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Saline: An API for Thermophysical Properties

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Nuclear Energy and Fuel Cycle Division

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CONTENTS

ABSTRACT

An initial interface for thermophysical data was generalized for broader incorporation into modeling and simulation codes used for molten salt reactor analysis. A quality assurance review of the thermophysical properties data was conducted; errors were fixed, and improvements were made with consistency and accuracy to references. The Saline code application programming interface was created to facilitate access and integration of thermophysical properties. This report describes the thermophysical data, the quality assurance improvements, and the Saline interface.

1. INTRODUCTION

Saline's predecessor, an initial interface for thermophysical data [1], was generalized into a C++ application programming interface (API) with Fortran interface bindings for broader incorporation into modeling and simulation codes. In addition, the thermophysical data used by the API was improved.

2. THERMOPHYSICAL PROPERTIES

Thermophysical properties of molten salts are important for the reactor design, operation, and safety [2]. Obtained from the thermal analyses or CALPHAD (Computer Coupling of Phase Diagrams and Thermochemistry) method, the melting and the boiling temperatures of the salts provide liquid-phase stability range. Density, viscosity, thermal conductivity, and heat capacity are important transport properties in determining parameters such as flow regimes, heat transfer, and volumetric flow rates [3]. For engineering design, thermophysical data and associated uncertainty values are required. Development of a thermophysical database is a utilitarian way to organize this information for use by end users with, for example, thermal hydraulics or multiphysics reactors simulation software.

2.1 THERMOPHYSICAL DATA

Thermophysical properties of molten salts have been studied by various authors, and the measured data have been published [4]–[10]. The data and the experimental measurements or theoretical estimation methods used to generate them were compiled in several publications [11]–[17]. Janz et al. prepared several reports on the existing thermophysical property data over the years [18]–[23]. Serrano-Lopez et al., Tasidou et al., and Magnusson et al. have compiled the most recent data [11],[16],[24]. These data sets and reports have been useful for finding the original data for further details such as measurement technique and error margins.

MSTDB-TP (Molten Salt Thermal Database-Thermophysical) [25],[26] was developed as an extension of the work performed by Jerden [15]. The report documented the first version of MSTDB-TP, an Excel spreadsheet. The current version of MTSDB-TP aims to improve the data with the source reference publication. It contains 62 entries. Of them, 27 are pure compounds, 8 are pseudobinary, 10 are pseudoternary and 5 are pseudoquaternary molten salt mixtures at specific compositions. The pure compounds and specific composition mixtures comprise fluorides and chlorides that are of interest to the molten salt reactor community. The following properties of the molten salts are provided.

- Melting and boiling temperatures
- Density
- Viscosity
- Thermal conductivity
- Heat capacity

Estimation of measurement errors are provided along with the original reference for each property. The melting temperature of almost all (61/62) of the compounds are included. Boiling temperatures are scarce in the literature for entries with two and more components in MSTDB-TP; currently, the database has 32 boiling point records out of 62 entries. Additional vapor pressure measurements and phase equilibrium calculations can help determine these boiling points. Most entries have density (54/62) and viscosity (48/62) records in the database. Heat capacity of all pure compounds and some of the molten salt mixtures are included (43/62). The scarcest property in the database is thermal conductivity (25/62). The scarcity stems from the inconsistency of the measurement results from different studies and insufficient modeling, for which a variable gap method was developed to provide data [27]–[29].

2.2 DATA IMPROVEMENTS

The Jerden report [15] was accompanied with an Excel spreadsheet. Quality assurance was performed on this first version of the spreadsheet. The data were compared with the original reference, and inconsistencies in the values and units were found and fixed. To ensure that the data were consistent, each property was compared with different literature values where possible. When the original data conflicted with the literature, more consistent values with lower uncertainties were selected.

Overall, the thermophysical data of molten salts are sparse, and the measurement results have different uncertainties. The laboratories that conducted the measurements have different standards, operational procedures, measurement techniques, sample purities, and sample characterization techniques that affect the thermophysical data results. Furthermore, simple mathematical expressions are needed that can describe the thermophysical properties of molten salts with respect to temperature and composition.

