Physical Properties Data Compilations Relevant to Energy Storage.

IV. Molten Salts: Data on Additional Single and Multi-Component Salt Systems

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Foreword

The National Standard Reference Data System provides access to the quantitative data of physical science, critically evaluated and compiled for convenience and readily accessible through a variety of distribution channels. The System was established in 1963 by action of the President's Office of Science and Technology and the Federal Council for Science and Technology, and responsibility to administer it was assigned to the National Bureau of Standards.

NSRDS receives advice and planning assistance from a Review Committee of the National Research Council of the National Academy of Sciences-National Academy of Engineering. A number of Advisory Panels, each concerned with a single technical area, meet regularly to examine major portions of the program, assign relative priorities, and identify specific key problems in need of further attention. For selected specific topics, the Advisory Panels sponsor subpanels which make detailed studies of users' needs, the present state of knowledge, and existing data resources as a basis for recommending one or more data compilation activities. This assembly of advisory services contributes greatly to the guidance of NSRDS activities.

The System now includes a complex of data centers and other activities in academic institutions and other laboratories. Components of the NSRDS produce compilations of critically evaluated data, reviews of the state of quantitative knowledge in specialized areas, and computations of useful functions derived from standard reference data. The centers and projects also establish criteria for evaluation and compilation of data and recommend improvements in experimental techniques. They are normally associated with research in the relevant field.

The technical scope of NSRDS is indicated by the categories of projects active or being planned: nuclear properties, atomic and molecular properties, solid state properties, thermodynamic and transport properties, chemical kinetics, and colloid and surface properties.

Reliable data on the properties of matter and materials are a major foundation of scientific and technical progress. Such important activities as basic scientific research, industrial quality control, development of new materials for building and other technologies, measuring and correcting environmental pollution depend on quality reference data. In NSRDS, the Bureau's responsibility to support American science, industry, and commerce is vitally fulfilled.

ERNEST AMBLER, *Director*

Preface

This series of publications is aimed at providing physical properties data on materials used in energy storage systems. It was inspired by a requirement in the Department of Energy's Division of Energy Storage Systems for materials property data needed by its contractors in the timely development of energy storage devices. As prime contractor for this program, the Lawrence Livermore Laboratory (LLL) has requested the Office of Standard Reference Data (OSRD) to manage the task of gathering the data, using its established network of data centers and other identified sources of expertise. The OSRD monitors the progress of work, reviews the results, and conveys the numerical data to LLL where the data are converted for entry into an automated data storage and retrieval system. Every effort is made to supply data which have been critically examined in light of the latest knowledge concerning theory and experiment. However it must be recognized that in a rapidly moving technology some of the data will be superseded rather quickly as new materials and techniques are introduced. Thus access to the data via computer terminal as well as publication in this series should help provide the practitioner with timely and useful data which he requires to solve his problems in energy storage. Funding for this series of projects from the Department of Energy, Division of Energy Storage, through the Lawrence Livermore Laboratory, is gratefully acknowledged.

Previous publications in the series "Physical Properties Data Compilations Relevant to Energy Storage":

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Janz, G. J., Allen, C. B., Bansal, N. P., Murphy, R. M., and Tomkins, R. P. T., Physical Properties Data Compilations Relevant to Energy Storage. II. Molten Salts: Data on Single and Multi-Component Salt Systems, Nat. Stand. Ref. Data Ser., Nat. Bur. Stand. (U.S.), 61, Part II, 442 pp. (Apr. 1979).

Miller, G. R., and Paquette, D. G., Physical Properties Data Compilations Relevant to Energy Storage. III. Engineering Properties of Single and Polycrystalline Sodium Beta and Beta" - Alumina, Nat. Stand. Ref. Data. Ser., Nat. Bur. Stand. (U.S.), 61, Part III, 19 pp. (June 1979).

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PHYSICAL PROPERTIES DATA COMPILATIONS RELEVANT TO ENERGY STORAGE

IV. MOLTEN SALTS: DATA ON ADDITIONAL SINGLE AND MULTI-COMPONENT SALT SYSTEMS

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The present work provides selected data with value judgements for an additional set of 107 salt systems of interest as candidate materials for thermal energy storage sub-systems, for electrochemical energy storage systems, and in electrochemical aluminum production. The physical properties assessed are: melting points; phase diagrams; eutectic compositions; density; surface tension; viscosity; electrical conductivity; diffusion constants for ions; heat of fusion; heat capacity; volume change on fusion; vapor pressure; thermal conductivity (liquid and solid); and cryoscopic constant. The status of corrosion studies in the form of annotated bibliographic summaries, and salient observations on safety and hazards are also reported. A summarizing series of tables is provided as index to the data-gaps status for this set of candidate materials.

Key words: Corrosion; data compilations; electrochemical aluminum production; electrochemical energy storage materials; molten salts; physical properties; safety and hazards; thermal energy storage materials; thermal properties; thermodynamic properties; transport properties.

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INTRODUCTION

This communication reports critically evaluated data for an additional list of some 107 molten salt systems. This work was undertaken for the NBS-LLL Data Banks for Energy Research [1-3] and provides a data base on molten salts that are candidate systems particularly for thermal energy storage and for electrochemical energy storage. For the preceding publications see [4-6]. Critically evaluated data were reported for some 49 single and multi-component salt systems in Part II [5]. This data base is extended from 49 to 157 candidate salt systems in the present work.

The energy storage areas within the scope of this task included:

(i) solar and thermal energy storage subsystems utilizing inorganic salts in the PCM mode (phase-change-materials)

(ii) high temperature (molten carbonate) fuel cell systems

(iii) high temperature (molten carbonate) coal gasification processes

(iv) super-batteries systems (the sodium-sulfur and the lithium-metal sulfide battery concepts)

(v) high temperature heat transfer fluids (e.g., Hi-tec)

(vi) molten electrolytes for high temperature electroplating of refractory metals (e.g., the Flinak electrolyte for tantalum plating)

(vii) molten electrolytes for electrowinning of light metals (such as aluminum production from molten cryolite)

Closely related research areas are applications encountered in environmental areas, viz:

- disposition of sulfur (oxides) in stack gases
- disposal of hazardous wastes without atmospheric pollution (e.g., "aged" high explosive and rocket propellants; chemical warfare agents,...)
- disposal of used photographic wastes (film) (with silver recovery)

Consideration of these areas were included in the selection of the candidate salt systems.

Candidate Salt Systems

The criteria for selection of candidate materials, and the generalized list of "likely" systems for the selection of specific candidate systems are in tables I.1 and I.2, respectively. The present candidate systems in this task have been limited to (anhydrous) inorganic salts (table I.2-A,B); for the salt hydrates (table I.2C), see Cantor [ref. 7]. The sequence of systems in the data tables follows an anion classification as used for molten salts data elsewhere [5,8,9]. Within each anion family, the systems are arranged by cations as in the periodic chart of elements. There are some exceptions (e.g., sulfur, while not a salt, is included as a component of the alkali metal polysulfides).

The cumulative list of candidate salt systems summarized in table I.3, is arranged alphabetically by metallic element of the salt system to provide a facile entry to the data compilations reported in the preceding and the present publications. An underscored entry indicates that the data for that system are in the preceding publication in this series [5]. The alphabetical listing (by element) has the feature of cross-indexing, so that the data for multi-component systems can be readily accessed by reference to the cumulative list in table I.3.

The following considerations were used in the selection of the candidate salt systems.

Molten carbonates - In working systems (fuel cells, coal gasification, sulfur emissions scrubbing, heat storage subsystems,..) additional compounds are formed in trace amounts, and increasing concentrations. Knowledge of the properties of carbonates with such additives is essential in evaluating the parameters contributing to the overall process(es).

The list was extended from pure carbonate systems to include a selection of such systems, e.g., Na_2CO_3-NaOH, Na_2CO_3-NaCl, Li_2CO_3-K_2SO_4, Na_2CO_3-NaCl-NaOH,...

Molten polysulfides - The lithium and potassium series of polysulfides were added to extend the coverage from sodium

polysulfides and sulfur to additional systems of interest in "super-battery" type R & D projects.

PCM candidate materials - The multicomponent systems included in the present list extend the coverage to priority 1 and priority 2 type systems (see: table 2, A and B) with due consideration to the factors of economy and safety, and to the desired thermal properties (see: table 1, A). The hydroxides and their mixtures, nitrate-nitrite mixtures, the ternary nitrite-nitrate system (Hi-tec), are examples of systems thus added.

Cryolite and related systems - In the industrial production of aluminum, the molten electrolyte is a mixture of Na_3AlF_6 and Al_2O_3 with smaller amounts of CaF_2 and AlF_3 as additives. The candidate list has thus been extended to include a selection of such systems, e.g.,

AlF_3, CaF_2, BaF_2, MgF_2, Na_3AlF_6, and mixtures, e.g., LiF-NaF, NaF-AlF_3, Na_3AlF_6-Al_2O_3...

Additional systems - Various molten salt systems, notably fluorides, and nitrate-nitrite mixtures have seen application in diverse areas, such as: refractory metals plating; metal treatment, heat transfer fluids,..., and the candidate list was extended accordingly. The KNO_3-$NaNO_3$-$NaNO_2$ and LiF-NaF-KF systems, widely known as "Hi-tec" and "Flinak" respectively are examples of systems thus included in this work.

Fundamental Constants, Symbols, Units

The fundamental constants and glossary of symbols and units are in Tables I.4 and I.5, respectively.

Treatment of Data

Statistical Analysis of Data

The recommended data values were selected based on the estimates of precision and uncertainty of the data surveyed in the literature. The Percent Departure also provided a guideline. The Percent Departure is defined as:

$$\text{Percent Departure} = \frac{\text{"compared value"}-\text{"tabulated value"}}{\text{"tabulated value"}} \times 100$$

Here "compared value" and "tabulated value" refer to the literature value and the value recommended in the present work. Both the "compared value" and the "tabulated value" were calculated from statistical derived equations since the results had to be interpolated to common temperatures and common compositions. Where the data sets from two or more studies were merged to provide the data base for the recommended values (either to extend the temperature range, or to fix the confidence level) this has been noted in the data tables. Unless otherwise noted, all values were recalculated to the Kelvin temperature scale and are thus reported throughout.

All calculations were made on the digital computer facilities at Rensselaer Polytechnic Institute. The data set of the recommended study were recalculated by a one-dimensional analysis, using the method of least squares, to establish equations indicating the variations of the physical quantities with temperature at the experimental compositions. If the data base was sufficient, calculations using a two-dimensional analysis, with a stepwise multiple regression routine were undertaken. In this way a physical property-temperature-composition matrix was developed. A result of this analysis is that it enables intercomparisons of property values at either common temperatures or at common compositions.

One-Dimensional Analysis

The criterion for choosing the equation of best fit in the one-dimensional analysis was the standard error of estimate.

This was defined by

$$s = \left[\frac{\sum^{n} (\gamma_e - \gamma)^2}{n - q}\right]^{1/2}$$

where γ_e = the experimental value at each temperature, γ = the value calculated from the least squares equation at the same temperature as γ_e, n = the number of experimental data points, and q = the number of coefficients in the least square equation (2 for linear, 3 for quadratic). The standard error of estimate was computed from the residuals in the least-squares routine.

Two-Dimensional Analysis

The computer programs consisted of the four routines, STPRG, CORRE, LOC and MSTR; the latter two are storage routines which have no effect on the accuracy of the results. In addition a subroutine STOUT was used to print the results of each regression step and the subroutine MATRIX, for printing a matrix of numerical values from the thus derived equation.

The abbreviated Doolittle method was used to select the variables entering the regression and for calculation of coefficients. The independent variable included in each step of analysis was selected by computing the reduction of sums of squares of each variable. The variable causing the largest reduction was added to the equation and deleted from the table of sums of squares. The coefficients, intercept, and statistical parameters for the new equation were computed and printed. This procedure was repeated until the maximum proportion of sums of squares to the total reduced was less than a limit set by the programmer.

The independent variables used in the initial selection were chosen from a generalized procedure, which generated 30 combinations of input variables using powers, reciprocals, logarithmic and exponential quantities. It was found that the procedure consistently selected the equation $(T + C)^3$, so that the working program used nine independent variables. After the final equation was produced, it was transferred to the MATRIX routine, which recalculates values at rounded compositions and temperatures, within specified boundary conditions. In the presentation of the matrix, due cognizance is taken of the experimental range of investigation and of the phase relationships for the system so that values are always "interpolated" rather than "extrapolated". The final step in the procedure involves the residual analysis (giving the deviations of the original values from those computed for the "best-fit" equations).

In the programs used (vide infra), a summary of significant parameters is printed by the computer at each step in the regression analysis. These are: the sum of the squares reduced, S_i; the ratio S_i/D where D is defined below; and the cumulative sum of these variables, S_{cum} and P_{cum}. These quantities give an indication of the effect of each variable in the final equation. The programmer's limit on P was always in the range $0.0001 < P_{cum} < 0.001$.

The standard error in the estimated y values adjusted for degrees of freedom, is then given by:

$$s = \left[\frac{D - S_{cum}}{n - q - 1}\right]^{\frac{1}{2}}$$

where $D = \sum(y_j - \bar{y})^2$, y_j = experimental values, $\bar{y}$ = average of all experimental values, and q = the number of independent variables in the equations.

An F value analysis of variance was used to determine if a particular model was acceptable. Tables of F values indicate that values greater than 2.0 are acceptable for the routine used here. In all cases values of F were greater than 1000. The F value is defined as:

$$F = \frac{S_{cum}/q}{(D - S_{cum})/(n - q - 1)}$$

where S_{cum}, q, D, and n are defined above.

Value Judgements

Precision

Estimates of precision were based on standard error of estimate analysis. The standard error of estimate is the end result of a statistical analysis of the numerical data, and the statistical analysis depends on various factors, such as the number of the data points, the nature of the concentration dependence and the temperature dependence of the particular physical property. The precision is the standard error expressed as a percent value. As a general guide, about 60% of the results lie within the estimate of precision, 95% within three times the value. Where the preceding approach was not possible, we refer to the published error estimates of the original authors.

Accuracy

Accuracy estimates were based on assessments of experimental details including method of measurements, techniques, analytical characterization of chemicals, and intercomparisons with results from the same and/or different laboratories. The accuracy estimates are more subjective than the estimates of precision.

For eutectic melting point data, the values are reported without limits of accuracy. This is largely because the experimental details (i.e., cooling/heating curves) are insufficient for accuracy estimates.

The various measurement techniques encountered are summarized in Table I.6. The range is considerable and shows some aspects of the complexities and diffculties in this part of the task, i.e., firming up accuracy estimates. Descriptions of experimental details, particularly for molten salts studies, may be found in recent surveys [8-13], and it is sufficient to note some particular points encountered in the present task. The most widely used techniques appear to be: Archimedean (density), maximum bubble pressure (surface tension), capillary and

oscillating sphere (viscosity), ac bridge (electrical conductance), chronopotentiometry (diffusion), drop calorimetry (heat of fusion; heat capacity), dilatometric (volume change on fusion) mass spectrometry-Knudsen cell (vapor pressure), hot wire (thermal conductivity), and heats of fusion (cryoscopic constants). The accuracy estimates based on these appear reasonably sound.

Concerning electrical conductivity, it is now apparent that the quartz capillary dipping cell technique may lead to values as much as 3-5% too high at temperatures greater than 900°C [13].

Relative to viscosity measurements, extreme care must be given to features of experimental design/technique if the damped oscillation method (oscillating sphere) is to be used with confidence. It is apparent that the recommended viscosity values for NaCl may be as much as 50% too high at 900°C, even though the technique, as conventionally used, should be capable of an accuracy better than ±5% [13].

Physical Properties Tables

Values are reported throughout on the Kelvin temperature scale with the exception of the melting point data. The Celsius scale was retained for melting points for ease of reference to source materials. Information has been included relative to two aspects that do not lend themselves readily to critical assessments, namely Corrosion and Containment, and Safety and Hazards. For these two, the information is reported simply as an annotated bibliography so as to provide ready access to the source literature.

The data status for the 157 salt systems is summarized in table I.7 in bar-graph format. An open field indicates no information found, i.e., a data gap. Some exceptions to this generalization are as follows.

The phase diagram field for one-component systems has been left open in general although the liquidus-solidus transition is known, i.e., it is characterized by a single temperature, namely the melting point temperature. When pressure - melting temperature is variant (at nominal pressures) a phase diagram has been included (e.g., sulfur).

For certain systems, such as the cryolite multi-component systems, the investigations were directed only to the properties of density, surface tension, viscosity, and conductance, largely from the viewpoints of the liquid state properties of this molten electrolyte and current efficiencies. While the open fields for the remaining properties do indicate that no information was found in these areas, the data gaps do not appear to be significant relative to the physical properties of cryolitic electrolytes for aluminum electrolysis.

It should be noted also that heats of fusion measurements for multi-component systems are meaningful normally only at points of fixed composition, such as stoichiometric compounds and/or eutectic compositions and/or minimum melting solid solutions. An open field for this property thus indicates a significant data gap if it is apparent from the liquidus-solidus equilibrium (i.e., the phase diagram) that one or more of the preceding features occur in this system.

A ready insight into the data status/data gaps for the salt systems is given from table I.7. The use of table I.3 (one-component, multi-component systems I.D. # index) together with table I.7 (data status/data gaps - systems I.D. # index) provides a useful and facile guide to the data compilations of this series [i.e., ref. 4 and present work].

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Table I.1. Criteria for the selection of candidate materials

A. (For thermal energy storage systems (PCM)[a] and for electrochemical energy storage (ESB)[b]

1. Thermodynamic properties	2. Chemical properties
(i) suitable melting point	(i) safety
(ii) high heat of fusion	(ii) stability
(iii) congruent melting	(iii) non-corrosive to container materials
(iv) small volume change on melting	
(v) high thermal conductivity	
(vi) heat capacity	
(vii) density	3. Economy
(viii) surface tension	(i) inexpensive
	(ii) availability

B. Additional considerations for electrochemical energy storage (ESB)

(i) electrical conductivity	(iv) cryoscopic constant
(ii) diffusion constants for ions	(v) emf series of metals
(iii) transport number for ions	(vi) reference electrodes
(vii) thermodynamic activity coefficients	

[a](PCM); phase-change materials; [b](ESB); electrochemical storage batteries

Table I.2. Likely candidates list (salt systems)

A. Systems utilizing single salts (I.IIa and I.IIb)		
I. Cations	II. Anions	
	a	b
lithium	chloride	bromides
sodium	nitrates	iodides
potassium	carbonates	sulfates
magnesium	polysulfides	phosphates
calcium	fluorides	thiocyanates
barium	hydroxides	vanadates
	nitrites	borates
	sulfides	tungstates
		chromates
		formates
		acetates

B. Systems utilizing mixtures of salts
(a) Eutectics (2 or more salts from I.IIa)
(b) Eutectics (2 or more salts from I.IIb)
(c) Eutectics (2 or more salts from I.IIa, I.IIb)

C. Systems utilizing salt hydrates
Congruently melting salts with water of hydration

Table I.3. List of candidate salt systems

[The underscored system numbers identify the systems that were in the first list of candidates (see: ref.[5]); the system numbers not underscored identify the systems in the second list of candidates (i.e., this work)]

Al	
$AlCl_3$	9
- KCl	31
- LiCl	29
- NaCl	30
- NaCl-KCl	36
AlF_3	53
- KF	86
- LiF	81
- Na_3AlF_6	135
- Na_3AlF_6-Al_2O_3	154
- NaF	85
Al_2O_3	
- K_3AlF_6	140
- Li_3AlF_6	141
- Na_3AlF_6	139
- Na_3AlF_6-AlF_3	154
- Na_3AlF_6-CaF_2	153
- Na_3AlF_6-Li_3AlF_6	156
- Na_3AlF_6-LiF	152
- Na_3AlF_6-NaCl	155
- Na_3AlF_6-SiO_2	157
Al_2S_3	64
B	
B_2O_3-Na_3AlF_6	138
Ba	
$BaCl_2$	54
- $CaCl_2$	100
- KCl	94
- LiCl	89
- $MgCl_2$	98
- Na_3AlF_6	139
- NaCl	91
BaF_2	52
- LiF	80
- Na_3AlF_6	134
- NaF	84
Be	
BeF_2	
- Na_3AlF_6	131
Ca	
$CaCl_2$	8
- $BaCl_2$	100
- KCl	93
- KCl-$MgCl_2$	99
- KCl-NaCl	95
- LiCl-KCl	37
- $MgCl_2$	97
- NaCl	32
CaF_2	51
- LiF	79
- Na_3AlF_6	133
- Na_3AlF_6-Al_2O_3	153
- NaF	83
$Ca(NO_3)_2$	72
- $NaNO_3$	103
K	
K_3AlF_6	67
- Al_2O_3	140
K_2CO_3	12
- KCl	120
- KOH	126
- Li_2CO_3	43
- Li_2SO_4	127
- Na_2CO_3	44
- Na_2CO_3-$LiCO_3$	41
- NaCl	114
KCl	6
- $AlCl_3$	31
- $BaCl_2$	94
- $CaCl_2$	93
- K_2CO_3	120
- K_2SO_4	121
- LiCl	27
- LiCl-$CaCl_2$	37
- $MgCl_2$	92
- $MgCl_2$-$CaCl_2$	99
- Na_2CO_3	119
- NaCl	28
- NaCl-$AlCl_3$	36
- NaCl-$CaCl_2$	95
- NaCl-LiCl	38
- NaCl-$MgCl_2$	147
KF	3
- AlF_3	86
- LiF	77
- Na_3AlF_6	130

Table I.3. List of candidate salt systems - Continued

Table I.3. List of candidate salt systems - Continued

Table I.3. List of candidate salt systems - Continued

Na_2S_2	21	S		Si	
Na_2S_3	22	Sulfur	19	SiO_2	
Na_2S_4	23	- K_2S_x	150	- Na_3AlF_6-Al_2O_3	157
Na_2S_5	24	- Li_2S_x	149		
Na_2S_x [Na_2S-Sulfur]	33	- Na_2S_x	33		
Na_2SO_4	17				
- K_2SO_4-Li_2SO_4	48				
- NaCl	117				

Table I.4. Fundamental constants

Symbol	Name	Values
N_A	Avogadro constant	$6.022045\ (31) \times 10^{23} mol^{-1}$
F	Faraday constant	$9.648456\ (27) \times 10^{4}\ C\ mol^{-1}$
e	Electron charge	$1.6021892\ (46) \times 10^{-19}\ C$
R	Gas constant	$8.31441\ (26)\ J\ K^{-1} mol^{-1}$ $1.98719\ (6)\ cal\ K^{-1} mol^{-1}$

Fundamental constants from: CODATA Bulletin No. 11 (Dec. 1973)

In each case the digits in parentheses following a numerical value represent the standard deviation of that value in the decimal places indicated for its final digits

Table I.5. Symbols and units

Symbol	Physical quantity	Units
a	Thermodynamically defined activity	dimensionless
A	Pre-exponential factor	as in text
C	Concentration	mol %
C_p	Heat capacity	cal $K^{-1}mol^{-1}$
D	Diffusion coefficient	cm^2s^{-1}
E	Energy of activation	cal mol^{-1}
ΔH_f°	Heat of fusion	kcal mol^{-1}
k_f	Cryoscopic constant	K mol^{-1} kg^{-1}
K_d	Equilibrium dissociation constant	atm
M_1	Apparent molecular weight	g mol^{-1}
p_{vap}	Vapor pressure	mm Hg
t	Temperature (Celsius)	°C
T	Temperature (Kelvin)	K
T_m	Melting temperature	°C
T_o	Ideal glass transition temperature	K
V_s	Molar volume of solid	cm^3mol^{-1}
ΔV_f	Change in molar volume on fusion	cm^3mol^{-1}
$(\Delta V_f/V_s)\%$	Percent molar volume change	dimensionless
X	Mol fraction	dimensionless
γ	Surface tension	dyn cm^{-1}
η	Viscosity	cp or poise
κ	Electrical conductance	ohm^{-1} cm^{-1}
λ	Thermal conductivity	cal $cm^{-1}s^{-1}K^{-1}$
ρ	Density	g cm^{-3}

For conversion between SI and other units:

1 mN s m^{-2} = 1 cp = 1 mPa s

1 mN m^{-1} = 1 dyn cm^{-1}

4.184 J mol^{-1} = 1 cal mol^{-1}

133.3 Pa = 1 torr = 1 mm Hg

For conversion of thermal conductivity:

to:	multiply by:
mW $m^{-1}K^{-1}$	4.184×10^5
W $m^{-1}K^{-1}$	4.184×10^2
J $cm^{-1}s^{-1}K^{-1}$	4.184
kcal $m^{-1}hr^{-1}K^{-1}$	3.600×10^2
BTU $ft^{-1}hr^{-1}F^{-1}$	2.419×10^2

Table I.6. High temperature experimental techniques

Density	Cryoscopic constants	Thermal conductivity (liquid, solid)
Archimedean	freezing point lowering (dilute solution)	hot wire - absolute and
dilatometric	freezing point depression (phase-rule)	modified hot wire
flotation	from heats of fusion	concentric cylinder - absolute and transient
maximum bubble		optical plane - absolute and transient
pycnometric	**Vapor pressure**	radial heat flux
Surface tension	manometry (sickle or spoon gauge)	linear heat flux
maximum bubble	dew point	flat plate - steady state
Wilhelmy slide plate	boiling/reduced pressure	comparative method
pin detachment	vapor transpiration	others
capillary rise	Knudsen effusion	
sessile bubble	Mass spectrometry and Knudsen effusion	**Diffusion**
pendant drop		chronopotentiometry
Viscosity	**Heat of fusion**	linear sweep voltammetry
capillary	**Heat capacity**	dc polarography
oscillating sphere	isothermal calorimetry	oscillographic polarography
oscillating cylinder	drop calorimetry	faradaic impedance
falling sphere	differential-scanning calorimetry (DSC)	chronoamperometry
	phase-rule (freezing point data)	rotating disc electrode
Electrical conductance	solution calorimetry	porous frit
dc bridge		electrophoresis
ac bridge	**Volume change on melting**	wave-front interferometry
transformer bridge	gas manometry	capillary
	dilatometric	
	pellet expansivity	

Table I.7

Molten Salts Candidate Systems

DATA STATUS SUMMARY

Data Available

Data Gap

	ID-No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	SYSTEM	LiF	NaF	KF	LiCl	NaCl	KCl	$MgCl_2$	$CaCl_2$	$AlCl_3$	Li_2CO_3	Na_2CO_3	K_2CO_3	$LiNO_3$	$NaNO_3$	KNO_3	Li_2SO_4	Na_2SO_4	K_2SO_4	Sulfur	Na_2S	Na_2S_2	Na_2S_3	Na_2S_4
1.	Melting temperature																							
2.	Phase diagram (liquidus-solidus)																							
3.	Density (melt)																							
4.	Surface Tension																							
5.	Viscosity																							
6.	Electrical Conductivity																							
7.	Corrosion and containment																							
8.	Safety and Hazards																							
9.	Diffusion constants for ions																							
10.	Heat of fusion																							
11.	Heat capacity (constant pressure)																							
12.	Volume change on fusion (percent)																							
13.	Vapor pressure																							
14.	Thermal conductivity (melt)																							
15.	Thermal conductivity																							
16.	Cryoscopic constant																							

continued

Table I.7 - continued

Molten Salts Candidate Systems

DATA STATUS SUMMARY

Data Available

Data Gap

	ID-No.	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
	SYSTEM	Na_2S_5	LiBr	LiI	LiCl-KCl	NaCl-KCl	LiCl-$AlCl_3$	NaCl-$AlCl_3$	KCl-$AlCl_3$	NaCl-$CaCl_2$	Na_2S_x	NaF-KF	LiF-LiCl	NaCl-KCl-$AlCl_3$	LiCl-KCl-$CaCl_2$	LiCl-NaCl-KCl	LiF-LiCl-LiBr	LiF-LiCl-LiI	Li_2CO_3-Na_2CO_3-K_2CO_3	Li_2CO_3-Na_2CO_3	Li_2CO_3-K_2CO_3	Na_2CO_3-K_2CO_3	$NaNO_3$-KNO_3	$LiNO_3$-$NaNO_3$-KNO_3
1.	Melting temperature																							
2.	Phase diagram (liquidus-solidus)																							
3.	Density (melt)																							
4.	Surface Tension																							
5.	Viscosity																							
6.	Electrical Conductivity																							
7.	Corrosion and containment																							
8.	Safety and Hazards																							
9.	Diffusion constants for Ions																							
10.	Heat of fusion																							
11.	Heat capacity (constant pressure)																							
12.	Volume change on fusion (percent)																							
13.	Vapor pressure																							
14.	Thermal conductivity (melt)																							
15.	Thermal conductivity																							
16.	Cryoscopic constant																							

continued

Table I.7 - continued

Molten Salts Candidate Systems

DATA STATUS SUMMARY

Data Available

Data Gap

	ID-No.	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69
	SYSTEM	Li_2SO_4-K_2SO_4	Li_2SO_4-Na_2SO_4-K_2SO_4 NaCl-Li_2SO_4		MgF_2	CaF_2	BaF_2	AlF_3	$BaCl_2$	Li_2S	Li_2S_2	Li_2S_4	K_2S	K_2S_2	K_2S_3	K_2S_4	K_2S_5	K_2S_6	Al_2S_3	Li_3AlF_6	Na_3AlF_6	K_3AlF_6	LiOH	NaOH
1.	Melting temperature																	•						
2.	Phase diagram (liquidus-solidus)																							
3.	Density (melt)																							
4.	Surface Tension																							
5.	Viscosity																							
6.	Electrical Conductivity																							
7.	Corrosion and containment																							
8.	Safety and Hazards																							
9.	Diffusion constants for ions																							
10.	Heat of fusion																							
11.	Heat capacity (constant pressure)																							
12.	Volume change on fusion (percent)																							
13.	Vapor pressure																							
14.	Thermal conductivity (melt)																							
15.	Thermal conductivity																							
16.	Cryoscopic constant																							

continued

Table I.7 - continued

Molten Salts Candidate Systems

DATA STATUS SUMMARY

Data Available

Data Gap

	ID-No.	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92
	SYSTEM	KOH	$Mg(NO_3)_2$	$Ca(NO_3)_2$	$LiNO_2$	$NaNO_2$	KNO_2	LiF-NaF	LiF-KF	LiF-NaF-KF	$LiF-CaF_2$	$LiF-BaF_2$	$LiF-AlF_3$	$NaF-MgF_2$	$NaF-CaF_2$	$NaF-BaF_2$	$NaF-AlF_3$	$KF-AlF_3$	LiCl-NaCl	$LiCl-MgCl_2$	$LiCl-BaCl_2$	$NaCl-MgCl_2$	$NaCl-BaCl_2$	$KCl-MgCl_2$
1.	Melting temperature																							
2.	Phase diagram (liquidus-solidus)																							
3.	Density (melt)																							
4.	Surface Tension																							
5.	Viscosity																							
6.	Electrical Conductivity																							
7.	Corrosion and containment																							
8.	Safety and Hazards																							
9.	Diffusion constants for ions																							
10.	Heat of fusion																							
11.	Heat capacity (constant pressure)																							
12.	Volume change on fusion (percent)																							
13.	Vapor pressure																							
14.	Thermal conductivity (melt)																							
15.	Thermal conductivity																							
16.	Cryoscopic constant																							

continued

Table I.7 - continued

Molten Salts Candidate Systems

DATA STATUS SUMMARY

Data Available

Data Gap

	ID. No.	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115
	SYSTEM	$KCl-CaCl_2$	$KCl-BaCl_2$	$KCl-NaCl-CaCl_2$	$KCl-NaCl-MgCl_2$	$MgCl_2-CaCl_2$	$MgCl_2-BaCl_2$	$KCl-MgCl_2-CaCl_2$	$CaCl_2-BaCl_2$	$LiNO_3-NaNO_3$	$LiNO_3-KNO_3$	$NaNO_3-Ca(NO_3)_2$	$KNO_3-Mg(NO_3)_2$	$LiNO_2-NaNO_2$	$NaNO_2-KNO_2$	NaOH-KOH	$Na_3AlF_6-Li_3AlF_6$	LiF-LiOH	LiCl-LiOH	$LiCl-LiNO_3$	$LiCl-Li_2CO_3$	$NaCl-Na_2CO_3$	$NaCl-K_2CO_3$	NaCl-NaOH
1.	Melting temperature																							
2.	Phase diagram (liquidus-solidus)																							
3.	Density (melt)																							
4.	Surface Tension																							
5.	Viscosity																							
6.	Electrical Conductivity																							
7.	Corrosion and containment																							
8.	Safety and Hazards																							
9.	Diffusion constants for ions																							
10.	Heat of fusion																							
11.	Heat capacity (constant pressure)																							
12.	Volume change on fusion (percent)																							
13.	Vapor pressure																							
14.	Thermal conductivity (melt)																							
15.	Thermal conductivity																							
16.	Cryoscopic constant																							

continued

Table I.7 - continued

Molten Salts Candidate Systems

DATA STATUS SUMMARY

Data Available

Data Gap

	ID-No.	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138
	SYSTEM	$NaCl-NaNO_3$	$NaCl-Na_2SO_4$	$NaCl-K_2SO_4$	$KCl-Na_2CO_3$	$KCl-K_2CO_3$	$KCl-K_2SO_4$	Li_2CO_3-LiOH	$Li_2CO_3-Li_2SO_4$	$Li_2CO_3-K_2SO_4$	Na_2CO_3-NaOH	K_2CO_3-KOH	$K_2CO_3-Li_2SO_4$	Na_3AlF_6-LiF	Na_3AlF_6-NaF	Na_3AlF_6-KF	$Na_3AlF_6-BeF_2$	$Na_3AlF_6-MgF_2$	$Na_3AlF_6-CaF_2$	$Na_3AlF_6-BaF_2$	$Na_3AlF_6-AlF_3$	Na_3AlF_6-NaCl	$Na_3AlF_6-BaCl_2$	$Na_3AlF_6-B_2O_3$
1.	Melting temperature																							
2.	Phase diagram (liquidus-solidus)																							
3.	Density (melt)																							
4.	Surface Tension																							
5.	Viscosity																							
6.	Electrical Conductivity																							
7.	Corrosion and containment																							
8.	Safety and Hazards																							
9.	Diffusion constants for ions																							
10.	Heat of fusion																							
11.	Heat capacity (constant pressure)																							
12.	Volume change on fusion (percent)																							
13.	Vapor pressure																							
14.	Thermal conductivity (melt)																							
15.	Thermal conductivity																							
16.	Cryoscopic constant																							

continued

Table I.7 - continued

Molten Salts Candidate Systems

DATA STATUS SUMMARY

Data Available

Data Gap

	ID-No.	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161
	SYSTEM	Na_3AlF_6-Al_2O_3	K_3AlF_6-Al_2O_3	Li_3AlF_6-Al_2O_3	LiOH-$LiNO_3$	NaOH-$NaNO_3$	KOH-KNO_3	$NaNO_3$-$NaNO_2$	$NaNO_3$-KNO_2	KNO_3-$NaNO_2$	$NaNO_3$-KNO_3-$NaNO_2$	Li_2S-Sulfur	K_2S-Sulfur	Na_2CO_3-NaOH-NaCl	Na_3AlF_6-Al_2O_3-LiF	Na_3AlF_6-Al_2O_3-CaF_2	Na_3AlF_6-Al_2O_3-AlF_3	Na_3AlF_6-Al_2O_3-NaCl	Na_3AlF_6-Al_2O_3-Li_3AlF_6	Na_3AlF_6-Al_2O_3-SiO_2				
1.	Melting temperature																							
2.	Phase diagram (liquidus-solidus)																							
3.	Density (melt)																							
4.	Surface Tension																							
5.	Viscosity																							
6.	Electrical Conductivity																							
7.	Corrosion and containment																							
8.	Safety and Hazards																							
9.	Diffusion constants for ions																							
10.	Heat of fusion																							
11.	Heat capacity (constant pressure)																							
12.	Volume change on fusion (percent)																							
13.	Vapor pressure																							
14.	Thermal conductivity (melt)																							
15.	Thermal conductivity																							
16.	Cryoscopic constant																							

System 50 MgF_2

1. *Melting Temperature (T_m)*

Melting point:
1263° ± 5°C

References [1-8].

2. *Density (ρ)*

Measurement method: Archimedean technique [9]

$$\rho = 3.235 - 5.24 \times 10^{-4} T \quad (50.1)$$

precision: not estimated uncertainty: ∿ ± 1.0%

Table 50.1. Density from equation (50.1)

T (K)	ρ ($g\ cm^{-3}$)	T (K)	ρ ($g\ cm^{-3}$)
1650	2.370	1900	2.239
1700	2.344	1950	2.213
1750	2.318	2000	2.187
1800	2.292	2050	2.161
1850	2.266	2100	2.135

References [9]

3. *Surface Tension (γ)*

No Data

4. *Viscosity (η)*

No Data

5. *Electrical Conductance (κ)*

No Data

(50) MgF_2

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritants

(ii) Vapor pressure: at m.pt, 1263°C, < 0.5 mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [10-15].

7. Corrosion

Table 50.2. Corrosion studies from primary research literature

Studies (various molten fluorides)	References
Cr	[20]
Ni-Cr-Fe	[18,21]
INOR-8	[18,22-24]
Al	[25,26]
Ni-Mo-Cr-Fe (Hastelloy)	[19]
Inconel	[24]
Corrosion: molten fluorides (survey)	[28-30]
Electro-chemical behaviour of oxide ions and related species in molten fluorides	[31]
Electro-analytical studies in molten fluorides	[16]
Annotated corrosion biblio.	[27,17]

For studies specific to molten MgF_2, see [27,17]. For thermodynamic (theoretical) considerations, and some considerations of impurities in the melts, and "gettering" techniques, see [17].

References [16-31]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

Measurement method: drop calorimetry [32]

Table 50.3. Heat of fusion

ΔH_f° (kcal mol^{-1})	Uncertainty
13.8	∿ ± 2%

References [32-34]

10. Heat Capacity (C_p)

Measurement method: drop calorimetry [39,40]

Table 50.4. Heat capacity

MgF_2	C_p (cal K^{-1} mol^{-1})	T range (K)	Uncertainty
ℓ	22.57	1536-1800	*
c	(a)	298-1536	*

* Insufficient data for estimate

$$^{(a)}C_p = 16.93 + 2.52 \times 10^{-3}T - 2.20 \times 10^{-5}T^{-2} \quad (50.2)$$

References [35-40]

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [41]

Table 50.5. Volume change on melting

$(\Delta V_f/V_s)$	Uncertainty
14.0%	∿ ± 8%

References [41]

12. *Vapor Pressure (p_{vap})*

Measurement methods: cited in table (50.6)

Table 50.6. Vapor pressure, measurements, techniques, and uncertainties

Vapor Pressure Measurements		T range	uncertainty (in
Ref.	Technique	(K)	vapor pressures)
[42,43]	Knudsen effusion, and torsion-effusion(a)	1413-1614(b)	∿ ± 3%
[41]	estimated from data base	1600-1940	∿ ± 15%
[44]	boiling pt - dynamic method	1930-2130	∿ ± 5%

(a) torsion-effusion data set selected as recommended data base for this temperature range

(b) melting point of MgF_2 is 1536 K

Equation:

$$\log p(mm) = A + B/T \quad (50.3)$$

precision: in table 50.7 uncertainty: in table 50.6

Table 50.7. Parameters of equation (50.3) and precisions

Equation	T range(K)	A	-B	Precision
[50.3 A]	1536-1614	9.6164	16488.0	∿ 6.4%
[50.3 B]	1600-1940	9.5296	16410.8	∿ 20%
[50.3 C]	1930-2130	9.6899	16762.3	∿ 15%

*for MgF_2 (solid) in the range 1410 to the m.pt (1536 K), the vapor pressure may be expressed by: log p(mm) = 12.002 - 20,1443/T (50.4); estimated precision and uncertainty are, ∿ ± 14% and ∿ ± 3%, respectively.

Table 50.8. Vapor pressure from equations in table 50.7

T (K)	p (mm)	T (K)	p (mm)
1536	0.076	1930	10.11
1540	0.081	1940	11.21
1560	0.111	1960	13.73
1580	0.152	1980	16.75
1600	0.205	2000	20.36
1610	0.237	2020	24.65
- - - -	- - - - -	2040	29.72
1620	0.25	2060	35.71
1650	0.38	2080	42.77
1700	0.75	2100	51.03
1750	1.42	2120	60.70
1800	2.59	2130	66.10
1850	4.56		
1900	7.80	2533	760
1920	9.601		

References [41-46]

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f° [41]

Table 50.9. Cryoscopic constant

k_f (K mol^{-1} kg)	Uncertainty
21.2	$\sim \pm$ 1%

References [41]

16. References

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System 51 CaF_2

1. *Melting Temperature (T_m)*

Melting point:
1418° ± 5°C [7]

References [1-8].

2. *Density (ρ)*

Measurement method: Archimedean technique [9]

$$\rho = 3.179 - 3.91 \times 10^{-4} T \quad (51.1)$$

precision: not estimated uncertainty: ∿ ± 1%

Table 51.1. Density from equation (51.1)

T (K)	ρ (g cm^{-3})	T (K)	ρ (g cm^{-3})
1650	2.534	2000	2.397
1700	2.514	2050	2.377
1750	2.495	2100	2.358
1800	2.475	2150	2.338
1850	2.456	2200	2.319
1900	2.436	2250	2.299
1950	2.417	2300	2.280

References [9,10]

3. *Surface Tension (γ)*

No Data

4. *Viscosity (η)*

No Data

5. *Electrical Conductance (κ)*

No Data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritants and toxic.

(ii) Vapor pressure: at m.pt., 1418°C, ∿ < 0.5 mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [11-16]

7. Corrosion

Corrosion studies from primary research literature

Studies	References
Cr	[17]
Ni-Cr-Fe	[18,19]
INOR-8	[19-22]
Al	[23,24]
Ni-Mo-Cr-Fe (Hastelloy)	[25]
Inconel	[22,26]
Corrosion: molten fluorides (survey)	[32,26]
Electro-chemical behaviour of oxide ions and related species in molten fluorides	[27-29]
Electro-analytical studies in molten fluorides	[30]
Annotated corrosion biblio.	[32]

For studies specific to molten CaF_2, see [26,32] . For thermodynamic (theroteical) considerations, and some considerations of impurities in the melts, and "gettering" techniques, see [32]

References [17-32]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

Measurement method: drop calorimetry [34]

Table 51.3. Heat of fusion

ΔH_f° (kcal mol^{-1})	Uncertainty
7.09	$\sim \pm$ 2%

CaF_2 (m.pt. 1414°C exhibits a solid-state transition at 1151°C, for which ΔH = 1.14 $\pm$ kcal mol^{-1}

References [33-35]

10. Heat Capacity (C_p)

Measurement method: drop calorimetry [36,38]

Table 51.4. Heat capacity

CaF_2	C_p (cal K^{-1} mol^{-1})	T range (K)	Uncertainty
c	(a)	293-1490	*
ℓ	23.91	1691-∿1791	*

(a) $C_p = 14.5610 + 8.4667 \times 10^{-3} T$ (51.2)

* Insufficient data for estimate

References [36-39]

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [40]

Table 51.5. Volume change on melting

$(\Delta V_f / V_s)$	Uncertainty
8.0%	∿ ± 10%

References [40]

12. Vapor Pressure (p_{vap})

Measurement method: cited in table 51.6

Table 51.6. Vapor pressure measurements, techniques, and uncertainties

Vapor pressure measurements		T range	Uncertainty (in
Ref.	Technique	(K)	vapor pressures)
[41]	torsion-effusion	1400-1850*	∿ ± 3%
[40]	established from data base		∿ ± 20%
[42]	boiling pt(dynamic)	2086-2210	∿ ± 5%

*melting point of CaF_2 is 1691 K

Equation: $\log p(\text{mm}) = A + B/T$ (51.3)

precision: in table 51.7 uncertainty: in table 51.7

Table 51.7. Parameters of equation (51.3) and precisions

Equation	T range(K)	A	-B	Precision
(51.3.A)	1691-1850(a)	11.709	21,708	∿ 3.4%
(51.3.B)	1840-2100	8.8853	16,738	∿ 20%
(51.3.C)	2086-2210	9.3648	17,833	∿ 6.7%

(a) for CaF_2 (solid) in the range 1400 to the m.pt. (1691 K), the vapor pressure may be expressed by: log p(mm) = 11.175-18,936/T(51.4); estimated precisions and uncertainties are ∿ ± 16% and ∿ ± 3% respectively.

Table 51.8. Vapor pressure from equation (51.3) in table 51.7

T (K)	p (mm)	T (K)	p (mm)
1691	0.074	1980	2.725
1700	0.087	2020	4.005
1720	0.123	2060	5.800
1740	0.171	---	---
1760	0.237	2090	6.796
1780	0.326	2110	8.187
1800	0.446	2130	9.829
1820	0.605	2150	11.76
1840	0.815	2170	14.02
---	---	2190	16.67
1870	0.867	2210	19.75
1900	1.201		
1940	1.824	2786	760

References [40-42]

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

Measurement method: comparative technique: modified parallel plate assembly [43]

$$\lambda = 8.8152 \times 10^{-2} - 0.3763 \times 10^{-3} T + 0.5331 \times 10^{-6} T^2 \quad (51.5)$$

precision; not estimated uncertainty; ∿ ± 10%

Table 51.9. Thermal conductivity of solid from equation (51.4)

T (K)	$\lambda \times 10^3$ (cal cm^{-1} s^{-1} K^{-1})	T (K)	$\lambda \times 10^3$ (cal cm^{-1} s^{-1} K^{-1})
270	0.0254	320	0.0223
280	0.0246	330	0.0220
290	0.0239	340	0.0218
300	0.0232	350	0.0218
310	0.0227	360	0.0218

The values reported by Charvat and Kingery [46] for polycrystalline calcium fluoride are about half as large.

References [43-52]

(51) CaF_2

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f° [40]

Table 51.10. Cryoscopic constant

k_f (K mol^{-1} kg)	Uncertainty
62.6	$\sim \pm$ 1%

References [40]

16. References

[1] Stull, D. R., and Prophet, H., *"JANAF Thermochemical Tables"*, 2nd Ed., NSRDS-NBS 37; U. S. Gov't Printing Office, Washington, D. C. (1971).

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[13] Vapor pressure, estimated; Janz, G. J. et al. (MSDC-RPI, 1980)

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System (52) BaF_2

1. *Melting Temperature (T_m)*

Melting point:
1320° ± 5°C [1]

References [1-8].

2. *Density (ρ)*

Measurement method: Archimedean technique [9,10]

$$\rho = 5.775 - 0.999 \times 10^{-3} T \quad (52.1)$$

precision: not estimated uncertainty: ∿ ± 1%

Table 52.1. Density from equation (52.1)

T (K)	ρ ($g\ cm^{-3}$)	T (K)	ρ ($g\ cm^{-3}$)
1600	4.177	1850	3.927
1650	4.127	1900	3.877
1700	4.077	1950	3.827
1750	4.027	2000	3.777
1800	3.977		

References [9,10]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritants and toxic.

(ii) Vapor pressure: at m.pt., 1320°C, ∿ < 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [11-16].

7. Corrosion

Table 52.2. Corrosion studies from primary research literature

Studies	References
Cr	[17]
Ni-Cr-Fe	[18,19]
INOR-8	[19-22]
Al	[23,24]
Ni-Mo-Cr-Fe (Hastelloy)	[25]
Inconel	[22,26]
Corrosion: molten fluorides (survey)	[26,32]
Electro-chemical behaviour of oxide ions and related species in molten fluorides	[27-29]
Electro-analytical studies in molten fluorides	[30]
Annotated corrosion biblio.	[31]

No studies specific to molten BaF_2 were found. For thermodynamic (theoretical) considerations, and some considerations of impurities in the melts, and "gettering" techniques, see [32].

References [17-32]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

Measurement method: drop calorimetry [34]

able 52.3. Heat of fusion

ΔH_f° (kcal mol^{-1})	Uncertainty
3.03	$\sim \pm$ 2%

References [33-37]

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [38]

Table 52.4. Volume change on melting

$(\Delta V_f/V_s)$	Uncertainty
1%	$\sim \pm$ 10%

References [38]

12. Vapor Pressure (p_{vap})

Measurement methods: dynamic boiling point technique [39]

$$\log p = 10.2506 - 17{,}910/T \quad (52.2)$$

precision: $\sim \pm$ 5% uncertainty: $\sim \pm$ 5%

Table 52.5. Vapor pressure from equation (52.2)

T (K)	p (mm)	T (K)	p (mm)
1960	12.97	2120	63.46
1980	16.04	2140	76.11
2000	19.75	2160	90.98
2020	24.23	2180	108.4
2040	29.59	2200	128.7
2060	36.01	- - -	- - - -
2080	43.65		
2100	52.73	2533	760

References [39]

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

Measurement method: comparative technique: modified parallel plate assembly [40]

$$\lambda = 0.1257 - 0.5831 \times 10^{-3}T + 0.8421 \times 10^{-6}T^2 \quad (52.3)$$

precision: not estimated uncertainty: $\sim \pm$ 10%

Table 52.6. Thermal conductivity of solid from equation (52.3)

T (K)	$\lambda \times 10^3$ (cal cm^{-1} s^{-1} K^{-1})	T (K)	$\lambda \times 10^3$ (cal cm^{-1} s^{-1} K^{-1})
270	29.7	330	25.0
280	28.5	340	24.8
290	27.4	350	24.8
300	26.5	360	24.9
310	25.9	370	25.2
320	25.3		

References [40-44]

(52) BaF_2

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f° [38]

Table 52.7. Cryoscopic constant

k_f (K $mol^{-1}kg$)	Uncertainty
292	∿ ± 1%

References [38]

16. References

[1] Stull, D. R., and Prophet, H., *"JANAF Thermochemical Tables"*, 2nd Ed., NSRDS-NBS 37; U. S. Gov't Printing Office, Washington, D. C. (1971).

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System 53 AlF_3

1. *Melting Temperature (T_m)*

Melting point:
does not melt; sublimes with 1 atm equil^m press. at ∿ 1255°C [9,66,68,71]; by extrapolating high pressure data, a triple point of 2250°C at 30,000 atm is predicted [69,74]

References [1-9,66,68,69,71,74]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure: m.pt., 1272°C; sublimes at ∿ 1257°C.

B. Disaster hazards

(i) Molten salt bath "explosion": i.e., explosive generation of steam due to bulk water "carry-over: and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [10-14]

7. Corrosion

Table 53.1. Corrosion studies from primary research literature

	Studies	References
A	Cr	[15]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[16,17]
	SSNI-12P	[18]
	Quartz	[19]
	Al	[20]
	Various metals	[21]
B	Pt	[22-26]
	Boron nitride, carbon, Inconel	[27-29]
	Fused MgO	[30]
C	Impurities in electrolyte	[31,32]
	Graphite	[31,32]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[33-35]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[36-51,58,59]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[52-54]
	Electroanalytical studies in molten fluorides	[55]
	Annotated corrosion biblio.	[56]
	Corrosion: molten fluorides (survey)	[57]

A: studies principally in molten NaF, KF, and LiF; no results reported specifically for molten AlF_3; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys

References [15-59]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

Measurement method: heat of solution calorimetry [70]

Table 53.2. Heat of fusion

Phase transition	T (K)	ΔH° (kcal mol^{-1})	Uncertainty
$AlF_3(s)(\alpha\rightarrow\beta)$*	718	0.16	∿ ± 1%
AlF_3 (fusion)	**	26.5	∿ ± 8%

* there appears some evidence for a second solid state transition at ∿ 1330°C [69]

** the heat of fusion value is gained from heat of solution calorimetry for $AlF_3(s)$ in molten alkali fluorides and ZnF_2 at 1025°C by extrapolation to $X_{AlF_3} = 1.0$ [70]

References [60-63,70]

10. Heat Capacity (C_p)

Measurement method: drop calorimetry [60,61]

Table 53.3. Heat capacity

AlF_3 phase	C_p (cal K^{-1} mol^{-1})	T range (K)	Uncertainty
$AlF_3(s,\alpha)$	(a)	298.1 - 718	∿ ± 1%
$AlF_3(s,\beta)$	(b)	714 - 1400	∿ ± 1%
AlF_3(liquid)	no data	1845 -	

The values in Table 53.3 are based on the calorimetric measurements of O'Brien and Kelley [60] corrected by Frank [61] for errors in temperature measurements.

(a) $C_{ps(\alpha)} = 17.152 + 1.189 \times 10^{-2}T - 1.953 \times 10^{-5}T^{-2}$ (53.1)

(b) $C_{ps(\beta)} = 21.227 + 3.26 \times 10^{-3}T$ (53.2)

References [60,61,64]

11. Volume Change on Melting (ΔV_f)

No data

12. *Vapor Pressure (p_{vap})*

Does not melt; sublimes with 1 atm equil^m press. at ∿ 1255°C [9,66,68,71]; by extrapolating high pressure data, a triple point at ∿ 2250°C and ∿ 30,000 atm is predicted [69].

Molten State: No data.

Table 53.4. Vapor pressure measurements for solid AlF_3

Vapor pressure measurements		T range	log p(atm) = A + B/T	
Ref.	Technique	(K)	A	-B
[71]	*	980-1613	11,433	17,109
[68]	high press. tech.	1550-1900	11,370	17,391

*cited in [71] as merge of Knudsen effusion technique data set for 980-1123K [72], and static equil^m manometric technique data set for 1314-1613K [73]. ΔH_{subl} = 78.2(± 0.8) kcal mol^{-1} between 980-1613K; at 298K, the value recommended is 78.0 kcal mol^{-1}. For additional related studies, see [71], pp. 225-229.

References [65-67,71-74]

13. *Thermal Conductivity (liquid) (λ_ℓ)*

No data

14. *Thermal Conductivity (solid) (λ_s)*

No data

15. *Cryoscopic Constant (k_f)*

No data

16. *References*

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System 54 $BaCl_2$

1. *Melting Temperature (T_m)*

Melting point:
962° ± 5°C [2]

References [1-8].

2. *Density (ρ)*

Measurement method: Archimedean technique [14]

$$\rho = 4.0152 - 0.6813 \times 10^{-3} T \quad (54.1)$$

precision: not estimated uncertainty: ∿ ± 5.0%

Table 54.1. Density from equation (54.1)

T (K)	ρ (g cm^{-3})	T (K)	ρ (g cm^{-3})
1240	3.170	1310	3.123
1250	3.164	1320	3.116
1260	3.157	1330	3.109
1270	3.150	1340	3.102
1280	3.143	1350	3.095
1290	3.136	1360	3.089
1300	3.130	1370	3.082

References [9-23]

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure [12]

$$\gamma = 263.2 - 0.0790\ T \quad (54.2)$$

precision: not estimated uncertainty: ∿ ± 2.0%

able 54.2. Surface tension from equation (54.2)

T (K)	γ (dyn cm^{-1})	T (K)	γ (dyn cm^{-1})
1240	165.2	1280	162.1
1250	164.5	1290	161.3
1260	163.7	1300	160.5
1270	162.9	1310	159.7

References [12,21,24-26]

4. *Viscosity* (η)

Measurement method: oscillating sphere [28]

$$\eta = 53.203\text{-}65.230 \times 10^{-3}T + 20.696 \times 10^{-6}T^2 \quad (54.3)$$

precision: ∿ ± 1.5% uncertainty: ∿ ± 10%

Table 54.3. Viscosity from equation (54.3)

T (K)	η (cp)	T (K)	η (cp)
1250	4.00	1300	3.38
1260	3.87	1310	3.27
1270	3.74	1320	3.16
1280	3.62	1330	3.06
1290	3.50	1340	2.96

References [16,26-30]

5. *Electrical Conductance* (κ)

Measurement method: classical ac technique [34]

$$\kappa = 17.479 \exp(-5274/RT) \quad (54.4)$$

precision: ∿ ± 0.2% uncertainty: ∿ ± 10%

Table 54.4. Electrical conductance from equation (54.4)

T (K)	κ ($ohm^{-1}cm^{-1}$)	T (K)	κ ($ohm^{-1}cm^{-1}$)
1240	2.055	1310	2.305
1250	2.091	1320	2.341
1260	2.127	1330	2.376
1270	2.162	1340	2.412
1280	2.198	1350	2.447
1290	2.234	1360	2.483
1300	2.269		

References [11,31-34]

(54) $BaCl_2$

6. Safety and Hazards

A. Hazard rating

(i) Toxicity, soluble barium compounds; such as the chloride, toxic (oral)

(ii) Vapor pressure: at m.pt., 962°C, ∿ < 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic chloride fumes when heated to decomposition, or contacted with acids.

References [35-40]

7. Corrosion

Table 54.5. Corrosion studies from primary research literature

Studies	References
Zr	[41]
Fe, steels	[42-47]
Ti, Zr, Hf, $ThCl_4$	[48]
Pb, Pb-Bi	[49]
Electrochemical aspects	[50-51]
Thermodynamic approach	[52-54]
Corrosion in molten salts/ annotated biblio.	[55]
Reviews: Corrosion in molten salts	[56-60]

No corrosion studies specifically with molten $BaCl_2$ found; the studies above for the use of molten alkali halides and their mixtures, some containing $BaCl_2$ as one component, e.g., see [42-45,49]. For trace amounts of Li_2CO_3 in molten chlorides, see [59]

References [41-60]

(54) $BaCl_2$

8. Diffusion

Measurement method: capillary [61]

List of diffusing species investigated in $BaCl_2$ as solvent

Ba^{2+}, Cl^-

precision: ∿ ± 0.1%, Ba^{2+}, ± 0.1%, Cl^- uncertainty: ∿ ± 20%

Equation:

$$D = A \exp [-E/RT] \quad (54.5)$$

Table 54.6. Parameters of diffusion equation (54.5)

Species	A x 10^3 (cm^2 s^{-1})	E (cal mol^{-1})	Temp. range (K)
Ba^{2+}	0.64	8960	1267-1480
Cl	2.00	9480	1266-1476

Table 54.7. Self-diffusion coefficients from equations in table (54.6)

T (K)	D x 10^5 (cm^2 s^{-1})		T (K)	D x 10^5 (cm^2 s^{-1})	
	Ba^{2+}	Cl		Ba^{2+}	Cl
1270	1.84	4.67	1380	2.44	6.30
1280	1.89	4.81	1390	2.50	6.46
1290	1.94	4.95	1400	2.56	6.62
1300	1.99	5.10	1410	2.61	6.79
1310	2.05	5.24	1420	2.67	6.95
1320	2.10	5.39	1430	2.73	7.12
1330	2.16	5.54	1440	2,79	7.28
1340	2.21	5.69	1450	2.86	7.45
1350	2.27	5.84	1460	2.92	7.62
1360	2.32	5.99	1470	2.98	7.79
1370	2.38	6.15	1480	3.04	7.96

References [61,62]

9. Heat of Fusion (ΔH_f°)

Measurement method: drop calorimetry [63]

Table 54.8. Heat of fusion

ΔH_f° (kcal mol^{-1})	Uncertainty
4.0	∿ ± 2.5%

$BaCl_2$ (m.pt. 962°C) exhibits a solid state transition at 920°C and for which ΔH = 4.10 kcal mol^{-1}.

References [63-66]

(54) $BaCl_2$

10. Heat Capacity (C_p)

Measurement method: drop calorimetry [64]

Table 54.9. Heat capacity

$BaCl_2$	C_p (cal K^{-1} mol^{-1})	T range (K)	Uncertainty
c	26.61	1198-1235	∿ ± 2%
ℓ	24.96	1235-1339	∿ ± 2%

References [64,67]

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [68]

Table 54.10. Volume change on melting

$(\Delta V_f/V_s)$	Uncertainty
9.7%	∿ ± 10%

References [68]

12. Vapor Pressure (p_{vap})

Measurement method: cited in table (54.11)

Table 54.11. Vapor pressure measurements, techniques, and uncertainties

Vapor pressure measurements		T range (K)	Uncertainty (in vapor pressures)
Ref.	Method		
[69]	boiling point technique	1590-1670	∿ ± 10%
[70]	modified manometric technique (static)	1340-1490	(a)

(a) the vapor pressures appear too high (∿ x 5); this method does not appear well suited for vapor pressures < 20mm

$$\log p(mm) = 8.5616 - 13317/T \quad (54.6)$$

precision: not estimated uncertainty: in table (54.11)

Table 54.12. Vapor pressure from equation (54.6)

T (K)	p (mm)	T (K)	p (mm)
1590	1.535	1650	3.095
1600	1.732	1660	3.462
1610	1.951	1670	3.867
1620	2.194		
1630	2.464		
1640	2.764	1835(a)	760

(a) normal boiling from modified manometric (static) measurements

References [69,70]

13. Thermal Conductivity (liquid) (λ_ℓ)

Measurement method: constriction technique [71,72]

$$\lambda = -2.8590 \times 10^{-2} + 25.13 \times 10^{-6} T \quad (54.7)$$

precision: not estimated uncertainty: ∿ ± 20%

Table 54.13. Thermal conductivity of melt from equation (54.7)

T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})	T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})
1240	25.7	1280	35.8
1250	28.2	1290	38.3
1260	30.7	1300	40.8
1270	33.3		

References [71,72]

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f° [68]

Table 54.14. Cryoscopic constant

k_f (K mol^{-1} kg)	Uncertainty
158	∿ ± 1%

References [68]

16. References

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System 55 Li_2S

1. *Melting Temperature (T_m)*

Melting point:
1365° ± 10°C [15]; 1372° (+10°,-5°C) [16]
cooling curve technique[15]; visually by optical pyrometry [16].

References [1-9,15,16]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Inhalation: variable rating

- as sulfides and polysulfides, the rating is similar to sodium hydroxide
- on reaction with moisture/water, H_2S is liberated; the inhalation hazard rating for H_2S is severe; i.e., highly toxic

(ii) vapor pressure: no data

B. Disaster hazards

(i) Molten sulfides and polysulfides may react violently (explosively) with strong oxidants: H_2S evolved on contact with moisture/water can form explosive mixtures with air; H_2S, highly toxic.

(ii) Sulfides and polysulfides when heated to decomposition or contacted with water, steam, acids, produce highly toxic fumes (oxides of sulfur, H_2S). Dangerous.

References [10-14].

7. *Corrosion*

For corrosion studies, see: Li_2S_x-Sulfur (System 149)

8. *Diffusion*

No data

9. *Heat of Fusion (ΔH_f°)*

No data

10. *Heat Capacity (C_p)*

No data

11. *Volume Change on Melting (ΔV_f)*

No data

12. *Vapor Pressure (p_{vap})*

No data

13. *Thermal Conductivity (liquid) (λ_ℓ)*

No data

14. *Thermal Conductivity (solid) (λ_s)*

No data

15. *Cryoscopic Constant (k_f)*

No data

16. *References*

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System 56 Li_2S_2

1. *Melting Temperature (T_m)*

Melting point:
369° ± 1°C [7]; in two recent re-investigations of the Li-sulfur system[15,16] no evidence is found for the existence of Li_2S_2; the earlier work [7] is thus not supported.

References [1-9,15,16].

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Inhalation: variable rating

- as sulfides and polysulfides, the rating is similar to sodium hydroxide
- on reaction with moisture/water, H_2S is liberated; the inhalation hazard rating for H_2S is severe; i.e., highly toxic

(ii) vapor pressure: no data

B. Disaster hazards

(i) Molten sulfides and polysulfides may react violently (explosively) with strong oxidants: H_2S evolved on contact with moisture/water can form explosive mixtures with air; H_2S, highly toxic.

(ii) Sulfides and polysulfides when heated to decomposition, or contacted with water, steam, acids, produce highly toxic fumes (oxides of sulfur, H_2S). Dangerous.

References [10-14].

7. *Corrosion*

For corrosion studies, see: Li_2S_x-Sulfur (System 149)

8. *Diffusion*

No data

9. *Heat of Fusion (ΔH_f°)*

No data

10. *Heat Capacity (C_p)*

No data

11. *Volume Change on Melting (ΔV_f)*

No data

12. *Vapor Pressure (p_{vap})*

No data

13. *Thermal Conductivity (liquid) (λ_ℓ)*

No data

14. *Thermal Conductivity (solid) (λ_s)*

No data

15. *Cryoscopic Constant (k_f)*

No data

16. *References*

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[16] Cunningham, P. T., Johnson, S. A., and Cairns, E. J., J. Electrochem. Soc., 119, 1448 (1972).

System 57 Li_2S_4

1. *Melting Temperature (T_m)*

Melting point:
unstable (decomposes) [7]; the existence of Li_2S_4 in the Li-sulfur system is not observed in two recent and independent studies; a monotectic mixture is found at ∿ 64 ± 2 atom % sulfur, at 365° ± 4°C [15,16]

References [1-9,15,16]

2. *Density (ρ)*

See: system 149 for $Li_2S_{3.9}$

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

See: system 149 for $Li_2S_{3.9}$

6. *Safety and Hazards*

A. Hazard rating

(i) Inhalation: variable rating

- as sulfides and polysulfides, the rating is similar to sodium hydroxide
- on reaction with moisture/water, H_2S is liberated; the inhalation hazard rating for H_2S is severe; i.e., highly toxic

(ii) vapor pressure: no data

B. Disaster hazards

(i) Molten sulfides and polysulfides may react violently (explosively) with strong oxidants: H_2S evolved on contact with moisture/water can form explosive mixtures with air; H_2S, highly toxic.

(ii) Sulfides and polysulfides when heated to decomposition, or contacted with water, steam, acids, produce highly toxic fumes (oxides of sulfur, H_2S). Dangerous.

References [10-14].

7. *Corrosion*

For corrosion studies, see: Li_2S_x-Sulfur (System 149)

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

[1] Stull, D. R., and Prophet, H., *"JANAF Thermochemical Tables"*, 2nd Ed., NSRDS-NBS 37; U. S. Gov't Printing Office, Washington, D. C. (1971).

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[10] *"Dangerous Properties of Materials"*, Sax, N. I., Van Nostrand Reinhold Co., N. Y. (1969).

[11] *"Registry of Toxic Effects of Chemical Substances"*, Christensen, H. E., and Lubinybyhl, T. T., eds., U. S. Dept. H.E.W; U. S. Gov't Printing Office, Washington, D. C. (1975).

[12] *"Potential Hazards in Molten Salt Baths for Heat Treatment of Metals"*, National Board Fire Underwriters Research Report No. 2. (1954).

[13] *"Handbook of Reactive Chemical Hazards"*, Bretherwick, L., Butterworths Co., London (1975).

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[15] Sharma, R. A., J. Electrochem. Soc. 119, 1439 (1972).

[16] Cunningham, P. T., Johnson, S. A., and Cairns, E. J., J. Electrochem. Soc. 119, 1448 (1972).

1. *Melting Temperature (T_m)*

Melting point:
840° ± 5°C [2]

References [1-10]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Inhalation: variable rating

- as sulfides and polysulfides, the rating is similar to sodium hydroxide

(ii) - on reaction with moisture/water, H_2S is liberated; the inhalation hazard rating for H_2S is severe; i.e., highly toxic

B. Disaster hazards

(i) Molten sulfides and polysulfides may react violently (explosively) with strong oxidants: H_2S evolved on contact with moisture/water can form explosive mixture with air; H_2S, highly toxic.

(ii) Sulfides and polysulfides when heated to decomposition, or contacted with water, steam, acids, produce highly toxic fumes (oxides of sulfur, H_2S). Dangerous.

References [11-15]

7. *Corrosion*

For corrosion studies, see: K_2S-Sulfur (System 150)

8. *Diffusion*

No data

9. *Heat of Fusion (ΔH°_f)*

No data

10. *Heat Capacity (C_p)*

No data

11. *Volume Change on Melting (ΔV_f)*

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

[1] Stull, D. R., and Prophet, H., *"JANAF Thermochemical Tables"*, 2nd Ed., NSRDS-NBS 37; U. S. Gov't Printing Office, Washington, D. C. (1971).

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[4] Janz, G. J., *"Molten Salts Handbook"*, Academic Press, N. Y. (1967).

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System 59 K_2S_2

1. *Melting Temperature (T_m)*

Melting point:
475° ± 5°C [7]

References [1-9]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Inhalation: variable rating

- as sulfides and polysulfides, the rating is similar to sodium hydroxide
- on reaction with moisture/water, H_2S is liberated; the inhalation hazard rating for H_2S is severe; i.e., highly toxic

(ii) vapor pressure: no data

B. Disaster hazards

(i) Molten sulfides and polysulfides may react violently (explosively) with strong oxidants: H_2S evolved on contact with moisture/water can form explosive mixtures with air; H_2S, highly toxic.

(ii) Sulfides and polysulfides when heated to decomposition, or contacted with water, steam, acids, produce highly toxic fumes (oxides of sulfur, H_2S). Dangerous.

References [10-14].

7. *Corrosion*

For corrosion studies, see: K_2S-Sulfur (System 150)

8. *Diffusion*

No data

(59) K_2S_2

9. Heat of Fusion (ΔH_f°)

Measurement method: drop calorimetry [15]

Table 59.1. Heat of fusion

ΔH_f° (kcal mol^{-1})	Uncertainty
2.665	∿ ± 2%

References [15]

10. Heat Capacity (C_p)

Measurement method: drop calorimetry [15]

Table 59.2. Heat capacity

Composition	C_p (cal K^{-1} mol^{-1})	T range (K)	Uncertainty
K_2S_2	38.52	750-810	∿ ± 2%

The heat capacity for K_2S_2 is practically constant up to melting. Apparently, K_2S_2 like K_2S_4, does not undergo a 1st order solid state transition in the vicinity of the melting point (cf. K_2S_3, K_2S_6, K_2S_5).

References [15]

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

[1] Stull, D. R., and Prophet, H., *"JANAF Thermochemical Tables"*, 2nd Ed., NSRDS-NBS 37; U. S. Gov't Printing Office, Washington, D. C. (1971).

[2] Rossini, F. D., Wagman, D. D., Evans, W. H., Levine, S., and Jaffe, I., *"Selected Values of Chemical Thermodynamic Properties"*, NBS, Circ. 500; U. S. Gov't Printing Office, Washington, D. C. (1952).

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System 60 K_2S_3

1. *Melting Temperature (T_m)*

   Melting point:
   ∿ 290° ± 10°C [7]

   References [1-10].

2. *Density (ρ)*

   No data

3. *Surface Tension (γ)*

   No data

4. *Viscosity (η)*

   No data

5. *Electrical Conductance (κ)*

   Measurement method: classical ac technique [11]

   $$\kappa = 5.434 \exp [-1940/R(T-343)] \quad (60.1)$$

   precision: ∿ ± 1.0% uncertainty: ∿ ± 4.0%

Table 60.1. Electrical conductance from equation (60.1)

T (K)	κ (ohm^{-1} cm^{-1})	T (K)	κ (ohm^{-1} cm^{-1})
570	0.199	640	0.435
580	0.229	650	0.472
590	0.260	660	0.510
600	0.293	670	0.548
610	0.327	680	0.587
620	0.362	690	0.626
630	0.398		

References [11]

6. *Safety and Hazards*

A. Hazard rating

(i) Inhalation: variable rating.

- as sulfides and polysulfides, the rating is similar to sodium hydroxide
- on reaction with moisture/water, H_2S is liberated; the inhalation hazard rating for H_2S is severe; i.e., highly toxic

(ii) vapor pressure: no data

B. Disaster hazards

(i) Molten sulfides and polysulfides may react violently (explosively) with strong oxidants: H_2S evolved on contact with moisture/water can form explosive mixtures with air; H_2S, highly toxic.

(ii) Sulfides and polysulfides when heated to decomposition, or contacted with water, steam, acids, produce highly toxic fumes (oxides of sulfur, H_2S). Dangerous.

References [12-16]

7. Corrosion

For corrosion studies, see: K_2S-Sulfur (System 150)

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

Measurement method: drop calorimetry and differential scanning calorimetry [17]

Table 60.2. Heat of fusion

Technique	ΔH_f° (kcal mol^{-1})	Uncertainty
drop calorimetry	3.860	$\sim \pm$ 2%
DSC	3.500	$\sim \pm$ 10%

(DSC, differential scanning calorimetry)

K_2S_3 exhibits a reversible solid state transition at $\sim$ 140°C, for which ΔH = 220 ($\pm$ 30) cal mol^{-1} [17].

References [17]

10. Heat Capacity (C_p)

Measurement method: drop calorimetry [17]

Table 60.3. Heat capacity

Composition	C_p (cal K^{-1} mol^{-1})	T range (K)	Uncertainty
K_2S_3	37.72	568-680	$\sim \pm$ 2%

The temperature dependence of the solid state heat capacity shows a relatively marked increase at $\sim$ 20° to 30° before the melting point, 295°C. This is apparently due to the onset of 1st order solid-state transition just preceding melting.

References [17,18]

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

[1] Stull, D. R., and Prophet, H., *"JANAF Thermochemical Tables"*, 2nd Ed., NSRDS-NBS 37; U. S. Gov't Printing Office, Washington, D. C. (1971).

[2] Rossini, F. D., Wagman, D. D., Evans, W. H., Levine, S., and Jaffe, I., *"Selected Values of Chemical Thermodynamic Properties"*, NBS, Circ. 500; U. S. Gov't Printing Office, Washington, D. C. (1952).

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[15] *"Handbook of Reactive Chemical Hazards"*, Bretherwick, L., Butterworth Co., London (1975).

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System 61 K_2S_4

1. *Melting Temperature (T_m)*

Melting point:
∿ 145° ± 10°C [7]

References [1-10].

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [11]

$$\kappa = 3.0188 \exp [-1295/R(T-341)] \quad (61.1)$$

precision: ∿ 1.1% uncertainty: ∿ ± 4.0%

Table 61.1. Electrical conductance from equation (61.1)

T (K)	κ (ohm^{-1} cm^{-1})	T (K)	κ (ohm^{-1} cm^{-1})
470	0.019	580	0.197
480	0.028	590	0.220
490	0.038	600	0.243
500	0.050	610	0.267
510	0.063	620	0.291
520	0.079	630	0.316
530	0.096	640	0.340
540	0.114	650	0.365
550	0.133	660	0.390
560	0.153	670	0.415
570	0.175	680	0.440

References [11]

6. *Safety and Hazards*

A. Hazard rating

(i) Inhalation: variable rating.

- as sulfides and polysulfides, the rating is similar to sodium hydroxide
- on reaction with moisture/water, H_2S is liberated; the inhalation hazard rating for H_2S is severe; i.e., highly toxic

(ii) vapor pressure: no data.

B. Disaster hazards

(i) Molten sulfides and polysulfides may react violently (explosively) with strong oxidants: H_2S evolved on contact with moisture/water can form explosive mixtures with air; H_2S, highly toxic.

(ii) Sulfides and polysulfides when heated to decomposition, or contacted with water, steam, acids, produce highly toxic fumes (oxides of sulfur, H_2S). Dangerous.

References [12-16]

7. Corrosion

For corrosion studies, see: K_2S-Sulfur (System 150)

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

Measurement method: drop calorimetry and differential scanning calorimetry [17]

Table 61.2. Heat of fusion

Technique	ΔH_f (kcal mol^{-1})	Uncertainty
drop calorimetry	1.985	$\sim \pm$ 2%
DSC	3.400	$\sim \pm$ 9%

DSC: differential scanning calorimetry

K_2S_4 has a tendency to transform from a crystalline solid to a glass at temperatures well below melting. The difference in the values of the ΔH_f (above) suggests that the DSC technique does not discriminate between prefusion and fusion phenomena.

References [17]

10. Heat Capacity (C_p)

Measurement method: drop calorimetry [17]

$$C_p = -2.131 + 100.6 \times 10^{-3} T \quad (61.2)$$

precision: $\sim \pm$ 0.1% uncertainty: $\sim \pm$ 2.0%

Table 61.3. Heat Capacity

T (K)	C_p (cal K^{-1} mol^{-1})	T (K)	C_p (cal K^{-1} mol^{-1})
435	41.6	475	45.6
440	42.1	500	48.2
450	43.1	525	50.7

K_2S_4: The solid state heat capacity for K_2S_4 is practically constant up to melting. Like K_2S_2, it apparently does not exhibit a lst order solid state transition just before melting (cf. K_2S_3, K_2S_5, K_2S_6). In the solid state, for the temperature range: 298 - ∿ 432 K, the heat capacity for K_2S_4 [1] is expressed by:

$$C_p = 7.859 + 89.76 \times 10^{-3} T \quad (61.3)$$

precision: ∿ ± 0.1% uncertainty: ∿ ± 2.0%

References [17]

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

[1] Stull, D. R., and Prophet, H., *"JANAF Thermochemical Tables"*, 2nd Ed., NSRDS-NBS 37; U. S. Gov't Printing Office, Washington, D. C. (1971).

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System 62. K_2S_5

1. *Melting Temperature (T_m)*

Melting point:
205° ± 5°C [7]

References [1-10].

2. *Density (ρ)*

No data

3. *Surface tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [11]

$$\kappa = 2.427 \exp [-1245/R(T-354)] \quad (62.1)$$

precision: ∿ ± 1.0% uncertainty: ∿ ± 4.0%

Table 62.1. Electrical conductance from equation (62.1)

T (K)	κ (ohm^{-1} cm^{-1})	T (K)	κ (ohm^{-1} cm^{-1})
520	0.055	600	0.190
530	0.069	610	0.210
540	0.083	620	0.230
550	0.099	630	0.250
560	0.115	640	0.271
570	0.133	650	0.292
580	0.151	660	0.313
590	0.170	670	0.334

References [11]

(62) K_2S_5

6. Safety and Hazards

A. Hazard rating

(i) Inhalation: variable rating.

- as sulfides and polysulfides, the rating is similar to sodium hydroxide
- on reaction with moisture/water, H_2S is liberated; the inhalation hazard rating for H_2S is severe; i.e., highly toxic

(ii) vapor pressure: no data

B. Disaster hazards

(i) Molten sulfides and polysulfides may react violently (explosively) with strong oxidants: H_2S evolved on contact with moisture/water can form explosive mixtures with air; H_2S, highly toxic.

(ii) Sulfides and polysulfides when heated to decomposition, or contacted with water, steam, acids, produce highly toxic fumes (oxides of sulfur, H_2S). Dangerous.

References [12-16].

7. Corrosion

For corrosion studies, see: K_2S-Sulfur (System 150)

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

Measurement method: drop calorimetry and differential scanning calorimetry [17]

Table 62.2. Heat of fusion

Technique	ΔH_f° (kcal mol^{-1})	Uncertainty
drop calorimetry	1.720	$\sim \pm$ 2%
DSC	6.000	$\sim \pm$ 8%

DSC: differential scanning calorimetry

K_2S_5 has a tendency to transform from a crystalline solid to a glass at temperatures well below melting. The difference in the values of ΔH_f (above) suggests that the DSC technique does discriminate between prefusion and fusion phenomena.

References [17]

(62) K_2S_5

10. Heat Capacity (C_p)

Measurement method: drop calorimetry [17]

Table 62.3. Heat capacity

Composition	C_p (cal K^{-1} mol^{-1})	T range (K)	Uncertainty
K_2S_5	61.54	480-580	$\sim \pm$ 2%

K_2S_5: The temperature dependence of the solid state heat capacity shows a relatively marked increase at ~ 50° to 60° before melting. This is apparently due to the onset of a 1st order solid state transition.

References [17,18]

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

[1] Stull, D. R., and Prophet, H., *"JANAF Thermochemical Tables"*, 2nd Ed., NSRDS-NBS 37; U. S. Gov't Printing Office, Washington, D. C. (1971).

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[13] *"Registry of Toxic Effects of Chemical Substances"*, Christensen, H. E., and Lubinybyhl, T. T., eds., U. S. Dept. H.E.W; U. S. Gov't Printing Office, Washington, D. C. (1975).

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System 63 K_2S_6

1. *Melting Temperature (T_m)*

Melting point:
190° ± 5°C [7]

References [1-10]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [11]

$$\kappa = 1.099 \exp [-798.3/R(T-393)] \quad (63.1)$$

precision: ∿ ± 1.5% uncertainty: ∿ ± 4.0%

Table 63.1. Electrical conductance from equation (63.1)

T (K)	κ (ohm^{-1} cm^{-1})	T (K)	κ (ohm^{-1} cm^{-1})
520	0.046	610	0.172
530	0.058	620	0.187
540	0.071	630	0.201
550	0.085	640	0.216
560	0.099	650	0.230
570	0.113	660	0.243
580	0.128	670	0.257
590	0.143	680	0.270
600	0.157	690	0.284

References [11]

6. Safety and Hazards

A. Hazard rating

(i) Inhalation: variable rating

- as sulfides and polysulfides, the rating is similar to sodium hydroxide
- on reaction with moisture/water, H_2S is liberated; the inhalation hazard rating for H_2S is severe; i.e., highly toxic

B. Disaster hazards

(i) Molten sulfides and polysulfides may react violently (explosively) with strong oxidants: H_2S evolved on contact with moisture/water can form explosive mixtures with air; H_2S, highly toxic

(ii) Sulfides and polysulfides when heated to decomposition, or contacted with water, steam, acids, produce highly toxic fumes (oxides of sulfur, H_2S). Dangerous

References [10-14]

7. Corrosion

For corrosion studies, see: K_2S-Sulfur (System 150)

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

Measurement method: drop calorimetry and differential scanning calorimetry [17]

Table 63.2. Heat of fusion

Technique	ΔH_f° (kcal mol^{-1})	Uncertainty
drop calorimetry	6.200	∿ ± 2%
DSC	6.300	∿ ± 10%

DSC: differential scanning calorimetry

The assessment of values from the two different calorimetric techniques appears to confirm that there is little to transform from the crystalline state to the glassy state as a pre-melting phenomena (cf. K_2S_4 and K_2S_5)

References [17]

(63) K_2S_6

10. Heat Capacity (C_p)

Measurement method: drop calorimetry [17]

Table 63.3. Heat capacity

Composition	(cal K^{-1} mol^{-1})	T range (K)	Uncertainty
K_2S_6	72.69	470-510	$\sim \pm$ 2%

K_2S_6: The temperature dependence of the solid state heat capacity shows a relatively marked increase at ~ 20° to 30° before melting. This is apparently due to the onset of a 1st order solid state transition in this temperature range.

References [17]

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

[1] Stull, D. R., and Prophet, H., *"JANAF Thermochemical Tables"*, 2nd Ed., NSRDS-NBS 37; U. S. Gov't Printing Office, Washington, D. C. (1971).

