Electron Mobilities in Solutions of Alkali Metals in Molten Alkali Halides

G.M. Haarberg and J.J. Egan *

Department of Electrochemistry
Norwegian University of Science and Technology
N-7034 Trondheim, Norway

*Brookhaven National Laboratory
Department of Applied Science
Upton, NY 11973

Abstract

The mobility of electrons in molten sodium and potassium halides was studied by potential step measurements using a Wagner polarization cell setup. The diffusion coefficient of electrons did not vary significantly with temperature and alkali metal activities lower than 0.2. The diffusion coefficient was found to be higher in the bromide and iodide systems than in the chlorides, the actual numbers varying in the range 0.01 - 0.02 cm²s⁻¹.

Introduction

This work is a continuation of measurements of electronic conductivities and electron mobilities in molten alkali halides. Previous papers on NaBr and NaI /1/, NaCl /2/, and cryolite alumina melts /3/, have explained the implementation of the Wagner polarization method to molten salts. Results are presented here for sodium and potassium halides; namely, NaCl, NaBr,
Nal, KCl, KBr, and KI. Some of the older results are included in the present paper. An earlier paper on LiCl-KCl (eut.) /4/ reports erroneous results on electronic conductivity and should be disregarded. The apparatus contained quartz which reacts with Li during the measurement. The electron-hole measurements reported in ref. 4 should be valid.

Bredig and coworkers /5/ carried out a comprehensive examination of physical properties of binary mixtures of molten salts and metals. The electrical conductivity was found to increase upon introduction of metal to the molten salt, especially in the potassium systems. The excess conductivity is electronic. At elevated temperatures the systems undergo a continuous transition of the electronic structure from nonmetallic to metallic states as the content of alkali metal increases. Interaction between alkali metals and molten alkali halides gives rise to formation of defects such as F-centers and mobile electrons. The properties of dilute solutions of alkali metals in molten alkali halides can be explained by using a thermodynamic defect model proposed by Egan and Freyland /6/. Results from conductivity measurements /1,2/ and optical absorption spectroscopy /7/ are in accordance with predictions from the model. Activities of sodium and potassium in the molten alkali halides have been determined by Smirnov et al. /8/ and Barnard et al. /9/.

Techniques for the Measurement of Electronic Conduction and Electron Mobilities

Electronic Conductivity

The Wagner polarization technique is usually used to study electrical conduction in solids exhibiting both ionic and electronic transport. The method has been thoroughly treated in the literature especially by Wagner in his original paper /10/ and in a more readily accessible review by Kroger /11/. A brief description of its implementation to molten salts is presented here for the convenience of the reader.

This is a dc method using cells of the following type

\[ Fe(s) | MX(l) | M - Bi(l)_{x = 0.04} \]

where the M-Bi (l) alloy serves as a reference electrode with known activity
of sodium or potassium and the iron serves as an inert electron conductor often referred to as a blocking electrode. MX is any of the six sodium and potassium salts studied. One applies potentials across the cell which are lower than those necessary to decompose the potassium salt, the iron electrode being negative. In this way ionic currents are suppressed and only electronic current flows. There is no gradient of electrical potential within the bulk of the potassium salt otherwise ions would move. Under steady state conditions which take up to 30 minutes after each potential change the current density is given by

\[ J_e = \frac{\kappa_e}{F} \left( \frac{\partial \eta_e}{\partial x} \right) \]  

where \( \kappa_e \) is the electronic conductivity in the melt, F is the Faraday and \( \eta_e \) is the electrochemical potential of electrons (see Wagner /10/ or Kroger /11/). The ionic current density is given by

\[ J_{\text{ion}} = -\frac{\kappa_{\text{ion}}}{F} \left( \frac{\partial \mu_{M}}{\partial x} - \frac{\partial \eta_e}{\partial x} \right) \]  

where \( \mu_{M} \) is the chemical potential of M in the melt. Since \( J_{\text{ion}} = 0 \)

\[ \frac{\partial \mu_{K}}{\partial x} = \frac{\partial \eta_e}{\partial x} \]  