This type of mathematical modeling has been implemented for the density of NaCl-KCl-UCl_3 and NaCl-KCl-YCl_3 molten salt mixtures successfully in comparison with the experimental data [29]. The Redlich-Kister expansion [30] has been used to account for the nonideal behavior in density. The same procedure can be applied for viscosity and thermal conductivity. Ideal behavior equations for density, viscosity, and thermal conductivity of binary liquids are given in Eqs. (1–3).

$$\rho_{id} = \frac{x_A MW_A + x_B MW_B}{\frac{x_A MW_A}{\rho_A} + \frac{x_B MW_B}{\rho_B}} \tag{1}$$

$$\log \mu_{id} = x_A \log \mu_A + x_B \log \mu_B \tag{2}$$

$$\lambda_{id} = x_A \lambda_A + x_B \lambda_B \tag{3}$$

The ideal density is the ratio of molar mass to molar volume as shown in Eq. (1), where x_i is the mole fraction of i, MW_i is the molecular weight of i, and ρ_i is the density of pure i. Ideal viscosity has a log dependence with respect to composition as demonstrated by Arrhenius [32] in Eq. (2), where μ_i is the viscosity of i. Thermal conductivity ideal behavior was adopted from Dul'nev and Zarichnyak [32]. Thermal conductivity of a liquid depends on the heat capacity at constant volume (C_v), heat capacity at constant pressure (C_p), and velocity of sound of the molten salts [34],[35]. Data are available for various molten salts in the literature [27],[36]. Therefore, Eq. (3) must be revised with accurate heat capacity and velocity data. Heat capacity is modeled as a part of MSTDB-TC (Molten Salt Thermal Database-Thermochemical) and is calculated using the CALPHAD method [37].

Nonideal behavior of density, viscosity, and thermal conductivity are described by the Redlich-Kister expansion [31]. Equation (4) is added as a nonideal behavior term (ρ_{nid}, μ_{nid}, λ_{nid}) in Eqs. (1–3).

$$\rho_{nid},\ \mu_{nid}, \lambda_{nid} = x_A x_B \sum_{j=1}^{n} L_j (x_A - x_B)^{j-1} \tag{4}$$

L_j is the interaction term that accounts for the nonideality. As shown in Eq. (5), it has a linear dependence with respect to temperature.

$$L_j = A_j + B_j T \tag{5}$$

The parameters A_j and B_j are parameter constants, which are specific to molten salt mixtures. The interaction parameters that are modeled from binary molten salts can be used to extrapolate to ternary and higher order molten phases using the Muggianu interpolation scheme [30][38][39].

The Redlich-Kister modeling approach outlined here will provide broader composition coverage and temperature range for coolant, carrier, or fueled molten salts. However, it requires experimental results or theoretical estimations on binary molten salt density, viscosity, and thermal conductivity as inputs and validating, confirmatory data. Thermophysical measurements need to be conducted on planned binary molten salt systems described in the roadmap by McMurray et al. [25]. If there are no thermophysical data on binary salts, one can estimate the properties using the ideal behavior equations from pure molten salts shown in Eqs. (1)–(3), which are outlined in MSTDB-TP.

3. SALINE API

Saline is an API for the quality-assured collection of molten salt thermophysical property data described in Section 2. It provides a collection of classes and methods to facilitate the integration of molten salt density, viscosity, thermal conductivity, and heat capacity data models into a broad collection of client applications. The interface is written in C++11 with Fortran bindings. Python language bindings are in draft form. The configuration and compilation of Saline is managed using CMake for support across operating systems.

3.1 C++ INTERFACE

Saline is an object-oriented application predominately written using C++11. The main class of interest is the `Thermophysical_Property` class. This class provides for setting a particular composition via the `setCompostion` method and looking up data provided for that composition via data accessors. A data accessor is provided for looking up each thermophysical property using either temperature in Kelvin or enthalpy in Joule per mole. Users are encouraged to use the temperature interface if possible. Currently, Saline does not check to ensure that the requested temperature/enthalpy is within the range of the data model. In subsequent versions of Saline, a warning or exception may be raised when an out-of-range request is made.

The data models employed by `Thermophysical_Properties` are implemented in a `Data_Store` class. This class is intended to be extensible to provide alternative data implementations to client codes without requiring substantial changes within the client. Although additional data sets are under development, only use of the `Default_Data_Store` is currently recommended. This class makes the data discussed in Section 2 available for use.

An additional data set that may be used with caution is the `R_Kister_Data_Store`. This `Data_Store` uses the binary data provided by the `Default_Data_Store` and applies a Redlich-Kister polynomial to support arbitrary salt compositions. This provides for a very robust interface, but currently, only the density models of specific salts are implemented. All other properties are still obtainable, but the provided data are obtained using an ideal mixing assumption with unquantified uncertainty.

```cpp
#include "default_data_store.hh"
#include "thermophysical_properties.hh"

// Construct the default data store object
Default_Data_Store d;

// Load the default data
d.load();

// Construct the thermophysical properties object
Thermophysical_Properties tp;

// Initialize it with the data store
tp.initialize(&d);

// Pick a composition
tp.setComposition({"LiF","NaF","KF"},{0.465,0.115,0.42});

// Obtain data using temperature in Kelvin
double density = tp.rho(900);
double viscosity= tp.mu(900);
double thermal_conductivity = tp.k(900);
double heat_capacity = tp.cp(900);
```

Figure 1 C++ example use of thermophysical properties

3.2 FORTRAN INTERFACE

Saline also provides a Fortran interface for use where required. This interface is a wrapper class that uses the ISO_C_Binding module to pass Fortran arguments back and forth. Aside from the syntax of the programming language, only a select few methods have a noticeable difference, which are listed as follows.

