Molten Salts for Energy Storage

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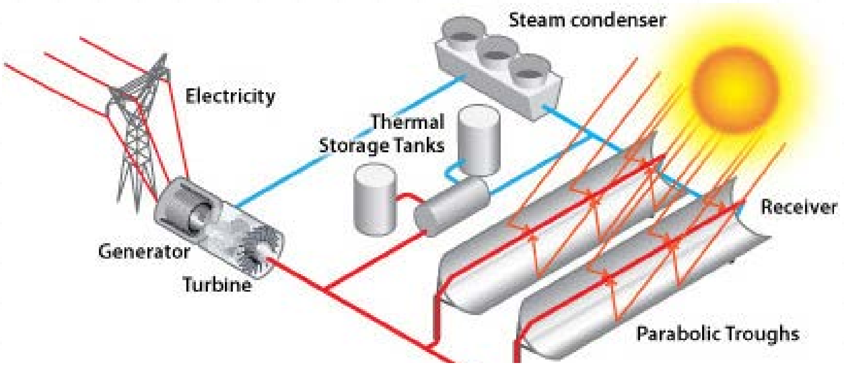
MIME 572

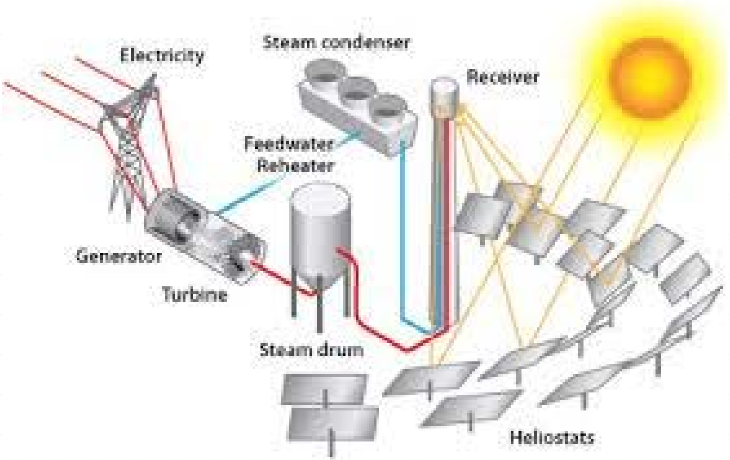
Breakdown

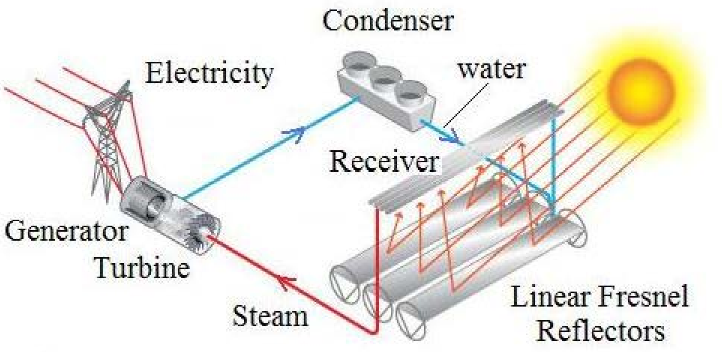
- Background
  - CSPs
  - Products in use now
- Approach
  - Phase diagrams
  - Equilibrium calculations
- Results and conclusions
  - dH vs T curves

Background

- Concentrated Solar Power (CSP)
  - Parabolic Troughs
  - Power Tower
  - Fresnel Reflectors







www.ecomena.org

Background

- How to save the sun's energy for a rainy day?
- Store it in Phase Change Materials (PCMs)
- Energy stored: S→L
- Energy released: L→S
- Locked as the latent heat of fusion
- Operating temperature: 150 C – 350 C

Background

- Paraffin compounds
- Organic compounds (acids, amides, glycols…)
- Inorganic compounds (salts, water)
- Eutectic compounds (organic or inorganic)