Since the cell is designed (see experimental section) so that the electrolyte compartment under study has a constant cross section, integration of eqn. (1) using eqn. (3) gives

\[ lJ_e = \frac{1}{F} \int_{\mu_{M}^{F_e}}^{\mu_{M}^{e}} \kappa_e d\mu_M \]  

where \( l \) is the length. The chemical potential of M at the iron electrode is related to the voltage impressed across the cell, E, by

\[ \mu_{M}^{F_e} - \mu_{M}^{e} = -FE \]  

Differentiation of (4) and (5) with respect to \( \mu_{M}^{F_e} \) and substitution gives

\[ \kappa_e = l \frac{d|J_e|}{dE} = G \frac{d|I|}{dE} \]
where \( G \) is the cell constant and \( I \) is the steady state current of cell (I). In order to obtain the electronic conductivity in the melt, steady state current-potential curves were obtained and then differentiated to yield \( \kappa_e \) from eqn. 6. The differentiation was performed by fitting the data points to the following exponential equation using a least square method /12/

\[
I = A_1 \left[ \exp \left( \frac{EF}{2RT} \right) - 1 \right] + A_2 \left[ \exp \left( \frac{3EF}{2RT} \right) - 1 \right]
\]  

(7)

where \( A_1 \) and \( A_2 \) are constants given by the least squares fit and \( E \) is the absolute potential. The electronic conductivity is then given by

\[
\kappa_e = G \left[ \frac{A_1 F}{2RT} \exp \left( \frac{EF}{2RT} \right) + \frac{3A_2 F}{2RT} \exp \left( \frac{3EF}{2RT} \right) \right].
\]  

(8)

Further, the conductivity was obtained as a function of sodium or potassium activity using

\[
a_K = \exp \left[ \frac{(E - E^0)F}{RT} \right]
\]  

(9)

where \( E^0 \) is the potential of the M-Bi electrode vs. pure sodium or potassium taken from the literature on the sodium /13,14,15,16/ and potassium system /16,17/.

**Electron mobilities**

The diffusion coefficient and mobility of electrons in the melt may also be measured by observing the cell's approach to steady state. When a potential is imposed on the iron electrode, a chemical potential of sodium is produced in the melt at this point and with it a given concentration of electrons. These electrons then diffuse toward the reference electrode according to Fick's second law. The concentration of electrons as a function of time and distance from the iron electrode is given by the following equation (see for example Crank /18/)

\[
c = c_1 + \left( c_0 - c_1 \right) \frac{x}{l} + \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{c_0 \cos n \pi - c_1}{n} \frac{n \pi x}{l} \exp \left( -\frac{Dn^2 \pi^2 t}{l^2} \right) \\
+ \frac{4c_0}{\pi} \sum_{m=0}^{\infty} \frac{1}{2m + 1} \sin \frac{(2m + 1) \pi x}{l} \exp \left( -\frac{D(2m + 1)^2 \pi^2 t}{l^2} \right)
\]  

(10)
where \( c_1 \) is the electron concentration at the iron electrode, \( c_0 \) is the concentration at the reference electrode, \( x \) is the distance from the iron electrode, \( D \) is the diffusion coefficient of electrons, \( l \) the distance between the iron electrode and the reference electrode, and \( t \) is the time in seconds. The flow of electrons, \( j \), is then given by

\[
j = -D \left( \frac{\partial c}{\partial x} \right)_{x=0} = \frac{D(c_1 - c_0)}{l} - \frac{2Dc_0}{l} \sum_{n=1}^{\infty} (-1)^n \exp \left( -\frac{Dn^2\pi^2t}{l^2} \right) + \frac{2Dc_1}{l} \sum_{n=1}^{\infty} \exp \left( -\frac{Dn^2\pi^2t}{l^2} \right) - \frac{4Dc_0}{l} \sum_{m=0}^{\infty} \left( -\frac{D(2m+1)^2\pi^2t}{l^2} \right) \quad (11)
\]