1. The data accessors argument for pressure is a required argument with no effect on output value.
2. `setComposition` takes a single character array for salt names, an array of doubles for mole percentages, and a count of the number of constituents. Salt names should be delimited with a hyphen (-).

```
#include "default_data_store.hh"
#include "thermophysical_properties.hh"

// Construct the default data store object
Default_Data_Store d;

// Load the default data
d.load();

// Construct the thermophysical properties object
Thermophysical_Properties tp;

// Initialize it with the data store
tp.initialize(&d);

// Pick a composition
tp.setComposition({"LiF","NaF","KF"},{0.465,0.115,0.42});

// Obtain data using temperature in Kelvin
double density = tp.rho(900);
double viscosity= tp.mu(900);
double thermal_conductivity = tp.k(900);
double heat_capacity = tp.cp(900);
```

Figure 2 Fortran example use of the thermophysical properties

3.3 BUILD PROCESS

Saline was developed to utilize the CMake-based TriBITS build integration and test system. This system should enable Saline to be added to other TriBITS or CMake projects with minimal effort. The TriBITS documentation provides additional details for users in this circumstance.

The process outlined as follows will build Saline into a library, `libSaline.so`, which may be linked for use in other codes.

- Meet the prerequisites
  - C++11 compliant C/C++ compiler
  - Cmake 3.1+
  - Git 2.15+
  - Python 2.6+ (Python3+ preferred)—optional
- Set up a source directory using the following commands
  - Clone saline `git clone https://code.ornl.gov/neams/saline.git ~/saline`
  - Change directory into saline `cd ~/saline`
  - Clone TriBITS `git clone https://github.com/lefebvre/TriBITS.git TriBITS`
  - Clone extra repos `./TriBITS/tribits/ci_support/clone_extra_repos.py`
  - Create a build directory `mkdir -p ~/build/saline`
  - Change into the build `cd ~/build/saline`

- Create the recommended configuration script. For this example, the script is called `configure.sh` and is saved in the ~/build directory.

```
#!/bin/bash
# Linux bash file example
rm -rf CMake*
cmake \
 -D CMAKE_BUILD_TYPE:STRING=RELEASE \
 -D saline_ENABLE_ALL_PACKAGES:BOOL=ON \
 -D saline_ENABLE_TESTS:BOOL=ON \
 -D CMAKE_INSTALL_PREFIX=`pwd`/install \
 -G "Unix Makefiles" \
 ~/saline
```

- Execute the following to configure, build, and test from the ~/build/saline directory.
  - Configure Saline va `../configure.sh`
  - Compile Saline via `make`
  - Run the Saline tests via `ctest`

3.3.1 Fortran Support

To enable Fortran support, execute the command, `export saline_ENABLE_Fortran=ON`, before running the configure script. Compiling the Fortran code requires an F2003-compliant Fortran compiler.

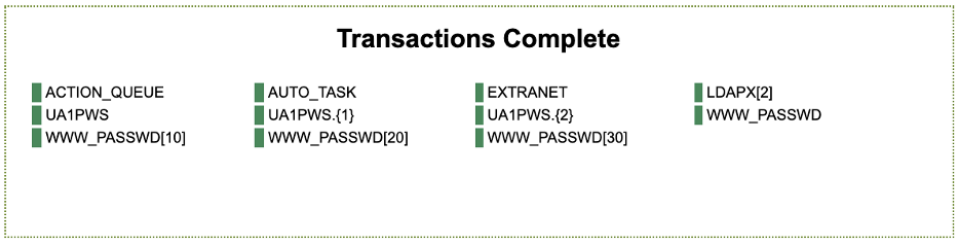
3.4 ACCESS PROCESS

The Saline project and associated thermophysical data are hosted on a publicly accessible server at Oak Ridge National Laboratory (ORNL), https://code.ornl.gov/neams/saline/. Access to this server requires an ORNL XCAMS account and a Saline project membership.

3.5 XCAMS Account Creation

XCAMS allows external, non-ORNL users to access code.ornl.gov. XCAMS accounts are created as follows:

1. Go to https://xcams.ornl.gov.
2. Select "**I need an account**."
3. Read and acknowledge the **User Agreement**.
4. Enter your **email address** and **username**, following the guidelines provided on the page.
5. Enter "**Personal Information**" and "**Contact Information**" according to the guidelines provided on the page.
6. Create an XCAMS password according to the guidelines provided on the page.
7. On the final step, note the activation sequence box. Wait until each action item turns green and the box heading reads "**Transactions Complete**."



