×10^{-4}
10	1.50	1320	27.6	8.6×10^{-4}
11	1.50	1320	27.6	2.5×10^{-3}
12	1.62	2280	43.3	6.8×10^{-2}
13	1.68	3030	54.5	4.1×10^{-1}
14	1.85	6150	79.0	3.26

[1/] V_o/V is the ratio of the original to the new volume.

Table 8.6 Compressibility of NaCl and KCl single crystals at room temperature.

Pressure ($10^3 kg/cm^2$)	Decrement of Volume ($\Delta V/V$) NaCl	Decrement of Volume ($\Delta V/V$) KCl
	(from Bridgman, 1940)	
0	0	0
10	0.0365	0.0478
20	0.0664	0.0841
30	0.0919	0.2225[1]
40	0.1130	0.2419
50	0.1309	0.2579
	(from Jacobs, 1940)[2]	
50	0.141	
100	0.216	
150	0.271	
200	0.310	

---

[1] Transition of KCl from face-centered to body-centered cubic structure occurs at 20,060 kg/cm^2 at room temperature. No transition was found for NaCl to 50,000 kg/cm^2.

[2] Data were derived theoretically, Jacobs concludes that no transition should occur to 200,000 kg/cm^2 in NaCl.

Table 8.7 Volumetric compressibility of rock salt at room temperature.[1]

(from Guido and Warner, 1960, table 2)

Pressure (10^3 psi)	Compressibility Sample A (10^{-6} psi^{-1})	 Sample B (10^{-6} psi^{-1})
0	1.71	1.46
2	0.62	0.91
4	0.41	0.52
6	0.31	0.32
10	0.22	0.26
14	0.22	0.23
16	0.22	0.23

---

[1] Samples were obtained from the Carey Salt mine, Winnfield, Louisiana. Linear compressibility was measured by liquid displacement, and the volume compressibility was calculated from it. Precision is estimated to be ± 10 percent.

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