The quantity of electrons flowing in the cell is given by

\[
Q_t = \int_0^t j \, dt = \frac{D(c_1 - c_0)}{l} t - \frac{2l}{\pi^2} \sum_{n=1}^{\infty} \frac{c_0 \cos n\pi - c_1}{n^2} \left[ 1 - \exp \left( -\frac{Dn^2\pi^2t}{l^2} \right) \right] - \frac{4c_0 l}{\pi^2} \sum_{m=0}^{\infty} \frac{1}{(2m+1)^2} \left[ 1 - \exp \left( -\frac{D(2m+1)^2\pi^2t}{l^2} \right) \right] \quad (12)
\]

At longer times with \( t \rightarrow \infty \) equation (10) reduces to

\[
Q_t = \frac{D(c_1 - c_0)}{l} t + \frac{l}{3} (c_1 - c_0) \quad (13)
\]

The total number of coulombs passed through the cell as a function of time is given by

\[
Q = \frac{D(c_1 - c_0)FA}{l} t + \frac{l}{3} (c_1 - c_0) FA \quad (14)
\]

where \( F \) is the Faraday constant and \( A \) is the area of the melt compartment. Thus if one imposes a voltage across the cell at \( t = 0 \) and measures the coulombs until steady state, one obtains the diffusion coefficient of electrons as follows. The slope of a plot of \( Q \) vs. \( t \) is given by

\[
\text{Slope} = \frac{D(c_1 - c_0)FA}{l} \cong \frac{Dc_1 FA}{l} \quad (15)
\]

when the concentration of electrons at the reference electrode is much smaller than that generated at the iron electrode. The intercept of the plot is given by

\[
\text{Intercept} = \frac{l}{3} (c_1 - c_0) FA \cong \frac{l}{3} c_1 FA \quad (16)
\]
\[ D = \frac{\text{Slope} \cdot I^2}{\text{Intercept} \cdot 3} \]  \hspace{1cm} (17) 

Since \( I = \frac{dQ}{dt} \)

\[ D = \frac{I I^2}{(Q - It)^3} \]  \hspace{1cm} (18) 

Therefore measurements of \( Q \) were taken for a time \( t \) until steady state was reached and eqn. (16) used to obtain values of \( D \). The mobility of electrons was then calculated from the Nernst-Einstein equation

\[ u_e = \frac{(DF)}{(RT)} \]  \hspace{1cm} (19)

**Experimental Details**

The experimental apparatus is shown in Fig. 1. A large tantalum crucible, which resides inside of a vacuum tight Vycor container (not shown), contains the molten salt in contact with a molten M-Bi alloy. The molten salts were obtained from single crystals of optical grade. The Fe electrode is placed inside a sapphire capillary (4.2 cm long, 3 mm inside diameter). A vacuum tight seal is formed between iron and sapphire. This seal prevents the evaporation of alkali metal, which is essential for obtaining good results. A constant potential is imposed across the cell making the Ta cup positive and the Fe electrode negative. The current through the cell is measured as a function of time, and the steady state value is recorded. A series of such corresponding data is measured to obtain a current versus potential curve. The electronic conductivity can be calculated as a function of potential. The cell constant is determined by the geometry of the sapphire capillary. ac resistance measurements are also made periodically between the Ta cup and the Fe electrode as a control.

A transient technique is applied to the same cell in order to measure the diffusion coefficient of electrons. The current response to a potential applied across the electrodes is measured until steady state is attained. The total number of coulombs passed is recorded along with the time and the diffusion coefficient calculated from eqn. (18).

A reference electrode consisting of a M-Bi alloy placed inside an alumina tube is also shown. The amount of Bi is accurately known. This reference
electrode is used to check the composition of the M-Bi alloy in the tantalum
cup which can vary over a period of several days due to evaporation of potas-
sium. All sodium or potassium is coulometrically removed from the reference
electrode and then added again until the potential between the reference al-
loy and the larger M-Bi alloy is zero. The composition of the M-Bi alloy in
the tantalum cup is then known, and the metal activity is calculated from
thermodynamic data for M-Bi alloys /13-17/.

Results and Discussion

Results of the I versus E curves taken on cell (I) at various temperatures were
fitted according to eqn. 7 and used to determine electronic conductivities as
a function of the alkali metal activity using eqns. 8 and 9. The electronic
conductivity was found to increase with increasing alkali metal activity and
increasing temperature for all the six systems /1,2,18/. Bredig and coworkers
/5/ have made a few measurements of total conductivity in the salt rich
regions studied here. Their results with ionic conduction subtracted showed
good agreement with our results.