[2] Rossini, F. D., Wagman, D. D., Evans, W. H., Levine, S., and Jaffe, I., *"Selected Values of Chemical Thermodynamic Properties"*, NBS, Circ. 500; U. S. Gov't Printing Office, Washington, D. C. (1952).

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[4] Janz, G. J., *"Molten Salts Handbook"*, Academic Press, N. Y. (1967).

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[14] *"Potential Hazards in Molten Salt Baths for Heat Treatment of Metals"*, National Board Fire Underwriters Research Report No. 2. (1954).

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[17] Bousquet, J., Letoffe, J-M, and Diot, M., J. Chem. Phys. 71, 1180(1974)

System 64 Al_2S_3

1. *Melting Temperature (T_m)*

Melting point:
1100° ± 10°C [4,8]

References [1-8]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Inhalation: variable rating.

- as sulfides and polysulfides, the rating is similar to sodium hydroxide
- on reaction with moisture/water, H_2S is liberated; the inhalation hazard rating for H_2S is severe; i.e., highly toxic

(ii) vapor pressure: no data; m.pt., 1100°C; b.pt., ∿ 1550°C (d).

B. Disaster hazards

(i) Molten sulfides and polysulfides may react violently (explosively) with strong oxidants: H_2S evolved on contact with moisture/water can form explosive mixtures with air; H_2S, highly toxic.

(ii) Sulfides and polysulfides when heated to decomposition, or contacted with water, steam, acids, produce highly toxic fumes (oxides of sulfur, H_2S). Dangerous.

References [9-13]].

7. *Corrosion*

No data

8. *Diffusion*

No data

9. *Heat of Fusion (ΔH_f)*

No data

10. *Heat Capacity (C_p)*

No data

11. *Volume Change on Melting (ΔV_f)*

No data

12. *Vapor Pressure (p_{vap})*

No data

13. *Thermal Conductivity (liquid) (λ_ℓ)*

No data

14. *Thermal Conductivity (solid) (λ_s)*

No data

15. *Cryoscopic Constant (k_f)*

No data

16. *References*

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System 65 Li_3AlF_6

1. *Melting Temperature (T_m)*

Melting point:
785° ± 5°C [1]

References [1-34]

2. *Density (ρ)*

Measurement method: Archimedean technique [35]

Equation:

$$\rho = 3.0475 - 8.400 \times 10^{-4} T \quad (65.1)$$

precision: insufficient data for estimate uncertainty: ∿ ± 1.5%

Table 65.1. Density from equation (65.1)

T (K)	ρ (g cm^{-3})	T (K)	ρ (g cm^{-3})
1220	2.023	1280	1.972
1230	2.014	1290	1.964
1240	2.006	1300	1.955
1250	1.997	1310	1.947
1260	1.989	1320	1.939
1270	1.981		

References [35]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

(65) Li_3AlF_6

6. Safety and Hazards

A. Hazard rating

(i) Toxicity inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure: at m.pt., ∿ 785°C, ∿ << 5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [36-41]

7. Corrosion

Table 65.2. Corrosion studies from primary research literature

	Studies	References
A	Cr	[42]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[43,44]
	SSNI-12P	[45]
	Quartz	[46]
	Al	[47]
	Various metals	[48]
B	Pt, Pt-Rh	[49-53,87,88]
	Boron nitride, carbon, Inconel	[54-56]
	Fused MgO	[57]
C	Impurities in electrolyte	[58,59]
	Graphite	[58,59]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[60-62]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[73-78,85,86]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[79-81]
	Electroanalytical studies in molten fluorides	[82]
	Annotated corrosion biblio.	[83]
	Corrosion: molten fluorides(survey)	[84]

continued

footnote to Table 65.2

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [42-84]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

Measurement method: modified drop calorimetry [94]

Table 65.3. Heat of fusion

T_m	ΔH_f° (kcal mol^{-1})	Uncertainty
785°C	21.0	∿ ± 1%

References [29,89-94]

10. Heat Capacity (C_p)

Measurement method: modified drop calorimetry [89]

Table 65.4. Heat capacity

Li_3AlF_6	C_p (cal K^{-1} mol^{-1})	T range (K)	Uncertainty
ℓ	92.20	1065-1130	∿ ± 1%

References [89]

11. Volume Change on Melting (ΔV_f)

No data

(65) Li_3AlF_6

12. Vapor Pressure (p_{vap})

Measurement method: boiling point technique [95]

Equation:

$$\log p = 8.5800 - 9884/T \quad (65.2)$$

precision: insufficient data for estimate uncertainty: ∿ ± 10%

Table 65.5. Vapor pressure from equation (65.2)

T (K)	p (mm)	T (K)	p (mm)
1220	3.009	1350	18.1
1230	3.501	1360	20.53
1240	4.065	1370	23.20
1250	4.708	1380	26.16
1260	5.439	1390	29.46
1270	6.270	1400	33.11
1280	7.213	1410	37.16
1290	8.279	1420	41.63
1300	9.483	1430	46.57
1310	10.834	1440	52.01
1320	12.363	1450	58.00
1330	14.074	1460	64.59
1340	15.991	1470	71.81

References [95]

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f° [96]

Table 65.6. Cryoscopic constant

k_f (K mol^{-1} kg)	Uncertainty
17.1	∿ ± 1%

References [96]

16. References

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System 66 Na_3AlF_6

1. Melting Temperature (T_m)

Melting point:
1010° ± 5°C [9] ; 1012° ± 2°C ("ultimate purity" cryolite) [25]

References [1-57]

2. Density (ρ)

Measurement method: Archimedean technique [58]

Equation:

$$\rho = 3.2733 - 9.20 \times 10^{-4} T \quad (66.1)$$

precision: ∿ ± 0.15% uncertainty: ∿ ± 1.0%

Table 66.1. Density from equation (66.1)

T (K)	ρ (g cm^{-3})	T (K)	ρ (g cm^{-3})
1275	2.100	1325	2.054
1280	2.096	1330	2.050
1285	2.091	1335	2.045
1290	2.087	1340	2.040
1295	2.082	1345	2.036
1300	2.077	1350	2.031
1305	2.072	1355	2.027
1310	2.068	1360	2.022
1315	2.064	1365	2.017
1320	2.059	1370	2.013

References [58]

3. Surface Tension (γ)

Measurement method: maximum bubble method [59]

Equation:

$$\gamma = 297.0 - 12.80 \times 10^{-2} T \quad (66.2)$$

precision: not estimated uncertainty: ∿ ± 5.0%

Table 66.2. Surface tension from equation (66.2)

T (K)	γ (dyn cm^{-1})	T (K)	γ (dyn cm^{-1})
1280	133.2	1330	126.8
1290	131.9	1340	125.5
1300	130.6	1350	124.2
1320	128.0	1360	122.9

References [59]

4. *Viscosity (η)*

Measurement method: oscillating cylinder [13]

Equation:

$$\eta = 1792.468 \times 10^{-5} \exp (12380.3/RT) \quad (66.3)$$

precision: ∿ ± 0.17% uncertainty: ∿ ± 5.0%

Table 66.3. Viscosity from equation (66.3)

T (K)	η (cp)	T (K)	η (cp)
1290	2.24	1350	1.81
1300	2.16	1360	1.75
1310	2.09	1370	1.69
1320	2.01	1380	1.64
1330	1.94	1390	1.59
1340	1.87		

References [13]

5. *Electrical Conductance (κ)*

Measurement method: classical technique [62]

Equation:

$$\kappa = - 0.03860 + 2.0206 \times 10^{-3}T + 0.1670 \times 10^{-6}T^2 \quad (66.4)$$

precision: not estimated uncertainty: ∿ ± 3.0%

Table 66.4. Electrical conductance from equation (66.4)

T (K)	κ (ohm^{-1} cm^{-1})
1280	2.821
1290	2.846
1300	2.870
1310	2.895
1320	2.920
1330	2.944
1340	2.969
1350	2.994
1360	3.018
1370	3.043

References [13,60-83]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure: at m.pt., 1000°C, ~ << 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [84-89]

7. Corrosion

Table 66.5. Corrosion studies from primary research literature

	Studies	References
A	Cr	[90]
	Ni-Cr-Mo alloys (INOR-8); Hastelloys B, W, and N)	[91,92]
	SSNI-12P	[93]
	Quartz	[94]
	Al	[95]
	Various metals	[96]
B	Pt	[74,76,80,82,97]
	Boron nitride, carbon, Inconel	[72,98,99]
	Fused MgO	[100]
C	Impurities in electrolyte	[9,101]
	Graphite	[9,101]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[102-104]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[105-120,127,128]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[121-123]
	Electroanalytical studies in molten fluorides	[124]
	Annotated corrosion biblio.	[125]
	Corrosion: molten fluorides (survey)	[126]

cont'd

footnote to Table 66.5

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys

References [9,72,74,76,80,82,90-128]

8. Diffusion

Measurement method: see table 66.6

List of diffusing species investigated in Na_3AlF_6 as solvent

^{26}Al, Al_2O_3, F^-, Na^+, Ta(V), CO_2

precision: in table 66.7 uncertainty: in table 66.6

Table 66.6. Diffusion techniques, uncertainties and species

Diffusion technique of recommended study	Uncertainty (in values of D)	Species
capillary	∿ ± 10%	Na^+, F^-
chronopotentiometry	∿ ± 10%	Ta(V)
double-layer impedance	∿ ± 20%	CO_2
rotating disc electrode	∿ ± 20%	Al_2O_3

Equation:

$$D = A \exp [-E/RT] \qquad (66.5)$$

Table 66.7. Parameters of diffusion equation (66.5), precisions, and recommended study

Species	A x 10^3 (cm^2 s^{-1})	E (cal mol^{-1})	Temp. range (K)	Precision	Recommended study
Na^+	4.58	10200	1307-1338	∿±2.2%	[130]
F^-	0.877	7106	1307-1338	∿±1.3%	[130]

(66) Na_3AlF_6

Table 66.8. Self-diffusion coefficients, D x 10^5 (cm^2 s^{-1}) from equations in table 66.7

T (K)	Na^+	F^-
1310	9.10	5.72
1320	9.37	5.84
1330	9.65	5.96
1340	9.93	6.08

Table 66.9. Diffusion coefficients for species not included in table 66.8

Species	T (K)	D x 10^5 (cm^2 s^{-1})	Recommended study
Ta(V)	1273	7.0	[129]
Al_2O_3	1323	2.0	(a)
^{26}Al	1324	6.9	[135]
^{26}Al	1325	6.77	[135]
CO_2		∿0.005	[136] (b)

(a) This value is a merge of the results reported by Desclaux and Rolin [131], Thonsted [139], and Shurygin et al. [133,137,138]. The values reported were, respectively:
[131] 1050°C, 2.7 x 10^{-5} cm^2s^{-1}
[139] 1020°C, 1.5 x 10^{-5} cm^2s^{-1}
[133,137,138] 1050°C, 1.33 x 10^{-5} cm^2s^{-1}, respectively

(b) This value is based on a solubility of CO_2 in molten cryolite of ∿ 5 x 10^{-6} mol/cm^2 at 700°C.

References: Na^+, [130,134]; F^-, [130,134]; Al_2O_3, [131-133,137-139]; Al, [135]; CO_2, [136].

9. Heat of Fusion (ΔH_f^o)

Measurement method: drop calorimetry [54,141,145]

Table 66.10. Heat of Fusion

Phase transition	T (K)	($kcal\ K^{-1} mol^{-1}$)	Uncertainty
solid state: $\alpha \rightarrow \beta$	833.5	2.22	$\sim \pm 1\%$
fusion: $\beta \rightarrow \ell_1$	1283	26.9	$\sim \pm 1\%$
fusion: $\beta \rightarrow \ell_2$	1283	18.76	$\sim \pm 1\%$

The melting process, $\beta \rightarrow \ell_1$, is normal melting of solid (β) cryolite; the molten state (ℓ_1) consists of cryolite and its dissociation products (e.g., NaF, $NaAlF_4$,...) and the enthalpy of fusion (26.71 kcal mol^{-1}) is a composite of the true heat of fusion and the substantial heat effect due to a partial dissociation of liquid cryolite into NaF, $NaAlF_4$, and the constituent ions.

The melting process, $\beta \rightarrow \ell_2$, is for the hypothetical melting process: solid (β)cryolite to liquid cryolite at unit activity (as molten cryolite in the "undissociated" state, i.e., as Na_3AlF_6, liquid).

The values in Table 66.10(above) are based on the calorimetric measurements of O'Brien and Kelley [141] as corrected for an apparent error in temperature measurement by Frank [54], and the measurements of Jenssen-Holm [145]

References [54,56,141-143,144-147]

10. Heat Capacity (C_p)

Measurement method: drop calorimetry [54,141,145]

Table 66.11. Heat capacity

Cryolite phase	C_p ($cal\ K^{-1}\ mol^{-1}$)	T range (K)	Uncertainty
Na_3AlF_6(s,α)	(a)	298.1-833.5	$\sim \pm 1\%$
Na_3AlF_6(s,β)	(b)	833.5-1283	$\sim \pm 1\%$
liquid 1.	95.86	1283-1350	$\sim \pm 1\%$
liquid 2.	76.12	1283-1350	$\sim \pm 1\%$

The normal melting of solid β cryolite results in the molten state, liquid 1, which consists of a solution of cryolite (Na_3AlF_6) and its constituent components (NaF, $NaAlF_4$..., and their ions) due to a partial dissociation: $Na_3AlF_6 \rightleftarrows 2NaF + NaAlF_4$ in the molten state of cryolite.

If this value is "corrected" for the heat capacities contribution of the dissociation products and the degree of dissociation, the "trace" heat capacity of liquid cryolite at unit activity in the molten state (i.e. for liquid 2) is obtained.

cont'd

The values in Table 66.11 (above) are based on the calorimetric measurements of O'Brien and Kelley [141] as corrected by Frank [54] for an error in the temperature measurements, and on the measurements of Jenssen-Holm [145]

$$(a)\ C_p(s,\alpha) = 45.51 + 3.206 \times 10^{-2}T - 1.755 \times 10^{-5}T^2$$
$$(b)\ C_p(s,\beta) = 36.4 + 3.428 \times 10^{-2}T$$

References [54,141,144-146,148-152]

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [153]

Table 66.12. Volume change on melting

$(\Delta V_f/V_s)$	Uncertainty
26.5%	$\sim \pm$ 10%

References [153]

12. Vapor Pressure (p_{vap})

Measurement method: boiling point technique [155]

Equation:

$$\log p = 8.6950 - 10400/T \quad (66.6)$$

precision: not estimated uncertainty: $\sim \pm$ 10%

Table 66.13. Vapor pressure from equation (66.6)

T (K)	p (mm)	T (K)	p (mm)
1280	3.715	1380	14.41
1290	4.295	1390	16.33
1300	4.955	1400	18.47
1310	5.703	1410	20.85
1320	6.550	1420	23.50
1330	7.507	1430	26.44
1340	8.586	1440	29.70
1350	9.802	1450	33.31
1360	11.17	1460	37.30
1370	12.70	1470	41.70

References [154,155,158]

13. Thermal Conductivity (liquid) (λ_ℓ)

Measurement method: modified coaxial-cylinder method [156]

Equation:

$$\lambda = - 2.280 \times 10^{-2} + 18.66 \times 10^{-6} T \quad (66.7)$$

precision: not estimated, graphical data only uncertainty: ∿ ± 15%

Table 66.14. Thermal conductivity of melt from equation (66.7)

T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})	T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})
1300	14.6	1330	20.2
1310	16.4	1340	22.0
1320	18.3		

References [156,157]

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f° [153]

Table 66.15. Cryoscopic constant

k_f (K mol^{-1} kg)	Uncertainty
25.5	∿ ± 1%

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16. References

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System 67 K_3AlF_6

1. *Melting Temperature (T_m)*

Melting point:
990°C ± 10°C [16,17]

References [1-19]

2. *Density (ρ)*

Measurement method: Archimedean technique [20]

Equation:

$$\rho = 2.770 - 7.398 \times 10^{-4} T \quad (67.1)$$

precision: insufficient data for estimate uncertainty: ∿ ± 1.5%

Table 67.1. Density from equation (67.1)

T (K)	ρ (g cm^{-3})	T (K)	ρ (g cm^{-3})
1270	1.8304	1300	1.8082
1280	1.8320	1310	1.8008
1290	1.8156	1320	1.7934

References [20]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [21]

Equation:

$$\kappa = -2.6020 + 3.8055 \times 10^{-3} T \quad (67.2)$$

precision: insufficient data for estimate uncertainty: ∿ ± 3.0%

Table 67.2. Specific conductance from equation (67.2)

T (K)	κ (ohm^{-1} cm^{-1})	T (K)	κ (ohm^{-1} cm^{-1})
1280	2.27	1320	2.42
1290	2.31	1330	2.46
1300	2.35	1340	2.50
1310	2.38		

References [21-24]

(67) K_3AlF_6

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure: at m.pt., 990°C, ∿ << 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [25-30]

7. Corrosion

Table 67.3. Corrosion studies from primary research literature

	Studies	References
A	Cr	[31]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[32,33]
	SSNI-12P	[34]
	Quartz	[35]
	Al	[36]
	Various metals	[37]
B	Pt	[38-42]
	Boron nitride, carbon, Inconel	[43-45]
	Fused MgO	[46]
C	Impurities in electrolyte	[47,48]
	Graphite	[47,48]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[49-51]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[52-67,74,75]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[68-70]
	Electroanalytical studies in molten fluorides	[71]
	Annotated corrosion biblio.	[72]
	Corrosion: molten fluorides(survey)	[73]

continued

footnote to Table 67.3
A: studies principally in molten NaF, KF,and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys

References [31-75]

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

Measurement method: modified drop calorimetry [76]

Table 67.4. Heat of fusion

T_m	ΔH°_f (kcal mol^{-1})	Uncertainty
1000°C	29.3	∿ ± 1%

References [76]

10. Heat Capacity

Measurement method: modified drop calorimetry [76]

Table 67.5. Heat capacity

K_3AlF_6	C_p (cal K^{-1} mol^{-1})	T range	Uncertainty
ℓ	93.84	1280-1330	∿ ± 1%

References [76]

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f°

Table 67.6. Cryoscopic constant

k_f (K mol^{-1}kg)	Uncertainty
27.9	$\sim \pm$ 1%

References [78]

16. References

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1. *Melting Temperature (T_m)*

Melting point:
462° ± 5°C [2]

References [1-8]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: very caustic and toxic.

(ii) Vapor pressure: at m.pt., 460°C, << 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Dangerous; reacts with water or steam with evolution of heat; the aqueous solution is very strongly caustic; attacks living tissue.

References [9-14]

7. *Corrosion*

Table 68.1. Corrosion studies from primary research literature

Studies	References
Ni, Cu, Armco Fe and steel	[15-17]
Fe, effects of H_2O	[18]
Pt, Ag, and alloys	[19-21]
Thermodynamics of corrosion	[22,24,25]
Corrosion - annotated biblio.	[26]
Electrochemical aspects	[27]
Reviews: corrosion - molten salts	[23,28-30]

References [15-30]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

Measurement method: drop calorimetry [32]

Table 68.2. Heat of fusion

ΔH_f° (kcal mol^{-1})	Uncertainty
5.01	$\sim \pm$ 2%

References [31-33]

10. Heat Capacity (C_p)

Measurement method: drop calorimetry [31]

Table 68.3. Heat capacity

C_p (cal K^{-1} mol^{-1})	T range (K)	Uncertainty
20.74	744-900	$\sim \pm$ 2%

For the crystalline state (400-744.3 K), the heat capacity is given by: $C_p = 11.988 + 8.24 \times 10^{-3}T - 0.2267 \times 10^{6}T^{-2}$. (68.1)

References [31,32]

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

Measurement method: comparative technique, flat slab [34]

$$\lambda = 1.5384 \times 10^{-3} + 6.500 \times 10^{-7}T \quad (68.2)$$

precision: not estimated uncertainty: ∿ ± 15%

Table 68.4. Thermal conductivity of melt from equation (68.2)

T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})	T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})
760	20.3	820	20.7
770	20.4	830	20.8
780	20.5	840	20.8
790	20.5	850	20.9
800	20.6	860	21.0
810	20.5	870	21.0

The preceding are for reagent grade quality LiOH. The thermal conductivity for commercial grade LiOH was also investigated [34] over the same temperature range (760-870 K), the thermal conductivity for the molten state of commercial grade LiOH may be expressed by:

$$\lambda = 1.3707 \times 10^{-3} + 8.7417 \times 10^{-7}T \quad (68.3)$$

The values of λ for reagent grade and commercial grades LiOH in the molten state are in close accord (± 1%). The data set was insufficient for precision estimates; the uncertainty limits are estimated as ± 15%.

References [34,35]

14. Thermal Conductivity (solid) (λ_s)

Measurement method: comparative technique, flat slab [34]

$$\lambda = 1.3269 \times 10^{-2} - 29.96 \times 10^{-6}T + 21.93 \times 10^{-9}T^2 \quad (68.4)$$

precision: ± 1.25% uncertainty: ∿ ± 15%

Table 68.5. Thermal conductivity of solid from equation (68.4)

T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})	T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})
320	59.3	570	33.2
370	51.9	620	31.2
420	45.5	670	30.4
470	40.3	710	30.5
520	36.2		

The preceding values are for reagent grade quality LiOH. The solid state thermal conductivity of commercial grade LiOH was also investigated [34] The solid state thermal conductivity of commercial grade LiOH over the same temperature range (320-710 K) may be expressed by:

$$\lambda = 1.5636 \times 10^{-2} - 33.28 \times 10^{-6}T + 22.25 \times 10^{-9}T^2 \quad (68.5)$$

The precision and uncertainty estimates are ∿ ± 2.9% and ∿ ± 15%, respectively. The λ values for the commercial grade quality LiOH are higher then for the reagent grade quality LiOH, (320 K, ∿ 20%; 710 K, ∿ 9%).

References [34,35]

(68) LiOH

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f° [11]

Table 68.6. Cryoscopic constant

k_f (K mol^{-1} kg)	Uncertainty
5.13	~ ± 1%

References [11]

16. References

[1] Stull, D. R., and Prophet, H., *"JANAF Thermochemical Tables"*, 2nd Ed., NSRDS-NBS 37; U. S. Gov't Printing Office, Washington, D. C. (1971).

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System 69 NaOH

1. *Melting Temperature (T_m)*

Melting Point:
318° ± 5°C [2]

References [1-8].

2. *Density (ρ)*

Measurement method: Archimedean technique [9]

$$\rho = 2.068 - 0.4784 \times 10^{-3} T \quad (69.1)$$

precision: not estimated uncertainty:

Table 69.1. Density from equation (69.1)

T (K)	ρ (g cm^{-3})	T (K)	ρ (g cm^{-3})
600	(1.781)	670	1.747
610	(1.776)	680	1.743
620	1.771	690	1.738
630	1.767	700	1.733
640	1.762	710	1.728
650	1.757	720	1.724
660	1.752	730	1.719

References [9]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

Measurement method: capillary technique [9]

$$\eta = 164.771 - 0.614833T + 7.80340 \times 10^{-4} T^2 - 3.33334 \times 10^{-7} T^3 \quad (69.2)$$

precision: ∿ ± 2% uncertainty: ∿ ± 5%

Table 69.2. Viscosity from equation (69.2)

T (K)	η (cp)	T (K)	η (cp)
630	3.79	730	2.11
640	3.52	740	2.03
650	3.28	750	1.96
660	3.07	760	1.90
670	2.87	770	1.84
680	2.70	780	1.78
690	2.55	790	1.72
700	2.42	800	1.66
710	2.31	810	1.59
720	2.20	820	1.52

References [9]

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [9]

$$\kappa = -3.230 + 9.00 \times 10^{-3} T \quad (69.3)$$

precision: ∿ ± 0.2%

uncertainty: insufficient data for estimate

Table 69.3. Electrical conductance from equation (69.3)

T (K)	κ (ohm^{-1} cm^{-1})	T (K)	κ (ohm^{-1} cm^{-1})
600	2.17	670	2.80
610	2.26	680	2.89
620	2.35	690	2.98
630	2.44	700	3.07
640	2.53	710	3.16
650	2.62	720	3.25
660	2.71	730	3.34

References [9]

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: very caustic; is corrosive to all body tissues.

(ii) Vapor pressure: at m.pt., 318°C, << 0.5mm; at ∿ 740°C, ∿ 1mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Dangerous; with water or steam, reacts with evolution of heat; the aqueous solution is very strongly caustic; attacks living tissue.

References [10-15]

7. Corrosion

Table 69.4. Corrosion studies from primary research literature

Studies	References
Metals	[22]
Metals, ceramics, alloys	[16,18,21-23,25,26,29]
Stainless steel, Fe-Cr-Ni alloys	[27]
Ni-Cr-Fe; Ni-Si-Cu	[18,28]
Ni-Mo	[30,31,35]
Ni, Cu, Armco Fe	
Al_2O_3, ZrO_2	[16]
Ni	[16,17,19-21,23-25]
Ni-steels	[36]
Fe (effects of H_2O)	[37]
Pt, Ag, and alloys	[32-34]
Thermodynamic and electrochemical approach	[38-40]
Reviews (molten salts corrosion)	[41-43]
Annotated corrosion biblio.	[44]

References [16-44]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

Measurement method: drop calorimetry [45]

Table 69.5. Heat of fusion

ΔH_f° (kcal mol^{-1})	Uncertainty
1.52	$\sim \pm$ 2%

NaOH (m.pt. 319°C) exhibits a solid-state transition at 293°C with ΔH = 1.52 $\pm \sim$ 2% kcal mol^{-1}.

References [45-50]

10. Heat Capacity (C_p)

Measurement method: drop calorimetry [45]

$$C_p = a + bT \quad (69.4)$$

precision: in table 69.6 uncertainty: ∿ ± 3%

Table 69.6. Parameters of equation (69.4) and precisions

NaOH phase	T range (K)	a	b x 10^3	Precision
solid-α	273.2-566.0	7.302	21.66	∿ ± 0.2%
solid-β	566.0-592.3	20.56	0	
liquid	593.3-1000	21.409	-1.400	∿ ± 0.1%

Table 69.7. Heat capacity from equation(69.4) and parameters for liquid NaOH in table 69.6

T (K)	C_p (cal K^{-1} mol^{-1})	T (K)	C_p (cal K^{-1} mol^{-1})
600	20.6	850	20.2
650	20.5	900	20.2
700	20.4	950	20.1
800	20.3	1000	20.0

References [45,49,51-56]

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [57]

Table 69.8. Volume change on melting

$(\Delta V_f/V_s)$	Uncertainty
15.7%	∿ ± 10%

References [57]

12. Vapor Pressure (p_{vap})

Measurement method: cited in table 69.9

Table 69.9. Vapor pressure measurements, techniques, and uncertainty

Vapor pressure measurements		T range	Uncertainty (in
Ref.	Technique	(K)	vapor pressures)
[58]	Knudsen cell effusion	870-1130	± 10%
[59]	boiling point	1283-1675	± 10%

Equation:

$$\log p(mm) = A + B/T \quad (69.5)$$

precision: in table 69.10 uncertainty: in table 69.9

Table 69.10. Parameters of equation (69.5) and precisions

Equation	T range(K)	A	-B	Precision
(69.5.A)	870-1130	7.0316	6750.9	*
(69.5.B)	1283-1675	6.9281	6706.4	∿ 22%

*insufficient data for estimate

Table 69.11. Vapor pressures from equation (69.5) in table 69.10

T (K)	p (mm)	T (K)	p (mm)
870	0.187	1360	99.31
880	0.229	1400	137.4
920	0.494	1440	186.6
960	0.999	1480	249.6
1000	1.909	1520	328.1
1040	3.471	1560	425.8
1080	6.037	1600	545.3
1110	7.843	1640	690.1
----	-----	1657	760
1280	48.84	1680	863.4
1320	70.40		

References [58,59]

13. *Thermal Conductivity (liquid) (λ_ℓ)*

Measurement method: modified parallel plate method [60]

$$\lambda = 6.3986 \times 10^{-4} + 2.271 \times 10^{-6} T \quad (69.6)$$

precision: ±9.6% uncertainty: ∿ ± 5%

Table 69.12. Thermal conductivity of melt from equation (69.6)

T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})	T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})
600	20.0	800	24.6
650	21.2	850	25.7
700	22.3	875	26.3
750	23.4		

*extrapolated values

The sodium hydroxide was analytical reagent grade quality, assaying at 97.6% NaOH with 0.32% Na_2CO_3. The thermal conductivity measurements were made in nickel under an atmosphere of purified hydrogen.

References [60-69]

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f° [57]

Table 69.13. Cryoscopic constant

k_f (K mol^{-1} kg)	Uncertainty
18.3	∿ ± 1%

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System 70 KOH

1. *Melting Temperature (T_m)*

Melting point:
360° ± 5°C [2]

References [1-8].

2. *Density (ρ)*

Measurement method: Archimedean technique [9]

$$\rho = 2.013 - 0.4396 \times 10^{-3} T \quad (70.1)$$

precision: not estimated uncertainty:

Table 70.1. Density from equation (70.1)

T (K)	ρ (g cm^{-3})	T (K)	ρ (g cm^{-3})
640	1.732	760	1.679
650	1.727	770	1.675
660	1.723	780	1.670
670	1.718	790	1.666
680	1.714	800	1.661
690	1.710	810	1.657
700	1.705	820	1.653
710	1.701	830	1.648
720	1.696	840	1.644
730	1.692	850	1.639
740	1.688	860	1.635
750	1.683	870	1.631

References [9]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

Measurement method: capillary technique [9]

$$\eta = 52.7561 - 0.166134T + 1.80314 \times 10^{-4} T^2 - 6.66494 \times 10^{-8} T^3 \quad (70.2)$$

precision: ∿ ± 1% uncertainty: ∿ ± 5%

Table 70.2. Viscosity from equation (70.2)

T (K)	η (cp)	T (K)	η (cp)
680	2.21	780	1.25
690	2.08	790	1.18
700	1.96	800	1.13
710	1.84	810	1.07
720	1.74	820	1.02
730	1.64	830	0.97
740	1.55	840	0.93
750	1.46	850	0.89
760	1.39	860	0.85
770	1.31	870	0.81

References [9]

5. Electrical Conductance (κ)

Measurement method: classical ac technique [9]

$$\kappa = -1.380 + 5.800 \times 10^{-3} T \quad (70.3)$$

precision: ∿ ± 0.5%

uncertainty: insufficient data for estimate

Table 70.3. Electrical conductance from equation (70.3)

T (K)	κ (ohm^{-1} cm^{-1})	T (K)	κ (ohm^{-1} cm^{-1})
670	2.51	780	3.14
680	2.56	790	3.20
690	2.62	800	3.26
700	2.68	810	3.32
710	2.74	820	3.38
720	2.80	830	3.43
730	2.85	840	3.49
740	2.91	850	3.55
750	2.97	860	3.61
760	3.03	870	3.67
770	3.09		

References [9]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: highly caustic; very corrosive to all body tissues.

(ii) Vapor pressure: at m.pt., 360°C, << 0.5mm; at ∿ 720°C ∿ 1mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Dangerous; reacts with water or steam with evolution of heat; the aqueous solution is very strongly caustic; attacks living tissue.

References [10-15].

7. Corrosion

Table 70.4. Corrosion studies from primary research literature

Studies	References
Ni, Cu, Armco Fe and steel	[16-18]
Fe, effects of H_2O	[19]
Pt, Ag, and alloys	[20-22]
Thermodynamics of corrosion	[23-26]
Corrosion - annotated biblio.	[27]
Electrochemical aspects	[28]
Reviews: corrosion - molten salts	[24,29-31]

References [16-31]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

Measurement method: calculated (cryoscopy) [32]

Table 70.5. Heat of fusion

ΔH_f° (kcal mol^{-1})	Uncertainty
1.98	∿ ± 5%

References [32-35]

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [36]

Table 70.6. Volume change on melting

$(\Delta V_f/V_s)$	Uncertainty
13.7%	∿ ± 10%

References [36]

12. *Vapor Pressure (p_{vap})*

Measurement method: boiling point technique [37]

$$\log p = 7.3701 - 7162/T \quad (70.4)$$

precision: ∿ ± 4% uncertainty: ∿ ± 10%

Table 70.7. Vapor pressure from equation (70.4)

T (K)	p (mm)	T (K)	p (mm)
1440	249.2	1530	488.7
1450	269.6	1540	524.1
1460	291.5	1550	561.6
1470	314.8	1560	601.3
1480	339.6	1570	643.2
1490	365.9	1580	687.4
1500	393.9	1590	734.0
1510	423.7	1595.4	760
1520	455.3	1600	783.2

References [37]

13. *Thermal Conductivity (liquid) (λ_ℓ)*

No data

14. *Thermal Conductivity (solid) (λ_s)*

No data

15. *Cryoscopic Constant (k_f)*

Measurement method: calculated from ΔH_f° [36]

Table 70.8. Cryoscopic constant

k_f (K mol^{-1} kg)	Uncertainty
22.6	∿ ± 1%

References [36]

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[37] von Wartenberg, H. and Albrecht, P., Z. Elektrochem. 27, 162 (1921).

1. *Melting Temperature (T_m)*

Melting point:
Decomposes [12,13]

Anhydrous $Mg(NO_3)_2$ has been reported stable in the crystalline state up to ∿ 325°C, although the thermodynamic data are consistent with complete decomposition to MgO at this temperature.

References [1-13].

2. *Density (ρ)*

No Data

3. *Surface Tension (γ)*

No Data

4. *Viscosity (η)*

No Data

5. *Electrical Conductance (κ)*

No Data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: inhalation: low; ingestion: moderate.

(ii) Vapor pressure: $Mg(NO_3)_2.2H_2O$ melts ∿ 129°C; $Mg(NO3)_2.6H_2O$ melts ∿ 95°C; little is known of the high temperature properties of anhydrous $Mg(NO_3)_2$; onset of decomposition reaction has been observed from ∿ 130°C to ∿ 390°C, and appears dependent on the composition of the gas phase.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) On decomposition, nitrates emit toxic fumes (oxides of nitrogen) viz:

$$MNO_3 \longrightarrow MNO_2 + \tfrac{1}{2}O_2 \qquad (71.1)$$

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \qquad (71.2)$$

The subsequent decomposition reactions are complex; if the gas phase is continuously removed, the nitrite decomposition (above) to NO and NO_2 is dominant. If the gas phase is not immediately removed, the NO may re-oxidize the nitrite to nitrate.

(iii) Nitrates are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds, oils, carbon,...); aluminum alloys and bath sludges (e.g.iron oxides); magnesium alloys. Dangerous.

References [9,14-20]

7. Corrosion

Table 71.1. Corrosion studies from primary research literature

Studies in molten nitrates and nitrites	References
Fe	[21,23,25]
Fe, Co, Ni, Cr, Al,...	[22,30,31]
Cu, Pt, Au, W,...	[24,30,31]
Zn, Pb, Cu, Ni, Al	[28]
Pt, S, steel	[26]
Zr	[29]
Oxide species	[27]
Electrochemical approach	[31,33]
Thermodynamic redox diagrams	[34,36]
Annotated corrosion biblio.	[36]
Reviews/molten salts	[37-39]

No compatibility studies with molten $Mg(NO_3)_2$ were found; for effects of alkaline earth chlorides added to nitrates, see [25].

References [21-39]

8. Diffusion

No Data

9. Heat of Fusion (ΔH_f°)

No Data

10. Heat Capacity (C_p)

No Data

11. Volume Change on Melting (ΔV_f)

No Data

12. Vapor Pressure (p_{vap})

No Data

13. Thermal Conductivity (liquid) (λ_ℓ)

No Data

14. Thermal Conductivity (solid) (λ_s)

No Data

15. Cryoscopic Constant (k_f)

No Data

16. References

[1] Stull, D. R., and Prophet, H., *"JANAF Thermochemical Tables"*, 2nd Ed., NSRDS-NBS 37; U. S. Gov't Printing Office, Washington, D. C. (1971).

[2] Rossini, F. D., Wagman, D. D., Evans, W. H., Levine, S., and Jaffe, I., *"Selected Values of Chemical Thermodynamic Properties"*, NBS, Circ. 500; U. S. Gov't Printing Office, Washington, D. C. (1952).

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[34] Bartlett, H. E., and Johnson, K. E., Canad. J. Chem., 44, 2119 (1966).

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System 72 $Ca(NO_3)_2$

1. *Melting Temperature (T_m)*

Melting point:
561° ± 4°C [7]

References [1-8].

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure [9]

precision: not estimated uncertainty: ∿ ± 2%

Table 72.1. Surface tension

T (K)	γ (dyn cm^{-1})
833	101.5

References [9]

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: ingestion, moderate.

(ii) Vapor pressure: Addison and Coldrey [10] report the formation of bubbles in molten $Ca(NO_3)_2$ at its m.pt., 561°C; $Ca(NO_3)_2$ loses NO_2 on decomposition, with formation of CaO and oxygen (see (ii) below and [4]).

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) On decomposition, nitrates emit toxic fumes (oxides of nitrogen) viz:

$$2MNO_3 \longrightarrow 2MNO_2 + O_2 \qquad (72.1)$$

$$2MNO_2 \longrightarrow M_2O + NO_2 \qquad (72.2)$$

The subsequent decomposition reactions are complex; if the gas phase is continuously removed, the nitrite decomposition (above) to NO and NO_2 is dominant.

(iii) Nitrates are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon,....); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous.

References [10-16]

7. Corrosion

Table 72.2. Corrosion studies from primary research literature

Studies in molten nitrates and nitrites	References
Fe	[17,19,21]
Fe, Co, Ni, Cr, Al,...	[18,26,27]
Cu, Pt, Au, W,...	[20,26,27]
Zn, Pb, Cu, Ni, Al	[24]
Pt, S, steel	[22]
Zr	[25]
Oxide species	[23]
Electrochemical approach	[28,31]
Thermodynamic redox diagrams	[30,31]
Annotated corrosion biblio.	[32]
Reviews/molten salts	[33-35]

No compatibility studies with molten $Ca(NO_3)_2$ were found; for effects of alkaline earth chlorides added to nitrates, see [21].

References [17-35]

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

Measurement method: drop calorimetry [36]

Table 72.3. Heat of fusion

ΔH°_f (kcal mol^{-1})	Uncertainty
5.67	$\sim \pm$ 2%

$Ca(NO_3)_2$ (m.pt. 561°C) exhibits two solid state transitions at -185°C and 15°C for which the ΔH values are $\sim$ 0.9 and $\sim$ 69 cal. mol^{-1} respectively.

References [36,37]

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f° [38]

Table 72.4. Cryoscopic constant

k_f (K mol^{-1} kg)	Uncertainty
40.0	∿ ± 1%

References [38]

16. References

[1] Stull, D. R., and Prophet, H., *"JANAF Thermochemical Tables"*, 2nd Ed., NSRDS-NBS 37; U. S. Gov't Printing Office, Washington, D. C. (1971).

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[14] *Vide infra*, Ref. [9]

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[29] Johnson, K. E., *"Electrochemical Approaches to Corrosion in Molten Salts"*, Proceedings International Symposium on Metal-Slag-Gas Reactions and Processes, The Electrochemical Society, Inc., Princeton, N. J. (1975).

[30] Bartlett, H. E., and Johnson, K. E., Canad. J. Chem., 44, 2119 (1966).

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[37] Kelley, K. K., U. S. Bur. Mines Bull. 393 (1936).

[38] Janz, G. J., et al. (MSDC-RPI), unpublished work (1980).

System 73 $LiNO_2$

1. *Melting Temperature (T_m)*

Melting point:
220° ± 5°C [7]

References [1-12].

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

Measurement method: capillary technique [13]

$$\eta = -14909.1 + 87.5812T - 0.171073T^2 + 1.11184 \times 10^{-4}T^3 \quad (73.1)$$

precision: ∿ ± 0.5% uncertainty: ∿ ± 3.0%

Table 73.1. Viscosity from equation (73.1)

T (K)	η (cp)
510	9.89
520	8.34

References [13]

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [14]

$$\kappa = -0.397585 - 1.51836 \times 10^{-3}T + 7.33374 \times 10^{-6}T^2 \quad (73.2)$$

precision: ∿ ± 0.1% uncertainty: ∿ ± 5.0%

Table 73.2. Electrical conductance from equation (73.2)

T (K)	κ ($ohm^{-1}cm^{-1}$)
510	0.736
520	0.796
530	0.858

References [14]

(73) $LiNO_2$

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: ingestion: severe toxicity; there appears to be some implication of increased cancer incidence with chronic ingestion of nitrites.

(ii) Vapor pressure: $LiNO_2$ (m.pt. 220°C) melts without decomposition and appears stable to ∿ 300°C; at ∿ 350°C, it is reported to decompose slowly, and this increases rapidly with increasing temperatures. The product gases are oxides of nitrogen (toxic); see B. Disaster hazards.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) On decomposition, nitrites emit toxic fumes (oxides of nitrogen) viz:

$$2\ MNO_2 \longrightarrow M_2O + NO + NO_2 \qquad (73.3)$$

$$2MNO_2 + O_2 \longrightarrow 2MNO_3 \qquad (73.4)$$

The subsequent decomposition reactions are complex; if the gas phase is not removed, the nitrite may be oxidized to nitrate ($LiNO_3$).

(iii) Nitrites, like nitrates, are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon,....); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous.

References [15-21]

7. Corrosion

Table 73.3. Corrosion studies from primary research literature

Studies in molten nitrates and nitrites	References
Fe	[22,24,26]
Fe, Co, Ni, Cr, Al,...	[23,31,32]
Cu, Pt, Au, W,...	[25,31,32]
Zn, Pb, Cu, Ni, Al	[29]
Pt, S, steel	[27]
Zr	[30]
Oxide species	[28]
Electrochemical approach	[33,34]
Thermodynamic redox diagrams	[35,36]
Annotated corrosion biblio.	[37]
Reviews/molten salts	[38-40]

References [22-40]

8. Diffusion

No Data

9. Heat of Fusion (ΔH°_f)

No Data

10. Heat Capacity (C_p)

No Data

11. Volume Change on Melting (ΔV_f)

No Data

12. Vapor Pressure (p_{vap})

No Data

13. Thermal Conductivity (liquid) (λ_ℓ)

No Data

14. Thermal Conductivity (solid) (λ_s)

No Data

15. Cryoscopic Constant (k_f)

No Data

16. References

[1] Stull, D. R., and Prophet, H., *"JANAF Thermochemical Tables"*, 2nd Ed., NSRDS-NBS 37; U. S. Gov't Printing Office, Washington, D. C. (1971).

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[39] Ketelaar, J. A. A., Chemie. Ing. Techn., 45, 667 (1973).

[40] Smirnov, M. V. and Ozeryanaya, Nauki Tekh. Korros. Zashch. Korros., 2, 171 (1973).

System 74 $NaNO_2$

1. *Melting Temperature (T_m)*

Melting point:
282° ± 4°C [11]

References [1-15].

2. *Density (ρ)*

Measurement method: Archimedean technique [16]

$$\rho = 2.226 - 0.746 \times 10^{-3} T \quad (74.1)$$

precision: not estimated uncertainty: ∿ ± 1.0%

Table 74.1. Density from equation (74.1)

T (K)	ρ (g cm^{-3})	T (K)	ρ (g cm^{-3})
570	1.801	650	1.741
580	1.793	660	1.734
590	1.786	670	1.726
600	1.778	680	1.719
610	1.771	690	1.711
620	1.763	700	1.704
630	1.756	710	1.696
640	1.749	720	1.689

References [16,17]

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure [18]

$$\gamma = 141.7 - 0.0378\ T \quad (74.2)$$

precision: ∿ 0.5% uncertainty: ∿ ± 2%

Table 74.2. Surface tension from equation (74.2)

T (K)	γ (dyn cm^{-1})	T (K)	γ (dyn cm^{-1})
550	120.9	670	116.4
560	120.5	680	116.0
570	120.2	690	115.6
580	119.8	700	115.2
590	119.4	710	114.9
600	119.0	720	114.5
610	118.6	730	114.1
620	118.3	740	113.7
630	117.9	750	113.4
640	117.5	760	113.0
650	117.2	770	112.6
660	116.8		

References [18,19]

4. Viscosity (η)

Measurement method: capillary technique [21]

$$\eta = 187.118 - 0.876094T + 1.41024 \times 10^{-3}T^2 - 7.71608 \times 10^{-7}T^3 \quad (74.3)$$

precision: ∿ ± 0.9% uncertainty: ∿ ± 5%

Table 74.3. Viscosity from equation (74.3)

T (K)	η (cp)	T (K)	η (cp)
570	3.04	600	2.48
580	2.84	610	2.31
590	2.66		

References [17,20,21]

5. Electrical Conductance (κ)

Measurement method: classical ac technique [16]

$$\kappa = 13.20 \exp(-2600/RT) \quad (74.4)$$

precision: not estimated uncertainty: ∿ ± 5%

Table 74.4. Electrical conductance from equation (74.4)

T (K)	κ ($ohm^{-1}cm^{-1}$)	T (K)	κ ($ohm^{-1}cm^{-1}$)
570	1.33	650	1.76
580	1.38	660	1.82
590	1.44	670	1.87
600	1.49	680	1.93
610	1.54	690	1.98
620	1.60	700	2.04
630	1.65	710	2.09
640	1.71	720	2.14

References [16]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: $NaNO_2$ is permitted in food for human consumption; there appears to be some implication of increased cancer incidence with chronic ingestion of nitrites

(ii) Vapor pressure: $NaNO_2$ (m.pt. 281°C) appears to melt without onset of decomposition; decomposition is reported at ∿ 300°C; with formation of oxides of nitrogen (toxic); this increases with increasing temperatures (see B. Disaster hazards)

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) On decomposition, nitrites emit toxic fumes (oxides of nitrogen)viz:

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \quad (74.5.1)$$

$$2MNO_2 + O_2 \longrightarrow MNO_3 \quad (74.5.2)$$

The subsequent decomposition reactions are complex; if the gas phase is not continuously removed, the nitrite may be oxidized to $NaNO_3$, i.e. to the nitrate

(iii) Nitrites, like nitrates, are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon,....); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous

References [41-49]

7. Corrosion

Table 74.5. Corrosion studies from primary research literature

Studies in molten nitrates and nitrites	References
Fe	[22,24,26]
Fe, Co, Ni, Cr, Al,...	[23,31,32]
Cu, Pt, Au, W,...	[25,31,32]
Zn, Pb, Cu, Ni, Al	[29]
Pt, S, steel	[27]
Zr	[30]
Oxide species	[28]
Electrochemical approach	[33,34]
Thermodynamic redox diagrams	[35,36]
Annotated corrosion biblio.	[37]
Reviews/molten salts	[38-40]

References [22-40]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f^o)

Measurement method: drop calorimetry [50]

Table 74.6. Heat of fusion

ΔH_f° (kcal mol^{-1})	Uncertainty
2.97	∿ ± 5%

References [50]

10. Heat Capacity (C_p)

Measurement method: drop calorimetry [50]

$$C_p = 115.21 - 200.49 \times 10^{-3}T + 126.86 \times 10^{-6}T^2 \quad (74.6)$$

Temp. range: 564-630 K

precision: ∿ ± 0.1% uncertainty: ∿ ± 5%

Table 74.7. Heat capacity from equation (74.6)

T (K)	C_{p_1} (cal K^{-1} mol^{-1})	T (K)	C_{p_1} (cal K^{-1} mol^{-1})
570	42.1	610	40.1
580	41.6	620	39.7
590	41.1	630	39.2
600	40.6		

In the solid state, for the temperature range: 383-533 K, the heat capacity for $NaNO_2$ [1] is expressed by:

$$C_p = 38.42 + 230.19 \times 10^{-3}T - 188.76 \times 10^{-6}T^2 \quad (74.7)$$

precision: ∿ ±1% uncertainty: ∿ ± 5%

References [50]

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [51]

Table 74.6. Volume change on melting

$(\Delta V_f/V_s)$	Uncertainty
16.5%	∿ ± 10%

References [51]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

Measurement method: steady-state method; coaxial cylinders [52]

$$\lambda = -4.9249 \times 10^{-4} + 3.745 \times 10^{-6} T \quad (74.8)$$

precision: ∿ ± 1% uncertainty: ∿ ± 10%

Table 74.7. Thermal conductivity of melt from equation (74.8)

T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})	T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})
560	16.0	580	16.8
570	16.4	590	17.2

References [52-56]

14. Thermal Conductivity (solid) (λ_s)

Measurement method: co-axial cylinders; steady-state method [52]

precision: not estimated uncertainty: ∿ ± 10%

Table 74.8. Thermal conductivity of solid $NaNO_2$

T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})
549	15.9

(Melting point, $NaNO_2$: 558 K)

References [52,54]

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f° [51]

Table 74.9. Cryoscopic constant

k_f (K mol^{-1} kg)	Uncertainty
14.2	∿ ± 1%

References [51]

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System 75 KNO_2

1. *Melting Temperature (T_m)*

Melting point:
440° ± 5°C [1]

References [1-13].

2. *Density (ρ)*

Measurement method: Archimedean technique [14]

$$\rho = 2.167 - 6.60 \times 10^{-4} T \quad (75.1)$$

precision: not estimated uncertainty: ∿ ± 2.0%

Table 75.1. Density from equation (75.1)

T (K)	ρ (g cm^{-3})
700	1.705
710	1.698
720	1.692
730	1.685
740	1.679
750	1.672

References [14]

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure [15]

$$\gamma = 151.6 - 0.0623\ T \quad (75.2)$$

precision: ∿ ± 0.5% uncertainty: ∿ ± 2%

Table 75.2. Surface tension from equation (75.2)

T (K)	γ (dyn cm^{-1})	T (K)	γ (dyn cm^{-1})
720	106.8	750	104.9
730	106.1	760	104.3
740	105.5	770	103.6

References [15]

4. *Viscosity (η)*

Measurement method: capillary technique [17]

$$\eta = 864.798 - 3.61760T + 5.06274 \times 10^{-3} T^2 - 2.36530 \times 10^{-6} T^3 \quad (75.3)$$

precision: ∿ ± 0.3% uncertainty: ∿ ± 2%

Table 75.3. Viscosity from equation (75.3)

T (K)	η (cp)
700	1.92
710	1.86
720	1.81

References [16-19]

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [18]

$$\kappa = -4.167433 + 1.148389 \times 10^{-2}T - 5.451471 \times 10^{-6}T^2 \quad (75.4)$$

precision: ∿ ± 0.1% uncertainty: ∿ ± 5%

Table 75.4. Electrical conductance from equation (75.4)

T (K)	κ (ohm^{-1} cm^{-1})	T (K)	κ (ohm^{-1} cm^{-1})
710	1.238	740	1.345
720	1.275	750	1.379
730	1.311		

References [18]

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: ingestion toxicity rating, severe; there appears some implication of increased cancer incidence with chronic ingestion of nitrites.

(ii) Vapor pressure: KNO_2 (m.pt.440°C) melts without decomposition, but at ∿ 500°C, thermally decomposes into oxides of nitrogen, and at higher temperatures, to nitrogen and oxygen as gaseous products (see: B. Disaster hazards).

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) On decomposition, nitrites emit toxic fumes (oxides of nitrogen) viz:

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \quad (75.5)$$

$$MNO_3 \longrightarrow MNO_2 + \tfrac{1}{2}O_2 \quad (75.6)$$

The subsequent decomposition reactions are complex; if the gas phase is continuously removed, the nitrite decomposition (above to NO and NO_2 is dominant.

In the temperature range 550-600°C, and under oxygen, the conversion of KNO_2 to KNO_3 goes to completion; between 650-750°C, the two salts interconvert (see above), KNO_3 becoming increasingly unstable; above 800°C, the nitrite decomposition: $2\ KNO_2 \longrightarrow K_2O + N_2 + {}^3/_2O_2$ goes to completion.

(iii) Nitrites, like nitrates, are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon,...); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous.

References [20-29]

7. Corrosion

Table 75.5. Corrosion studies from primary research literature

Studies in molten nitrates and nitrites	References
Fe	[30,32,34]
Fe, Co, Ni, Cr, Al,...	[31,39,40]
Cu, Pt, Au, W,...	[33,39,40]
Zn, Pb, Cu, Ni, Al	[37]
Pt, S, steel	[35]
Zr	[38]
Oxide species	[36]
Electrochemical approach	[41,42]
Thermodynamic redox diagrams	[43,44]
Annotated corrosion biblio.	[45]
Reviews/molten salts	[46-48]

References [30-48]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f^o)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [49]

Table 75.6. Volume change on melting

$(\Delta V_f/V_s)$	Uncertainty
8.0%	$\sim \pm$ 10%

References [49]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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1. *Melting Temperatures (T_m)*

Pure substance melting points:

LiF: 848°C

NaF: 995°C

Eutectic melting point:

649°C, composition: 39 mol % NaF

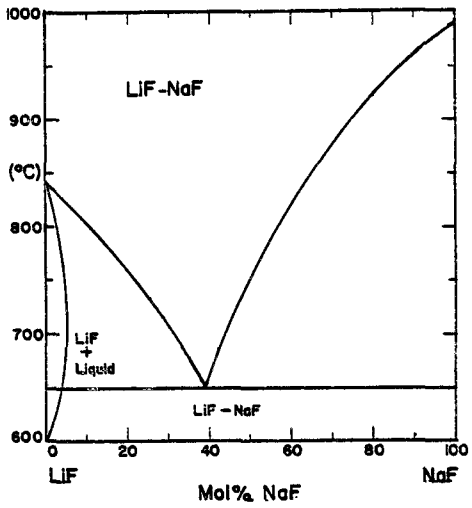

Figure 76.1 LiF-NaF phase diagram

References [1-26]

2. *Density (ρ)*

Measurement method: Archimedean technique [27]

Equation:

$$\rho = a + bT \quad (76.1)$$

precision: in table 76.1 uncertainty: ∿ ± 1.0%

Table 76.1. Parameters of equation (76.1) and precisions

(mol % NaF)	a	$-b \times 10^4$	Precision	T range(K)
10	2.3981	5.102	0.01%	1130-1320
20	2.4254	5.118	0.02%	1130-1320
30	2.4709	5.277	0.01%	1130-1320
40	2.5325	5.552	0.01%	1130-1320
50	2.5565	5.596	0.01%	1130-1320
60	2.5791	5.575	0.01%	1130-1320
70	2.5784	5.434	0.01%	1130-1320
80	2.6766	6.043	0.28%	1230-1320
90	2.9187	7.789	0.01%	1280-1320

Table 76.2. Density (g cm^{-3}) from equations in table 76.1

T (K)	Mol % NaF					
	10	30	50	70	80	90
1130	1.822	1.875	1.924	1.964		
1140	1.816	1.869	1.919	1.959		
1150	1.811	1.864	1.913	1.953		
1160	1.806	1.859	1.907	1.948		
1170	1.801	1.853	1.902	1.943		
1180	1.796	1.848	1.896	1.937		
1190	1.791	1.843	1.891	1.932		
1200	1.786	1.838	1.885	1.926		
1210	1.781	1.832	1.879	1.921		
1220	1.776	1.827	1.874	1.915		
1230	1.770	1.822	1.868	1.910	1.933	
1240	1.765	1.817	1.863	1.905	1.927	
1250	1.760	1.811	1.857	1.899	1.921	
1260	1.755	1.806	1.851	1.894	1.915	
1270	1.750	1.801	1.846	1.888	1.909	
1280	1.745	1.795	1.840	1.883	1.903	1.922
1290	1.740	1.790	1.835	1.877	1.897	1.914
1300	1.735	1.785	1.829	1.872	1.891	1.906
1310	1.730	1.780	1.823	1.867	1.885	1.898
1320	1.725	1.774	1.818	1.861	1.879	1.891

References [27-31]

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure [32]

Equation:

$$\gamma = a + bT \quad (76.2)$$

precision: in table 76.3 uncertainty: $\sim \pm 3.0\%$

Table 76.3. Parameters of equation 76.2 and precision

LiF-NaF (mol % NaF)	a	b x 10^3	Precision	T range(K)
40	321.52	-99.33	*	970-1210

*not estimated; parameters from graphical data

Table 76.4. Surface tension LiF-NaF (40mol% NaF) from equation in table 76.3

T (K)	γ (dyn cm^{-1})	T (K)	γ (dyn cm^{-1})
970	225.17	1110	211.27
990	223.19	1130	209.28
1010	221.20	1150	207.29
1030	219.21	1170	205.31
1050	217.23	1190	203.32
1070	215.24	1210	201.33
1090	213.25		

References [32,33]

4. *Viscosity (η)*

Measurement method: capillary, and oscillational sphere techniques [34]

Data set was limited to 2 points; the experimental values [34] are given in table 76.5.

Table 76.5. Viscosity at 40 mol% NaF

T (K)	η (cp)
973.2	3.20
1073.2	2.35

References [34]

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [35]

Equation:

$$\kappa = a + bT \quad (76.3)$$

precision: in table 76.6 uncertainty: $\sim \pm 3.0\%$

Table 76.6. Parameters of equation (76.3) and precisions

Mol % NaF	-a	b x 10^3	Precision	T range(K)
15.0	0.4123	6.964	0.03%	1060-1340
30.0	0.4307	6.115	0.02%	1020-1340
38.0	0.1798	5.551	0.03%	1030-1340
50.0	0.6533	5.653	0.03%	1070-1340
60.0	0.2936	4.354	0.02%	1130-1340
80.0	0.8848	5.166	0.03%	1180-1340

Table 76.7. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 76.6

T (K)	Mol % NaF					
	15.0	30.0	38.0	50.0	60.0	80.0
1020		5.81				
1040		5.93	5.59			
1060	6.97	6.05	5.70			
1080	7.11	6.17	5.82	5.45		
1100	7.25	6.30	5.93	5.57		
1120	7.39	6.42	6.04	5.68		
1140	7.53	6.54	6.15	5.79	5.26	
1160	7.67	6.66	6.26	5.90	5.34	
1180	7.81	6.79	6.37	6.02	5.43	5.21
1200	7.95	6.91	6.48	6.13	5.52	5.31
1220	8.09	7.03	6.59	6.24	5.61	5.42
1240	8.22	7.15	6.70	6.36	5.69	5.52
1260	8.36	7.27	6.81	6.47	5.78	5.62
1280	8.50	7.40	6.93	6.58	5.87	5.73
1300	8.64	7.52	7.04	6.70	5.95	5.83
1320	8.78	7.61	7.15	6.81	6.04	5.93
1340	8.92	7.76	7.26	6.92	5.13	6.04

References [35]

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritants and toxic.

(ii) Vapor pressure: LiF, at m.pt. (848°C), $\sim 8.8 \times 10^{-3}$ mm; NaF at m.pt. (995°C), ~ 0.5 mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure: i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [36-41]

7. Corrosion

Table 76.8. Corrosion studies from primary research literature

Studies	References
Cr	[42]
Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[43,44]
SSNI-12P	[45]
Quartz	[46]
Al	[47]
Various metals	[48]
Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[49-64,71,72]
Electrochemical behavior of oxide ions and related species in molten fluorides	[65-67]
Electroanalytical studies in molten fluorides	[68]
Annotated corrosion biblio.	[69]
Corrosion: molten fluorides (survey)	[70]

Compatability studies: various molten fluorides and principally with LiF and NaF. For thermodynamic (theoretical) considerations, and some considerations relative to commercial grade fluorides, and the use of "gettering" to lower impurity levels, see [70]

References [42-72]

8. Diffusion

No data

9. Heat of fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [73]

Table 76.9. Volume change on melting

Binary eutectic (mol % NaF)	$(\Delta V_f/V_s)$	Uncertainty
39%	19.6%	$\sim \pm$ 10%

References [73]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 77 LiF-KF

1. *Melting Temperatures (T_m)*

Pure substance melting points:

LiF: 848°C
KF: 856°C

Eutectic melting point:

492°C, composition: 50 mol % LiF

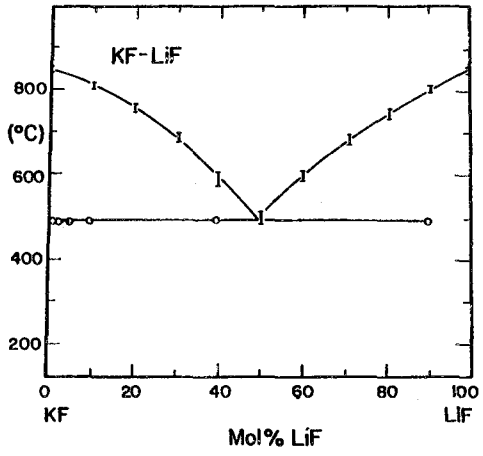

Figure 77.1. LiF-KF phase diagram

References [1-27]

2. *Density (ρ)*

Measurement method: Archimedean technique [32]

Equation:

$$\rho = a + bT \quad (77.1)$$

precision: in table 77.1 uncertainty: ∿ ± 10%

Table 77.1. Parameters of equation (77.1) and precisions

(Mol % LiF)	a	$-b \times 10^4$	Precision	T range(K)
0.0	2.555	6.241	0.3%	1140-1340
20.0	2.483	5.680	0.7%	1080-1340
35.0	2.484	5.872	0.6%	980-1340
50.0	2.407	5.362	0.4%	1120-1340
70.0	2.273	4.663	1.0%	1120-1340
85.0	2.278	4.663	0.6%	1140-1340
100.0	2.074	3.321	0.7%	1140-1340

Table 77.2. Density (g cm^{-3}) from equations in table 77.1

T (K)	Mol % LiF				
	20.0	35.0	50.0	70.0	85.0
980		1.909			
1000		1.879			
1020		1.885			
1040		1.873			
1060		1.862			
1080	1.870	1.850			
1100	1.858	1.838			
1120	1.847	1.826	1.806	1.721	1.756
1140	1.835	1.815	1.796	1.711	1.746
1160	1.824	1.803	1.785	1.701	1.737
1180	1.813	1.791	1.774	1.692	1.728
1200	1.801	1.779	1.764	1.682	1.718
1220	1.790	1.768	1.753	1.672	1.709
1240	1.779	1.756	1.742	1.662	1.700
1260	1.767	1.744	1.731	1.652	1.690
1280	1.756	1.732	1.721	1.642	1.681
1300	1.745	1.721	1.710	1.632	1.672
1320	1.733	1.709	1.690	1.623	1.662
1340	1.722	1.697	1.688	1.613	1.653

References [28-33]

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure [34]

Equation: (surface tension-composition isotherm)

$$\gamma = a + bC + cC^2 + dC^3 \quad (77.2)$$

(C = mol % LiF)

precision: in table 77.3 uncertainty: $\sim \pm 5.0\%$

Table 77.3. Parameters of equation (77.2) and precisions

T (K)	a	$-b \times 10^2$	$c \times 10^3$	$d \times 10^4$	Precision
1073.16	148.38	1.96	1.32	0.98	0.9%
1173.16	140.96	2.94	0.10	1.09	0.3%

Table 77.4. Surface tension (dyn cm^{-1}) from equations in table 77.3

Mol % LiF	T(°K)	
	1073.16	1173.16
0	148.4	141.0
10	148.4	140.8
20	149.3	141.3
30	151.6	143.1
40	156.0	146.9
50	163.0	153.4
60	173.2	163.1
70	187.2	176.8
80	205.6	195.1
90	229.0	218.6
100	257.9	248.0

References [34]

4. *Viscosity* (η)

No data

5. *Electrical Conductance* (κ)

Measurement method: classical ac technique [31]

Equation:

$$\kappa = a + bT \qquad (77.3)$$

precision: in table 77.5 uncertainty: $\sim \pm 5.0\%$

Table 77.5. Parameters of equation (77.3) and precisions

Mol % LiF	-a	b x 10^3	Precision	T range(K)
20.0	0.3994	3.434	0.02%	1110-1340
35.0	1.1870	4.064	0.04%	1020-1340
50.0	1.5420	4.448	0.04%	1020-1340
70.0	0.9420	4.610	0.03%	1110-1340
85.0	0.3625	5.475	0.03%	1140-1340

Table 77.6. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 77.5

T (K)	Mol % LiF				
	20.0	35.0	50.0	70.0	85.0
1020		2.96	3.00		
1050		3.08	3.13		
1080		3.20	3.26		
1110	3.41	3.32	3.40	4.18	
1140	3.52	3.45	3.53	4.31	5.88
1170	3.62	3.57	3.66	4.45	6.04
1200	3.72	3.69	3.80	4.59	6.21
1230	3.82	3.81	3.93	4.73	6.37
1260	3.93	3.93	4.06	4.87	6.54
1290	4.03	4.06	4.20	5.01	6.70
1320	4.13	4.18	4.33	5.14	6.87

References [31]

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: LiF, severe; KF, severe; inorganic fluorides are generally irritant and toxic.

(ii) Vapor pressure: LiF, at m.pt. (848°C), $\sim 8.8 \times 10^{-3}$mm; KF at m.pt. (856°C), $\sim$ 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosion": i.e., explosive generating of steam due to bulk water "carry-over: and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [35-40]

7. Corrosion

Table 77.7. Corrosion studies from primary research literature

Studies	References
Cr	[41]
Ni-Cr-Fe alloys (INOR-8; Hastelloys N, B, W,...)	[42-47]
Al	[48]
Cb-Zr (99-1)	[49,50]
Ta-W-Zr-Cb (28-10.5-0.9-60.6) Ta, W-Cb (10-10-80)	[50]
Electrochemical behavior of oxide ions and related species in molten fluorides	[51-53]
Electroanalytical studies in molten fluorides	[54]
Annotated corrosion biblio.	[55]
Corrosion: molten fluorides (survey)	[56]

Compatibility studies with various molten fluorides, including LiF and KF. No studies specifically with LiF-KF molten mixtures found.

References [41-56]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

Measurement method: calculated [57]

Table 77.8. Heat of fusion

Composition (mol % LiF)	T_m (°C)	ΔH_f° (kcal mol^{-1})	Uncertainty
52.4	492°	7.0	∿ ± 5%

References [57]

10. Heat Capacity (C_p)

Measurement method: calculated [58]

Table 77.9. Heat capacity

Composition LiF:KF(mol %)	C_p (cal K^{-1} mol^{-1})	T range (K)	Uncertainty
52.4:47.6	16.1	T_m(765) - 850	$\sim \pm$ 10%

For the above composition, $C_{p(s)}$ = 13.2 (cal K^{-1} mol^{-1}); uncertainty of estimated value, $\sim \pm$ 10%.

References [58]

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [59]

Table 77.10. Volume change on melting

Binary eutectic (mol % KF)	$(\Delta V_f/V_s)$	Uncertainty
50	21%	$\sim \pm$ 10%

References [59]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f° [59]

Table 77.11. Cryoscopic constant

Binary eutectic (mol % KF)	K_f (K mol^{-1}kg)	Uncertainty
47.6	6.86	$\sim \pm$ 1.0%

References [59]

16. References

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System 78 LiF-NaF-KF

1. *Melting Temperatures (T_m)*

Pure substance melting points:

LiF: 848°C

NaF: 995°C

KF: 856°C

Eutectic melting point:

454°C, composition: 46.5 mol % LiF; 11.5 mol % NaF; 42.0 mol % KF

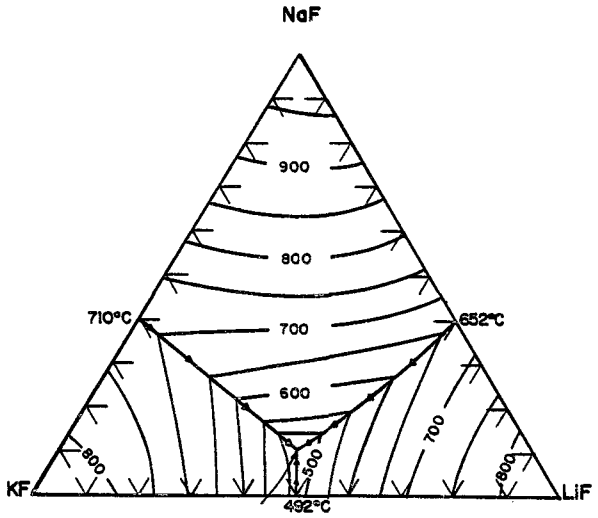

Figure 78.1. LiF-NaF-KF phase diagram

References [1-21]

2. *Density (ρ)*

Measurement method: Archimedean technique [22]

Equation:

$$\rho = a + bT \quad (78.1)$$

precision: in table 78.1 uncertainty: ∿ ± 2.0%

Table 78.1. Parameters of equation (78.1) and precision

Composition	a	$-b \times 10^3$	Precision	T range(K)
ternary eutecic[a]	2.5793	0.624	*	940-1170

[a] LiF:NaF:KF::46.5:11.5:42.0 (mol %)

(*) insufficient data for estimate

Table 78.2. Density of LiF-NaF-KF eutectic from equation in table 78.1

T (K)	ρ (g cm^{-3})	(K)	ρ (g cm^{-3})
940	1.993	1060	1.918
950	1.987	1070	1.912
960	1.980	1080	1.905
970	1.974	1090	1.899
980	1.968	1100	1.893
990	1.962	1110	1.887
1000	1.955	1120	1.880
1010	1.949	1130	1.874
1020	1.943	1140	1.868
1030	1.937	1150	1.862
1040	1.930	1160	1.855
1050	1.924	1170	1.849

References [22]

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure technique [23]

Equation:

$$\gamma = a + bT \quad (78.2)$$

precision: in table 78.3 uncertainty: $\sim \pm$ 2.0%

Table 78.3. Parameters of equation (78.2) and precision

Composition	a	b x 10^3	Precision	T range(K)
ternary eutectic[a]	272.6	-101.4	$\sim$ 0.1%	770-1040

[a] LiF:NaF:KF::46.5:11.5:42.0 (mol %)

Table 78.4. Surface tension of LiF-NaF-KF eutectic from equation in table 78.3

T (K)	γ (dyn cm^{-1})	T (K)	γ (dyn cm^{-1})
770	194.5	910	180.3
780	193.5	920	179.3
790	192.5	930	178.3
800	191.5	940	177.3
810	190.5	950	176.3
820	189.5	960	175.3
830	188.4	970	174.2
840	187.4	980	173.2
850	186.4	990	172.2
860	185.4	1000	171.2
870	184.4	1010	170.2
880	183.4	1020	169.2
890	182.4	1030	168.2
900	181.3	1040	167.1

References [23]

4. *Viscosity (η)*

Measurement method: oscillating cylinder technique [24]

Equation:

$$\eta = A \exp (E/RT) \quad (78.3)$$

precision: in table 78.5 uncertainty: ∿ ± 2.0%

Table 78.5. Parameters of equation (78.3) and precision

Composition	A x 10^2	E (cal mol^{-1})	Precision	T range(K)
ternary eutectic[a]	2.487	8894	∿ ± 4%[b]	770-970

[a] LiF:NaF:KF::46.5:11.5:420 (mol %)

[b] Tørklep and Øye [24] reported second order exponential function:

$$\eta = 1.633 \exp (-2762.9/T + 3.1095 \times 10^6/T^2) \quad (78.3.1)$$

fitted the data over the whole range with a precision of ∿ 0.27%.

Table 78.6. Viscosity of LiF-NaF-KF ternary eutectic from equation (78.3)

T (K)	η (cp)	T (K)	η (cp)
770	8.319	880	4.023
780	7.722	890	3.799
790	7.181	900	3.593
800	6.690	910	3.402
810	6.243	920	3.225
820	5.836	930	3.060
830	5.465	940	2.908
840	5.125	950	2.765
850	4.814	960	2.633
860	4.528	970	2.509
870	4.265		

References [24,25]

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [26,27]

Equation:

$$\kappa = a + bT + cT^2 \quad (78.4)$$

precision: in table 78.7 uncertainty: ∿ ± 5.0%

Table 78.7. Parameters of equation (78.4) and precision

Composition	a	b x 10^3	c x 10^6	Precision	T range(K)
Ternary eutectic (a)	-7.0271	15.740	-7.025	∿2%	790-1100

(a) LiF:NaF:KF::46.5:11.5:42.0 (mol %)

Table 78.8. Specific conductance of LiF-NaF-KF eutectic from equation in table 78.7

T (K)	κ ohm^{-1} cm^{-1}	T (K)	κ (ohm^{-1} cm^{-1})
790	1.023	950	1.586
800	1.069	960	1.609
810	1.113	970	1.631
820	1.156	980	1.651
830	1.196	990	1.670
840	1.238	1000	1.688
850	1.276	1010	1.704
860	1.314	1020	1.719
870	1.349	1030	1.732
880	1.384	1040	1.744
890	1.417	1050	1.755
900	1.449	1060	1.764
910	1.479	1070	1.772
920	1.508	1080	1.778
930	1.535	1090	1.783
940	1.561	1100	1.787

References [26-28]

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritants and toxic.

(ii) Vapor pressure: KF, at m.pt. (856°C), ∿ 0.5mm; NaF, at m.pt. (995°C), ∿ 0.5mm; LiF at m.pt. (848°C) ∿ 8.8 x 10^{-5}mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [29-34]

7. Corrosion

Table 78.9. Corrosion studies from primary research literature

Studies	References
Cr	[35]
Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[36,37]
SSNI-12P	[38]
Quartz	[39]
Al	[40]
Various Metals	[41]
Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[42-57,64,65]
Electro-chemical behavior of oxide ions and related species in molten fluorides	[58-60]
Electroanalytical studies in molten fluorides	[61]
Annotated corrosion biblio.	[62]
Corrosion: molten fluorides (survey)	[63]

Compatibility studies: various molten fluorides and principally with LiF, NaF and KF. For thermodynamic (theoretical) considerations, and some considerations relative to commercial grade fluorides, and the use of "gettering" to lower impurity levels, see [63].

References [35-65]

8. Diffusion

Measurement method: cited in tabulations

List of diffusing species investigated in LiF-Na-KF [46.5-11.5- 42 mol %] as solvent

Fe^{2+}, Nb(IV), Nb(V), Ni^{2+}, Ta(V), Th(IV), Ti(IV)

precision: in table 78.11 uncertainty: **in table 78.10**

Table 78.10. *Diffusion techniques, uncertainties and species*

Diffusion technique of recommended study	Uncertainty (in values of D)	Species
chronopotentiometry	∿ ± 10%	Ta(V), Nb(IV), Nb(V), Ti(IV)
rapid scan voltammetry	∿ ± 10%	Fe^{2+}, Ti(IV), Ni^{2+}, Th(IV)

Equation:

$$D = A \exp [-E/RT] \quad (78.5)$$

Table 78.11. Parameters of diffusion equation (78.5) and recommended study

Species	A x 10^3 (cm^2 s^{-1})	E (cal mol^{-1})	Temp. range (K)	Precision	Recommended study
Ni^{2+}	391.6	19810	773-873	∿ ± 10.8%	1

Table 78.12. Diffusion coefficients for Ni^{2+} from equation in table 78.11

T (K)	D x 10^5 (cm^2 s^{-1})	T (K)	D x 10^5 (cm^2 s^{-1})
770	0.09	830	0.24
780	0.11	840	0.27
790	0.13	850	0.32
800	0.15	860	0.36
810	0.18	870	0.41
820	0.21		

Table 78.13. Diffusion coefficients for species not in tables 78.11 and 78.12

Species	T (K)	D x 10^5 (cm^2 s^{-1})	Recommended study
Fe^{2+}	773	∿ 0.1	2
Nb(IV)	1023	∿ 5.02	6
Nb(V)	1023	∿ 1.5	6
Ta(V)	1023	∿ 1.5	5,7
Ti(IV)	773	∿ 0.22	3
Th(IV)	773	∿ 0.18	4

References Fe^{2+}, 68; Nb(IV), 72; Nb(V), 72; Ni^{2+},67; Ta(V), Th(IV), 70; Ti(IV), 69

9. Heat of Fusion (ΔH_f°)

Measurement method: differential scanning calorimetry [83]

Table 78.14. Heat of fusion

Composition NaF:KF:LiF (mol %)	T_m (°C)	ΔH_f° (kcal mol^{-1})	Uncertainty
11.5:42.0:46.5	462°	3.95	∿ ± 2%

The melting point on p. 192 is based on phase-rule type (cooling) curves; the value above is recommended as more exact [83].

References [73,83]

10. Heat Capacity (C_p)

Measurement method: differential scanning calorimetry [83]

Table 78.15. Heat capacity

Composition LiF:NaF:KF (mol %)	C_p (cal K^{-1} mol^{-1}	T range (K)	Uncertainty
46.5:11.5:42.0	18.8	750-830	∿ ± 4%

For the above composition, $C_{p(s)}$ = 12.8 (cal K^{-1} mol^{-1}); uncertainty, ∿ ± 4%.

References [74,83,84]

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

Measurement method: modified parallel plate [75,76]

Equation:

$$\lambda = a + bT + cT^2 \quad (78.6)$$

precision: in table 78.16 uncertainty: ∿ ± 25%;

Table 78.16. Parameters of equation (78.6), precision, and temp. range

Composition	a x 10^2	-b x 10^3	c x 10^6	Precision	T range(K)
ternary eutectic(a)	5.8049	0.1444	0.1009	*	800-920

(a) LiF:NaF:KF::46.5:11.5:42.0 (mol %) * not estimated; graphical data

Table 78.17. Thermal conductivity of molten eutectic from equation in table 78.16

T (K)	λ x 10^4 (cal cm^{-1} s^{-1} K^{-1})	T (K)	λ x 10^4 (cal cm^{-1} s^{-1} K^{-1})
800	71.1	870	87.9
810	72.9	880	91.1
820	74.9	890	94.6
830	77.1	900	98.2
840	79.5	910	102.0
850	82.1	920	106.0
860	84.9		

The containing material was Inconel. An analysis of the eutectic prior to the the measurements showed the following impurity content initially (by weight, as metals): total, 0.13%; by trace metal content: Fe, 0.055%; Al, 0.012% Ni, 0.009%, Pb, 0.014%, Mn, 0.010%, Mg, 0.008%, and "others", 0.002%. On completion of the measurements, the above showed little change, except that chromium had increased to ∿ 0.12%.

The thermal conductivity was observed to decrease with prolonged contact of the molten eutectic with Inconel. After cycling the above melt approximately three times between the limits 850°C-500°C over a period 6-10 days, the λ values were 20-30% lower. The thermal conductivity, over the same temperature range, was given by:

$$\lambda = 1.7726 \times 10^{-2} - 40.81 \times 10^{-6}T + 32.67 \times 10^{-9}T^2 \quad (78.7)$$

The uncertainty limits are ∿ ± 25%, the precision could not be estimated, since the results were reported graphically. The decrease in radiant transmission is presumably due to the solution of an absorbing species in the dissolution of the Inconel by the molten fluoride mixture.

References [75-82]

14. Thermal Conductivity (solid) (λ_s)

Measurement method: modified parallel plate technique : solid state [76]

Table 78.18. Thermal conductivity of eutectic solid

Composition(mol %)				λ	Precision	Uncertainty
NaF	KF	LiF	(K)	(cal cm^{-1} s^{-1} K^{-1})		
11.5	42.0	46.5	(a)	11.16	*	$\sim \pm$ 20%

(a) temperature of solid-state measurement not cited in [76]
* not estimated; insufficient data

References [76]

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f° [83]

Table 78.19. Cryoscopic Constant

Composition	k_f (K mol^{-1} kg)	Uncertainty
Ternary eutectic (a)	11.2	$\sim \pm$ 1%

(a) LiF:NaF:KF: 46.5:11.5:42.0 (mol %)

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System 79 CaF_2-LiF

1. *Melting Temperatures (T_m)*

Pure substance melting points:

LiF: 848°C

CaF_2: 1418°C

Eutectic melting point:

765°C, composition: 79 mol % LiF

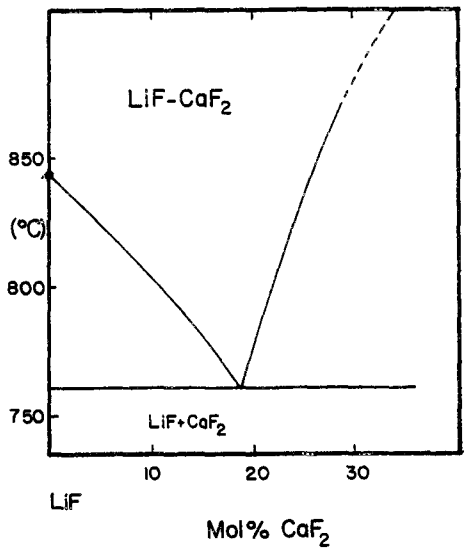

Figure 79.1. CaF_2-LiF phase diagram

References [1-29]

2. *Density (ρ)*

Measurement method: Archimedean technique [31]

Equation

$$\rho = a + bT \quad (79.1)$$

precision: in table 79.1 uncertainty: ∿ ± 1.0%

Table 79.1. Parameters of equation (79.1) and precisions

(Mol % LiF)	a	$-b \times 10^4$	Precision	T range(K)
70.0	2.809	5.755	1.9%	1155-1350
80.0	2.453	3.704	1.1%	1080-1350
86.0	2.336	3.640	0.7%	1095-1350
93.0	2.120	2.621	0.7%	1125-1350
100.0	2.074	3.321	0.7%	1125-1350

Table 79.2. Density (g cm^{-3}) from equations in table 79.1

T (K)	Mol % LiF			
	70.0	80.0	86.0	93.0
1080		2.053		
1110		2.042	1.932	
1140		2.031	1.921	1.821
1170	2.136	2.020	1.910	1.813
1200	2.118	2.009	1.899	1.805
1230	2.101	1.997	1.888	1.798
1260	2.084	1.986	1.877	1.790
1290	2.067	1.975	1.866	1.782
1335	2.049	1.964	1.856	1.774
1350	2.032	1.953	1.845	1.766

References [30,31]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [30]

Equation:

$$\kappa = a + bT \quad (79.2)$$

precision: in table 79.3 uncertainty: $\sim \pm 10\%$

Table 79.3. Parameters of equation (79.2) and precisions

Mol % LiF	a	b x 10^3	Precision	T range(K)
70.0	-0.3716	5.722	0.05%	1160-1340
80.0	-1.514	7.448	0.05%	1090-1340
86.0	-0.0841	6.636	0.03%	1090-1340
93.0	1.786	5.673	0.03%	1130-1340

Table 79.4. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 79.3

T (K)	Mol % LiF			
	70.0	80.0	86.0	93.0
1090		6.60	6.39	
1110		6.75	6.52	
1130		6.90	6.66	8.20
1150		7.05	6.79	8.31
1170	6.32	7.20	6.92	8.42
1190	6.44	7.35	7.06	8.54
1210	6.55	7.50	7.19	8.65
1230	6.67	7.65	7.32	8.76
1250	6.78	7.80	7.45	8.88
1270	6.90	7.95	7.59	8.99
1290	7.01	8.09	7.72	9.10
1310	7.12	8.24	7.85	9.22
1330	7.24	8.39	7.98	9.33

References [30,31]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritant and toxic.