8. Log in to https://code.ornl.gov using your new XCAMS username and password.

3.6 Request MSTDB membership

Send an email to Rob Lefebvre, lefebvrera@ornl.gov, with subject "Saline Access Request," and include the following information:

1. Your XCAMS ID
2. A summary of the purpose of your access

You will receive an email from code.ornl.gov indicating your Saline access has been granted and a link to the project page.

4. SUMMARY

This milestone report highlights improvements to thermophysical properties data and the creation of the Saline API. The Saline API was created to provide capabilities that can be integrated into C++ and Fortran molten salt reactor modeling and simulation codes.

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APPENDIX A. **MOLTEN SALT THERMOPHYISCAL DATA**

References		Douglas1954	O'Brien1957	Beilmann2013	Naylor1945
Uncertainty (%)		1.5	0.1	18	1-2
Heat capacity of liquid (J/K mol): A + B*T(K) + C*T^{-2}(K) + D*T^{2}(K)	D	—	—	—	—
	C	—	—	—	—
	B	—	—	—	—
	A	6.5E+01	6.9E+01	7.1E+01	9.4E+01
References		Gheribi2014	Gheribi2014	Gheribi2014	Gheribi2014
Uncertainty (%)		20	20	20	20
Applicable temperature range (K)		1118.5-1900	1268.15-1800	1129.15-1800	1536.1524
Thermal conductivity (W/m K): A + B*T(K)	B	-4.0E-04	-2.8E-04	-2.5E-04	-1.4E-04
	A	1.9E+00	1.3E+00	8.6E-01	8.7E-01
References		Abe1981	Brockner197	Janz1988	Takeda2015
Uncertainty (%)		<1	1	1-2	3
Applicable temperature range (K)		1133-1772	1273-1373	1141.2-1327.6	1514.7-1853.2
Viscosity (mN*s/m^{2}): 10^(A + B/T + C/T**2)	C	—	—	—	—
	B	—	—	—	—
	A	—	—	—	—
Viscosity (mN*s/m^{2}): A*exp(B/(R*T(K)))	B	2.7E+04	2.6E+04	2.4E+04	3.2E+04
	A	1.1E-01	1.2E+00	1.1E-01	1.9E-01
References		Hill1967	Paucirova197	Yaffe1956	Kirshenbaum1960
Uncertainty (%)		<1	0.2	<1	0.07
Applicable temperature range (K)		1123.6-1367.5	1273-1373	1154.2-1310.2	1650-2100
Density (g/cm^{3}): A - BT(K)	B	5.0E-04	6.4E-04	6.5E-04	5.2E-04
	A	2.4E+00	2.8E+00	2.6E+00	3.2E+00
References		Ruff1922	Ruff1922	Ruff1922	Ruff1928
Uncertainty (K)		—	—	—	—
Boiling temperature (K)		1943.0	1978.0	1771.0	2512.0
References		Douglas1954	Cantor1961	Johnson1958	Kojima1968
Uncertainty (K)		±1	±0.5	±0.5	±1
Melting temperature (K)		1121.2	1268.0	1131.2	1534.2
Composition (mole %)		Pure Salt	Pure Salt	Pure Salt	Pure Salt
#		1	2	3	4
Formula		LiF	NaF	KF	MgF2

Naylor1945	Efremova1970	Glushko1994	Beilmann201	Barin1995	Lemire2001	Rand2000
1-2	—	—	5		15	15
—	—	3.0E-09	—	—	—	—
—	—	-1.6E+07	—	—	—	—
—	—	-1.5E-03	—	—	—	—
1.0E+02	9.9E+01	1.0E+02	1.3E+02	1.7E+02	1.3E+02	1.3E+02
Gheribi2014	Gheribi2014	Gheribi2014	—	—	—	—
20	20	20	—	—	—	—
1691.15-2500	1673.15-	1070.15-	—	—	—	—
-6.0E-05	-7.3E-05	-2.1E-06				
6.7E-01	5.2E-01	8.0E-01	—	—	—	—
Takeda2015	Takeda2015	Moynihan196	—	Kulifeev1971	—	—
3	3	3	—	10	—	—
1703.3-1868.1	1743.4-1864.6	846.9-1252.2	—	1338-1618	—	—
—	—	6.4E+05	—	2.8E+07	—	—
—	—	1.1E+04	—	-3.5E+04	—	—
—	—	-8.1E+00	—	1.1E+01	—	—
4.8E+04	5.4E+04	—	—	—	—	—
1.0E-01	7.0E-02	—	—	—	—	—
Kirshenbaum1	Kirshenbaum1	Cantor1969	—	Kirshenbaum	—	—
0.07	0.07	0.5	—	<1	—	—
1640-2300	1750-2200	1073-1123	—	1309-1614	—	—
3.9E-04	7.5E-04	1.5E-05	—	9.9E-04	—	—
3.2E+00	4.8E+00	2.0E+00	—	7.8E+00	—	—
Ruff1928	Ruff1928	Cantor1965	Glushko1994	Langer1960	Barin1977	Barin1977
—	—	—	—	—	—	—
2724.0	2762.0	1442.0	2550.0	1723.0	2500.0	2493.0
Mukerji1965	Kojima1968	Thoma1960	D'Eye1957	Langer1960	Lemire2001	Westrum1951
±1	±1	±1	±20	±2	±30	±2
1692.0	1746.0	821.2	1768.2	1309.0	1735.0	1699.0
Pure Salt	Pure Salt	Pure Salt	Pure Salt	Pure Salt	Pure Salt	Pure Salt
5	6	7	8	9	10	11
CaF2	SrF2	BeF2	UF3	UF4	NpF3	PuF3