Mohammed M Farid, Amar M Khudhair, Siddique Ali K Razack, Said Al-Hallaj, A review on phase change energy storage: materials and applications, Energy Conversion and Management, Volume 45, Issues 9–10, June 2004, Pages 1597-1615, ISSN 0196-8904, 10.1016/j.enconman.2003.09.015. (http://www.sciencedirect.com/science/article/pii/S0196890403002668)

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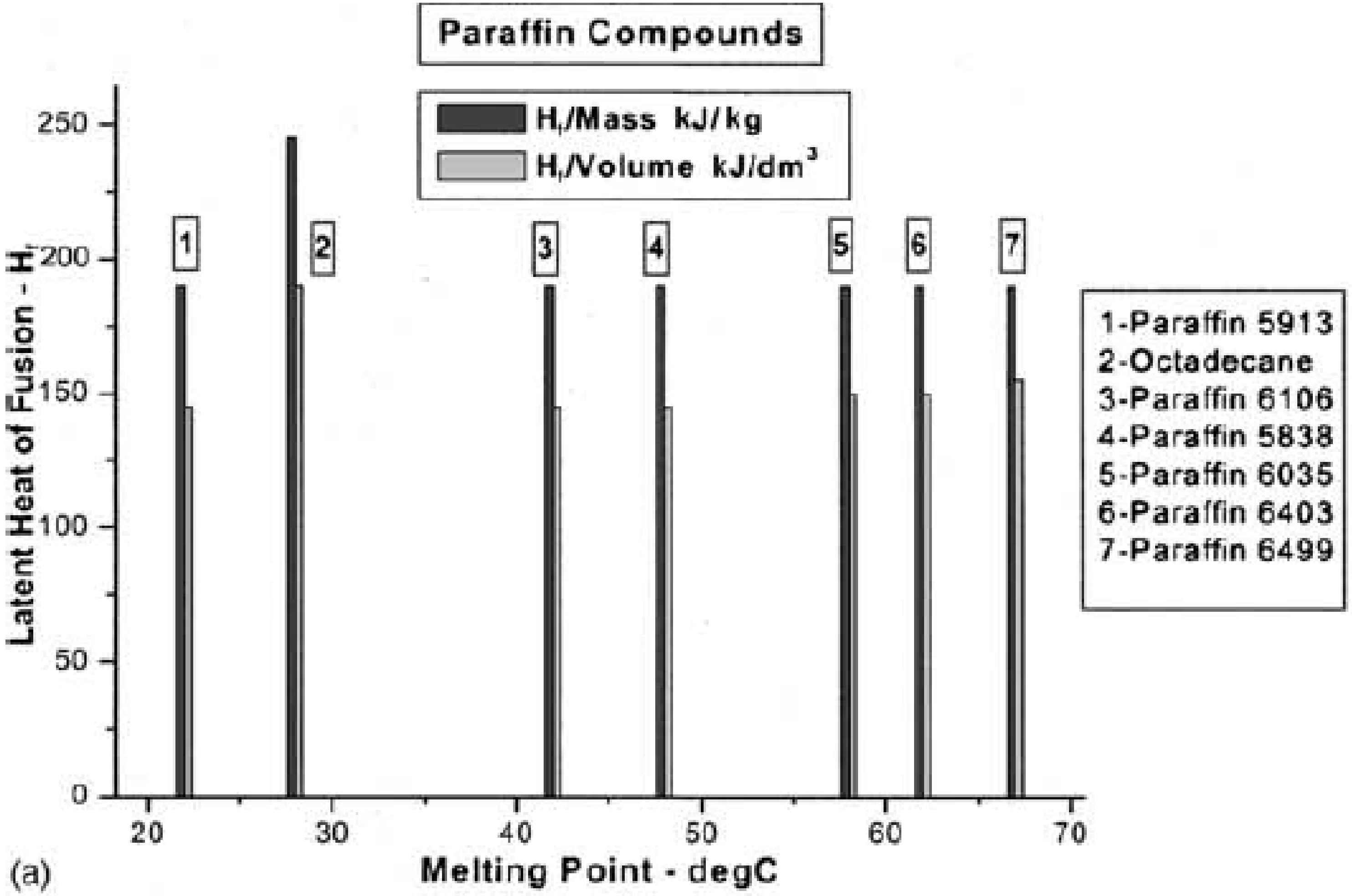