(ii) Vapor pressure: LiF at m.pt. (848°C), $\sim 8.8 \times 10^{-3}$mm; CaF_2 at m.pt. (1418°C) $\sim < 0.5$mm.

B. Disaster hazards

(i) Molten salt bath "explosion": i.e., explosive generating of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [32-38]

7. Corrosion

Table 79.5. Corrosion studies from primary research literature

Studies	References
Cr	[39]
Ni-Cr-Fe	[40,41]
INOR-8	[41-44]
Al	[45,46]
Ni-Mo-Cr-Fe (Hastelloy)	[47-49]
Inconel	[44]
Cb-Zr; Ta-W-Zr-Cr; Ta-W-Cb	[50,51]
Corrosion: molten fluorides (survey)	[52,53]
Electrochemical behavior of oxide ions and related species in molten fluorides	[54-56]
Electroanalytical studies in molten fluorides	[57]
Annotated corrosion biblio.	[58]

Compatibility studies: various molten fluorides, but principally with molten LiF. No compatibility studies with CaF_2-LiF found. See [53] for discussion of impurity effects, and "gettering" techniques.

References [39-58]

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [59]

Table 79.6. Volume change on melting

Binary eutectic (mol % LiF)	$(\Delta V_f/V_s)$	Uncertainty
79	21.7%	$\sim \pm$ 10%

References [59]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 80 LiF-BaF_2

1. *Melting Temperatures (T_m)*

Pure substance melting points:

LiF: 848°C
BaF_2: 1418°C

Eutectic melting point:

765°C, composition: 18.3 mol % BaF_2 (36.6 equiv. % BaF_2)

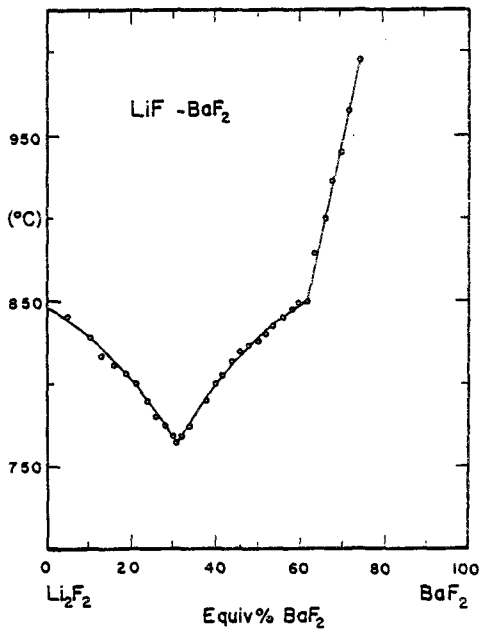

Figure 80.1. LiF-BaF_2 phase diagram

References: [1-22]

2. *Density (ρ)*

Measurement method: Archimedean technique [23]

Equation:
(composition-density isotherms)

$$\rho = a + bC + cC^2 + dC^3 \quad (80.1)$$

(C = mol % BaF_2)

precision: in table 80.1 uncertainty: ∿ ± 1.5%

Table 80.1. Parameters of equation (80.1) and precision

T (K)	a	b x 10^2	c x 10^4	d x 10^6	Precision
1573	1.5873	6.920	-7.386	2.808	∿ 1%

Table 80.2. Density for isotherm at 1573K from equation in table 80.1

Mol % BaF_2	ρ (g cm^{-3})	Mol % BaF_2	ρ (g cm^{-3})
0	1.587	60	3.687
10	2.208	70	3.775
20	2.698	80	3.834
30	3.074	90	3.880
40	3.353	100	3.929
50	3.552		

References [23]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritants and toxic.

(ii) Vapor pressure: at m.pt. (848°C), ∿ 8.8 x 10^{-3}mm; BaF_2, at m.pt. (1320°C), ∿ < 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosion": i.e., explosive generating of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [24-29]

7. Corrosion

Table 80.3. Corrosion studies from primary research literature

Studies (various molten fluorides)	References
Cr	[31]
Ni-Cr-Fe	[32,33]
INOR-8	[33-36]
Al	[37,38]
Ni-Mo-Cr-Fe (Hastelloy)	[39,47,48]
Inconel	[36]
Cb-Zr; Ta-W-Zr-Cr; Ta-W-Cb	[49.50]
Corrosion: molten fluorides (survey)	[41-43]
Electro-chemical behaviour of oxide ions and related species in molten fluorides	[44]
Electro-analytical studies in molten fluorides	[45]
Annotated corrosion biblio.	[40,46]

Compatibility studies: various molten fluorides, and principally with molten LiF. No studies specific to BaF_2 were found. For thermodynamic (theoretical) considerations, and some considerations relative to commercial grade fluorides, and the use of "gettering" to lower impurity levels, see [46].

References [30-50]

8. Diffusion

Measurement method: chronopotentiometry [51]

Diffusing species investigated in $LiF-BaF_2$ [38.0-62.0 mol %] as solvent:

$$Cl^{3+},\ U^{4+},\ Zr^{4+}$$

precision: not estimated uncertainty: in table 80.4

Table 80.4. Diffusion coefficients and uncertainties

Species	T (K)	D x 10^5 (cm^2 s^{-1})	Uncertainty
Cl^{3+}	1089	1.5	∿ ± 13%
U^{4+}	1113	1.9	∿ ± 10%
Zr^{4+}	1123	0.8	∿ ± 10%

References [51]

9. Heat of Fusion (ΔH_f°)

No Data

10. Heat Capacity (C_p)

No Data

11. Volume Change on Melting (ΔV_f)

No Data

12. Vapor Pressure (p_{vap})

No Data

13. Thermal Conductivity (liquid) (λ_ℓ)

No Data

14. Thermal Conductivity (solid) (λ_s)

No Data

15. Cryoscopic Constant (k_f)

No Data

16. References

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System 81 $LiF\text{-}AlF_3$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

LiF: 848°C

AlF_3: does not melt; sublimes with 1 atm equil^m press. at ∿ 1255°C.

Eutectic melting point:

E_1: 710°C, composition: 85.5 mol % LiF

E_2: 709°C, composition: 64.5 mol % LiF

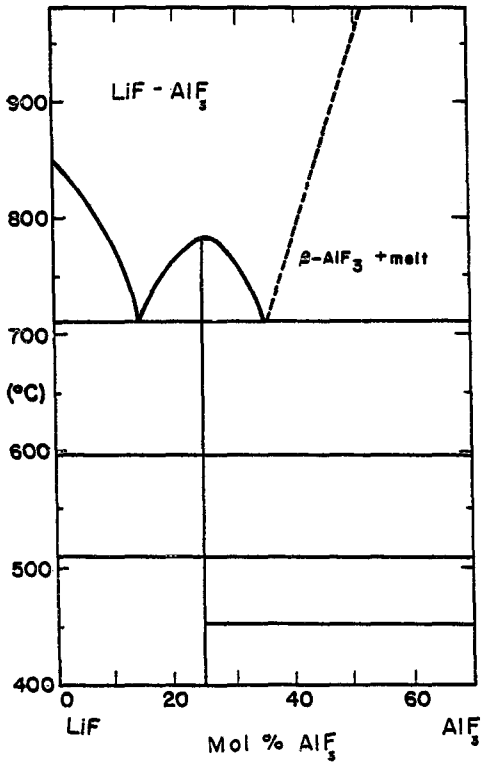

Figure 81.1. $LiF\text{-}AlF_3$ phase diagram

References [1-29]

2. *Density (ρ)*

Measurement method: Archimedean technique [30,34]

Equation:

$$\rho = a + bT \quad (81.1)$$

precision: in table 81.1 uncertainty: ∿ ± 1.0%

Table 81.1. Parameters of equation (81.1) and precision

Mol % LiF	a	$-b \times 10^4$	Precision	T range(K)
55	2.9235	9.402	*	1130-1320
60	3.1147	10.201	*	1130-1320
65	3.2050	10.300	*	1130-1320
70	3.1456	9.360	*	1130-1320
75	3.0422	8.359	*	1130-1320
80	2.8751	7.102	*	1130-1320
85	2.7935	6.698	*	1130-1320
90	2.6660	6.143	*	1130-1320
95	2.4298	4.822	*	1130-1320
100	2.3283	4.676	*	1130-1320

*insufficient data; not estimated

Table 81.2. Density (g cm^{-3}) from equations in table 81.1

	Mol % LiF				
T (K)	55	65	75	85	95
1130	1.861	2.041	2.098	2.037	1.885
1150	1.842	2.021	2.081	2.023	1.875
1170	1.823	2.000	2.064	2.010	1.866
1190	1.805	1.979	2.048	1.996	1.856
1210	1.786	1.959	2.031	1.983	1.846
1230	1.767	1.938	2.014	1.970	1.837
1250	1.748	1.918	1.997	1.956	1.827
1270	1.729	1.897	1.981	1.943	1.817
1290	1.711	1.876	1.964	1.929	1.808
1310	1.692	1.856	1.947	1.916	1.798
1320	1.682	1.845	1.939	1.909	1.793

References [30-37]

3. *Surface Tension (γ)*

No data

4. *Viscosity* (η)

Measurement method: oscillating sphere technique [38]

Equation:

$$\eta = a + bT + cT^2 \qquad (81.2)$$

precision: in table 81.3 uncertainty: $\sim \pm 20\%$

Table 81.3. Parameters of equation (81.2) and precisions

LiF (mol %)	a	$-b \times 10^3$	$c \times 10^6$	Precision	T range(K)
65.0	31.948	42.467	14.642	0.64%	1210-1340
70.0	43.107	57.349	19.616	1.88%	1240-1390
75.0	61.138	85.263	30.527	2.01%	1180-1340
77.5	7.031	-0.619	-3.559	0.46%	1180-1350
90.0	5.647	2.750	-0.218	0.93%	1240-1400

Table 81.4. Viscosity (cp) from equations in table 81.3

	Mol % LiF				
T (K)	65.0	70.0	75.0	77.5	90.0
1180			3.03	2.81	
1200			2.78	2.65	
1220	1.93		2.55	2.49	
1240	1.80	2.16	2.35	2.33	1.90
1260	1.69	1.99	2.17	2.16	1.84
1280	1.58	1.84	2.02	1.99	1.77
1300	1.49	1.70	1.89	1.82	1.70
1320	1.40	1.59	1.78	1.65	1.64
1340	1.33	1.48	1.70	1.47	1.57
1360		1.39			1.50
1380		1.32			1.44
1400					1.37

References [38]

5. *Electrical Conductance* (κ)

Measurement method: classical ac technique [40]

Equation:

$$\kappa = a + bT + cT^2 \quad (81.4)$$

precision: in table 81.6 uncertainty: $\sim \pm 3.0\%$

Table 81.5. Parameters of equation (81.4) and precisions

Mol % LiF	a	b x 10^3	c x 10^6	Precision	T range(K)
10	3.274	-4.118	2.419	0.18%	1170-1320
20	-9.990	17.907	-6.380	0.28%	1170-1320
30	-7.977	15.351	-5.242	0.35%	1170-1320
40	0.499	2.425	0.022	0.36%	1170-1320
50	4.720	-3.429	2.431	0.15%	1170-1320
60	3.503	-0.649	1.454	0.10%	1170-1320
70	-8.592	19.653	-6.502	0.12%	1170-1320
80	1.214	5.025	-0.507	1.33%	1170-1320
90	-6.393	18.160	-5.400	0.25%	1170-1320

Table 81.6. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 81.5

	Mol % LiF						
T (K)	10	30	50	60	70	80	90
1170	1.77	2.79	4.03	4.73	5.50	6.40	7.46
1190	1.80	2.85	4.08	4.79	5.57	6.48	7.57
1210	1.82	2.91	4.13	4.85	5.67	6.55	7.67
1230	1.87	2.96	4.18	4.90	5.74	6.63	7.78
1250	1.91	3.01	4.23	4.96	5.81	6.70	7.87
1270	1.94	3.05	4.28	5.02	5.88	6.78	7.96
1290	1.99	3.09	4.34	5.09	5.94	6.85	8.05
1310	2.03	3.12	4.40	5.15	5.99	6.93	8.13

References [31,35,39-47]

(81) $LiF-AlF_3$

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritant and toxic .

(ii) Vapor pressure: LiF at m.pt. (848°C), ∿ 8.8×10^{-3}mm; AlF_3 (m.pt. 1291°C), sublimes ∿ 1260°C.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [48-54]

7. Corrosion

Table 81.7. Corrosion studies from primary research literature

	Studies	References
A	Cr	[55]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[56,57]
	SSNI-12P	[58]
	Quartz	[59]
	Al	[60]
	Various metals	[61]
B	Pt, Pt-Rh	[62-66,75,76]
	Boron nitride, carbon, Inconel	[67-69]
	Fused MgO	[70]
C	Impurities in electrolyte	[15,71]
	Graphite	[15,71]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[72-74]
D	Corrosion studies in molten salts with NaF as one component(e.g., Cl, CO_3,...)	[77-92,99,100]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[95-95]
	Electroanalytical studies in molten fluorides	[96]
	Annotated corrosion biblio.	[97]
	Corrosion: molten fluorides (survey)	[98]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides, physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys

References [15,55-100]

8. Diffusion

No data

9.. Heat of Fusion (ΔH°_f)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

Measurement method: boiling point technique [101]

Equation:

$$\log p = A + B/T \quad (81.5)$$

precision: in table 81.9 uncertainty: ∿ ± 10%

Table 81.8. Parameters of equation (81.5) and precision

Mol % AlF_3	A	-B	Precision	T range (K)
47.7	8.3920	9311	*	1110-1470
57.8	8.3080	8903	*	1130-1470
64.6	8.1810	8479	*	1260-1470

*data presented in equation form; insufficient information for estimate.

Table 81.9. Vapor pressure (mm) from equations in table 81.8

	Mol % AlF_3		
T (K)	47.7	57.8	64.6
1120	1.198		
1140	1.677	3.150	
1180	3,172	5.795	
1220	5.755	10.24	
1260	10.05	17.46	28.29
1300	16.97	28.81	45.57
1340	27.76	46.13	71.35
1380	44.15	71.87	108.8
1420	68.38	109.2	162.1
1460	103.4	162.2	236.3

References [101]

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 82 $NaF-MgF_2$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

NaF: 995°C

MgF_2: 1263°C

Eutectic melting point:

E_1: 830°C, composition: 25 mol % MgF_2

E_2: 1000°C, composition: 64 mol % MgF_2

Compound: 1030°C, composition: 50 mol % MgF_2

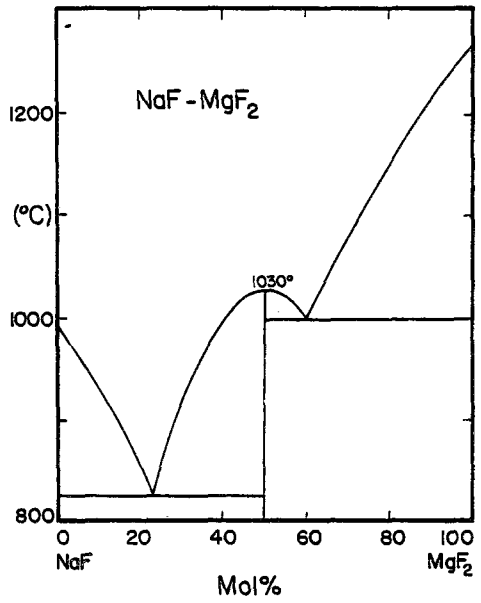

Figure 82.1. $NaF-MgF_2$ phase diagram

References [1-16]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

(82) $NaF-MgF_2$

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritant and toxic.

(ii) Vapor pressure: NaF at m.pt. (995°C), ~ 0.5mm; MgF_2 at m.pt. (1263°C) < 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure: i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [17-22]

7. Corrosion

Table 82.1. Corrosion studies from primary research literature

Studies	References
Cr	[23]
Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[24,25]
SSNI-12P	[26]
Quartz	[27]
Al	[28]
Various metals	[29]
Inconel	[30]
Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[31-48]
Electrochemical behavior of oxide ions and related species in molten fluorides	[49-51]
Electroanalytical studies in molten fluorides	[52]
Annotated corrosion biblio.	[53]
Corrosion: molten fluorides (survey)	[54]

Compatibility studies with various molten fluorides, including NaF and MgF_2. No compatibility studies specific to mixtures of molten $NaF-MgF_2$ found.

References [23-54]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

Measurement method: calculated [55]

Table 82.2. Heat capacity

Composition $NaF:MgF_2$ (mol %)	C_p (cal K^{-1} mol^{-1})	T range (K)	Uncertainty
75.1:24.9	15.5	T_m(1105) - 1200	$\sim \pm$ 10%

For the above composition, $C_{p(s)}$ = 16.0 (cal K^{-1} mol^{-1}); uncertainty of estimate, $\sim \pm$ 10%.

References [55]

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 83 CaF_2-NaF

1. *Melting Temperatures (T_m)*

Pure substance melting points:

NaF: 995°C

CaF_2: 1418°C

Eutectic melting point:

818°C, composition: 32.5 mol % CaF_2

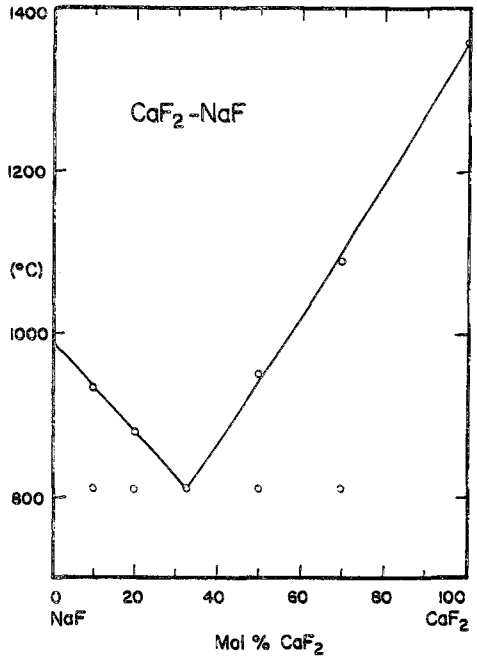

Figure 83.1. CaF_2-NaF phase diagram

References [1-40]

2. *Density (ρ)*

Measurement method: Archimedean technique [41]

Equation:

$$\rho = a + bT \quad (83.1)$$

precision: in table 83.1 uncertainty: ∿ ± 1.0%

Table 83.1. Parameters of equation (83.1) and precisions

(Mol % NaF)	a	$-b \times 10^4$	Precision	T range(K)
50.0	3.0783	5.4195	0.2%	1330-1440
66.8	2.9258	5.4489	0.5%	1150-1430
83.5	2.8803	6.0380	0.4%	1210-1440
100.0	2.7571	6.2513	0.2%	1290-1390

Table 83.2. Density (g cm^{-3}) from equations in table 83.1

T (K)	Mol % NaF 50.0	66.8	83.5
1150		2.299	
1180		2.283	
1210		2.266	2.150
1240		2.250	2.132
1270		2.234	2.113
1300		2.217	2.095
1330	2.357	2.201	2.077
1360	2.341	2.185	2.059
1390	2.325	2.168	2.041
1420	2.309	2.152	2.023

References [41]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [16]

Equation:

$$\kappa = a + bT \qquad (83.2)$$

precision: in table 83.3 uncertainty: $\sim \pm 3.0\%$

Table 83.3. Parameters of equation (83.2) and precision

Mol % NaF	a	b x 10^3	Precision	T range(K)
48.2	-1.1188	5.0660	0.1%	1180-1360

Table 83.4. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 83.3

T (K)	κ (ohm^{-1} cm^{-1})	T (K)	κ (ohm^{-1} cm^{-1})
1180	4.859	1280	5.366
1200	4.960	1300	5.467
1230	5.062	1320	5.568
1240	5.162	1340	5.670
1260	5.264	1360	5.771

References [16,19,42]

6. Safety and Hazards

A. Hazard rating

(i) Toxocity: inorganic fluorides are generally irritant and toxic

(ii) Vapor pressure: NaF at m.pt. (995°C), ~ 0.5mm; CaF_2 at m.pt. (1418°C) ~ < 0.5mm

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure: i.e., explosive expansion of "trapped" air

(ii) Fluorides evolve highly toxic fumes when heated to decomposition, or contacted with acids

References [43-49]

7. Corrosion

Table 83.5. Corrosion studies from primary research literature

Studies	References
Cr	[50]
Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[51,52]
SSNI-12P	[53]
Quartz	[54]
Al	[55]
Mild steel	[56]
Various metals	[57]
Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[58-74]
Electrochemical behavior of oxide ions and related species in molten fluorides	[75-77]
Electroanalytical studies in molten fluorides	[78]
Annotated corrosion biblio.	[79]
Corrosion: molten fluorides (survey)	[80]

Compatibility studies: various molten fluorides, but principally NaF, CaF_2, and BaF_2. For studies specifically with molten CaF_2-NaF mixtures, see [56]

References [50-80]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

(83) CaF_2-NaF

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [81]

Table 83.6. Volume change on melting

Binary eutectic (mol % NaF)	$(\Delta V_f/V_s)$	Uncertainty
67	8.8%	$\sim \pm$ 10%

References [81]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 84 $NaF-BaF_2$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

NaF	995°C
BaF_2:	1320°C

Eutectic melting point:

812°C, composition: 63 mol % NaF (31.5 equiv. % Na_2F_2)

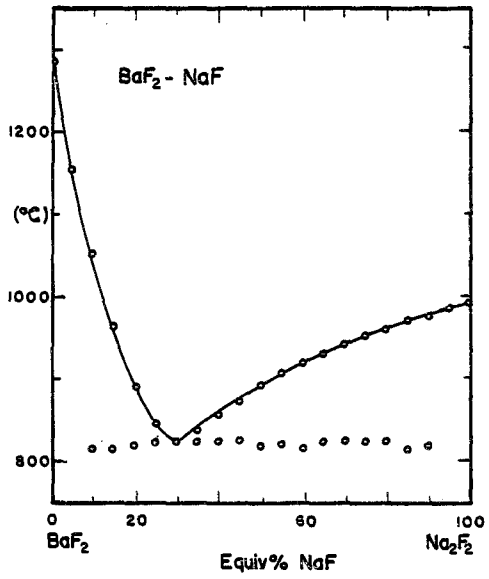

Figure 84.1. $NaF-BaF_2$ phase diagram

References [1-23]

2. *Density (ρ)*

Measurement method: Archimedean technique [24]

Equation:

$$\rho = a + bT \quad (84.1)$$

precision: in table 84.1 uncertainty: ∿ ± 2.0%

Table 84.1. Parameters of equation (84.1) and precisions

Mol % NaF	a	$-b \times 10^4$	Precision	T range(K)
50.0	4.3643	6.2311	0.43%	1230-1450
66.8	3.9022	5.9959	0.87%	1250-1430
83.5	3.3934	5.7600	0.73%	1230-1430

Table 84.2. Density (g cm^{-3}) from equation in table 84.1

T (K)	Mol % NaF 50.0	66.8	83.5
1230	3.598		2.685
1250	3.585	3.153	2.673
1270	3.573	3.141	2.662
1290	3.560	3.129	2.650
1310	3.548	3.117	2.639
1330	3.536	3.105	2.627
1350	3.523	3.093	2.616
1370	3.511	3.081	2.604
1390	3.498	3.069	2.593
1410	3.486	3.057	2.581
1430	3.473	3.045	2.570
1450	3.461		

References [24]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [25]

Equation:

$$\kappa = a + bT \quad (84.2)$$

precision: in table 84.3 uncertainty: $\sim \pm 3.0\%$

Table 84.3. Parameters of equation (84.2) and precision

Mol % NaF	a	b x 10^3	Precision	T range(K)
67.6	-3.7363	6.6000	4.36%	1180-1370

Table 84.4. Specific conductance at 67.6 mol% NaF from equation in table 84.3

T (K)	κ (ohm^{-1} cm^{-1})	T (K)	κ (ohm^{-1} cm^{-1})
1180	4.052	1280	4.712
1190	4.118	1290	4.778
1200	4.184	1300	4.844
1210	4.250	1310	4.910
1220	4.316	1320	4.976
1230	4.382	1330	5.042
1240	4.448	1340	5.108
1250	4.514	1350	5.174
1260	4.580	1360	5.240
1270	4.646	1370	5.306

References [25-27]

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritants and toxic.

(ii) Vapor pressure: NaF, at m.pt. (995°C), $\sim$) 0.5mm; BaF_2, at m.pt. (1320°C) $\sim$ < 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [28-33]

7. Corrosion

Table 84.5. Corrosion studies from primary research literature

Studies	References
Cr	[34]
Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[35,36]
SSNI-12P	[37]
Quartz	[38]
Al	[39]
Various metals	[40]
Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[41-46,53,54]
Electro-chemical behaviour of oxide ions and related species in molten fluorides	[47-49]
Electroanalytical studies in molten fluorides	[50]
Annotated corrosion biblio.	[51]
Corrosion: molten fluorides (survey)	[52]

Compatibility studies: various molten fluorides and principally with molten NaF. No studies specific to BaF_2 were found. For thermodynamic (theoretical) considerations, and some considerations relative to commercial grade fluorides, and the use of "gettering" to lower impurity levels, see [52].

References [34-52]

8. Diffusion

No data

9. *Heat of Fusion* (ΔH_f°)

No data

10. *Heat Capacity* (C_p)

No data

11. *Volume Change on Melting* (ΔV_f)

No data

12. *Vapor Pressure* (p_{vap})

No data

13. *Thermal Conductivity (liquid)* (λ_ℓ)

No data

14. *Thermal Conductivity (solid)* (λ_s)

No data

15. *Cryoscopic Constant* (k_f)

No data

16. *References*

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System 85 $NaF-AlF_3$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

NaF: 995°C

AlF_3: does not melt; sublimes with 1 atm equil^m press. at ∿ 1255°C

Eutectic melting point:

E. 888°C, composition: 15 mol % AlF_3

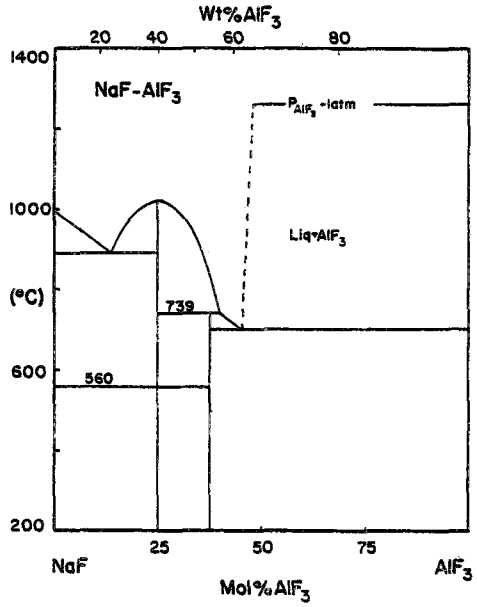

Figure 85.1. $NaF-AlF_3$ phase diagram

References [1-31].

2. *Density (ρ)*

Measurement method: Archimedean technique [40,47]

Equation:

$$\rho = a + bT \quad (85.1)$$

precision: in table 85.1 uncertainty: ∿ ± 1.0%

Table 85.1. Parameters of equation (85.1) and precisions

Mol % NaF	a	$-b \times 10^4$	Precision	T range(K)
50	2.4950	6.90	0.18%	1275-1370
55	2.7198	7.82	0.10%	1275-1370
60	2.9921	8.90	0.14%	1275-1370
64	3.1679	9.35	0.19%	1275-1370
70	3.2258	9.20	0.15%	1275-1370
76	3.2733	9.20	0.05%	1275-1370
77	3.2612	9.12	0.07%	1275-1270
80	3.2415	8.98	0.15%	1275-1370
85	3.0535	7.65	0.13%	1275-1370
90	2.8780	6.48	0.15%	1275-1370
100	2.7550	6.36	0.15%	127501370

Table 85.2. Density (g cm^{-3}) from equations in table 85.1

	Mol % NaF							
T (K)	50	60	65	70	75	77	85	90
1275	1.615	1.857	1.976	2.053	2.100	2.098	2.078	2.042
1280	1.612	1.853	1.971	2.048	2.096	2.094	2.074	2.039
1290	1.605	1.844	1.962	2.039	2.087	2.085	2.067	2.032
1300	1.598	1.835	1.952	2.030	2.077	2.076	2.059	2.026
1310	1.591	1.826	1.943	2.021	2.068	2.066	2.051	2.019
1320	1.584	1.817	1.934	2.011	2.059	2.057	2.044	2.013
1330	1.577	1.808	1.924	2.002	2.050	2.048	2.036	2.006
1340	1.570	1.800	1.915	1.993	2.040	2.039	2.028	2.000
1350	1.563	1.791	1.906	1.984	2.031	2.030	2.021	1.993
1360	1.557	1.782	1.896	1.975	2.022	2.021	2.013	1.987
1370	1.550	1.773	1.887	1.965	2.013	2.012	2.005	1.980

References [32-53]

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure [54]

Equation:

$$\gamma = a + bT \quad (85.2)$$

precision: in table 85.3. uncertainty: $\sim \pm 5.0\%$

Table 85.3. Parameters of equation (85.2) and precisions

Mol % AlF_3	a	$-b \times 10^2$	Precision	T range(K)
27.4	262.5	10.6	*	1275-1350
25.0	297.0	12.8	*	1275-1350
21.9	309.3	13.0	*	1275-1350
19.0	328.8	14.0	*	1275-1350
13.6	304.5	11.3	*	1275-1350

*not estimated; insufficient data

Table 85.4. Surface tension (dyn cm^{-1}) from equations in table 85.3.

T (K)	Mol % AlF_3 13.6	19.0	21.9	25.0	27.4
1275	160.4	150.4	143.6	133.8	127.3
1280	159.8	149.6	142.9	133.1	126.8
1290	158.7	148.2	141.6	131.8	125.7
1300	157.6	146.8	140.3	130.6	124.7
1310	156.4	145.4	139.0	129.3	123.6
1320	155.3	144.0	137.7	128.0	122.5
1330	154.2	142.6	136.4	126.7	121.5
1340	153.0	141.2	135.1	125.4	120.4
1350	151.9	139.8	133.8	124.2	119.4

References [44,54]

4. *Viscosity (η)*

Measurement method: oscillating cylinder [53]

Equation:

$$\eta = a + bT + cT^2 \quad (85.3)$$

precision: in table 85.5 uncertainty: $\sim \pm 10\%$

Table 85.5. Parameters of equation (85.3) and precisions

NaF (mol %)	a	$-b \times 10^3$	$c \times 10^6$	Precision	T range (K)
65	44.192	62.11	22.50	0.9%	1220-1310
70	10.475	6.825	0.164	1.0%	1270-1330
80	27.405	31.85	9.538	0,6%	1270-1370
85	40.892	53.97	18.46	0.6%	1220-1370
90	20.254	24.03	7.526	0.3%	1220-1370
95	15.457	18.16	5.727	0.1%	1270-1370
100	8.392	8.245	2.198	0.2%	1270-1370

References [53]

Table 85.6. Viscosity (cp) from equations in table 85.5

T (K)	Mol % NaF						
	65	70	80	85	90	95	100*
1220	1.907			2.524	2.139		
1240	1.772			2.353	2.029		
1260	1.654			2.197	1.924		
1280	1.555	2.008	2.264	2.055	1.826	1.595	1.440
1300	1.474	1.880	2.119	1.928	1.734	1.528	1.388
1320		1.752	1.982	1.816	1.648	1.465	1.338
1340			1.852	1.719	1.567	1.406	1.290
1360			1.730	1.636	1.493	1.352	1.244
1370			1.672	1.601	1.458	1.327	1.222

* The values for 100% NaF, based on the work of Brockner, et al [53], supersede the previous recommendations [57].

References [44,45,52,53,55-57]

5. *Electrical Conductance* (κ)

Measurement method: classical ac technique [35,51]

Equation:

$$\kappa = a + bT \quad (85.4)$$

precision: in table 85.7 uncertainty: $\sim \pm 3.0\%$

Table 85.7. Parameters of equation (85.4) and precisions

Mol % NaF	-a	b x 10^{-3}	Precision	T range(K)
86.2	0.5838	3.488	0.04%	1270-1350
80.0	0.2956	2.738	0.04%	1270-1350
78.1	0.2346	2.639	0.10%	1270-1350
75.0	0.3512	2.475	0.06%	1270-1350
70.3	0.1693	2.237	0.13%	1270-1350
67.7	-0.0230	2.025	0.06%	1270-1350

Table 85.8. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 85.7

T (K)	Mol % NaF					
	67.7	70.3	75.0	78.1	80.0	86.2
1270	2.595	2.672	2.792	3.116	3.182	2.846
1280	2.615	2.694	2.817	3.142	3.209	3.881
1290	2.635	2.716	2.842	3.168	3.236	3.916
1300	2.656	2.739	2.866	3.195	3.264	3.951
1310	2.676	2.761	2.891	3.221	3.291	3.985
1320	2.696	2.784	2.916	3.248	3.319	4.030
1330	2.716	2.806	2.941	3.274	3.346	4.055
1340	2.737	2.828	2.965	3.300	3.373	4.090
1350	2.757	2.851	2.990	3.327	3.401	4.125

References [8,35,36,42-44,51,58-75]

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure: no information for this system; but see NaF [78], and AlF_3 [82].

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [76-82].

7. Corrosion

Table 85.9. Corrosion studies from primary research literature

	Studies	References
A	Cr	[83]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[84,85]
	SSNI-12P	[86]
	Quartz	[87]
	Al	[88]
	Various metals	[89]
B	Pt	[35,51,68,70,74,90]
	Boron nitride, carbon, Inconel	[8,91,92]
	Fused MgO	[60]
C	Impurities in electrolyte	[93,94]
	Graphite	[93,94]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[95-97]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[98-113,120,121]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[114-116]
	Electroanalytical studies in molten fluorides	[117]
	Annotated corrosion biblio.	[118]
	Corrosion: molten fluorides (survey)	[119]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys

References [8,35,51,60,68,70,74,83-121]

(85) $NaF-AlF_3$

8. Diffusion

Measurement method: capillary

Diffusing species investigated in $NaF-AlF_3$ as solvent:

Na^+, Al(III), F^-

precision: in table 85.10 uncertainty: ∿ ± 10%

Equation:

$$D = A \exp [-E/RT] \quad (85.5)$$

Table 85.10. Parameters of diffusion equation (85.5), precisions, and recommended study

Species	A x 10^3 (cm^2 s^{-1})	E (cal mol^{-1})	Temp. range (K)	Precision	Recommended study
(a) $NaF-AlF_3$ (2.06 mol % AlF_3)					
Al(III)	*insufficient data for t-dependent parameters*				[123]
(b) $NaF-AlF_3$ (13.5 mol % AlF_3)					
Na^+	3.798	9595	1211-1343	∿±7.5%	[122]
Al(III)	*insufficient data for t-dependent parameters*				[123]
F^-	14.956	14030	1211-1324	∿±9.8%	[122]
(c) $NaF-AlF_3$ (25 mol % AlF_3)‡‡					
Na^+	*insufficient data for t-dependent parameters*				[122]
Al(III)	*insufficient data for t-dependent parameters*				[123]
F^-	*insufficient data for t-dependent parameters*				[122]
(d) $NaF-AlF_3$ (37.5 mol % AlF_3)					
Na^+	5.412	10040	1201-1273	∿±3.8%	[122]
F^-	0.712	6165	1201-1273	∿±2.6%	[122]

‡‡:-the composition $NaF-AlF_3$ (25 mol % AlF_3) corresponds to that of cryolite ε, Na_3AlF_6. See system 66, this work, for additional studies in molten cryolite.

Table 85.11. Diffusion coefficients in $NaF-AlF_3$

T (K)	D x 10^5 (cm^2 s^{-1})											
	(2.06 mol % $LiNO_3$)			(13.5 mol % $LiNO_3$)			(25 mol % $LiNO_3$)			(37.5 mol % $LiNO_3$)		
	Na^+	Al(III)	F^-	Na^+	Al(III)	F^-	Na^+	Al(III)	F^-	Na^+	Al(III)	F^-
1050		5.3[a]								8.03		5.37
1200												
1210				7.02		4.37				8.31		5.48
1220				7.25		4.58				8.60		5.60
1230				7.49		4.81				8.90		5.71
1240				7.73		5.03				9.20		5.83
1250				7.98		5.27				9.50		5.95
1260				8.23		5.51				9.81		6.07
1270				8.48		5.76				10.13		6.19
1280				8.73		6.01						
1290				8.99		6.28						
1300				9.25		6.55						
1310				9.52	7.44[b]	6.82						
1320				9.79		7.11	9.37[c]		5.7[d]			
1330				10.06				6.83 at 1325K				
1340				10.34								

[a] based on 3 data points in the temp. range: 1049-1054K.

[b] based on 2 data points at 1307 and 1314K, respectively.

[c] average of 2 values, 9.30 and 9.44, reported at 1321 and 1322K, respectively.

[d] based on 2 data points at 1321 and 1322K, respectively; see also system 66 (Na_3AlF_6), this work.

References [122,123]

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [124]

Table 85.12. Volume change on melting.

Binary eutectic (mol % NaF)	($\Delta V_f/V_s$)	Uncertainty
48	85%	$\sim \pm$ 10%

References [124]

(85) $NaF-AlF_3$

12. Vapor Pressure (p_{vap})

Measurement methods: boiling point technique [125]

Equation:

$$\log p = A + B/T \quad (85.6)$$

precision: in table 85.13 uncertainty: ∿ ± 10%

Table 85.13. Parameters of equation (85.6) and precisions

Mol % AlF_3	A	-B	Precision	T range(K)
11.11	8.9800	11728	*	1190-1470
17.65	8.8801	11275	*	1230-1470
25.00	8.9650	10399	*	1280-1470
26.58	8.5690	10107	*	1280-1470
33.33	8.4780	9491	*	1220-1470
42.86	8.3040	8842	*	1000-1470
50.00	8.2470	8568	*	1150-1470
53.85	8.1751	8239	*	1290-1470

*data reported in graphical form; insufficient details for estimates

Table 85.14. Vapor pressure (mm) from equations in table 85.13

T (K)	Mol % AlF_3							
	11.11	17.65	25.00	26.58	33.33	42.86	50.00	53.85
1000						0.296		
1040						0.634		
1080						1.309		
1120						2.567		
1160						4.804	7.258	
1200	0.161					8.623	12.79	
1240	0.333	0.613			6.668	14.91	21.74	
1280	0.657	1.179	6.931	4.709	11.56	24.90	35.75	
1320	1.245	2.180	12.22	8.169	19.40	40.32	57.03	85.79
1360	2.272	3.887	20.83	13.72	31.57	63.56	88.51	130.9
1400	4.007	5.707	34.45	22.37	49.97	97.34	134.0	195.0
1440	6.848	11.23	55.40	35.50	77.10	145.8	198.2	284.2
1460	8.854	14.37	69.57	44.30	94.91	176.9	239.1	340.4

References [125-127]

(85) $NaF-AlF_3$

13. Thermal Conductivity (liquid) (λ_ℓ)

Measurement method: modified coaxial-cylinder technique [128]

Equation:

$$\lambda = a + bT \quad (85.7)$$

precision: in table 85.15 uncertainty: ∿ ± 15%

Table 85.15. Parameters of equation (85.7), precisions and temp. range

Mol % NaF	$-a \times 10^3$	$b \times 10^6$	Precision	T range(K)
70	8.6982	7.704	*	1290-1320
73	12.276	10.48	*	1290-1330
75	22.800	18.66	*	1300-1340
86	5.5906	5.199	*	1200-1300
92	19.138	16.40	*	1255-1330

*insufficient information for estimates

Table 85.16. Thermal conductivity ($\times 10^4$ cal cm^{-1} s^{-1} K^{-1}) from equations in table 85.15

T	Mol % NaF				
(K)	70	73	75	86	92
1200				6.48	
1210				7.00	
1220				7.52	
1230				8.04	
1240				8.56	
1250				9.08	
1260				9.60	15.3
1270				10.1	16.9
1280				10.6	18.5
1290	12.4	12.4		11.2	20.2
1300	13.2	13.5	14.6	11.7	21.8
1310	13.9	14.5	16.4		23.5
1320	14.7	15.6	18.3		25.1
1330		16.6	20.2		26.7
1340			22.0		

References [128,129]

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 86 KF-AlF_3

1. *Melting Temperatures (T_m)*

Pure substance melting points:

KF: 856°C

AlF_3: does not melt; sublimes with 1 atm equil^m press. at ∿ 1255°C.

Eutectic melting point:

E_1: 840°C, composition: 6.8 mol % AlF_3; [9.6 wt % AlF_3]
E_2: 570°C. composition: 4.5 mol % AlF_3; [54.2 wt % AlF_3]
P: 580°C, composition 47.5 mol % AlF_3; [56.7 wt % AlF_3]

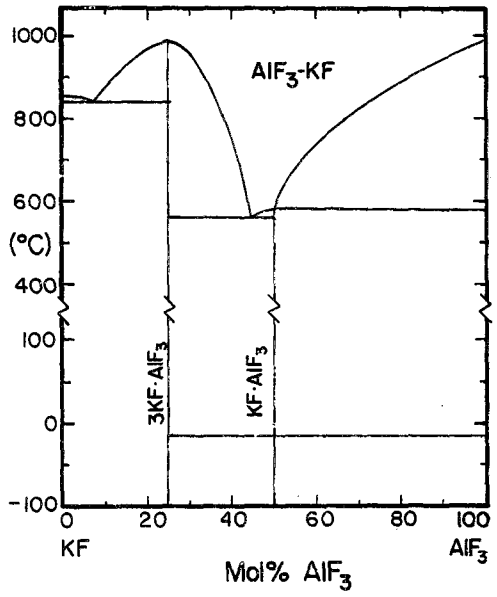

Figure 86.1. KF-AlF_3 phase diagram

References [1-21]

2. *Density (ρ)*

Measurement method: Archimedean technique [22]

Equation:

$$\rho = a + bT \quad (86.1)$$

precision: in table 86.1 uncertainty: ∿ ± 1.5%

Table 86.1. Parameters of equation (86.1) and precision

(mol % KF)	a	$-b \times 10^4$	Precision	T range(K)
75[a]	2.770	7.398	*	1270-1320

*insufficent data; not estimated

[a]composition corresponds to K_3AlF_6 (vide infra: System 67)

Table 86.2. Density (g cm^{-3}) form equation in table 86.1

T (K)	ρ (g cm^{-3})	T (K)	ρ (g cm^{-3})
1270	1.8304	1300	1.8082
1280	1.8230	1310	1.8008
1290	1.8156	1320	1.7934

References [22]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Meausrement method: classical ac technique [24]

Equation:

$$\kappa = a + bT \quad (86.2)$$

precision: in table 86.3 uncertainty: ∿ ± 30%

Table 86.3. Parameters of equation (86.2) and precisions

Mol % AlF_3	-a	b x 10^3	Precision	T range(K)
10	2.5485	4.782	0.9%	1200-1290
20	7.1770	7.938	1.6%	1280-1320
(a)25	(13.859)	(13.01)	*	1290-1320
30	(8.0807)	(8.359)	*	1290-1320
40	(1.7653)	(3.154)	*	1200-1320

*The values in ( ) are based on a minimal data set; insufficient data for estimates of precision

(a)This composition corresponds to K_3AlF_6; for the best values data set for K_3AlF_6, see System 67; this work

Table 86.4. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 86.3

T (K)	Mol % AlF_3				
	10	20	25(a)	30	40
1200	3.190				2.020
1220	3.286				2.083
1240	3.381				(2.146)
1260	3.477				2.209
1280	3.572	2.984			(2.272)
1290	3.620	3.063	(2.924)	(2.702)	(2.303)
1300		3.142	(3.054)	2.786	(2.335)
1310		3.222	(3.184)	(2.870)	(2.366)
1320		3.301	(3.314)	(2.953)	(2.398)

(a)This composition (25 mol % AlF_3) corresponds to K_3AlF_6; the values are ∿ 25-40% higher than the "best values" data set for K_3AlF_6 (vide infra: System 67).

The values in ( ) are based on a minimal data set.

References [23-26]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure: no information for this system; but see KF [29] and AlF_3 [33]

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over and/or equipment failure; i.e., explosive expansion of "trapped air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [27-33]

7. Corrosion

Table 86.5. Corrosion studies from primary research literature

	Studies	References
A	Cr	[34]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[35,36]
	SSNI-12P	[37]
	Quartz	[38]
	Al	[39]
	Various metals	[40]
B	Pt	[41-45]
	Boron nitride, carbon, Inconel	[46-48]
	Fused MgO	[49]
C	Impurities in electrolyte	[50,51]
	Graphite	[50,51]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[52-54]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[55-70,77,78]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[71-73]
	Electroanalytical studies in molten fluorides	[71-73]
	Annotated corrosion biblio.	[75]
	Corrosion: molten fluorides(survey)	[76]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [34-78]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 87 LiCl-NaCl

1. *Melting Temperatures (T_m)*

Pure substance melting points:

LiCl: 610°C

NaCl: 800°C

Eutectic melting point:

557°C, composition: 77.5 mol % LiCl

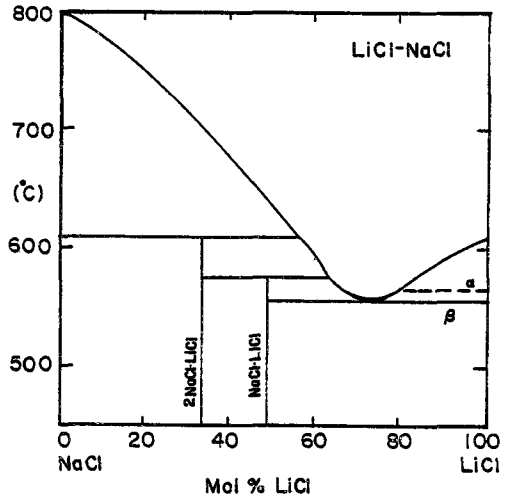

Figure 87.1. LiCl-NaCl phase diagram

References [1-26]

2. *Density (ρ)*

Measurement method: Archimedean technique [27]

Equation:

$$\rho = a + bT \quad (87.1)$$

precision: in table 87.1 uncertainty: ∿ ± 1.5%

Table 87.1. Parameters of equation (87.1) and precision

Mol % NaCl	a	$-b \times 10^4$	Precision	T range(K)
50	2.0121	4.858	0.06%	890-1120

Table 87.2. Density (g cm^{-3}) from equation in table 87.1

T (K)	ρ (g cm^{-3})	T (K)	ρ (g cm^{-3})
900	1.575	1020	1.517
920	1.565	1040	1.507
940	1.555	1060	1.497
960	1.546	1080	1.487
980	1.536	1100	1.478
1000	1.526	1120	1.468

References [27-30]

3. Surface Tension (γ)

Measurement method: maximum bubble pressure [31]

Equation:

$$\gamma = a + bT \quad (87.2)$$

precision: in table 87.3 uncertainty: ∿ ± 3.0%

Table 87.3. Parameters of equation (87.2) and precisions

Mol % NaCl	a	$-b \times 10^3$	Precision	T range(K)
20	206.05	80.69	0.20%	980-1170
40	203.57	78.97	0.12%	980-1170
60	197.26	73.79	0.45%	980-1100

Table 87.4. Surface tension (dyn cm^{-1}) from equations in table 87.3

	Mol % NaCl		
T (K)	20	40	60
980	127.0	126.2	125.0
990	126.2	125.4	124.2
1000	125.4	124.6	123.5
1010	124.6	123.8	122.7
1020	123.7	123.0	122.0
1030	122.9	122.2	121.3
1040	122.1	121.4	120.5
1050	121.3	120.7	119.8
1060	120.5	119.9	119.1
1070	119.7	119.1	118.3
1080	118.9	118.3	117.6
1090	118.1	117.5	116.1
1100	117.3	116.7	116.1
1110		115.9	115.4
1120		115.1	114.6
1130		114.3	113.9
1140		113.5	113.2
1150		112.8	112.4
1160		112.0	111.7
1170		111.2	110.9

References [31]

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [32]

Equation:

$$\kappa = a + bT + cT^2 \quad (87.3)$$

precision: in table 87.5 uncertainty: ∿ ± 2.0%

Table 87.5. Parameters of equation (87.3), and precision

Mol % NaCl	-a	b x 10^3	-c x 10^6	Precision	T range(K)
50	3.9723	13.0062	4.7073	0.18%	920-1130

Table 87.6. Specific conductance (ohm^{-1} cm^{-1}) from equation in table 87.5

T (K)	κ (ohm^{-1} cm^{-1})	T (K)	κ (ohm^{-1} cm^{-1})
920	4.009	1040	4.463
940	4.094	1060	4.525
960	4.175	1080	4.584
980	4.253	1100	4.639
1000	4.327	1120	4.689
1020	4.397		

References [32]

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: LiCl, slight; NaCl, very slow.

(ii) Vapor pressure: LiCl, at m.pt. (610°C), ∿ 0.25mm; NaCl, at m.pt. (800°C), ∿ 0.34mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic chloride fumes when heated to decomposition, or contacted with acids.

References [33-38]

7. Corrosion

Table 87.7. Corrosion studies from primary research literature

Studies	References
Mo	[39]
Armco Fe	[40-42]
NiCr	[43]
Ti, Zr, Hf, $ThCl_4$	[44,45]
Cr	[46]
Cr, Fe-Cr	[47]
Ni alloys	[48]
Ni-Cr-Al, Ni-Cr-W-Fe, Ni-Cr Mg, Ni, Zr, Ti	[49]
Au, Pt, MgO, Al_2O_3, Zirconia [NaCl with added Na_2O]	[50]
Electrochemical aspects of corrosion	[51,52]
Corrosion - annotated biblio.	[53]
Thermodynamic redox potentials (diagrammatic analysis)	[49,54,55]
Reviews: corrosion in molten salts	[56-58]

With the exception of [45], in which compatibility of Ti in molten LiCl-NaCl was investigated, LiCl, KCl, and NaCl and mixtures (e.g., LiCl-KCl, NaCl-KCl,...) were used in the studies listed in Table 87.7 (above).

References [39-58]

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 88 $LiCl-MgCl_2$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$LiCl$: 610°C

$MgCl_2$: 714°C

Eutectic melting point:

570°C, composition: 60 mol % $LiCl$

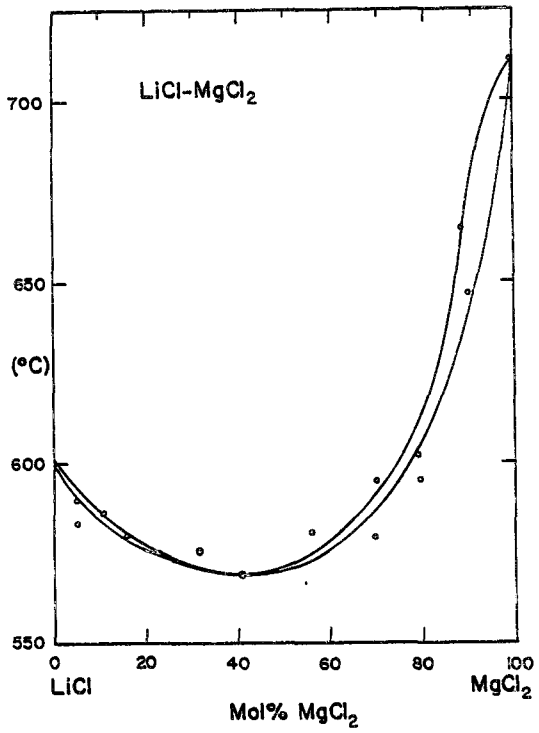

Figure 88.1. $LiCl-MgCl_2$ phase diagram

References [1-15].

2. *Density (ρ)*

Measurement method: Archimedean technique [16]

Equation:

$$\rho = a + bT \quad (88.1)$$

precision: in table 88.1 uncertainty: ∿ ± 1.5%

Table 88.1. Parameters of equation (88.1) and precisions

Mol % $MgCl_2$	a	$-b \times 10^4$,	Precision	T range(K)
5.7	2.4116	8.906	0.05%	1030-1120
18.0	2.0351	4.953	0.02%	980-1080
30.8	2.1408	5.525	0.02%	1030-1120
45.4	2.0892	4.618	0.04%	980-1080
56.4	2.1623	5.035	0.04%	980-1080
77.4	2.1334	4.415	0.02%	970-1030

Table 88.2. Density (g cm^{-3}) from equations in table 88.1

T (K)	Mol % $MgCl_2$ 5.7	18.0	30.8	45.4	56.4	77.4
970						1.705
980		1.550		1.637	1.669	1.701
990		1.545		1.632	1.664	1.697
1000		1.540		1.627	1.659	1.692
1010		1.535		1.623	1.654	1.688
1020		1.530	1.577	1.618	1.649	1.683
1030	1.494	1.525	1.572	1.614	1.644	1.679
1040	1.485	1.520	1.566	1.609	1.639	
1050	1.476	1.515	1.561	1.604	1.634	
1060	1.468	1.510	1.555	1.600	1.629	
1070	1.459	1.505	1.550	1.595	1.624	
1080	1.450	1.500	1.544	1.590		
1090	1.441		1.539			
1100	1.432		1.533			
1110	1.423		1.528			
1120	1.414		1.522			

References [16-19]

3. *Surface Tension (γ)*

Measurement method: flat pin (detachment) [20]

Equation:

$$\gamma = a + bT \quad (88.2)$$

precision: in table 88.3 uncertainty: $\sim \pm 2.0\%$

Table 88.3. Parameters of equation (88.2) and precisions

Mol % $MgCl_2$	a	-b x 10^3	Precision	T range(K)
17.2	152.52	49.87	0.09%	950-1040
18.0	149.70	47.79	0.03%	990-1040
36.2	127.20	35.96	0.07%	920-1020
45.4	110.39	24.83	0.12%	980-1080
53.1	109.40	26.47	0.04%	940-1040
56.4	105.13	25.98	0.11%	970-1080
73.5	86.08	13.30	0.08%	950-1060

Table 88.4. Surface tension (dyn cm^{-1}) from equations in table 88.3

T (K)	Mol % $MgCl_2$				
	18.0	36.2	45.4	53.1	56.4
920		94.1			
930		93.8			
940		93.4		84.5	
950		93.0		84.3	
960		92.7		84.0	
970		92.3		83.7	79.9
980		92.0	86.1	83.5	79.7
990	102.4	91.6	85.8	83.2	79.4
1000	101.9	91.2	85.6	82.9	79.2
1010	101.4	90.9	85.3	82.7	78.9
1020	101.0	90.5	85.1	82.4	78.6
1030	100.5		84.8	82.1	78.4
1040	100.0		84.6	81.9	78.1
1050			84.3		77.9
1060			84.1		77.6
1070			83.8		77.3
1080			83.6		77.1

References [16,20]

4. *Viscosity (η)*

Measurement method: oscillating sphere technique [21]

Equation:

$$\eta = a + bT + cT^2 \quad (88.3)$$

precision: in table 88.5 uncertainty: $\sim \pm 10\%$

Table 88.5. Parameters of equation (88.3) and precisions

$MgCl_2$ (mol %)	a	$-b \times 10^2$	$c \times 10^5$	Precision	T range(K)
4.7	-18.522	-4.359	-2.392	0.23%	930- 990
7.3	2.774	-1.163	-0.769	0.60%	970-1000
10.0	-33.060	-7.177	-3.748	1.95%	960-1030
16.0	30.387	5.592	2.676	2.44%	940-1020
19.3	4.942	0.371	0	2.19%	940-1020
22.9	24.434	4.346	2.033	2.24%	940-1020
30.8	3.958	0.261	0	0.61%	940-1010
40.0	5.024	0.363	0	2.40%	930-1030
50.9	25.077	4.343	1.984	0.82%	960-1010
71.6	13.568	1.876	0.691	0.63%	940-1010

Table 88.6. Viscosity (cp) from equations in table 88.5

T (K)	Mol % $MgCl_2$ 71.6	40.0	22.9	16.0	4.7
920					
930		1.65			1.33
940	2.04	1.61	1.55	1.47	1.32
950	1.98	1.58	1.50	1.41	1.30
960	1.92	1.54	1.45	1.36	1.28
970	1.87	1.50	1.41	1.32	1.25
980	1.82	1.47	1.37	1.28	1.22
990	1.76	1.43	1.34	1.25	1.19
1000	1.71	1.39	1.31	1.23	1.15
1010	1.67	1.36	1.28	1.20	
1020		1.32	1.26	1.19	
1030		1.29			

References [21]

5. *Electrical Conductance* (κ)

Measurement method: classical ac technique [17]

Equation:

$$\kappa = a + bT + cT^2 \quad (88.4)$$

precision: in table 88.7 uncertainty: $\sim \pm 3.0\%$

Table 88.7. Parameters of equation (88.4) and precisions

Mol % $MgCl_2$	-a	b x 10^3	-c x 10^6	Precision	T range(K)
4.7	5.000	17.57	6.67	*	910-1130
10.0	4.811	16.23	6.11	*	910-1130
16.0	4.374	14.47	5.34	*	910-1130
20.0	4.712	14.53	5.40	*	910-1130
30.0	4.007	11.88	4.26	*	910-1130
40.0	3.717	10.69	3.80	*	910-1130

*not estimated; insufficient data

Table 88.8. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 88.7

T (K)	Mol % $MgCl_2$ 4.7	10.0	16.0	20.0	30.0	40.0
910	5.47	4.90	4.37	4.04	3.28	2.87
930	5.57	5.00	4.46	4.13	3.36	2.94
950	5.67	5.10	4.55	4.21	3.43	3.01
970	5.77	5.19	4.63	4.30	3.51	3.08
990	5.86	5.27	4.71	4.38	3.58	3.14
1010	5.94	5.35	4.79	4.45	3.65	3.21
1030	6.02	5.43	4.86	4.52	3.71	3.26
1050	6.10	5.50	4.93	4.49	3.77	3.32
1070	6.17	5.56	4.99	4.65	3.83	3.37
1090	6.23	5.63	5.05	4.71	3.88	3.42
1110	6.29	5.68	5.10	4.76	3.93	3.47
1130	6.34	5.73	5.15	4.81	3.98	3.51

References [17]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: LiCl, slight; $MgCl_2$, slight.

(ii) Vapor pressure: LiCl, at m.pt. (610°C), ∿ 0.11mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic fumes when heated to decomposition, or contacted with acids.

References [22-27].

7. Corrosion

Table 88.9. Corrosion studies from primary research literature

Studies	References
Mg, Ni, Zr, Ti	[28]
Ti, Zr, Hf, $ThCl_4$	[29]
Armco Fe	[30-36]
Zr	[37]
Solubility of metal oxides (Ni, Ca, Zn, Mg)	[28,38]
Thermodynamics of corrosion	[28,39,40]
Corrosion - annotated biblio.	[41]
Electrochemical aspects	[42]
Reviews: corrosion - molten salts	[43-45]

No compatibility studies specifically with molten $LiCl-MgCl_2$ were found, for $MgCl_2$ as a component in molten NaCl and KCl, see [32-36].

References [28-45]

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

10. Heat Capacity (C_p)

No data

(88) $LiCl-MgCl_2$

11. *Volume Change on Melting (ΔV_f)*

Measurement method: estimated from densities [46]

Table 88.10. Volume change on melting

Binary eutectic (mol % $MgCl_2$)	$(\Delta V_f/V_s)$	Uncertainty
40%	20.5%	$\sim \pm$ 10%

References [46]

12. *Vapor Pressure (p_{vap})*

No data

13. *Thermal Conductivity (liquid) (λ_ℓ)*

No data

14. *Thermal Conductivity (solid) (λ_s)*

No data

15. *Cryoscopic Constant (k_f)*

No data

16. *References*

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System 89 $LiCl-BaCl_2$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$LiCl$: 610°C

$BaCl_2$: 962°C

Eutectic melting point:

512°C, composition: 70.7 mol % $LiCl$

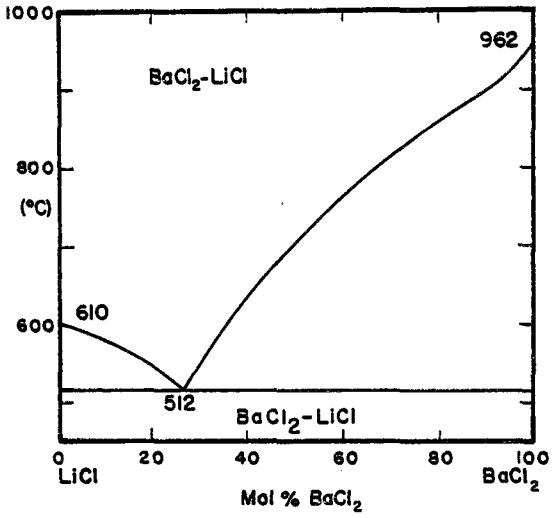

Figure 89.1. $LiCl-BaCl_2$ phase diagram

References [1-20].

2. *Density (ρ)*

Measurement method: modified maximum bubble pressure [21,22]

Equation:

$$\rho = a + bT \quad (89.1)$$

precision: in table 89.1. uncertainty: ∿ ± 2.0%

Table 89.1. Parameters of equation (89.1) and precisions

Mol % LiCl	a	$-b \times 10^4$	Precision	T range(K)
15.0	3.977	8.000	*	1160-1220
32.3	3.868	8.710	*	1070-1150
46.7	3.735	9.410	*	990-1060
60.6	3.430	8.430	*	980-1070
75.0	3.069	7.920	*	950-1070
89.8	2.689	8.300	*	880-1070

*not estimated; insufficient data

Table 89.2. Density (g cm^{-3}) from equation in table 89.1

T (K)	Mol % LiCl					
	15.0	32.3	46.7	60.6	75.0	89.9
880						
900						
920				2.654		
940				2.638		
960				2.621	2.309	1.892
980				2.604	2.293	1.876
1000			2.794	2.587	2.277	1.859
1020			2.775	2.570	2.261	1.842
1040			2.756	2.553	2.245	1.826
1060			2.738	2.536	2.229	1.809
1080		2.927				
1100		2.910				
1120		2.892				
1140		2.875				
1160	3.049	2.858				
1180	3.033					
1200	3.017					
1220	3.001					

References [21-23]

3. *Surface Tension* (γ) .

Measurement method: maximum bubble pressure [24]

Equation:

$$\gamma = a + bT \quad (89.2)$$

precision: in table 89.3 uncertainty: $\sim \pm 3.0\%$

Table 89.3. Parameters of equation (89.2) and precisions

Mol % LiCl	a	$-b \times 10^2$	Precision	T range(K)
15.0	216.6	4.50	0.3%	1160-1220
32.3	214.5	5.28	0.1%	1080-1160
46.7	211.0	5.82	0.2%	1000-1060
60.6	215.2	6.75	0.2%	920-1060
75.0	215.4	7.92	0.1%	960-1060
89.8	216.2	7.99	0.2%	880-1060

Table 89.4. Surface tension (dyn cm^{-1}) from equations in table 89.3

T (K)	Mol % LiCl				
	32.3	46.7	60.6	75.0	89.8
880					145.89
900					144.29
920			153.10		142.69
940			151.75		141.09
960			150.40	139.37	139.50
980			149.05	137.78	137.90
1000		152.80	147.70	136.20	136.30
1020		151.64	146.35	134.62	134.70
1040		150.47	145.00	133.03	133.10
1060		149.31	143.65	131.45	131.51
1080	157.48				
1100	156.42				
1120	155.36				
1140	154.31				
1160	153.25				
1180					

References [24]

4. *Viscosity (η)*

Measurement method: oscillating sphere technique [24]

Equation:

$$\eta = A \exp (E/RT) \quad (89.3)$$

precision: in table 89.5 uncertainty: ∿ ± 10%

Table 89.5. Parameters of equation (89.3) and precisions

LiCl (mol %)	A x 10^2	E (cal mol^{-1})	Precision	T range(K)
15.0	13.51	7701	3.0%	1160-1230
32.0	20.15	6161	3.0%	1130-1250
46.7	18.16	5821	4.0%	1070-1220
60.6	25.26	4469	3.0%	1010-1070
75.0	23.56	3810	2.0%	1020-1170
89.8	18.96	3909	2.0%	1010-1060

Table 89.6. Viscosity (cp) from equations in table 89.5

T (K)	Mol % LiCl					
	15.0	32.0	46.7	60.6	75.0	89.8
1010						1.33
1020					1.54	1.30
1030					1.52	1.28
1040					1.49	1.26
1050					1.46	1.23
1060				2.11	1.44	1.21
1070			2.81	2.07	1.41	1.19
1080			2.74	2.03	1.39	1.17
1090			2.67	1.99	1.37	1.15
1100			2.60	1.95	1.35	1.13
1110			2.54	1.92	1.33	1.12
1120			2.48	1.88	1.31	1.10
1130		3.13	2.43	1.85	1.29	1.08
1140		3.06	2.37	1.82	1.27	1.07
1150		2.99	2.32	1.79	1.25	1.05
1160	3.82	2.92	2.27	1.76	1.23	1.03
1170	3.71	2.85	2.22	1.73	1.21	
1180	3.61	2.79	2.17	1.70		
1190	3.51	2.73	2.13	1.67		
1200	3.41	2.67	2.09	1.65		
1210	3.32	2.61	2.04	1.62		
1220	3.24	2.56	2.00	1.60		
1230	3.16	2.51				
1240		2.46				
1250		2.41				
1260						
1270						
1280						
1290						

References [24]

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [25]

Equation:

$$\kappa = a + bT + cT^2 \quad (89.4)$$

precision: in table 89.7 uncertainty: ∿ ± 3.0%

Table 89.7. Parameters of equation (89.4) and precisions

Mol % LiCl	a	b x 10^3	c x 10^6	Precision	T range(K)
10.5	-2.545	3.911	0	*	1240-1270
21.6	-3.723	5.187	0	*	1180-1270
35.0	-3.899	5.763	0	*	1140-1270
52.4	3.746	-7.291	6.070	*	1080-1270
64.4	2.064	-3.041	4.127	*	1080-1270
77.6	-2.543	6.416	0	*	1080-1270

*not estimated; insufficient data

(89) $LiCl-BaCl_2$

Table 89.8. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 89.7

T (K)	Mol % LiCl					
	10.5	21.6	35.0	52.4	64.4	77.6
1080			2.325	2.952	3.593	4.386
1100			2.440	3.071	3.713	4.515
1120			2.556	3.194	3.853	4.543
1140		2.190	2.671	3.323	3.961	4.771
1160		2.294	2.786	3.456	4.090	4.900
1180	2.070	2.398	2.901	3.594	4.222	5.028
1200	2.148	2.501	3.017	3.738	4.358	5.156
1220	2.226	2.605	3.132	3.886	4.497	5.285
1240	2.305	2.709	3.247	4.038	4.639	5.413
1260	2.383	2.813	3.362	4.196	4.784	5.541

References [25]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: LiCl, slight; $BaCl_2$, poisonous when taken orally.

(ii) Vapor pressure: LiCl at m.pt. (610°C), ∿ 0.25mm; $BaCl_2$, at m.pt. (962°C) < 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure;i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic chloride fumes when heated to decomposition, or contacted with acids.

References [26-31]

7. Corrosion

Table 89.9. Corrosion studies from primary research literature

Studies	References
Mg, Ni, Zr, Ti	[32]
Ti, Zr, Hf, $ThCl_4$	[33]
Armco Fe	[34-40]
Zr	[41]
Solubility of metal oxides (Ni, Ca, Zn, Mg)	[32,42]
Thermodynamics of corrosion	[32,43,44]
Corrosion - annotated biblio.	[45]
Electrochemical aspects	[46]
Reviews: corrosion - molten salts	[47-49]

No compatibility studies specifically with molten $LiCl-BaCl_2$ were found, for $BaCl_2$ as a component in molten NaCl and KCl, see [36-40].

References [32-49]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [50]

Table 89.10 Volume change on melting

Binary eutectic (mol % $BaCl_2$)	$(\Delta V_f/V_s)$	Uncertainty
29.3%	0.6%	$\sim \pm$ 10%

References [50]

12. Vapor Pressure (p_{vap})

No data

(89) $LiCl-BaCl_2$

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 90 $NaCl-MgCl_2$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

NaCl: 800°C
$MgCl_2$: 714°C

Eutectic melting point:

E_i: 450°C, composition: 60.1 mol % NaCl
P_1: 465°C, composition: 53.1 mol % NaCl
P_2: 485°C, composition: 64.7 mol % NaCl

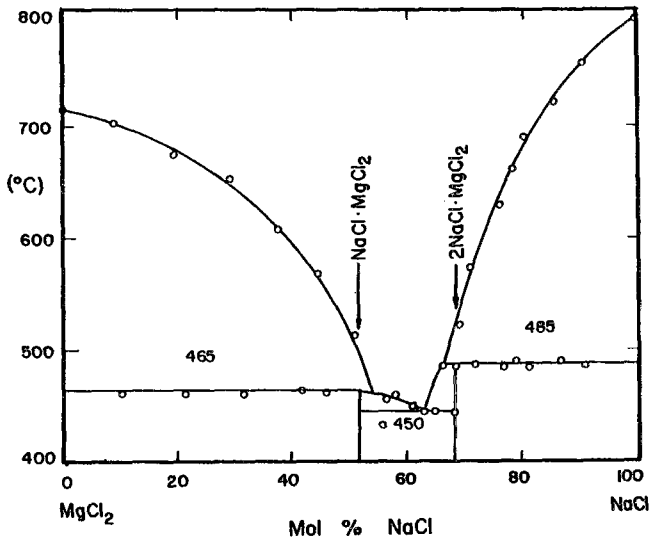

Figure 90.1. $NaCl-MgCl_2$ phase diagram

References [1-24]

2. *Density (ρ)*

Measurement method: Archimedean technique [26]

Equation:

$$\rho = a + bT \quad (90.1)$$

precision: in table 90.1 uncertainty: ∿ ± 2.0%

(90) $NaCl-MgCl_2$

Table 90.1. Parameters of equation (90.1) and precisions

Mol % NaCl	a	$-b \times 10^4$	Precision	T range (K)
0	1.9483	2.6917	0.03%	1020-1090
17.7	2.1501	4.4361	0.01%	1020-1110
25.6	2.1348	4.3414	0.01%	1050-1120
37.7	2.2029	5.1352	0.07%	1030-1120
48.5	2.1967	5.2669	0.04%	1040-1120
58.2	2.1253	4.7419	0.02%	1030-1100
66.3	2.1182	4.8222	0.03%	1050-1110
71.1	2.0431	4.1877	0.03%	1040-1100
76.4	2.0488	4.2896	0.02%	1050-1090
89.0	2.1392	5.3070	0.01%	1080-1120
95.0	2.1429	5.3845	0.02%	1030-1540
100	2.1321	5.2995	0.04%	1090-1090

Equation: (two-independent-variables equation)

$$\rho = a + bT + cT^2 + dC^2 + eC^3 + fTC^2 \quad (90.2)$$

Table 90.2. Parameters of two-independent-variables equation (90.2)

a	$b \times 10^3$	$c \times 10^7$	$d \times 10^5$	$e \times 10^7$	$f \times 10^8$	Precision
1.85184	-5.72548	-2.48988	2.44756	-3.61076	2.01655	0.15%

Table 90.3. Density (g cm^{-3}) from equations in table 90.1

	Mol % NaCl						
T (K)	17.7	37.7	48.5	58.2	66.3	71.1	95.0
1020	1.698						
1030	1.693	1.674		1.637			1.588
1040	1.689	1.669	1.649	1.632		1.608	1.583
1050	1.684	1.664	1.644	1.627	1.612	1.603	1.578
1060	1.680	1.659	1.638	1.623	1.607	1.599	1.572
1070	1.675	1.653	1.633	1.618	1.602	1.595	1.567
1080	1.671	1.648	1.628	1.613	1.597	1.591	1.561
1090	1.667	1.643	1.623	1.608	1.593	1.587	1.556
1100	1.662	1.638	1.617	1.604	1.588	1.582	1.551
1110	1.658	1.633	1.612		1.583		1.545
1120		1.628	1.607				1.540

References [25-30]

(90) $NaCl-MgCl_2$

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure [32]

Equation:

$$\gamma = a + bT \quad (90.3)$$

precision: in table 90.4. uncertainty: $\sim \pm 2.0\%$

Table 90.4. Parameters of equation (90.3) and precision

Mol % NaCl	a	$-b \times 10^2$	Precision	T range(K)
10	81.8	1.20	*	980-1170
20	88.1	1.40	*	980-1170
30	98.5	2.00	*	980-1170
40	105.5	2.30	*	980-1170
50	114.7	2.70	*	980-1170
60	124.4	3.30	*	980-1170
70	130.1	3.50	*	980-1170
80	142.7	4.30	*	980-1170
90	163.9	5.60	*	1030-1170

*not estimated; insufficient data.

Table 90.5. Surface tension (dyn cm^{-1}) from equations in table 90.4

T (K)	Mol % NaCl					
	10	40	50	60	70	90
980	70.0	83.0	88.2	92.1	95.8	
990	69.9	82.7	88.0	91.7	95.5	
1000	69 8	82.5	87.7	91.4	95.1	
1010	69.7	82.3	87.4	91.1	94.8	
1020	69.6	82.0	87.2	90.7	94.4	
1030	69.4	81.8	86.9	90.4	94.1	106.2
1040	69.3	81.6	86.6	90.1	93.7	105.7
1050	69.2	81.4	86.4	89.8	93.4	105.1
1060	69.1	81.1	86.1	89.4	93.0	104.5
1070	69.0	80.9	85.8	89.1	92.7	104.0
1080	68.8	80.7	85.5	88.8	92.3	103.4
1090	68.7	80.4	85.3	88.4	92.0	102.9
1100	68.6	80.2	85.0	88.1	91.6	102.3
1110	68.5	80.0	84.7	87.8	91.3	101.7
1120	68.4	79.7	84.5	87.4	90.0	101.2
1130	68.2	79.5	84.2	87.1	90.6	100.6
1140	68.1	79.3	83.9	86.8	90.2	100.1
1150	68.0	79.1	83.7	86.5	89.9	99.5
1160	67.9	78.8	83.4	86.1	89.5	98.9
1170	67.8	78.6	83.1	85.8	89.2	98.4

References [26,31-34]

(90) $NaCl-MgCl_2$

4. *Viscosity (η)*

Measurement method: oscillating sphere technique [36]

Equation:

$$\eta = a + bT \qquad (90.4)$$

precision: in table 90.6 uncertainty: ∿ ± 15%

Table 90.6. Parameters of equation (90.4) and precisions

NaCl (mol %)	a	b x 10^3	Precision	T range(K)
10	6.166	-4.200	0.00%	980-1080

Equation:

$$\eta = A \exp (E/RT) \qquad (90.5)$$

precision: in table 90.7 uncertainty: ∿ ± 25%

Table 90.7. Parameters of equation (90.5) and precisions

NaCl (mol %)	A x 10^2	E (cal mol^{-1})	Precision	T range(K)
20	10.89	5604	1.81%	980-1020
30	11.89	5234	2.50%	980-1020
40	10.28	5297	1.66%	980-1020
50	08.64	5385	0.12%	980-1020
60	08.27	5196	0.77%	980-1020
70	10.09	5070	1.77%	980-1020
80	13.57	4603	3.14%	980-1020

Table 90.8. Viscosity (cp) from equations in tables 90.6 and 90.7

	Mol % NaCl							
T (K)	10	20	30	40	50	60	70	80
980		1.936	1.748	1.561	1.373	1.192	1.363	1.443
1000		1.828	1.656	1.478	1.299	1.130	1.294	1.376
1020	1.882	1.729	1.573	1.403	1.231	1.074	1.231	1.315
1040	1.798	1.640	1.497	1.334	1.170	1.022	1.173	1.259
1060	1.714	1.558	1.427	1.271	1.114	0.975	1.120	1.207
1080	1.630	1.483	1.363	1.213	1.062	0.931	1.071	1.159

At 1073°K, the experimental values for 90 mol % and 100 mol % NaCl were 1.19 and 1.20 respectively. These values are within 16% of NSRDS values [36].

References [31,35,36]

(90) $NaCl-MgCl_2$

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [37]

Equation:

$$\kappa = a + bT \quad (90.6)$$

precision: in table 90.9 uncertainty: ∿ ± 2.0%

Table 90.9. Parameters of equation (90.6) and precisions

Mol % NaCl	a	b x 10^3	Precision	T range(K)
20	-0.8585	2.378	0.30%	980-1040
40	-1.1875	3.063	0.31%	960-1060
60	0.1275	2.029	0.35%	990-1090
80	0.4203	2.409	0.08%	1020-1060

Table 90.10. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 90.9

	Mol % NaCl			
T (K)	20	40	60	80
960		1.753		
970		1.784		
980	1.472	1.815		
990	1.496	1.845	2.136	
1000	1.520	1.876	2.156	
1010	1.544	1.907	2.177	
1020	1.567		2.197	2.877
1030	1.591		2.217	2.902
1040	1.615		2.238	2.926
1050	1.639		2.258	2.950
1060			2.278	2.974
1070			2.299	
1080			2.319	
1090			2.339	
1100				
1110				
1120				
1130				

References [4,25,28,36-39]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: NaCl, permitted in foods; $MgCl_2$, slight.

(ii) Vapor pressure: NaCl at m.pt. (800°C), ∿ 0.34mm; $MgCl_2$ at m.pt. (714°C), ∿ 0.11mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides, when heated to decomposition or contacted with acids, highly toxic chloride fumes are evolved.

References [40-45]

7. Corrosion

Table 90.11. Corrosion studies from primary research literature

Studies	References
Mo	[46]
Armco Fe	[47-49]
NiCr	[50]
Ti, Zr, Hf, $ThCl_4$	[51,52]
Cr	[53]
Cr, Fe-Cr	[54]
Ni alloys	[55]
Ni-Cr-Al, Ni-Cr-W-Fe, Ni-Cr, Mg, Ni, Zr, Ti,	[56]
Au, Pt, MgO, Al_2O_3, Zirconia (NaCl with added Na_2O)	[57]
Electrochemical aspects of corrosion	[58,59]
Corrosion - annotated biblio.	[60]
Thermodynamic redox potentials (diagrammatic analysis)	[56,61,62]
Reviews: corrosion in molten salts	[63-65]

Compatibility studies for various molten chlorides and mixtures. For some studies specifically with molten $NaCl-MgCl_2$ mixtures, see [51]

References [46-65]

(90) $NaCl-MgCl_2$

8. Diffusion

Measurement method: in table 90.12

List of diffusing species investigated in $NaCl-MgCl_2$ as solvent

Fe^{3+}, Cl_2

precision: in table 90.13 uncertainty: in table 90.12

Table 90.12. Diffusion techniques, uncertainties and species

Diffusion technique of recommended study	Uncertainty (in values of D)	Species
faradaic impedance	∿± 20%	Cl_2
rotating disc electrode	∿± 20%	Fe^{3+}

Equation:

$$D = A \exp(-E/RT) \quad (90.7)$$

Table 90.13. Parameters of diffusion equation (90.7), precisions, and recommended study

Species	A x 10^3 (cm^2 s^{-1})	E (cal mol^{-1})	Temp. range (K)	Precision	Recommended study
(a) $NaCl-MgCl_2$ (50 mol % NaCl)					
Fe^{3+}	0.404	5130	970-1120	∿±0.1%	[66]
Cl_2	47.930	13510	863-1125	∿±20.1%	[67]
(b) $NaCl-MgCl_2$ (75 mol % NaCl)					
Cl_2	0.000165	-13600	949-1053	∿±1.1%	[67]

Table 90.14. Diffusion coefficients, D x 10^5 (cm^2 s^{-1}) from equations in table 90.13

T (K)	25 mol % NaCl	50 mol % NaCl		75 mol % NaCl
	Cl_2	Fe^{3+}	Cl_2	Cl_2
863			1.82	
875			2.03	
900			2.52	
925			3.09	
950	0.50 at 952		3.75	22.21
975	1.00 at 973	2.86	4.50	18.46
1000		3.06	5.36	15.49
1025		3.25	6.32	13.11
1050		3.46	7.40	11.18
1075		3.66	8.61	
1100		3.86	9.94	
1125		4.07	11.40	

References: Fe^{3+}[66]; Cl_2 [67].

9. *Heat of Fusion (ΔH_f°)*

Measurement method: calculated [69]

Table 90.15. Heat of fusion

Composition (mol % NaCl)	T_m (°C)	ΔH_f° (kcal mol^{-1})	Uncertainty
60%	450°	8.0	∿ ± 5.0%

References [69]

10. *Heat Capacity (C_p)*

Measurement method: calculated [70]

Table 90.16. Heat capacity

Composition $NaCl:MgCl_2$ (mol %)	C_p (cal K^{-1} mol^{-1})	T range (K)	Uncertainty
60:40	16.8	T_m(723) ∿ 823	∿ ± 10%

For the above composition, $C_{p(s)}$ = 15.4 (cal K^{-1} mol^{-1}); uncertainty of estimated value, ∿ ± 10%.