Spedding1971	Spedding1971	Spedding1974	Douglas1959	Dawson1963	Murgulescu1977
3	3	3	0.5	3-4	2
—	—	—	—	-1.8E-05	—
-4.3E+08	-1.2E+07	—	—	4.0E+07	—
-1.4E-01	-4.4E-03	—	6.4E-03	7.7E-02	—
7.3E+02	1.8E+02	1.3E+02	7.1E+01	-2.7E+01	7.3E+01
—	—	—	Nagasaka1992	Nagasaka1992	Nagasaka1992
—	—	—	20	8	8
—	—	—	967-1321	1170-1441	1056-1335
			-2.9E-04	-1.8E-04	-1.7E-04
—	—	—	8.8E-01	7.1E-01	5.7E-01
—	—	—	Wakao1991	Torklep1979	Ejima1982
—	—	—	2	<1	<1
—	—	—	886-1275	1083.2-1203.2	1050.7-1190.9
—	—	—	—	—	—
—	—	—	—	—	—
—	—	—	—	—	—
—	—	—	2.2E+04	2.2E+04	2.4E+04
—	—	—	7.3E-02	8.9E-02	7.1E-02
Kirshenbaum1	—	—	Van Artsdalen1955	Van Artsdalen1955	Van Artsdalen1955
0.07	—	—	<1	<1	<1
1750-2450	—	—	893.2-1053.2	1076.2-1303.2	1053.2-1213.2
6.8E-04	—	—	4.3E-04	5.4E-04	5.8E-04
5.8E+00	—	—	1.9E+00	2.1E+00	2.1E+00
Janz1967	Knacke1991	Landolt2000	Wartenberg1921	Ruff1921	Ruff1921
—	—	—	—	—	—
2600.0	2573.0	2550.0	1655.0	1715.0	1688.0
Spedding1971	Spedding1971	Spedding1974	Haendler1959	Dawson1963	Johnson1958
±3	±3	±3	±2	±1	±0.5
1766.0	1650.0	1505.0	883.2	1073.8	1042.7
Pure Salt	Pure Salt	Pure Salt	Pure Salt	Pure Salt	Pure Salt
12	13	14	15	16	17
LaF3	NdF3	GdF3	LiCl	NaCl	KCl

Moore1943	Moore1943	Janz1963	McDonald1965	Barin1995	Lemire2001	Rand2000
<1	<1	1	<1	—	11	10
—	—	—	—	—	—	—
—	—	—	—	—	—	—
—	—	—	—	—	—	—
9.2E+01	1.0E+02	1.1E+02	1.2E+02	1.3E+02	1.4E+02	1.5E+02
Gheribi2014	Gheribi2014	Gheribi2014	—	—	—	—
20	20	20	—	—	—	—
987.15-1700	1055.15-1700	1148.15-1800	—	—	—	—
-2.0E-05	-1.2E-04	-1.2E-04				
2.2E-01	5.7E-01	5.2E-01	—	—	—	—
Toerklep1982	Toerklep1982	Toerklep1982	—	—	—	—
<1	<1	<1	—	—	—	—
993-1173	987-1239	1152-1318	—	—	—	—
—	5.5E+05	8.8E+05	—	—	—	—
—	6.0E+02	4.0E+02	—	—	—	—
—	-5.5E-01	-4.4E-01	—	—	—	—
2.1E+04	—	—	—	—	—	—
1.8E-01	—	—	—	—	—	—
Katyshev1981	Yaffe1956	Yaffe1956	Klemm1926	Mochinaga196	—	—
1	<1	<1	2	1.5	—	—
990-1211	1060-1223	1167.2-1310.2	706-746	1219-1304	—	—
3.3E-04	4.2E-04	5.8E-04	1.1E-03	7.9E-03	—	—
2.0E+00	2.5E+00	3.4E+00	2.3E+00	1.4E+01	—	—
Glushko1972	Glushko1972	Glushko1972	Brewer1963	Knacke1991	Barin1977	Barin1977
±20	±30	±50	—	—	—	—
1640.0	2230.0	2310.0	760.0	2000.0	1800.0	2063.0
Moore1943	Moore1943	Dworkin1963	McDonald1965	Borowitz1971	Lemire2001	Bjorklund1959
±1	±1	±2	±2	±1	±30	±2
987.0	1055.0	1146.0	688.0	1114.0	1075.0	1040.0
Pure Salt	Pure Salt	Pure Salt	Pure Salt	Pure Salt	Pure Salt	Pure Salt
18	19	20	21	22	23	24
MgCl2	CaCl2	SrCl2	BeCl2	UCl3	NpCl3	PuCl3