Transient measurements on the approach to steady state yield diffusion
coefficients and mobilities of electrons and are shown in Tables 1-6. The
mobilities of electrons in these systems remain constant with increasing M
activity and electron concentration up to an alkali metal activity of about
0.1. For the KI system several transient measurements were deliberately
made at K activities greater than 0.1 (E≥0.78) as shown in Table 6. The
results show that the diffusion coefficient is starting to vary with K activity.
Since the diffusion equations used in our transient method require a constant
diffusion coefficient, the method is not valid at higher K activities. Thus the
values obtained at K activities too high to be valid are shown in parentheses.
Table 7 shows typical values for the concentration of electrons at relatively
high K activities. The sodium systems show similar behavior. The electron
mobility does not vary significantly with temperature, while the electronic
conductivity increases with increasing temperature due to increasing electron
concentration. The electron mobility was found to be higher in the bromide
and iodide systems than the chlorides.

The work reported here and in the previous papers shows that molten
alkali halides under reducing conditions are mixed conductors and contain
a considerable concentration of electrons that have mobilities of the order of 0.1 cm²volt⁻¹sec⁻¹. This has a noticeable effect on the efficiency of the production of metals, as was shown in the case of cryolite. It must also be taken into consideration in the design of molten salt batteries because self-discharge currents are affected. Other measurements that could be affected include double-layer capacitance and electrode kinetics.

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Fig. 1: Experimental arrangement used for cell (I).
Table 1: Results of Transient Measurements on NaCl.

\[ T = 850^\circ C \quad E^0 = 0.867 \quad V_m = 38.20 \]

| E [volts] | D [cm^2 sec^{-1}] | I_{steady} [\muamps] | \nu_e [cm^2 volt^{-1} sec^{-1}] |
|-----------|--------------------|-----------------------|-------------------------------|
| 0.650     | 0.0094             | 284                   | .097                          |
| 0.675     | 0.0093             | 349                   | .096                          |
| 0.700     | 0.0095             | 454                   | .098                          |
| 0.675     | 0.0095             | 590                   | .098                          |
| 0.675     | 0.0101             | 787                   | .104                          |

\[ T = 900^\circ C \quad E^0 = 0.874 \quad V_m = 38.91 \]

| E [volts] | D [cm^2 sec^{-1}] | I_{steady} [\muamps] | \nu_e [cm^2 volt^{-1} sec^{-1}] |
|-----------|--------------------|-----------------------|-------------------------------|
| 0.675     | 0.0120             | 596                   | .119                          |
| 0.700     | 0.0123             | 670                   | .122                          |
| 0.725     | 0.0123             | 814                   | .122                          |
| 0.750     | 0.0125             | 1011                  | .124                          |

Table 2: Results of Transient Measurements on NaBr

\[ T = 850^\circ C \quad E^0 = 0.774 \quad V_m = 45.58 \]

| E [volts] | D [cm^2 sec^{-1}] | I_{steady} [\muamps] | \nu_e [cm^2 volt^{-1} sec^{-1}] |
|-----------|--------------------|-----------------------|-------------------------------|
| 0.450     | 0.023              | 483                   | .242                          |
| 0.500     | 0.021              | 690                   | .218                          |
| 0.550     | 0.020              | 1042                  | .208                          |
| 0.600     | 0.020              | 1625                  | .210                          |

\[ T = 900^\circ C \quad E^0 = 0.777 \quad V_m = 46.41 \]

| E [volts] | D [cm^2 sec^{-1}] | I_{steady} [\muamps] | \nu_e [cm^2 volt^{-1} sec^{-1}] |
|-----------|--------------------|-----------------------|-------------------------------|
| 0.450     | 0.028              | 789                   | .277                          |
| 0.500     | 0.026              | 1093                  | .258                          |
| 0.550     | 0.023              | 1551                  | .231                          |
| 0.600     | 0.024              | 2327                  | .242                          |
Table 3: Results of Transient Measurements on NaI.