References [70]

(90) $NaCl-MgCl_2$

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [71]

Table 90.17. Volume change on melting

Binary eutectic (mol % NaCl)	$(\Delta V_f/V_s)$	Uncertainty
60	19.5%	$\sim \pm$ 10%

References [71]

12. Vapor Pressure (p_{vap})

Measurement method: boiling point technique [72]

Equation:

$$\log p = A + B/T \quad (90.8)$$

precision: in table 90.18 uncertainty: $\sim \pm$ 10%

Table 90.18. Parameters of equation (90.8) and precision

Mol % $MgCl_2$	A	-B	Precision	T range(K)
71.0	7.2701	7730	*	1170-1320
58.9	7.3101	7830	*	1170-1320
46.9	7.20(a)	7940	*	1170-1320
35.8	8.2200	9370	*	1170-1320
29.0	8.1800	9180	*	1170-1320

*data reported in equation form; insufficient information for estimate

(a) reported as 3.30 [72], possibly due to typographical error

Table 90.19. Vapor pressure (mm) from equations in table 90.18

T (K)	Mol % $MgCl_2$				
	71.0	58.9	46.9	35.8	29.0
1170	4.604	4.147	3.263	1.627	2.157
1180	5.238	4.725	3.726	1.902	2.514
1200	6.735	6.095	4.823	2.580	3.388
1220	8.580	7.798	6.192	3.465	4.523
1240	10.87	9.897	7.885	4.608	5.981
1260	13.65	12.47	9.964	6.074	7.839
1280	17.02	15.59	12.50	7.938	10.19
1300	21.08	19.36	15.57	10.29	13.14
1320	25.94	23.89	19.27	13.23	16.81

References [72]

(90) $NaCl-MgCl_2$

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f° [71]

Table 90.20. Cryoscopic constant

Binary eutectic (mol % NaCl)	k_f (K mol^{-1} kg)	Uncertainty
60.0	9.50	$\sim \pm$ 1%

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System 91 $BaCl_2$-NaCl

1. *Melting Temperatures (T_m)*

Pure substance melting points:

NaCl: 800°C

$BaCl_2$: 962°C

Eutectic melting point:

654°C, composition: 39 mol % $BaCl_2$

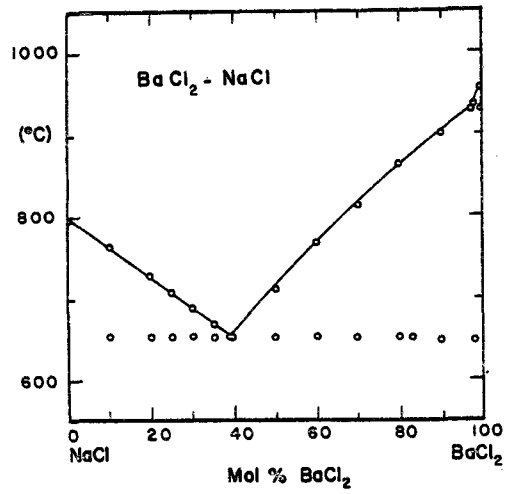

Figure 91.1. $BaCl_2$-NaCl phase diagram

References [1-25]

2. *Density (ρ)*

Measurement method: Archimedean technique [28]

Equation:

$$\rho = a + bT \quad (91.1)$$

precision: in table 91.1 uncertainty: ∿ ± 1.0%

(91) $BaCl_2$-NaCl

Table 91.1. Parameters of equation (91.1) and precisions

Mol % NaCl	a	$-b \times 10^3$	Precision	T range(K)
40.0	3.6349	0.8399	0.15%	1040-1120
47.0	3.6532	0.9586	0.19%	1040-1120
54.0	3.7799	1.1645	0.12%	1000-1120
57.5	3.2956	0.7440	0.01%	1000-1070
60	3.4208	0.9123	0.09%	990-1100
61.0	3.2735	0.7840	0.01%	1000-1070
64.5	3.3008	0.8840	0.02%	1000-1070
67	3.1909	0.8150	0.06%	990-1110
68.0	2.9889	0.6400	0.00%	1000-1070
71.5	3.0067	0.7200	0.00%	1000-1070
74	2.5799	0.3698	0.01%	1060-1110
75.0	2.6709	0.4680	0.01%	1000-1070
81	2.6378	0.5837	0.09%	1060-1070
82.0	[2.2436]	[0.2400]	0.00%	1050-1070
89.0	[2.1654]	[0.3200]	0.00%	1050-1070
100	2.2259	0.640	0.00%	1080-1120

Table 91.2. Density (g cm^{-3}) from equations in table 91.1

T (K)	Mol % NaCl							
	54.0	57.5	60.0	61.0	64.5	67.0	68.0	71.5
990			2.518			2.384		
1000	2.615	2.552	2.509	2.490	2.417	2.376	2.349	2.287
1010	2.604	2.544	2.499	2.482	2.408	2.368	2.343	2.280
1020	2.592	2.537	2.490	2.474	2.399	2.360	2.336	2.272
1030	2.580	2.529	2.481	2.466	2.390	2.352	2.330	2.265
1040	2.569	2.522	2.472	2.458	2.381	2.343	2.323	2.258
1050	2.557	2.514	2.463	2.450	2.373	2.335	2.317	2.251
1060	2.546	2.507	2.454	2.442	2.364	2.327	2.310	2.244
1070	2.534	2.500	2.445	2.435	2.355	2.319	2.304	2.236
1080	2.522		2.436			2.311		
1090	2.511		2.426			2.303		
1100	2.499		2.417			2.294		
1110	2.487					2.286		
1120	2.476							

References [26-31]

(91) $BaCl_2$-NaCl

3. Surface Tension (γ)

Measurement method: maximum bubble pressure [33]

Equation:

$$\gamma = a + bT \quad (91.2)$$

precision: in table 91.3 uncertainty: $\sim \pm 3.0\%$

Table 91.3. Parameters of equation (91.2) and precisions

Mol % NaCl	a	$-b \times 10^2$	Precision	T range(K)
20	235.4	6.70	0.20%	1200-1230
30	213.8	5.50	0.14%	1180-1230
40	210.7	5.90	0.23%	1100-1240
50	197.1	6.00	0.10%	1080-1190
70	178.3	4.80	0.10%	1080-1190
80	191.3	6.40	0.20%	1080-1180

Table 91.4. Surface tension (dyn cm^{-1}) from equations in table 91.3

	Mol % NaCl					
T (K)	20	30	40	50	70	80
1080				132.7	126.5	122.0
1100				131.5	125.6	120.7
1120			144.7	130.3	124.6	119.4
1140			143.5	129.1	123.7	118.1
1160			142.3	127.9	122.7	116.8
1180		148.8	141.2	126.7	121.7	115.6
1200	155.5	147.7	140.0			
1220	154.1	146.5	138.8			
1240			137.6			

References [32-35]

4. Viscosity (η)

Measurement method: oscillating sphere technique [28]

Equation:

$$\eta = a + bT + cT^2 + dT^3 \quad (91.3)$$

precision: in table 91.5 uncertainty: $\sim \pm 35\%$

Table 91.5. Parameters of equation (91.3) and precisions

NaCl (mol %)	a	$-b \times 10^2$	$-c \times 10^5$	$d \times 10^8$	Precision	T range(K)
40	45.232	2.585	5.013	3.541	0.9%	1050-1140
47	-27.572	-18.504	25.252	9.968	1.5%	1030-1140
54	48.026	1.215	8.274	5.137	11.9%	1000-1140
60	36.842	1.118	5.828	3.659	1.3%	1000-1140
67	32.640	2.127	3.196	2.397	0.6%	1000-1140
74	34.626	2.797	2.448	2.101	1.0%	1000-1140
81	33.133	3.572	0.658	1.209	0.7%	1030-1140

Equation:

$$\eta = A \exp (E/RT) \quad (91.4)$$

precision: in table 91.6 uncertainty: $\sim \pm 35\%$

Table 91.6. Parameters of equation (91.4) and precisions

NaCl (mol %)	$A \times 10^2$	E ($cal\ mol^{-1}$)	Precision
100	1.134	10553	1.58%

Table 91.7. Viscosity (cp) from equations in tables 91.5 and 91.6

T (K)	Mol % NaCl						
	40	47	54	60	67	74	81
1000			4.51	3.97	3.38	3.19	
1010			4.28	3.80	3.25	3.05	
1020			4.06	3.63	3.13	2.92	
1030		4.05	3.87	3.48	3.02	2.80	2.57
1040		3.87	3.68	3.34	2.91	2.69	2.47
1050	3.80	3.71	3.51	3.21	2.82	2.59	2.37
1060	3.67	3.56	3.36	3.19	2.73	2.50	2.28
1070	3.55	3.43	3.23	2.98	2.66	2.41	2.19
1080	3.44	3.30	3.11	2.88	2.59	2.33	2.11
1090	3.34	3.19	3.00	2.80	2.53	2.26	2.04
1100	3.26	3.10	2.92	2.73	2.48	2.20	1.97
1110	3.19	3.02	2.85	2.67	2.44	2.15	1.91
1120	3.13	2.96	2.80	2.62	2.40	2.11	1.86
1130	3.09	2.91	2.77	2.59	2.38	2.08	1.81
1140	3.06	2.88	2.75	2.57	2.37	2.05	1.77

References [27,28,36]

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [38]

Equation:

$$\kappa = a + bT + cT^2 \quad (91.5)$$

precision: in table 91.8 uncertainty: ∿ ± 3.0%

Table 91.8. Parameters of equation (91.5) and precisions

Mol % NaCl	-a	b x 10^3	-c x 10^6	Precision	T range(K)
16.5	7.5250	12.250	3.5782	0.65%	1200-1400
32.5	11.2053	18.833	6.2943	0.83%	1160-1340
52	4.6329	8.854	2.4643	0.40%	1020-1300
64.6	6.6683	12.884	4.2384	0.62%	960-1300
76.05	3.3793	8.140	2.4368	1.33%	1020-1300
87	3.7821	9.225	2.8480	0.31%	1080-1380

(91) $BaCl_2$-NaCl

Table 91.9. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 91.8

T (K)	Mol % NaCl					
	16.5	32.5	52	64.6	76.05	87
960				1.78		
1000				1.96		
1040			1.91	2.13	2.45	
1080			2.05	2.29	2.57	2.86
1120			2.19	2.43	2.68	2.98
1160		2.17	2.32	2.56	2.78	3.09
1200	2.02	2.33	2.44	2.67	2.88	3.19
1240	2.16	2.47	2.56	2.78	2.97	3.28
1280	2.29	2.59	2.66	2.86	3.05	3.36
1320	2.41	2.69				3.43
1360	2.52					3.50
1400	2.61					

References [27-29,34,36-38]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: NaCl, permitted in foods; $BaCl_2$, toxic (orally).

(ii) Vapor pressure: NaCl at m.pt. (800°C) ~ 0.34mm; $BaCl_2$ at m.pt. (962°C) ~ < 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic fumes when heated to decomposition, or contacted with acids.

References [39-45]

7. Corrosion

Table 91.10. Corrosion studies from primary research literature

	Studies	References
A	Zr	[46]
	Fe, steels	[47-51]
	Ti, Zr, Hf, $ThCl_4$	[52]
	Pb, Pb-Bi	[53]
B	Mo	[54]
	Armco Fe	[55-57]
	NiCr	[58]
	Ti, Zr, Hf, $ThCl_4$	[52]
	Cr	[59]
	Cr, Fe-Cr	[60]
	Ni alloys	[61]
	Ni-Cr-Al, Ni-Cr-W-Fe, Ni-Cr, Mg, Ni, Zr, Ti	[62]
	Au, Pt, MgO, Al_2O_3, Zirconia (NaCl with added Na_2O)	[63]
C	Electrochemical aspects of corrosion	[64,65]
	Corrosion - annotated biblio.	[66]
	Thermodynamic redox potentials (diagrammatic analysis)	[62,67,68]
	Reviews: corrosion in molten salts	[69-71]

Compatibility studies: A: principally molten $BaCl_2$; B: principally molten NaCl; C: basic principles, reviews, biblios. No compatibility studies specifically for molten $BaCl_2$-NaCl mixtures.

References [46-71]

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

10. Heat Capacity (C_p)

No data

(91) $BaCl_2$-NaCl

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [72]

Table 91.11. Volume change on melting

Binary eutectic (mol % NaCl)	$(\Delta V_f/V_s)$	Uncertainty
61	3.7%	$\sim \pm$ 10%

References [72]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 92 $KCl-MgCl_2$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

KCl: 770°C

$MgCl_2$: 714°C

Eutectic melting point:

E_1: ∿ 435°C, composition: 30 mol % $MgCl_2$

E_2: ∿ 435°C, composition: 36 mol % $MgCl_2$

E_3: ∿ 470°C, composition: 58 mol % $MgCl_2$

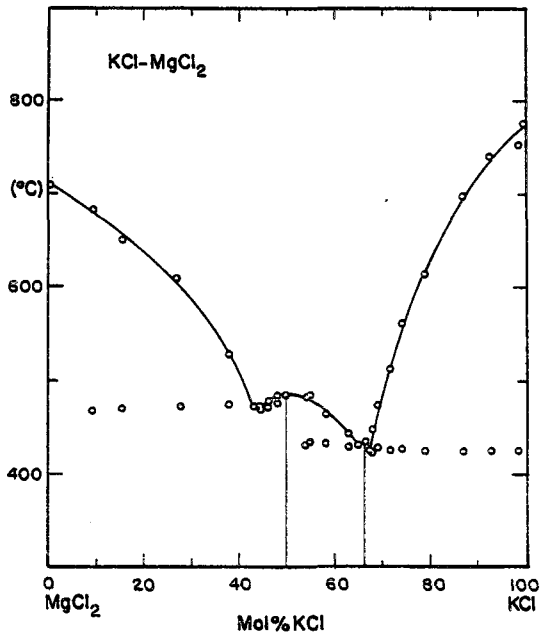

Figure 92.1. $KCl-MgCl_2$ phase diagram

References [1-21]

2. *Density (ρ)*

Measurement method: Archimedean technique [26]

Equation:

$$\rho = a + bT \quad (92.1)$$

precision: in table 92.1 uncertainty: ∿ ± 1.5%

Table 92.1. Parameters of equation (92.1) and precisions

Mol % $MgCl_2$	a	$-b \times 10^4$	Precision	T range(K)
6.6	2.1380	5.840	0.04%	1050-1140
12.0	2.1561	6.062	0.04%	1080-1140
25.0	2.0796	5.327	0.02%	1050-1120
32.8	2.0007	4.571	0.03%	1030-1140
42.2	2.1387	5.550	0.02%	1030-1140
50.3	2.0998	5.029	0.05%	1080-1170
53.5	2.1900	5.705	0.05%	1060-1130
61.7	2.1923	5.563	0.01%	1060-1140
66.3	2.1587	5.086	0.04%	1050-1120
67.5	2.2582	6.008	0.02%	1060-1160
77.4	2.2238	5.392	0.01%	1060-1130
90.0	2.0844	3.937	0.01%	1060-1110

Table 92.2. Density (g cm^{-3}) from equations in table 92.1

	Mol % $MgCl_2$						
T (K)	25.0	32.8	42.2	50.3	53.5	61.7	66.3
1030		1.530	1.567				
1040		1.525	1.562				
1050	1.520	1.521	1.556				1.625
1060	1.515	1.516	1.550		1.585	1.603	1.620
1070	1.510	1.512	1.545		1.580	1.597	1.614
1080	1.504	1.507	1.539	1.557	1.574	1.591	1.609
1090	1.499	1.502	1.534	1.552	1.568	1.586	1.604
1100	1.494	1.498	1.528	1.547	1.562	1.580	1.599
1110	1.488	1.493	1.523	1.542	1.557	1.575	1.594
1120	1.483	1.489	1.517	1.537	1.551	1.569	1.589
1130		1.484	1.512	1.532	1.545	1.564	
1140		1.480	1.506	1.526		1.558	
1150		1.475		1.521			
1160							
1170							

References [22-31]

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure [34]

Equation:

$$\gamma = a + bT \quad (92.2)$$

precision: in table 92.3 uncertainty: $\sim \pm 2\%$

Table 92.3. Parameters of equation (92.2) and precisions

Mol % $MgCl_2$	a	$-b \times 10^2$	Precision	T range(K)
10	160.4	6.60	*	980-1160
20	147.7	5.80	*	980-1160
30	133.0	4.80	*	980-1160
40	119.3	3.80	*	980-1160
50	123.0	4.30	*	980-1160
60	116.3	3.80	*	980-1160
70	109.5	3.30	*	980-1160
80	100.7	2.70	*	980-1160
90	91.2	2.10	*	980-1160

*not estimated; insufficient data

Table 92.4. Surface tension (dyn cm^{-1}) from equations in table 92.3

T (K)	Mol % $MgCl_2$				
	30	40	50	60	70.
980	86.0	82.1	80.9	79.1	77.2
990	85.5	81.7	80.4	78.7	76.8
1000	85.0	81.3	80.0	78.3	76.5
1010	84.5	80.9	79.6	77.9	76.2
1020	84.0	80.5	79.1	77.5	75.8
1030	83.6	80.2	78.7	77.2	75.5
1040	83.1	79.8	78.3	76.8	75.2
1050	82.6	79.4	77.9	76.4	74.9
1060	82.1	79.0	77.4	76.0	74.5
1070	81.6	78.6	77.0	75.6	74.2
1080	81.2	78.3	76.6	75.3	73.9
1090	80.7	77.9	76.1	74.9	73.5
1100	80.2	77.5	75.7	74.5	73.2
1110	79.7	77.1	75.3	74.1	72.9
1120	79.2	76.7	74.8	73.7	72.5
1130	78.8	76.4	74.4	73.4	72.2
1140	78.3	76.0	74.0	73.0	71.9
1150	77.8	75.6	73.6	72.6	71.6
1160	77.3	75.2	73.1	72.2	71.2
1170	76.8	74.8	72.7	71.8	70.9
1180					

References [32-36]

4. *Viscosity (η)*

Measurement method: oscillating sphere technique [26]

Equation:

$$\eta = a + bT + cT^2 + dT^3 \quad (92.3)$$

precision: in table 92.5 uncertainty: $\sim \pm 15\%$

Table 92.5. Parameters of equation (92.3) and precisions

$MgCl_2$ (mol%)	a	$-b \times 10^2$	$c \times 10^5$	$d \times 10^9$	Precision	T range(K)
8.0	22.743	2.808	-0.133	8.032	2.8%	1030-1180
16.4	8.033	0.543	-0.663	5.201	1.3%	950-1100
32.4	9.346	2.253	2.501	-10.455	2.1%	900-1030
34.3	12.051	2.018	1.069	-1.335	0.4%	910-1090
49.9	[94.173]	[25.555]	[23.547]	[-72.802]		980-1140

Equation:

$$\eta = A \exp (E/RT) \quad (92.4)$$

precision: in table 92.6 uncertainty: $\sim \pm 15\%$

Table 92.6. Parameters of equation (92.4) and precisions

$MgCl_2$ (mol %)	$A \times 10^2$	E (cal mol^{-1})	Precision	T range(K)
25.1	11.894	4508	3.6%	900-1080
43.9	7.757	5469	2.5%	900-1040
54.0	17.399	4025	4.4%	970-1060

Table 92.7. Viscosity (cp) from equations in tables 92.5 and 92.6

	Mol % $MgCl_2$							
T (K)	8.0	16.4	25.1	32.4	34.3	43.9	49.9	54.0
900			1.48	1.71		1.65		
920			1.40	1.65	1.49	1.54		
940			1.33	1.58	1.42	1.45		
960		1.31	1.26	1.52	1.35	1.36		
980		1.24	1.20	1.45	1.28	1.29	(1.36)	1.37
1000		1.18	1.15	1.37	1.23	1.22	(1.29)	1.32
1020		1.12	1.10	1.29	1.17	1.15	(1.24)	1.27
1040	1.14	1.07	1.05		1.12	1.09	(1.20)	1.22
1060	1.05	1.02	1.01		1.08		(1.16)	1.18
1080	0.98	0.99	0.97		1.04		(1.12)	
1100	0.94	0.96					(1.09)	
1120	0.91						(1.05)	
1140	0.90						(1.01)	
1160	0.92							

The values in ( ) are based on a minimal data set

References [26,28,33,37-41]

(92) $KCl-MgCl_2$

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [47]

Equation:

$$\kappa = a + bT + cT^2 \quad (92.5)$$

precision: in table 92.8 uncertainty: $\sim \pm 5.0\%$

Table 92.8. Parameters of equation (92.5) and precisions

Mol % $MgCl_2$	-a	b x 10^3	c x 10^6	Precision	T range(K)
18.5	7.6274	15.958	-6.959	0.04%	880-1020
22.0	5.220	10.975	-4.417	0.08%	830-1020
24.5	3.2951	6.944	-2.326	0.58%	830-1020
31.8	1.3943	2.993	-0.318	0.10%	830-1020
34.0	1.0872	2.2795	0.084	0.04%	830-1020
37.0	1.1279	2.402	0	0.05%	830-1020
39.9	0.8689	1.907	0.228	0.14%	830-1020
45.5	0.9227	2.184	0	0.48%	830-1020
48.8	0.9039	2.160	0	0.21%	830-1020
52.0	2.9434	6.363	-2.152	0.70%	830-1020
58.8	1.0490	2.450	-0.145	0.06%	830-1020
72.1	0.5571	1.486	0.297	0.07%	880-1020
84.0	[0.1479]	[0.024]	[1.000]	0.00%	930-1020

Table 92.9. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 92.8

T (K)	Mol % $MgCl_2$						
	31.8	34.0	37.0	45.5	48.8	52.0	58.8
830	0.871	0.863	0.866	0.890	0.899	0.856	0.885
850	0.920	0.911	0.914	0.934	0.932	0.910	0.929
870	0.969	0.959	0.962	0.977	0.975	0.964	0.973
890	1.018	1.008	1.010	1.021	1.019	1.015	1.017
910	1.066	1.057	1.058	1.065	1.062	1.065	1.060
930	1.114	1.105	1.106	1.108	1.105	1.113	1.104
950	1.162	1.154	1.154	1.152	1.148	1.159	1.148
970	1.210	1.203	1.202	1.196	1.191	1.204	1.191
990	1.257	1.252	1.250	1.239	1.235	1.247	1.234
1010	1.304	1.301	1.298	1.283	1.278	1.288	1.278

References [22,25,28,30,42-48]

(92) $KCl-MgCl_2$

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: slight.

(ii) Vapor pressure: at m.pt (770°C), ∿ 0.42mm; $MgCl_2$, at m.pt (714°C) ∿ 0.11mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic fumes when heated to decomposition, or contacted with acids.

References [1,49-53]

7. Corrosion

Table 92.10. Corrosion studies from primary research literature

	Studies	References
A	Armco Fe; various steels	[54-57]
	Cr	[58]
	Cr, Fe-Cr	[59]
	Mg, Ni, Zr, Ti	[60]
	Ti, Zr, Hf, $ThCl_4$	[61]
B	Zr	[62]
	Ti, Zr, Hg, $ThCl_4$	[61]
	Pb, Pb-Bi	[63]
	Armco Fe	[63-67]
C	Solubility of oxides (ni, Ca, Zn, Mg)	[60,68]
	Electrochemical aspects	[69]
	Corrosion - annotated biblio.	[70]
	Thermodynamic approach	[60,71,72]
	Reviews: corrosion in molten salts	[73-75]

Compatibility studies: A: principally molten KCl; B: principally molten $CaCl_2$, $MgCl_2$, or $BaCl_2$; C: general discussion and reviews. For compatibility studies with $KCl-MgCl_2$ mixtures, see [66]

References [54-75]

(92) $KCl-MgCl_2$

8. Diffusion

Measurement method: cited in tabulations

List of diffusing species investigated in $KCl-MgCl_2$ as solvent

Fe^{3+}, Cl_2

precision: in table 92.12 uncertainty: in table 92.11

Table 92.11. Diffusion techniques, uncertainties and species

Diffusion technique of recommended study	Uncertainty (in values of D)	Species
chronopotentiometry	∿ ± 15%	Cl_2
double layer impedance	∿ ± 15%	Cl_2
rotating disc electrode	∿ ± 15%	Fe^{3+}

Equation:

$$D = A \exp [-E/RT] \quad (92.6)$$

Table 92.12. Parameters of diffusion equation (92.6), precisions and recommended study

Species	A x 10^3 (cm^2 s^{-1})	-E (cal mol^{-1})	Temp. range (K)	Precision	Recommended study
(a) $KCl-MgCl_2$ (50 mol % KCl)					
Fe^{3+}	0.779	6180	873-1123	∿ ± 0.1%	[77]
Cl_2	2.467	7865	913-1140	∿ ± 18.5%	[78]
(b) $KCl-MgCl_2$ (75 mol % KCl)					
Cl_2	3.980	6171	913-1061	∿ ± 4.4%	[78]

Table 92.13. Diffusion coefficients, D x 10^5 (cm^2 s^{-1}) from equation in table 92.12

T	25 mol % KCl	50 mol % KCl		75 mol % KCl
(K)	Cl_2	Fe^{3+}	Cl_2	Cl_2
870		2.18		
880		2.27		
900		2.46		
920	1.0 at 926K	2.65	3.34	13.61
940		2.85	3.66	14.63
960		3.05	4.00	15.67
980		3.26	4.35	16.74
1000		3.48	4.71	17.83
1020		3.69	5.09	18.95
1040		3.92	5.49	20.09
1060		4.14	5.90	21.26
1080		4.38	6.32	
1100		4.61	6.75	
1120		4.85	7.20	

The diffusion of Cl_2 has also been investigated chronopotentiometrically in the 50% mol KCl mixture [76]; the values of the diffusion coefficients appear high (∿ x 10) relative to the values in the table above. There are insufficient details in the publication to resolve this.

References: Cl_2, 76, 78; Fe^{3+}, 77

9. Heat of Fusion (ΔH_f°)

Measurement method: drop calorimetry [79,80]

Table 92.14. Heat of fusion

Composition (mol % KCl)	T_m (°C)	ΔH_f° (kcal mol^{-1})	Uncertainty
42%	470°	8.1	∿ ± 5%
50%	480°	6.6	∿ ± 3%
66%	435°	6.9	∿ ± 5%

References [79,80]

(92) $KCl-MgCl_2$

10. Heat Capacity (C_p)

Measurement method: calculated [81]

Table 92.15. Heat capacity

Composition $KCl:MgCl_2$ (mol %)	C_p (cal K^{-1} mol^{-1})	T range (K)	Uncertainty
41.8:58.2(%)	19.9	T_m(608)-700	∿ ± 10%
66.6:33.4(%)	18.7	T_m(608)-700	∿ ± 10%

For these 2 compositions, the values for C_p(s) are estimated to be: 17.3 and 15.5 (cal K^{-1} mol^{-1}) respectively; uncertainty estimates: ∿ ± 10%.

References [81]

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [82]

Table 92.16. Volume change on melting

Composition (mol % KCl)	$(\Delta V_f/V_s)$	Uncertainty
70 (a)	18.6%	∿ ± 10%
60 (a)	22.0%	∿ ± 10%
42 (a)	17.0%	∿ ± 10%
52 (b)	19.3%	∿ ± 10%

(a) eutectic compositions; (b) equi-molar compound

References [82]

12. Vapor Pressure (p_{vap})

Measurement method: boiling point technique [84]

Equation:

$$\log p(mm) = A + B/T \quad (92.7)$$

precision: in table 92.17 uncertainty: ∿ ± 5.0%

Table 92.17. Parameters of equation (92.7) and precisions

Mol % $MgCl_2$	A	-B	Precision	T range(K)
0	8.4711	9290	2.9%	1189-1418
9.9	8.5386	9488	0.8%	1281-1410
20.8	8.1541	9060	1.1%	1299-1421
28.6	8.5182	9701	1.8%	1316-1422
30.5	8.3438	9437	0.7%	1323-1426
33.1	8.5960	9805	1.5%	1316-1425
39.4	8.4961	9662	0.6%	1313-1424
48.8	8.4596	9555	0.7%	1314-1426
49.4	8.4648	9589	1.7%	1358-1429
59.1	8.5726	9620	1.7%	1280-1412
69.7	8.4555	9366	1.1%	1260-1399
76.3	8.4653	9308	3.0%	1262-1415
89.9	8.6596	9481	1.4%	1245-1410
100	8.7012	9462	1.6%	1208-1413

Table 92.18. Vapor pressure from equations in table 92.17

T	Mol % $MgCl_2$							
(K)	20.8	28.6	33.1	39.4	48.8	49.4	59.1	69.7
1260								10.52
1280							11.40	13.75
1300	15.31						14.88	17.82
1320	19.52	14.76	14.72	15.01	16.63		19.26	22.91
1340	24.71	19.00	19.00	19.30	21.33		24.75	29.24
1360	31.07	24.27	24.35	24.64	27.16	25.95	31.56	37.05
1380	38.81	30.80	30.97	31.24	34.33	32.83	39.96	46.62
1400	48.16	38.81	39.12	39.32	43.11	41.26	50.25	58.28
1420	59.40	48.59	49.10	49.19	53.79	51.52		
1430			54.87		59.95	57.44		

References [83-85]

13. *Thermal Conductivity (liquid)* (λ_ℓ)

Measurement method: coaxial cylinder technique [86,87]

Equation:

$$\lambda = a + bT \quad (92.8)$$

precision: in table 92.19 uncertainty: $\sim \pm 20\%$

(92) $KCl-MgCl_2$

Table 92.19. Parameters of equation (92.8), precisions, and temp. range

Mol % $MgCl_2$	a x 10^4	b x 10^6	Precision	T range(K)
0	-29.674	5.042	0.7%	1055-1095
24	6.5213	1.644	0.8%	850-870
25	1.3817	1.805	0.4%	830-860
29	-21.644	4.652	0.2%	740-780
34	5.9011	1.201	0.4%	725-765
50	-33.776	6.361	1.9%	780-815
60	-40.848	7.133	1.3%	780-800
80	-51.321	6.714	3.8%	930-950

Table 92.20. Thermal conductivity (x 10^4 cal cm^{-1} s^{-1} K^{-1}) from equations in table 92.19

T (K)	Mol % $MgCl_2$						
	24	25	29	34	50	60	80
730				14.7			
740			12.8	14.8			
760			13.7	15.0			
780			14.6		15.8	14.8	
800					17.1	16.2	
840		16.5					
850	20.5	16.7					
860	20.7	16.9					
870	20.8						
930							11.1
940							11.8
950							12.5

The λ values for pure KCl reported in [86] are uniformly higher er ($\sim$ 20%) than the recommended values [88]

Table 92.21. Isotherm of thermal conductivity at 973K

Mol % $MgCl_2$	λ x 10^4 (cal cm^{-1} s^{-1} K^{-1})	Mol % $MgCl_2$	λ x 10^4 (cal cm^{-1} s^{-1} K^{-1})
0	19.4	34	17.6
24	22.5	50	28.1
25	18.9	60	28.6
29	23.6	80	14.0

A number of metallurgical processes with $KCl-MgCl_2$ as a component take place at $\sim$ 700°C, i.e. $\sim$ 973K. The data (above) illustrate the thermal conductivity-composition isotherm at this temperature. In systems of nitrates not showing compound formation, the thermal conductivity generally shows a negative deviation from additivity (passing through a minimum at the equimolar composition).

References [86-88]

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f° [82]

Table 92.22. Cryoscopic constant

Binary system (mol % KCl)	k_f (K mol^{-1} kg)	Uncertainty
E_1 42	11.7	∿ ± 1%
E_2 66	11.8	∿ ± 1%
Cpd. 50	14.5	∿ ± 1%

References [82]

16. References

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System 93 $KCl-CaCl_2$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$CaCl_2$: 782°C

KCl: 770°C

Eutectic melting point:

E_1: 594°C, composition: 75.7 mol % KCl

E_2: 640°C, composition: 25.9 mol % KCl

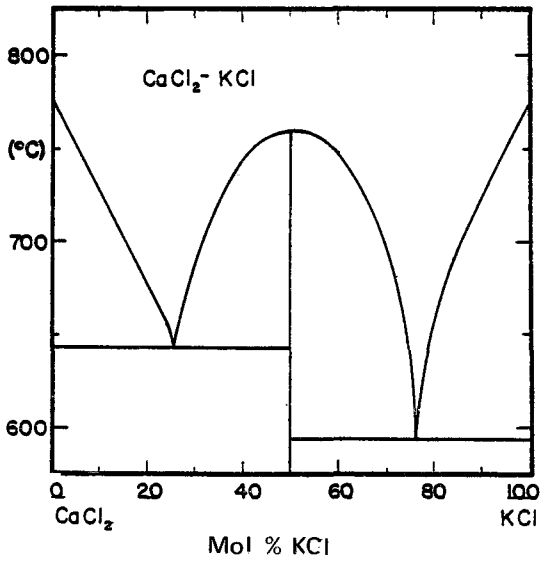

Figure 93.1. $KCl-CaCl_2$ phase diagram

References [1-29].

2. *Density (ρ)*

Measurement method: Archimedean technique [30]

Equation:

$$\rho = a + bT \quad (93.1)$$

precision: in table 93.1 uncertainty: ∿ ± 1.5%

Table 93.1. Parameters of equation (93.1) and precisions

Mol % KCl	a	-b x 10^4	Precision	T range(K)
22.3	2.3534	3.951	0.14%	1090-1170
31.9	2.4067	4.891	0.01%	1080-1170
49.9	2.3934	5.628	0.01%	1080-1170
71.8	2.2650	5.524	0.03%	1090-1170
83.8	2.2540	6.002	0.05%	1070-1170
92.8	2.2231	6.188	0.03%	1060-1130

Two-independent-variables equation

$$\rho = a + bC + cC^2 + dT^3 + eC^3 + fCT^2 \quad (93.2)$$

(C = mol % $CaCl_2$)

(93) $KCl-CaCl_2$

Table 93.2. Parameters of two-independent variables equation (93.2) and precisions

a	b x 10^3	c x 10^5	d x 10^{10}	e x 10^7	f x 10^9	Precision
1.72672	4.92335	-2.48640	-1.71243	1.85373	1.10542	0.09%

Table 93.3. Density (g cm^{-3}) from equations in table 93.1

	Mol % KCl					
T (K)	22.3	31.9	49.9	71.8	83.8	92.8
1070					1.612	1.561
1080		1.878	1.786		1.606	1.555
1090	1.923	1.874	1.780	1.663	1.600	1.549
1100	1.919	1.869	1.774	1.657	1.594	1.542
1110	1.915	1.864	1.769	1.652	1.588	1.536
1120	1.911	1.859	1.763	1.646	1.582	1.530
1130	1.907	1.854	1.757	1.641	1.576	1.524
1140	1.903	1.849	1.752	1.635	1.570	
1150	1.899	1.844	1.746	1.630	1.564	
1160	1.895	1.839	1.741	1.624	1.558	
1170	1.891	1.834	1.735	1.619	1.552	

References [14,30-36]

3. *Surface Tension* (γ)

Measurement method: flat pin (detachment) [30]

Equation:

$$\gamma = a + bT \quad (93.3)$$

precision: in table 93.4 uncertainty: $\sim \pm 2.0\%$

Table 93.4. Parameters of equation (93.3) and precisions

Mol % KCl	a	-b x 10^3	Precision	T range(K)
9.8	186.26	49.86	0.03%	1080-1170
22.6	183.46	55.78	0.11%	1050-1170
31.9	183.55	58.97	0.09%	1070-1170
44.5	182.70	63.44	0.05%	1070-1170
44.7	181.36	63.50	0.05%	1080-1140
57.8	185.42	71.42	0.01%	1050-1140
83.6	182.51	75.77	0.07%	1070-1150
92.8	170.68	67.45	0.09%	1070-1140

Table 93.5. Surface tension (dyn cm^{-1}) from equations in table 93.4

T (K)	Mol % KCl				
	22.6	31.9	44.5	44.7	57.8
1050	124.9				110.4
1060	124.3				109.7
1070	123.8	120.5	114.8		109.0
1080	123.2	119.9	114.2	112.8	108.3
1090	122.7	119.3	113.6	112.2	107.6
1100	122.1	118.7	112.9	111.5	106.9
1110	121.6	118.1	112.3	110.9	106.1
1120	121.0	117.5	111.7	110.2	105.4
1130	120.4	116.9	111.0	109.6	104.7
1140	119.9	116.3	110.4	109.0	104.0
1150	119.3	115.7	109.7		
1160	118.8	115.1	109.1		
1170	118.2	114.6	108.5		

References [30,34,37-43]

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [45]

Equation:

$$\kappa = a + bT \quad (93.4)$$

precision: in table 93.6 uncertainty: $\sim \pm 2.0\%$

Table 93.6. Parameters of equation (93.4) and precisions

Mol % KCl	-a	b x 10^3	Precision	T range(K)
20	2.0217	3.409	0.14%	1060-1100
40	1.8903	3.109	0.24%	1010-1050
60	1.4617	2.708	0.31%	1080-1110
80	1.7129	3.159	0.23%	1000-1050

Table 93.7. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 93.6

T (K)	Mol % KCl			
	20	40	60	80
1000				1.446
1010		1.249		1.478
1020		1.280		1.509
1030		1.311		1.541
1040		1.342		1.572
1050		1.374		1.604
1060	1.592			
1070	1.626			
1080	1.660		1.463	
1090	1.694		1.490	
1100	1.728		1.517	
1110			1.545	

References [14,32,44-49]

(93) $KCl-CaCl_2$

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: very low.

(ii) Vapor pressure: KCl, at m.pt. (770°C) ∿ 0.42mm; $CaCl_2$, at m.pt. (782°C), ∿ 2 x 10^{-4}mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic fumes when heated to decomposition, or contacted with acids.

References [50-55]

7. Corrosion

Table 93.8. Corrosion studies from primary research literature

	Studies	References
A	Armco Fe; various steels	[56-59]
	Cr	[60]
	Cr, Fe-Cr	[61]
	Mg, Ni, Zr, Ti	[62]
	Ti, Zr, Hf, $ThCl_4$	[63]
B	Zr	[64]
	Ti, Zr, Hg, $ThCl_4$	[63]
	Pb, Pb-Bi	[65]
	Armco Fe	[65-69]
C	Solubility of oxides (Ni, Ca, Zn, Mg)	[62,70]
	Electrochemical aspects	[71]
	Corrosion - annotated biblio.	[72]
	Thermodynamic approach	[62,73,74]
	Reviews: corrosion in molten salts	[75-77]

Compatibility studies: A: principally molten KCl; B: principally molten $CaCl_2$; C: general discussion and reviews. For compatibility studies in molten $KCl-CaCl_2$ mixtures, see [68].

References [56-77]

(93) $KCl-CaCl_2$

8. Diffusion

Measurement method: capillary [78]

Diffusing species investigated in $KCl-CaCl_2$ as solvent:

Ca^{2+}

precision: ∿ ± 0.2% uncertainty: ∿ ± 10%

Equation:

$$D = 1.281 \times 10^3 \exp [-7907/RT] \quad (93.5)$$

Table 93.9. Self-diffusion coefficients from equation (93.5)

T (K)	$D_{Ca^{2+}} \times 10^5$ ($cm^2\ s^{-1}$)	T (K)	$D_{Ca^{2+}} \times 10^5$ ($cm^2\ s^{-1}$)
1055	2.95	1120	3.67
1060	3.00	1130	3.79
1070	3.11	1140	3.90
1080	3.22	1150	4.02
1090	3.33	1160	4.15
1100	3.44	1170	4.27
1110	3.55	1175	4.33

Solvent composition: 0.2 mol % $CaCl_2$

References [78]

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

Measurement method: Rodebush-Dixon [79,80]

precision: ± 3.0% uncertainty: ∿ ± 5.0%

Table 93.10. Vapor pressure (mm)

Mol % KCl	1373 K	1423 K	Mol % KCl	1373 K	1423 K
22	2.19	5.26	70	25.02	43.51
32		9.50	79	32.63	53.33
37	5.30		83	34.93	58.49
43	8.00	16.09	90	43.34	72.00
47	10.09	18.60	100	54.52	87.80
60	17.57	32.26			

Values at 100% KCl are 2-8% higher than the recommended vapor pressure [81] for KCl at 1373 and 1423 K.

References [79-81]

(93) $KCl-CaCl_2$

13. Thermal Conductivity (liquid) (λ_ℓ)

Measurement method: coaxial cylinders technique [82]

Equation:

$$\lambda = a + bT \quad (93.6)$$

precision: in table 93.11 uncertainty: ∿ ± 20%

Table 93.11. Parameters of equation (93.6), precisions, and temp. range

Mol % $CaCl_2$	$-a \times 10^3$	$b \times 10^6$	Precision	T range(K)
0	2.9674	5.042	0.7%	1055-1090
10	4.4423	6.070	1.7%	1010-1070
20	2.1855	3.818	1.0%	940-1060
27	1.0439	2.572	2.2%	920-1010
30	2.8515	4.312	0.9%	940-1040
40	5.7367	7.339	2.0%	1010-1040
50	6.5010	8.668	0.6%	1050-1080
60	8.9394	10.84	1.6%	1035-1060
73	2.3451	4.337	0.9%	970-1040
80	1.8352	4.244	0.5%	1020-1050
100	16.383	17.98	3.3%	1070-1130

Table 93.12. Thermal conductivity ($\times 10^4$ cal cm^{-1} $s^{-1}K^{-1}$) from equations in table 93.11

T	Mol % $CaCl_2$								
(K)	10	20	27	30	40	50	60	73	80
920			13.3						
940		14.0	13.8	12.0					
960		14.8	14.3	12.9					
980		15.6	14.8	13.7				19.0	
1000		16.3	15.3	14.6				19.9	
1020	17.5	17.1		15.5	17.5			20.8	24.9
1040	18.7	17.9		16.3	19.0		23.3	21.7	25.8
1060	19.9	18.6				26.9	25.5		
1080						28.6			

The values for pure KCl reported in [82] are uniformly higher (∿ 20%) than the recommended values [84].

Table 93.13. Isotherm of thermal conductivity at 1073 K

$CaCl_2$	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})	$CaCl_2$	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})
0	24.4	50	28.0
10	20.7	60	26.9
20	19.1	73	23.1
27	17.2	80	27.2
30	17.8	100	29.1
40	21.4		

The data (above) illustrate the thermal conductivity-composition isotherm at this temperature. In systems of nitrates not showing compound formation, the thermal conductivity generally shows a negative deviation from additivity (passing through a minimum at the equimolar composition).

References [82-84]

(93) $KCl-CaCl_2$

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 94 $BaCl_2$-KCl

1. *Melting Temperatures (T_m)*

Pure substance melting points:

KCl: 770°C

$BaCl_2$: 962°C

Eutectic melting point:

E_1: 658°C, composition: 25.9 mol % $BaCl_2$

E_2: 648°C, composition: 42.9 mol % $BaCl_2$

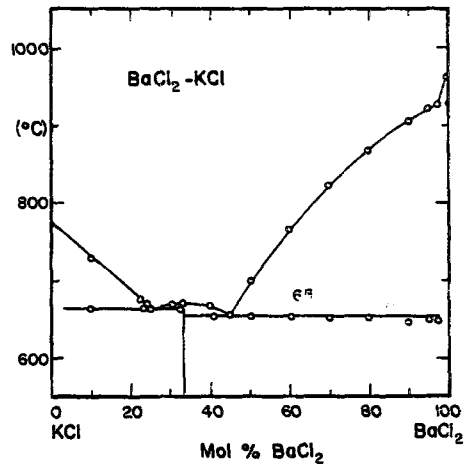

Figure 94.1. $BaCl_2$-KCl phase diagram

References [1-19]

2. *Density (ρ)*

Measurement method: Archimedean technique [20]

Equation:

$$\rho = a + bT \quad (94.1)$$

precision: in table 94.1 uncertainty: ∿ ± 3.0%

(94) $BaCl_2$-KCl

Table 94.1. Parameters of equation (94.1) and precisions

Mol % KCl	a	$-b \times 10^3$	Precision	T range(K)
0	3.9881	0.6819	0.02%	1250-1280
20.9	3.7621	0.7240	0.05%	1160-1210
36.7	3.4446	0.6486	0.04%	1100-1180
50.5	3.1602	0.6349	0.07%	1060-1150
54.3	3.2396	0.7643	0.04%	1070-1150
66.4	2.9626	0.6944	0.17%	1070-1160
66.7 *	3.3804	1.0900	0.44%	1070-1160
70.2	2.8580	0.6838	0.06%	1080-1170
75.6	2.7114	0.6173	0.06%	1070-1160
86.9	2.2758	0.4769	0.18%	1070-1160
91.6	2.4850	0.7405	0.21%	1070-1160
100	2.1559	0.6103	0.08%	1070-1160

*Better estimated by quadratic fit to 0.29% precision.

Table 94.2. Density (g cm^{-3}) from equations in table 94.1

	Mol % KCl						
T (K)	36.7	50.5	54.3	66.4	70.2	75.6	86.9
1060		2.487					
1070		2.481	2.422	2.220		2.051	1.766
1080		2.475	2.414	2.213	2.120	2.045	1.761
1090		2.468	2.407	2.206	2.113	2.039	1.756
1100	2.731	2.462	2.399	2.199	2.106	2.032	1.751
1110	2.725	2.456	2.391	2.192	2.009	2.026	1.746
1120	2.718	2.449	2.384	2.185	2.092	2.020	1.742
1130	2.712	2.443	2.376	2.178	2.085	2.014	1.737
1140	2.705	2.436	2.368	2.171	2.079	2.008	1.732
1150	2.699	2.430	2.361	2.164	2.072	2.002	1.727
1160	2.692			2.157	2.065	1.995	1.723
1170	2.686				2.058		
1180	2.679						
1190							

References [20-23]

(94) $BaCl_2$-KCl

3. Surface Tension (γ)

Measurement method: maximum bubble pressure [20]

Equation:

$$\gamma = a + bT \quad (94.2)$$

precision: in table 94.3 uncertainty: $\sim \pm 3.0\%$

Table 94.3. Parameters of equation (94.2.) and precisions

Mol % KCl	a	$-b \times 10^2$	Precision	T range(K)
17.9	233.95	7.642	0.26%	1180-1260
37.7	224.63	8.425	0.80%	1130-1230
52.3	176.16	5.208	0.54%	1100-1160
57.7	168.90	4.870	0.27%	1100-1170
62.7	186.07	6.669	0.28%	1100-1160
66.0	175.64	5.880	0.24%	1080-1170
70.6	166.18	5.209	0.27%	1090-1180
75.6	180.40	6.629	0.32%	1090-1160
86.5	178.02	7.013	0.46%	1100-1060
91.6	163.28	5.879	0.46%	1090-1160
96.1	178.71	7.512	0.40%	1100-1170

Table 94.4. Surface tension (dyn cm^{-1}) from equations in table 94.3

	Mol % KCl						
T (K)	52.3	57.7	62.7	66.0	70.6	75.6	86.5
1080				112.1			
1090				111.6			
1100	118.9	115.3	112.7	111.0	108.9	107.5	100.9
1110	118.4	114.9	112.0	110.4	108.4	106.8	100.2
1120	117.8	114.4	111.4	109.8	107.8	106.2	99.5
1130	117.3	113.9	110.7	109.2	107.3	105.5	98.8
1140	116.8	113.4	110.0	108.6	106.8	104.8	98.1
1150	116.3	112.9	109.4	108.0	106.3	104.2	97.4
1160	115.7	112.4	108.7	107.4	105.8	103.5	96.7
1170		111.9			105.2		

References [20,24,25]

4. Viscosity (η)

No data

5. Electrical Conductance (κ)

No data

6. Safety and Hazards

A. Hazard rating [26-28,32]

(i) Toxicity: Soluble barium compounds, such as the chloride, are poisonous when taken orally.

(ii) Vapor pressure: no information for this system; but see KCl [28] and $BaCl_2$ [32]

B. Disaster hazards [29-31]

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic fumes when heated to decomposition, or contacted with acids.

References [26-32]

7. Corrosion

Table 94.5. Corrosion studies from primary research literature

	Studies	References
A	Armco Fe, various steels	[33,34,39,40]
	Cr	[35]
	Cr, Fe-Cr	[36]
	Mg, Ni, Zr, Ti	[37]
	Ti, Zr, Hf, $ThCl_4$	[38]
B	Zr	[41]
	Fe, steels	[42-46]
	Ti, Zr, Hf, $ThCl_4$	[47]
	Pb, Pb-Bi	[48]
C	Solubility of oxides (Ni, Ca, Zn, Mg)	[37,49]
	Electrochemical aspects	[50]
	Corrosion - annotated biblio.	[51]
	Thermodynamic approach	[37,52,53]
	Reviews: corrosion in molten salts	[54-56]

Compatibility studies: A: principally with molten KCl; B: principally with molten $BaCl_2$; C: basic principles, reviews, biblios. For specific studies with molten $BaCl_2$-KCl mixtures, see [42,44]

References [33-56]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

(94) $BaCl_2$-KCl

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [57]

Table 94.6. Volume change on melting

Composition (mol % KCl)	$(\Delta V_f/V_s)$	Uncertainty
74 (a)	8.0%	$\sim \pm$ 10%
57 (a)	3.0%	$\sim \pm$ 10%

(a) binary eutectic mixtures

References [57]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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1. *Melting Temperatures (T_m)*

Pure substance melting points:

NaCl: 800°C
KCl: 770°C
$CaCl_2$: 782°C

Eutectic melting point:

E_1: 504°C, composition: 42 mol % NaCl, 6 mol % KCl
E_2: 558°C, composition: 38 mol % NaCl, 31 mol % KCl
E_3: 532°C, composition: 26 mol % NaCl, 50 mol % KCl

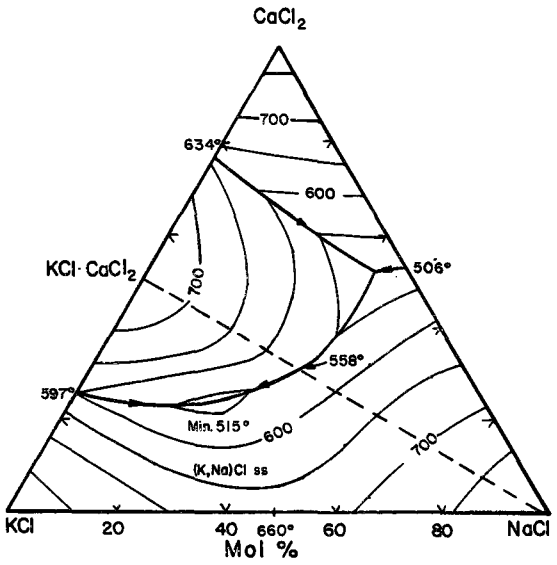

Figure 95.1. KCl-NaCl-$CaCl_2$ phase diagram

References [1-18]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

(95) $KCl-NaCl-CaCl_2$

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: NaCl, permitted in foods; KCl, very low; $CaCl_2$, slight.

(ii) Vapor pressure: NaCl at m.pt (800°C), ∿ 0.34mm; KCl at m.pt. (770°C) ∿ 0.42 mm; $CaCl_2$ at m.pt. (782°C) ∿ 2 x 10^4mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air

(ii) Chlorides, when heated to decomposition or contacted with acids, highly toxic chloride fumes are evolved.

References [19-24].

7. Corrosion

Table 95.1. Corrosion studies from primary research literature

Studies	References
Ni, Fe	[25]
Zr, Be, Ti, Hf, U	[26]
Ni-Cr-Fe	[27]
Ti	[28,29]
Cr_2O_3 + C electrode	[30]
Fe	[31]
Ni-Cr	[32]
Fe, Ni	[33]
Steel 3	[34]
Ni-Fe	[25,35]
Au, Pt, W	[36]
Several metals	[37]
Fe	[38]
Ni	[39]
Zr	[26]
Rh	[40]
Al	[41]
Cr, Fe-Cr	[42]
W	[43]
Various steels	[44]
Armco Fe, steels	[45]
EMF series	[37]
Thermodynamic redox diagrams	[25,46]
Electrochemical approach	[47,48]
Reviews (molten salts corrosion)	[49-51]
Annotated corrosion biblio.	[52]

No compatibility studies found for molten KCl-NaCl-$CaCl_2$ mixtures. For compatibility studies with binary systems see: KCl-$CaCl_2$ [44]; NaCl-$CaCl_2$ [45]; NaCl-KCl [all except 44,45].

References [25-52]

8. Diffusion

No data

(95) KCl-NaCl-$CaCl_2$

9. Heat of Fusion (ΔH_f°)

Measurement method: calculated [53]

Table 95.2. Heat of fusion

Composition KCl:NaCl:$CaCl_2$ (mol %)	T_m (°C)	ΔH_f° (kcal mol^{-1})	Uncertainty
5.8:42.8:51.4	504°	6.3	∿ ± 5%

References [53]

10. Heat Capacity (C_p)

Measurement method: calculated [54]

Table 95.3. Heat capacity

Composition KCl:NaCl:$CaCl_2$ (mol %)	C_p (cal K^{-1} mol^{-1})	T range (K)	Uncertainty
5.8:42.8:51.4	20.1	T_m(777) - 850	∿ ± 10%

For the above composition, $C_{p(s)}$ = 23.4 (cal K^{-1} mol^{-1}); uncertainty ∿ ± 10%

References [54]

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

(95) KCl-NaCl-$CaCl_2$

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f° [55]

Table 95.4. Cryoscopic constant

Composition	k_f (K mol^{-1} kg)	Uncertainty
Ternary eutectic (a)	16.5	∿ 2%

(a) KCl: NaCl: $CaCl_2$:: 5.8: 4.28: 51.4 (mol %).

References [55]

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System 96 $KCl-NaCl-MgCl_2$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

NaCl:	800°C
KCl:	770°C
$MgCl_2$:	714°C

Eutectic melting point:

385°C, composition: 21.6 mol % KCl; 33.0 mol % NaCl; 45.4 mol % $MgCl_2$

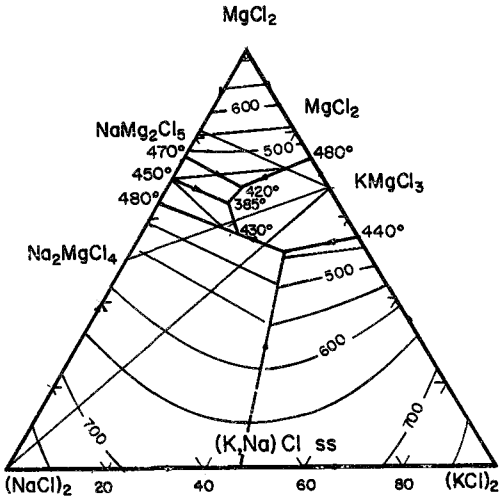

Figure 96.1. $KCl-NaCl-MgCl_2$ phase diagram

References [1-22]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

(96) $KCl-NaCl-MgCl_2$

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: NaCl, permitted in foods; KCl, very low; $MgCl_2$, slight.

(ii) Vapor pressure: $MgCl_2$ at m.pt. (714°C), ~ 0.11mm; NaCl at m.pt. (800°C), ~ 0.34mm; KCl at m.pt. (770°C), ~ 0.42mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over: and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic fumes when heated to decomposition, or contacted with acids.

References [23-28]

(96) $KCl-NaCl-MgCl_2$

7. Corrosion

Table 96.1. Corrosion studies from primary research literature

Studies	References
Ni, Fe	[29]
Zr, Be, Ti, Hf, U	[30]
Ni-Cr-Fe	[31]
Ti	[32,33]
Cr_2O_3 + C electrode	[34]
Fe	[35]
Ni-Cr	[36]
Fe, Ni	[37]
Steel 3	[38]
Ni-Fe	[29,39]
Au, Pt, W	[40]
Several metals	[41]
Fe	[42]
Ni	[43]
Zr	[30]
Rh	[44]
Al	[45]
Cr, Fe-Cr	[46]
W	[47]
Fe, steels	[38,48,49]
Emf. series	[41]
Thermodynamic redox diagrams	[29,50]
Electrochemical approach	[51,52]
Reviews (molten salts corrosion)	[53-55]
Annotated corrosion biblio.	[56]

For studies with binary systems, see $KCl-MgCl_2$ [38, 48,49]; $NaCl-MgCl_2$ [48]; NaCl-KCl [all except 38,48, 49]. For compatibility studies with molten $KCl-NaCl-MgCl_2$ see [57]; corrosion is not a problem if storage salts are dried before use, and if mild steel is used as a container.

References [29-57]

8. Diffusion

No data

(96) KCl-NaCl-$MgCl_2$

9. Heat of Fusion (ΔH_f°)

Measurement method: drop calorimetry [58]

Table 96.2. Heat of fusion

Composition $MgCl_2$:NaCl:KCl (mol %)	ΔH_f° (kcal mol^{-1})	Uncertainty
45.4:33.0:21.6	4.4	∿ ± 2%

References [58]

10. Heat Capacity (C_p)

Measurement method: drop calorimetry [58]

Table 96.3. Heat capacity

Composition $MgCl_2$:NaCl:KCl (mol %)	T (K)	C_p (cal $K^{-1} mol^{-1}$)	Uncertainty
45.4:33.0:21.6	673	19.0	∿ ± 2%

For the above composition:

$$Cp_{(s)} = 14.019 + 7.323 \times 10^{-3} T \quad (96.1)$$

for the temperature range 290 - 620°K

References [58]

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

Measurement method: transpiration technique [59]

Equation:

$$\log p = A + B/T \quad [96.1)$$

precision: in table 96.4 uncertainty: ∿ ± 30%

Table 96.4. Parameters of equation (96.1) and precision

Composition (mol %)			A	-B	Precision	T range(K)
KCl	NaCl	$MgCl_2$				
21.8	25.5	52.7	4.3404	4554	*	820-1125

*insufficient information for estimate; results reported in graphical format

Table 96.5. Vapor pressure (mm) of ternary mixture from equation in table 96.4.

T (K)	p (mm)	T (K)	p (mm)
820	0.061	975	0.467
825	0.066	1000	0.612
850	0.096	1025	0.790
875	0.137	1050	1.008
900	0.191	1075	1.271
925	0.261	1100	1.586
950	0.352	1125	1.961

References [59]

13. *Thermal Conductivity (liquid)* (λ_ℓ)

No data

14. *Thermal Conductivity (solid)* (λ_s)

No data

15. *Cryoscopic Constant* (k_f)

Measurement method: calculated from ΔH_f° [60]

Table 96.6. Cryoscopic constant

Composition	k_f	Uncertainty
$MgCl_2$:NaCl:KCl (mol %)	(K $mol^{-1}kg$)	
45.4:33.0:21.6	16.1	$\sim \pm$ 2%

References [60]

(96) $KCl-NaCl-MgCl_2$

16. References

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System 97 $CaCl_2$-$MgCl_2$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$CaCl_2$ 782°C
$MgCl_2$: 714°C

Eutectic melting point:

621°C, composition: 39 mol % $CaCl_2$

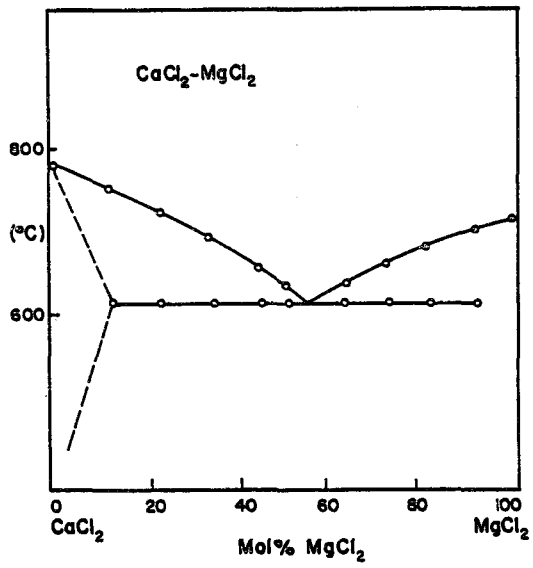

Figure 97.1. $CaCl_2$-$MgCl_2$ phase diagram

References [1-17].

2. *Density (ρ)*

Measurement method: Archimedean technique [18]

Equation:

$$\rho = a + bT \quad (97.1)$$

precision: in table 97.1 uncertainty: ∿ ± 1.0%

Table 97.1. Parameters of equation (97.1) and precisions

Mol % $MgCl_2$	a	$-b \times 10^3$	Precision	T range(K)
0.0	2:4986	0.3976	0.05%	1070-1140
13.3	2.1352	0.3697	0.03%	1080-1160
32.1	2.2379	0.3955	0.05%	1090-1170
34.6	2.2680	0.3977	0.01%	1100-1180
40.9	2.3656	0.4577	0.02%	1090-1160
59.9	2.3796	0.4093	0.05%	1070-1130
80.6	2.4864	0.4436	0.01%	1060-1130
100.0	1.9497	0.2705	0.03%	1020-1090

Table 97.2. Density (g cm^{-3}) from equations in table 97.1

T (K)	Mol % $MgCl_2$ 13.3	32.1	34.6	40.9	59.9	80.6
1060						2.016
1070					1.942	2.012
1080					1.938	2.007
1090	1.732	1.807		1.867	1.933	2.003
1100	1.729	1.803	1.831	1.863	1.929	1.999
1110	1.725	1.799	1.827	1.858	1.925	1.990
1120	1.721	1.795	1.823	1.854	1.921	1.985
1130	1.718	1.791	1.819	1.849	1.917	
1140	1.714	1.787	1.815	1.844		
1150	1.710	1.783	1.811	1.840		
1160	1.706	1.779	1.807	1.835		
1170		1.775	1.803			
1180			1.799			

References [18-22]

3. *Surface Tension (γ)*

Measurement method: flat pin detachment [20]

Equation:

$$\gamma = a + bT \quad (97.2)$$

precision: in table 97.3 uncertainty: $\sim \pm 3.0\%$

Table 97.3. Parameters of equation (97.2) and precisions

Mol % $MgCl_2$	a	-b x 10^3	Precision	T range(K)
15.2	160.53	30.65	0.01%	1080-1170
34.6	128.32	18.71	0.06%	1090-1170
53.0	106.85	14.83	0.11%	1090-1170
65.4	93.49	11.05	0.05%	1100-1180
83.4	79.01	07.65	0.00%	1080-1150
86.7	75.87	06.67	0.09%	1090-1170

Equation: (two-independent-variables equation)

$$\gamma = a + bC + cC^2 + dT^3 + eTC^2 + fCT^2 \quad (97.3)$$

(C = mol % $CaCl_2$)

Table 97.4. Parameters of two-independent-variables equation (97.3)

a	b x 10^{-1}	c x 10^3	d x 10^{10}	e x 10^6	f x 10^8	precision
63.14053	5.00268	6.83865	-7.82398	-2.43231	-6.82139	0.43%

Table 97.5. Surface tension (dyn cm^{-1}) from equations in table 97.2

T (K)	Mol % $MgCl_2$ 15.2	34.6	53.0	65.4	83.4	86.7
1080	127.4				70.8	
1090	127.1	107.9	90.7		70.7	68.6
1100	126.8	107.7	90.5	81.3	70.6	68.5
1100	126.5	107.6	90.4	81.2	70.5	68.5
1120	126.2	107.4	90.2	81.1	70.5	68.4
1130	125.9	107.2	90.1	81.0	70.4	68.3
1140	125.6	107.0	89.9	81.0	70.3	68.3
1150	125.3	106.8	89.8	80.8	70.2	68.2
1160	125.0	106.6	89.6	80.7		68.1
1170	124.7	106.4	89.5	80.6		68.1
1180				80.4		
1190						

References [20,23,24]

4. *Viscosity* (η)

Measurement method: oscillating sphere technique [25]

Equation:

$$\eta = a + bT + cT^2 + dT^3 \quad (97.4)$$

precision: in table 97.6 uncertainty: $\sim \pm 5.0\%$

Table 97.6. Parameters of equation (97.4) and precisions

$MgCl_2$ (mol %)	a	b x 10^2	-c x 10^5	d x 10^8	Precision	T range(K)
30	52.661	-5.244	2.348	2.698	0.80%	1070-1110
45	1.945	0.646	0.556		0.29%	1070-1110
60	3.389	0.406	0.473		0.26%	1090-1110
75	8.968	-0.569	0.334	0.246	0.46%	1070-1120
90	18.555	-1.616	0.969	0.952	0.29%	1070-1120

Table 97.7. Viscosity (cp) from equations in table 97.6

T (K)	Mol % $MgCl_2$ 30	45	60	75	90
1070	2.718	2.491		2.066	1.830
1080	2.624	2.437	2.262	2.023	1.790
1090	2.543	2.381	2.200	1.980	1.754
1100	2.475	2.323	2.137	1.938	1.7225
1110	2.420	2.265	2.073	1.897	1.695
1120				1.857	1.673

References [25]

5. *Electrical Conductance* (κ)

Measurement method: classical ac technique [26]

Equation:

$$\kappa = a + bT + cT^2 \quad (97.5)$$

precision: in table 97.8 uncertainty: $\sim \pm 5.0\%$

Table 97.8. Parameters of equation (97.5) and precisions

Mol % $MgCl_2$	a	b x 10^3	c x 10^6	Precision	T range(K)
20	-3.2418	5.025	0	0.28%	1050-1080
40	5.3906	-10.262	6.677	0.11%	1000-1050
60	-1.5310	3.275	0	0.24%	980-1040
80	2.5710	-4.414	3.346	0.12%	1000-1050

Table 97.9. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 97.8

T (K)	Mol % $MgCl_2$ 20	40	60	80
980			1.678	
990			1.711	
1000		1.805	1.744	1.503
1010		1.836	1.776	1.527
1020		1.869	1.809	1.550
1030		1.903	1.842	1.575
1040		1.939	1.875	1.600
1050	2.034	1.976		1.626
1060	2.084			
1070	2.135			
1080	2.185			
1090	2.235			

References [18,26]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: $CaCl_2$, very low; $MgCl_2$, slight.

(ii) Vapor pressure: at m.pt. (782°C), ∿ 2 x 10^{-4}mm; $MgCl_2$ at m.pt. (714°C), ∿ 0.11mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over: and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic fumes when heated to decomposition, or contacted with acids.

References [27-32]

7. Corrosion

Table 97.10. Corrosion studies from primary research literature

Studies	References
Zr	[33]
Ti, Zr, Hf, $ThCl_4$	[34]
Pb, Pb-Bi	[35]
Fe	[36]
Electrochemical aspects	[37,38]
Thermodynamic approach	[39-41]
Corrosion in molten salts, annotated biblio.	[42]
Reviews: corrosion in molten salts	[43-45]

Compatibility studies for various molten chlorides and mixtures. For studies specifically with molten $CaCl_2$-$MgCl_2$ see [36].

References [33-45]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

(97) $CaCl_2$-$MgCl_2$

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 98 $BaCl_2$-$MgCl_2$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$BaCl_2$: 962°C
$MgCl_2$: 714°C

Eutectic melting point:

E: 556°C, composition: 65 mol % $MgCl_2$
P: 590-600°C, composition: 60 mol % $MgCl_2$

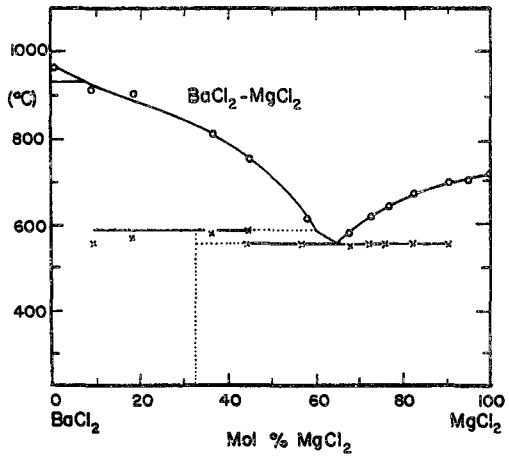

Figure 98.1. $BaCl_2$-$MgCl_2$ phase diagram

References [1-19]

2. *Density (ρ)*

Measurement method: Archimedean technique [20]

Equation:

$$\rho = a + bT \quad (98.1)$$

precision: in table 98.1 uncertainty: ∿ ± 1.0%

Table 98.1. Parameters of equation (98.1) and precision

Mol % $MgCl_2$	a	$-b \times 10^4$	Precision	T range(K)
19.6	3.836	7.1	*	1030-1190
42.2	3.569	7.5	*	1030-1190
68.6	3.010	6.4	*	1030-1190
86.8	2.461	4.7	*	1030-1190
95.2	2.171	3.6	*	1030-1190
100.0	1.988	3.0	*	1030-1190

* not estimated, insufficient data

(98) $BaCl_2$-$MgCl_2$

Table 98.2. Density (g cm^{-3}) from equations in table 98.1

T (K)	Mol % $MgCl_2$ 19.6	42.2	68.6	86.6	95.2
1030	3.105	2.797	2.351	1.977	1.801
1050	3.090	2.782	2.338	1.968	1.793
1070	3.076	2.767	2.325	1.958	1.786
1090	3.062	2.752	2.312	1.949	1.779
1110	3.048	2.737	2.299	1.940	1.772
1130	3.034	2.722	2.287	1.930	1.765
1150	3.019	2.707	2.274	1.921	1.757
1170	3.005	2.692	2.261	1.911	1.750
1190	2.991	2.677	2.248	1.902	1.743

References [20-22]

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure [23]

Equation:

$$\gamma = a + bT \quad (98.2)$$

precision: in table 98.3 uncertainty: $\sim \pm$ 3.0%

Table 98.3. Parameters of equation (98.2) and precision

Mol % $MgCl_2$	a	$-b \times 10^2$	Precision	T range(K)
25.0	217.5	7.0	*	1030-1190
40.0	164.2	4.1	*	1030-1190
60.0	143.1	4.0	*	1030-1190
80.0	121.4	3.5	*	1030-1190

* not estimated; insufficient data

Table 98.4. Surface tension (dyn cm^{-1}) from equations in table 98.3

T (K)	Mol % $MgCl_2$			
	25.0	40.0	60.0	80.0
1030	145.4	122.0	101.9	85.4
1050	144.0	121.2	101.1	84.7
1070	142.6	120.3	100.3	84.0
1090	141.2	119.5	99.5	83.3
1110	139.8	118.7	98.7	82.6
1130	138.4	117.9	97.9	81.9
1150	137.0	117.1	97.1	81.2
1170	135.6	116.2	96.3	80.5
1190	134.2	115.4	95.5	79.8

References [22,23]

4. *Viscosity (η)*

Measurement method: oscillating sphere technique [24]

Equation:

$$\eta = a + bT + cT^2 \quad (98.3)$$

precision: in table 98.5 uncertainty: $\sim \pm 10\%$

Table 98.5. Parameters of equation (98.3) and precisions

$BaCl_2$ (mol %)	a	$-b \times 10^2$	$c \times 10^5$	Precision	T range(K)
10	35.938	6.006	2.633	0.96%	970-1070
20	47.397	8.192	3.686	1.23%	970-1070
30	46.139	7.752	3.403	1.00%	970-1070
40	51.269	8.474	3.658	0.96%	970-1070
50	88.348	14.88	6.443	1.36%	970-1070
60	24.375	1.940		*	

*Precision not estimated; insufficient data set.

Table 98.6. Viscosity (cp) from equations in table 98.5

T (K)	Mol % $BaCl_2$ 10	20	30	40	50	60
970	2.45	2.62	2.96	3.49	4.63	
980	2.37	2.52	2.85	3.36	4.40	
990	2.29	2.42	2.75	3.23	4.18	
1000	2.21	2.34	2.65	3.11	3.98	
1010	2.14	2.26	2.56	3.00	3.78	
1020	2.07	2.19	2.47	2.89	3.61	4.59
1030	2.01	2.12	2.40	2.80	3.44	4.39
1040	1.95	2.07	2.33	2.70	3.28	4.20
1050	1.90	2.02	2.26	2.62	3.14	4.01
1060	1.86	1.98	2.20	2.55	3.01	3.81
1070	1.82	1.94	2.15	2.48	2.90	3.62

References [24]

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [21]

Equation:

$$\kappa = a + bT + cT^2 \quad (98.4)$$

precision: in table 98.7 uncertainty: ∿ ± 3.0%

Table 98.7. Parameters of equation (98.4) and precisions

Mol % $MgCl_2$	-a	b x 10^3	c x 10^6	Precision	T range(K)
35.5	1.046	2.42	0	0.81%	1180-1320
44.4	0.687	2.15	0	1.27%	1140-1340
68.6	2.302	5.20	-1.37	0.24%	1040-1340

Table 98.8. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 98.7

T (K)	Mol % $MgCl_2$		
	35.5	44.4	68.6
1040			1.63
1060			1.67
1080			1.72
1100			1.76
1120			1.81
1140			1.85
1160		1.80	1.89
1180	1.80	1.84	1.93
1200	1.85	1.88	1.97
1220	1.90	1.93	2.01
1240	1.95	1.97	2.04
1260	2.00	2.01	2.08
1280	2.05	2.05	2.11
1300	2.09	2.10	2.15
1320	2.14	2.14	2.18
1340		2.18	2.21

References [21,22,24]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: $MgCl_2$, slight; $BaCl_2$, toxic (orally).

(ii) Vapor pressure: $MgCl_2$ at m.pt. (714°C) ~ 0.11mm; $BaCl_2$ at m.pt. (962°C), ~ < 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic fumes when heated to decomposition, or contacted with acids.

References [25-31]

7. Corrosion

Table 98.9. Corrosion studies from primary research literature

Studies	References
Zr	[32]
Fe, steels	[33-37]
Mg, Ni, Zr, Ti	[38]
Ti, Zr, Hf, $ThCl_4$	[39]
Pb, Pb-Bi	[40]
Thermodynamics of corrosion	[39,41,42]
Electrochemical approach	[43,44]
Corrosion in molten salts, annotated biblio.	[45]

Compatibility studies: Principally with molten $BaCl_2$ or molten $MgCl_2$, for some studies with molten mixtures of $BaCl_2$-$MgCl_2$, see [33].

References [32-45]

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [46]

Table 98.10. Volume change on melting

Binary eutectic (mol % $BaCl_2$)	$(\Delta V_f/V_s)$	Uncertainty
35	9.0%	$\sim \pm$ 10%

References [46]

(98) $BaCl_2$-$MgCl_2$

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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[44] Johnson, K. E., *"Electrochemical Approaches to Corrosion in Molten Salts"*, Proceedings International Symposium on Metal-Slag-Gas Reactions and Processes, The Electrochemical Society Inc., Princeton, N. J., p. 581 (1975).

[45] Janz, G. J., and Tomkins, R. P. T., Corrosion, 35, 485 (1979).

[46] Janz, G. J., et al. (MSDC-RPI), unpublished work (1980).

System 99 $KCl-MgCl_2-CaCl_2$

1. *Melting Temperature (T_m)*

Pure substance melting points

KCl: 770°C
$MgCl_2$: 714°C
$CaCl_2$: 782°C

Eutectic melting point:

E_1: 440°C, composition: 28 wt % KCl, 49 wt % $MgCl_2$, 23 wt % $CaCl_2$
E_2: 434°C, composition: 62 wt % KCl, 35 wt % $MgCl_2$, 3 wt % $CaCl_2$
P_1: 446°C, composition: 26 wt % KCl, 49 wt % $MgCl_2$, 25 wt % $CaCl_2$
P_2: 437°C, composition: 59 wt % KCl, 38 wt % $MgCl_2$, 3 wt % $CaCl_2$

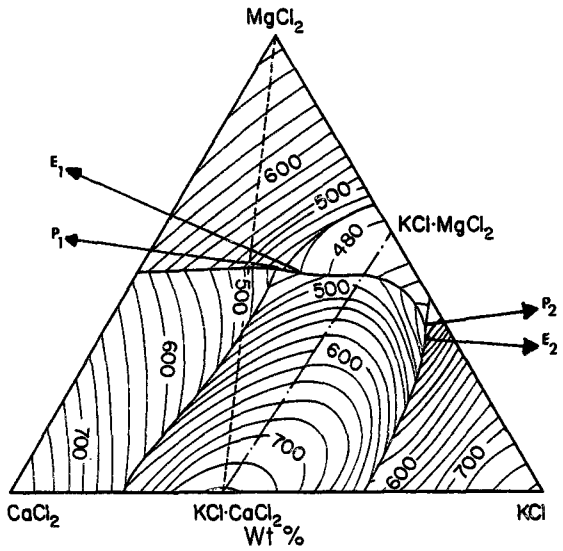

Figure 99.1. $KCl-MgCl_2-CaCl_2$ phase diagram

References [1-16]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

(99) $KCl-MgCl_2-CaCl_2$

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: KCl, slight; $MgCl_2$, slight, $CaCl_2$, slight.

(ii) Vapor pressure: KCl at m.pt. (770°C), ~ 0.42mm; $MgCl_2$ at m.pt. (714°C), ~ 0.11mm; $CaCl_2$ at m.pt. (782°C), ~ 2×10^{-4}mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic fumes when heated to decomposition, or contacted with acids.

References [17-22]

7. Corrosion

Table 99.1. Corrosion studies from primary research literature

Studies	References
Armco Fe, various steels	[23,24,29,30]
Cr	[25]
Cr, Fe-Cr	[26]
Mg, Ni, Zr, Ti	[27]
Ti, Zr, Hf, $ThCl_4$	[28]
Solubility of oxides (Ni, Ca, Zn, Mg)	[27,31]
Zr	[32]
Fe, steels	[33-37]
Pb, Pb-Bi	[38]
Electrochemical aspects	[31,39]
Thermodynamic approach	[27,40,41]
Corrosion in molten salts, annotated biblio.	[42]
Reviews: corrosion in molten salts	[43-47]

Compatibility studies for various molten chlorides and their mixtures. No compatibility studies found specifically for molten $KCl-MgCl_2-CaCl_2$. For studies with the binaries see: $KCl-MgCl_2$ [92]; $KCl-CaCl_2$ [93]; $MgCl_2-CaCl_2$ [97].

References [23-47]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

Measurement method: calculated [48]

Table 99.2. Heat of fusion

Composition KCl : $CaCl_2$: $MgCl_2$ (mol %)	T_m (°C)	ΔH_f° (kcal mol^{-1})	Uncertainty
24:25:51	487°	7.7	∿ ± 5%

References [48]

10. Heat Capacity (C_p)

Measurement method: calculated [49]

Table 99.3. Heat capacity

Composition KCl:$CaCl_2$:$MgCl_2$ (mol %)	C_p (cal K^{-1} mol^{-1})	T range (K)	Uncertainty
23.9:24.7:51.3	20.3	T_m(733) - 823	∿ ± 10%

For the above composition, $C_{p(s)}$ = 17.5 (cal K^{-1} mol^{-1}); uncertainty of estimate, ∿ ± 10%.

References [49]

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

(99) $KCl-MgCl_2-CaCl_2$

15. *Cryoscopic Constant (k_f)*

Measurement method: calculated from ΔH_f° [50]

Table 99.4. Cryoscopic constant

Composition	k_f (K mol^{-1} kg)	Uncertainty
Ternary eutectic (a)	14	$\sim \pm$ 2%

(a) KCl: $MgCl_2$: $CaCl_2$: 24:51:25 mol %

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System 100 $BaCl_2$-$CaCl_2$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$CaCl_2$: 782°C
$BaCl_2$: 962°C

Eutectic melting point:

E: 594 C, composition: 36.5 mol % $BaCl_2$
P: 624 C, composition: 54 mol % $BaCl_2$

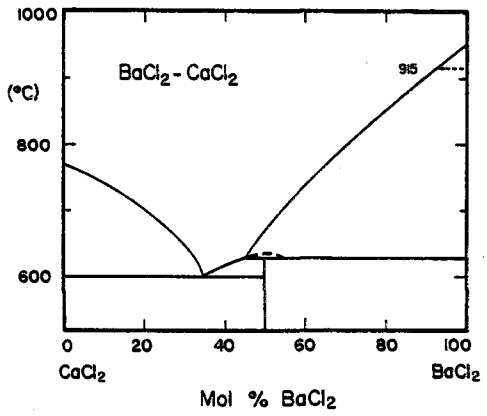

Figure 100.1. $BaCl_2$-$CaCl_2$ phase diagram

References [1-21]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure [22]

Equation:

$$\gamma = a + bT \quad (100.1)$$

precision: in table 100.1 uncertainty: ∿ ± 3.0%

Table 100.1. Parameters of equation (100.1) and precisions

Mol % $CaCl_2$	a	-b x 10^2	Precision	T range(K)
60	210.4	5.01	*	980-1070
75.0	203.7	4.70	*	930-1070

* not estimated; insufficient data

(100) $BaCl_2$-$CaCl_2$

Table 100.2. Surface tension (dyn cm^{-1}) from equations in table 100.1

T (K)	Mol % $CaCl_2$ 60	75.0
880	166.31	
900	165.31	
920	164.31	
940	163.30	159.51
960	162.30	158.57
980	161.30	157.63
1000	160.30	156.69
1020	159.29	155.75
1040	158.29	154.81
1060	157.29	153.87

References [22]

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [25]

Equation:

$$\kappa = a + bT + cT^2 \quad (100.2)$$

precision: in table 100.3 uncertainty: $\sim \pm 10\%$

Table 100.3. Parameters of equation (100.2) and precisions

Mol % $CaCl_2$	-a	b x 10^3	-c x 10^6	Precision	T range(K)
10	1.639	2.940	0	0.66%	1240-1360
20	5.449	8.867	2.273	0.60%	1180-1360
30	1.690	3.057	0	0.68%	1140-1360
40	2.470	4.322	0.476	0.45%	1080-1360
50	3.188	5.538	0.954	0.72%	1040-1360
60	2.607	4.671	0.598	0.73%	980-1360
70	1.835	3.348	0	0.62%	980-1360
80	1.825	3.391	0	0.64%	980-1360
90	3.377	6.057	1.097	0.72%	1040-1360

Table 100.4. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 100.3

T (K)	Mol % $CaCl_2$						
	10	30	40	50	60	70	80
980					1.40	1.45	1.50
1000					1.47	1.51	1.57
1040				1.54	1.60	1.65	1.70
1080			1.64	1.68	1.74	1.78	1.84
1120			1.77	1.82	1.87	1.92	1.97
1160		1.86	1.90	1.95	2.01	2.05	2.11
1200		1.98	2.03	2.08	2.14	2.18	2.24
1240	2.01	2.10	2.16	2.21	2.27	2.32	2.38
1280	2.13	2.22	2.28	2.34	2.39	2.45	2.52
1220	2.24	2.35	2.41	2.46	2.52	2.58	2.65
1260	2.36	2.47	2.53	2.58	2.64	2.72	2.79

References [23-25]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: $CaCl_2$, slight; $BaCl_2$, toxic (orally).

(ii) Vapor pressure: $CaCl_2$ at m.pt. (782°C), $\sim 2 \times 10^{-4}$mm; $BaCl_2$ at m.pt. (962°C), $\sim$ < 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic fumes when heated to decomposition, or contacted with acids.

References [26-32]

7. *Corrosion*

Table 100.5. Corrosion studies from primary research literature

Studies	References
Zr	[33]
Fe, steels	[34-38]
Mg, Ni, Zr, Ti	[39]
Ti, Zr, Hf, $ThCl_4$	[40]
Pb, Pb-Bi	[41]
Thermodynamics of corrosion	[40,42,43]
Electrochemical approach	[44,45]
Corrosion in molten salts, annotated biblio.	[46]

Compatibility studies: principally with molten $BaCl_2$, $CaCl_2$ or $MgCl_2$. No compatibility studies with molten mixtures of $CaCl_2$-$BaCl_2$ found.