Dworkin1963a	Dworkin1963a	Dworkin1971	Redkin2017	Rogers1982	Rosenthal196
5	5	<1	—	2	1.4
—	—	—	—	—	—
—	—	—	—	—	—
—	—	—	—	4.4E-02	—
1.6E+02	1.5E+02	1.4E+02	7.1E+01	4.0E+01	8.0E+01
—	—	—	—	An2015	Manohar2010
—	—	—	—	4	—
—	—	—	—	773-973	500–650
			—	1.3E-03	5.0E-04
—	—	—	—	-3.5E-01	6.3E-01
Smirnov1966	Hayashi1997	Cho1972a	Williams 2006b	Toerklep1980	Cantor1968
1	3	2	1	2	15
1183-1276	1030-1237	1060-1233	625-1070	770–970	873–1073
—	—	9.8E+06	—	1.4E+06	—
—	—	-1.6E+04	—	-1.2E+03	—
—	—	6.4E+00	—	2.1E-01	—
5.5E+04	3.7E+04	—	2.1E+04	—	3.1E+04
2.1E-02	8.5E-02	—	8.6E-02	—	1.2E-01
Yaffe1956	Cho1972	Cho1972	Van	Cibulkova2006	Cantor1973
<1	1	1	<1	<1	<1
1146.2-1246.2	1082-1272	932-1280	668-866	933-1163	787.7-1093.5
7.8E-04	9.3E-04	6.7E-04	5.3E-04	6.2E-04	4.9E-04
4.1E+00	4.3E+00	4.2E+00	2.0E+00	2.6E+00	2.4E+00
Glushko1972	Glushko1972	Glushko1972	Williams 2006b	Williams 2006b	Jerden2019
±20	±10	±10	—	—	—
1983.0	1897.0	1868.0	1673.2	1843.2	1673.2
Keneshea1961	Druding1961	Dworkin1971	Basin2008	Rogers1982	Thoma1968
±2	±2	±2	±2	±2	±3
1132.0	1031.0	875.0	625.0	735.0	731.0
Pure Salt	Pure Salt	Pure Salt	0.582-418	0.465-0.115-0.42	0.66-0.34
25	26	27	28	29	30
LaCl3	NdCl3	GdCl3	LiCl-KCl	LiF-NaF-KF	LiF-BeF2

Xu2018	—	Powers1956	Powers1956	—	Powers1956
5	—	16	16	—	15
—	—	—	—	—	—
—	—	—	—	—	—
8.5E-03	—	—	—	—	-4.0E-02
7.7E+01	8.6E+01	1.2E+02	8.2E+01	—	1.5E+02
Xu2018	—	Powers1963	Powers1963	—	Powers1963
7	—	25	25	—	25
723-1073	—	—	—	—	—
-1.0E-04		—	—	—	—
5.0E-01	7.0E-01	8.6E-01	4.0E+00	—	2.3E+00
Xu2018	Cohen1957	Cohen1957	Cohen1957	Cohen1957	Cohen1957
7		10	10	10	10
723-1073	—	973-1173	773-1073	773-1073	873-1073
1.5E+06	—	—	—	—	—
-3.7E+03	—	—	—	—	—
2.8E+00	—	—	—	—	—
—	4.7E+03	3.9E+04	3.5E+04	2.6E+04	3.2E+04
—	3.4E-05	7.7E-02	3.5E-02	1.6E-01	9.8E-02
Xu2018	Shishido2017	Cohen1954	Cohen1954	Cohen1954	Cohen1954
1.2	—	3	3	—	—
723-1073	—	973-1273	793-1123	—	—
5.5E-04	4.8E-04	1.2E-03	9.0E-04	8.4E-04	9.3E-04
2.1E+00	2.4E+00	4.7E+00	2.7E+00	3.4E+00	3.9E+00
Williams	—	—	—	—	—
—	—	—	—	—	—
>1691.2	—	—	—	—	—
Xu2018	Williams2006a	Cohen1954	Cohen1957	Cohen1957	Cohen1954
±1	—	—	—	—	—
697.6	588.0	803.2	725.2	698.2	793.2
0.68-0.32	0.31-0.31-0.38	0.465-0.26-	0.109-0.445-	0.05-0.52-0.43	0.50-0.46-0.04
31	32	33	34	35	36
KCl – MgCl2	LiF-NaF-BeF2	NaF-KF-UF4	NaF-LiF-KF-UF4	NaF-KF-ZrF4	NaF-ZrF4-UF4