| E [volts] | D [cm² sec⁻¹] | I_{steady} [µamps] | u_e [cm² volt⁻¹ sec⁻¹] |
|-----------|---------------|-------------------|------------------------|
| 0.676     | 0.015         | 490               | 0.174                  |
| 0.717     | 0.013         | 930               | 0.151                  |
| 0.733     | 0.013         | 733               | 0.151                  |
| 0.758     | 0.013         | 1040              | 0.151                  |
| 0.843     | (0.017)       | 2495              | (0.198)                |

$T = 750^\circ C$  $E^0 = 0.901$  $V_m = 55.44$

| E [volts] | D [cm² sec⁻¹] | I_{steady} [µamps] | u_e [cm² volt⁻¹ sec⁻¹] |
|-----------|---------------|-------------------|------------------------|
| 0.704     | 0.016         | 752               | 0.182                  |
| 0.725     | 0.012         | 863               | 0.136                  |
| 0.739     | 0.013         | 1056              | 0.147                  |
| 0.814     | 0.016         | 2155              | 0.182                  |

$T = 775^\circ C$  $E^0 = 0.906$  $V_m = 56.10$

| E [volts] | D [cm² sec⁻¹] | I_{steady} [µamps] | u_e [cm² volt⁻¹ sec⁻¹] |
|-----------|---------------|-------------------|------------------------|
| 0.678     | 0.015         | 742               | 0.166                  |
| 0.749     | 0.014         | 1315              | 0.155                  |
| 0.780     | 0.014         | 1700              | 0.155                  |
| 0.820     | 0.015         | 2479              | 0.166                  |
| 0.850     | (0.017)       | 3270              | (0.188)                |

$T = 800^\circ C$  $E^0 = 0.910$  $V_m = 56.90$

| E [volts] | D [cm² sec⁻¹] | I_{steady} [µamps] | u_e [cm² volt⁻¹ sec⁻¹] |
|-----------|---------------|-------------------|------------------------|
| 0.730     | 0.015         | 1208              | 0.162                  |
| 0.819     | 0.016         | 2630              | 0.173                  |

$T = 850^\circ C$  $E^0 = 0.919$  $V_m = 58.52$

| E [volts] | D [cm² sec⁻¹] | I_{steady} [µamps] | u_e [cm² volt⁻¹ sec⁻¹] |
|-----------|---------------|-------------------|------------------------|
| 0.762     | 0.015         | 1815              | 0.155                  |
| 0.822     | 0.016         | 3025              | 0.165                  |

$T = 900^\circ C$  $E^0 = 0.928$  $V_m = 59.12$

| E [volts] | D [cm² sec⁻¹] | I_{steady} [µamps] | u_e [cm² volt⁻¹ sec⁻¹] |
|-----------|---------------|-------------------|------------------------|
| 0.766     | 0.016         | 2155              | 0.158                  |
Table 6: Results of Transient Measurements on KI.

| $T$ (°C) | $E^0$ | $V_m$ | $D$ ($cm^2 sec^{-1}$) | $I_{steady}$ (µamps) | $u_e$ ($cm^2 volt^{-1} sec^{-1}$) |
|----------|-------|-------|------------------------|----------------------|----------------------------------|
| 725      | 0.983 | 69.01 | 0.700                  | 0.016                | 352                              |
|          |       |       | 0.800                  | 0.015                | 904                              |
|          |       |       | 0.850                  | (0.023)              | 1570                             |
| 750      | 0.984 | 69.70 | 0.750                  | 0.016                | 780                              |
|          |       |       | 0.800                  | (0.019)              | 1271                             |
| 800      | 0.986 | 71.12 | 0.727                  | 0.017                | 980                              |
|          |       |       | 0.765                  | (0.020)              | 1415                             |
|          |       |       | 0.785                  | (0.024)              | 1790                             |
| 830      | 0.986 | 72.01 | 0.712                  | 0.016                | 1175                             |
|          |       |       | 0.733                  | 0.017                | 1418                             |
|          |       |       | 0.759                  | (0.019)              | 1740                             |
|          |       |       | 0.789                  | (0.026)              | 2310                             |
| 850      | 0.987 | 72.61 | 0.684                  | 0.015                | 1050                             |
|          |       |       | 0.708                  | 0.016                | 1275                             |
|          |       |       | 0.735                  | 0.018                | 1595                             |
|          |       |       | 0.755                  | (0.021)              | 1935                             |
| 885      | 0.988 | 73.61 | 0.685                  | 0.016                | 1295                             |
|          |       |       | 0.716                  | 0.018                | 1695                             |
|          |       |       | 0.735                  | (0.020)              | 1985                             |
Table 5: Results of Transient Measurements on KBr.