References [33-46]

8. *Diffusion*

No data

9. *Heat of Fusion (ΔH°_f)*

No data

10. *Heat Capacity (C_p)*

No data

11. *Volume Change on Melting (ΔV_f)*

No data

12. *Vapor Pressure (p_{vap})*

No data

13. *Thermal Conductivity (liquid) (λ_ℓ)*

No data

14. *Thermal Conductivity (solid) (λ_s)*

No data

15. *Cryoscopic Constant (k_f)*

No data

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System 101 $LiNO_3$-$NaNO_3$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$LiNO_3$: 253°C

$NaNO_3$: 307°C

Eutectic melting point:

∿ 192°C, composition: ∿ 55 mol % $LiNO_3$

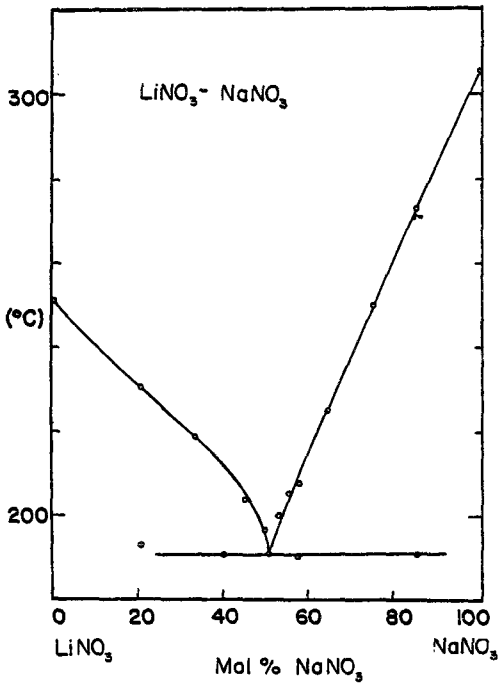

Figure 101.1. $LiNO_3$-$NaNO_3$ phase diagram

References [1-19].

2. *Density (ρ)*

Measurement method: Archimedean technique [20]

Equation:

$$\rho = a + bT \quad (101.1)$$

precision: in table 101.1 uncertainty: ∿ ± 1.5%

Table 101.1. Parameters of equation (101.1) and precisions

Mol % $LiNO_3$	a	-b x 10^4	Precision	T range(K)
20	2.2680	6.778	0.02%	550-730
40	2.2214	6.510	0.02%	500-740
60	2.1781	6.183	0.02%	610-700
80	2.1400	6.088	0.01%	550-710

(101) $LiNO_3$-$NaNO_3$

Two-independent-variables equation

$$\rho = a + bT + cT^3 + dTC + eT^2C \quad (101.2)$$

(C = mol % $CaCl_2$)

Table 101.2. Parameters of two-independent variables equation (101.2) and precisions

a	b x 10^4	c x 10^{10}	d x 10^6	e x 10^9	Precision
2.1797	-4.0766	-2.1051	-5.3868	4.9943	0.2%

Table 101.3. Density (g cm^{-3}) from equations in table 101.1

T (K)	Mol % $LiNO_3$			
	20	40	60	80
500		1.896		
520		1.883		
540		1.870		
560	1.888	1.857		1.799
580	1.875	1.844		1.787
600	1.861	1.831		1.775
620	1.848	1.818	1.795	1.763
640	1.834	1.805	1.782	1.750
660	1.821	1.792	1.770	1.738
680	1.807	1.779	1.758	1.726
700	1.794	1.766	1.745	1.714
720	1.780	1.753		
740		1.740		

References [20,21]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

Measurement method: oscillating sphere technique [20]

Equation:

$$\eta = a + bT + cT^2 + dT^3 \quad (101.3)$$

precision: in table 101.4 uncertainty: $\sim \pm$ 10%

Table 101.4. Parameters of equation (101.3) and precisions

$NaNO_3$ (mol %)	a	b x 10^2	c x 10^5	d x 10^8	Precision	T range(K)
40	48.2920	-15.255	16.055	-5.3434	1.36%	530-690
60	17.2248	-1.3799	-4.7702	5.1212	0.50%	530-690
80	18.1724	-2.5460	-1.9191	3.1344	0.68%	580-690

Equation:

$$\eta = A \exp (E/RT) \quad (101.4)$$

precision: in table 101.5 uncertainty ∿ ± 10%

Table 101.5. Parameters of equation (101.4) and precision

$NaNO_3$ (mol %)	A x 10^2	E (cal mol^{-1})	Precision	T range(K)
20	9.815	4164	0.75%	530-690

Table 101.6. Viscosity (cp) from equations in tables 101.4 and 101.5

T (K)	Mol % $NaNO_3$ 20	40	60	80
530	5.125	4.584	4.136	
540	4.763	4.318	3.927	
550	4.438	4.066	3.726	
560	4.147	3.829	3.529	
570	3.882	3.606	3.345	
580	3.644	3.397	3.167	3.065
590	3.428	3.202	2.996	2.908
600	3.230	3.019	2.834	2.758
610	3.051	2.849	2.682	2.615
620	2.886	2.693	2.538	2.480
630	2.735	2.548	2.404	2.353
640	2.596	2.415	2.280	2.234
650	2.469	2.294	2.165	2.123
660	2.352	2.184	2.062	2.020
670	2.243	2.085	1.969	1.926
680	2.141	1.996	1.887	1.841
690	2.047	1.918	1.816	1.765

References [20]

5. *Electrical Conductance (κ)*

Measurement method: classical dc technique [23]

Equation:

$$\kappa = a + bT + cT^2 \quad (101.5)$$

precision: in table 101.7 uncertainty: ∿ ± 3.0%

Table 101.7. Parameters of equation (101.5) and precisions

Mol % $NaNO_3$	-a	b x 10^2	-c x 10^5	Precision	T range(K)
25.3	2.7074	0.7792	0.2217	0.08%	560-670
50.0	2.3808	0.6906	0.1757	0.35%	560-670
75.0	2.8718	0.8549	0.3217	0.08%	550-690

Table 101.8. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 101.7

T (K)	Mol % $NaNO_3$ 25.3	50.0	75.0
550			0.857
560	0.961	0.935	0.907
570	1.014	0.985	0.956
580	1.066	1.033	1.005
590	1.118	1.082	1.052
600	1.170	1.130	1.100
610	1.221	1.178	1.146
620	1.271	1.225	1.192
630	1.321	1.272	1.237
640	1.371	1.319	1.282
650	1.421	1.366	1.326
660	1.469	1.412	1.369
670	1.518	1.457	1.412
680			1.454
690			1.496

References [22-25]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: $LiNO_3$, moderate; $NaNO_3$, permitted in food additive.

(ii) Vapor pressure: $LiNO_3$ decomposed just above its m.pt. (253°C) to the nitrite and oxygen; $NaNO_3$ (m.pt., 307°C), decomposition to nitrite onsets ∿ 500°C.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) On decomposition, nitrates emit toxic fumes (oxides of nitrogen) viz:

$$MNO_3 \longrightarrow MNO_2 + \tfrac{1}{2}O_2 \qquad (101.6)$$

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \qquad (101.7)$$

The subsequent decomposition reactions are complex; if the gas phase is continuously removed, the nitrite decomposition (above) to NO and NO_2 is dominant. If the gas phase is not immediately removed, the NO may re-oxidize the nitrite to nitrate.

(iii) Nitrates are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds, oils, carbon;...); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous.

References [26-31]

7. Corrosion

Table 101.9. Corrosion studies from primary research literature

Studies in molten nitrates and nitrites	References
Fe	[32-34]
Fe, Co, Ni, Cr, Al,...	[35-37]
Cu, Pt, Au, W,...	[36-38]
Zn, Pb, Cu, Ni, Al	[39]
Pt, S, steel	[40]
Zr	[41]
Oxide species	[42]
Electrochemical approach	[43,44]
Thermodynamic redox diagrams	[45,46]
Annotated corrosion biblio.	[47]
Reviews/molten salts	[48-50]

The studies in Table 101.9 (above) relate to studies with various molten nitrates, principally NaNO, KNO_3, and their mixtures. No compatibility studies with molten $LiNO_3$-$NaNO_3$; for studies in molten $LiNO_3$-KNO_3, see [34].

References [32-50]

8. Diffusion

Measurement method: capillary [51]

Diffusing species investigated in $LiNO_3$-$NaNO_3$ as solvent:

Li^+, Na^+, NO_3^-

precision: insufficient data for estimate uncertainty: ∿ ± 20%

Table 101.10. Self-diffusion coefficients, D x 10^5 (cm^2 s^{-1})

T (K)	Li^+	Na^+	NO_3^-
$LiNO_3$-$NaNO_3$(20 mol % $NaNO_3$)			
624	2.64	2.45	1.21
$LiNO_3$-$NaNO_3$(53 mol % $NaNO_3$)			
626	2.61	2.41	1.31

References [51]

(101) $LiNO_3$-$NaNO_3$

9. *Heat of Fusion (ΔH_f°)*

Measurement method: drop calorimetry [52]

Table 101.11. Heat of fusion

Composition		ΔH_f° (kcal mol^{-1})	Uncertainty
T_f	mol % ($LiNO_3$)		
193.5°C	54%	4.775	∿ ± 2%

Saturation concentrations of the eutectic solid solutions : 9.1 mol % $LiNO_3$ and 1.7 mol % $NaNO_3$; heat of mixing of the eutectic solid solutions at 9.1 mol % $LiNO_3$, 122 cal mol^{-1}; and at 1.7 mol % $NaNO_3$, 35 cal mol^{-1}; heat of mixing in the liquid state:

$$\Delta H_x = -x\ (1-x)\ (464+11.5x) \text{ cal mol}^{-1};\ x = \text{mol \% } LiNO_3.$$

References [52]

10. *Heat Capacity (C_p)*

No data

11. *Volume Change on Melting (ΔV_f)*

Measurement method: estimated from densities [53]

Table 101.12. Volume change on melting

Binary eutectic (mol % $NaNO_3$)	($\Delta V_f/V_s$)	Uncertainty
46	13.0%	∿ ± 15%

References [53]

12. *Vapor Pressure (p_{vap})*

No data

13. *Thermal Conductivity (liquid) (λ_ℓ)*

No data

14. *Thermal Conductivity (solid) (λ_s)*

No data

15. *Cryoscopic Constant (k_f)*

Measurement method: calculated from ΔH_f° [53]

Table 101.13. Cryoscopic Constant

Binary eutectic (mol % $NaNO_3$)	k_f (K mol^{-1} Kg)	Uncertainty
46.0	6.9	∿ ± 1%

References [53]

16. References

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System 102 $LiNO_3$- KNO_3

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$LiNO_3$: 253°C

KNO_3: 335°C

Eutectic melting point:

133°C, composition: 58.8 mol % KNO_3

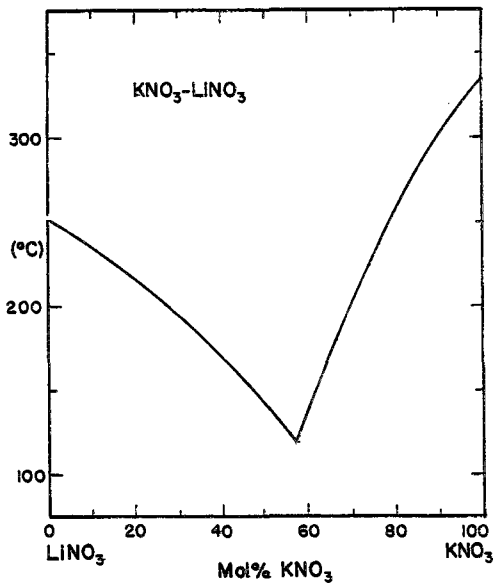

Figure 102.1. $LiNO_3$-KNO_3 phase diagram

References [1-20].

2. *Density (ρ)*

Measurement method: Archimedean technique [21]

Equation:

$$\rho = a + bT \quad (102.1)$$

precision: in table 102.1 uncertainty: ∿ ± 1.5%

Table 102.1. Parameters of equation (102.1) and precisions

Mol % $LiNO_3$	a	-b x 10^4	Precision	T range(K)
20	2.1473	6.217	0.02%	530-710
40	2.2085	6.723	0.02%	520-720
60	2.2823	7.495	0.01%	540-710
80	2.3056	7.475	0.02%	540-710

Two-independent-variables equation

$$\rho = a + bT + cC + dC^2 + eC^3 \quad (102.2)$$

(C = mol % $CaCl_2$)

Table 102.2. Parameters of two-independent variables equation (102.2) and precision

a	b x 10^4	c x 10^3	d x 10^4	e x 10^6	Precision
2.27224	-6.6950	-8.0899	2.1427	-1.4547	0.5%

Table 102.3. Density (g cm^{-3}) from equation in table 102.1

T (K)	Mol % $LiNO_3$			
	20	40	60	80
520		1.859		
540	1.812	1.845	1.878	1.902
560	1.799	1.832	1.863	1.887
580	1.787	1.819	1.848	1.872
600	1.774	1.805	1.833	1.857
620	1.762	1.792	1.818	1.842
540	1.749	1.778	1.803	1.827
660	1.737	1.765	1.788	1.812
680	1.725	1.751	1.773	1.797
700	1.712	1.738	1.758	1.782
720		1.724		

References [21-24]

3. *Surface Tension (γ)*

Measurement method: Wilhelmy slide-plate (detachment) [25]

Equation:

$$\gamma = a + bT \quad (102.3)$$

precision: in table 102.4 uncertainty: ∿ ± 3.0%

Table 102.4. Parameters of equation (102.3) and precisions

Mol % KNO_3	a	-b x 10^3	Precision	T range(K)
25	143.2	56.0	*	460-670
50	146.5	62.0	*	440-670
75	152.7	70.0	*	490-670

*not estimated; insufficient data

Two-independent-variables equation

$$\gamma = a + bT + cC^3 + dCT^2 + eC^2 + fTC$$

$$(C = \text{mol \% } KNO_3) \quad (102.4)$$

Table 102.5. Parameters of two-independent variable equation (102.4)

a	b x 10^2	c x 10^6	d x 10^8	e x 10^3	f x 10^4	Precision
142.69394	-5.12562	-6.25975	1.12949	2.22139	-2.52894	0.1%

Table 102.6. Surface tension (dyn cm^{-1}) from equations in table 102.4

T (K)	Mol % KNO_3 25	50	75
440		119.2	
460	117.4	118.0	
480	116.3	116.7	
500	115.2	115.5	117.7
520	114.1	114.3	116.3
540	113.0	113.0	114.9
560	111.8	111.8	113.5
580	110.7	110.5	112.1
600	109.6	109.3	110.7
620	108.5	108.1	109.3
640	107.4	106.8	107.9
660	106.2	105.6	106.5
670	105.7	105.0	105.8

References [25]

4. *Viscosity (η)*

Measurement method: oscillating sphere [21]

Equation:

$$\eta = a + bT + cT^2 + dT^3 \quad (102.5)$$

precision: in table 102.7 uncertainty: ∿ ± 5.0%

Table 102.7. Parameters of equation (102.5) and precisions

$LiNO_3$ (mol %)	a	b x 10^2	c x 10^5	d x 10^8	Precision	T range(K)
40	76.5978	-28.379	35.751	-14.972	2.18%	530-690
60	99.3868	-37.296	47.197	-19.751	2.47%	530-690
80	64.1768	-20.614	21.143	-6.2709	2.30%	550-690

Equation:

$$\eta = A \exp (E/RT) \quad (102.6)$$

precision: in table 102.8 uncertainty: ∿ ± 5%

Table 102.8. Parameters of equation (102.6) and precision

$LiNO_3$ (mol %)	A x 10^2	E (cal mol^{-1})	Precision	T range(K)
20	9.139	4081	1.51%	550-690

Table 102.9. Viscosity (cp) from equations in tables 102.7 and 102.8

T (K)	Mol % $LiNO_3$ 20	40	60	80
530		4.324	4.889	
540		4.026	4.514	
550	3.825	3.750	4.169	4.324
560	3.579	3.497	3.853	4.030
570	3.356	3.265	3.565	3.575
580	3.153	3.054	3.304	3.505
590	2.970	2.862	3.069	3.274
600	2.802	2.688	2.858	3.062
610	2.649	2.532	2.670	2.871
620	2.509	2.392	2.504	2.698
630	2.381	2.269	2.360	2.545
640	2.263	2.160	2.235	2.410
650	2.154	2.065	2.129	2.294
660	2.053	1.984	2.040	2.195
670	1.960	1.915	1.967	2.113
680	1.873	1.856	1.910	2.049
690	1.793	1.809	1.866	2.002

References [21]

5. *Electrical Conductance (κ)*

Measurement method: classical dc technique [26]

Equation:

$$\kappa = a + bT + cT^2 \quad (102.7)$$

precision: in table 102.10 uncertainty: $\sim \pm 2.0\%$

Table 102.10. Parameters of equation (102.7) and precisions

Mol % $LiNO_3$	-a	b x 10^3	-c x 10^6	Precision	T range(K)
23.0	1.8330	4.938	1.245	0.27%	550-690
50.1	1.5558	4.096	0.283	0.11%	560-700
74.8	3.0806	9.076	3.875	0.21%	560-640

Table 102.11. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 102.10

T (K)	Mol % $LiNO_3$		
	23.31	50.1	74.8
550	0.506		
560	0.542	0.649	0.787
570	0.577	0.687	0.834
580	0.612	0.725	0.880
590	0.647	0.763	0.926
600	0.682	0.800	0.970
610	0.716	0.838	1.014
620	0.750	0.875	1.057
630	0.784	0.913	1.099
640	0.817	0.950	1.141
650	0.851	0.987	
660	0.884	1.025	
670	0.917	1.062	
680	0.949	1.099	
690	0.982	1.136	
700		1.173	

References [26-29]

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: $LiNO_3$, slight; KNO_3, permitted as food additive.

(ii) Vapor pressure: $LiNO_3$ decomposes just above its m.pt. (253°C) to $LiNO_2$ and oxygen. KNO_3 (m.pt. 335°C), decomposition similarly onsets ~ 530°C.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) On decomposition, nitrates emit toxic fumes (oxides of nitrogen) viz:

$$MNO_3 \longrightarrow MNO_2 + \tfrac{1}{2}O_2 \qquad (102.8.1)$$

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \qquad (102.8.2)$$

The subsequent decomposition reactions are complex; if the gas phase is continuously removed, the nitrite decomposition (above) to NO and NO_2 is dominant. If the gas phase is not immediately removed, the NO may re-oxidize the nitrite to nitrate.

(iii) Nitrates are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon;...); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous.

References [30-35]

7. Corrosion

Table 102.12. Corrosion studies from primary research literature

Studies	References
Fe	[36-38]
Fe, Co, Ni, Cr, Al,...	[39-41]
Cu, Pt, Au, W,...	[40-42]
Zn, Pb, Cu, Ni, Al	[43]
Pt, S, steel	[44]
Zr	[45]
Oxide species	[46]
Electrochemical approach	[47,48]
Thermodynamic redox diagrams	[49,50]
Annotated corrosion biblio.	[51]
Reviews/molten salts	[52-54]

The studies in Table 102.12 (above) relate principally to molten KNO_3, $NaNO_3$ and their mixtures; for some studies in molten $LiNO_3$-KNO_3, see [40].

References [36-54]

8. Diffusion

Measurement method: cited in tabulations

List of diffusing species investigated in $LiNO_3$-KNO_3 as solvent

Li^+, Na^+, K^+, Ag^+, Cd^{2+}, Cd^{2+}(EDTA), Pb^{2+}, Pb^{2+}(EDTA), NO_3^-, Cl^-, Br^-, I^-.

precision: in table 102.14 uncertainty: in table 102.13

Equation:

$$D = A \exp [-E/RT] \quad (102.9)$$

Table 102.13. Diffusion techniques, uncertainties and species

Diffusion technique of recommended study	Uncertainty (in values of D)	Species
capillary	$\sim\pm$20%	K^+, Li^+, Na^+, NO_3^-
chronopotentiometry	$\sim\pm$10%	Ag^+, Br^-, Cl^-, I^-
dc polarography	$\sim\pm$20%	Cd^{2+}, Pb^{2+}

For numerical values: see tables

(102) $LiNO_3$-KNO_3

Table 102.14. Parameters of diffusion equation (102.9), precisions and recommended study

Species	A x 10^3 (cm^2 s^{-1})	E (cal mol^{-1})	Temp. range (K)	Precision	Recommended study
(a) $LiNO_3$-KNO_3 (4 mol % $LiNO_3$)					
Li^+	1.072	4884	600-660	∿±3%	[55]
Na^+	1.107	5054	600-660	∿±2%	[55]
K^+	1.007	5159	600-660	∿±1%	[55]
NO_3^-	*insufficient data for t-dependent parameters*				[56]
(b) $LiNO_3$-KNO_3 (20 mol % $LiNO_3$)					
Ag^+	0.591	4107	560-630	∿±2%	[59]
(c) $LiNO_3$-KNO_3 (25 mol % $LiNO_3$)					
Li^+	1.020	4754	550-620	∿±1%	[55]
Na^+	1.424	5239	550-620	∿±1%	[55]
K^+	1.516	5552	550-620	∿±1%	[56]
NO_3^-	*insufficient data for t-dependent parameters*				[56]
(d) $LiNO_3$-KNO_3 (34 mol % $LiNO_3$)					
Li^+	1.415	5135	470-625	∿±1%	[55]
Na^+	1.340	5151	470-625	∿±3%	[55]
K^+	1.395	5415	470-625	∿±2%	[55,56]
NO_3^-	1.077	5349	550-620	∿±1%	[55]
(e) $LiNO_3$-KNO_3 (38.6 mol % $LiNO_3$)					
Cd^{2+}	35.056	8820	430-480	∿±4%	[57]
Cd^{2+}(EDTA)	6.604	8773	430-480	∿±2%	[57]
(f) $LiNO_3$-KNO_3 (40 mol % $LiNO_3$)					
Ag^+	0.508	3837	530-630	∿±3%	[59]
(g) $LiNO_3$-KNO_3 (43 mol % $LiNO_3$)					
Ag^+	1.891	5226		∿±3%	[58]
Cl^-	2.726	6235		∿±3%	[58]
Br^-	8.770	7589		∿±6%	[58]
I^-	12.294	7821		∿±4%	[58]

cont'd

Table 102.14. Parameters of diffusion equation (109.9), precisions and recommended study - cont'd

Species	A x 10^3 (cm^2 s^{-1})	E (cal mol^{-1})	Temp. range (K)	Precision	Recommended study
(h) $LiNO_3$-KNO_3 (50 mol % $LiNO_3$)					
Li^+	1.168	4792	550-620	∿±1%	[55]
Na^+	1.387	5076	550-620	∿±1%	[55]
K^+	1.722	5576	550-620	∿±1%	[56]
NO_3^-	*insufficient data for t-dependent parameters*				[56]
(i) $LiNO_3$-KNO_3 (60 mol % $LiNO_3$)					
Ag^+	0.821	4410	530-630	∿±2%	[59]
(j) $LiNO_3$-KNO_3 (75 mol % $LiNO_3$)					
Li^+	1.367	4903	550-620	∿±1%	[55]
Na^+	1.654	5222	550-620	∿±1%	[55]
K^+	1.269	5182	550-620	∿±1%	[55]
(k) $LiNO_3$-KNO_3 (80 mol % $LiNO_3$)					
Ag^+	2.098	5636	530-630	∿±6%	[59]
(l) $LiNO_3$-KNO_3 (99 mol % $LiNO_3$)					
Li^+	1.332	4826	535-625	∿±2%	[55]
Na^+	1.236	4835	535-625	∿±2%	[55]
K^+	1.176	5082	535-625	∿±2%	[55]
NO_3^-	1.523	6044	550-625	∿±1%	[56]

Table 102.14a. Diffusion coefficients in $LiNO_3$-KNO_3 (4 mol % $LiNO_3$)

T (K)	D x 10^5 (cm^2 s^{-1})			
	Li^{+*}	Na^+	K^{+*}	NO_3^{-*}
600	1.78	1.60	1.33	
610	1.91	1.71	1.43	
620	2.03	1.83	1.53	1.35(‡)
630	2.17	1.95	1.63	
640	2.30	2.08	1.74	
650	2.44	2.21	1.85	
660	2.59	2.35	1.97	

*:-self-diffusion coefficients

‡:-based on sole data point at 623K

Table 102.14b. Diffusion coefficients in $LiNO_3$-KNO_3(20 mol % $LiNO_3$)

T (K)	$D_{Ag^+} \times 10^5$ ($cm^2\ s^{-1}$)	T (K)	$D_{Ag^+} \times 10^5$ ($cm^2\ s^{-1}$)
560	1.47	600	1.89
570	1.57	610	2.00
580	1.67	620	2.11
590	1.78	630	2.22

Table 102.14c. Diffusion coefficients in $LiNO_3$-KNO_3 (25 mol % $LiNO_3$)

T (K)	D x 10^5 ($cm^2\ s^{-1}$)			
	Li^{+*}	Na^+	K^{+*}	NO_3^{-*}
550	1.32	1.18	0.94	
560	1.42	1.28	1.03	
570	1.53	1.40	1.13	
580	1.65	1.51	1.23	
590	1.77	1.63	1.33	
600	1.89	1.76	1.44	
610	2.02	1.89	1.55	
620	2.15	2.03	1.67	1.41(‡)

*:-self-diffusion coefficients

‡:-based on sole data point at 624K

Table 102.14d. Diffusion coefficients in $LiNO_3$-KNO_3(34 mol % $LiNO_3$)

T (K)	D x 10^5 ($cm^2\ s^{-1}$)			
	Li^{+*}	Na^+	K^{+*}	NO_3^-
470	0.58	0.54	0.42	
480	0.65	0.60	0.48	
490	0.72	0.68	0.54	
500	0.81	0.75	0.60	
510	0.89	0.83	0.67	
520	0.98	0.92	0.74	
530	1.08	1.01	0.82	
540	1.18	1.10	0.90	
550	1.29	1.20	0.98	0.81
560	1.40	1.31	1.07	0.88
570	1.52	1.42	1.17	0.96
580	1.64	1.53	1.27	1.04
590	1.77	1.66	1.38	1.12
600	1.91	1.78	1.49	1.21
610	2.05	1.91	1.60	1.31
620	2.19	2.05	1.72	1.40
625	2.26	2.12	1.78	

*:-self-diffusion coefficients

Table 102.14e. Diffusion coefficients in $LiNO_3$-KNO_3(38.6 mol % $LiNO_3$)

T (K)	D x 10^5 (cm^2 s^{-1})			
	Cd^{2+}	Cd^{2+}(EDTA)	Pb^{2+}	Pb^{2+}(EDTA)
430	0.12	0.02		
440	0.15	0.03	0.25(‡)	0.04(‡)
450	0.18	0.04		
460	0.23	0.04		
470	0.28	0.05		
480	0.34	0.07		

‡:-based on sole data point at 443K [3]

Table 102.14f. Diffusion coefficients in $LiNO_3$-KNO_3(40 mol % $LiNO_3$)

T (K)	D_{Ag^+} x 10^5 (cm^2 s^{-1})	T (K)	D_{Ag^+} x 10^5 (cm^2 s^{-1})
530	1.33	590	1.93
540	1.42	600	2.03
550	1.52	610	2.14
560	1.62	620	2.26
570	1.72	630	2.37
580	1.82		

Table 102.14g. Diffusion coefficients in $LiNO_3$-KNO_3(43 mol % $LiNO_3$)

T (K)	D x 10^5 (cm^2 s^{-1})			
	Ag^+	Cl^-	Br^-	I^-
420	0.35	0.15	0.09	0.10
430	0.41	0.18	0.12	0.13
440	0.48	0.22	0.15	0.16
450	0.56	0.26	0.19	0.20
460	0.64	0.31	0.23	0.25
470	0.72	0.35	0.27	0.29
480	0.80	0.40	0.32	0.34
490	0.89	0.46	0.37	0.39
500	0.98	0.51	0.42	0.45
510	1.07	0.57	0.47	
520	1.17	0.63	0.53	

Table 102.14h. Diffusion coefficients in $LiNO_3$-KNO_3(50 mol % $LiNO_3$)

T (K)	D x 10^5 (cm^2 s^{-1})			
	Li^{+*}	Na^+	K^{+*}	NO_3^{-*}
550	1.46	1.33	1.05	
560	1.57	1.45	1.15	
570	1.70	1.57	1.25	
580	1.83	1.70	1.36	
590	1.96	1.83	1.48	
600	2.10	1.96	1.60	
610	2.24	2.11	1.73	
620	2.39	2.25	1.86	1.33(‡)

*:-self-diffusion coefficients

‡:-based on 2 data points at 617 and 623K, respectively.

Table 102.14i. Diffusion coefficients in $LiNO_3$-KNO_3(60 mol % $LiNO_3$)

T (K)	D_{Ag^+} x 10^5 (cm^2 s^{-1})	T (K)	D_{Ag^+} x 10^5 (cm^2 s^{-1})
530	1.25	590	1.91
540	1.35	600	2.03
550	1.45	610	2.16
560	1.56	620	2.29
570	1.67	630	2.42
580	1.79		

Table 102.14j. Diffusion coefficients in $LiNO_3$(75 mol % $LiNO_3$)

T (K)	D x 10^5 (cm^2 s^{-1})			
	Li^{+*}	Na^+	$K^{+}*$	NO_3^-
550	1.54	1.39	1.11	
560	1.67	1.51	1.20	
570	1.80	1.64	1.31	
580	1.94	1.78	1.41	
590	2.09	1.92	1.53	
600	2.24	2.07	1.64	
610	2.39	2.23	1.76	
620	2.55	2.39	1.89	

*:-self-diffusion coefficients.

Table 102.14k. Diffusion coefficients in $LiNO_3$-KNO_3(80 mol % $LiNO_3$)

T (K)	$D_{Ag^+} \times 10^5$ ($cm^2\ s^{-1}$)	T (K)	$D_{Ag^+} \times 10^5$ ($cm^2\ s^{-1}$)
530	0.99	590	1.71
540	1.10	600	1.86
550	1.21	610	2.01
560	1.32	620	2.16
570	1.45	630	2.33
580	1.58		

Table 102.141. Diffusion coefficients in $LiNO_3$-KNO_3(99 mol % $LiNO_3$)

T (K)	D x 10^5 ($cm^2\ s^{-1}$)			
	Li^{+*}	Na^+	K^{+*}	NO_3^{-*}
535	1.42	1.31	0.99	
540	1.48	1.36	1.03	
550	1.61	1.48	1.12	0.60
560	1.74	1.60	1.22	0.67
570	1.88	1.73	1.32	0.73
580	2.02	1.86	1.43	0.80
590	2.17	2.00	1.54	0.88
600	2.33	2.14	1.66	0.96
610	2.48	2.29	1.78	1.04
620	2.65	2.44	1.90	1.13
625	2.73	2.52	1.96	1.17

*:-self-diffusion coefficients

References [55-59]

9. *Heat of Fusion (ΔH_f°)*

No data

10. *Heat Capacity (C_p)*

No data

11. *Volume Change on Melting (ΔV_f)*

Measurement method: estimated from densities [60]

Table 102.15. Volume change on melting

Binary eutectic (mol % KNO_3)	($\Delta V_f/V_s$)	Uncertainty
58.5	13.5%	$\sim \pm$ 20%

References [60]

(102) $LiNO_3$-KNO_3

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 103 $NaNO_3$-$Ca(NO_3)_2$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$NaNO_3$: 307°C

$Ca(NO_3)_2$: 561°C

Eutectic melting point:

226°C, composition: 30 mol % $Ca(NO_3)_2$

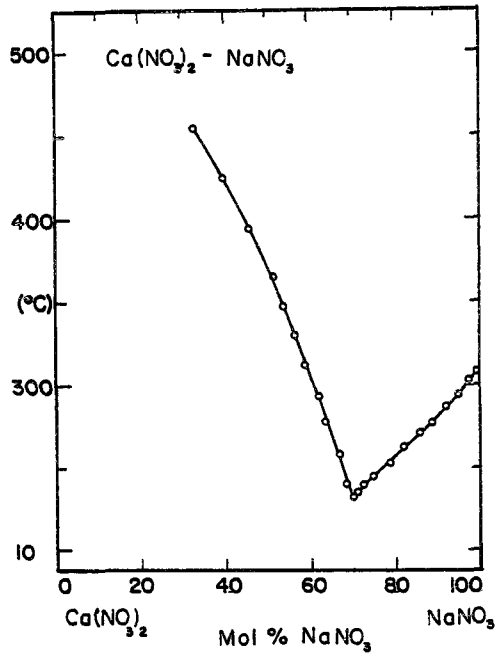

Figure 103.1. $NaNO_3$-$Ca(NO_3)_2$ phase diagram

References [1-19].

2. *Density (ρ)*

Measurement method: manometric densitometer [20]

Equation:

$$\rho = a + bT \quad (103.1)$$

precision: in table 103.1 uncertainty: ∿ ± 1.0%

Table 103.1. Parameters of equation (103.1) and precisions

(mol % $NaNO_3$)	a	-b x 10^3	Precision	T range(K)
55.4	2.4269	0.6700	0.02%	630-660
66.9	2.4017	0.6738	0.01%	530-640
72.8	2.3956	0.6850	0.02%	530-640
77.0	2.3980	0.7070	0.03%	530-660
83.8	2.4226	0.7330	0.02%	550-670
89.1	2.3920	0.7553	0.02%	570-670
92.0	2.3573	0.7173	0.02%	580-670
96.5	2.3475	0.7249	0.02%	590-670

Table 103.2. Density (g cm^{-3}) from equations in table 103.1

T (K)	Mol % $NaNO_3$ 55.4	66.9	72.8	83.8	89.1	92.0	96.5
530		2.045	2.033				
540		2.038	2.026				
550		2.031	2.019	2.019			
560		2.024	2.012	2.012			
570		2.018	2.005	2.005	1.961		
580		2.011	1.998	1.997	1.954	1.941	
590		2.004	1.991	1.990	1.946	1.934	1.920
600		1.997	1.985	1.983	1.939	1.927	1.913
610		1.991	1.978	1.975	1.931	1.920	1.905
620		1.984	1.971	1.968	1.924	1.913	1.898
630	2.005	1.977	1.964	1.961	1.916	1.905	1.891
640	1.998	1.970	1.957	1.953	1.909	1.898	1.884
650	1.991			1.946	1.901	1.891	1.876
660	1.985			1.939	1.894	1.884	1.869
670				1.931	1.886	1.877	1.862
680						1.870	1.855

References [20]

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure [21]

Equations:

$$\gamma = a + bT \quad (103.2)$$

precision: in table 103.3 uncertainty: ~ ± 2.0%

Table 103.3. Parameters of equation (103.2) and precisions

Mol % $Ca(NO_3)_2$	a	$-b \times 10^2$	Precision	T range(K)
5.27	163.1	5.59	*	583-703
11.12	160.0	5.25	*	572-700
17.68	160.6	5.29	*	548-683
25.00	163.3	5.54	*	540-689
29.79	164.5	5.62	*	520-704
37.93	168.5	6.00	*	586-690
46.00	167.1	5.82	*	637-690

*not estimated; insufficient data

Two-independent-variables equation

$$\gamma = a + bT + cC^2 + dTC^2 \quad (103.3)$$

(C = mol % $Ca(NO_3)_2$

Table 103.4. Parameters of two-independent-variables equation (103.3)

a	$b \times 10^2$	$c \times 10^3$	$d \times 10^6$	Precision
146.19339	-5.33522	4.10095	4.7775	0.16%

Table 103.5. Surface tension (dyn cm^{-1}) from equations in table 103.3

T (K)	Mol % $Ca(NO_3)_2$						
	5.27	11.12	17.68	25.00	29.79	37.93	46.00
520					135.3		
540				133.4	134.2		
560			131.0	132.3	133.0		
580	130.7	129.6	129.9	131.2	131.9		
600	129.6	128.5	128.9	130.1	130.8	132.5	
620	128.4	127.5	127.8	129.0	129.7	131.3	
640	127.3	126.4	126.7	127.8	128.5	130.1	129.9
660	126.2	125.4	125.7	126.7	127.4	128.9	123.7
680	125.1	124.3	124.6	125.6	126.3	127.7	127.5
700	124.0	123.3			125.2		

References [21]

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [22]

Equation:

$$\kappa = a + bT + cT^2 \quad (103.4)$$

precision: in table 103.6 uncertainty: $\sim \pm 2.0\%$

Table 103.6. Parameters of equation (103.4) and precisions

Mol % $NaNO_3$	-a	b x 10^3	-c x 10^6	Precision	T range(K)
50	1.7551	4.800	2.182	0.31%	570-640
75	1.3922	2.893	-0.385	0.02%	550-670
90	1.9995	5.336	1.083	0.28%	580-690

Table 103.7. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 103.6

T (K)	Mol % $NaNO_3$		
	50	75	90
550		0.316	
560		0.349	
570	0.272	0.382	
580	0.295	0.415	0.731
590	0.317	0.449	0.772
600	0.340	0.482	0.813
610	0.361	0.516	0.853
620	0.382	0.550	0.893
630	0.403	0.583	0.933
640	0.423	0.617	0.972
650		0.651	1.012
660		0.685	1.051
670		0.719	1.090
680			1.129
690			1.167

References [22]

(103) $NaNO_3$-$Ca(NO_3)_2$

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: $NaNO_3$, permitted as food additive; $Ca(NO_3)_2$, rated moderate.

(ii) Vapor pressure: Nitrates will decompose with heating to nitrites and oxygen; onset of decomposition: $NaNO_3$ (m.pt. 307°C) ∿ 500°C; $Ca(NO_3)_2$ (m.pt. 561°C), ∿ m.pt.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) On decomposition, nitrates emit toxic fumes (oxides of nitrogen) viz:

$$2MNO_3 \longrightarrow 2MNO_2 + O_2 \qquad (103.5.1)$$

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \qquad (103.5.2)$$

The subsequent decomposition reactions are complex; if the gas phase is continuously removed, the nitrite decomposition (above) to NO and NO_2 is dominant.

(iii) Nitrates are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon,...); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous.

References [23-28]

(103) $NaNO_3$-$Ca(NO_3)_2$

7. Corrosion

Table 103.8. Corrosion studies from primary research literature

Studies	References
Fe	[29-31]
Fe, Co, Ni, Cr, Al,...	[32-34]
Cu, Pt, Au, W,...	[33-35]
Zn, Pb, Cu, Ni, Al	[36]
Pt, S, steel	[37]
Zr	[38]
Oxide species	[39]
Electrochemical approach	[40,41]
Thermodynamic redox diagrams	[42,43]
Annotated corrosion biblio.	[44]
Reviews/molten salts	[45-47]

The studies in Table 103.8 (above) related to studies with various molten nitrates, principally $NaNO_3$, KNO_3, and their mixtures. For studies with added alkaline earth cations, see [31].

References [29-47]

8. Diffusion

Measurement method: chronopotentiometry [48]

List of diffusing species investigated in $NaNO_3$-$Ca(NO_3)_2$

Ag^+

precision: ∿ ± 3.4% uncertainty: ∿ ± 10%

Equation:

$$D = 0.676 \times 10^{-3} \exp [-4248/RT] \quad (103.6)$$

Table 103.9. Diffusion coefficients in $NaNO_3$-$Ca(NO_3)_2$(94 mol % $NaNO_3$)

T (K)	$D_{Ag^+} \times 10^5$ ($cm^2\ s^{-1}$)	T (K)	$D_{Ag^+} \times 10^5$ ($cm^2\ s^{-1}$)
570	1.59	630	2.27
580	1.69	640	2.39
590	1.80	650	2.52
600	1.92	660	2.65
610	2.03	670	2.78
620	2.15		

References [48]

(103) $NaNO_3$-$Ca(NO_3)_2$

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [49]

Table 103.10. Volume change on melting

Binary eutectic (mol % $NaNO_3$)	($\Delta V_f/V_s$)	Uncertainty
70	9.2%	$\sim \pm$ 10%

References [49].

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 104 KNO_3-$Mg(NO_3)_2$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

KNO_3: 335°C

$Mg(NO_3)_2$: anhydrous $Mg(NO_3)_2$ decomposes at t ∿ 400°C

Eutectic melting point:

E_1: 178°C, composition: 56 mol % KNO_3

E_2: 195°C, composition: 81 mol % KNO_3

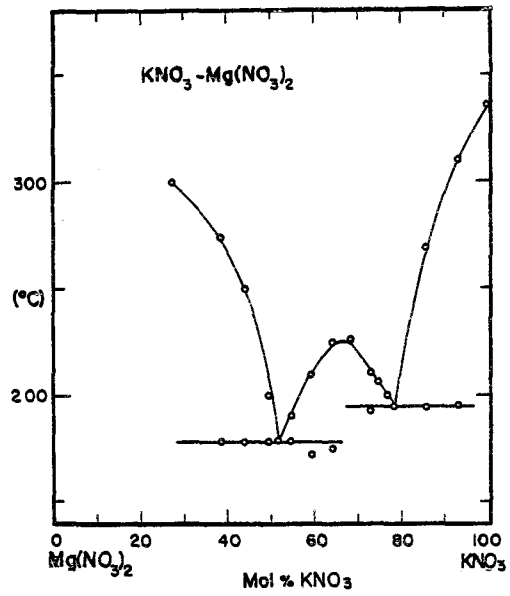

Figure 104.1. KNO_3-$Mg(NO_3)_2$ phase diagram

References [1-16].

2. *Density (ρ)*

Measurement method: manometric densitometer [17]

Equation:

$$\rho = a + bT \quad (104.1)$$

precision: in table 104.1 uncertainty: ∿ ± 1.0%

Table 104.1. Parameters of equation (104.1) and precisions

Mol % $Mg(NO_3)_2$	a	-b x 10^3	Precision	T range(K)
5.3	2.5389	0.8667	0.2%	590-660
11.0	2.6148	0.8786	0.01%	560-620
17.0	2.7417	0.8982	0.02%	520-610
24.4	2.9356	0.9927	0.02%	480-570
33.4	3.1403	1.0500	0.01%	500-520

Table 104.2. Density (g cm^{-3}) from equations in table 104.1

T (K)	Mol % $Mg(NO_3)_2$ 5.3	11.0	17.0	24.4	33.4
480				2.459	
490				2.449	2.626
500				2.439	2.615
510				2.429	2.605
520			2.275	2.419	2.594
530			2.266	2.409	
540			2.257	2.400	
550			2.248	2.390	
560		2.124	2.239	2.380	
570		2.114	2.230	2.370	
580		2.105	2.221		
590	2.028	2.096	2.212		
600	2.019	2.088	2.203		
610	2.010	2.079	2.194		
620	2.002	2.070			
630	1.993				
640	1.984				
650	1.976				
660	1.967				

References [17]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: KNO_3, permitted as food additive; $Mg(NO_3)_2$, rated moderate.

(ii) Vapor pressure: Nitrates decompose, on heating, to nitrites and oxygen; onset of decomposition for KNO_3 (m.pt. 335°C); is ∿ 530°C; little is known about the high temperature behavior of anhydrous $Mg(NO_3)_2$; onset of decomposition has been reported from ∿ 130°C to ∿ 390°C.

(104) KNO_3-$Mg(NO_3)_2$

B. Disaster hazards

(i) Molten salt bath "explosions": violent generation of steam due to bulk water "carry-over" and/or equipment failure; sudden explosive expansion of "trapped" air.

(ii) On decomposition, nitrates emit toxic fumes (oxides of nitrogen) viz:

$$MNO_3 \longrightarrow MNO_2 + \tfrac{1}{2}O_2 \qquad (104.2)$$

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \qquad (104.3)$$

The subsequent decomposition reactions are complex; if the gas phase is continuously removed, the nitrite decomposition (above) to NO and NO_2 is dominant.

In the temperature range 550-600°C, and under oxygen, the conversion of KNO_2 to KNO_3 goes to completion; between 650-750°C, the two salts interconvert (see above), KNO_3 becoming increasingly unstable; above 800°C; the nitrite decomposition: $2\ KNO_2 \longrightarrow K_2O + N_2 + {}^3/_2O_2$ goes to completion.

(iii) Nitrates are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon,...); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous.

References [18-23]

7. *Corrosion*

Table 104.3. Corrosion studies from primary research literature

Studies	References
Fe	[24-26]
Fe, Co, Ni, Cr, Al,...	[27-29]
Cu, Pt, Au, W,...	[28-30]
Zn, Pb, Cu, Ni, Al	[31]
Pt, S, steel	[32]
Zr	[33]
Oxide species	[34]
Electrochemical approach	[35,36]
Thermodynamic redox diagrams	[37,38]
Annotated corrosion biblio.	[39]
Reviews/molten salts	[40-42]

The studies in Table 104.3 (above) related to studies with various molten nitrates, principally NaNO, KNO_3, and their mixtures. For studies with added alkaline earth cations, see [26].

References [24-42]

(104) KNO_3-$Mg(NO_3)_2$

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 105 $LiNO_2$-$NaNO_2$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$LiNO_2$: 220°C

$NaNO_2$: 282°C

Eutectic melting point:

150°C, composition: 63 mol % $LiNO_2$

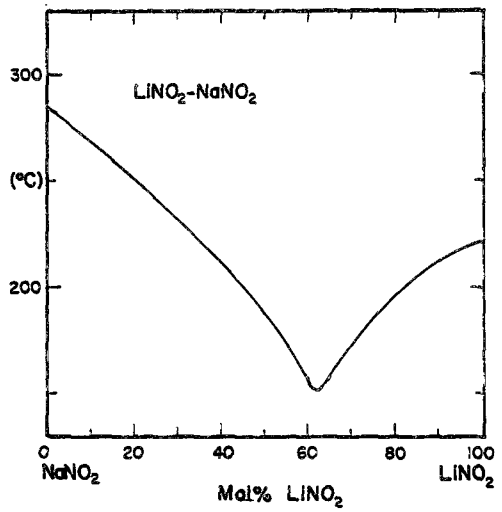

Figure 105.1. $LiNO_3$-$NaNO_2$ phase diagram

References [1-16].

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [17]

Equation:

$$\kappa = a + bT + cT^2 \quad (105.1)$$

precision: in table 105.1 uncertainty: $\sim \pm 3.0\%$

(105) $LiNO_2$-$NaNO_2$

Table 105.1. Parameters of equation (105.1) and precisions

Mol % $LiNO_2$	-a	b x 10^2	-c x 10^5	Precision	T range(K)
20	17.793	6.363	5.277	0.3%	530-570
30	9.7457	3.473	2.700	0.6%	530-570
40	6.4316	2.240	1.570	1.1%	490-570
50	5.8379	2.016	1.376	0.8%	470-570
60	4.8060	1.604	0.983	0.7%	470-550
70	6.2311	2.168	1.557	0.6%	470-550
80	3.6193	1.175	0.631	0.2%	490-550
90	7.2069	2.550	1.964	0.6%	490-550

Table 105.2. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 105.1

	Mol % $LiNO_2$							
T (K)	20	30	40	50	60	70	80	90
470				0.596	0.561	0.520		
480				0.667	0.628	0.588		
490			0.772	0.735	0.693	0.654	0.623	0.572
500			0.840	0.800	0.756	0.717	0.678	0.632
510		0.945	0.905	0.863	0.817	0.776	0.732	0.689
520		1.014	0.968	0.923	0.876	0.833	0.784	0.742
530	1.108	1.078	1.027	0.980	0.933	0.886	0.836	0.790
540	1.179	1.136	1.083	1.034	0.989	0.936	0.886	0.835
550	1.240	1.189	1.135	1.086	1.042	0.983	0.934	0.876
560	1.291	1.237	1.185	1.345				
570	1.331	1.279	1.231	1.181				

References [17]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: $LiNO_2$, severe; $NaNO_2$, permitted in food; there appears to be some implication of increased cancer with chronic ingestion of nitrites

(ii) Vapor pressure: no data for this system; but see: $LiNO_2$ [28], and $NaNO_2$ [28]

(105) $LiNO_2$-$NaNO_2$

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air

(ii) On decomposition, nitrites emit toxic fumes (oxides of nitrogen) viz:

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \quad (105.2)$$

$$2MNO_2 + O_2 \longrightarrow 2MNO_3 \quad (105.3)$$

The subsequent decomposition reactions are complex; if the gas phase is not continuously removed, the nitrite may be oxidized to $NaNO_3$, i.e., to the nitrate

(iii) Nitrites, like nitrates, are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon,....); aluminum alloys and bath sludges (e.g. iron oxides)

References [18-28]

7. Corrosion

Table 105.3. Corrosion studies from primary research literature

Studies in molten nitrates and nitrites	References
Fe	[29-31]
Fe, Co, Ni, Cr, Al,...	[32-34]
Cu, Pt, Au, W,...	[33-35]
Zn, Pb, Cu, Ni, Al	[36]
Pt, S, steel	[37]
Zr	[38]
Oxide species	[39]
Electrochemical approach	[40,41]
Thermodynamic redox diagrams	[42,43]
Annotated corrosion biblio.	[44]
Reviews/molten salts	[45-47]

No compatibility studies with $LiNO_2$-$NaNO_2$ found; the studies in Table 105.3 (above) related principally to Na and K nitrates and their mixtures; for passivation studies in molten $NaNO_2$, see [31].

References [29-47]

(105) $LiNO_2$-$NaNO_2$

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

[1] Shisholina, R. P., Protsenko, P. I., Zhur. Neorg. Khim., 8, 1436 (1963).

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[4] Janz, G. J., Downey, J. R., Jr., Allen, C. B., and Tomkins, R. P. T., *"Physical Properties Data Compilations Relevant to Energy Storage. I. Molten Salts: Eutectic Data"*, NSRDS-NBS-61; U. S. Gov't Printing Office, Washington, D. C. (1978).

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[28] *vide:* this work, System 73, $LiNO_2$ and 74, $NaNO_2$.

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System 106 KNO_2-$NaNO_2$

1. *Melting Temperatues (T_m)*

Pure substance melting points:

$NaNO_2$: 282°C

KNO_2: 440°C

Eutectic melting point:

∿ 228°C, composition: 65 Mol % $NaNO_2$

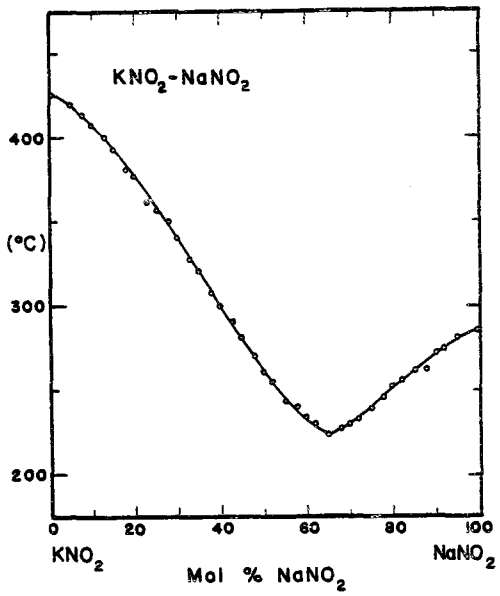

Figure 106.1. KNO_2-$NaNO_2$ phase diagram

References [1-17].

2. *Density (ρ)*

Measurement method: Archimedean technique [18]

Equation:

$$\rho = a + bT \quad (106.1)$$

precision: in table 106.1 uncertainty: ∿ ± 1.5%

Table 106.1. Parameters of equation (106.1) and precisions

Mol % KNO_2	a	$-b \times 10^4$	Precision	T range(K)
15	2.1147	5.835	0.03%	530-770
25	2.1260	6.033	0.29%	510-770
40	2.1232	5.937	0.08%	510-770
45	2.1098	5.789	0.30%	510-770
50	2.1030	5.707	0.30%	550-770
60	2.1377	6.229	0.15%	570-770
70	2.1202	5.979	0.03%	590-770
75	2.1205	5.998	0.02%	610-770

(106) KNO_2-$NaNO_2$

Two-independent-variables equation

$$\rho = a + bT + cCT \quad (106.2)$$

(C = mol % $CaCl_2$)

Table 106.2. Parameters of two-independent-variables equation (106.2) and precision

a	$-b \times 10^4$	$-c \times 10^{10}$	Precision
2.1196	5.902	1.1284	0.002%

Table 106.3. Density (g cm^{-3}) from equations in table 106.2

	Mol % KNO_2							
T (K)	15	25	40	45	50	60	70	75
510		1.818	1.820	1.815				
530	1.805	1.806	1.809	1.803				
550	1.794	1.794	1.797	1.791	1.789			
570	1.782	1.782	1.785	1.780	1.778	1.783		
590	1.770	1.770	1.773	1.768	1.766	1.770	1.767	
610	1.759	1.758	1.761	1.757	1.755	1.758	1.755	1.755
630	1.747	1.746	1.749	1.745	1.743	1.745	1.744	1.743
650	1.735	1.734	1.737	1.734	1.732	1.733	1.732	1.731
670	1.724	1.722	1.725	1.722	1.721	1.720	1.720	1.719
690	1.712	1.710	1.714	1.710	1.709	1.708	1.708	1.707
710	1.700	1.698	1.702	1.699	1.698	1.695	1.696	1.695
730	1.689	1.686	1.690	1.687	1.686	1.683	1.684	1.683
750	1.677	1.674	1.678	1.676	1.675	1.671	1.672	1.671
770	1.665	1.661	1.666	1.664	1.664	1.658	1.660	1.659

References [18]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

Measurement method: capillary [19]

Equation:

$$\eta = a + bT + cT^2 + dT^3 \quad (106.3)$$

precision: in table 106.4 uncertainty: $\sim \pm 3.0\%$

Table 106.4. Parameters of equation (106.3) and precisions

$NaNO_2$ (mol %)	a	$b \times 10^2$	$c \times 10^5$	$d \times 10^9$	Precision	T range(K)
10	(5.9792)	(-0.600)				700-730
20	(-119.7038)	(55.833)	(-84.15)	(416.67)		650-710
80	1.3444	7.897	-22.64	163.56	0.15%	580-650
90	(39.3925)	(-10.648)	(7.50)			

The values in ( ) are based on a minimal data set

(106) KNO_2-$NaNO_2$

Equation:

$$\eta = A \exp (E/RT) \quad (106.4)$$

precision: in table 106.5 uncertainty: ∿ ± 3.0%

Table 106.5. Parameters of equation (106.4) and precisions

$NaNO_2$ (mol %)	A x 10^2	E (cal mol^{-1})	Precision	T range(K)
30	9.819	3945	0.89%	620-710
40	8.506	4104	0.54%	580-710
50	7.052	4315	0.74%	580-710
60	6.768	4348	0.88%	580-690
70	6.095	4460	0.72%	580-670

Table 106.6. Viscosity (cp) from equations in tables 106.4 and 106.5

	Mol % $NaNO_2$								
T (K)	10	20	30	40	50	60	70	80	90
570									
580				2.99	2.98	2.95	2.92	2.89	(2.86)
590				2.82	2.80	2.76	2.74	2.71	(2.68)
600				2.66	2.63	2.60	2.57	2.54	(2.50)
610				2.51	2.48	2.45	2.42	2.39	(2.35)
620			2.41	2.38	2.34	2.31	2.28	2.25	(2.20)
639			2.30	2.26	2.21	2.18	2.15	2.12	(2.08)
649			2.18	2.14	2.10	2.07	2.03	2.02	
650		(2.10)	2.08	2.04	1.99	1.96	1.93	0.93	
660		(2.03)	1.99	1.94	1.89	1.86	1.83		
670		(1.95)	1.90	1.86	1.80	1.77	1.74		
680		(1.87)	1.82	1.77	1.72	1.69			
690		(1.79)	1.75	1.70	1.64	1.61			
700	(1.78)	(1.71)	1.67	1.63	1.57				
710	(1.72)	(1.64)	1.61	1.56	1.50				
720	(1.66)								
730	(1.60)								
740									

The values in ( ) are based on a minimal data set

References [19]

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [20]

Equation:

$$\kappa = a + bT + cT^2 \quad (106.5)$$

precision: in table 106.7 uncertainty: ∿ ± 3.0%

Table 106.7. Parameters of equation (106.5) and precisions

Mol % $NaNO_2$	-a	b x 10^3	c x 10^6	Precision	T range(K)
10	(1.8358)	(5.308)	(-1.250)		700-730
20	1.5901	4.400	-0.360	0.03%	660-730
25	1.6783	4.699	-0.531	0.05%	640-730
30	1.6797	4.770	-0.545	0.05%	620-730
35	1.4183	4.074	0	0.06%	600-730
40	1.4137	4.015	0.162	0.06%	580-730
45	1.3695	3.807	0.478	0.07%	580-730
50	1.8106	5.167	-0.463	0.08%	580-710
55	1.6384	4.649	0	0.05%	580-710
60	1.7987	5.139	-0.289	0.03%	580-690
65	1.8752	5.331	-0.329	0.04%	580-690
70	1.7730	5.026	0	0.04%	580-670
75	2.0842	6.177	-0.944	0.03%	580-670
80	1.7527	5.110	0	0.07%	580-650
85	1.7818	5.230	0	0.04%	580-650
90	1.7639	5.280	0	0.11%	580-630
95	2.9256	9.099	-2.983	0.02%	580-630

The values in ( ) are based on a minimal data set

Table 106.8. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 106.7

T (K)	Mol % $NaNO_2$						
	35	45	55	65	75	85	95
580		0.999	1.058	1.106	1.181	1.252	1.348
600	1.026	1.086	1.151	1.205	1.282	1.356	1.460
620	1.107	1.174	1.244	1.303	1.382	1.461	1.569
640	1.180	1.262	1.337	1.402	1.482	1.565	
660	1.270	1.350	1.430	1.500	1.581		
680	1.352	1.439	1.523	1.598			
700	1.433	1.529	1.616				
720	1.515	1.618					

References [20]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: $NaNO_2$; low; KNO_2, low; (permitted in food); there appears to be some implication of increased cancer with chronic ingestion of nitrites.

(ii) Vapor pressure: no data for this system; but see $NaNO_2$ [30] and KNO_2 [30]

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) On decomposition, nitrites emit toxic fumes (oxides of nitrogen) viz:

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \quad (106.6)$$

$$2MNO_2 + O_2 \longrightarrow 2MNO_3 \quad (106.7)$$

The subsequent decomposition reactions are complex; if the gas phase is not continuously removed, the nitrite may be oxidized to $NaNO_3$, i.e., to the nitrate.

(iii) Nitrites, like nitrates, are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon,....); aluminum alloys and bath sludges (e.g. iron oxides).

References [21-30].

7. *Corrosion*

Table 106.9. Corrosion studies from primary research literature

Studies in molten nitrates and nitrites	References
Fe	[31-33]
Fe, Co, Ni, Cr, Al,...	[34-36]
Cu, Pt, Au, W,...	[35-37]
Zn, Pb, Cu, Ni, Al	[38]
Pt, S, steel	[39]
Zr	[40]
Oxide species	[41]
Electrochemical approach	[42,43]
Thermodynamic redox diagrams	[44,45]
Annotated corrosion biblio.	[46]
Reviews/molten salts	[47-49]

No compatibility studies with $NaNO_2$-KNO_2 found; the studies in Table 106.9 (above) related principally to Na and K nitrates and their mixtures; for passivation studies in molten $NaNO_2$, see [32].

References [31-49]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [50]

Table 106.10. Volume change on melting

Binary eutectic (mol % $NaNO_2$)	$(\Delta V_f/V_s)$	Uncertainty
65	11.6%	$\sim \pm$ 15%

References [50]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

[1] Vetyukov, M. M., Sheherbinin, V. I., Jour. Appl. Chem. USSR, 36, 2314 (1963).

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1. *Melting Temperatures (T_m)*

Pure substance melting points:

KOH: 360°C

NaOH: 318°C

Eutectic melting point:

170°C, *composition:* 50.6 mol % KOH

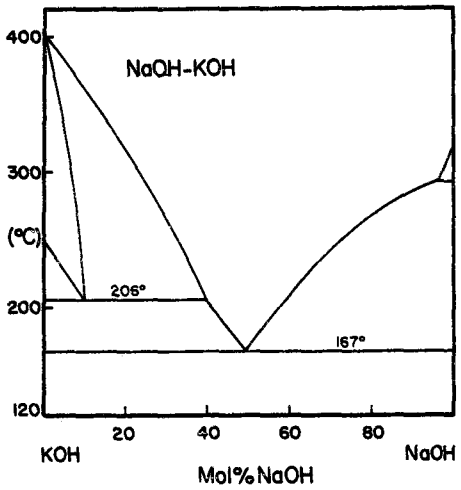

Figure 107.1 KOH-NaOH phase diagram

References [1-18]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: very caustic; attacks all body tissue.

(ii) Vapor pressure: no information for this system; but see NaOH [69] and KOH [70].

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Hydroxides react exothermically with water or steam; the aqueous solution is strongly caustic;attacks living tissue; dangerous.

References [19-24]

7. Corrosion

Table 107.1 Corrosion studies from primary research literature

Studies	References
Metals	[25]
Metals, ceramics, alloys	[25-27]
Stainless steel, Fe-Cr-Ni alloys	[33]
Ni-Cr-Fe; Ni-Si-Cu	[32,34]
Ni-Mo	[35-37]
Ni, Cu, Armco Fe	
Al_2O_3, ZrO_2	[26]
Ni	[26,27,31,35,38-41]
Ni-steels	[42]
Fe (effects of H_2O)	[43]
Pt, Ag, and alloys	[44-46]
Thermodynamic and electrochemical approach	[47-49]
Reviews (molten salts corrosion)	[50-52]
Annotated corrosion biblio.	[53]

With the exception of [41] in which compatibility with molten NaOH-KOH was investigated, LiOH, KOH, and NaOH as single hydroxides were used in the studies listed in Table 107.1 (above).

References [25-53]

8. Diffusion

Measurement method: cited in tabulations

List of diffusing species investigated in NaOH-KOH [50-50 mol %] as solvent

H_2O; Am(VI)

precision: in table 107.3 uncertainty: in table 107.2

Table 107.2. Diffusion techniques, uncertainties and species

Diffusion technique of recommended study	Uncertainty (in values of D)	Species
chronopotentiometry	$\sim \pm$ 10%	Am(VI)
	$\sim \pm$ 20%	H_2O

Equation: $D = A \exp [-E/RT]$ (107.1)

Table 107.3. Parameters of diffusion equation (107.1), precisions, and recommended study

Species	A x 10^3 (cm^2 s^{-1})	E (cal mol^{-1})	Temp. range (K)	Precision	Recommended Study
H_2O	71.95	6240	460-530	insufficient information for estimate	[54]

Table 107.4. Diffusion coefficients for H_2O in NaOH-KOH from equation (107.1)

T (K)	D x 10^5 (cm^2 s^{-1})	T (K)	D x 10^5 (cm^2 s^{-1})
460	7.8	500	13.5
470	9.0	510	15.2
680	10.4	520	17.2
490	11.9	530	19.2

D_{H_2O} values are about 10 x larger than for various ions in molten salts

Table 107.5. Diffusion coefficients for species not included in table 107.4

Species	T (K)	D x 10^5 (cm^2 s^{-1})	Recommended Study
Am(VI)	523	$\sim$ 0.65 $\pm$ 0.20	[55]

The diffusion entities of Am(VI) are uncertain; most probably AmO_2^{2+} or AmO_4^{2-}

References H_2O, [54], Am(VI), [55].

9. *Heat of Fusion* (ΔH_f°)

No data

10. *Heat Capacity* (C_p)

No data

11. *Volume Change on Melting* (ΔV_f)

No data

12. *Vapor Pressure* (p_{vap})

No data

13. *Thermal Conductivity (liquid)* (λ_ℓ)

No data

14. *Thermal Conductivity (solid)* (λ_s)

No data

15. *Cryoscopic Constant* (k_f)

No data

16. *References*

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System 108 Na_3AlF_6-Li_3AlF_6

1. *Melting Temperatures (T_m)*

Pure substance melting points:

Na_3AlF_6: 1010°C

Li_3AlF_6: 785°C

Eutectic melting point:

713°C, composition: 36 mol % Na_3AlF_6

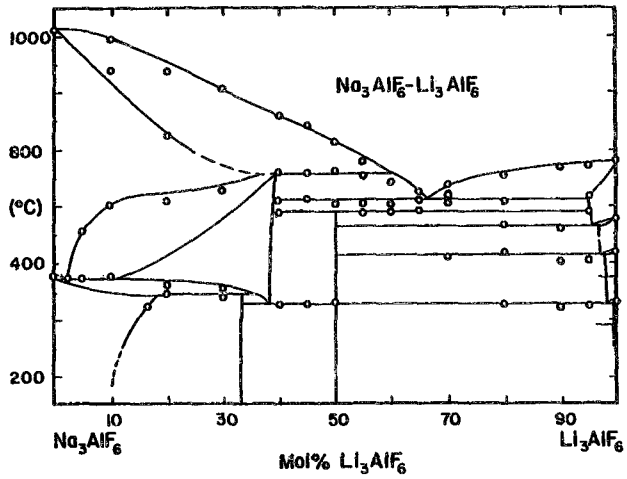

Figure 108.1. Na_3AlF_6-Li_3AlF_6 phase diagram

References [1-29]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

Measurement method: oscillational sphere [30]

Equation: (viscosity-composition isotherm @ 1273 K)

$$\eta = 2.7387 - 3.3523 \times 10^{-2}C + 2.4530 \times 10^{-4}C^2 \quad (108.1)$$

precision: ∿ ± 2.5% uncertainty: ∿ ± 2.5%

(108) Na_3AlF_6-Li_3AlF_6

Table 108.1. Viscosity (cp) at 1273K from equation (108.1)

Li_3AlF_6 (mol %)	η (cp)	Li_3AlF_6 (mol %)	η (cp)
0	2.739	60	1.610
10	2.428	70	1.594
20	2.166	80	1.627
30	1.954	90	1.709
40	1.790	100	1.839
50	1.676		

References [30,31]

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [32]

Equation:

$$\kappa = a + bT + cT^2 \quad (108.2)$$

precision: in table 108.2 uncertainty: ∿ ± 3.0%

Table 108.2. Parameters of equation (108.2) and precisions

Mol % Li_3AlF_6	-a	b x 10^2	-c x 10^6	Precision	T range(K)
20	14.083	2.442	8.679	0.2%	1220-1320
30	12.033	2.114	7.313	0.1%	1170-1320
40	13.932	2.452	8.739	0.2%	1170-1320
50	16.141	2.842	10.364	0.2%	1120-1320
60	12.346	2.273	8.184	0.3%	1120-1320
70	14.726	2.684	9.846	0.4%	1120-1320
80	7.593	1.557	5.261	0.4%	1120-1320
90	8.029	1.687	5.873	0.1%	1120-1320

(108) Na_3AlF_6-Li_3AlF_6

Table 108.3. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 108.2

T (K)	Mol % Li_3AlF_6						
	20	40	50	60	70	80	90
1120			2.69	2.84	2.98	3.25	3.50
1140			2.79	2.93	3.08	3.32	3.57
1160			2.88	3.01	3.16	3.39	3.64
1180		2.84	2.96	3.08	3.24	3.46	3.70
1200		2.91	3.04	3.14	3.30	3.52	3.76
1220	2.79	2.98	3.11	3.20	3.36	3.58	3.81
1240	2.85	3.31	3.16	3.25	3.42	3.63	3.86
1260	2.91	3.09	3.21	3.30	3.46	3.68	3.90
1280	2.95	3.04	3.26	3.34	3.50	3.72	3.94
1300	3.00	3.18	3.29	3.37	3.53	3.76	3.97
1320	3.03	3.21	3.32	3.40	3.55	3.80	4.00

References [32-38]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritants and toxic.

(ii) Vapor pressure: Na_3AlF_6 at its m.pt. (1000°C), << 0.5mm Li_3AlF_6 at its m.pt. (785°C), << 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [39-44].

(108) Na_3AlF_6-Li_3AlF_6

7. Corrosion

Table 108.4. Corrosion studies from primary research literature

	Studies	References
A	Cr	[45]
	Ni-Cr-Mo alloys (INOR -8; Hastelloys B, W, and N)	[46,47]
	SSNI-12P	[48]
	Quartz	[49]
	Al	[50]
	Various metals	[51]
B	Pt, Pt-Rh	[52-56,89,90]
	Boron nitride, carbon, Inconel	[57-59]
	Fused MgO	[60]
C	Impurities in electrolyte	[15,61]
	Graphite	[15,61]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[62-64]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[65-80,87,88]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[81-83]
	Electroanalytical studies in molten fluorides	[84]
	Annotated corrosion biblio.	[85]
	Corrosion: molten fluorides (survey)	[86]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluoride physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References 15,45-90]

(108) Na_3AlF_6-Li_3AlF_6

8. Diffusion

No data

9. Heat of Fusion (ΔH_f)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f°)

No data

12. Vapor Pressure (p_{vap})

Measurement method: boiling point technique [91]

Equation:

$$\log p = A + B/T \quad (108.3)$$

precision: in table 108.5 uncertainty: $\sim \pm 5\%$

Table 108.5. Parameters of equation (108.3) and precisions

Mol % Li_3AlF_6	A	-B	Precision	T range(K)
30.0	8.5800	9884	*	1220-1470
48.2	8.5031	9658	*	1220-1470
72.0	8.5590	9766	*	1220-1470

*data reported in equation form; insufficient information for precision estimates

Table 108.6. Vapor pressure (mm) from equations in table 108.5

	Mol % Li_3AlF_6		
T (K)	30.0	48.2	72.0
1200	3.009	3.860	3.582
1260	5.439	6.885	6.430
1300	9.483	11.85	11.14
1340	15.99	19.75	18.66
1380	26.16	31.95	30.35
1420	41.63	50.30	48.03
1460	64.59	77.26	74.12
1470	71.81	85.69	82.31

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(108) Na_3AlF_6-Li_3AlF_6

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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1. *Melting Temperature (T_m)*

Pure substance melting points:

LiF: 848°C
LiOH: 462°C

Eutectic melting point:

430°C, composition: 80 mol % LiOH

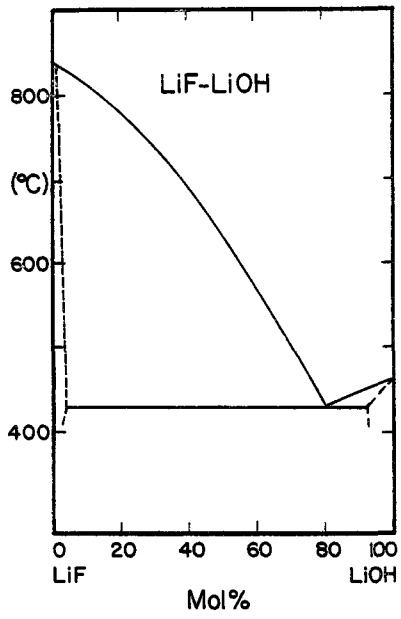

Figure 109.1. LiF-LiOH phase diagram

References [1-15]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: LiF, severe; LiOH, very caustic and toxic.

(ii) Vapor pressure: LiF at m.pt. (848°C), $\sim 8.8 \times 10^{-3}$mm; LiOH at m.pt. (460°C) << 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosion": i.e., explosive generating of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

(iii) Hydroxides, react with water or steam with evolution of heat; the aqueous solution is very caustic and attacks living tissue; dangerous.

References [16-21]

7. Corrosion

Table 109.1. Corrosion studies from primary research literature

Studies	References
Cr	[22]
Ni-Cr-Fe (INOR-8 s-s, Hastelloy s-s)	[23-28]
Al	[29]
Cb-Zr	[30,31]
Ta-W-Zr-Cb, Ta-W-Cb	[31]
Electrochemical behavior of oxide ions in molten fluorides	[32-34]
Ni, Cu, Armco Fe	[35-37]
Fe, effects of H_2O	[38]
Pt, Ag, and alloys	[39-41]
Thermodynamics of corrosion	[42-44]
Corrosion - annotated biblio.	[45]
Electrochemical aspects	[46]
Reviews: corrosion - molten salts	[47-49]

References [22-49]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

Measurement method: calculated [50]

Table 109.2. Heat of fusion

Composition (mol % LiF)	T_m (°C)	ΔH_f° (kcal mol^{-1})	Uncertainty
18.7	426°	5.0	∿ ± 5%

References [50]

10. Heat Capacity (C_p)

Measurement method: calculated [51]

Table 109.3. Heat capacity

Composition LIF:LiOH(mol %)	C_p (cal K^{-1} mol^{-1})	T range (K)	Uncertainty
18.7:81.3	5.83	T_m(672) - 773	∿ ± 10%

For the above composition, $C_{p(s)}$ = 5.10 (cal K^{-1} mol^{-1}), uncertainty of estimate, ∿ ± 10%.

References [51]

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

Measurement method: calculated from ΔH_f° [52]

Table 109.4. Cryoscopic constant

Binary eutectic (Mol % LiF)	k_f (K mol^{-1} kg)	Uncertainty
18.7	4.7	$\sim \pm$ 1%

References [52]

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System 110 LiCl-LiOH

1. *Melting Temperatures (T_m)*

Pure substance melting points:

LiCl: 610°C

LiOH: 462°C

Eutectic melting point:

composition: E_1: 274°C, composition: 34.5 mol % LiCl

E_2: 268°C, composition: 42 % LiCl

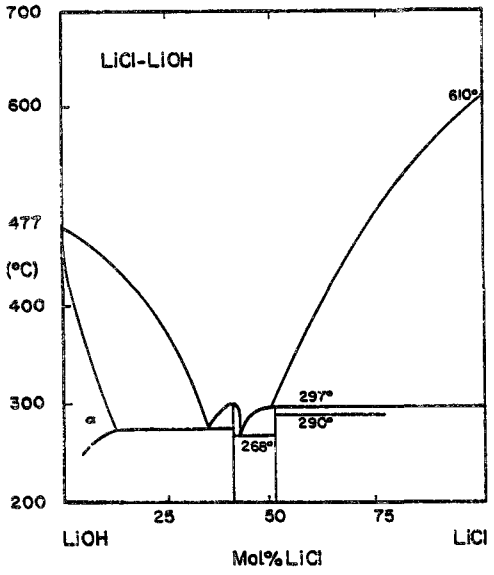

Figure 110.1 LiCl-LiOH phase diagram

References [1-18]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: LiCl, slight; LiOH, very caustic and toxic.

(ii) Vapor pressure: no information for this system;

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic chloride fumes when heated to decomposition, or contacted with acids.

(iii) Hydroxides react with water or steam with evolution of heat; the aqueous solution is very caustic and attacks living tissue; dangerous.

References [19-25]

7. Corrosion

Table 110.1 Corrosion studies from primary research literature

	Studies	References
A	Mg, Ni, Zr, Ti	[26]
	Ti, Zr, Hf, $ThCl_4$	[27]
	Armco Fe	[28,29]
	Solubility of metal oxides (Ni, Ca, Zn, Mg)	[26,30]
B	Ni Cu Armco Fe, Steel	[31-33]
	Fe, effects of H_2O	[34]
	Pt, Ag, and alloys	[35-37]
C	Thermodynamics of corrosion	[26,38,39]
	Corrosion - annotated biblio.	[40]
	Electrochemical aspects	[41]
	Reviews: corrosion - molten salts	[42-44]

Compatibility studies: A, molten LiCl; B, molten LiOH; and C, general and review studies. No studies with molten mixtures of LiOH-LiCl were found.

References [26-44]

8. *Diffusion*

No data

9. *Heat of Fusion* (ΔH_f°)

No data

10. *Heat Capacity* (C_p)

No data

11. *Volume Change on Melting* (ΔV_f)

No data

12. *Vapor Pressure* (p_{vap})

No data

13. *Thermal Conductivity (liquid)* (λ_ℓ)

Measurement method: comparative technique; flat slab [45]

Composition: LiOH:LiCl::63:37 (mol %)

$$\lambda = 6.1264 \times 10^{-4} + 1.9100 \times 10^{-6} T \quad (110.1)$$

precision: insufficient data for estimate uncertainty: ∿ ± 15%

Table 110.2. Thermal conductivity of melt from equation (110.1)

T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})	T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})
550	16.6	610	17.8
560	16.8	620	18.0
570	17.0	630	18.2
580	17.2	640	18.3
590	17.4	650	18.5
600	17.6		

The preceding are for mixtures from reagent grade quality LiOH and and LiCl. With commercial grade chemicals, the thermal conductivity for this molten mixture over the same temperature range may be expressed by:

$$\lambda = 5.1625 \times 10^{-4} + 2.0300 \times 10^{-6} T \quad (110.2)$$

The values of λ for mixtures from reagent grade and commercial grades LiOH and LiCl are in close accord (∿ ± 1%). The data set was insufficient for precision estimates; the uncertainty limits are established to be ∿ ± 15%.

References [45,46]

(110) LiCl-LiOH

14. Thermal Conductivity (solid) (λ_s)

Measurement method: comparative technique; flat slab [45]

Composition: LiOH:LiCl::63:37 (mol %)

$$\lambda = 3.7282 \times 10^{-3} - 1.7220 \times 10^{-6} T \quad (110.3)$$

precision: ∿ ± 1.0% uncertainty: ∿ ± 15%

Table 110.3. Thermal conductivity of melt from equation (110.3)

T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})	T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})
320	31.8	440	29.7
340	31.4	460	29.4
360	31.1	480	29.0
380	30.7	500	28.7
400	30.4	520	28.3
420	30.0		

The preceding are for mixtures of reagent grade quality LiOH and LiCl; with commencial grade chemicals, the λ values were found to be uniformly somewhat smaller (∿ 2-5%); the thermal conductivity equation over the same temperature range is:

$$\lambda = 3.6455 \times 10^{-3} - 1.6660 \times 10^{-6} T \quad (110.4)$$

The data set was insufficient for precision estimates; the uncertainty limits are estimated to be ∿ ± 15%.

References [45]

15. Cryoscopic Constant (k_f)

No data

16. References

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System 111 $LiCl-LiNO_3$

1. *Melting Temperatues (T_m)*

Pure substance melting points:

$LiCl$: 610°C

$LiNO_3$: 253°C

Eutectic melting point:

244°C, composition: 87.5 mol % $LiNO_3$

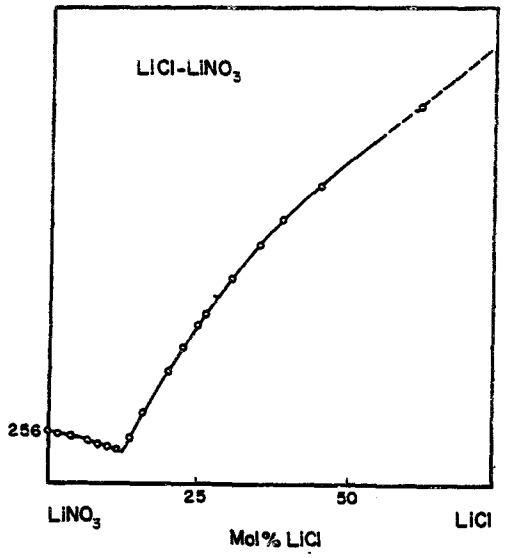

Figure 111.1. $LiCl-LiNO_3$ phase diagram

References [1-16].

2. *Density (ρ)*

Measurement method: Archimedean technique [17]

Equation:

$$\rho = a + bT \quad (111.1)$$

precision: in table 111.1 uncertainty: ∿ ± 1.0%

Table 111.1. Parameters of equation (111.1) and precisions

Mol % $LiNO_3$	a	$-b \times 10^4$	Precision	T range(K)
70.0	2.0322	5.241	0.01%	650-770
79.9	2.0499	5.380	0.01%	610-770
90.0	2.0575	5.366	0.01%	550-600

Table 111.2. Density (g cm^{-3}) from equations in table 111.1

T (K)	Mol % $LiNO_3$		
	70.0	79.0	90.0
550			1.7623
580			1.7462
610		1.7218	1.7301
640		1.7056	1.7140
670	1.6811	1.6895	1.6979
700	1.6653	1.6734	1.6818
730	1.6496	1.6572	
760	1.6339	1.6411	

References [17]

3. *Surface Tension. (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: LiCl, slight, $LiNO_3$, moderate

(ii) Vapor pressure: LiCl at m.pt. (625°C) ∿ 0.25mm, $LiNO_3$ decomposes with heating to the nitrite and oxygen; decomposition onsets just above m.pt. (235°C).

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic chloride fumes when heated to decomposition, or contacted with acids.

(iii) On decomposition, nitrates emit toxic fumes (oxides of nitrogen) viz:

$$MNO_3 \longrightarrow MNO_2 + \tfrac{1}{2}O_2 \qquad (111.2)$$

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \qquad (111.3)$$

The subsequent decomposition reactions are complex; if the gas phase is continuously removed, the nitrite decomposition (above) to NO and NO_2 is dominant. If the gas phase is not immediately removed, the NO may re-oxidize the nitrite to nitrate.

(iv) Nitrates are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds oils; carbon;...); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous.

References [18-24]

7. Corrosion

Table III.3. Corrosion studies from primary research literature

	Studies	References
A	Mg, Ni, Zr, Ti	[25]
	Ti, Zr, Hf, $ThCl_4$	[26]
	Armco Fe	[27-29]
	Solubility of metal oxides (Ni, Ca, Zn, Mg)	[30,31]
B	Fe	[32]
	Cu	[33]
C	Thermodynamic approach	[34,35]
	Electrochemical approach	[31,36]
	Annotated corrosion biblio.	[37]
	Reviews, corrosion	[38-40]

Compatibilty studies: A: LiCl; B: $LiNO_3$; C: basic principles, reviews. No compatibility studies with molten $LiCl-LiNO_3$ were found; for $LiCl-NaNO_3$, see [29].

References [25-40]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

(111) $LiCl-LiNO_3$

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [41]

Table 111.3. Volume change on melting

Binary eutectic (mol % LiCl)	$(\Delta V_f/V_s)$	Uncertainty
12.5	28%	$\sim \pm$ 10%

References [41]

12.. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 112 $LiCl-Li_2CO_3$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$LiCl$: 610°C

Li_2CO_3: 723°C

Eutectic melting point:

506°C, composition: 75.6 mol % $LiCl$; [60 equiv. % Li_2Cl_2]

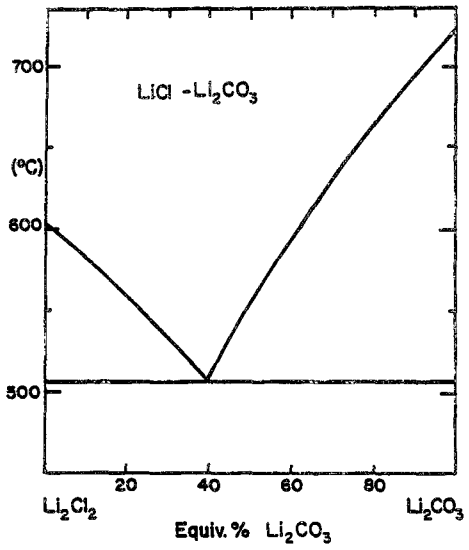

Figure 112.1. $LiCl-Li_2CO_3$ phase diagram

References [1-16]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

(112) $LiCl-Li_2CO_3$

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: LiCl, slight; Li_2CO_3, very toxic; lethal dose (oral), 0.7 mg/kg.