Powers1956	—	—	Powers1956	Powers1956	—	—
15	—	—	15	15	—	—
—	—	—	—	—	—	—
—	—	—	—	—	—	—
-4.7E-02	—	—	—	-2.8E-02	—	—
1.5E+02	—	—	1.1E+02	1.3E+02	—	—
—	Powers1963	—	Powers1963	—	—	—
—	25	—	25	—	—	—
—	—	—	—	—	—	—
—	—	—	—	—	—	—
—	4.2E+00	—	2.1E+00	—	—	—
Cohen1957	Cohen1957	Cohen1957	Powers1963	Cohen1957	Cohen1957	Cohen1957
10	10	10	10	10	10	10
873-1073	873-1073	973-1173	873-1123	873-1073	873-1073	873-1073
—	—	—	—	—	—	—
—	—	—	—	—	—	—
—	—	—	—	—	—	—
3.5E+04	4.3E+04	3.3E+04	2.7E+04	3.2E+04	3.0E+04	2.9E+04
7.1E-02	3.5E-02	1.8E-01	1.9E-01	1.0E-01	1.2E-01	1.1E-01
Cohen1954	Powers1963	Cohen1954	Cohen1954	Powers1963	Powers1963	Powers1963
3	—	3	3	5	5	5
973-1273	—	923-1373	873-1073	—	—	—
9.3E-04	3.7E-04	1.3E-03	1.1E-03	9.2E-04	4.0E-04	4.1E-04
3.8E+00	2.3E+00	5.5E+00	4.0E+00	3.9E+00	2.2E+00	2.2E+00
—	Jerden2019	—	—	—	—	—
—	—	—	—	—	—	—
—	1673.2	—	—	—	—	—
Cohen1954	Cohen1954	Cohen1957	Cohen1957	Cohen1957	Cohen1957	Cohen1957
—	—	—	—	—	—	—
783.2	633.2	938.2	813.2	803.2	778.2	751.2
0.50-0.50	0.57-0.43	0.667-0.333	0.535-0.40-0.065	0.56-0.39-0.05	0.69-0.31	0.56-0.16-0.28
37	38	39	40	41	42	43
NaF-ZrF4	NaF-BeF2	NaF-UF4	NaF-ZrF4-UF4	NaF-ZrF4-UF4	LiF-BeF2	NaF-LiF-BeF2

Powers1963	Powers1956	Powers1963	—	—	—
10	15	10	—	—	—
—	—	—	—	—	—
—	—	—	—	—	—
-3.1E-02	-4.4E-02	-6.5E-02	—	—	—
1.2E+02	1.3E+02	1.7E+02	—	—	—
—	—	Powers1963	—	—	—
—	—	25	—	—	—
—	—	—	—	—	—
—	—	—	—	—	—
—	—	1.7E+00	—	—	—
Cohen1957	Cohen1957	Cohen1957	Cohen1957	Cohen1957	Cohen1957
10	10	10	10	10	10
873-1073	873-1073	873-1073	873-1073	873-1073	873-1073
—	—	—	—	—	—
—	—	—	—	—	—
—	—	—	—	—	—
3.9E+04	3.9E+04	3.0E+04	2.9E+04	3.3E+04	3.4E+04
5.9E-01	5.9E-02	1.2E-01	1.4E-01	8.1E-02	6.6E-02
Powers1963	Powers1963	Powers1963	Powers1963	Powers1963	Powers1963
5	5	5	5	5	5
—	—	—	—	—	—
8.1E-04	8.5E-04	9.3E-04	5.0E-04	3.8E-04	9.3E-04
3.2E+00	3.5E+00	4.0E+00	2.4E+00	2.3E+00	4.0E+00
—	—	—	—	—	—
—	—	—	—	—	—
—	—	—	—	—	—
Cohen1957	Cohen1957	Cohen1957	Cohen1957	Cohen1957	Cohen1957
—	—	—	—	—	—
843.2	818.2	698.2	828.2	828.2	773.2
0.22-0.55-0.23	0.20-0.55-0.21-0.04	0.48-0.48-0.04	0.64-0.05-0.31	0.49-0.15-0.36	0.50-0.46-0.04
44	45	46	47	48	49
NaF-LiF-ZrF4	NaF-LiF-ZrF4-UF4	RbF-ZrF4-UF4	NaF-LiF-BeF2	NaF-KF-BeF2	RbF-ZrF4-UF4