\[ T = 780^\circ C \quad E^0 = 0.985 \quad V_m = 56.96 \]

| E[volts] | D[cm\(^2\)sec\(^{-1}\)] | \(I_{steady}[\muamps]\) | \(u_e[cm^2volt^{-1}sec^{-1}]\) |
|---------|-----------------|----------------|-----------------|
| 0.700   | 0.016           | 617            | .176            |
| 0.780   | 0.016           | 1207           | .176            |
| 0.800   | 0.017           | 1391           | .187            |

\[ T = 800^\circ C \quad E^0 = 0.986 \quad V_m = 57.41 \]

| E[volts] | D[cm\(^2\)sec\(^{-1}\)] | \(I_{steady}[\muamps]\) | \(u_e[cm^2volt^{-1}sec^{-1}]\) |
|---------|-----------------|----------------|-----------------|
| 0.730   | 0.016           | 962            | .173            |
| 0.750   | 0.018           | 1130           | .194            |
| 0.770   | 0.016           | 1291           | .173            |

\[ T = 850^\circ C \quad E^0 = 0.987 \quad V_m = 58.58 \]

| E[volts] | D[cm\(^2\)sec\(^{-1}\)] | \(I_{steady}[\muamps]\) | \(u_e[cm^2volt^{-1}sec^{-1}]\) |
|---------|-----------------|----------------|-----------------|
| 0.608   | 0.0170          | 543            | .176            |
| 0.750   | 0.0170          | 1444           | .176            |
| 0.770   | 0.0170          | 1712           | .176            |
Table 6: Results of Transient Measurements on KI.

| $T$ = 725°C | $E^0$ = 0.983 | $V_m$ = 69.01 |
|-------------|---------------|---------------|
| E[vols]     | D[$cm^2sec^{-1}$] | $I_{steady} [\muamps]$ | $u_e [cm^2volt^{-1}sec^{-1}]$ |
| 0.700       | 0.016          | 352           | 0.186 |
| 0.800       | 0.015          | 904           | 0.175 |
| 0.850       | (0.023)        | 1570          | (0.268) |

| $T$ = 750°C | $E^0$ = 0.984 | $V_m$ = 69.70 |
|-------------|---------------|---------------|
| E[vols]     | D[$cm^2sec^{-1}$] | $I_{steady} [\muamps]$ | $u_e [cm^2volt^{-1}sec^{-1}]$ |
| 0.750       | 0.016          | 780           | 0.182 |
| 0.800       | (0.019)        | 1271          | (0.216) |

| $T$ = 800°C | $E^0$ = 0.986 | $V_m$ = 71.12 |
|-------------|---------------|---------------|
| E[vols]     | D[$cm^2sec^{-1}$] | $I_{steady} [\muamps]$ | $u_e [cm^2volt^{-1}sec^{-1}]$ |
| 0.727       | 0.017          | 980           | 0.184 |
| 0.765       | (0.020)        | 1415          | (0.216) |
| 0.785       | (0.024)        | 1790          | (0.260) |

| $T$ = 830°C | $E^0$ = 0.986 | $V_m$ = 72.01 |
|-------------|---------------|---------------|
| E[vols]     | D[$cm^2sec^{-1}$] | $I_{steady} [\muamps]$ | $u_e [cm^2volt^{-1}sec^{-1}]$ |
| 0.712       | 0.016          | 1175          | 0.168 |
| 0.733       | 0.017          | 1418          | 0.179 |
| 0.759       | (0.019)        | 1740          | (0.200) |
| 0.789       | (0.026)        | 2310          | (0.274) |