(ii) Vapor pressure: LiCl at m.pt. (610°C), ∿ 0.25mm; Li_2CO_3 (m.pt. 723°C), dissociates on heating to the oxide and CO_2; CO_2 pressure at 730°C, ∿ 10mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic chloride fumes when heated to decomposition, or contacted with acids.

(iii) Carbonates, when heated with CO_2 pressures less than equilibrium dissociation pressures, decompose to form alkali metal oxides; the toxicology and disaster hazards are the same as those of very caustic solutions, i.e. react with water or steam (exothermic) to form solutions that are markedly aggressive to all body tissues (chemical burns). Lithium carbonate itself is classified as a strong caustic.

References [17-22]

(112) $LiCl-Li_2CO_3$

7. Corrosion

Table 112.1. Corrosion studies from primary research literature

	Studies	References
A	Mg, Ni, Zr, Ti	[23]
	Ti, Zr, Hf, $ThCl_4$	[24]
	Armco Fe	[25,26]
	Solubility of metal oxides	[23,27]
	Thermodynamic principles	[23,28,29]
	Electrochemical principles	[30]
	Reviews, annotated biblio.	[31-34]
B	Ti alloys	[35]
	Au, Pt, Ag, Ni, Au-Pd, BN MgO, Co	[36-39]
	Metals, alloys	[40]
	Pt, Pd, Rh, Ir (O_2 environment)	[41]
	Pt, Ag, Ni, (Li_2CO_3, Li_2O)	[42-45]
	Ag, Pt, Ni, quartz, porcelain (Li_2CO_3, Li_2O)	[46]
	Acid-base relationships	[47-51]
	Hydrolysis reactions	[42,49,51,52]
	Corrosion biblio.	[53]
	Molten carbonates in: fuel cells, thermal energy storage, and gasification, stack gas scrubbing	[54-59]

Compatibilty studies: A: molten chlorides, principally LiCl; B: molten carbonates, principally Li_2CO_3. No compatibility studies found specifically for molten $LiCl-Li_2CO_3$ mixtures.

References [23-59]

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

10. Heat Capacity (C_p)

No data

(112) $LiCl-Li_2CO_3$

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 113 $NaCl-Na_2CO_3$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$NaCl$: 800°C

Na_2CO_3: 858°C

Eutectic melting point:

634°C, composition: 76.9 mol % NaCl

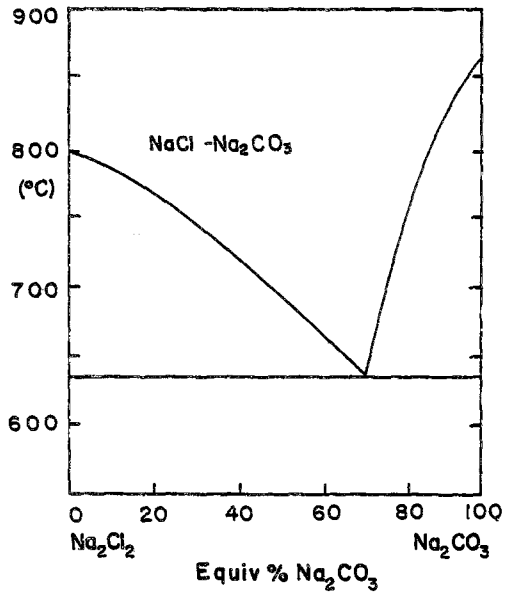

Figure 113.1. $NaCl-Na_2CO_3$ phase diagram

References [1-17]

2. *Density (ρ)*

Measurement method: Archimedean technique [18]

Equation:

$$\rho = a + bT \quad (113.1)$$

precision: in table 113.1 uncertainty: ∿ ± 2.5%

Table 113.1. Parameters of equation (113.1) and precisions

Mol % NaCl	a	$-b \times 10^4$	Precision	T range(K)
16.77	2.3645	3.800	0.01%	1100-1150
31.19	2.2831	3.440	0.01%	1070-1150
43.73	2.2172	3.286	0.01%	1000-1150
54.73	2.1485	3.085	0.03%	1000-1150
59.74	2.1823	3.571	0.04%	1000-1150
64.46	2.2411	4.367	0.06%	970-1150
68.91	2.2051	4.228	0.02%	1000-1150
73.12	2.1209	3.679	0.07%	1050-1150
80.88	2.0025	2.999	0.09%	1100-1150
87.88	2.2168	5.198	0.00%	1100-1150
100.00	1.8564	3.202	0.08%	1100-1150

Table 113.2. Density (g cm^{-3}) from equations in table 113.1

T (K)	Mol % NaCl						
	16.77	43.73	59.74	64.46	68.91	73.12	87.88
970				1.818			
980				1.813			
990				1.809			
1000		1.889	1.825	1.804	1.782		
1010		1.885	1.822	1.800	1.778		
1020		1.882	1.818	1.796	1.774		
1030		1.879	1.814	1.791	1.770		
1040		1.875	1.811	1.787	1.765		
1050		1.872	1.807	1.783	1.761	1.735	
1060		1.869	1.804	1.778	1.757	1.731	
1070		1.866	1.800	1.774	1.753	1.727	
1080		1.862	1.797	1.769	1.748	1.724	
1090		1.859	1.793	1.765	1.744	1.720	
1100	1.947	1.856	1.789	1.761	1.740	1.716	1.645
1110	1.943	1.852	1.786	1.756	1.736	1.713	1.640
1120	1.939	1.849	1.782	1.752	1.732	1.709	1.635
1130	1.935	1.846	1.779	1.748	1.727	1.705	1.629
1140	1.931	1.843	1.775	1.743	1.723	1.701	1.624
1150	1.928	1.839	1.772	1.739	1.719	1.698	1.619

References [18]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [18]

Equation:

$$\kappa = a + bT + cT^2 \qquad (113.2)$$

precision: in table 113.3 uncertainty: $\sim \pm 5.0\%$

Table 113.3. Parameters of equation (113.2) and precisions

Mol % NaCl	-a	b x 10^2	-c x 10^5	Precision	T range(K)
66.6	18.600	3.4876	1.3980	4.32%	930-1310
80	9.413	1.813	0.623	7.43%	970-1330

Table 113.4. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 113.3

T (K)	Mol % NaCl	
	66.6	80
930	1.744	
970	2.077	2.313
1010	2.365	2.545
1050	2.608	2.757
1090	2.806	2.949
1130	2.960	3.121
1170	3.069	3.273
1210	3.133	3.405
1250	3.152	3.518
1290	3.127	3.610
1330		3.682

References [18]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: NaCl, very low; Na_2CO_3, moderate.

(ii) Vapor pressure: no information for this system, but see NaCl [21] and Na_2CO_3 [21]

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) When bulk NaCl is heated at high temperatures, vapor is evolved which is particularly irritating to the eyes; when heated to decomposition or contacted with acids, highly toxic chloride fumes are evolved.

When heated with CO_2 pressures less than equilibrium dissociation pressures, decomposes to form alkali metal oxides; the toxicology and disaster hazards are the same as those of very caustic solutions, i.e., react with water or steam (exothermic) to form solutions that are remarkedly aggressive to all body tissues (chemical burns).

References [19-24].

7. Corrosion

Table 113.5. Corrosion studies from primary research literature

	Systems, Studies, [References]
A	Mo [25], Armco Fe [26-28], Ni, Cr [29], Ti, Zr, Hf, $ThCl_4$ [30,31], Cr [32,33], Fe-Cr [33], Ni alloys [31,34], Au, Pt, Al_2O_3, MgO, Zirconia (NaCl with Na_2O) [35], thermodynamic redox potentials [31,36,37], electrochemical aspects [38,39], annotated corrosion biblio. [40], reviews [41-43].
B	Si [44], Pt [45], Metals [46], Cu-Zn [47], Pt, Au, Ag, MgO [48-51], Pt, Rh, Pd, Ir (O_2 environment) [52], Au, Ag, Al_2O_3 (N_2 atmosphere; Na_2CO_3-Na_2O) [53-55], quartz, Porcelain, Ag, Pt, Ni (N_2 atmosphere; Na_2CO_3-Na_2O) [56], boron nitride [51,57], β-alumina [57], Fe (Na_2CO_3-Na halides) [58], acid-base relationships [59-62], H_2O hydrolysis reactions [63-65], molten carbonates: fuel cells, thermal energy storage, coal gasification [26,57,58,66-70]

Compatibility studies: A: principally in molten NaCl; B: principally in molten Na_2CO_3. No data found for $NaCl-Na_2CO_3$ mixtures.

References [25-70]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 114 K_2CO_3-NaCl

1. *Melting Temperatures (T_m)*

Pure substance melting points:

NaCl: 800°C

K_2CO_3: 898°C

Minimum melting mixtures

574°C, composition: 28 equiv. % $(NaCl)_2$

576°C, composition: 67.5 equiv. % $(NaCl)_2$

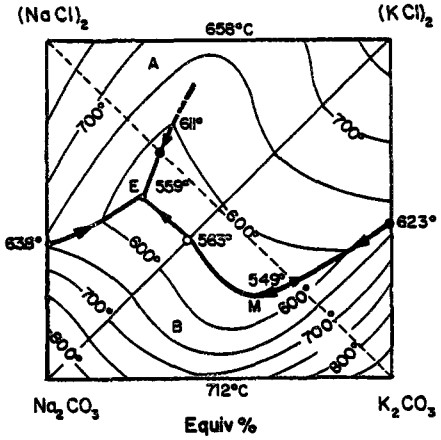

Figure 113.1. K_2CO_3-$(NaCl)_2$ phase diagram

References [1-17].

2. *Density (ρ)*

Measurement method: Archimedean technique [18]

Equation:

$$\rho = a + bT \quad (114.1)$$

precision: in table 114.1 uncertainty: ∿ ± 1.5%

Table 114.1. Parameters of equation (114.1) and precisions

Mol % NaCl	a	$-b \times 10^4$	Precision	T range(K)
37.16	2.3815	4.800	0.19%	1000-1100
50.34	2.3094	4.531	0.04%	920-1150
61.19	2.2292	4.233	0.02%	920-1150
65.93	2.0997	3.166	0.05%	920-1150
70.28	2.1813	4.152	0.11%	920-1150
74.30	2.2026	4.577	0.09%	920-1150
78.01	2.1911	4.601	0.11%	920-1150
84.66	2.1099	4.266	0.02%	950-1150
90.44	2.1786	5.128	0.02%	1000-1150

Table 114.2. Density (g cm^{-3}) from equations in table 114.1

T (K)	Mol % NaCl						
	37.16	61.19	65.93	70.28	74.30	84.66	90.44
920		1.840	1.808	1.799	1.781		
940		1.831	1.802	1.791	1.772		
960		1.823	1.796	1.783	1.763	1.700	
980		1.814	1.789	1.774	1.754	1.692	
1000	1.902	1.806	1.783	1.766	1.744	1.683	1.666
1020	1.892	1.797	1.777	1.758	1.736	1.675	1.656
1040	1.882	1.789	1.770	1.750	1.727	1.666	1.645
1060	1.873	1.781	1.764	1.741	1.718	1.658	1.635
1080	1.863	1.772	1.758	1.733	1.708	1.649	1.625
1100	1.854	1.764	1.751	1.725	1.699	1.641	1.615
1120		1.755	1.745	1.716	1.690	1.632	1.604
1140		1.747	1.739	1.708	1.680	1.624	1.594

References [18]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: NaCl, permitted in foods; K_2CO_3, classified as strongly caustic.

(ii) Vapor pressure: NaCl at m.pt. (800°C), $\sim$ 0.34mm; K_2CO_3 decomposes on heating to the oxide and oxygen; CO_2 pressure at 1050°C, $\sim$ 1mm.

B. Disaster hazards

(i) Molten salt bath "explosions"; i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides, when heated to decomposition or contacted with acids, highly toxic chloride fumes are evolved.

(iii) Carbonates, when heated with CO_2 pressures less than equilibrium dissociation pressures, decompose to form alkali metal oxides; the toxicology and disaster hazards are the same as those of very caustic solutions, i.e. react with water or steam (exothermic) to form solutions that are markedly aggressive to all body tissues (chemical burns). Potassium carbonate itself is classified as a strong caustic.

References [19-24].

7. Corrosion

Table 114.3. Corrosion studies from primary research literature

	Studies	References
A	Stainless steel	[25]
	Acid-base relationships in molten carbonates	[26-29]
	Hydrolysis (H_2O) reactions	[30-32]
	Corrosion in molten salts (annotated biblio.)	[33]
	Molten carbonates: fuel cells, thermal energy storage, coal gasification, stack gases	[25,34-38]
B	Mo	[39]
	Armco Fe	[40-42]
	Ni, Cr	[43]
	Ti, Zr, Hf, $ThCl_4$	[44]
	Cr	[45]
	Fe-Cr	[46]
	Ni alloys	[47,48]
	Au, Pt, Al_2O_3, MgO, Zirconia (NaCl with Na_2O)	[49]
	Thermodynamic redox potentials	[47,52,53]
	Electrochemical aspects	[50,51]
	Annotated corrosion biblio.	[33]
	Reviews	[54-56]
C	Electrochemical aspects	[51]
	Thermodynamic approach	[48,52,53]
	Corrosion reviews	[33]
	Corrosion biblio.	[54-56]

Compatibility studies: A: various molten carbonates, principally K_2CO_3; B: various molten chlorides, principally NaCl; C: general surveys, reviews and biblios. No compatibility studies specifically for K_2CO_3-NaCl mixtures found.

References [25-56]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity

No data

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [57]

Table 114.4. Volume change on melting

Composition (mol % NaCl)	$(\Delta V_f/V_s)$	Uncertainty
28 (a)	2.0%	$\sim \pm$ 10%
68 (a)	15.8%	$\sim \pm$ 10%

(a) binary eutectic mixtures

References [57]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 115 NaCl-NaOH

1. *Melting Temperatures (T_m)*

Pure substance melting points:

NaCl: 800°C
NaOH: 318°C

Eutectic melting point:

314°C, composition: 93.7 mol % NaOH

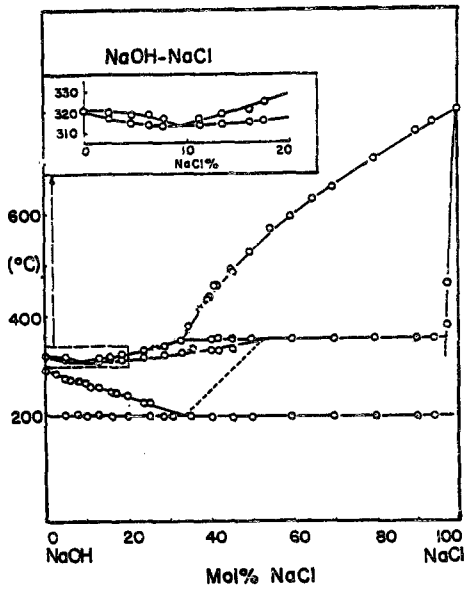

Figure 115.1. NaCl-NaOH phase diagram

References [1-16].

2. *Density (ρ)*

Measurement method: Archimedean technique [17]

Equation: (density-composition isotherm)

$$\rho = a + bC \quad (115.1)$$

(C = mol % NaCl)

precision: in table 115.1 uncertainty: ∿ ± 1.5%

Table 115.1. Parameters of equation (115.1) and precision

T (K)	a	b x 10^3	Precision
693	1.737	0.00	*

*not estimated; insufficient data

Table 115.2. Density for composition isotherm at 693K from equation in table 115.1

Mol % NaCl	ρ (g cm^{-3})	Mol % NaCl	ρ (g cm^{-3})
0	1.737	14	1.737
7	1.737	21	1.737

References [17]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

Measurement method: oscillating sphere technique [17]

Equation: (viscosity-composition isotherm)

$$\eta = a + bC + cC^2 \quad (115.2)$$

(C = mol % NaCl)

precision: in table 115.3 uncertainty: ∿ ± 5.0%

Table 115.3. Parameters of equation (115.2) and precision

T (K)	a	b x 10^3	c x 10^5	Precision
693	2.2970	27.617	-27.830	0.34%

Table 115.4. Viscosity (cp) at 639K from equation in table 115.3

NaCl (mol %)	η (cp)	NaCl (mol %)	η (cp)
0	2.30	12.5	2.60
2.5	2.36	15.0	2.65
5.0	2.43	17.5	2.70
7.5	2.49	20.0	2.74
10.0	2.55	22.5	2.78

References [17]

5. *Electrical Conductance (κ)*

No data

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: NaCl, permitted in foods; NaOH, very caustic and toxic.

(ii) Vapor pressure: NaCl, at m.pt. (800°C), ∿ 0.34mm; NaOH, at m.pt. (460°C), << 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides, when heated to decomposition or contacted with acids, highly toxic chloride fumes are evolved.

(iii) Dangerous; reacts with water or steam with evolution of heat; the aqueous solution is very strongly caustic; attacks living tissue.

References [18-23]

7. Corrosion

Table 115.5. Corrosion studies from primary research literature

	Systems, Studies, [References]
A	Metals [24], metals, ceramics, alloys [24-31], stainless steel [32], Ni-Cr-Fe, Ni-Si-Cu [28,33], Ni-Mo, Ni, Cu, Armco Fe [34-36], Al_2O_3, ZrO_2 [27], Ni [25-27,34,37-40], Ni-steels [41], Fe (effects of H_2O) [42], Pt, Ag, alloys [43-45], thermodynamic and electrochemical approach [46-48], reviews [49-51], annotated corrosion biblio. [52].
B	Mo [53], Armco Fe [54-56], Ni, Cr [57], Ti, Zr, Hf, $ThCl_4$ [58], Cr [59], Fe-Cr [60], Ni alloys [61], Au, Pt, Al_2O_3, MgO, Zirconia (NaCl with Na_2O) [62], thermodynamic redox potential [48,63,64], electrochemical aspects [46,47], annotated corrosion biblio. [52], reviews [49-51].

Compatibility studies: A: principally molten NaOH; B: principally molten NaCl. No data found for molten NaOH-NaCl mixtures.

References [24-64]

8. Diffusion

No data

9. *Heat of Fusion* (ΔH°_{f})

No data

10. *Heat Capacity* (C_p)

No data

11. *Volume Change on Melting* (ΔV_f)

No data

12. *Vapor Pressure* (p_{vap})

No data

13. *Thermal Conductivity (liquid)* (λ_{ℓ})

No data

14. *Thermal Conductivity (solid)* (λ_s)

No data

15. *Cryoscopic Constant* (k_f)

No data

16. *References*

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System 116 $NaCl-NaNO_3$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$NaCl$: 800°C

$NaNO_3$: 307°C

Eutectic melting point:

297°C, composition: 95 mol % $NaNO_3$

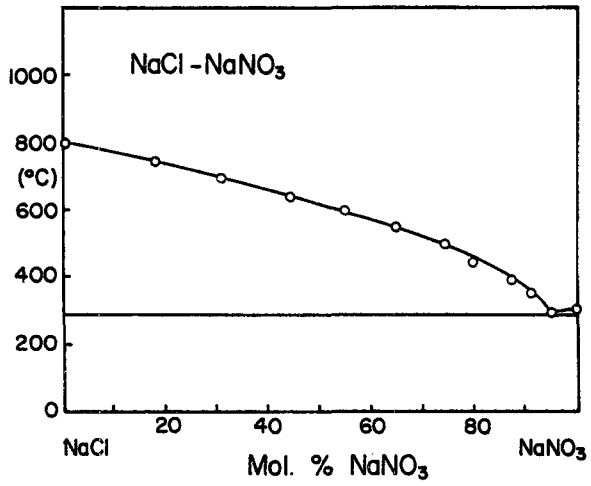

Figure 116.1. $NaCl-NaNO_3$ phase diagram

References [1-18].

2. *Density (ρ)*

Measurement method: Archimedean technique [19]

Equation:

$$\rho = a + bT \quad (116.1)$$

precision: in table 116.1 uncertainty: ∿ ± 1.0%

Table 116.1. Parameters of equation (116.1) and precisions

Mol % NaCl	a	$-b \times 10^4$	Precision	T range(K)
0	2.3389	7.360	0.02%	600-720
0.97	2.3156	7.017	0.01%	600-720
2.00	2.3331	7.292	0.02%	600-720
3.09	2.3240	7.154	0.03%	600-720
4.00	2.3405	7.418	0.01%	600-720
5.00	2.3330	7.303	0.01%	600-720
6.00	2.3313	7.257	0.02%	600-720
6.98	2.3368	7.384	0.01%	600-720
8.00	2.3333	7.348	0.02%	600-720
9.90	2.3277	7.258	0.02%	600-720
11.92	2.3352	7.361	0.01%	650-720
13.90	2.3207	7.200	0.01%	670-720

Table 116.2. Density (g cm^{-3}) from equations in table 116.1

T (K)	Mol % NaCl					
	0.97	3.09	5.00	6.98	9.90	13.90
600	1.895	1.895	1.895	1.895	1.892	
610	1.888	1.888	1.888	1.886	1.885	
620	1.880	1.880	1.889	1.879	1.878	
630	1.874	1.873	1.873	1.872	1.870	
640	1.867	1.866	1.866	1.864	1.863	
650	1.860	1.859	1.858	1.857	1.856	
660	1.852	1.852	1.851	1.850	1.849	
670	1.845	1.845	1.844	1.842	1.841	1.838
680	1.838	1.838	1.836	1.835	1.834	1.831
690	1.831	1.839	1.829	1.827	1.827	1.824
700	1.824	1.823	1.922	1.820	1.819	1.817
710	1.817	1.816	1.815	1.813	1.812	1.809
720	1.810	1.809	1.807	1.805	1.805	1.802

References [19]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

Measurement method: oscillating body [19]

Equation:

$$\eta = a + bT + cT^2 \quad (116.2)$$

precision: in table 116.3 uncertainty: $\sim$ ± 10%

Table 116.3. Parameters of equation (116.2) and precisions

NaCl (mol %)	a	$-b \times 10^2$	$c \times 10^5$	Precision	T range(K)
2	28.173	6.917	4.51	1.00%	580-720
4	29.517	7.341	4.87	0.86%	580-720
6	41.733	10.895	7.47	2.65%	580-720
8	48.867	13.047	9.08	1.83%	600-720
10	79.1414	21.929	15.57	4.26%	620-720
12	146.176	40.226	28.00	3.74%	650-720
14	65.613	17.747	12.41	1.02%	670-720

Table 116.4. Viscosity (cp) from equations in table 116.3

T (K)	Mol % NaCl						
	2	4	6	8	10	12	14
580	3.228	3.330	3.674				
590	3.064	3.166	3.458				
600	2.909	3.012	3.258				
610	2.763	2.868	3.072				
620	2.626	2.733	2.901	2.879	3.030		
630	2.498	2.608	2.746	2.709	2.783		
640	2.379	2.492	2.605	2.558	2.567		
650	2.269	2.387	2.479	2.425	2.383	3.007	
660	2.168	2.291	2.368	2.309	2.230	2.652	
670	2.076	2.205	2.272	2.212	2.107	2.354	2.415
680	1.994	2.128	2.191	2.133	2.016	2.111	2.315
690	1.920	2.062	2.125	2.073	1.956	1.925	2.241
700	1.855	2.005	2.074	2.030	1.928	1.794	2.191
710	1.799	1.958	2.038	2.006	1.930	1.719	2.166
720	1.753	1.920	2.017	1.999	1.963	1.701	2.166

References [19]

5. *Electrical Conductance* (κ)

Measurement method: classical ac technique [19]

Equation:

$$\kappa = a + bT + cT^2 \quad [116.3)$$

precision: in table 116.5 uncertainty: $\sim \pm$ 3.0%

Table 116.5. Parameters of equation (116.3) and precisions

Mol % NaCl	-a	b x 10^2	-c x 10^6	Precision	T range(K)
1.07	4.4397	1.3524	7.167	0.17%	600-720
2.07	4.1582	1.2430	6.164	0.34%	600-720
3.10	5.7807	0.7713	10.400	0.20%	600-720
3.96	2.4414	0.7143	2.099	0.74%	600-720
4.34	5.4532	1.6567	9.441	0.32%	600-720
5.15	4.7768	1.4479	7.814	0.32%	600-720
5.96	3.8245	1.1125	4.968	0.31%	600-720
7.05	5.9910	1.7152	9.972	0.40%	600-720
8.01	5.8169	1.7317	9.776	0.40%	600-720
9.20	4.2843	1.2616	6.222	0.46%	600-720
9.97	4.4719	1.3189	6.611	0.18%	610-720
11.00	6.1456	1.7816	9.801	0.25%	640-720
13.20	10.3688	3.0168	18.828	0.23%	670-720

Table 116.6. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 116.5

T (K)	Mol % NaCl						
	1.07	2.07	3.96	5.15	8.01	11.00	13.20
600	1.095	1.081	1.089	1.098	1.054		
610	1.143	1.131	1.135	1.148	1.109		
620	1.190	1.179	1.180	1.197	1.162		
630	1.236	1.227	1.225	1.244	1.213		
640	1.280	1.262	1.270	1.289	1.262		
650	1.323	1.317	1.315	1.333	1.309	1.294	
660	1.364	1.361	1.358	1.376	1.354	1.344	
670	1.404	1.403	1.402	1.417	1.397	1.392	1.392
680	1.443	1.444	1.445	1.456	1.438	1.438	1.440
690	1.480	1.484	1.488	1.494	1.477	1.482	1.483
700	1.515	1.523	1.530	1.530	1.515	1.523	1.523
710	1.550	1.560	1.572	1.564	1.550	1.563	1.560
720	1.582	1.596	1.613	1.597	1.583	1.601	1.592

References [19]

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: NaCl, $NaNO_3$; permitted as food additives.

(ii) Vapor pressure: NaCl at m.pt. (800°C), ∿ 0.34mm; $NaNO_3$ (m.pt. 335°C) decomposes on heating to the nitrite and oxygen; decomposition onsets ∿ 500°C.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Inorganic chlorides, when heated to decomposition or contacted with acids, highly toxic chloride fumes are evolved.

(iii) On decomposition, nitrates emit toxic fumes (oxides of nitrogen)viz:

$$2MNO_3 \longrightarrow 2MNO_2 + O_2 \qquad (116.4)$$

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \qquad (116.5)$$

The subsequent decomposition reactions are complex; if the gas phase is continuously removed, the nitrite decomposition (above) to NO and NO_2 is dominant.

(iv) Nitrates are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon,...); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous.

References [20-26]

7. Corrosion

Table 116.7. Corrosion studies from primary research literature

	Studies	References
A	Mo	[27]
	Armco Fe	[28-30,53]
	NiCr	[31]
	Ti, Zr, Hf, $ThCl_4$	[32]
	Cr	[33]
	Cr, Fe-Cr	[34]
	Ni alloys	[35]
	Ni-Cr-Al, Ni-Cr-W-Fe, Ni-Cr Mg, Ni, Zr, Ti	[36]
	Au, Pt, MgO, Al_2O_3, Zirconia [NaCl with added Na_2O]	[37]
B	Fe	[38-40]
	Fe, Co, Ni	[41]
	Cu	[42]
	Pt, S, steel	[43]
	Oxide species	[44]
C	Electrochemical approach	[45,46]
	Thermodynamic redox diagrams	[47,48]
	Annotated corrosion biblio.	[49]
	Reviews/molten salts	[50-52]

Compatibility studies: A: molten NaCl, B: molten $NaNO_3$, C: basic principles, surveys, reviews. No compatibility studies for $NaCl-NaNO_3$ found; for $NaCl-KNO_3$, see [53]

References [27-53]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

(116) $NaCl-NaNO_3$

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [54]

Table 116.8. Volume change on melting

Binary eutectic (mol % NaCl)	$(\Delta V_f/V_s)$	Uncertainty
5	14.4%	$\sim \pm$ 10%

References [54]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 117 $NaCl-Na_2SO_4$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$NaCl$: 800°C

Na_2SO_4: 884°C

Eutectic melting point:

628°C, composition: 52 mol % $NaCl$ (35 equiv % $NaCl$)

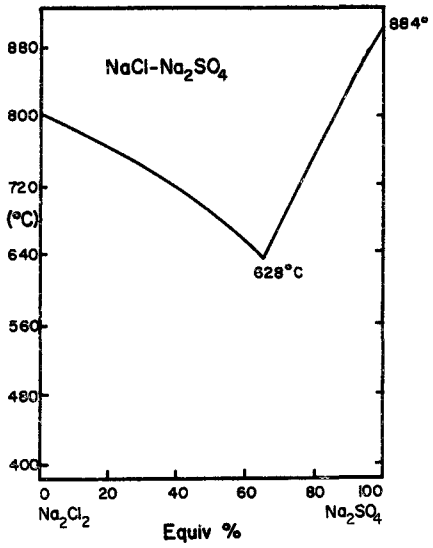

Figure 117.1. $NaCl-Na_2SO_4$ phase diagram

References [1-25]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

(117) $NaCl-Na_2SO_4$

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: NaCl, permitted in foods; Na_2SO_4, unknown; in general the toxicity of inorganic sulfates are those of the cations; in this case sodium (slight)

(ii) Vapor pressure: NaCl at m.pt. (800°C), ∿ 0.34mm; Na_2SO_4 at m.pt. (884°C), $\sim<10^{-5}$mm; while sulfates decomposed to oxides of sulfur on heating, Na_2SO_4 is relatively stable in the range of m.pt.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air

(ii) Chlorides, when heated to decomposition or contacted with acids, highly toxic chloride fumes are evolved

(iii) Sulfates, when heated to decomposition, evolve SO_3, which in turn dissociates to SO_2 and O_2; toxic, aggressive fumes

References [26-31]

(117) $NaCl-Na_2SO_4$

7. Corrosion

Table 117.1. Corrosion studies from primary research literature

	Studies	References
A	Mo	[32]
	Armco Fe	[33-35]
	Ni, Cr	[36]
	Ti, Zr, Hf, $ThCl_4$	[37,38]
	Cr	[39,40]
	Fe-Cr	[40]
	Ni alloys	[38,41]
	Au,Pt, Al_2O_3, MgO, Zirconia (NaCl with Na_2O)	[42]
	Thermodynamic redox potentials	[38,43,44]
	Electrochemical aspects	[45,46]
	Annotated corrosion biblio.	[47]
	Reviews	[48-50]
B	Ni, Co, Co-W, Ni-W, Co-Mo, Co-Cr, Cr-Ni, Ni-Cr-Mo, Co-Cr-Mo, Co-Cr-Nb, Co-Cr-Ta, Ni-Cr-Al, Co-Cr-Mn, Co-Cr-Fe	[51,57]
	Ni, various metals, Fe	[52-56]
	Ag	[57]
	"Hot corrosion" studies	[58]
	Electrochemical principles	[46]
	Thermodynamic redox diagrams	[54,56,59,60]
	Corrosion reviews	[48-50]
	Corrosion biblio.	[47]

Compatibility studies: A: molten chlorides, largely NaCl; B: molten sulfates, largely Na_2SO_4. For compatibility studies in molten mixtures of $NaCl-Na_2SO_4$, see [51].

References [32-60]

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

10. Heat Capacity (C_p)

No data

(117) $NaCl-Na_2SO_4$

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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[41] Bogdanov, N. I., Varganov, B. Ya., and Kholomonova, N. D., Zh. Prikl. Khim. (Leningrad), 46, 1698 (1973).

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System 118 $NaCl-K_2SO_4$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

NaCl: 800°C

K_2SO_4: 1069°C

Minimum melting mixture:

540°C, composition: 65 mol % NaCl; [50 equiv. % Na_2Cl_2]

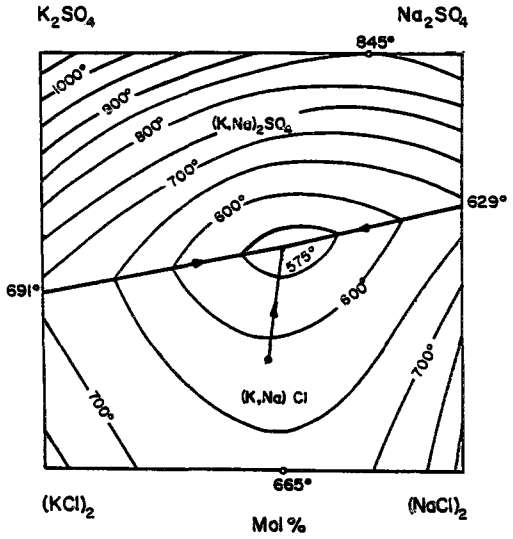

Figure 118.1. $NaCl-K_2SO_4$ phase diagram

References [1-20]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: NaCl, permitted in food; K_2SO_4, severe.

(ii) Vapor pressure: NaCl at m.pt. (800°C), ∿ 0.34mm; K_2SO_4 at m.pt. (1069°C) ∿ 0.07mm; while sulfates dissociate on heating to oxides of sulfur, K_2SO_4 is relatively stable.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides, when heated to decomposition or contacted with acids, highly toxic chloride fumes are evolved.

(iii) Sulfates, when heated to decomposition, evolve SO_3, which, in turn, dissociates to SO_2 and O_2; toxic, aggressive fumes.

References [21-26].

7. Corrosion

Table 118.1. Corrosion studies from primary research literature

	Studies	References
A	Mo	[27]
	Armco Fe	[28-30]
	NiCr	[31]
	Ti, Zr, Hf, $ThCl_4$	[32]
	Cr	[33]
	Cr, Fe-Cr	[34]
	Ni alloys	[35]
	Ni-Cr-Al, Ni-Cr-W-Fe, Ni-Cr Mg, Ni, Zr, Ti	[36]
	Au, Pt, MgO, Al_2O_3, Zirconia (NaCl with added Na_2O)	[37]
B	Metals	[38]
	Metals, Fe	[39]
	Ag	[40]
C	Electrochemical approach	[41]
	Thermodynamic redox diagrams	[38,39,42,43]
	Molten salts corrosion: reviews	[44-46]
	Annotated corrosion biblio.	[47]

cont'd

footnote to Table 118.1

Compatibility studies: A: molten chlorides, principally NaCl; B: molten sulfates, principally K_2SO_4; C: basic principles, reviews, biblio. No compatibility studies reported specific for molten $NaCl-K_2SO_4$ mixtures.

References [27-47]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

[1] Jänecke, E., Z. anorg. Chem., 261, 213 (1950).

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System 119 $KCl-Na_2CO_3$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

KCl: 770°C
Na_2CO_3: 858°C

Eutectic melting point:

588°C, composition: 44.4 mol % Na_2CO_3

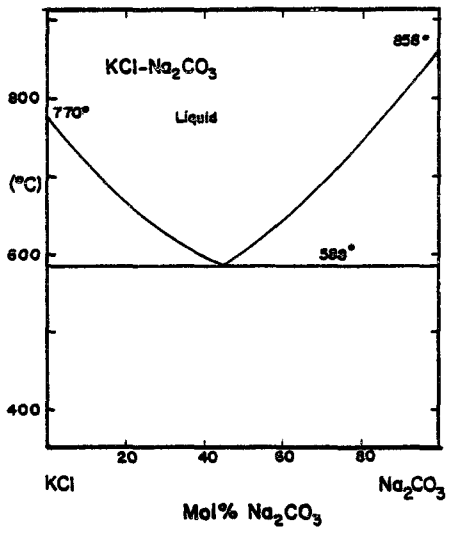

Figure 119.1. $KCl-Na_2CO_3$ phase diagram

References [1-18].

2. *Density (ρ)*

Measurement method: Archimedean technique [19]

Equation:

$$\rho = a + bT \quad (119.1)$$

precision: in table 119.1 uncertainty: ∿ ± 3.0%

Table 119.1. Parameters of equation (119.1) and precisions

Mol % KCl	a	$-b \times 10^4$	Precision	T range(K)
13.64	2.4029	4.198	0.02%	1100-1150
26.22	2.3318	4.086	0.03%	1000-1150
37.86	2.2639	3.967	0.02%	970-1150
48.66	2.2206	4.067	0.03%	920-1150
58.71	2.2066	4.395	0.03%	920-1150
68.08	2.1828	4.614	0.02%	970-1150
76.84	2.1473	4.695	0.02%	970-1150
85.04	2.1619	5.199	0.00%	1020-1150
92.75	2.3705	7.393	0.66%	1020-1150
100	1.7952	3.079	0.02%	1070-1150

Table 119.2. Density (g cm^{-3}) from equations in table 119.1

T (K)	Mol % KCl						
	13.64	26.22	48.66	58.71	76.84	85.04	92.75
920			1.846	1.802			
940			1.838	1.793			
960			1.830	1.785			
980			1.822	1.776	1.687		
1000		1.923	1.814	1.767	1.678		
1020		1.915	1.806	1.758	1.668	1.632	1.616
1040		1.907	1.798	1.750	1.659	1.621	1.602
1060		1.899	1.789	1.741	1.650	1.611	1.587
1080		1.891	1.781	1.732	1.640	1.600	1.572
1100	1.941	1.882	1.773	1.723	1.631	1.590	1.557
1120	1.933	1.874	1.765	1.714	1.621	1.580	1.542
1140	1.924	1.866	1.757	1.706	1.612	1.569	1.528
1150	1.920	1.862	1.753	1.701	1.607	1.564	1.520

References [19]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: KCl, very low; Na_2CO_3, moderate.

(ii) Vapor pressure: no information of this system; but see KCl [22], and Na_2CO_3 [22]

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic fumes when heated to decomposition, or contacted with acids.

(iii) When heated with CO_2 pressures less than equilibrium dissociation pressures, decomposes to form alkali metal oxide; the toxicology and disaster hazards are the same as those of very caustic solutions, i.e., react with water or steam (exothermic) to form solutions that are markedly aggressive to all body tissues.

References [20-25]

7. Corrosion

Table 119.3. Corrosion studies from primary research literature

	Systems, Studies, [References]
A	Armco Fe, various steels [26-30], Cr [28,31], Mg, Ni, Zn, Ti [32], Ti, Zr, Hf, $ThCl_4$ [33], solubility of oxides of Mo, Ca, Zn, Mg [32,34], electrochemical aspects [35], thermodynamic redox potentials [32,36 37], annotated biblio.[38], reviews, surveys [39-41].
B	Si [42], Pt [43], Metals [44], Cu-Zn [45], Pt, Au, Ag, MgO [46-49], Pt, Rh, Pd, Ir (O_2 environment) [50], Au, Ag, Al_2O_3 (N_2 atmosphere, $Na_2CO_3-Na_2O$) [51-53], quartz, porcelain, Ag, Pt, Ni, (N_2 atmosphere; $Na_2CO_3-Na_2O$) [54], boron nitride [49,55], β-alumina [55], Fe (Na_2CO_3-Na halides) [56], acid-base relationships [56-60], H_2O hydrolysis reactions [61-63], molten carbonates: fuel cells, thermal energy storage, coal gasification [55,56,64-69]

Compatibility studies: A: principally with molten KCl; B: principally with molten NaCl. No corrosion studies with molten $KCl-Na_2CO_3$ found.

References [26-60]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

(119) KCl-Na_2CO_3

15. Cryoscopic Constant (k_f)

No data

16. References

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System 120 K_2CO_3-KCl

1. *Melting Temperatures (T_m)*

Pure substance melting points:

KCl: 770°C

K_2CO_3: 898°C

Eutectic melting point:

632°C, composition: 61.6 mol % KCl

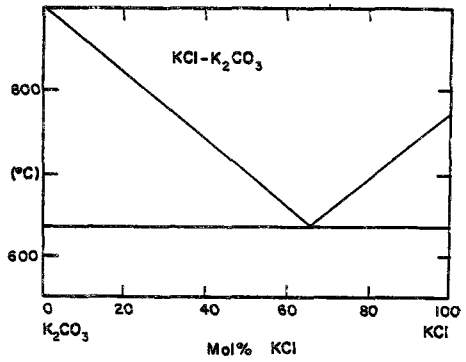

Figure 120.1. K_2CO_3-KCl phase diagram

References [1-18].

2. *Density (ρ)*

Measurement method: Archimedean technique [19]

Equation:

$$\rho = a + bT \quad (120.1)$$

precision: in table 120.1 uncertainty: ∿ ± 1.0%

Table 120.1. Parameters of equation (120.1) and precisions

Mol % KCl	a	-b x 10^4	Precision	T range(K)
18.02	2.1593	2.406	0.00%	1150-1170
33.28	2.3173	4.202	0.01%	1100-1150
46.25	2.3095	4.560	0.01%	1080-1150
56.60	2.2794	4.714	0.02%	1000-1150
66.04	2.2178	4.643	0.15%	970-1150
75.15	2.2319	5.128	0.02%	1000-1150
77.72	2.0633	3.838	0.06%	1020-1150
88.90	2.1600	5.200	0.00%	1050-1150
94.35	2.1319	5.199	0.00%	1120-1150

Table 120.2. Density (g cm^{-3}) from equations in table 120.1

T (K)	Mol % KCl						
	18.02	33.28	56.60	66.04	75.15	88.90	94.35
970				1.767			
980				1.763			
990				1.758			
1000			1.808	1.753	1.719		
1010			1.803	1.749	1.714		
1020			1.799	1.744	1.709		
1030			1.794	1.740	1.704		
1040			1.789	1.735	1.699		
1050			1.785	1.730	1.693	1.614	
1060			1.780	1.725	1.688	1.609	
1070			1.775	1.721	1.683	1.604	
1080			1.770	1.716	1.678	1.598	
1090			1.766	1.712	1.673	1.593	
1100		1.855	1.761	1.707	1.668	1.588	
1110		1.851	1.756	1.702	1.663	1.583	
1120		1.847	1.752	1.698	1.658	1.578	1.550
1130		1.842	1.747	1.693	1.652	1.572	1.544
1140		1.838	1.742	1.689	1.647	1.567	1.539
1150	1.883	1.834	1.737	1.684	1.642	1.562	1.534
1160	1.880						
1170	1.878						

References [19]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: KCl, very low; K_2CO_3, classified as strongly caustic.

(ii) Vapor pressure: KCl at m.pt. (770°C), $\sim$ 0.42mm; K_2CO_3 decomposes on heating to the oxide and CO_2; CO_2 pressure at $\sim$ 1mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic fumes when heated to decomposition, or contacted with acids.

(iii) Carbonates, when heated with CO_2 pressures less than equilibrium dissociation pressures, decompose to form alkali metal oxides; the toxicology and disaster hazards are the same as those of very caustic solutions, i.e. react with water or steam (exothermic) to form solutions that are markedly aggressive to all body tissues (chemical burns). Potassium carbonate itself is classified as a strong caustic.

References [20-25]

7. Corrosion

Table 120.3. Corrosion studies from primary research literature

	Studies	References
A	Stainless steel	[26]
	Acid-base relationships in molten carbonates	[27-30]
	Hydrolysis (H_2O) reactions	[31-33]
	Corrosion in molten salts (annotated biblio.)	[34]
	Molten carbonates: fuel cells, thermal energy storage, coal gasification, stack gases	[26,35,39]
B	Armco Fe, steels	[40,41,46-48]
	Cr, Fe-Cr	[42,43]
	Mg, Ni, Zr, Ti	[44]
	Ti, Zr, Hf, $ThCl_4$	[45]
	Solubility of metal oxides	[44,49]
C	Electrochemical aspects	[50]
	Thermodynamic approach	[44,51,52]
	Corrosion reviews	[34]
	Corrosion biblio.	[53-55]

Compatibility studies: A: principally K_2CO_3; B: principally KCl; C: general review surveys, biblios. No compatibility studies found specifically for K_2CO_3-KCl molten mixtures.

References [26-55]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [56]

Table 120.4. Volume change on melting

Binary eutectic (mol % KCl)	$(\Delta V_f/V_s)$	Uncertainty
62	12.2%	$\sim \pm$ 10%

References [56]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

[1] Bergman, A. G., Sementsova, A. K., Zhur. Neorg. Khim., 3, 201 (1958).

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System 121 $KCl-K_2SO_4$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

KCl: 770°C

K_2SO_4: 1069°C

Eutectic melting point:

∿ 691°C, composition: ∿ 73 mol % KCl; [∿ 57.4 equiv. % K_2Cl_2]

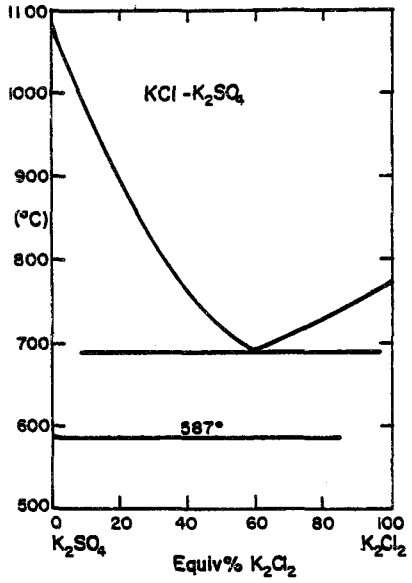

Figure 121.1 $KCl-K_2SO_4$ phase diagram

References [1-22]

2. *Density (ρ)*

Measurement method: Archimedean technique [23]

Equation:

$$\rho = a + bT \quad (121.1)$$

precision: in table 121.1 uncertainty: ∿ ± 1.0%

(121) $KCl-K_2SO_4$

Table 121.1. Parameters of equation (121.1) and precisions

Mol % K_2SO_4	a	$-b \times 10^4$	Precision	T range(K)
0	2.0865	5.476	0.09%	1060-1260
15.3	2.2536	6.010	0.04%	1080-1200
22.3	2.3420	6.234	0.04%	1080-1180
32.4	2.4057	6.183	0.05%	1080-1160
43.1	2.4453	5.989	0.04%	1120-1180
45.0	2.4194	5.680	0.05%	1120-1180
55.2	2.4994	5.991	0.04%	1160-1220
69.4	2.4145	4.785	0.16%	1240-1320
80.2	2.4495	4.784	0.05%	1280-1360
100	2.4761	4.519	0.06%	1360-1400

Table 121.2. Density (g cm^{-3}) from equations in table 121.1

T (K)	Mol % K_2SO_4					
	0	22.3	32.4	43.1	69.4	80.2
1080	1.604	1.669	1.738			
1100	1.592	1.656	1.725			
1120	1.580	1.644	1.713	1.775		
1140	1.568	1.631	1.701	1.763		
1160	1.556	1.619	1.689	1.751		
1180	1.544	1.606		1.739		
1200	1.532					
1220						
1240					1.821	
1260					1.812	
1280					1.802	1.837
1300					1.792	1.828
1320					1.783	1.818
1340						1.809
1360						1.799

References [23]

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure [23,24]

Equation: (surface tension-temperature dependence) [23]

$$\gamma = a + bT \quad (121.2)$$

precision: in table 121.3 uncertainty: ∿ ± 1.0%

Equation: (surface tension-composition isotherm) [24]

$$\gamma = a' + b'C + c'C^2 \quad (121.3)$$

(C = mol % KCl)

precision: in table 121.4 uncertainty: ∿ ± 1.5%

Table 121.3. Parameters of equation (121.2) and precision

Mol % K_2SO_4	a	$-b \times 10^2$	Precision	T range(K)
15.2	177.5	7.20	*	1090-1180
21.3	186.9	7.50	*	1090-1200
35.4	186.2	6.70	*	1090-1180
44.7	196.1	7.20	*	1090-1180
60.2	212.0	7.50	*	1180-1250
69.9	198.3	6.10	*	1220-1270
79.2	205.9	6.20	*	1270-1320

*not estimated; insufficient data

Table 121.4. Parameters of equation (121.3) and precision

T (K)	a'	$b' \times 10^2$	$c' \times 10^3$	Precision
1348	143.5	222.	117.	*

*not estimated; insufficient data

Table 121.5. Surface tension (dyn cm^{-1}) from equations in table 121.3

T (K)	Mol % K_2SO_4						
	15.2	21.3	35.4	44.7	60.2	69.9	79.2
1090	99.2	105.6	113.2	117.6			
1100	98.4	104.9	112.5	116.9			
1120	97.0	103.4	111.2	115.5			
1140	95.6	101.9	109.8	114.0			
1160	94.1	100.4	108.5	112.6			
1180	92.7	98.9	107.1	111.1	123.5		
1200		97.4			122.0		
1220					120.5	123.3	
1240					119.0	122.1	
1260						120.8	
1280							126.4
1300							125.2
1320							124.0

Table 121.6. Surface tension of isotherm at 1348 K from equation in table 121.4

Mol % KCl	γ (dyn cm^{-1})	Mol % KCl	γ (dyn cm^{-1})
1.0	141.4	4.0	136.5
2.0	139.5	5.0	135.3
3.0	137.9	6.0	133.0

References [23,24]

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: KCl, very low; K_2SO_4, severe.

(ii) Vapor pressure: KCl at m.pt. (770°C), ~ 0.42 mm; K_2SO_4 at m.pt. (1069°C) ~ 0.07mm; sulfates dissociate on heating to form oxides of sulfur; K_2SO_4 is relatively stable.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Chlorides evolve highly toxic fumes when heated to decomposition, or contacted with acids.

(iii) Sulfates, when heated to decomposition, evolve SO_3, which, in turn, dissociates to SO_2 and O_2; toxic, aggressive fumes.

References [25-30]

7. Corrosion

Table 121.7. Corrosion studies from primary research literature

	Studies	References
A	Armco Fe, various steels	[31,32,37,38
	Cr	[33]
	Cr, Fe-Cr	[34]
	Mg, Ni, Zr, Ti	[35]
	Ti, Zr, Hf, $ThCl_4$	[36]
	Solubility of oxides (Ni, Ca, Zn, Mg)	[35,39]
B	Metals	[40]
	Metals, Fe	[41]
	Ag	[42]
C	Electrochemical approach	[43]
	Thermodynamic redox diagrams	[40,41,44,45]
	Molten salts corrosion: reviews	[46-48]
	Annotated corrosion biblio.	[49]

Compatibility studies: A: molten chlorides, principally KCl; B: molten sulfates, principally K_2SO_4; C: basic principles, reviews and biblios. No compatibility studies reported specifically for molten mixtures of $KCl-K_2SO_4$

References [31-49]

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

(121) $KCl-K_2SO_4$

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [50]

Table 121.8. Volume change on melting

Binary eutectic (mol % KCl)	$(\Delta V_f/V_s)$	Uncertainty
73	15.9%	∿ ±10%

References [50]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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[50] Janz, G. J., et al. (MSDC-RPI), unpublished work (1980).

System 122 Li_2CO_3-LiOH

1. *Melting Temperatures (T_m)*

Pure substance melting points:

Li_2CO_3: 723°C
LiOH: 462°C

Eutectic melting point:

E_1: 442°C, composition: 10.2 mol % Li_2CO_3 [18.5 equiv. % Li_2CO_3]

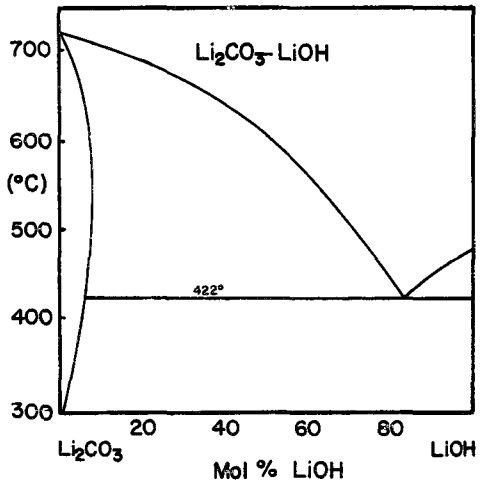

Figure 122.1. Li_2CO_3-LiOH phase diagram

References [1-18]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure [19]

Equation: (surface tension-composition isotherm)

$$\gamma = a + bC + cC^2 + dC^3 \quad (122.1)$$

precision: in table 122.1 uncertainty: ∿ ± 1.5%

Table 122.1. Parameters of equation (122.1) and precision

T (K)	a	-b	-c x 10^2	d x 10^4	Precision
1038	242.4	41.20	1.200	1.310	0.1%

Table 122.2. Surface tension isotherm at 1038 K from equation in table 122.1

Mol % LiOH	γ (dyn cm^{-1})	Mol % LiOH	γ (dyn cm^{-1})
5	240.02	25	226.61
10	237.17	30	222.74
15	233.92	35	218.86
20	230.37		

References [19]

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: Li_2CO_3, very toxic; lethal (oral) dose, 0.7mg/kg; LiOH, very caustic and toxic.

(ii) Vapor pressure: LiOH at m.pt. (460°C), << 0.5mm; Li_2CO_3 (m.pt. 732°C) dissociates, on heating, to form the oxide and CO_2; CO_2 pressures at 730°C, ~ 10mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e. explosive expansion of "trapped" air.

(ii) Carbonates, when heated with CO_2 pressures less than equilibrium dissociation pressures, decompose to form alkali metal oxides, the toxicology and disaster hazards are the same as those of very caustic solutions, i.e. react with water or steam (exothermic) to form solutions that are markedly aggressive to all body tissues (chemical burns). Lithium carbonate itself is classified as a strong caustic.

(iii) Hydroxides react with water or steam with evolution of heat; the aqueous solution is very caustic and attacks living tissue; dangerous.

References [20-26]

7. Corrosion

Table 122.3. Corrosion studies from primary research literature

	Studies	References
A	Ti alloys	[27]
	Au, Ag, Pt, Ni, Au-Pd, BN, MgO, Co	[28-31]
	Metals, alloys	[32]
	Pt, Pd, Rh, Ir (O_2 environment)	[33]
	Pt, Ag, Ni, (Li_2CO_3, Li_2O)	[34-37]
	Ag, Pt, Ni, quartz, porcelain, (Li_2CO_3, Li_2O)	[38]
	Acid-base relationships	[39-43]
	Hydrolysis reactions	[34,41,43,44]
	Corrosion biblio.	[45]
	Molten carbonates in: fuel cells, thermal energy storage, coal gasification, stack gas scrubbing	[46-51]
B	Ni	[52]
	Cu	[53]
	Armco Fe, steel	[54]
	Fe, effects of H_2O	[55]
	Pt, Ag and alloys	[56-58]
	Thermodynamics of corrosion	[59,61,62]
	Corrosion-annotated biblio.	[63]
	Electrochemical aspects	[64]
	Reviews: corrosion - molten salts	[60,65-67]

Compatibility studies: A: molten carbonates, principally Li_2CO_3; B: molten hydroxides, mainly LiOH. No compatibility studies specifically for Li_2CO_3-LiOH mixtures found.

References [27-67]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 123 Li_2CO_3-Li_2SO_4

1. *Melting Temperature (T_m)*

Pure substance melting points:

Li_2CO_3: 723°C
Li_2SO_4: 859°C

Eutectic melting point:

534°C, composition: 38.5 mol % Li_2CO_3

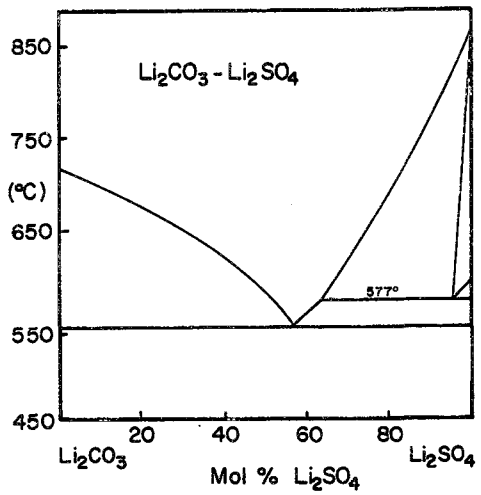

Figure 123.1. Li_2CO_3-Li_2SO_4 phase diagram

References [1-19]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

(123) Li_2CO_3-Li_2SO_4

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: Li_2CO_3, very toxic; lethal (oral) dose, 0.7mg/kg.; Li_2SO_4, unknown; for an inorganic sulfate , the toxicity is generally that of the cation, i.e. in this case, lithium .

(ii) Vapor pressure: Li_2CO_3 (m.pt. 723°C) dissociates on heating to the oxide and CO_2; CO_2 pressure at 730°C, ∿ 10mm; Li_2SO_4 (m.pt. 8/59°C), decomposes to oxides of sulfur (aggressive and toxic fumes) just above its m.pt.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e. explosive expansion of "trapped" air.

(ii) Carbonates, when heated with CO_2 pressures less than equilibrium dissociation pressures, decompose to form alkali metal oxides; the toxicology and disaster hazards are the same as those of very caustic solutions, i.e. react with water or steam (exothermic) to form solutions that are markedly aggressive to all body tissues (chemical burns). Lithium carbonate itself is classified as a strong caustic.

(iii) Sulfates when heated to decomposition, decompose, evolving SO_3, which in turn dissociates to SO_2 and O_2 (see above); toxic, corrosive fumes.

References [20-26]

7. *Corrosion*

Table 123.1. Corrosion studies from primary research literature

	Studies	References
A	Ti alloys	[27]
	Au, Ag, Pt, Ni, Au-Pd, BN, MgO, Co	[28-31]
	Metals, alloys	[32]
	Pt, Pd, Rh, Ir (O_2 environment)	[33]
	Pt, Ag, Ni, (Li_2CO_3, Li_2O)	[34-37]
	Ag, Pt, Ni, quartz, porcelain (Li_2CO_3, Li_2O)	[38]
	Acid-base relationships	[39-43]
	Hydrolysis reactions	[34,41,43,44]
	Corrosion biblio.	[45]
	Molten carbonates in: thermal energy storage, coal gasification, stack gas scrubbing	[46-51]
B	Fe, various metals	[52-54]
	Ag	[55]
	Thermodynamic redox diagrams	[31,52,55,56]
	Electrochemical aspects	[57]Reviews
	Reviews and annotated corrosion biblio.	[45,58-60]

Compatibility studies: A:molten carbonates, principally Li_2CO_3; B: molten sulfates, principally Li_2SO_4. No compatibility studies specifically for molten Li_2CO_3-Li_2SO_4 mixtures found.

References [27-60]

8. *Diffusion*

No data

9. *Heat of Fusion (ΔH_f°)*

No data

10. *Heat Capacity (C_p)*

No data

11. *Volume Change on Melting (ΔV_f)*

No data

(123) Li_2CO_3-Li_2SO_4

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 124 Li_2CO_3-K_2SO_4

.1. *Melting Temperature (T_m)*

Pure substance melting points:

Li_2CO_3: 723 ± 3°C

K_2SO_4: 1069 ± 3°C

Eutectic 1, melting point:
470°C, composition: 60 mol % Li_2SO_4;26.5 mol % Li_2CO_3;13.5 mol % K_2SO_4

Eutectic 2, melting point:
562°C, composition: 55 mol % Li_2CO_3;35 mol % K_2SO_4;10 mol % Li_2SO_4

Peritectic melting point:
565°C, composition: 65.83 mol % K_2SO_4;34.17 mol % Li_2CO_3

Reciprocal Salt Pair Reaction:
$Li_2SO_4 + K_2CO_3 \rightleftharpoons K_2SO_4 + Li_2CO_3 + 5.3$ kcal equiv^{-1}

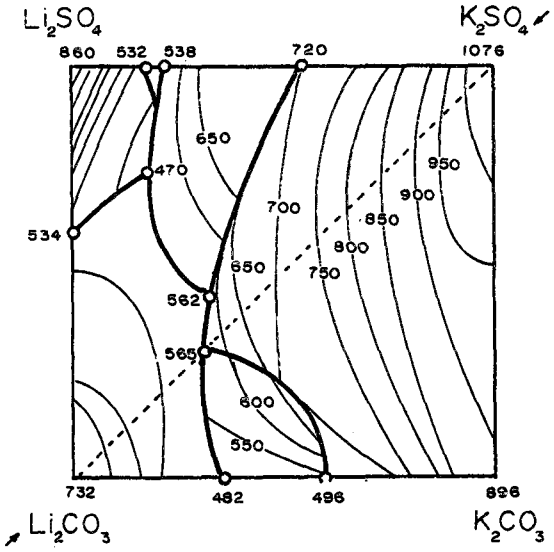

Figure 124.1. Phase diagram for Li, K/CO_3, SO_4 system.
System Li_2CO_3-K_2SO_4 is the diagonal as marked; note the reciprocal salt pair reaction
$Li_2SO_4 + K_2CO_3 = K_2SO_4 + Li_2CO_3 + 5.3$ kcal equiv^{-1}

References [1-15]

2. *Density (ρ)*

Measurement method: Archimedean technique [16]

Equation:

$$\rho = a + bT \quad (124.1)$$

precision: in table 124.1 uncertainty: ∿ ± 3.0%

(124) Li_2CO_3-K_2SO_4

Table 124.1. Parameters of equation (124.1) and precision

Mol % K_2SO_4	a	-b x 10^3	Precision	T range(K)
10	2.2439	0.3778	*	1270-1370
20	2.3014	0.4046	*	1170-1370
30	2.3792	0.4439	*	1070-1370
40	2.4014	0.4441	*	1020-1370
50	2.3591	0.3881	*	970-1370
60	2.4054	0.4150	*	870-1370
70	2.4265	0.4261	*	870-1370
80	2.4139	0.4036	*	870-1370

* not estimated, data in equation form

Table 124.2. Density (g cm^{-3}) from equations in table 124.1

T (K)	Mol % K_2SO_4							
	10	20	30	40	50	60	70	80
870						2.044	2.056	2.063
910						2.028	2.039	2.047
950						2.011	2.022	2.030
990					1.975	1.995	2.005	2.014
1030				1.944	1.959	1.978	1.988	1.998
1070			1.904	1.926	1.944	1.961	1.971	1.982
1110			1.886	1.908	1.928	1.945	1.954	1.966
1150			1.869	1.891	1.913	1.928	1.936	1.950
1190		1.820	1.851	1.873	1.897	1.912	1.919	1.934
1230		1.804	1.833	1.855	1.882	1.895	1.902	1.917
1270	1.764	1.788	1.815	1.837	1.866	1.878	1.885	1.901
1310	1.749	1.771	1.798	1.820	1.851	1.862	1.868	1.885
1350	1.734	1.755	1.780	1.802	1.835	1.845	1.851	1.869
1370	1.726	1.747	1.771	1.793	1.827	1.837	1.843	1.861

References [16]

3. *Surface Tension* (γ)

No data

4. *Viscosity* (η)

No data

(124) Li_2CO_3-K_2SO_4

5. Electrical Conductance (κ)

Measurement method: classical ac technique [17]

Equation:

$$\kappa = 2.6403 - 7.332 \times 10^{-2}C + 9.919 \times 10^{-4}C^2 - 4.470 \times 10^{-6}C^3 \quad (124.2)$$

(C = mol % K_2SO_4)

precision: ∿ ± 6.5% uncertainty: ∿ ± 3.0%

Table 124.3. Specific conductance from equation (124.2)

Mol % K_2SO_4	κ (ohm^{-1} cm^{-1})	Mol % K_2SO_4	κ ($ohm^{-1}cm^{-1}$)
10	2.002	50	0.895
20	1.535	60	0.846
30	1.213	70	0.835
40	1.008	80	0.834

Specific conductance calculated from equivalent conductance data interpolated from [17] and density data equations from [16].

References [16,17]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: K_2CO_3, classified as strongly caustic; Li_2SO_4; the toxic qualities are those of the cation, lithium.

(ii) Vapor pressure: K_2CO_3 (m.pt. 898°C) decomposes on heating to the oxide and oxygen.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Carbonates, when heated with CO_2 pressures less than equilibrium dissoication pressures, decompose to form alkali metal oxides; the toxicology and disaster hazards are the same as those of very caustic solutions, i.e. react with water or steam (exothermic) to form solutions that are markedly aggressive to all body tissues (chemical burns). Potassium carbonate itself is classified as a strong caustic.

(iii) Sulfates, when heated to decomposition, decompose, evolving SO_3, which in turn dissociates to SO_2 and O_2 (see above); toxic, corrosive fumes.

References [18-24].

(124) Li_2CO_3-K_2SO_4

7. Corrosion

Table 124.4. Corrosion studies from primary research literature

	Studies	References
A	Ti alloys	[25]
	Au, Ag, Pt, Ni, Au-Pd, BN, MgO, Co	[26-29]
	Metals, alloys	[30]
	Pt, Pd, Rh, Ir (O_2 environment)	[31]
	Pt, Ag, Ni (Li_2CO_3, Li_2O)	[32-35]
	Ag, Pt, N, quartz, porcelain, (Li_2CO_3, Li_2O)	[36]
	Acid-base relationships	[37-41]
	Hydrolysis reactions	[32,39,41,42]
	Corrsoion biblio.	[43]
	Molten carbonates in: fuel cells, thermal energy storage, coal gasification, stack gas scrubbing	[44-49]
B	Fe, metals	[50,51]
	Ag	[52]
	Electrochemical approach	[53]
	Thermodynamic redox diagrams	[50,51,54,55]
	Molten salts corrosion rev.	[56-58]
	Annotated corrosion biblio.	[43]

Compatibility studies: A: various molten carbonates, principally Li_2CO_3; B: various molten sulfates, principally K_2SO_4. No compatibility studies for molten Li_2CO_3-K_2SO_4 mixtures found.

References [25-58]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

(124) Li_2CO_3-K_2SO_4

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 125 $NaOH-Na_2CO_3$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

Na_2CO_3: 858°C

NaOH: 318°C

Eutectic melting point:

283°C, composition: 7.2 mol % Na_2CO_3

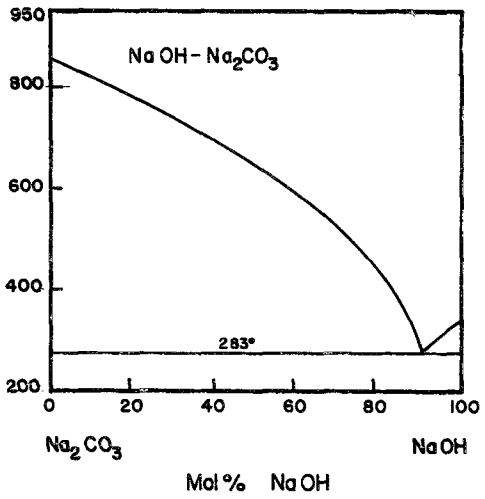

Figure 125.1. $NaOH-Na_2CO_3$ phase diagram

References [1-18]

2. *Density (ρ)*

Measurement method: Archimedean technique [19]

Equation:

$$\rho = a + bT \quad (125.1)$$

precision: in table 125.1 uncertainty: ∿ ± 2.0%

Table 125.1. Parameters of equation (125.1) and precisions

Mol % Na_2CO_3	a	$-b \times 10^4$	Precision	T range(K)
2.09	2.1026	5.000	0.00%	590-720
3.61	2.1037	4.837	0.01%	590-720
7.19	2.1411	4.928	0.02%	590-720
9.37	2.1648	5.061	0.02%	590-720

Table 125.2. Density (g cm^{-3}) from equations in table 125.1

T (K)	Mol % Na_2CO_3 2.09	3.61	7.19	9.37
590	1.808	1.818	1.850	1.866
600	1.803	1.813	1.845	1.861
610	1.797	1.809	1.840	1.856
620	1.793	1.804	1.835	1.851
630	1.788	1.798	1.831	1.846
640	1.783	1.794	1.826	1.841
650	1.778	1.789	1.821	1.836
660	1.773	1.784	1.816	1.831
670	1.768	1.780	1.811	1.826
680	1.763	1.775	1.806	1.821
690	1.758	1.770	1.801	1.816
700	1.753	1.765	1.796	1.811
710	1.748	1.760	1.791	1.805
720	1.743	1.755	1.786	1.800

References [19]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: NaOH, very caustic and corrosive to all body tissue; Na_2CO_3, moderate toxicity.

(ii) Vapor pressure: no information for this system; but see Na_2CO_3 [22], and NaOH [23]

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) NaOH: Hydroxides react exothermically with water or steam; the aqueous solution is strongly caustic; attacks living tissue; dangerous.

Na_2CO_3: When heated with CO_2 pressures less than equilibrium dissociation pressures, decomposes to form alkali metal oxide; the toxicology and disaster hazards are the same as those of very caustic solutions, i.e. react with water or steam (exothermic) to form solutions that are markedly aggressive to all body tissues (chemical burns).

References [20-26].

7. *Corrosion*

Table 125.3. Corrosion studies from primary research literature

	Systems, Studies, and [References]
A	Si [27], Pt [28], Metals [29], Cu-Zn [30], Pt, Au, Ag, MgO [31-34], Pt, Rh, Pd, Ir (O_2 environment) [35], Au, Ag, Al_2O_3 (N_2 atmosphere; Na_2CO_3-Na_2O) [36-38], quartz, porcelain, Ag, Pt, Ni (N_2 atmosphere; Na_2CO_3-Na_2O) [39], boron nitride [34,40], β-alumina [40], Fe (Na_2CO_3-Na halides) [41], acid-base relationships [42-45], H_2O hydrolysis reactions [46-48], molten carbonates: fuel cells, thermal energy storage, coal gasification [40,41,49-54]
B	Metals [55], metals, ceramics, alloys [55-62], stainless steel [63], Ni-Cr-Fe, Ni-Si-Cu [59,64], Ni-Mo, Ni, Cu, Armco Fe [65-67], Al_2O_3, ZrO_2 [58], Ni [56-58,65,68-71], Ni-steels [72], Fe (effects of H_2O) [73], Pt,Ag, alloys [74-76], thermodynamic and electrochemical approach [77-79], reviews [80-82], annotated corrosion biblio. [83]

A: corrosion studies in molten carbonates; principally molten Na_2CO_3; B: corrosion studies in molten hydroxides; principally molten NaOH. No compatibility studies with molten mixtures of Na_2CO_3-NaOH found.

References [27-83]

8. *Diffusion*

No data

9. *Heat of Fusion (ΔH°_f)*

No data

10. *Heat Capacity (C_p)*

No data

11. *Volume Change on Melting (ΔV_f)*

Measurement method: estimated from densities [84]

Table 125.4. Volume change on melting

Binary eutectic (mol % Na_2CO_3)	$(\Delta V_f/V_s)$	Uncertainty
7.2%	12.5%	$\sim \pm$ 10%

References [84]

(125) $NaOH-Na_2CO_3$

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 126 K_2CO_3-KOH

1. *Melting Temperatures (T_m)*

Pure substance melting points:

K_2CO_3: 898°C
KOH: 360°C

Eutectic melting point:

366°C, composition: 9.3 mol % K_2CO_3

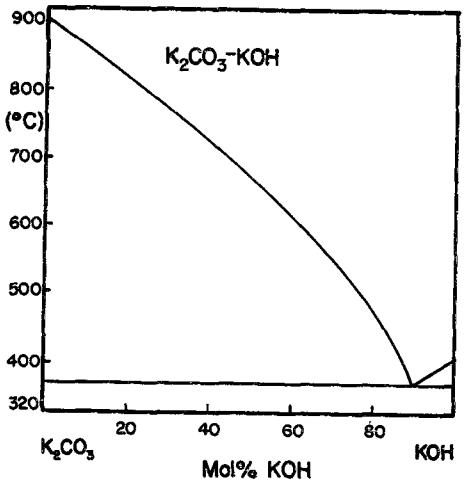

Figure 126.1. K_2CO_3-KOH phase diagram

References [1-16]

2. *Density (ρ)*

Measurement method: Archimedean technique [17]

Equation:

$$\rho = a + bT \quad (126.1)$$

precision: in table 126.1 uncertainty: ∿ ± 1.5%

Table 126.1. Parameters of equation (126.1) and precisions

Mol % K_2CO_3	a	-b x 10^4	Precision	T range(K)
1.75	2.0414	4.580	0.03%	670-820
2.83	2.0541	4.520	0.02%	670-820
4.50	2.0552	4.400	0.00%	670-820
8.54	2.1268	4.860	0.02%	670-820

Table 126.2. Density (g cm^{-3}) from equations in table 126.1

T (K)	Mol % K_2CO_3 1.75	2.83	4.50	8.64
670	1.734	1.751	1.760	1.801
690	1.725	1.742	1.752	1.791
710	1.716	1.733	1.743	1.782
730	1.707	1.724	1.734	1.772
750	1.698	1.715	1.725	1.762
770	1.6889	1.706	1.716	1.753
790	1.680	1.697	1.708	1.743
810	1.670	1.688	1.699	1.733

References [17]

3. *Surface Tension* (γ)

No data

4. *Viscosity* (η)

No data

5. *Electrical Conductance* (κ)

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: K_2CO_3, classified as a strong caustic; KOH, very caustic and toxic.

(ii) Vapor pressure: KOH at m.pt. (360°C) << 0.5mm; K_2CO_3 decomposes on heating to the oxide and CO_2; at 1080°C, CO_2 ~ 1mm press.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Hydroxides, react with water or steam with evolution of heat; the aqueous solution is very caustic and attacks living tissue; dangerous.

(iii) Carbonates, when heated with CO_2 pressures less than equilibrium dissociation pressures, decompose to form alkali metal oxides; the toxicology and disaster hazards are the same as those of very caustic solutions, i.e., react with water or steam (exothermic) to form solutions that are markedly aggressive to all body tissues (chemical burns). Potassium carbonate itself is classified as a strong caustic.

References [18-23]

7. Corrosion

Table 126.3. Corrosion studies from primary research literature

	Studies	References
A	Stainless steel	[24]
	Acid-base relationships in molten carbonates	[25-28]
	Hydrolysis (H_2O) reactions	[29-31]
	Corrosion in molten salts, annotated biblio.	[32]
	Molten carbonates: fuel cells, thermal energy storage, and coal gasification, stack gases	[24,33,37]
B	Ni, Armco Fe, steels	[38-40]
	Fe (effects of H_2O)	[41]
	Pt, Ag and alloys	[42-44]
	Thermodynamics of corrosion	[45-48]
	Annotated corrosion biblio.	[32]
	Electrochemical aspects	[49]
	Reviews	[46,50-52]

Compatibility studies: A: principally molten K_2CO_3; B: principally molten KOH. No compatibility studies found specifically for molten mixtures of K_2CO_3-KOH.

References [24-52]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [53]

Table 126.4. Volume change on melting

Binary eutectic (mol % K_2CO_3)	$(\Delta V_f/V_s)$	Uncertainty
9.3	10.5%	$\sim \pm$ 10%

References [53]

12. *Vapor Pressure (p_{vap})*

No data

13. *Thermal Conductivity (liquid) (λ_ℓ)*

No data

14. *Thermal Conductivity (solid) (λ_s)*

No data

15. *Cryoscopic Constant (k_f)*

No data

16. *References*

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System 127 K_2CO_3-Li_2SO_4

1. *Melting Temperature (T_m)*

Pure substance melting points:

K_2CO_3: 898°C

Li_2SO_4: 859°C

Eutectic 1, melting point:

470°C, composition: 60 mol % Li_2SO_4;26.5 mol % Li_2CO_3;13.5 mol % K_2SO_4

Eutectic 2, melting point:

562°C, composition: 55 mol % Li_2CO_3;35 mol % K_2SO_4;10 mol % Li_2SO_4

Peritectic melting point:

565°C, composition: 65.83 mol % K_2SO_4;34.17 mol % Li_2CO_3

Reciprocal Salt Pair Reaction:

$$Li_2SO_4 + K_2CO_3 \rightleftharpoons K_2SO_4 + Li_2CO_3 + 5.3 \text{ kcal equiv}^{-1}$$

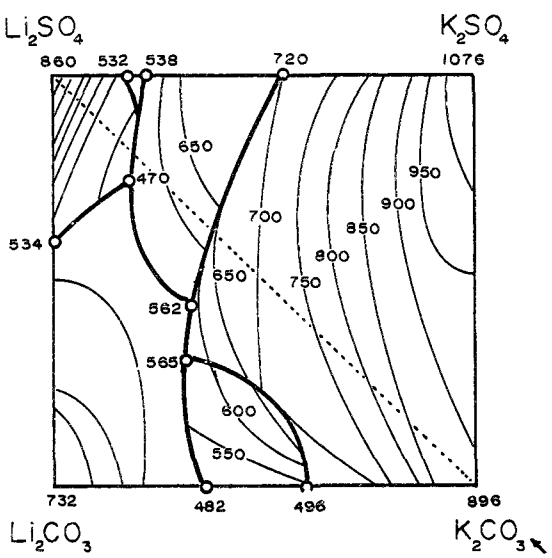

Figure 127.1. Phase diagram for Li, K/CO_3, SO_4 system.

System K_2CO_3-Li_2SO_4 is the diagonal as marked; note the reciprocal salt pair reaction

$$Li_2SO_4 + K_2CO_3 = K_2SO_4 + Li_2CO_3 + 5.3 \text{ kcal equiv}^{-1}$$

References [1-15]

2. *Density (ρ)*

Measurement method: Archimedean technique [16]

Equation:

$$\rho = a + bT \quad (127.1)$$

precision: in table 127.1 uncertainty: ∿ ± 3.0%

(127) K_2CO_3-Li_2SO_4

Table 127.1. Parameters of equation (127.1) and precision

Mol % Li_2SO_4	a	-b x 10^3	Precision	T range(K)
10	2.3897	0.4262	*	1120-1220
20	2.4419	0.4695	*	1070-1220
30	2.3685	0.4057	*	1020-1220
40	2.3895	0.4268	*	1020-1220
50	2.3813	0.4101	*	970-1220
60	2.4047	0.4232	*	920-1220
70	2.4620	0.4611	*	920-1220
80	2.4156	0.4088	*	770-1220
90	2.5517	0.5088	*	1020-1220

*not estimated, data in equation form only.

Table 127.2. Density (g cm^{-3}) from equations in table 127.1

T (K)	Mol % Li_2SO_4								
	10	20	30	40	50	60	70	80	90
860								2.064	
900								2.048	
940						2.007	2.029	2.031	
980					1.979	1.990	2.010	2.015	
1020			1.955	1.954	1.963	1.973	1.992	1.999	2.033
1060			1.938	1.937	1.947	1.956	1.973	1.982	2.012
1100		1.925	1.922	1.920	1.930	1.939	1.955	1.966	1.992
1140	1.904	1.907	1.906	1.903	1.914	1.922	1.936	1.950	1.972
1180	1.887	1.888	1.890	1.886	1.897	1.905	1.918	1.933	1.951
1220	1.870	1.869	1.874	1.869	1.881	1.888	1.899	1.917	1.931

References [16]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

(127) K_2CO_3-Li_2SO_4

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [17]

Equation:

$$\kappa = 1.0494 - 1.314 \times 10^{-2}C + 2.265 \times 10^{-4}C^2 \quad (127.2)$$

(C = mol % Li_2SO_4)

precision: $\sim \pm 3.18\%$ uncertainty: $\sim \pm 3.0\%$

Table 127.3. Specific conductance from equation (127.2)

Mol % Li_2SO_4	κ (ohm^{-1} cm^{-1})	Mol % Li_2SO_4	κ (ohm^{-1} cm^{-1})
10	0.941	60	1.076
20	0.877	70	1.239
30	0.859	80	1.448
40	0.886	90	1.701
50	0.959		

Specific conductance calculated from equivalent conductance data interpolated from [17] and density data from [16].

References [16,17]

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: K_2CO_3, classified as strongly caustic; Li_2SO_4; the toxic qualities are those of the cation, lithium.

(ii) Vapor pressure: K_2CO_3 (m.pt. 898°C) decomposes on heating to the oxide and oxygen.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Carbonates, when heated with CO_2 pressures less than equilibrium dissociation pressures, decompose to form alkali metal oxides; the toxicology and disaster hazards are the same as those of very caustic solutions, i.e. react with water or steam (exothermic) to form solutions that are markedly aggressive to all body tissues (chemical burns). Potassium carbonate itself is classified as a strong caustic.

(iii) Sulfates, when heated to decomposition, decompose, evolving SO_3, which in turn dissociates to SO_2 and O_2 (see above); toxic, corrosive fumes.

References [18-24].

(127) K_2CO_3-Li_2SO_4

7. Corrosion

Table 127.4. Corrosion studies from primary research literature

	Studies	References
A	Stainless steel	[25]
	Acid-base relationships in molten carbonates	[26-29]
	Hydrolysis (H_2O) reactions	[30-32]
	Corrosion in molten salts (annotated biblio.)	[33]
	Molten carbonates: fuel cells, thermal energy storage, coal gasification, stack gases	[25,34-38]
B	Fe, various metals	[39-41]
	Ag	[42]
	Thermodynamic redox diagrams	[39,42-44]
	Electrochemical aspects	[45]
	Reviews and annotated corrosion biblio.	[33,46-48]

Compatibility studies: A: various molten carbonates, principally K_2CO_3; B: various sulfates, principally Li_2SO_4. No compatibility studies specific for K_2CO_3-Li_2SO_4 mixtures found.

References [25-48]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change an Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

(127) K_2CO_3-Li_2SO_4

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 128 Na_3AlF_6-LiF

1. *Melting Temperatures (T_m)*

Pure substance melting points:

Na_3AlF_6: 1010°C

LiF: 848°C

Eutectic melting point:

694°C, composition: 15.0 mol % Na_3AlF_6

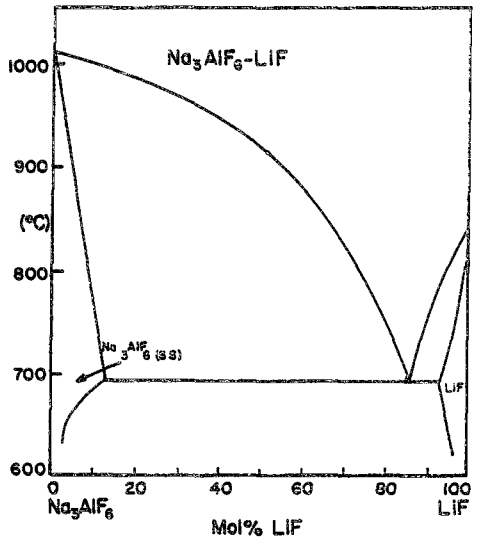

Figure 128.1. Na_3AlF_6-LiF phase diagram

References [1-23].