—	—	—	Powers1963	Powers1963	—
—	—	—	10	10	—
—	—	—	—	—	—
—	—	—	—	—	—
—	—	—	-6.7E-02	-4.8E-02	—
—	—	—	1.3E+02	1.2E+02	—
—	—	—	Smirnov198	Powers1963	—
—	—	—	1	25	—
—	—	—	1160-1265	—	—
—	—	—	1.9E-03	—	—
—	—	—	-1.1E+00	2.1E+00	—
Cohen1957	Cohen1957	Cohen1957	Cohen1957	Cohen1957	Cohen1957
10	10	10	10	10	10
873-1073	873-1073	873-1073	973-1073	773-923	873-973
—	—	—	—	—	—
—	—	—	—	—	—
—	—	—	—	—	—
2.6E+04	2.5E+04	3.3E+04	2.7E+04	3.9E+04	3.7E+04
1.6E-01	1.7E-01	7.4E-02	1.2E-01	2.1E-02	2.9E-02
Powers1963	Powers1963	Powers1963	Cohen1954	Powers1963	Powers1963
5	5	5	3	5	5
—	—	—	973-1223	—	—
3.9E-04	3.9E-04	4.8E-04	5.5E-04	6.9E-04	7.2E-04
2.3E+00	2.4E+00	2.7E+00	2.4E+00	3.3E+00	2.7E+00
—	—	—	—	—	—
—	—	—	—	—	—
—	—	—	—	—	—
Cohen1957	Cohen1957	Cohen1957	Holm1965	Cohen1957	Cohen1957
—	—	—	—	—	—
808.2	870.2	778.2	925.2	748.2	763.2
0.53-0.24-0.23	0.49-0.36-0.15	0.56-0.21-0.2-0.03	0.40-0.60	0.43-0.57	0.112-0.453-0.41-0.025
50	51	52	53	54	55
NaF-LiF-BeF2	NaF-LiF-BeF2	NaF-LiF-BeF2-UF4	NaF-LiF	LiF-RbF	NaF-LiF-KF-UF4

—	—	—	—	—
—	—	—	—	—
—	—	—	—	—
—	—	—	—	—
—	—	—	—	—
—	—	—	—	—
—	—	—	—	—
—	—	—	—	—
—	—	—	—	—
—	—	—	—	—
—	—	—	—	—
Cohen1957	Cantor1973	—	—	—
10	15	—	—	—
873-1073	799-926	—	—	—
—	—	—	—	—
—	—	—	—	—
—	—	—	—	—
3.9E+04	3.6E+04	—	—	—
6.2E-02	6.6E-02	—	—	—
Powers1963	Cantor1973	Cantor1973	Cantor1973	Cantor1973
5	<1	<1	<1	<1
—	828.3-980.6	806.4-1014.4	816.6-1022.7	725.2-977.1
8.2E-04	6.7E-04	8.1E-04	9.5E-04	5.8E-04
3.8E+00	3.3E+00	4.0E+00	4.4E+00	2.7E+00
—	—	—	—	—
—	—	—	—	—
—	—	—	—	—
—	Cantor1973	Cantor1973	Cantor1973	Cantor1973
—	—	—	—	—
—	<828.3	<806.4	<816.6	<725.2
0.71-0.16-0.01-0.12	0.7011-0.2388-0.0601	0.7006-0.1796-0.1198	0.6998-0.1499-0.1503	0.647-0.301-0.052
56	57	58	59	60
LiF-BeF2-UF4-ThF4	LiF-BeF2-ThF4	LiF-BeF2-ThF4	LiF-BeF2-ThF4	LiF-BeF2-ZrF4

—	—
—	—
—	—
—	—
—	—
—	—
—	—
—	—
—	—
—	—
—	—
—	Cantor1973
—	15
—	826-946
—	—
—	—
—	—
—	3.4E+04
—	1.1E-01
Cantor1973	—
<1	—
797.5-1034.3	—
5.6E-04	—
2.7E+00	—
—	—
—	—
—	—
Cantor1973	Cantor1973
—	—
<797.5	<826.2
0.6479-0.2996-0.0499-0.0026	0.727-0.157-0.116
61	62
LiF-BeF2-ZrF4-UF4	LiF-BeF2-ThF4

APPENDIX B. **MOLTEN SALT THERMOPHYISCAL DATA**

APPENDIX B. MOLTEN SALT THERMOPHYISCAL DATA

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