| $T$ = 850°C | $E^0$ = 0.987 | $V_m$ = 72.61 |
|-------------|---------------|---------------|
| E[vols]     | D[$cm^2sec^{-1}$] | $I_{steady} [\muamps]$ | $u_e [cm^2volt^{-1}sec^{-1}]$ |
| 0.684       | 0.015          | 1050          | 0.155 |
| 0.708       | 0.016          | 1275          | 0.165 |
| 0.735       | 0.018          | 1595          | 0.186 |
| 0.755       | (0.021)        | 1935          | (0.217) |

| $T$ = 885°C | $E^0$ = 0.988 | $V_m$ = 73.61 |

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Table 7: Number of Electrons at Different Activities in KI

| E [volts] | $a_K$ | $\kappa_e$ [ohm$^{-1}$ cm$^{-1}$] | $n_e$ [no./cm$^3$] | $u_e$ [cm$^2$ volt$^{-1}$ sec$^{-1}$] |
|-----------|-------|---------------------------------|-------------------|-----------------------------------|
| 0.700     | 0.037 | .175                            | 5.88 x 10$^{18}$ | .186                              |
| 0.800     | 0.119 | .566                            | 2.02 x 10$^{19}$ | .175                              |

$T = 725^0C$ $E^0 = 0.983$ $V_m = 69.01$

| E [volts] | $a_K$ | $\kappa_e$ [ohm$^{-1}$ cm$^{-1}$] | $n_e$ [no./cm$^3$] | $u_e$ [cm$^2$ volt$^{-1}$ sec$^{-1}$] |
|-----------|-------|---------------------------------|-------------------|-----------------------------------|
| 0.750     | 0.070 | .395                            | 1.36 x 10$^{19}$ | .182                              |

$T = 750^0C$ $E^0 = 0.984$ $V_m = 69.70$

| E [volts] | $a_K$ | $\kappa_e$ [ohm$^{-1}$ cm$^{-1}$] | $n_e$ [no./cm$^3$] | $u_e$ [cm$^2$ volt$^{-1}$ sec$^{-1}$] |
|-----------|-------|---------------------------------|-------------------|-----------------------------------|
| 0.727     | 0.061 | .527                            | 1.79 x 10$^{19}$ | .184                              |

$T = 800^0C$ $E^0 = 0.986$ $V_m = 71.12$

| E [volts] | $a_K$ | $\kappa_e$ [ohm$^{-1}$ cm$^{-1}$] | $n_e$ [no./cm$^3$] | $u_e$ [cm$^2$ volt$^{-1}$ sec$^{-1}$] |
|-----------|-------|---------------------------------|-------------------|-----------------------------------|
| 0.712     | 0.056 | .550                            | 2.05 x 10$^{19}$ | .168                              |
| 0.733     | 0.070 | .681                            | 2.35 x 10$^{19}$ | .179                              |

$T = 830^0C$ $E^0 = 0.986$ $V_m = 72.01$

| E [volts] | $a_K$ | $\kappa_e$ [ohm$^{-1}$ cm$^{-1}$] | $n_e$ [no./cm$^3$] | $u_e$ [cm$^2$ volt$^{-1}$ sec$^{-1}$] |
|-----------|-------|---------------------------------|-------------------|-----------------------------------|
| 0.684     | 0.044 | .487                            | 1.95 x 10$^{19}$ | .155                              |
| 0.708     | 0.056 | .612                            | 2.32 x 10$^{19}$ | .165                              |

$T = 850^0C$ $E^0 = 0.987$ $V_m = 72.61$

| E [volts] | $a_K$ | $\kappa_e$ [ohm$^{-1}$ cm$^{-1}$] | $n_e$ [no./cm$^3$] | $u_e$ [cm$^2$ volt$^{-1}$ sec$^{-1}$] |
|-----------|-------|---------------------------------|-------------------|-----------------------------------|
| 0.685     | 0.047 | .625                            | 2.41 x 10$^{19}$ | .162                              |
| 0.716     | 0.064 | .845                            | 2.90 x 10$^{19}$ | .182                              |

$T = 885^0C$ $E^0 = 0.988$ $V_m = 73.61$

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