2. *Density (ρ)*

Measurement method: Archimedean technique [24]

Equation:

$$\rho = a + bT \quad (128.1)$$

precision: in table 128.1 uncertainty: ∿ ± 1.5%

Table 128.1. Parameters of equation (128.1) and precisions

Mol % Na_3AlF_6	a	$-b \times 10^4$	Precision	T range(K)
0	2.3289	4.681	0.00%	1220-1320
10	2.6020	5.540	0.00%	1220-1320
20	2.8927	7.102	0.01%	1220-1320
30	2.9439	7.201	0.00%	1220-1320
40	2.9929	7.421	0.00%	1220-1320
60	3.0951	8.020	0.00%	1220-1320
80	3.1759	8.502	0.05%	1220-1320
100	3.2732	9.199	0.00%	1220-1320

Table 128.2. Density (g cm^{-3}) from equations in Table 128.1

T (K)	Mol % Na_3AlF_6 10	20	30	40	60	80
1220	1.926	2.026	2.065	2.088	2.117	2.139
1230	1.921	2.019	2.058	2.080	2.109	2.130
1240	1.915	2.012	2.051	2.073	2.101	2.122
1250	1.910	2.005	2.044	2.065	2.093	2.113
1260	1.904	1.998	2.037	2.058	2.085	2.105
1270	1.898	1.991	2.029	2.050	2.077	2.096
1280	1.893	1.984	2.022	2.043	2.069	2.088
1290	1.887	1.977	2.015	2.036	2.061	2.079
1300	1.882	1.970	2.008	2.028	2.053	2.071
1310	1.876	1.962	2.001	2.021	2.045	2.062
1320	1.871	1.955	1.993	2.013	2.037	2.054

References [24]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

Measurement method: torsion pendulum [25]

Equation:

$$\eta = a + bT + cT^2 + dT^3 \quad (128.2)$$

precision: in table 128.3 uncertainty: $\sim \pm 25\%$

Table 128.3. Parameters of equation (128.3) and precisions

LiF (mol %)	a	$-b \times 10^2$	$-c \times 10^5$	$d \times 10^8$	Precision	T range(K)
53.874	31.63	1.894	2.144	1.38	2.01%	1130-1320
75.696	33.06	1.921	2.513	1.60	2.90%	1130-1320
87.512	13.84	0.631	0.900	0.48	0.32%	1130-1320
94.921	12.55	0.567	0.783	0.42	0.38%	1130-1320
100.0	11.92	0.582	0.731	0.44	1.01%	1130-1320

Table 128.4. Viscosity (cp) from equations in table 128.3

T (K)	Mol % LiF 53.87	75.70	87.51	94.92
1170	2.323	1.890	1.824	1.958
1180	2.110	1.772	1.748	1.892
1200	1.884	1.555	1.601	1.765
1220	1.680	1.364	1.461	1.643
1240	1.500	1.200	1.327	1.527
1260	1.343	1.064	1.201	1.418
1280	1.212	0.956	1.082	1.315
1300	1.105	0.877	0.971	1.219
1320	1.024	0.828	0.867	1.130

References [25,26]

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [27]

Equation:

$$\kappa = a + bT \quad (128.3)$$

precision: in table 128.5 uncertainty: $\sim \pm 3.0\%$

Table 128.5. Parameters of equation (128.3) and precisions

Mol % LiF	a	b x 10^3	Precision	T range(K)
0	-0.3746	2.500	0.49%	
25	0.4536	2.000	0.00%	1270-1370
42.85	0.5789	2.000	0.91%	1220-1370
56.25	-0.1925	2.700	0.48%	1220-1370
66.66	-2.5361	5.000	1.59%	1120-1320
75.01	-1.2388	4.143	2.18%	1070-1320
81.81	0.3235	3.300	0.79%	1120-1320
87.5	0.8789	3.500	0.27%	1120-1320
92.3	1.4521	3.800	0.52%	1120-1320
96.43	5.7223	1.200	0.22%	1120-1320
100	6.1837	2.000	0.32%	

Table 128.6. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 128.5

T (K)	Mol % LiF					
	66.66	75.0	81.81	87.5	92.3	96.43
1070		3.19				
1100		3.32				
1130	3.11	3.44	4.05	4.80	5.75	7.08
1160	3.26	3.57	4.15	4.90	5.86	7.11
1190	3.41	3.69	4.25	5.01	5.97	7.15
1220	3.56	3.82	4.35	5.11	6.09	7.19
1250	3.71	3.94	4.45	5.22	6.20	7.22
1280	3.86	4.06	4.55	5.32	6.32	7.26
1310	4.01	4.19	4.65	5.43	6.43	7.30
1340						
1370						

References [27,28]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritant and toxic

(ii) Vapor pressure: Na_3AlF_6 at its m.pt. (1000°C), << 0.5mm; LiF, at its m.pt. (848°C), ~ 8.8×10^{-3}mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [29-34]

Table 128.7. Corrosion studies from primary research literature

	Studies	References
A	Cr	[35]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[36,37]
	SSNI-12P	[38]
	Quartz	[39]
	Al	[40]
	Various metals	[41]
B	Pt, Pt-Rh	[42-46,79,80]
	Boron nitride, carbon, Inconel	[47-49]
	Fused MgO	[50]
C	Impurities in electrolyte	[9,51]
	Graphite	[9,51]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[52-54]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[55-70,77,78]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[71-73]
	Electroanalytical studies in molten fluorides	[74]
	Annotated corrosion biblio.	[75]
	Corrosion: molten fluorides (survey)	[76]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys

References [35-80]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

Measurement method: boiling point technique [81]

Equation:

$$\log p = A + B/T \qquad (128.4)$$

precision: in table 128.8 uncertainty: $\sim \pm 10\%$

Table 128.8. Parameters of equation (128.4) and precisions

Mol % Na_3AlF_6	A	-B	Precision
11.0	9.7650	10999	*
15.6	8.7580	10882	*
22.4	8.7380	10719	*
33.0	8.7050	10556	*
52.6	8.6800	10436	*

*data reported graphically; insufficient details for estimate

Table 128.9. Vapor pressure (mm) from equations in table 128.8

T (K)	Mol % Na_3AlF_6				
	11.0	15.6	22.4	33.0	52.6
1280	14.86	1.805	2.311	2.872	3.364
1300	20.15	2.439	3.109	3.846	4.491
1320	27.07	3.266	4.145	5.105	5.942
1340	36.04	4.336	5.480	6.720	7.797
1360	47.59	5.709	7.184	8.775	10.15
1380	62.33	7.456	9.346	11.37	13.11
1400	81.02	9.664	12.07	14.62	16.82
1420	104.5	12.43	15.47	18.67	21.41
1440	133.9	15.89	19.69	23.68	27.09
1460	170.4	20.16	24.90	29.84	34.05

References [81]

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 129 Na_3AlF_6-NaF

1. *Melting Temperature (T_m)*

Pure substance melting point:

Na_3AlF_6: 1010°C

NaF: 995°C

Eutectic melting point:

888°C, composition: 60 mol % Na_3AlF_6

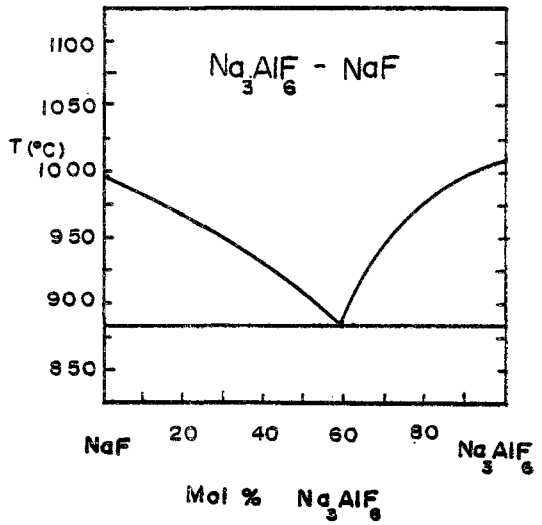

Figure 129.1. Na_3AlF_6-NaF phase diagram

References [1-25]

2. *Density (ρ)*

Measurement method: Archimedean technique [26]

Equation:

$$\rho = a + bT \quad (129.1)$$

precision: in table 129.1 uncertainty: ∿ ± 1.0%

(129) Na_3AlF_6-NaF

Table 129.1. Parameters of equation (129.1) and precision

Mol % NaF	a	$-b \times 10^4$	Precision	T range(K)
0	3.2884	9.373	*	1270-1350
20.93	3.3110	9.504	*	1270-1350
35.71	3.2754	9.201	*	1270-1350
46.88	3.2649	9.103	*	1260-1350
55.56	3.2633	9.098	*	1250-1350
76.92	3.0830	7.902	*	1220-1340
100	2.7334	6.098	*	1260-1340

*insufficient data; not estimated

Table 129.2. Density (g cm^{-3}) from equations in table 129.1

T (K)	Mol % NaF				
	20.93	35.71	46.88	55.56	76.92
1220					2.119
1230					2.111
1240					2.103
1250				2.126	2.095
1260			2.118	2.117	2.087
1270	2.104	2.107	2.109	2.108	2.080
1280	2.095	2.098	2.100	2.099	2.072
1290	2.085	2.089	2.091	2.090	2.064
1300	2.076	2.079	2.082	2.081	2.056
1310	2.066	2.070	2.073	2.072	2.048
1320	2.057	2.061	2.063	2.052	2.040
1330	2.047	2.052	2.054	2.053	2.053
1340	2.038	2.043	2.045	2.044	2.024
1350	2.028	2.033	2.036	2.035	

References [26]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

Measurement method: oscillating body [27]

Equation:

$$\eta = a + bT + cT^2 + dT^3 \quad (129.2)$$

precision: in table 129.3 uncertainty: ± 20%

Table 129.3. Parameters of equation (129.2) and precision

T(K)	a	b x 10^2	c x 10^3	d x 10^5	Precision
1273	6.9382	-4.377	1.865	-4.041	1%

Table 129.4. Viscosity (cp) from equations in table 129.3

Mol % NaF	(cp)	Mol % NaF	(cp)
0	6.938	30	6.213
10	6.647	40	5.586
20	6.486	50	4.362

References [27]

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [26]

Equation:

$$\kappa = a + bT \quad (129.3)$$

precision: in table 129.5 uncertainty: ∿ ± 3.0%

Table 129.5. Parameters of equation (129.3) and precisions

Mol % NaF	-a	b x 10^3	Precision	T range(K)
35.7	0.2343	2.6376	0.10%	1270-1350
50.0	0.2953	2.7374	0.04%	1270-1350
76.9	0.5997	3.4998	0.04%	1270-1350

Table 129.6. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 129.5

T (K)	Mol % NaF		
	35.7	50.0	76.9
1270	3.12	3.18	3.85
1280	3.14	3.21	3.88
1290	3.17	3.24	3.92
1300	3.20	3.26	3.95
1310	3.22	3.29	3.99
1320	3.24	3.32	4.02
1330	3.27	3.35	4.06
1340	3.30	3.37	4.09
1350	3.33	3.34	4.13

References [26]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure: Na_3AlF_6 at m.pt., 1010°C, $\sim$ << 0.5mm; NaF at m.pt., 995°C, $\sim$0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [28-33]

7. Corrosion

Table 129.7. Corrosion studies from primary research literature

	Studies	References
A	Cr	[34]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[35,36]
	SSNI-12P	[37]
	Quartz	[38]
	Al	[39]
	Various metals	[40]
B	Pt	[41-45]
	Boron nitride, carbon, Inconel	[46-48]
	Fused MgO	[49]
C	Impurities in electrolyte	[50,51]
	Graphite	[50,51]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[52-54]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[55-70,77,78]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[71-73]
	Electroanalytical studies in molten fluorides	[74]
	Annotated corrosion biblio.	[75]
	Corrosion: molten fluorides(survey)	[76]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [34-78]

8. Diffusion

Measurement method: chronopotentiometry [79]

Diffusing species investigated in Na_3AlF_6-NaF as solvent:

Fe^{3+}, Ni^{2+}, Zn^{2+}

precision: not estimated uncertainty: ∿ ± 10%

Table 129.8 Diffusion coefficients

Species	$D \times 10^5$ T (K)	($cm^2\ s^{-1}$)
Fe^{3+}	1273	1.00
Ni^{2+}	1273	0.20
Zn^{2+}	1273	0.90

References Fe^{3+}, Ni^{2+}, Zn^{2+} [79]

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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1. *Melting Temperature (T_m)*

Pure substance melting points:

Na_3AlF_6: 1010°C

KF: 856°C

Eutectic 1, melting point:

890°C, composition: 55.9 mol % KF
25 wt % KF

Eutectic 2, melting point:

740°C, composition: 91.9 mol % KF
75.7 wt % KF

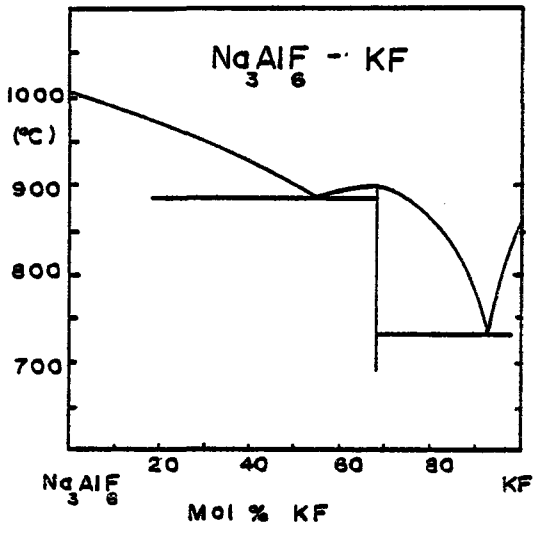

Figure 130.1. Na_3AlF_6-KF phase diagram

References [1-19]

2. *Density (ρ)*

Measurement method: Archimedean technique [20]

Equation: (density-composition isotherm)

$$\rho = a + bC + cC^2 + dC^3 \quad (130.1)$$

(C = mol % KF)

precision: in table 130.1 uncertainty: ∿ ± 1.5%

Table 130.1. Parameters of equation (130.1) and precision

T (K)	a	b x 10^3	-c x 10^4	d x 10^7	Precision
1273	2.0611	3.258	1.124	6.024	0.4%

Table 130.2. Density-composition isotherm at 1273K from equation in table 130.1

Mol % KF	ρ (g cm^{-3})	Mol % KF	ρ (g cm^{-3})
10	2.0831	60	1.9820
20	2.0861	70	1.9450
30	2.0740	80	1.9107
40	2.0501	90	1.8829
50	2.0183		

References [20]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

(130) Na_3AlF_6-KF

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure: Na_3AlF_6, at m.pt. 1000°C, $\sim << 0.5$mm, KF, at m.pt., 856°C, $\sim$ 0.5mm.

B. Disaster hazards

(i) Molten salts bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [21-26]

7. Corrosion

Table 130.3. Corrosion studies from primary research literature

	Studies	References
A	Cr	[27]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[28,29]
	SSNI-12P	[30]
	Quartz	[31]
	Al	[32]
	Various metals	[33]
B	Pt	[34-38]
	Boron nitride, carbon, Inconel	[39-41]
	Fused MgO	[42]
C	Impurities in electrolyte	[43,44]
	Graphite	[43,44]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[45-47]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[48-63,70,71]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[64-66]
	Electroanalytical studies in molten fluorides	[67]
	Annotated corrosion biblio.	[68]
	Corrosion: molten fluorides(survey)	[69]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technologicl aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [27-71]

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

(130) Na_3AlF_6-KF

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 131 Na_3AlF_6-BeF_2

1. *Melting Temperature (T_m)*

Pure substance melting points:

Na_3AlF_6: 1010°C

BeF_2: 797°C

Eutectic melting point:

760°C, composition: 16 wt % BeF_2

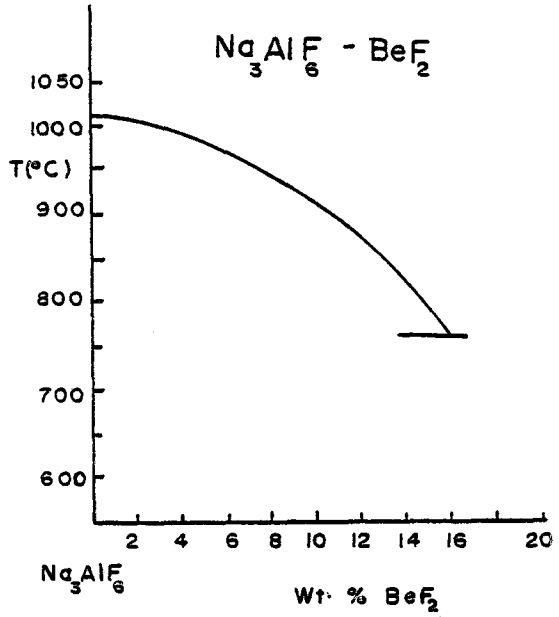

Figure 131.1. Na_3AlF_6-BeF_2 phase diagram

References [1-14]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [15]

Equation:

$$\kappa = a + bC \quad (131.1)$$

(C = mol % BeF_2)

precision: in table 131.1 uncertainty: ∿ ± 10%

Table 131.1. Parameters of equation (131.1) and precision

T (K)	a	$-b \times 10^3$	Precision
1273	2.7716	12.766	0.5%

Table 131.2. Specific conductance at 1273 K from equation in table 131.1

Mol % BeF_2	κ (ohm^{-1} cm^{-1})	Mol % BeF_2	κ (ohm^{-1} cm^{-1})
20	2.516	40	2.261
30	2.389	50	2.133

References [15]

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally quite irritant and toxic; toxicity of berylium compounds is rated high (i.e. may cause death or permanent injury after very short exposure to small quantities).

(ii) Vapor pressure: Na_3AlF_6, at m.pt. 1000°C, ∿ << 0.5mm; BeF_2, at m.pt. 797°C, ∿<< 0.5mm.

B. Disaster Hazards

(i) Molten salts bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [16-21]

(131) Na_3AlF_6-BeF_2

7. Corrosion

Table 131.3. Corrosion studies from primary research literature

	Studies	References
A	Cr	[22]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys W, B, and N)	[23,24]
	SSNI-12P	[25]
	Quartz	[26]
	Al	[27]
	Various metals	[28]
B	Pt	[29-33]
	Boron nitride, carbon, Inconel	[34-36]
	Fused MgO	[37]
C	Impurities in electrolyte	[38,39]
	Graphite	[38,39]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[40-42]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[43-58,65,66]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[59-61]
	Electroanalytical studies in molten fluorides	[62]
	Annotated corrosion biblio.	[63]
	Corrosion: molten fluorides(survey)	[64]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [22-66]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

(131) Na_3AlF_6-BeF_2

10. Heat Capacity (C_p)

No Data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

[1] Chu, Y. A. and Belyaev, A. I., Izv. Vyssh. Ucheb. Zaved., Tsvet. Met. 2 69 (1959).

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System 132 Na_3AlF_6-MgF_2

1. *Melting Temperatures (T_m)*

Pure substance melting points:

MgF_2: 1263°C

Na_3AlF_6: 1010°C

Eutectic melting point:

924°C, composition: 57.5 mol % Na_3AlF_6; [82.0 wt %, Na_3AlF_6]

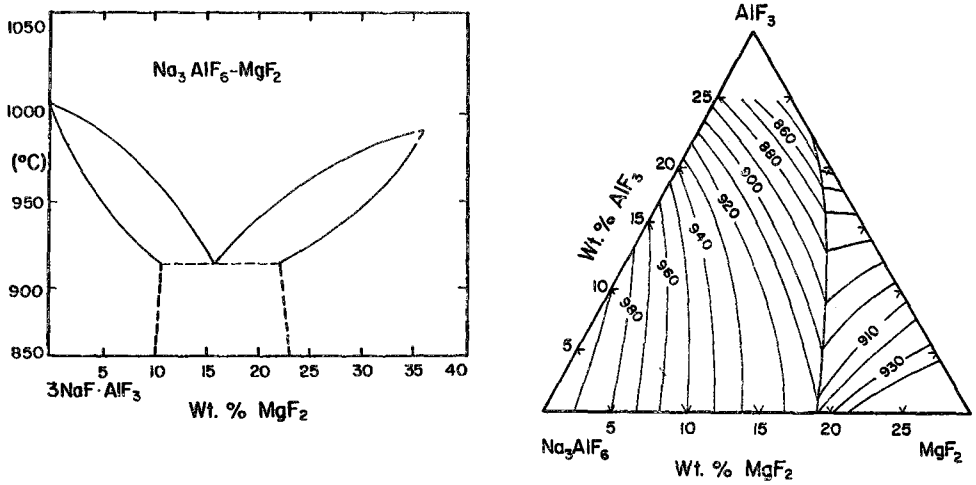

Figure 132.1. Na_3AlF_6-MgF_2 phase diagram

References [1-23]

2. *Density (ρ)*

Measurement method: Archimedean technique [24]

Equation:

$$\rho = 2.096 + 1.724 \times 10^{-3} C \quad (132.1)$$

(C = mol % MgF_2)

precision: not estimated, graphical data. uncertainty: ∿ ± 5.0%

Table 132.1. Density-composition isotherm at 1273°K from equation (132.1)

Mol % MgF_2	ρ ($g\ cm^{-3}$)
10	2.11
20	2.13
30	2.15

References [24]

(132) Na_3AlF_6-MgF_2

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

Measurement method: oscillating sphere technique [25]

Equation: (viscosity-composition isotherm)

$$\eta = a + bC + cC^2 \quad (132.2)$$

(C = mol % MgF_2)

precision: in table 132.3 uncertainty: $\sim \pm 15\%$

Table 132.2. Parameters of equation (132.2) and precisions

T(K)	a	$-b \times 10^3$	$c \times 10^4$	Precision
1273	2.7901	4.659	7.930	1.8%
1323	2.3380	7.945	7.209	1.6%

Table 132.3. Viscosity (cp) from equations in table 132.2

Mol % MgF_2	1273 K	1323 K
0	2.79	2.34
10	2.82	2.33
20	3.01	2.47
30	3.36	2.75
40	3.87	3.17
50	4.54	3.74

References [25]

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [26]

Equation:

$$\kappa = a + bT \quad (132.3)$$

precision: in table 132.5 uncertainty: $\sim \pm 10\%$

Table 132.4. Parameters of equation (132.3) and precisions

Mol % MgF_2	a	b x 10^3	Precision	T range(K)
6.05	0.2176	1.771	0.12%	1270-1420
37.29	0.1725	1.729	0.12%	1270-1420
49.45	0.0206	1.800	0.11%	1270-1420
94.08	-0.4457	2.043	0.03%	1270-1420

Table 132.5. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 132.4

T (K)	Mol % MgF_2			
	6.05	37.29	49.45	94.08
1270	2.47	2.37	2.31	2.15
1290	2.50	2.40	2.34	2.19
1310	2.54	2.44	2.38	2.23
1330	2.57	2.47	2.43	2.27
1350	2.61	2.51	2.45	2.31
1370	2.64	2.54	2.49	2.35
1390	2.68	2.58	2.52	2.39
1410	2.72	2.61	2.56	2.44

References [26]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure: *no information for this system;* but see Na_3AlF_6 [29] and MgF_2 [29].

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [27-32]

7. Corrosion

Table 132.6. Corrosion studies from primary research literature

	Studies	References
A	Cr	[33]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[34,35]
	SSNI-12P	[36]
	Quartz	[37]
	Al	[38]
	Various metals	[39]
B	Pt	[40-44]
	Boron nitride, carbon, Inconel	[45-47]
	Fused MgO	[48]
C	Impurities in electrolyte	[49,50]
	Graphite	[49,50]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[51-53]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[54-69,76,77]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[70-72]
	Electroanalytical studies in molten fluorides	[73]
	Annotated corrosion biblio.	[74]
	Corrosion: molten fluorides(survey)	[75]

A: studies principally in molten NaF, KF and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [33-77]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

(132) Na_3AlF_6-MgF_2

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 133 Na_3AlF_6-CaF_2

1. *Melting Temperatures (T_m)*

Pure substance melting points:

Na_3AlF_6: 1010°C
CaF_2: 1418°C

Eutectic melting point:

946°C, composition: 50 mol % Na_3AlF_6; [72.9 wt % Na_3AlF_6]

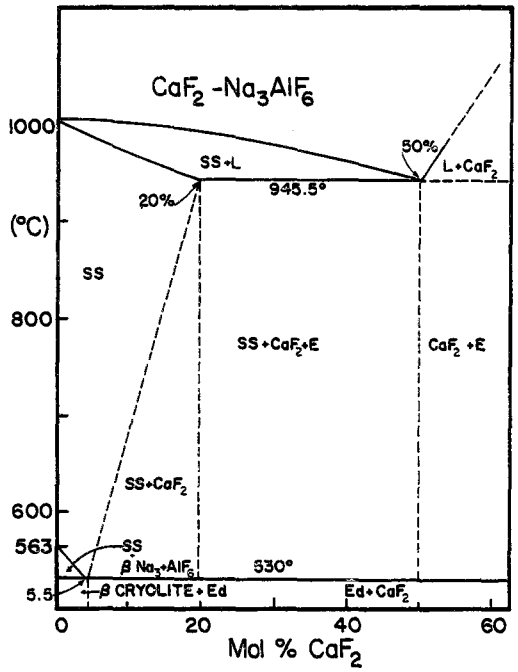

Figure 133.1. Na_3AlF_6-CaF_2 phase diagram

References [1-23]

2. *Density (ρ)*

Measurement method: Archimedean technique [24]

Equation:

$$\rho = a + bT \quad (133.1)$$

precision: in table 133.1 uncertainty: ∿ ± 1.5%

(133) Na_3AlF_6-CaF_2

Table 133.1. Parameters of equation (133.1) and precision

Mol % CaF_2	a	-b x 10^4	Precision	T range(K)
0	3.2884	9.373	*	1270-1350
12.4	3.2559	8.906	*	1260-1350
23.0	3.2653	8.705	*	1260-1350
32.18	3.2949	8.702	*	1270-1370
40.2	3.2892	8.398	*	1260-1360
64.19	3.4023	8.406	*	1280-1370

*insufficient data for estimate

Table 133.2. Density (g cm^{-3}) from equations in table 133.1

	Mol % CaF_2				
T (K)	12.4	23.0	32.18	40.2	64.19
1260	2.134	2.169		2.231	
1270	2.125	2.160	2.190	2.223	
1280	2.116	2.151	2.181	2.214	2.326
1290	2.107	2.142	2.172	2.206	2.318
1300	2.098	2.134	2.164	2.197	2.310
1310	2.089	2.125	2.155	2.189	2.301
1320	2.080	2.116	2.146	2.181	2.293
1330	2.071	2.108	2.138	2.172	2.284
1340	2.063	2.099	2.129	2.164	2.276
1350	2.054	2.090	2.120	2.156	2.267
1360			2.111	2.147	2.259
1370			2.103		2.251

References [24]

3. *Surface Tension* (γ)

No data

4. *Viscosity* (η)

Measurement method: oscillating sphere technique [25]

Equation: (viscosity - composition isotherm)

$$\eta = a + bC + cC^2 + dC^3 \quad (133.2)$$

(C = mol % CaF_2)

precision: in table 133.3 uncertainty: $\sim \pm 15\%$

Table 133.3. Parameters of equation (133.2) and precisions

T (K)	a	b x 10^2	c x 10^4	d x 10^6	Precision
1273	2.777	1.327	-2.230	7.598	1.3%
1323	2.331	0.191	3.492		1.8%

Table 133.4. Viscosity (cp) from equations in table 133.3

Mol % CaF_2	1273 K	1323 K
0	2.78	2.33
10	2.90	2.39
20	3.01	2.51
30	3.18	2.70
40	3.44	2.97
50	3.83	3.30
60	4.41	3.70

References [25]

5. *Electrical Conductance (κ)*

Measurement method: in table 133.5

precision: in tables 133.6 and 133.7 uncertainty: in table 133.5

Table 133.5. Conductance studies, techniques, systems and uncertainties

Study	Conductance technique	Na_3AlF_6-CaF_2 (mol % CaF_2)	T range (K)	Uncertainty (in conductance values)
<u>24</u>	classical ac	0 - 32%	1270-1350	∿ ± 3%
<u>26</u>	classical ac	0 - 50%	1273	∿ ± 5%
27	classical ac	0%	1250-1300	∿ ± 5%

The underscored studies are the recommended data sets

(133) Na_3AlF_6-CaF_2

Equations:

(conductance-temperature dependence) [24]

$$\kappa = a + bT \quad (133.3)$$

(conductance-composition isotherm) [26]

$$\kappa = a' + b'C + c'C^2 \quad (133.4)$$

(C = mol % CaF_2)

Table 133.6. Parameters of equation (133.3) and precisions

Mol % CaF_2	-a	b x 10^2	Precision	T range(K)
12.3	0.6854	0.2688	0.09%	1270-1350
23.0	0.7725	0.2712	0.05%	1270-1350
32.3	0.7643	0.2687	0.05%	1270-1350

Table 133.7. Parameters of equation (133.4) and precision

T (K)	a'	b' x 10^3	c' x 10^4	Precision
1273	2.8695	6.7638	2538.7	0.30%

Table 133.8. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 133.6

T (K)	Mol % CaF_2		
	12.3	23.0	32.3
1270	2.728	2.672	2.649
1280	2.755	2.699	2.676
1290	2.782	2.727	2.703
1300	2.809	2.754	2.731
1310	2.836	2.781	2.757
1320	2.862	2.808	2.783
1330	2.889	2.835	2.810
1340	2.916	2.862	2.837
1350	2.943	2.889	2.864

Table 133.9. Electrical conductance at 1273K from equation (133.4)

CaF_2 (mol %)	κ (ohm^{-1} cm^{-1})	CaF_2 (mol %)	κ (ohm^{-1} cm^{-1})
0	2.87	30	2.69
10	2.80	40	2.64
20	2.74	50	2.60

References [24,26,27]

(133) Na_3AlF_6-CaF_2

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure: no information for this system; but see Na_3AlF_6 [30], and CaF_2 [30].

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [28-33].

(133) Na_3AlF_6-CaF_2

7. Corrosion

Table 133.10. Corrosion studies from primary research literature

	Studies	References
A	Cr	[34]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[35,36]
	SSNI-12P	[37]
	Quartz	[38]
	Al	[39]
	Various metals	[40]
B	Pt	[41-45]
	Boron nitride, carbon, Inconel, Mo	[46-48]
	Fused MgO	[49]
C	Impurities in electrolyte	[50,51,79]
	Graphite	[50,51,80]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[52-54]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,....)	[55-70,77,78]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[71-73]
	Electroanalytical studies in molten fluorides	[74]
	Annotated corrosion biblio.	[75]
	Corrosion: molten fluorides (survey)	[76]

A: studies principally in molten NaF, KF and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles and surveys.

References [34-80]

(133) Na_3AlF_6-CaF_2

8. Diffusion

Measurement method: rotating disc electrode [81]

List of diffusing species investigated in Na_3AlF_6-CaF_2 as solvent

Al_2O_3

precision: insufficient data for estimate uncertainty: ∿ ± 20%

Equation: (diffusion coefficient-composition isotherm)

$$D = a + bC + cC^2 + dC^3 \quad (133.5)$$

(C = mol % CaF_2)

Table 133.12. Parameters of equation (133.5) and precision

T (K)	a x 10^5	b x 10^7	c x 10^8	d x 10^{10}	Precision
1353	1.342	5.57	-2.68	2.69	*

Table 133.11. Diffusion coefficients at 1353°K from equation (133.5)

CaF_2 (mol %)	$D_{Al_2O_3}$ x 10^5 (cm^2 s^{-1})	CaF_2 (mol %)	$D_{Al_2O_3}$ x 10^5 (cm^2 s^{-1})
0	1.34	40	1.00
10	1.66	50	0.79
20	1.60	60	0.85
30	1.33		

References: Al_2O_3, [81]; see systems 66, 139 for diffusion studies of Al_2O_3 in Na_3AlF_6.

9. Heat of Fusion (ΔH_f)

No data

10. Heat Capacity (C_p)

No data

(133) Na_3AlF_6-CaF_2

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 134 Na_3AlF_6-BaF_2

1. *Melting Temperature (T_m)*

Pure substance melting points:

Na_3AlF_6: 1010°C

BaF_2: 1320°C

Eutectic melting point:

835°C composition: 62.5 wt % BaF_2 (67 mol % BaF_2)

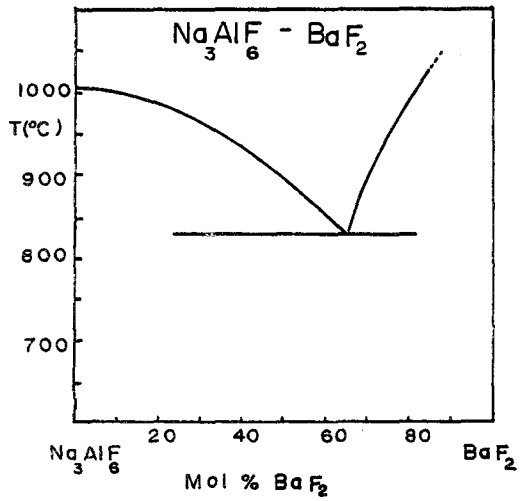

Figure 134.1 Na_3AlF_6-BaF_2 phase diagram

References [1-17]

2. *Density (ρ)*

Measurement method: Archimedean technique [18]

Equation:

$$\rho = a + bT \quad (134.1)$$

precision: in table 134.1 uncertainty: $\sim \pm 1.0\%$

(134) Na_3AlF_6-BaF_2

Table 134.1. Parameters of equation (134.1) and precisions

Mol % BaF_2	a	-b x 10^4	Precision	T range(K)
0	3.0943	8.046	0.16%	1310-1400
25	3.4250	7.938	0.03%	1280-1370
54.4	3.9212	7.626	0.19%	1220-1330
66.6	4.5725	10.480	0.08%	1220-1330
75.1	4.7093	7.359	0.03%	1250-1330

Table 134.2. Density (g cm^{-3}) from equations in table 134.1

	Mol % BaF_2			
T (K)	25	54.4	66.6	75.1
1220		2.991	3.294	
1230		2.983	3.283	
1240		2.976	3.273	
1250		2.968	3.263	3.789
1260		2.960	3.252	3.782
1270		2.953	3.242	3.775
1280	2.409	2.945	3.231	3.767
1290	2.401	2.937	3.221	3.760
1300	2.393	2.930	3.210	3.753
1310	2.385	2.922	3.200	3.745
1320	2.377	2.915	3.189	3.738
1330	2.369	2.907	3.179	3.731
1340	2.361			
1350	2.353			
1360	2.345			
1370	2.338			
1380				
1390				
1400				

References [18,19]

3. *Surface Tension* (γ)

No data

4. *Viscosity* (η)

No data

5. *Electrical Conductance* (κ)

No data

(134) Na_3AlF_6-BaF_2

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritant and toxic.

(ii) Vapor pressure: BaF_2, at m.pt., 1320°C, $\sim$ < 0.5mm; Na_3AlF_6, at m.p.t., 1010°C, $\sim$ << 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contracted with acids, emit highly toxic fumes.

References [20-25]

(134) Na_3AlF_6-BaF_2

7. Corrosion

Table 134.3. Corrosion studies from primary research literature

	Studies	References
A	Cr	[26]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[27,28]
	SSNI-12P	[29]
	Quartz	[30]
	Al	[31]
	Various metals	[32]
B	Pt	[33-37]
	Boron nitride, carbon, Inconel	[38-40]
	Fused MgO	[41]
C	Impurities in electrolyte	[42,43]
	Graphite	[42,43]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[44-46]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[47-62,69,60]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[63-65]
	Electroanalytical studies in molten fluorides	[66]
	Annotated corrosion biblio.	[67]
	Corrosion: molten fluorides(survey)	[68]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [26-70]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 135 Na_3AlF_6-AlF_3

1. *Melting Temperature (T_m)*

Pure substance melting points:

Na_3AlF_6: 1010°C
AlF_3: does not melt; sublimes with 1 atm equil^m press. at ∿ 1255°C.

Eutectic melting point:

737°C, composition: 30 wt % AlF_3

694°C, composition: 39 wt % AlF_3

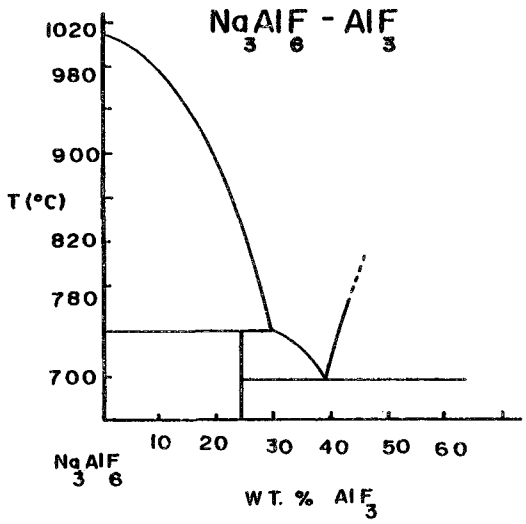

Figure 135.1 Na_3AlF_6-AlF_3 phase diagram

References [1-25]

2. *Density (ρ)*

Measurement method: Archimedean technique [26]

Equation:

$$\rho = a + bT \quad [135.1)$$

precision: in table 135.1 uncertainty: ∿ ± 1.0%

(135) Na_3AlF_6-AlF_3

Table 135.1. Parameters of equation (135.1) and precision

Mol % AlF_3	a	-b x 10^4	Precision	T range(K)
0	3.3070	9.515	*	1300-1340
8.31	3.2349	9.008	*	1300-1340
15.69	3.2549	9.253	*	1300-1340
23.52	3.2415	9.265	*	1300-1340
28.21	3.2294	9.259	*	1300-1340

*insufficient data; not estimated

Table 135.2. Density (g cm^{-3}) from equations in table 135.1

	Mol % AlF_3				
T (K)	0	8.31	15.69	23.52	28.21
1300	2.070	2.064	2.052	2.037	2.026
1310	2.061	2.055	2.043	2.028	2.017
1320	2.051	2.046	2.034	2.019	2.007
1330	2.042	2.037	2.024	2.009	1.998
1340	2.032	2.028	2.015	2.000	1.989

References [26]

3. Surface Tension (γ)

No data

4. Viscosity (η)

Measurement method: oscillating sphere technique [27]

Equation:

$$\eta = a + bT + cT^2 \quad (135.2)$$

precision: in table 135.3 uncertainty: $\sim \pm 30\%$

Table 135.3. Parameters of equation (135.2) and precisions

AlF_3 (mol %)	a	-b x 10^2	c x 10^6	Precision	T range(K)
21.7	20.847	0.604	-4.46	0.6%	1250-1290
30.6	58.889	7.332	24.23	1.3%	1270-1320

Table 135.4. Viscosity (cp) from equation in table 135.3

	Mol % AlF_3	
T (K)	21.7	30.6
1250	6.49	
1260	6.32	
1270	6.15	4.85
2180	5.98	4.74
1290	5.80	4.63
1300		4.52
1310		4.42
1320		4.33

References [27]

5. *Electrical Conductivity* (κ)

Measurement method: classical ac technique [28]

Equation:

$$\kappa = a + bT \quad (135.3)$$

precision: in table 135.5. uncertainty: $\sim \pm 30\%$

Table 135.5. Parameters of equation (135.3) and precisions

Mol % AlF_3	a	b x 10^3	Precision	T range(K)
11.6	-0.1692	2.237	0.14%	1270-1350
17.9	0.0231	2.025	0.06%	1270-1350

(135) Na_3AlF_6-AlF_3

Table 135.6. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 135.5

T (K)	Mol % AlF_3	
	11.6	17.9
1270	2.67	2.60
1280	2.70	2.62
1290	2.72	2.64
1300	2.74	2.66
1310	2.76	2.68
1320	2.78	2.70
1330	2.81	2.72
1340	2.83	2.74
1350	2.85	2.76

References [28]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritants and toxic; alumina is classed as a nuisance particulate

(ii) Vapor pressure: no information on this system; Na_3AlF_6 at its m.pt. (1010°C), << 0.5mm, AlF_3 sublimes at ∿ 1260°C.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [29-34]

7. Corrosion

Table 135.7. Corrosion studies from primary research literature

	Studies	References
A	Cr	[35]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[36,37]
	SSNI-12P	[38]
	Quartz	[39]
	Al	[40]
	Various metals	[41]
B	Pt	[42-46]
	Boron nitride, carbon, Inconel	[47-49]
	Fused MgO	[50]
C	Impurities in electrolyte	[51,52]
	Graphite	[51,52]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[53-55]
D	Corrosion studies in molten salts with NaF as one component (e.g. Cl, CO_3,...)	[56-71,78,79]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[72-74]
	Electroanalytical studies in molten fluorides	[75]
	Annotated corrosion biblio.	[76]
	Corrosion: molten fluorides(survey)	[77]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [35-79]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f)

No data

(135) Na_3AlF_6-AlF_3

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 136 Na_3AlF_6-NaCl

1. *Melting Temperatures (T_m)*

Pure substance melting points:

Na_3AlF_6: 1010°C
NaCl: 800°C

Eutectic melting point:

734°C, composition: 11.3 mol % Na_3AlF_6

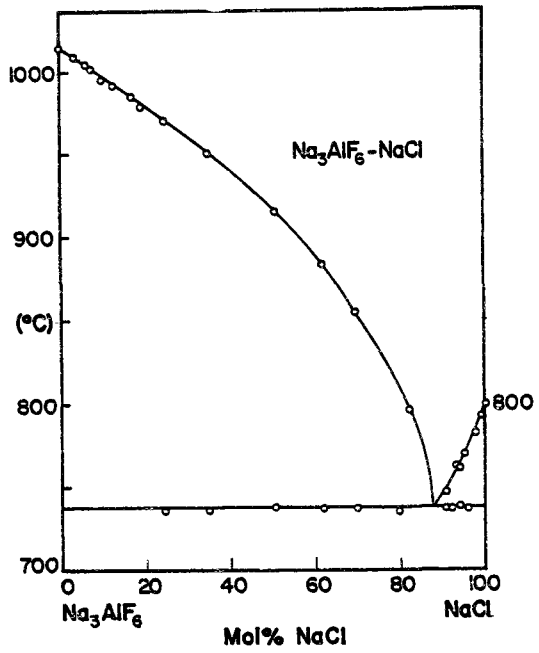

Figure 136.1. Na_3AlF_6-NaCl phase diagram

References [1-26].

2. Density (ρ)

Measurement method: Archimedean technique [27]

Equation: (density-composition isotherm)

$$\rho = a + bC + cC^2 \quad (136.1)$$

precision: in table 136.1 uncertainty: ∿ ± 1.5%

Table 136.1. Parameters of equation (136.1) and precision

T (K)	a	$-b \times 10^3$	$c \times 10^5$	Precision
1273	2.1045	6.013	3.712	0.22%

Table 136.2. Density of (Na_3AlF_6-NaCl) composition isotherm at 1273K from equation in table 136.1

Mol % NaCl	ρ (g cm^{-3})	Mol % NaCl	ρ (g cm^{-3})
0	2.1045	30	1.9575
10	2.0480	40	1.9233
20	1.9990	50	1.8966

References [27]

3. Surface Tension (γ)

No data

4. Viscosity (η)

Measurement method: oscillational sphere [28]

Equation:

$$\eta = a + bT + cT^2 \quad (136.2)$$

precision: in table 136.3 uncertainty: ∿ ± 25%

Table 136.3. Parameters of equation (136.2) and precisions

NaCl (mol %)	a	$-b \times 10^2$	$c \times 10^5$	Precision	T range(K)
28.53	-3.699	-1.837	-1.075	0.07%	1220-1320
47.31	33.025	4.326	1.480	0.67%	1170-1320
60.62	-14.557	-3.107	-1.439	1.50%	1170-1320
70.54	41.713	6.034	2.244	4.71%	1170-1320
78.22	-3.293	-1.019	-0.522	0.30%	1170-1320
84.35	-17.223	-3.352	-1.507	1.02%	1170-1320
89.34	68.911	10.533	4.072	4.50%	1170-1320
93.49	37.285	5.469	2.048	2.23%	1120-1320
97.00	24.490	3.492	1.278	2.36%	1120-1320

Table 136.4. Viscosity (cp) from equations in table 136.3

	Mol % NaCl						
T (K)	28.53	47.31	60.62	70.54	84.35	89.34	93.49
1120						2.012	1.713
1140						1.746	1.545
1160						1.512	1.393
1180		2.586	2.072	1.757	1.349	1.311	1.258
1200		2.425	2.009	1.619	1.302	1.143	1.138
1220	2.715	2.276	1.934	1.498	1.243	1.007	1.036
1240	2.554	2.139	1.847	1.395	1.172	0.903	0.949
1260	2.384	2.014	1.750	1.311	1.089	0.832	0.879
1280	2.205	1.901	1.640	1.244	0.994	0.794	0.825
1300	2.018	1.799	1.519	1.195	0.887	0.788	0.788
1320	1.822	1.710	1.386	1.164	0.768	0.815	0.767

References [28,29]

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [30]

Equation:

$$\kappa = a + bT \quad (136.3)$$

precision: in table 136.5 uncertainty: ∿ ± 3.0%

Table 136.5. Parameters of equation (136.3) and precisions

Mol % NaCl	a	$b \times 10^3$	Precision	T range(K)
15.8	-0.1150	2.3407	0.26%	1250-1360
28.5	-0.3202	2.5343	0.32%	1250-1340
38.8	-0.1254	2.4114	0.24%	1240-1360
47.4	-0.1345	2.4191	0.29%	1240-1350
60.6	0.0943	2.2631	0.34%	1200-1330
70.5	0.5431	1.9764	0.23%	1200-1320
78.2	0.9560	1.7571	0.22%	1200-1330
84.2	1.4848	1.4381	0.23%	1210-1340
89.3	1.5749	1.4556	0.23%	1200-1330
93.5	1.6617	1.1613	0.31%	1200-1320
97.1	2.1141	1.4300	0.14%	1180-1320

Table 136.6. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 136.5

T (K)	Mol % NaCl						
	15.8	38.8	60.6	70.5	84.2	93.5	97.1
1200			2.81				
1220			2.86				
1240		2.87	2.90	2.30	3.27	3.66	3.89
1260	2.83	2.91	2.95	3.03	3.30	3.69	3.93
1280	2.88	2.96	2.99	3.07	3.33	3.73	3.94
1300	2.93	3.01	3.04	3.11	3.35	3.76	3.97
1320	2.98	3.06	3.08	3.15	3.38		4.00
1340	3.02	3.10			3.41		
1360	3.07	3.15					

References [30]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: NaCl, very low; Na_3AlF_6, inorganic fluorides are generally irritant and toxic

(ii) Vapor pressure: NaCl, at m.pt. (800°C), ~ 0.34mm; Na_3AlF_6,

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Inorganic halides when heated to decomposition or contacted with acids, highly toxic chloride fumes are evolved.

References [31-3o]

7. Corrosion

Table 136.7. Corrosion studies from primary research literature

	Studies	References
A	Cr	[37]
A	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[38,39]
A	SSNI-12P	[40]
A	Quartz	[41]
A	Al	[42]
A	Various metals	[43]
B	Pt	[44-48]
B	Boron nitride, carbon, Inconel	[49-51]
B	Fused MgO	[52]
C	Impurities in electrolyte	[12,53]
C	Graphite	[12,53]
C	TiC, TiB_2, CrB_2, ZrN, NbB_2	[54-56]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[57-72,79,80]
D	Electrochemical behavior of oxide ions and related species in molten fluorides	[73-75]
D	Electroanalytical studies in molten fluorides	[76]
D	Annotated corrosion biblio.	[77]
D	Corrosion: molten fluorides (survey)	[78]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys

References [12,37-80]

8. Diffusion

Measurement method: rotating disc electrode [81]

List of diffusing species investigated in Na_3AlF_6-NaCl as solvent

Al_2O_3

precision: * uncertainty: ∿ ± 20%

*insufficient data for estimate

Equation: (isothermal study at 1353K)

$$D = 1.30 \times 10^{-5} + 5.72 \times 10^{-7}W \quad (136.4)$$

where W is the weight fraction of NaCl in the Na_3AlF_6-NaCl mixture

Table 136.8. Diffusion coefficients at 1353K from equation (136.4)

NaCl (wt %)	D x 10^5 Al_2O_3 (cm^2 s^{-1})	NaCl (wt %)	D x 10^5 Al_2O_3 (cm^2 s^{-1})
0	1.30	30	3.02
10	1.87	40	3.59
20	2.44	50	4.16

References Al_2O_3, [81]; see Systems 66 and 139 for diffusion studies of Al_2O_3 and Na_3AlF_6

9. Heat of Fusion (ΔH_f)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 137 Na_3AlF_6-$BaCl_2$

1. *Melting Temperature (T_m)*

Pure substance melting points:

Na_3AlF_6: 1010°C

$BaCl_2$: 962°C

Eutectic 1, melting point:

745°C, composition: ∿ 65 mol % $BaCl_2$

Eutectic 2, melting point:

762°C, composition: ∿ 91 mol % $BaCl_2$

Compound melting point:

786°C, composition: 80 mol % $BaCl_2$ (i.e., $Na_3AlF_6.4BaCl_2$)

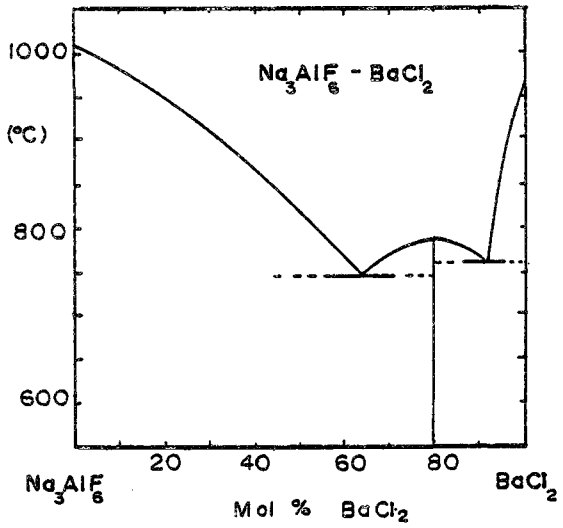

Figure 137.1. Na_3AlF_6-$BaCl_2$ phase diagram

References [1-15]

2. *Density (ρ)*

Measurement method: Archimedean technique [16]

Equation:

$$\rho = a + bT \quad (137.1)$$

precision: in table 137.1 uncertainty: ∿ ± 10%

(137) Na_3AlF_6-$BaCl_2$

Table 137.1. Parameters of equation (137.1) and precisions

Mol % $BaCl_2$	a	-b x 10^4	Precision	T range(K)
25	3.1217	9.043	0.07%	1030-1120
50	3.2910	9.052	0.16%	1030-1110
75	3.5173	8.124	0.12%	1030-1120

Table 137.2. Density (g cm^{-3}) from equations in table 137.1

	Mol % $BaCl_2$		
T (K)	25	50	75
780		2.585	
820		2.549	
860		2.513	2.819
900		2.476	2.786
940	2.272	2.440	2.754
980	2.236	2.404	2.721
1020	2.199	2.368	2.689
1060	2.163	2.332	2.656
1100	2.127	2.295	2.624

References [16,17]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

Measurement method: oscillating sphere technique [18]

Equation:

$$\eta = a + bC + cT^2 \quad (137.2)$$

precision: in table 137.3 uncertainty: $\sim \pm 10\%$

Table 137.3. Parameters of equation (137.2) and precision

$BaCl_2$ (mol %)	a	b x 10^2	c x 10^5	Precision	T range(K)
60	45.047	-5.861	1.878	*	1050-1130

*insufficient data for estimation.

Table 137.4. Viscosity (cp) at 60 mol % $BaCl_2$ from equation in table 137.3

T (K)	η (cp)	T (K)	η (cp)
1050	4.21	1100	3.30
1060	4.02	1110	3.12
1070	3.83	1120	2.96
1080	3.65	1130	2.79
1090	3.47		

References [18]

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [19]

Equation:

$$\kappa = a + bT \quad (137.3)$$

precision: in table 137.5 uncertainty: ∿ ± 5.0%

Table 137.5. Parameters of equation (137.3) and precision

Mol % $BaCl_2$	-a	b x 10^3	Precision	T range(K)
10	1.1634	3.260	*	1270-1370
30	4.1164	4.984	*	1270-1370
50	3.3199	3.929	*	1270-1370
70	3.2316	3.694	*	1270-1370
90	3.0751	3.620	*	1270-1370

(137) Na_3AlF_6-$BaCl_2$

Table 137.6. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 137.5

T (K)	Mol % $BaCl_2$				
	10	30	50	70	90
1270	2.977	2.213	1.670	1.460	1.523
1280	3.009	2.263	1.709	1.497	1.559
1290	3.042	2.313	1.748	1.534	1.595
1300	3.075	2.363	1.788	1.571	1.631
1310	3.107	2.413	1.827	1.608	1.667
1320	3.140	2.463	1.866	1.645	1.704
1330	3.172	2.512	1.905	1.682	1.740
1340	3.205	2.562	1.945	1.719	1.776
1350	3.238	2.612	1.984	1.756	1.812
1360	3.270	2.662	2.023	1.793	1.848
1370	3.303	2.712	2.063	1.830	1.885

References [19,20]

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritants and toxic, soluble barium compounds are classed as toxic.

(ii) Vapor pressure: Na_3AlF_6 at m.pt., 1010°C, ∿ < 0.5mm; $BaCl_2$, at m.pt., 962°C, ∿ < 0.5mm.

B. Disaster hazard

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides and chlorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [21-26]

(137) Na_3AlF_6-$BaCl_2$

7. Corrosion

Table 137.7. Corrosion studies from primary research literature

	Studies	References
A	Cr	[27]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[28,29]
	SSNI-12P	[30]
	Quartz	[31]
	Al	[32]
	Various metals	[33]
B	Pt	[34-38]
	Boron nitride, carbon, Inconel	[39-41]
	Fused MgO	[42]
C	Impurities in electrolyte	[43,44]
	Graphite	[43,44]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[45-47]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[48-63,70,71]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[64-66]
	Electroanalytical studies in molten fluorides	[67]
	Annotated corrosion biblio.	[68]
	Corrosion: molten fluorides(survey)	[69]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [27-71]

(137) Na_3AlF_6-$BaCl_2$

8. Diffusion

No diffusion studies reported. For a related but more complex system, i.e., Na_3AlF_6-AlF_3-$BaCl_2$, a limited chronopotentiometric study of Cu^+ has been reported [72]. $D_{Cu^+} \times 10^5$ ($cm^2\ s^{-1}$) was reported as 2.8 ($\sim \pm 15\%$) at 1023K.

References [72]

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 138 Na_3AlF_6-B_2O_3

1. *Melting Temperature (T_m)*

Pure substance melting points:

Na_3AlF_6: 1010°C

B_2O_3: 450°C

Invariant points:

The solubility of B_2O_3 in molten cryolite appears unlimited [1].

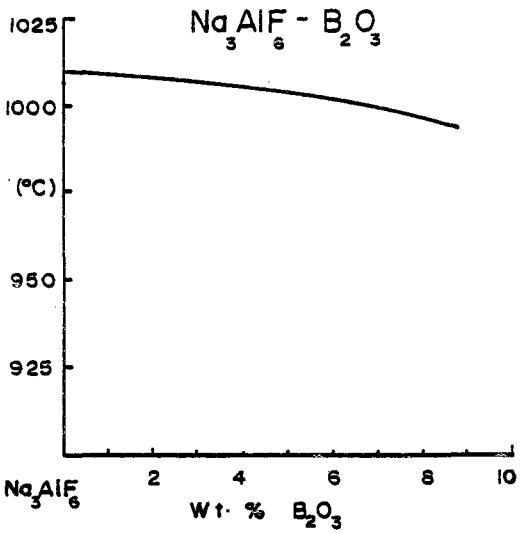

Figure 138.1. Freezing point depression of molten Na_3AlF_6 with B_2O_3 as additive

References [1-14]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

Measurement method: rotating spindle technique [15]

Equation:

$$\eta = a + bT + cT^2 \quad (138.1)$$

precision: in table 138.1 uncertainty: $\sim \pm 40\%$

(138) Na_3AlF_6-B_2O_3

Table 138.1. Parameters of equation (138.1) and precisions

Na_3AlF_6 (mol %)	a	-b x 10^2	c x 10^4	Precision	T range(K)
1.6	562.99	112.08	5.592	18.0%	870-1020
3.2	279.08	56.005	2.816	22.3%	870-1020

Table 138.2. Viscosity (poise) from equations in table 138.1

Mol % Na_3AlF_6	1.6	3.2	Mol % Na_3AlF_6	1.6	3.2
T(K)	η(p)	η(p)	T(K)	η(p)	η(p)
870	11.1	4.96	950	2.89	1.15
880	9.72	4.29	960	2.37	0.93
890	8.41	3.67	970	1.95	0.76
900	7.21	3.11	980	1.65	0.66
910	6.12	2.61	990	1.45	0.60
920	5.15	2.16	1000	1.37	0.60
930	4.28	1.77	1010	1.41	0.66
940	3.53	1.43	1020	1.55	0.78

References [15]

5. *Electrical Conductance (κ)*

No data

(138) Na_3AlF_6-B_2O_3

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritants and toxic; alumina is classed as a nuisance particulate.

(ii) Vapor pressure: no information on this system; Na_3AlF_6 at its m.pt. (1010°C), << 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions", i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [16-21]

(138) Na_3AlF_6-B_2O_3

7. Corrosion

Table 138.3. Corrosion studies from primary research literature

	Studies	References
A	Cr	[22]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[23,24]
	SSNI-12P	[25]
	Quartz	[26]
	Al	[27]
	Various metals	[28]
B	Pt	[29-33]
	Boron nitride, carbon, Inconel	[34-36]
	Fused MgO	[37]
C	Impurities in electrolyte	[38,39]
	Graphite	[38,39]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[40-42]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[43-58,65,66]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[59-61]
	Electroanalytical studies in molten fluorides	[62]
	Annotated corrosion biblio.	[63]
	Corrosion: molten fluorides(survey)	[64]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [22-66]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 139 Na_3AlF_6-Al_2O_3

1. *Melting Temperatues (T_m)*

Pure substance melting points:

Na_3AlF_6: 1010°C
Al_2O_3: 2040°C

Eutectic melting point:

E. 960-963°C, composition: 18.6-21.1 mol % Al_2O_3

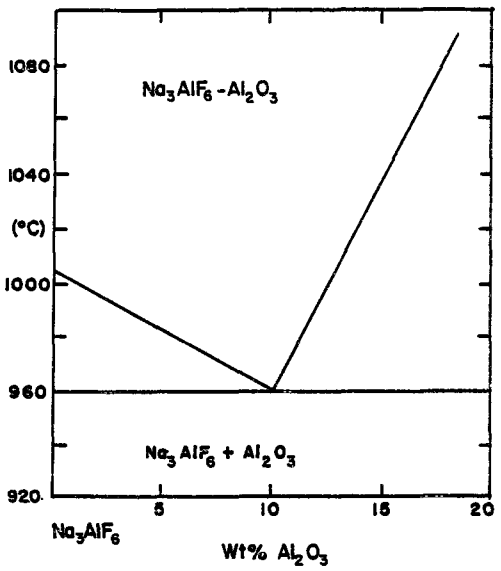

Figure 139.1 Na_3AlF_6-Al_2O_3 phase diagram

References [1-28,30-33]

2. *Density (ρ)*

Measurement method: Archimedean technique [34]

Equation:

$$\rho = a + bT \quad (139.1)$$

precision: in table 139.1 uncertainty: ∿ ± 2%

Table 139.1. Parameters of equation (139.1) and precisions

Mol % Al_2O_3	a	-b x 10^4	Precision	T range(K)
0	2.7334	6.098	*	1270-1350
9.78	3.1832	8.806	*	1280-1360
18.62	3.0733	8.100	*	1250-1350
26.66	2.9505	7.206	*	1270-1360

* insufficient data for estimate.

Table 139.2. Density (g cm^{-3}) from equations in table 139.1

T (K)	Mol % Al_2O_3			
	0	9.78	18.62	26.66
1250			2.0608	
1260			2.0527	
1270	1.9589		2.0446	2.0353
1280	1.9528	2.0560	2.0365	2.0281
1290	1.9467	2.0472	2.0284	2.0209
1300	1.9406	2.0384	2.0203	2.0137
1310	1.9345	2.0296	2.0122	2.0065
1320	1.9284	2.0208	2.0041	1.9993
1330	1.9223	2.0120	1.9960	1.9921
1340	1.9162	2.0032	1.9879	1.9849
1350	1.9101	1.9944	1.9798	1.9776
1360		1.9855		1.9704

References [34-38]

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure [39]

Equation:

$$\gamma = a + bT \quad (139.2)$$

precision: in table 139.3 uncertainty: ∿ ± 5.0%

Table 139.3. Parameters of equation (139.2) and precision

Mol % Al_2O_3	a	$-b \times 10^2$	Precision	T range(K)
9.78	257.8	9.9	*	1270-1350
18.62	272.8	11.5	*	1270-1350
26.66	298.3	13.0	*	1270-1350

*not estimated; insufficient data

Table 139.4. Surface tension (dyn cm^{-1}) from equations in table 139.3

T (K)	Mol % Al_2O_3		
	9.78	18.62	26.66
1270	132.0	126.7	133.1
1280	131.0	125.5	131.8
1290	130.0	124.4	130.5
1300	129.0	123.2	129.2
1310	128.1	122.1	127.9
1320	127.1	120.9	126.6
1330	126.1	119.8	125.3
1340	125.1	118.6	124.0
1350	124.1	117.5	122.7

References [39]

(139) Na_3AlF_6-Al_2O_3

4. *Viscosity (η)*

Measurement method: cited in table 139.5

precision: in table 139.6 uncertainty: in table 139.6

Table 139.5. Viscosity techniques, uncertainties, and systems

Viscosity technique and recommended study	Uncertainty (in values of η)	Na_3AlF_6-Al_2O_3 (mol % Al_2O_3)
oscillating cylinder [36]	∿ ± 5%	2.10-6.56
capillary [9]	∿ ± 10%	8.25-30.0

Equation:

$$\eta = a + bT + cT^2 + dT^3 \quad (139.3)$$

Table 139.6. Parameters of equation (139.3), precisions and recommended study

Al_2O_3 (mol %)	a	b x 10^2	c x 10^6	d x 10^9	Precision	T range (K)
*2.10	29.469	-2.546	-3.146	5.084	0.01%	1260-1380
*4.3	34.586	-2.814	-6.754	7.226	0.27%	1250-1370
*6.6	22.929	2.301	-62.294	25.213	0.32%	1240-1370
8.25	50.91	-6.513	21.47		2.1747%	1280-1450
16.0	36.788	-4.344	13.25		1.9799%	1290-1460
24.0	44.972	-2.769	-20.47	13.275	2.6164%	1280-1460
30.00	95.998	-12.114	39.31		1.6516%	1280-1480

*These parameters are based on the work of Tørklep and Øye for the composition range: 2.10-6.6 mol % Al_2O_3 [36].
The 8.25, 16.0, 24.0 and 30.0 mol % Al_2O_3 composition range is based on the work of Abramov et al. [9].

Table 139.7. Viscosity (cp) from equations in table 139.6

T (K)	Mol % Al_2O_3						
	2.1*	4.3*	6.6*	8.25	16.0	24.0	30.0
1240			3.750				
1250		2.975	3.601				
1280	2.390	2.659	3.195	2.709		3.823	
1300	2.226	2.469	2.958	2.514	2.704	3.538	4.940
1320	2.076	2.297	2.750	2.337	2.529	3.279	4.577
1340	1.939	2.141	2.572	2.177	2.365	3.045	4.245
1360	1.816	2.004	2.426	2.033	2.212	2.837	3.945
1380	1.707			1.907	2.069	2.656	3.676
1400				1.799	1.937	2.503	3.438
1420				1.707	1.815	2.378	3.233
1440				1.632	1.704	2.282	3.058
1460					1.604	2.215	2.915
1480							2.803

*These values correspond to wt % values of 4, 8, and 12 as reported by Tørklep and Øye. [36].

References [9,36,37]

f. *Electrical Conductance (κ)*

Measurement method: in table 139.8

Equations:

(conductance-temperature dependence) [34]

$$\kappa = a + bT + cT^2 \quad (139.4)$$

(conductance-composition isotherm) [35]

$$\kappa = a' + b'C + c'C^2 \quad (139.5)$$

(C = mol % Al_2O_3)

precision: in table 139.9 uncertainty: in table 139.8

Table 139.8. Conductance studies, techniques, systems, and uncertainties

Studies	Conductance Technique	Na_3AlF_6-Al_2O_3 (mol % Al_2O_3)	T range (K)	Uncertainty (in conductance values)
[34]	classical ac	0 - 17%	1270-1350	∿ ± 3%
[35]	classical ac	0 - 26%	1273	∿ ± 3%
[40]	classical ac	0 - 26%	1230-1320	∿ ± 25%
[5]	classical ac	0 - 20%	1170-1310	∿ ± 20%

Footnote: The underscored studies are the recommended data sets

(139) Na_3AlF_6-Al_2O_3

Table 139.9. Parameters of equation (139.4) and precisions

Mol % Al_2O_3	-a	b x 10^3	c x 10^6	Precision	T range(K)
0.0	0.0386	2.0206	0.1670	0.07%	1280-1350
9.7	0.1215	2.100	-	0.66%	1270-1350
17.2	0.2027	1.987	-	0.60%	1270-1350

Table 139.10. Parameters of equation (139.5) and precisions

T (K)	a'	b' x 10^2	c' x 10^4	Precision
1273	2.8626	-3.308	2.632	*

*insufficient data for estimate

Table 139.11. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 139.9

T (K)	Mol % Al_2O_3		
	0.0	9.7	17.2
1270		2.545	2.322
1280	2.821	2.566	2.341
1290	2.846	2.587	2.361
1300	2.870	2.608	2.381
1310	2.895	2.629	2.401
1320	2.920	2.650	2.421
1330	2.944	2.671	2.441
1340	2.969	2.692	2.461
1350	2.994	2.713	2.481

Table 139.12. Specific conductance at 1373K from equation (139.5)

Mol % Al_2O_3	κ (ohm^{-1} cm^{-1})	Mol % Al_2O_3	κ (ohm^{-1} cm^{-1})
0	2.86	14	2.45
2	2.80	16	2.40
4	2.73	18	2.35
6	2.67	20	2.31
8	2.61	22	2.22
10	2.56	24	2.22
12	2.50	26	2.18

References [5,34,35,40]

(139) Na_3AlF_6-Al_2O_3

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritants and toxic; alumina is classed as a nuisance particulate.

(ii) Vapor pressure : no information on this system; Na_3AlF_6 at its m.pt. (1000°C), << 0.5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [41-46].

7. Corrosion

Table 139.13. Corrosion studies from primary research literature

	Studies	References
A	Cr	[47]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[48,49]
	SSNI-12P	[50]
	Quartz	[51]
	Al	[52]
	Various metals	[53]
B	Pt	[54-58]
	Boron nitride, carbon, Inconel	[59-61]
	Fused MgO	[62]
C	Impurities in electrolyte	[63,64]
	Graphite	[63,64]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[65-67]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[68-83,90,91]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[84-86]
	Electroánalytical studies in molten fluorides	[87]
	Annotated corrosion biblio.	[88]
	Corrosion: molten fluorides (survey)	[89]

cont'd

footnote to Table 139.13

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys

References [47-91]

8. Diffusion

Measurement method: cited in tabulations

Diffusing species investigated in Na_3AlF_6-Al_2O_3 as solvent

Na^+; F^-; Al_2O_3; dissolved Al metal

Equation:

$$D = A \exp [-E/RT] \quad (139.6)$$

precision: in table 139.15 uncertainty: in table 139.14

Table 139.14. Diffusion techniques, uncertainties, and species

Diffusion technique of recommended study	Uncertainty (in value of D)	Species
capillary	~±10%	$^{22}Na^+$ and $^{78}F^-$ containing species
chronopotentiometry	~±15%	Al_2O_3 (diffusion coefficient of oxygen containing ions); Al metal (diffusion coefficient of fluoride containing ions)
voltammetry	~±20%	CO_2

(139) Na_3AlF_6-Al_2O_3

Table 139.15. Parameters of diffusion equation (139.6), precisions and recommended studies

Species	A ($cm^2\ s^{-1}$)	E ($cal\ mol^{-1}$)	Temp. range (K)	Precision	Recommended study
(a) Na_3AlF_6-Al_2O_3 (2.5 wt % Al_2O_3)					
Al_2O_3	3.111×10^{-3}	12,940	1273-1323	*	[94]
(b) Na_3AlF_6-Al_2O_3					
Al_2O_3	2.665	30,850	1273-1323	*	[94]
(c) Na_3AlF_6-Al_2O_3					
Al_2O_3	922.9	46,400	1253-1323	*	[94]
(d) Na_3AlF_6-Al_2O_3 (10 wt % Al_2O_3)					
Al_2O_3	3.541×10^{8}	80,160	1253-1323	*	[94]
(e) Na_3AlF_6-Al_2O_3 (12.5 wt % Al_2O_3)					
Al_2O_3	9.893×10^{5}	65,220	1273-1323	*	[94]

*:-equations derived from digitized graphical results; insufficient data for estimates of precision of measurements.

Table 139.16. Diffusion coefficients, D x 10^5 ($cm^2\ s^{-1}$) from equation in table 139.15

T (K)	D x 10^5 ($cm^2\ s^{-1}$)				
	2.5 wt % Al_2O_3	5 wt % Al_2O_3	7.5 wt % Al_2O_3	10 wt % Al_2O_3	12.5 wt % Al_2O_3
1250			0.71	0.34	
1260			0.83	0.44	
1270	1.85	1.31	0.96	0.57	0.59
1280	1.92	1.44	1.10	0.73	0.72
1290	2.00	1.58	1.27	0.93	0.88
1300	2.08	1.74	1.46	1.18	1.07
1310	2.16	1.90	1.68	1.50	1.30
1320	2.24	2.08	1.92	1.89	1.57

Thonstad [95] reported a value of 1.5×10^{-5} $cm^2\ s^{-1}$ for $D_{Al_2O_3}$ at 1293K, and the diffusion coefficient was constant (within limits of experimental error (±15%)) over the investigated concentration range (0.25-12 wt% Al_2O_3). At 1353K, Shurygin et al. [96,100] reported a value of 1.33×10^{-5} $cm^2\ s^{-1}$ for $D_{Al_2O_3}$.

Table 139.17. Diffusion coefficients for species not included in tables 139.15 and 139.16

Species	Melt composition (wt % Al_2O_3)	T (K)	D x 10^5 (cm^2 s^{-1})	Recommended study
Na^+	14	1318	7.50	[93]
Na^+	14			
Na^+	12.9	1326	7.73	[93]
F^-	12.9	1326	3.81	[93]
Na^+	12.0	1327	8.09	[93]
Al	3.2	1270-1345	‡	[92]
CO_2	sat'd,i.e. ∿12-13.5	1273	0.005*	[97,98]

‡: for dissolved Al, the diffusing species probably are sub-fluorides containing ions; the values of D in this study appear unusually high, i.e. ∿ 10^{-4} cm^2 s^{-1}(by a factor of 10),

*: this value is based on a CO_2 solubility of 3.32 x 10^{-6} mol cm^{-3} [29]; with the earlier (less reliable) CO_2 solubility (0.8 x 10^{-7}mol cm^{-3}[31]), D_{CO_2} is ∿ 12 x 10^{-5} cm^2 s^{-1}.

References: Na^+, 93; F^-, 93; Al, 92; Al_2O_3, 94-96,99; CO_2, 97,98; 100.

9. *Heat of Fusion (ΔH_f°)*

No data

10. *Heat Capacity (C_p)*

No data

11. *Volume Change on Melting (ΔV_f)*

No data

12. *Vapor Pressure (p_{vap})*

Measurement method: boiling point technique [101]

Equation:

$$\log p = A + B/T \quad (139.7)$$

precision: in table 139.18 uncertainty:

Table 139.18. Parameters of equation (139.7) and precisions

Mol % Al_2O_3	A	-B	Precision	T range(K)
5.0	8.817	10620	*	1370-1430
9.8	8.712	10513	*	1380-1430
14.3	8.773	10640	*	1385-1430
18.6	8.708	10575	*	1380-1440
34.0	8.794	10847	*	1400-1465

*not estimated; results presented in equation form only

Table 139.19. Vapor pressure (mm) from equations in table (139.18)

T (K)	Mol % Al_2O_3				
	5.0	9.8	14.3	18.6	34.0
1370	11.6				
1380	13.2	12.4		11.1	
1390	15.0	14.1	13.1	12.6	
1400	17.0	15.9	14.9	14.3	11.1
1410	19.3	18.0	16.9	16.1	12.6
1420	21.8	20.3	19.1	18.2	14.3
1430	24.6	22.9	21.5	20.6	16.2
1440				23.1	18.3
1450					20.6
1460					23.2

References [101]

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 140 K_3AlF_6-Al_2O_3

1. *Melting Temperature (T_m)*

Pure substance melting points:

K_3AlF_6: 990°C

Al_2O_3: 2040°C

Eutectic melting point:

837°C, composition: 55 mol % K_3AlF_6
75.6 wt % K_3AlF_6

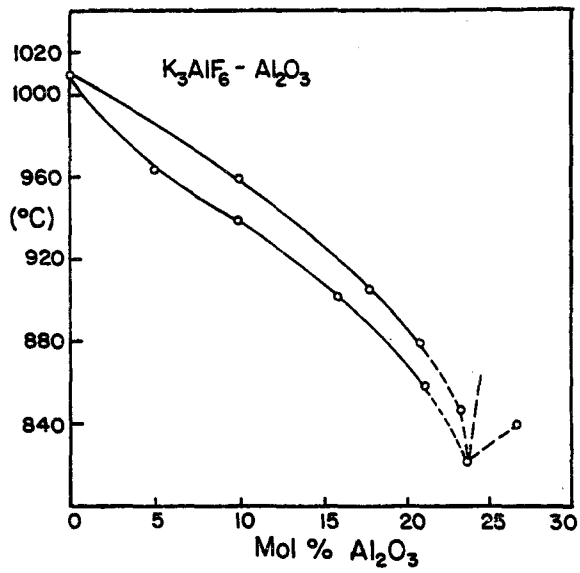

Figure 140.1. K_3AlF_6-Al_2O_3 phase diagram

References [1-16]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

Mo data

4. *Viscosity (η)*

No data

(140) K_3AlF_6-Al_2O_3

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [2]

Equation:

$$\kappa = a + bT + cT^2 + dT^3 \quad (140.1)$$

precision: in table 140.1 uncertainty: ∿ ± 30%

Table 140.1. Parameters of equation (140.1) and precisions

Mol % Al_2O_3	a	b x 10^2	-c x 10^6	d x 10^9	Precision
11.8	7.669	-0.739	1.21	2.95	0.19%
22.0	-4.948	1.524	13.05	4.34	0.61%
30.9	9.010	-0.582	6.07	5.02	0.95%

Table 140.2. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 140.1

	Mol % Al_2O_3		
T (K)	11.8	22.0	30.9
1230			2.01
1240			2.03
1250		2.20	2.05
1260		2.23	2.08
1270	2.37	2.26	2.11
1280	2.42	2.29	2.14
1290	2.46	2.32	2.17
1300	2.50	2.35	2.21
1310	2.55	2.39	2.25
1320	2.59	2.42	2.29

References [2]

(140) K_3AlF_6-Al_2O_3

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure, no data.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [17-21]

(140) K_3AlF_6-Al_2O_3

7. Corrosion

Table 140.2. Corrosion studies from primary research literature

	Studies	References
A	Cr	[22]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[23,24]
	SSNI-12P	[25]
	Quartz	[26]
	Al	[27]
	Various metals	[28]
B	Pt	[29-33]
	Boron nitride, carbon, Inconel	[34-36]
	Fused MgO	[37]
C	Impurities in electrolyte	[38,39]
	Graphite	[38,39]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[40-42]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[43-58,65,66]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[59-61]
	Electroanalytical studies in molten fluorides	[62]
	Annotated corrosion biblio.	[63]
	Corrosion: molten fluorides(survey)	[64]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles and surveys.

References [22-66]

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

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System 141 Li_3AlF_6-Al_2O_3

1. *Melting Temperature (T_m)*

Pure substance melting points:

Li_3AlF_6: 785°C

Al_2O_3: 2040°C

Eutectic melting point:

775 ± 3°C, composition: ∿ 1.5 mol % Al_2O_3

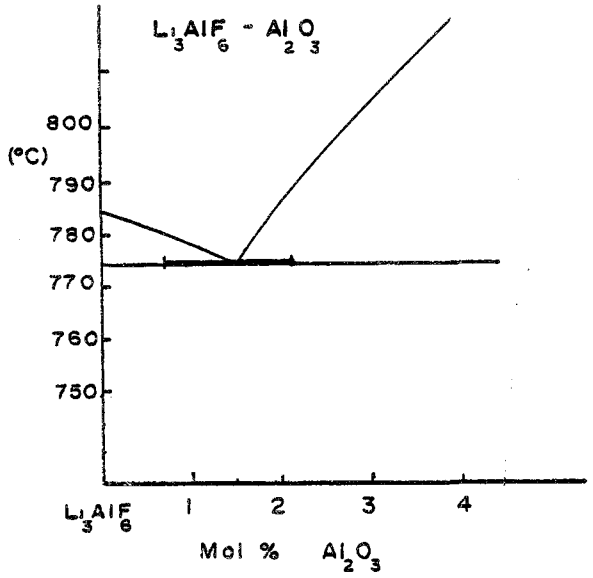

Figure 141.1. Li_3AlF_6-Al_2O_3 phase diagram

References [1-18]

2. *Density (ρ)*

Measurement method: Archimedean technique [20]

Equation:

$$\rho = a + bT \quad (141.1)$$

precision: in table 141.1 uncertainty: ∿ ± 1.5%

(141) Li_3AlF_6-Al_2O_3

Table 141.1. Parameters of equation (141.1) and precision

Mol % Al_2O_3	a	-b x 10^4	Precision	T range (K)
3	3.0466	8.460	*	1220-1320
6	2.9730	7.920	*	1220-1320

* insufficient data for estimate

Table 141.2. Density (g cm^{-3}) from equations in table 141.1

	Mol % Al_2O_3	
T (K)	3	6
1220	2.0145	2.0067
1240	1.9975	1.9909
1260	1.9806	1.9750
1280	1.9637	1.9592
1300	1.9468	1.9434
1320	1.9299	1.9275

References [19,20]

3. *Surface Tension* (γ)

No data

4. *Viscosity* (η)

No data

5. *Electrical Conductance* (κ)

No data

(141) Li_3AlF_6-Al_2O_3

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure: no information on this system; Li_3AlF_6 at its m.pt., $\sim$ 785°C, $\sim$ << 5mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [21-26]

(141) Li_3AlF_6-Al_2O_3

7. Corrosion

Table 141.2. Corrosion studies from primary research literature

	Studies	References
A	Cr	[27]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[28,29]
	SSNI-12P	[30]
	Quartz	[31]
	Al	[32]
	Various metals	[33]
B	Pt, Pt-Rh	[34-38,72,73]
	Boron nitride, carbon, Inconel	[39-41]
	Fused MgO	[42]
C	Impurities in electrolyte	[43,44]
	Graphite	[43,44]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[45-47]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[48-63,70,71]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[64-66]
	Electroanalytical studies in molten fluorides	[67]
	Annotated corrosion biblio.	[68]
	Corrosion: molten fluorides(survey)	[69]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [27-73]

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 142 $LiOH-LiNO_3$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$LiNO_3$: 253°C
LiOH: 462°C

Eutectic melting point:

E_1: 182°C, composition: 40.5 mol % LiOH

Tr: 195°C, composition: 48 mol % LiOH

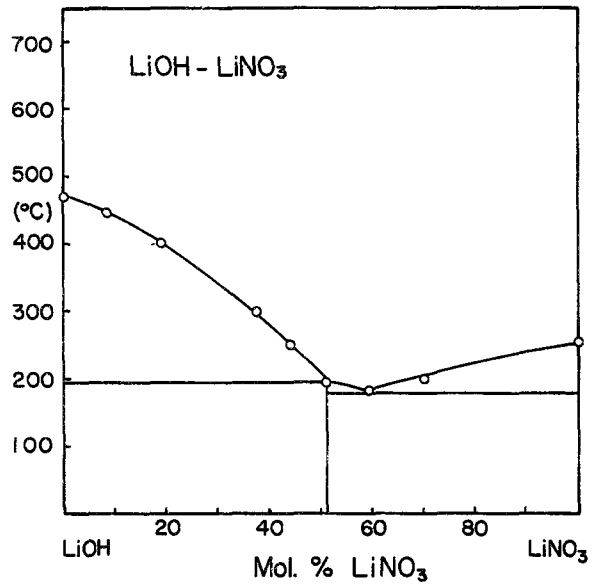

Figure 142.1. $LiOH-LiNO_3$ phase diagram

References [1-16].

2. *Density (ρ)*

Measurement method: dilatometric technique [17]

Equation:

$$\rho = a + bT \quad (142.1)$$

precision: in table 142.1 uncertainty: ∿ ± 1.0%

Table 142.1. Parameters of equation (142.1) and precision

Mol % LiOH	a	$-b \times 10^4$	Precision	T range(K)
7.6	2.3681	8.065		410-440

Table 142.2. Density (g cm^{-3}) at 7.6 mol % LiOH from equation in table 142.1

T (K)	ρ (g cm^{-3})	T (K)	ρ (g cm^{-3})
410	2.0374	430	2.021
420	2.029	440	2.013

References [17]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [17]

Equation:

$$\kappa = a + bT + cT^2 \quad (142.2)$$

precision: in table 142.3 uncertainty: ∿ ± 3.0%

Table 142.3. Parameters of equation (142.2.) and precision

Mol % LiOH	a	b x 10^3	c x 10^6	Precision	T range(K)
7.6	0.4421	-3.7749	7.265	∿ ± 1.0%	410-440

Table 142.4. Specific conductance at 7.6. mol % LiOH from equation in table 142.3.

T (K)	κ (ohm^{-1} cm^{-1})	T (K)	κ (ohm^{-1} cm^{-1})
410	0.116	430	0.162
420	0.138	440	0.188

References [17]

(142) $LiOH-LiNO_3$

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: LiOH, very caustic and toxic; $LiNO_3$, moderate.

(ii) Vapor pressure: LiOH, at m.pt. (460°C), << 0.5mm; $LiNO_3$ (m.pt. 253°C) decomposes with heating to the nitrite and oxygen just above its m.pt.

B. Disaster hazards

(i) Molten salt bath "explosions": violent generation of steam due to bulk water "carry-over" and/or equipment failure; sudden explosive expansion of "trapped" air.

(ii) Hydroxides react with water or steam with evolution of heat; the aqueous solution is very caustic and attacks living tissue; dangerous.

(iii) On decomposition, nitrates emit toxic fumes (oxides of nitrogen) viz:

$$MNO_3 \longrightarrow MNO_2 + \tfrac{1}{2}O_2 \qquad (142.3)$$

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \qquad (142.4)$$

The subsequent decomposition reactions are complex; if the gas phase is continuously removed, the nitrite conversion (above) to NO and NO_2 is dominant.

In the temperature range 550-660°C, and under oxygen, the conversion of KNO_2 to KNO_3 goes to completion; between 650-750°C, the two salts interconvert (see above), KNO_3 becoming increasingly unstable; above 800°C, the nitrite decomposition: $2\ KNO_2 \longrightarrow K_2O + N_2 + {}^3/_2O_2$ goes to completion.

(iv) Nitrates are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon,...); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous.

References [18-23]

7. Corrosion

Table 142.5. Corrosion studies from primary research literature

	Studies	References
A	Ni, Cu, Armco Fe and steel	[24-26]
A	Fe, effects of H_2O	[27]
A	Pt, Ag, and alloys	[28-30]
B	Fe	[31]
B	Cu	[32]
C	Thermodynamic approach	[33,34]
C	Electrochemical approach	[35,36]
C	Annotated corrosion biblio.	[37]
C	Reviews, corrosion	[38-40]

Compatibility studies: A; principally molten LiOH; B: principally molten $LiNO_3$; C: general survey, reviews and biblios. No compatibility studies specifically for molten $LiOH-LiNO_3$

References [24-40]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

(142) $LiOH-LiNO_3$

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 143 $NaOH-NaNO_3$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$NaNO_3$: 307°C

NaOH: 318°C

Eutectic melting point:

E_1: 258°C, composition: 18.5 mol % $NaNO_3$

E_2: 266°C, composition: 41 mol % $NaNO_3$

E_3: 246°C, composition: 72 mol % $NaNO_3$

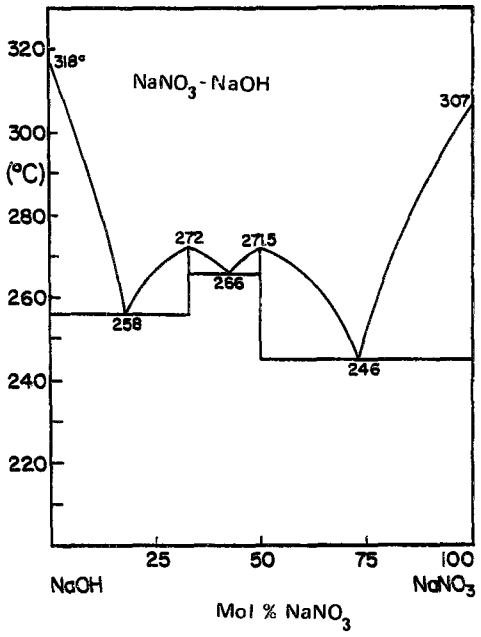

Figure 143.1. $NaOH-NaNO_3$ phase diagram

Table 143.1. Additional variant points

Composition	t(°C)	Composition	t(°C)
$2NaOH \cdot NaNO_3$	272°C	$NaOH \cdot NaNO_3$	271.5°C

References [1-16]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: $NaNO_3$, permitted as a food additive; NaOH, very caustic and is corrosive to all body tissues.

(ii) Vapor pressure: no information for this system, but see $NaNO_3$ [23], and NaOH [23].

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) On decomposition, nitrates emit toxic fumes (oxides of nitrogen) viz:

$$2MNO_3 \longrightarrow 2MNO_2 + O_2 \qquad (143.1)$$

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \qquad (143.2)$$

The subsequent decomposition reactions are complex; if the gas phase is continuously removed, the nitrite decomposition (above) to NO and NO_2 is dominant.

(iii) Nitrates are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon,....); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous.

(iv) Dangerous; with water or steam, reacts with evolution of heat; the aqueous solution is very strongly caustic; attacks living tissue.

References [17-24]

7. *Corrosion*

Table 143.2. Corrosion studies from primary research literature

	Studies	References
A	Fe	[25-27]
	Fe, Co, Ni	[28]
	Cu	[29]
	Pt, S, steel	[30]
	Oxide species	[31]
B	Metals	[32]
	Metals, Ceramics, alloys	[32-39]
	Stainless steel, Fe-Ni-Cr alloys	[40]
	Ni, Cr, and various Ni based alloys	[41-44]
	Ni-steels	[45]
	Fe (effect of H_2O)	[46]
	Pt, Ag, and alloys	[47-49]
C	Electrochemical approach	[50,51]
	Thermodynamic redox diagrams	[52,53]
	Annotated corrosion biblio.	[54]
	Reviews/molten salts	[55-57]

Compatibility studies: A: molten $NaNO_3$; B: molten NaOH; C: basic principles and reviews. No studies specific to molten $NaNO_3$-NaOH found.

References [25-57]

8. *Diffusion*

No data

9. *Heat of Fusion* (ΔH°_f)

No data

10. *Heat Capacity* (C_p)

No data

11. *Volume Change on Melting* (ΔV_f)

No data

12. *Vapor Pressure* (p_{vap})

No data

13. *Thermal Conductivity (liquid)* (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 144 KNO_3-KOH

1. *Melting Temperatures (T_m)*

Pure substance melting points:

KNO_3: 335°C
KOH: 360°C

Eutectic melting point:

E_1: 214°C, composition: 31.5 mol % KOH
E_2: 220°C, composition: 68 mol % KOH

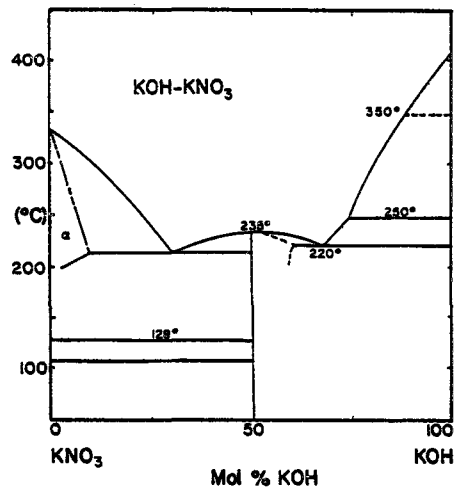

Figure 144.1. KNO_3-KOH phase diagram

References [1-15].

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: KNO_3, permitted as a food additive; KOH, highly caustic and is very corrosive to all body tissue

(ii) Vapor pressure: no information for this system, but see KNO_3 [73], and KOH [68]

B. Disaster hazards

(i) Molten salt bath "explosions": violent generation of stean due to bulk water "carry-over" and/or equipment failure; sudden exposive expansion of "trapped" air

(ii) On decomposition, nitrates emit toxic fumes (oxides of nitrogen) viz:

$$MNO_3 \longrightarrow MNO_2 + \tfrac{1}{2}O_2 \qquad (144.1)$$

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \qquad (144.2)$$

The subsequent decomposition reactions are complex; if if the gas phase is continuously removed, the nitrite decomposition (above) to NO and NO_2 is dominant.

In the temperature range 550-600°C, and under oxygen, the conversion of KNO_2 to KNO_3 goes to completion; between 650-750°C, the two salts interconvert (see above), KNO_3 becoming increasingly unstable; above 800°C, the nitrite decomposition: $2\ KNO_2 \longrightarrow K_2O + N_2 + {}^3/_2O_2$ goes to completion

(iii) Nitrates are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon,...); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous

(iv) Hydroxides, dangerous; react with water or steam with evolution of heat; the aqueous solution is very strongly caustic; attacks living tissue

References [16-23]

7. Corrosion

Table 144.1. Corrosion studies from primary research literature

	Studies	References
A	Fe	[24]
	Pt, Rh, Ag	[25]
	Oxide species	[26]
B	Ni, Cu, Armco Fe	[27-29]
	Fe (effects of H_2O)	[30]
	Pt, Ag, and alloys	[31-33]
C	Electrochemical approach	[34,35]
	Thermodynamic redox diagrams	[36,37]
	Reviews/corrosion: molten salts	[38-40]
	Annotated corrosion biblio.	[41]

Compatibility studies: A: molten KNO_3; B: molten KOH; C: basic principles and survey reviews. No studies with molten KNO_3-KOH found.

References [24-41].

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 145 $NaNO_3$-$NaNO_2$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$NaNO_3$: 307°C

$NaNO_2$: 282°C

Eutectic melting point:

E_1: 233°C, composition: ∿ 40 mol % $NaNO_3$

E_2: 235°C, composition: ∿ 50 mol % $NaNO_3$

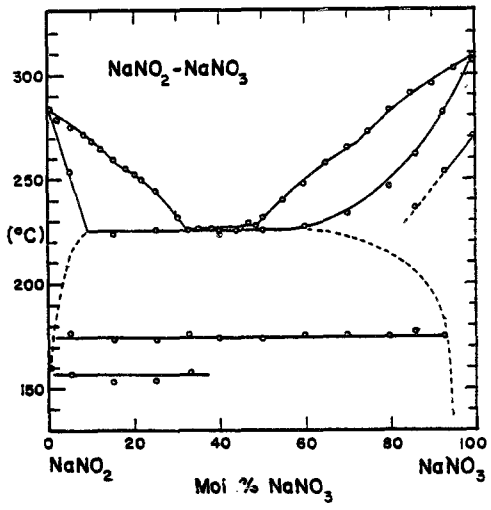

Figure 145.1. $NaNO_3$-$NaNO_2$ phase diagram

References [1-17]

2. *Density (ρ)*

Measurement method: Archimedean technique [19]

Equation:

$$\rho = a + bT \quad (145.1)$$

precision: in table 145.1 uncertainty: ∿ ± 1.5%

Table 145.1. Parameters of equation (145.1) and precisions

Mol % $NaNO_2$	a	-b x 10^4	Precision	T range(K)
25	2.2532	6.435	±0.14%	550-770
35	2.2456	6.608	±0.04%	510-770
40	2.2287	6.495	±0.03%	490-770
50	2.1912	6.124	±0.10%	490-770
55	2.1900	6.137	±0.10%	490-770
60	2.1973	6.320	±0.03%	510-770
65	2.1927	6.343	±0.05%	550-770
75	2.1922	6.421	±0.04%	550-770

(145) $NaNO_3$-$NaNO_2$

Two-independent-variables equation

$$\rho = a + bT + cC \quad (145.2)$$

(C = mol % $CaCl_2$)

Table 145.2. Parameters of two-independent-variables equation (145.2) and precision

a	-b x 10^4	c x 10^3	Precision
2.26498	-6.2576	-1.1945	0.02%

Table 145.3. Density (g cm^{-3}) from equations in table 145.1

T (K)	Mol % $NaNO_2$							
	25	35	40	50	55	60	65	75
490			1.910	1.891	1.889			
510		1.909	1.897	1.879	1.877	1.875		
530		1.895	1.884	1.867	1.865	1.862		
550	1.899	1.882	1.871	1.854	1.852	1.850	1.844	1.839
570	1.886	1.869	1.858	1.842	1.840	1.837	1.831	1.826
590	1.874	1.856	1.845	1.830	1.828	1.824	1.818	1.813
610	1.861	1.843	1.833	1.818	1.816	1.812	1.806	1.801
630	1.848	1.829	1.820	1.805	1.803	1.799	1.793	1.788
650	1.835	1.816	1.807	1.793	1.791	1.787	1.780	1.775
670	1.822	1.803	1.794	1.781	1.779	1.774	1.768	1.762
690	1.809	1.790	1.781	1.769	1.767	1.761	1.755	1.749
710	1.796	1.776	1.768	1.756	1.754	1.749	1.742	1.736
730	1.783	1.763	1.755	1.744	1.742	1.736	1.730	1.723
750	1.771	1.750	1.742	1.732	1.730	1.723	1.717	1.711
770	1.758	1.737	1.729	1.720	1.717	1.711	1.704	1.698

References [18,19]

3. *Surface Tension (γ)*

Measurement method: maximum bubble pressure [20]

Equation:

$$\gamma = a + bT \quad (145.3)$$

precision: in table 145.4 uncertainty: $\sim \pm 2.5\%$

Table 145.4. Parameters of equation (145.3) and precisions

Mol % $NaNO_2$	a	-b x 10^3	Precision	T range(K)
20	138.6	39.0	*	530-710
40	136.7	35.0	*	520-690
60	139.3	38.0	*	530-710
80	135.0	30.0	*	560-740

*not estimated; insufficient data

(145) $NaNO_3$-$NaNO_2$

Two-independent-variables equation

$$\gamma = a + bT + cT^2 + dC^3 + eTC$$

(C = mol % $NaNO_2$) (145.4)

Table 145.5. Parameters of two-independent-variables equation (145.4)

a	b x 10^2	c x 10^5	d x 10^6	e x 10^5	Precision
142.36398	-4.81341	1.34004	2.76423	-9.2449	0.17%

Table 145.6. Surface tension (dyn cm^{-1}) from equations in table 145.4

T (K)	Mol % $NaNO_2$			
	20	40	60	80
520		118.5		
540	117.5	117.8	118.8	
560	116.8	117.1	118.0	118.2
580	116.0	116.4	117.3	117.6
600	115.2	115.7	116.5	117.0
620	114.4	115.0	115.7	116.4
640	113.6	114.3	115.0	115.8
660	112.9	113.6	114.2	115.2
680	112.1	112.9	113.5	114.6
700	111.3		112.7	114.0
720				113.4
740				112.8

References [20,21].

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [22]

Equation:

$$\kappa = A \exp(-E/RT) \quad (145.5)$$

precision: in table 145.7 uncertainty: $\sim \pm 5.0\%$

Table 145.7. Parameters of equation (145.5) and precisions

Mol % $NaNO_3$	A	E (cal mol^{-1})	Precision	T range(K)
7.5	13.2	2640	*	560-720
15.5	12.6	2630	*	550-720
30.0	12.0	2620	*	520-720
50.0	11.2	2620	*	520-720
75.0	11.7	2750	*	560-720
80.0	12.4	2860	*	570-720

*not estimated; insufficient data

Table 145.8. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 145.7

T (K)	Mol % $NaNO_3$					
	7.5	15.0	30.0	50.0	75.0	80.0
520			0.950	0.887		
540			1.044	0.974		
560	1.242	1.185	1.139	1.063	0.988	
580	1.347	1.286	1.236	1.153	1.076	1.037
600	1.454	1.388	1.333	1.244	1.165	1.126
620	1.561	1.490	1.431	1.335	1.255	1.217
640	1.699	1.593	1.529	1.427	1.346	1.308
660	1.777	1.696	1.628	1.519	1.437	1.401
680	1.885	1.799	1.726	1.611	1.529	1.493
700	1.992	1.902	1.824	1.703	1.620	1.586
720	2.100	2.004	1.922	1.794	1.712	1.680

References [22]

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: $NaNO_3$, permitted as a food additive; $NaNO_2$, permitted in food; there appears some implication of increased cancer with chronic ingestion of nitrites.

(ii) Vapor pressure: no information for this system; but see $NaNO_3$ [32], and $NaNO_2$ [33]

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) On decomposition, nitrates emit toxic fumes (oxides of nitrogen) viz:

$$2MNO_3 \longrightarrow 2MNO_2 + O_2 \qquad (145.6)$$

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \qquad (145.7)$$

The subsequent decomposition reactions are complex; if the gas phase is continuously removed, the nitrite decomposition (above) to NO and NO_2 is dominant.

(iii) Nitrates and nitrites are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon,....); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous.

References [23-33]

7. Corrosion

Table 145.9. Corrosion studies from primary research literature

Studies in molten nitrates and nitrites	References
Fe	[34-36]
Fe, Co, Ni, Cr, Al,...	[37-39]
Cu, Pt, Au, W,...	[38-40]
Zn, Pb, Cu, Ni, Al	[41]
Pt, S, steel	[42]
Zr	[43]
Oxide species	[44]
Electrochemical approach	[45,46]
Thermodynamic redox diagrams	[47,48]
Annotated corrosion biblio.	[49]
Reviews/molten salts	[50-52]

The compatibility studies in Table 145.9 are largely for $NaNO_3$, KNO_3, and their molten mixtures. For studies in molten $NaNO_3$-$NaNO_2$, and thermodynamic pO_2 diagrams, see [37].

References [34-52]

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

(145) $NaNO_3$-$NaNO_2$

10. Heat Capacity (C_p)

Measurement method: drop calorimetry [53]

Composition: 45.1 mol % $NaNO_3$ Temp. range: 508-766 K

$$C_p = 61.50 - 35.33 \times 10^{-3}T \quad (145.8)$$

precision: ∿ ± 1.5% uncertainty: ∿ ± 10%

Table 145.10. Heat capacity from equation (145.8)

T (K)	C_p (cal K^{-1} mol^{-1})	T (K)	C_p (cal K^{-1} mol^{-1})
510	43.5	700	36.8
550	42.1	750	35.0
600	40.3	770	34.3
650	38.5		

The heat capacity of this mixture in the crystalline state, for the temperature range 380°-487 K, is given by:

$$C_p = -28.19 + 132.2 \times 10^{-3}T \text{ [53]} \quad (145.8)$$

References [53]

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [54]

Table 145.11. Volume change on melting

Binary eutectic (mol % $NaNO_3$)	$(\Delta V_f/V_s)$	Uncertainty
40 (a)	10.8%	∿ ± 15%
50 (a)	10.0%	

(a) binary eutectic mixtures

References [54]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 146 KNO_2-$NaNO_3$

1. *Melting Temperatures (T_m)*

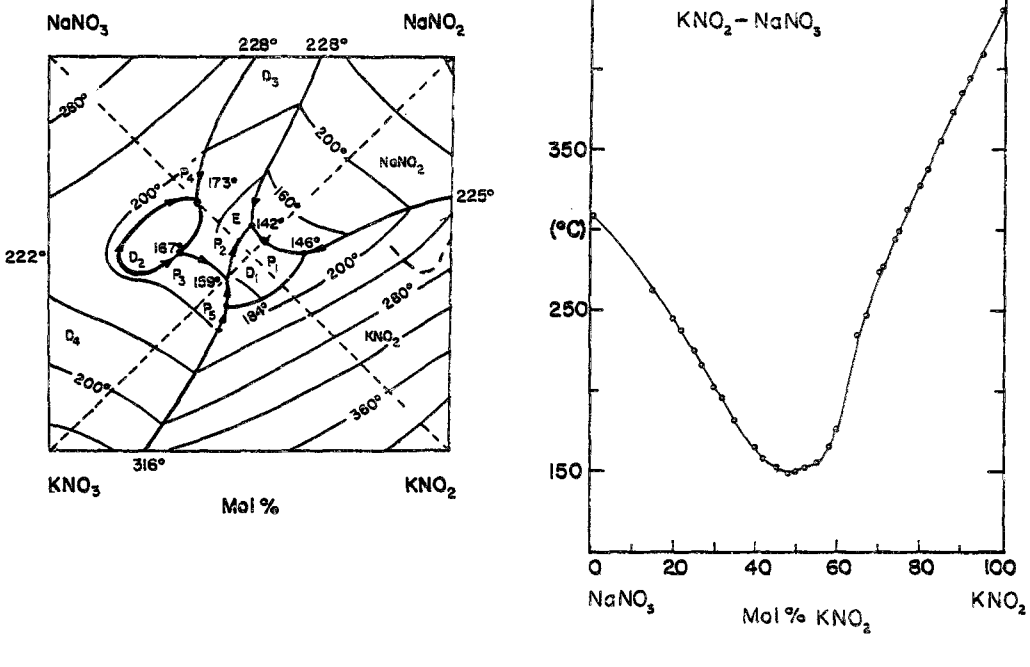
Pure substance melting points:

KNO_2 440°C

$NaNO_3$: 307°C

Minimum melting mixture:

∿ 149°C, composition: ∿ 48 mol % KNO_2



(A) $NaNO_3$-KNO_2-$NaNO_2$-KNO_3 (B) Diagonal Pair KNO_2-$NaNO_3$

Figure 146.1 KNO_2-$NaNO_3$ phase diagram

This system is a diagonal in the system: $NaNO_2$-$NaNO_3$-KNO_3-KNO_2; for the ternary system: $NaNO_2$-$NaNO_3$-KNO_3, see system 148.

References [1-19]

2. *Density (ρ)*

Measurement method: Archimedean technique [20]

Equation:

$$\rho = a + bT \quad (146.1)$$

precision: in table 146.1 uncertainty: ∿ ±1.5%

Table 146.1. Parameters of equation (146.1) and precisions

Mol % KNO_3	a	-b x 10^4	Precision	T range(K)
15	2.3072	6.963	± 0.14%	530-770
25	2.2934	6.903	± 0.25%	510-770
35	2.2577	6.677	± 0.04%	470-770
45	2.2658	6.983	± 0.10%	470-770
50	2.2266	6.539	± 0.13%	470-770
55	2.2234	6.602	± 0.11%	470-770
65	2.2057	6.550	± 0.07%	490-770
75	2.1839	6.402	± 0.02%	550-770
85	2.1638	6.285	± 0.02%	590-770

Two-independent-variable equation:

$$\rho = a + bT + cC \quad (146.2)$$

(C = mol % KNO_2)

Table 146.2. Parameters of two-independent-variable equation (146.2)

a	-b x 10^4	-c x 10^3	Precision
2.30556	6.70079	1.3431	0.22%

Table 146.3. Density (g cm^{-3}) from equations in table 146.1

	Mol % KNO_3								
T (K)	15	25	35	45	50	55	65	75	85
470			1.944	1.938	1.919	1.913			
490			1.931	1.924	1.906	1.900	1.885		
510		1.941	1.917	1.910	1.893	1.887	1.872		
530	1.938	1.928	1.904	1.896	1.880	1.873	1.859		
550	1.924	1.914	1.890	1.882	1.867	1.860	1.845	1.832	
570	1.910	1.900	1.877	1.868	1.854	1.847	1.832	1.819	
590	1.896	1.886	1.864	1.854	1.841	1.834	1.819	1.806	1.793
610	1.882	1.872	1.850	1.840	1.828	1.821	1.806	1.793	1.780
630	1.869	1.859	1.837	1.826	1.815	1.807	1.793	1.781	1.768
650	1.855	1.845	1.824	1.812	1.802	1.794	1.780	1.768	1.755
670	1.841	1.831	1.810	1.798	1.788	1.781	1.767	1.755	1.743
690	1.827	1.817	1.797	1.784	1.775	1.768	1.754	1.742	1.730
710	1.813	1.803	1.784	1.770	1.762	1.755	1.741	1.729	1.718
730	1.799	1.789	1.770	1.756	1.749	1.741	1.728	1.717	1.705
750	1.785	1.776	1.757	1.742	1.736	1.728	1.714	1.704	1.692
770	1.771	1.762	1.744	1.728	1.723	1.715	1.701	1.691	1.680

References [20]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: $NaNO_3$, permitted as a food additive; KNO_2 toxicity rating, severe; there appears some implication of increased cancer with chronic ingestion of nitrates.

(ii) Vapor pressure: no information for this system; but see $NaNO_3$ [53] and KNO_2 [54].

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) On decomposition, nitrates and nitrites emit toxic fumes (oxides of nitrogen) viz:

$$2MNO_3 \longrightarrow 2MNO_2 + O_2 \qquad (146.3)$$

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \qquad (146.4)$$

The subsequent decomposition reactions are complex; if the gas phase is continuously removed, the nitrite decomposition (above) to NO and NO_2 is dominant.

(iii) Nitrates and nitrites are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon,....); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous.

References [21-32]

7. Corrosion

Table 146.4. Corrosion studies from primary research literature

Studies in molten nitrates and nitrites	References
Fe	[33,35,37]
Fe, Co, Ni, Cr, Al,...	[34,42,43]
Cu, Pt, Au, W,...	[36,42,43]
Zn, Pb, Cu, Ni, Al	[40]
Pt, S, steel	[38]
Zr	[41]
Oxide species	[39]
Electrochemical approach	[44,45]
Thermodynamic redox diagrams	[46,47]
Annotated corrosion biblio.	[48]
Reviews/molten salts	[49-51]

References [33-51]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f^o)

No data

10. Heat Capacity (C_p)

No data

(146) KNO_2-$NaNO_3$

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [52]

Table 146.5. Volume change on melting

Binary eutectic (mol % $NaNO_3$)	$(\Delta V_f/V_s)$	Uncertainty
52%	3.6%	$\sim \pm$ 10%

References [52]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 147 KNO_3-$NaNO_2$

1. *Melting Temperatures (T_m)*

Pure substance melting points:

KNO_3: 335°C

$NaNO_2$: 282°C

Minimum melting solid solution:

140.9°C, composition: 46 mol % KNO_3

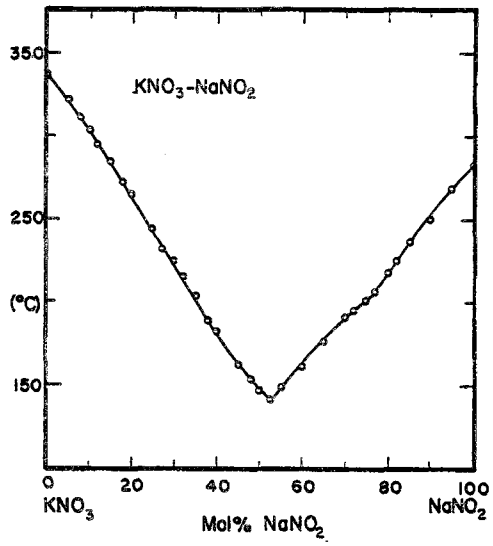

Figure 147.1. KNO_3-$NaNO_2$ phase diagram

References [1-19].

2. *Density (ρ)*

Measurement method: Archimedean technique [20]

Equation:

$$\rho = a + bT \quad (147.1)$$

precision: in table 147.1 uncertainty: ∿ ± 1.5%

Table 147.1. Parameters of equation (147.1) and precisions

Mol % $NaNO_2$	a	-b x 10	Precision	T range(K)
15	2.2982	7.233	0.03%	550-770
25	2.2662	6.890	0.05%	490-770
35	2.2433	6.693	0.03%	450-770
45	2.2344	6.674	0.02%	450-770
50	2.2292	6.650	0.02%	450-770
65	2.2106	6.625	0.03%	450-770
75	2.1932	6.507	0.02%	490-770
85	2.1664	6.260	0.03%	510-770

(147) KNO_3-$NaNO_2$

Two-independent-variables equation

$$\rho = a + bT + cC + dTC^2 \quad (147.2)$$

(C = mol % $CaCl_2$)

Table 147.2. Parameters of two-independent-variables equation (147.2) and precision

a	b x 10^4	c x 10^3	d x 10^9	Precision
2.16190	-6.4965	1.3016	5.1505	0.11%

Table 147.3. Density (g cm^{-3}) from equations in table 147.1

T (K)	Mol % $NaNO_2$							
	15	25	35	45	50	65	75	85
450			1.942	1.934	1.930	1.912		
470			1.929	1.921	1.917	1.899		
490		1.929	1.915	1.907	1.903	1.886	1.874	
510		1.915	1.902	1.894	1.890	1.873	1.861	1.847
530		1.901	1.889	1.881	1.877	1.859	1.848	1.835
550	1.900	1.887	1.875	1.867	1.863	1.846	1.835	1.822
570	1.886	1.873	1.862	1.854	1.850	1.833	1.822	1.810
590	1.871	1.860	1.848	1.841	1.837	1.820	1.809	1.797
610	1.857	1.846	1.835	1.827	1.824	1.806	1.796	1.785
630	1.843	1.832	1.822	1.814	1.810	1.793	1.783	1.772
650	1.828	1.818	1.808	1.801	1.797	1.780	1.770	1.760
670	1.814	1.805	1.795	1.787	1.784	1.767	1.757	1.747
690	1.799	1.791	1.781	1.774	1.770	1.753	1.744	1.734
710	1.785	1.777	1.768	1.761	1.757	1.740	1.731	1.722
730	1.770	1.763	1.755	1.747	1.744	1.727	1.718	1.709
750	1.756	1.749	1.741	1.734	1.730	1.714	1.705	1.697
770	1.741	1.736	1.728	1.721	1.717	1.700	1.692	1.684

References [20]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [21]

Equation:

$$\kappa = a + bT + cT^2 \quad (147.3)$$

precision: insufficient data for estimate uncertainty: $\sim \pm$ 25%

Conductance data in [21] are graphical; the large uncertainty limits limits assigned above are due to insufficient information on the temperatures at which the measurements were made.

Table 147.4. Parameters of equation (147.3) and precisions

Mol % KNO_3	a	b x 10^3	c x 10^6	Precision	T range(K)
25	0.9124	-4.770	7.667	*	630-690
45	0.7329	-4.469	7.438	*	630-690
60	-5.2331	13.920	-6.872	*	630-690
75	-8.3966	23.849	-14.810	*	630-690
85	-4.9728	13.854	-7.654	*	630-690

Table 147.5. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 147.4

T (K)	Mol % KNO_3				
	25	45	60	75	85
630	0.950	0.870	0.809	0.750	0.717
640	1.000	0.920	0.861	0.801	0.758
650	1.051	0.971	0.912	0.848	0.798
660	1.104	1.024	0.961	0.892	0.836
670	1.158	1.078	1.009	0.934	0.873
680	1.214	1.134	1.055	0.972	0.908
690	1.271	1.191	1.100	1.008	0.942

References [21]see comments on experimental uncertainty limits (*vide infra* p779)

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: KNO_3, permitted as a food additive; $NaNO_2$, permitted in food; there appears some implication of increased cancer with chronic ingestion of nitrites

(ii) Vapor pressure: no information for this system; but see see KNO_3 [74], and $NaNO_2$ [75]

(147) KNO_3-$NaNO_2$

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped air".

(ii) On decomposition, nitrates emit toxic fumes (oxides of nitrogen) viz:

$$MNO_3 \longrightarrow MNO_2 + \tfrac{1}{2}O_2 \qquad (147.4)$$

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \qquad (147.5)$$

The subsequent decomposition reactions are complex; if the gas phase is continuously removed, the nitrite decomposition (above) to NO and NO_2 is dominant.

In the temperature range 550-600°C, and under oxygen, the conversion of KNO_2 to KNO_3 goes to completion; between 650-750°C, the two salts interconvert (see above), KNO_3 becoming increasingly unstable; above 800°C, the nitrite decomposition: $2\ KNO_2 \longrightarrow K_2O + N_2 + {}^3/_2O_2$ goes to completion.

Nitrates and nitrites are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon,...); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous.

References [22-29]

7. Corrosion

Table 147.6. Corrosion studies from primary research literature

Studies in molten nitrates and nitrites	References
Fe	[30-32]
Fe, Co, Ni, Cr, Al,...	[33-35]
Cu, Pt, Au, W,...	[34-36]
Zn, Pb, Cu, Ni, Al	[37]
Pt, S. steel	[38]
Zr	[39]
Oxide species	[40]
Electrochemical approach	[41,42]
Thermodynamic redox diagrams	[43,44]
Annotated corrosion biblio.	[45]
Reviews/molten salts	[46-48]

Compatibility studies specifically for molten KNO_3-$NaNO_2$. This system is a diagonal of the ternary system $NaNO_2$-$NaNO_3$-KNO_3. For the latter, see [37].

References [30-48]

(147) KNO_3-$NaNO_2$

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [49]

Table 147.7. Volume change on melting

Binary eutectic (mol % KNO_3)	$(\Delta V_f/V_s)$	Uncertainty
46	8.7%	$\sim \pm$ 15%

References [49]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

Measurement method: transient method [50,51]

$$\lambda = 1.5017 \times 10^{-3} - 0.5904 \times 10^{-6} T \quad (147.6)$$

precision: $\sim \pm$ 1.0% uncertainty: $\sim \pm$ 10%

Table 147.8. Thermal conductivity of melt from equation (147.6)

T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})	T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})
455	12.3	530	11.9
460	12.3	540	11.8
470	12.2	550	11.8
480	12.2	560	11.7
490	12.1	570	11.7
500	12.1	580	11.6
510	12.0	590	11.5
520	11.9	600	11.5

Small amounts of water ($\sim$ 5 mol %) were found to increase the thermal conductivity in the vicinity of the melting point i.e. $\sim$ 150°C by $\sim$ 3%, and appeared to have no effect at somewhat higher temperatures (i.e. $\sim$ 250°C).

The thermal conductivity could be increased by $\sim$ 20% at 250°C by adding about 10 mol % KF; this is close to the saturation solubility, and KF may deposit on cooling.

References [50-60]

(147) KNO_3-$NaNO_2$

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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[29] *vide:* this work, System 74, $NaNO_2$

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System 148 $NaNO_2$-$NaNO_3$-KNO_3

1. *Melting Temperatures (T_m)*

Pure substance melting points:

$NaNO_2$: 282°C

$NaNO_3$: 307°C

KNO_3 : 335°C

Eutectic melting point:

142°C, composition: 44 mol % KNO_3, 49 mol % $NaNO_2$, 7 mol % $NaNO_3$

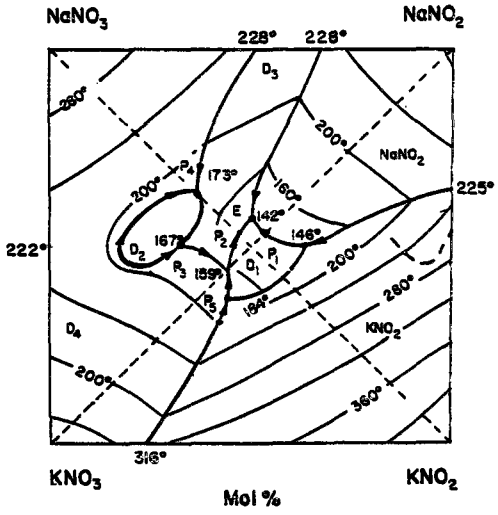

Figure 148.1 $NaNO_2$-$NaNO_3$-KNO_3 phase diagram

References [1-17]

2. *Density (ρ)*

Measurement method: Archimedean technique [2]

Equation:

$$\rho = a + bT \quad (148.1)$$

precision: in table 148.1 uncertainty: ∿ ± 2.0%

(148) $NaNO_2$-$NaNO_3$-KNO_3

Table 148.1. Parameters of equation (148.1) and precision

Composition	a	$-b \times 10^3$	Precision	T range(K)
ternary eutectic[a]	2.2936	0.7497	*	470-870

(a) $NaNO_2$:$NaNO_3$:KNO_3::48.9:6.9:44.2 (mol %) * insufficient data for estimate

Table 148.2. Densities of $NaNO_2$-$NaNO_3$-KNO_3 eutectic from equation in table 148.1

T (K)	ρ (g cm^{-3})	T (K)	ρ (g cm^{-3})
470	1.941	690	1.776
490	1.926	710	1.761
510	1.911	730	1.746
530	1.896	750	1.731
550	1.881	770	1.716
570	1.866	790	1.701
590	1.851	810	1.686
610	1.836	830	1.671
630	1.821	850	1.656
650	1.806	870	1.641
670	1.791		

References [2]

3. *Surface Tension (γ)*

Measurement method: calculated from single salts data [18]

Equation:

$$\gamma = a + bT \quad (148.2)$$

precision: in table 148.3 uncertainty: $\sim \pm 10\%$

Table 148.3. Parameters of equation (148.2) and precision

Composition	a	$b \times 10^3$	Precision	T range(K)
ternary eutectic[a]	149.28	-55.60	0.03%	570-670

(a) $NaNO_2$:$NaNO_3$:KNO_3::48.9:6.9:44.2 (mol %)

Table 148.4. Surface tension of ternary eutectic from equation in table 148.3

T (K)	γ (dyn cm^{-1})	T (K)	γ (dyn cm^{-1})
570	117.58	630	114.25
580	117.03	640	113.60
590	116.47	650	113.14
600	115.92	660	112.58
610	115.36	670	112.02

References [18]

(148) $NaNO_2$-$NaNO_3$-KNO_3

4. *Viscosity (η)*

Measurement method: Ostwald capillary technique [2]

Equation:

$$\eta = a + bT + cT^2 \quad (148.3)$$

precision: in table 148.5 uncertainty: ∿ ± 5.0%

Table 148.5. Parameters of equation (148.3) and precision

Composition	a	b	c x 10^3	d x 10^6	Precision	T range (K)
ternary eutetic[(a)]	473.7	-2.297	3.731	-2.019	16%	420-710

[(a)] KNO_3:$NaNO_2$:$NaNO_3$::44:49:7 (mol %).

Table 148.6. Viscosity of ternary eutectic from equation in table 148.5

T (K)	η (cp)	T (K)	η (cp)
420	17.53	580	2.62
440	13.36	600	2.56
460	10.04	620	2.57
480	7.48	640	2.57
500	5.58	660	2.45
520	4.25	680	2.12
540	3.36	700	1.47
560	2.85		

References [2].

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: $NaNO_2$, permitted in food; $NaNO_3$, KNO_3, permitted as food addivites, there appears some implication of increased cancer incidence with chronic ingestion of nitrites.

(ii) Vapor pressure: no information for this system; but see $NaNO_2$ [25], $NaNO_3$ [26], and KNO_3 [26]

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) On decomposition, nitrates and nitrites emit toxic fumes (oxides of nitrogen) viz:

$$2MNO_3 \longrightarrow 2MNO_2 + O_2 \qquad (148.4.1)$$

$$2MNO_2 \longrightarrow M_2O + NO + NO_2 \qquad (148.4.2)$$

The subsequent decomposition reactions are complex; if the gas phase is continuously removed, the nitrite decomposition (above) to NO and NO_2 is dominant.

(iii) Nitrates and nitrites are powerful oxidizing agents; violent (explosive) reactions possible in molten nitrates and carbonaceous materials (organic cpds., oils, carbon,....); aluminum alloys and bath sludges (e.g. iron oxides); magnesium alloys. Dangerous.

References [19-29]

7. Corrosion

Table 148.7. Corrosion studies from primary research literature

Studies in molten nitrates and nitrites	References
Fe	[30,32,34]
Fe, Co, Ni, Cr, Al,...	[31,39,40]
Cu, Pt, Au, W,...	[33,39,40]
Zn, Pb, Cu, Ni, Al	[37]
Pt, S, steel	[35]
Zr	[38]
Oxide species	[36]
Electrochemical approach	[41,42]
Thermodynamic redox diagrams	[43,44]
Annotated corrosion biblio.	[45]
Reviews/molten salts	[46-48]

For studies specific to molten $NaNO_2$-$NaNO_3$-KNO_3, see [37].

References [30-48]

(148) $NaNO_2$-$NaNO_3$-KNO_3

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

10. Heat Capacity (C_p)

Measurement method: drop calorimetry [49]

Table 148.8. Compositions and temperature ranges

Composition (mol %)				Phase	T range (K)
#	KNO_3	$NaNO_3$	$NaNO_2$		
1	53.0	7.0	40	ℓ	426-776
2	53.5	18.0	28.5	ℓ	447-775

For composition no. 1 the heat capacity in the crystalline state, for the temperature range 384 -409 K, is given by: $C_p = -24.20 + 163.5 \times 10^{-3}T$ (148.5)

Similarly for composition no. 2, the heat capacity in the crystalline state, for the temperature range 373-433 K, is given by: $C_p = 613.09-312.6 \times 10^{-3}T + 4160 \times 10^{-6}T^2$. (148.6)

Equation:

$$C_p = a + bT + cT^2 \quad (148.7)$$

precision: in table 148.9 uncertainty: ∿ ± 5.0%

Table 148.9. Parameters of equation (148.7) and precisions

Mixture	a	b x 10^3	c x 10^6	Precision
no. 1	120.91	-225.60	150.80	∿ ± 1.6%
no. 2	77.05	-114.05	77.47	∿ ± 1.0%

Table 148.10. Heat capacity (cal K^{-1} mol^{-1}) from equations in table 148.9

T (K)	Mixture		T (K)	Mixture	
	#1	#2		#1	#2
430	51.8		650	38.0	35.7
450	49.9	41.4	700	36.9	35.2
500	45.8	39.4	750	36.5	35.1
550	42.4	37.8	775	36.6	35.2
600	39.8	36.5			

References [49]

(148) $NaNO_2$-$NaNO_3$-KNO_3

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

Measurement method: transient techniques; resistance [50,51]

Equation:

$$\lambda = a + bT \quad (148.8)$$

precision: in table 148.11 uncertainty: ∿ ± 10%

Table 148.11. Parameters of equation (148.8), precision, and temp. range

Composition	a x 10^3	-b x 10^6	Precision	T range(K)
ternary eutectic(a)	1.6639	1.100	∿ ± 1%	430-670

(a) KNO_3:$NaNO_2$:$NaNO_3$::44:49:7 (mol %)

Table 148.12. Thermal conductivity of molten eutectic from equation in table 148.11

T (K)	λ x 10^4 (cal cm^{-1} s^{-1} K^{-1})	T (K)	λ x 10^4 (cal cm^{-1} s^{-1} K^{-1})
430	11.9	570	10.4
450	11.7	590	10.1
470	11.5	610	9.9
490	11.2	630	9.7
510	11.0	650	9.5
530	10.8	670	9.3
550	10.6		

The thermal conductivity of two additional mixtures was investigated, (mol %) A (mpt. 140° K): KNO_3, 40; $NaNO_2$, 60; and B (mpt. 120° C): KNO_3, 48; $NaNO_3$, 14; $LiNO_3$, 48. For the thermal conductivity of the binary system (A) see system 147, present work; for the ternary system (B), the thermal conductivity may be expressed with:

$$\lambda = 2.277 \times 10^{-3} - 5.059 \times 10^{-6}T + 5.115 \times 10^{-9}T^2 \quad (148.9)$$

for the T range: 421-526(K); precision ∿ ± 1%, uncertainty, ∿ ± 10%.

References [2,50-60]

(148) $NaNO_2$-$NaNO_3$-KNO_3

14. Thermal Conductivity (solid) (λ_s)

Measurement method: transient technique; resistance wire [50,51]

ternary eutectic mixture: (mol %), KNO_3, 44; $NaNO_2$, 49; $NaNO_3$, 7.

$$\lambda = 1.2351 \times 10^{-2} - 51.99 \times 10^{-6} T + 60.50 \times 10^{-9} T^2 \quad (148.10)$$

precision: ∿ ± 1.0% uncertainty: ∿ ± 10%

Table 148.13. Thermal conductivity of solid from equation (148.10)

T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})	T (K)	$\lambda \times 10^4$ (cal cm^{-1} s^{-1} K^{-1})
295	22.8	360	14.8
300	22.0	370	14.0
310	20.5	380	13.3
320	19.1	390	12.8
330	17.8	400	12.4
340	16.7	410	12.1
350	15.7		

References [50,51,55]

15. Cryoscopic Constant (k_f)

No data

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System 149 Li_2S-S

1. *Melting Temperatures (T_m)*

Pure substance melting points:

Li_2S: ∿ 1372°C

Sulfur : 118°C

Monotectic melting mixture:

364° ± 4°C, composition: 64 ± 2 atom % sulfur

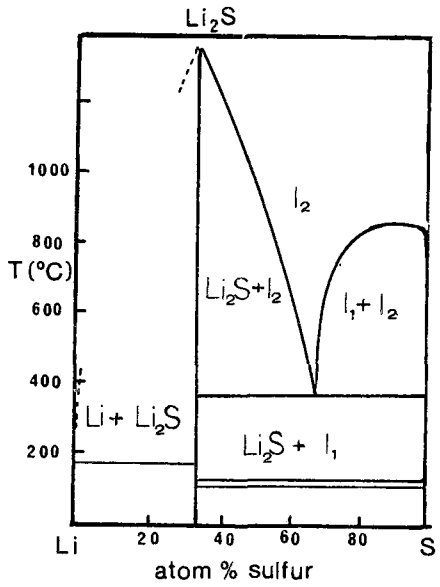

Figure 149.1 Lithium-sulfur phase diagram

References [1-15,35,36]

2. *Density (ρ)*

Measurement method: dilatometric technique [37]

Equation

$$\rho = a + bT \quad (149.1)$$

precision: in table 149.1 uncertainty: ∿ ± 1.0%

Table 149.1. Parameters of equation (149.1) and precision

(Mol % S)	a	-b x 10^3	Precision	T range(K)
66.0*	2.1307	0.5849	0.12%	637-724

*corresponds to $Li_2S_{3.9}$

Table 149.2. Density (g cm^{-3}) from equation in table 149.1

T (K)	Mol % S 66.0*	T (K)	Mol % S 66.0*
640	1.756	690	1.727
650	1.751	700	1.721
660	1.745	710	1.715
670	1.739		

*corresponds to $Li_2S_{3.9}$

References [37,38]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [37]

Equation

$$\kappa = A \exp -E/RT \quad (149.2)$$

precision: in table 149.3 uncertainty: $\sim \pm 2.0\%$

Table 149.3. Parameters of equation (149.2) and precision

Mol % S	A	E	Precision	T range(K)
66.0*	56.146	5350	0.47%	727-802

Table 149.4. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 149.3

T (K)	Mol % S 66.0*	T (K)	Mol % S 66.0*
730	1.405	770	1.701
740	1.477	780	1.779
750	1.550	790	1.859
760	1.625		

*corresponds to $Li_2S_{3.9}$

References [37,38]

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: sulfur, low; Li_2S, variable [18].

(ii) Vapor pressure: Li_2S, no data; sulfur;at m.pt. (115°C), $\sim$ 0.03mm; at 185°C, $\sim$ 1mm;at 444.6°C, $\sim$ 1 atm (b.pt.).

B. Disaster hazards

(i) Molten sulfides and polysulfides may react violently (explosively) with strong oxidants: H_2S evolved on contact with moisture/water can form explosive mixtures with air; H_2S, highly toxic.

(ii) Sulfides and polysulfides when heated to decomposition, or contacted with water, steam, acids, produce highly toxic fumes (oxides of sulfur, H_2S). Dangerous.

(iii) Sulfur burns with the formation of oxides of sulfur (SO_2;SO_3); toxic and corrosive fumes.

References [16-21]

7. *Corrosion*

Table 149.1 Corrosion studies from primary research literature

	Systems, Studies, [References]
A	Cast iron, mild steel, various stainless steels, various metals [22], Fe [23], Ag alloys [24], various metals (survey) [25]
B	Screening studies [26-28], static studies [26-28], Fe, stainless steels (dynamic studies) [26,29-31], saturation solubilities of Cr, Mn, Ni and Fe sulfides [26-28,32], intrinsically corrosion resistant materials [26-28,33], graphite, niobium, glass, porcelain, silica [35-38]
C	Annotated molten salts corrosion biblio. [34]

Compatibility studies with: A: molten sulfur; B: with the exception of [35-38] which deal with the Li-sulfur system, the studies are for molten sodium polysulfides; C: general survey; molten salts.

References [22-38]

8. *Diffusion*

No data

9. *Heat of Fusion* (ΔH_f°)

No data

10. *Heat Capacity* (C_p)

No data

11. *Volume Change on Melting* (ΔV_f)

No data

12. *Vapor Pressure* (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 150 K_2S-S

1. *Melting Temperatures (T_m)*

Pure substance melting points:

K_2S: 840°C
Sulfur: 115°C

Eutectic melting point:

E_1: 110°C, composition: 72.5 wt % sulfur
E_2: 183°C, composition: 83.5 wt % sulfur

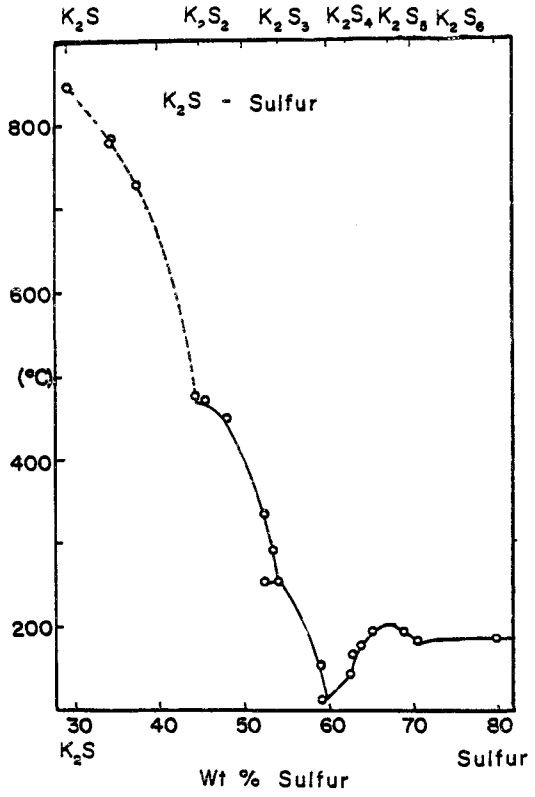

Figure 150.1. K_2S-Sulfur phase diagram

Table 150.1. Additional invariant points

Composition	T (°C)	Composition	T (°C)
K_2S_2	475	K_2S_5	206
K_2S_3	~250	K_2S_6	189
K_2S_4	144		

References [1-15].

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

Measurement method: classical ac technique [16]

$$\kappa = 6.260 \exp(-1777/R(T-306)) \quad (150.1)$$

precision: ∿ ± 7.0% uncertainty: ∿ ± 3.0%

Table 150.2. Electrical conductance from equation (150.1)

T (K)	κ (ohm^{-1} cm^{-1})	T (K)	κ (ohm^{-1} cm^{-1})
490	0.048	590	0.267
500	0.062	600	0.298
510	0.078	610	0.329
520	0.095	620	0.362
530	0.115	630	0.395
540	0.136	640	0.429
550	0.159	650	0.464
560	0.184	660	0.499
570	0.211	670	0.535
580	0.238		

References [16]

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: sulfur, low; K_2S, variable [56].

(ii) Vapor pressure: K_2S, no data; sulfur; at m.pt (115°C), ∿ 0.03mm; at 185°C, ∿ 1mm; at 444.6°C, ∿ 1 atm (b.pt.).

B. Disaster hazards

(i) Molten sulfides and polysulfides may react violently (explosively) with strong oxidants: H_2S evolved on contact with moisture/water can form explosive mixtures with air; H_2S, highly toxic.

(ii) Sulfides and polysulfides when heated to decomposition, or contacted with water, steam, acids, produce highly toxic fumes (oxides of sulfur, H_2S). Dangerous.

(iii) Sulfur burns with the formation of oxides of sulfur (SO_2;SO_3); toxic and corrosive fumes.

References [17-22].

7. *Corrosion*

Table 150.3. Corrosion studies from primary research literature

	Systems, Studies, [References]
A	Cast iron, mild steel, various stainless steels, various metals [23], Fe [24], Ag alloys [25], various metals (survey) [26]
B	Screening studies [27-29], static studies [27-29], Fe, stainless steel (dynamic studies) [27,30-32], saturation solubilities of Cr, Mn, Ni and Fe sulfides [27-29,33], intrinsically corrosion resistant materials [27-29,34]
C	-Annotated molten salts corrosion biblio. [35]

Compatibility studies with: A: molten sulfur, B: molten sodium polysulfides; C: general survey: molten salts. No corrosion studies with K_2S-Sulfur found.

References [23-35]

8. *Diffusion*

No data

9. *Heat of Fusion (ΔH°_f)*

No data

10. *Heat Capacity (C_p)*

No data

11. *Volume Change on Melting (ΔV_f)*

No data

12. *Vapor Pressure (p_{vap})*

No data

13. *Thermal Conductivity (liquid) (λ_ℓ)*

No data

14. *Thermal Conductivity (solid) (λ_s)*

No data

15. *Cryoscopic Constant (k_f)*

No data

16. References

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[23] West, J. R., Chem. Engineering, p. 225 (October, 1946).

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System 151 Na_2CO_3-NaOH-NaCl

1. *Melting Temperatures (T_m)*

Pure substance melting points:

NaCl: 800°C; NaOH: 318°C; Na_2CO_3: 858°C

Eutectics:

	mpt.	Composition(wt %)		mpt.	Composition(wt %)
E_1:	282°C	6.8% NaCl; 78.2% NaOH	E_3:	298°C	10% NaCl; 75.2% NaOH
E_2:	291°C	7.7% NaCl; 76.8% NaOH	E_4:	318°C	20% NaCl; 65.2% NaOH

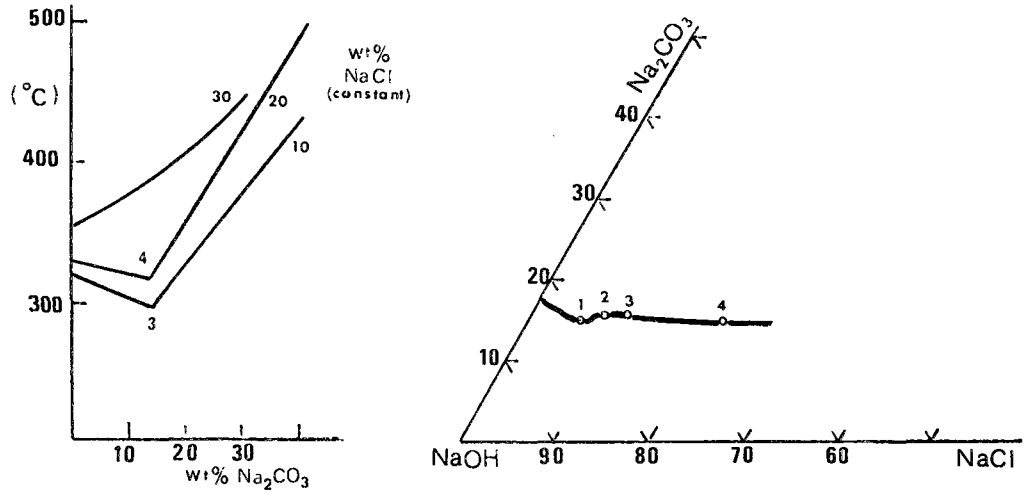

Figure 151.1 Na_2CO_3-NaOH-NaCl phase diagram

References [1-15]

2. *Density (ρ)*

Measurement method: Archimedean technique [16]

Equation:

$$\rho = a + bT \quad (151.1)$$

precision: in table 151.1 uncertainty: ∿ ± 1.5%

Table 151.1. Parameters of equation (151.1) and precisions

Composition (mol %)			a	$-b \times 10^4$	Precision	T range(K)
NaOH	Na_2CO_3	NaCl				
95.9	2.1	2.0	2.0986	5.000	0.01%	590-720
92.7	2.1	5.2	2.1065	5.163	0.01%	590-720
87.7	2.2	10.1	2.1212	5.316	0.01%	590-720

Table 151.2. Density (g cm^{-3}) from equations in table 151.1

NaOH	95.9 (mol %)	92.7 (mol %)	87.7 (mol %)
Na_2CO_3	2.1 (mol %)	2.1 (mol %)	2.2 (mol %)
NaCl	2.0 (mol %)	5.2 (mol %)	10.1 (mol %)
T(K)	ρ(g cm^{-3})	ρ(g cm^{-3})	ρ(g cm^{-3})
590	1.804	1.802	1.808
610	1.794	1.792	1.797
630	1.784	1.781	1.786
650	1.774	1.771	1.776
670	1.764	1.761	1.765
690	1.754	1.750	1.754
710	1.744	1.740	1.744
720	1.739	1.735	1.739

References [16]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

Measurement method: oscillating sphere technique [17]

Equation: (viscosity-composition isotherm, at fixed wt % Na_2CO_3)

$$\eta = a + bC + cC^2 \quad (151.2)$$

(C = mol % NaCl)

precision: in table 151.3 uncertainty: $\sim \pm 5.0\%$

Table 151.3. Parameters of equation (151.2) and precisions

Wt % Na_2CO_3	a	b x 10^2	-c x 10^4	Precision
10	2.619	3.969	2.953	0.07%
20	3.102	4.174	0.727	0.13%
30(a)	3.680	3.798	-2.307	0.00%

(a)Equation derived from three data points.

Table 151.4. Viscosity (cp) at 693K from equations in table 151.3

NaOH-NaCl (Mol % NaCl)	Wt % Na_2CO_3		
	10	20	30
0	2.62	3.10	3.68
2.5	2.72	3.21	3.78
5.0	2.81	3.31	3.88
7.5	2.90	3.42	3.98
10.0	2.99	3.53	4.08
12.5	3.07	3.64	4.19
15.0	3.15	3.74	4.30
17.5	3.22	3.85	4.42
20.0	3.30	3.97	4.53
22.5	3.36	4.08	
25.0	3.43	4.19	
27.5		4.30	

References [17]

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: NaCl, permitted in foods; NaOH, strongly caustic and toxic; Na_2CO_3, moderate, classified as caustic.

(ii) Vapor pressure: NaCl, at m.pt. (800°C), ~ 0.34mm; NaOH, at m.pt. (318°C), << 0.5mm; Na_2CO_3 (m.pt. 858°C) decomposes on heating to the oxide and CO_2; CO_2 pressure at 950°C, ~ 1mm.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over: and/or equipment failure;; i.e., explosive expansion of "trapped" air.

(ii) Chlorides, when heated to decomposition or contacted with acids, highly toxic chloride fumes are evolved.

(iii) Hydroxides react with water or steam with evolution of heat; the aqueous solution is very caustic and attacks living tissue; dangerous.

(iv) Carbonates, when heated with CO_2 pressures less than equilibrium dissociation pressures, decompose to form alkali metal oxides; the toxicology and disaster hazards are the same as those of very caustic solutions, i.e. react with water or steam (exothermic) to form solutions that are markedly aggressive to all body tissues (chemical burns).

References [18-23]

7. Corrosion

Table 151.5. Corrosion studies from primary research literature

	Systems, Studies, [References]
A	Silica [24], Pt [25], Metals [26], Cu-Zn [27], Pt, Au, Ag, MgO [28-31], Pt, Rh, Pd, Ir (O_2 environment) [32], Au, Ag, Al_2O_3 (O_2 environment) Na_2CO_3-Na_2O) [33], Al_2O_3, Pt, (N_2 atmosphere) [34-36], quartz, porcelain, Ag, Pt, Ni (N_2 atmosphere; Na_2CO_3-Na_2O) [37], boron nitride [31,38], Na-β-alumina [31,38], Fe (Na_2CO_3-Na halides) [39], acid-base relationships [40-43], H_2O hydrolysis reactions [33,44,45], molten carbonates: fule cells, thermal energy storage, coal gasification[39,46-50]
B	Metals [51], metals ceramics, alloys [51,52-58], stainless steel, Fe-Cr-Ni alloys [59], Ni-Cr-Fe, Ni-Si-Cu [53,60], Ni-Mo, Ni, Cu, Armco Fe [61-63], Al_2O_3, ZrO_2 [52], Ni, [52,54-56,64-67], Ni-steels [68], Fe (effects of water) [69], Pt, Ag, alloys [70-72], thermodynamic and electrochemical approach [73-75], reviews [76-78], annotated corrosion biblio. [79].
C	Mo [80], Armco Fe [81-83], Ni, Cr, [84], Ti, Zr, Hf, $ThCl_4$ [85], Cr [86], Fe-Cr [87], Ni alloys [88], Ni-Cr-Al, Ni-Cr-W, Fe, Ni-Cr, Mg, Ni, Zr, Ti [89], Au, Pt, Al_2O_3, MgO, Zirconia (NaCl with Na_2O) [90], thermodynamic redox potentials [89,91,92], electrochemical aspects [73,74], annotated corrosion biblio. [78], reviews[76-78].

Compatibility studies: A: molten carbonates, principally Na_2CO_3; B: molten hydroxides, principally NaOH; C: molten chlorides, principally NaCl. No compatibility studies found specifically for molten Na_2CO_3-NaOH-NaCl mixtures.

References [24-92]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f°)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

Measurement method: estimated from densities [93]

Table 151.6. Volume change on melting

Composition	$(\Delta V_f/V_s)$	Uncertainty
ternary eutectic (a)	5.3%	$\sim \pm$ 10%

(a) Na_2CO_3: NaOH: NaCl:: 7: 86: 7 (mol %)

References [93]

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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[1] Lantratov, M. F., Alabyshev, A. F., Zhur. Priklad. Khim., 32, 65 (1959).

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System 152 Na_3AlF_6-Al_2O_3-LiF

1. *Melting Temperatures (T_m)*

Pure substance melting points:

LiF:	848°C
Na_3AlF_6:	1010°C
Al_2O_3:	2040°C

Eutectic melting point:

697°C, composition 59.8 mol % Na_3AlF_6; 4.5 mol % Al_2O_3; 35.7 mol % LiF

56.5 wt % Na_3AlF_6; 2.0 wt % Al_2O_3; 41.5 wt % LiF

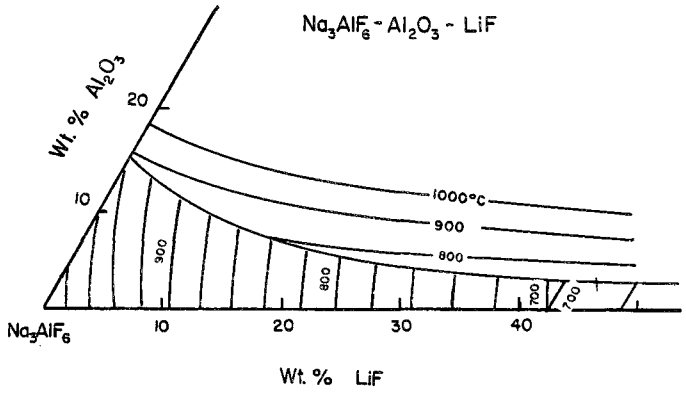

Figure 152.1 Na_3AlF_6-Al_2O_3-LiF phase diagram

References [1-21]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity : inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure: no information for this system; but see Na_3AlF_6 [24] and NaF [28].

(152) Na_3AlF_6-Al_2O_3-LiF

B. Disaster hazards

(i) Molten salt bath "explosion": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [22-28]

7. Corrosion

Table 152.1. Corrosion studies from primary research literature

	Studies	References
A	Cr	[29]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[30,31]
	SSNI-12P	[32
	Quartz	[33]
	Al	[34]
	Various metals	[35]
B	Pt	[36-40,74,75]
	Boron nitride, carbon, Inconel	[41-43]
	Fused MgO	[44]
C	Impurities in electrolyte	[45,46]
	Graphite	[45,46]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[47-49]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[50-65,72,73]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[66-68]
	Electroanalytical studies in molten fluorides	[69]
	Annotated corrosion biblio.	[70]
	Corrosion: molten fluorides (survey)	[71]

A: studies principally in molten NaF, KF and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [29-75]

(152) Na_3AlF_6-Al_2O_3-LiF

9. *Diffusion*

No data

10. *Heat of Fusion (ΔH°_f)*

No data

11. *Heat Capacity (C_p)*

No data

12. *Volume Change on Melting (ΔV_f)*

No data

13. *Vapor Pressure (p_{vap})*

No data

14. *Thermal Conductivity (liquid) (λ_ℓ)*

No data

15. *Thermal Conductivity (solid) (λ_s)*

No data

16. *Cryoscopic Constant (k_f)*

No data

16. *References*

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System 153 Na_3AlF_6-Al_2O_3-CaF_2

1. *Melting Temperatures (T_m)*

Pure substance melting points:

Na_3AlF_6:	1010°C
CaF_2:	1418°C
Al_2O_3:	2040°C

Eutectic melting point:

927°C, composition 58.4 mol % Na_3AlF_6; 7.4 mol % Al_2O_3; 34.2 mol % CaF_2
78.0 wt % Na_3AlF_6; 5.0 wt % Al_2O_3; 17 wt % CaF_2

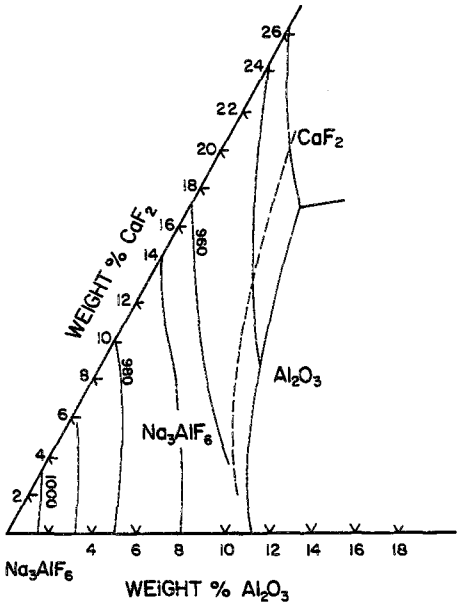

Figure 153.1. Na_3AlF_6-Al_2O_3-CaF_2 phase diagram

References [1-19].

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

(153) Na_3AlF_6-Al_2O_3-CaF_2

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure: no information for this system; but see Na_3AlF_6 [22] and CaF_2 [22].

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [20-25].

(153) Na_3AlF_6-Al_2O_3-CaF_2

7. Corrosion

Table 153.1. Corrosion studies from primary research literature

	Studies	References
A	Cr	[26]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[27,28]
	SSNI-12P	[29]
	Quartz	[30]
	Al	[31]
	Various metals	[32]
B	Pt	[33-37,71]
	Boron nitride, carbon, Inconel, Mo	[38-40,72]
	Fused MgO	[41]
C	Impurities in electrolyte	[42,43]
	Graphite	[42,43]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[44-46]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[47-62,69,70]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[63-65]
	Electroanalytical studies in molten fluorides	[66]
	Annotated corrosion biblio.	[67]
	Corrosion: molten fluorides(survey)	[68]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [26-72]

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

(153) Na_3AlF_6-Al_2O_3-CaF_2

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 154 Na_3AlF_6-AlF_3-Al_2O_3

1. *Melting Temperature (T_m)*

Pure substance melting points:

Na_3AlF_6: 1010°C
Al_2O_3: 2040°C
AlF_3: does not melt; sublimes with 1 atm equil^m press. at ∿ 1255°C

Eutectic melting point:

E_1: 684°C, composition: 67.3 wt % Na_3AlF_6, 4.4 wt % Al_2O_3
37.4 mol % Na_3AlF_6, 4.1 mol % Al_2O_3

P_1: 723°C, composition: 59.5 wt % Na_3AlF_6, 3.2 wt % Al_2O_3
45.6 mol % Na_3AlF_6, 5.8 mol % Al_2O_3

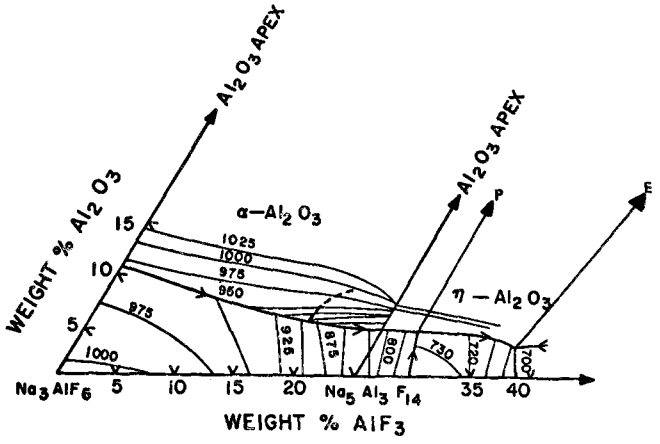

Figure 154.1. Na_3AlF_6-AlF_3-Al_2O_3

References [1-21]

(154) Na_3AlF_6-AlF_3-Al_2O_3

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

Measurement method: oscillation technique [22]

Equation:

$$\eta = a + bT + cT^2 + dT^3 \quad (154.1)$$

precision: in table 154.2 uncertainty: ∿ ± 2%

Table 154.1. Compositions and temperature ranges

#	Composition (mol %)			T range(K)
	Na_3AlF_6	Al_2O_3	AlF_3	
1	85.06	2.31	12.64	1192-1313
2	86.99	6.80	6.21	1263-1367
3	89.19	4.45	6.37	1243-1355
4	91.78	2.22	6.00	1253-1358
5	92.97	4.70	12.33	1173-1314

Table 154.2. Parameters of equation (154.1) and precisions

Mixture	a	b x 10^3	-c x 10^6	d x 10^9	Precision
No. 1	12.907	- 1.743	13.76	6.440	0.30%
No. 2	23.546	-24.41	- 6.345	-	1.03%
No. 3	6.778	16.46	27.83	9.565	0.84%
No. 4	17.060	0.933	23.18	10.40	0.53%
No. 5	24.058	-12.41	17.45	10.59	0.70%

Table 154.3. Viscosity (cp) from equations in tables 154.1 and 154.2

T	Mixture				
(K)	#1	#2	#3	#4	#5
1180					2.517
1200	2.129				2.338
1220	1.994				2.175
1240	1.867		2.634		2.030
1260	1.748	2.863	2.468	2.239	1.902
1280	1.637	2.697	2.309	2.087	1.792
1300	1.535	2.536	2.158	1.948	1.701
1320		2.380	2.013	1.822	
1340		2.230	1.877	1.712	
1360		2.084	1.750	1.616	

References [22]

(154) Na_3AlF_6-AlF_3-Al_2O_3

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally irritants and toxic; alumina is classed as a nuisance particulate.

(ii) Vapor pressure: Na_3AlF_6 at m.pt. (1000°C), << 0.5mm; AlF_3 at its m.pt. (1291°C), no data; sublimes at ∿ 1240°C.

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [23-28]

(154) Na_3AlF_6-AlF_3-Al_2O_3

7. Corrosion

Table 154.4. Corrosion studies from primary research literature

	Studies	References
A	Cr	[29]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[30,31]
	SSNI-12P	[32]
	Quartz	[33]
	Al	[34]
	Various metals	[35]
B	Pt	[36-40]
	Boron nitride, carbon, Inconel	[41-43]
	Fused MgO	[44]
C	Impurities in electrolyte	[7,45]
	Graphite	[7,45]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[46-48]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[49-64,71,72]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[65-67]
	Electroanalytical studies in molten fluorides	[68]
	Annotated corrosion biblio.	[69]
	Corrosion: molten fluorides (survey)	[70]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluoride physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [29-72,7]

(154) Na_3AlF_6-AlF_3-Al_2O_3

8. Diffusion

No data

9. Heat of Fusion (ΔH_f)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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[1] Foster, P. A., J. Am. Ceram. Soc., 58, 288 (1975).

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System 155 Na_3AlF_6-Al_2O_3-NaCl

1. *Melting Temperatures (T_m)*

Pure substance melting points:

NaCl:	800°C
Na_3AlF_6:	1010°C
Al_2O_3:	2040°C

Eutectic melting point:

735°C, composition: < 1 wt % Al_2O_3, ∿ 31.5 wt % Na_3AlF_6, ∿ 68.5 wt % NaCl

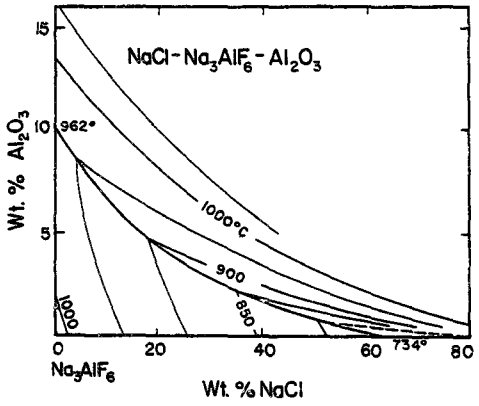

Figure 155.1. Na_3AlF_6-Al_2O_3-NaCl phase diagram

References [1-22]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

5. *Electrical Conductance (κ)*

No data

(155) Na_3AlF_6-Al_2O_3-NaCl

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure: no information for this system; but see Na_3AlF_6 [25] and NaCl [29].

B. Disaster hazards

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides and chlorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [23-29]

(155) Na_3AlF_6-Al_2O_3-NaCl

7. Corrosion

Table 155.1. Corrosion studies from primary research literature

	Studies	References
A	Cr	[30]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[31,32]
	SSNI-12P	[33]
	Quartz	[34]
	Al	[35]
	Various metals	[36]
B	Pt	[37-41]
	Boron nitride, carbon, Inconel	[42-44]
	Fused MgO	[45]
C	Impurities in electrolyte	[46,47]
	Graphite	[46,47]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[48-50]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[51-66,73,74]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[67-69]
	Electroanalytical studies in molten fluorides	[70]
	Annotated corrosion biblio.	[71]
	Corrosion: molten fluorides (survey)	[72]

A: studies principally in molten NaF, KF and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [30-74]

8. Diffusion

No data

9. Heat of Fusion (ΔH°_f)

No data

(155) Na_3AlF_6-Al_2O_3-NaCl

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

16. References

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System 156 Na_3AlF_6-Al_2O_3-Li_3AlF_6

1. *Melting Temperature (T_m)*

Pure substance melting points:

Na_3AlF_6:	1010°C
Al_2O_3:	2040°C
Li_3AlF_6:	785°C

Eutectic melting point:

760°C composition: ∿ 27 mol % Na_3AlF_6; ∿ 65 mol % Li_3AlF_6; ∿ 8 mol % Al_2O_3

Reaction point:

693°C composition: ∿ 33 mol % Na_3AlF_6 ∿ 63 mol % Li_3AlF_6 ∿ 4 mol % Al_2O_3

Peritectic melting point:

683°C composition: ∿ 33 mol % Na_3AlF_6 ∿ 61 mol % Li_3AlF_6 ∿ 6 mol % Al_2O_3

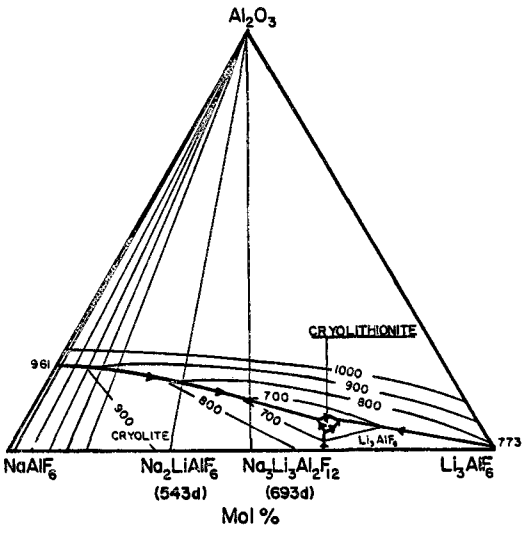

Figure 156.1. Na_3AlF_6-Al_2O_3-Li_3AlF_6 phase diagram

References [1-15]

2. *Density (ρ)*

No data

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

(156) Na_3AlF_6-Al_2O_3-Li_3AlF_6

5. *Electrical Conductance (κ)*

No data

6. *Safety and Hazards*

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure: no information for this system; but see Na_3AlF_6 [18] and Li_3AlF_6 [18].

B. Disaster hazards

(i) Molten salt bath "explosions": i.e. explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [16-21]

(156) Na_3AlF_6-Al_2O_3-Li_3AlF_6

7. Corrosion

Table 156.1. Corrosion studies from primary research literature

	Studies	References
A	Cr	[22]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[23,24]
	SSNI-12P	[25]
	Quartz	[26]
	Al	[27]
	Various metals	[28]
B	Pt, Pt-Rh	[29-33,67,68]
	Boron nitride, carbon, Inconel	[34-36]
	Fused MgO	[37]
C	Impurities in electrolyte	[38,39]
	Graphite	[38,39]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[40-42]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[43-58,65,66]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[59-61]
	Electroanalytical studies in molten fluorides	[62]
	Annotated corrosion biblio.	[63]
	Corrosion: molten fluorides(survey)	[64]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [22-68]

8. Diffusion

No data

9. Heat of Fusion (ΔH_f)

No data

(156) Na_3AlF_6-Al_2O_3-Li_3AlF_6

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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System 157 Na_3AlF_6-Al_2O_3-SiO_2

1. *Melting Temperature (T_m)*

Pure substance melting points:

Na_3AlF_6:	1010°C
Al_2O_3:	2040°C
SiO_2:	quartz: 1610°C tridymite:1680°C cristobalite: 1728°C

Invariant points:

The large solubility of SiO_2 and Al_2O_3 at the invariant points (69 wt % SiO_2, 14 wt % Al_2O_3 at 1010°C, and 50 wt % SiO_2, 17 wt % Al_2O_3 at 800°C) imply substantial solubilities of the aluminum silicates in this system. The restricted field of liquid at 800°C indicates that the liquidus does not extend much below this temperature [2].

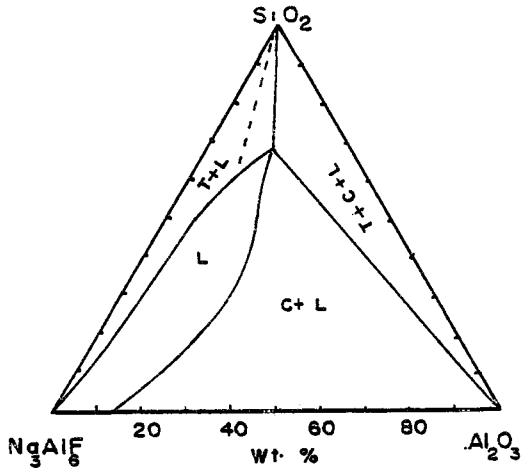

Figure 157.1. Phase diagram of isothermal section at 1010°C for Na_3AlF_6-Al_2O_3-SiO_2

(C: corundum; T: tridymite; L: liquid)

References [1-15]

(157) Na_3AlF_6-Al_2O_3-SiO_2

2. *Density (ρ)*

Measurement method: Archimedean technique [16]

Equation:

$$\rho = a + bC \quad (157.1)$$

(C = mol % Al_2O_3)

precision: in table 157.1 uncertainty: ∿ ± 2%

Table 157.1. Parameters of equation (157.1) and precisions

Wt % SiO_2	T (K)	a	-b x 10^3	Precision
2	1273	2.0981	2.2279	0.0995%
4	1273	2.0983	1.8884	0.0386%
6	1273	2.0973	1.4937	0.0520%

Table 157.2. Density (g cm^{-3}) from equations in table 157.1

Na_3AlF_6-Al_2O_3 (mol % Al_2O_3)	Wt % SiO_2		
	2	4	6
0	2.098	2.098	2.097
5	2.087	2.089	2.090
10	2.076	2.079	2.082
15	2.065	2.070	2.075
20	2.054	2.061	

References [16]

3. *Surface Tension (γ)*

No data

4. *Viscosity (η)*

No data

(157) Na_3AlF_6-Al_2O_3-SiO_2

5. *Electrical Conductance* (κ)

Measurement method: classical ac technique [16]

Equation: (conductance-composition isotherm)

$$\kappa = a + bC + cC^2 + dC^3 \quad (157.2)$$

(C = mol % Al_2O_3)

precision: in table 157.3 uncertainty: $\sim \pm 3\%$

Table 157.3. Parameters of equation (157.2) and precisions

Wt % SiO_2	a	b x 10^3	- c x 10^3	d x 10^6	Precision
0	2.802	-19.167	0.3381		0.1207%
2	2.631	0.879	2.6304	74.718	0.3718%
4	2.573	-9.015	2.03927	72.228	1.0218%
6	2.503	-10.596	1.77613	65.011	0.8396%

Table 157.4. Specific conductance (ohm^{-1} cm^{-1}) from equations in table 157.3

Na_3AlF_6-Al_2O_3 (mol % Al_2O_3)	Wt % SiO_2			
	0	2	4	6
0	2.80	2.63	2.57	2.50
5	2.70	2.58	2.49	2.41
10	2.58	2.45	2.35	2.28
15	2.44	2.30	2.22	2.16
20	2.28	2.19	2.15	2.10

References [16]

(157) Na_3AlF_6-Al_2O_3-SiO_2

6. Safety and Hazards

A. Hazard rating

(i) Toxicity: inorganic fluorides are generally quite irritant and toxic.

(ii) Vapor pressure: no information on this system; Na_3AlF_6 at its m.pt. (1010°C), $\sim << 0.5$mm.

B. Disaster hazard

(i) Molten salt bath "explosions": i.e., explosive generation of steam due to bulk water "carry-over" and/or equipment failure; i.e., explosive expansion of "trapped" air.

(ii) Fluorides, when heated to decomposition, or contacted with acids, emit highly toxic fumes.

References [17-22]

(157) Na_3AlF_6-Al_2O_3-SiO_2

7. Corrosion

Table 157.5. Corrosion studies from primary research literature

	Studies	References
A	Cr	[23]
	Ni-Cr-Mo alloys (INOR-8; Hastelloys B, W, and N)	[24,25]
	SSNI-12P	[26]
	Quartz	[27]
	Al	[28]
	Various metals	[29]
B	Pt	[30-34]
	Boron nitride, carbon, Inconel	[35-37]
	Fused MgO	[38]
C	Impurities in electrolyte	[39,40]
	Graphite	[39,40]
	TiC, TiB_2, CrB_2, ZrN, NbB_2	[41-43]
D	Corrosion studies in molten salts with NaF as one component (e.g., Cl, CO_3,...)	[44-59,66,67]
	Electrochemical behavior of oxide ions and related species in molten fluorides	[60-62]
	Electroanalytical studies in molten fluorides	[63]
	Annotated corrosion biblio.	[64]
	Corrosion: molten fluorides(survey)	[65]

A: studies principally in molten NaF, KF, and LiF; B: used largely in fluorides physical properties measurements; C: technological aspects, in aluminum reduction cells; D: more general studies, basic principles, and surveys.

References [23-67]

(157) Na_3AlF_6-Al_2O_3-SiO_2

8. Diffusion

No data

9. Heat of Fusion (ΔH_f)

No data

10. Heat Capacity (C_p)

No data

11. Volume Change on Melting (ΔV_f)

No data

12. Vapor Pressure (p_{vap})

No data

13. Thermal Conductivity (liquid) (λ_ℓ)

No data

14. Thermal Conductivity (solid) (λ_s)

No data

15. Cryoscopic Constant (k_f)

No data

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The present work provides selected data with value judgements for an additional set of 107 salt systems of interest as candidate materials for thermal energy storage sub-systems, for electrochemical energy storage systems, and in electrochemical aluminum production. The physical properties assessed are: melting points; phase diagrams; eutectic compositions; density; surface tension; viscosity; electrical conductivity; diffusion constants for ions; heat of fusion; heat capacity; volume change on fusion; vapor pressure; thermal conductivity (liquid and solid); and cryoscopic constant. The status of corrosion studies in the form of annotated bibliographic summaries, and salient observations on safety and hazards are also reported. A summarizing series of tables is provided as index to the data-gaps status for this set of candidate materials

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