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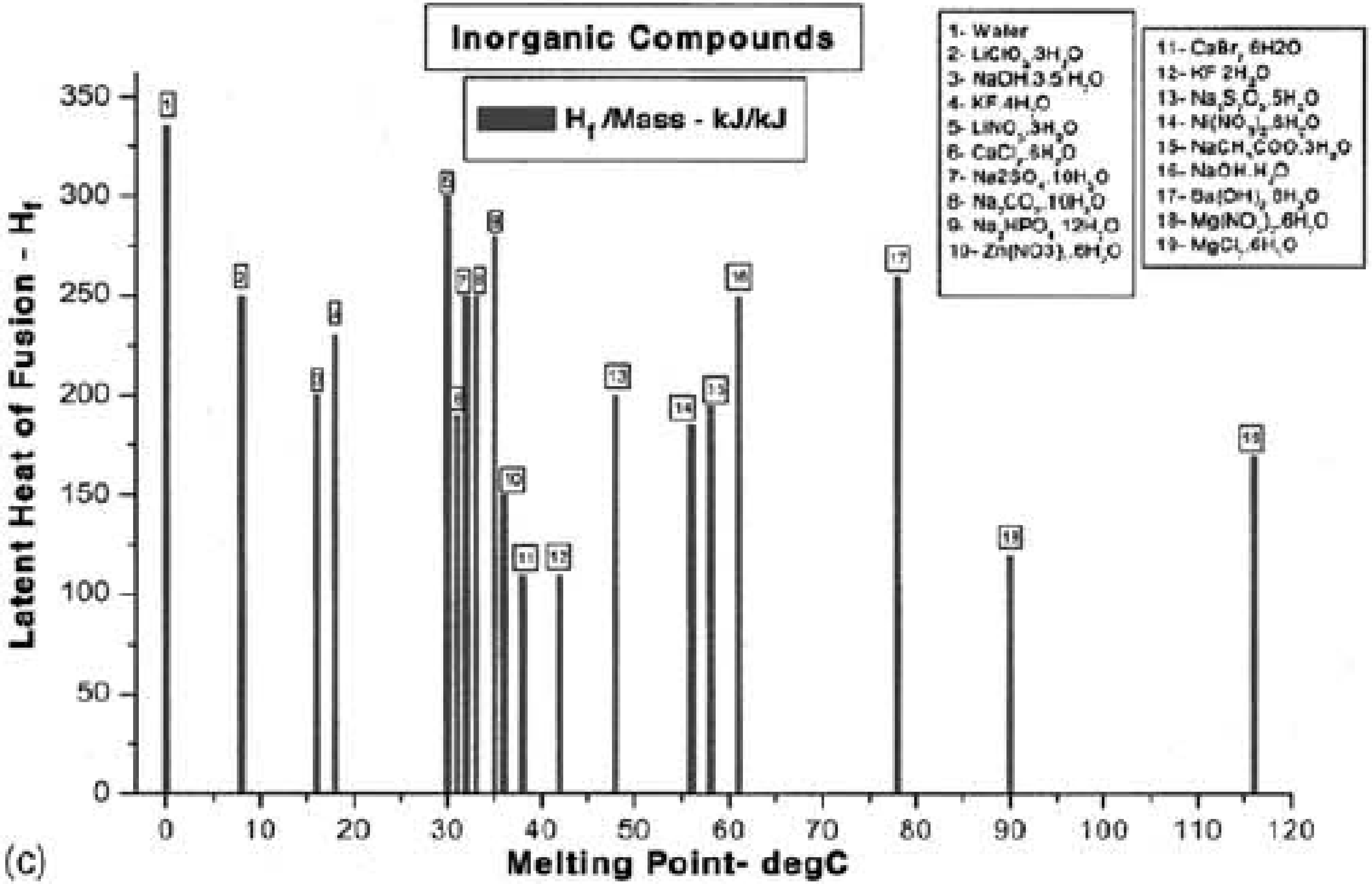

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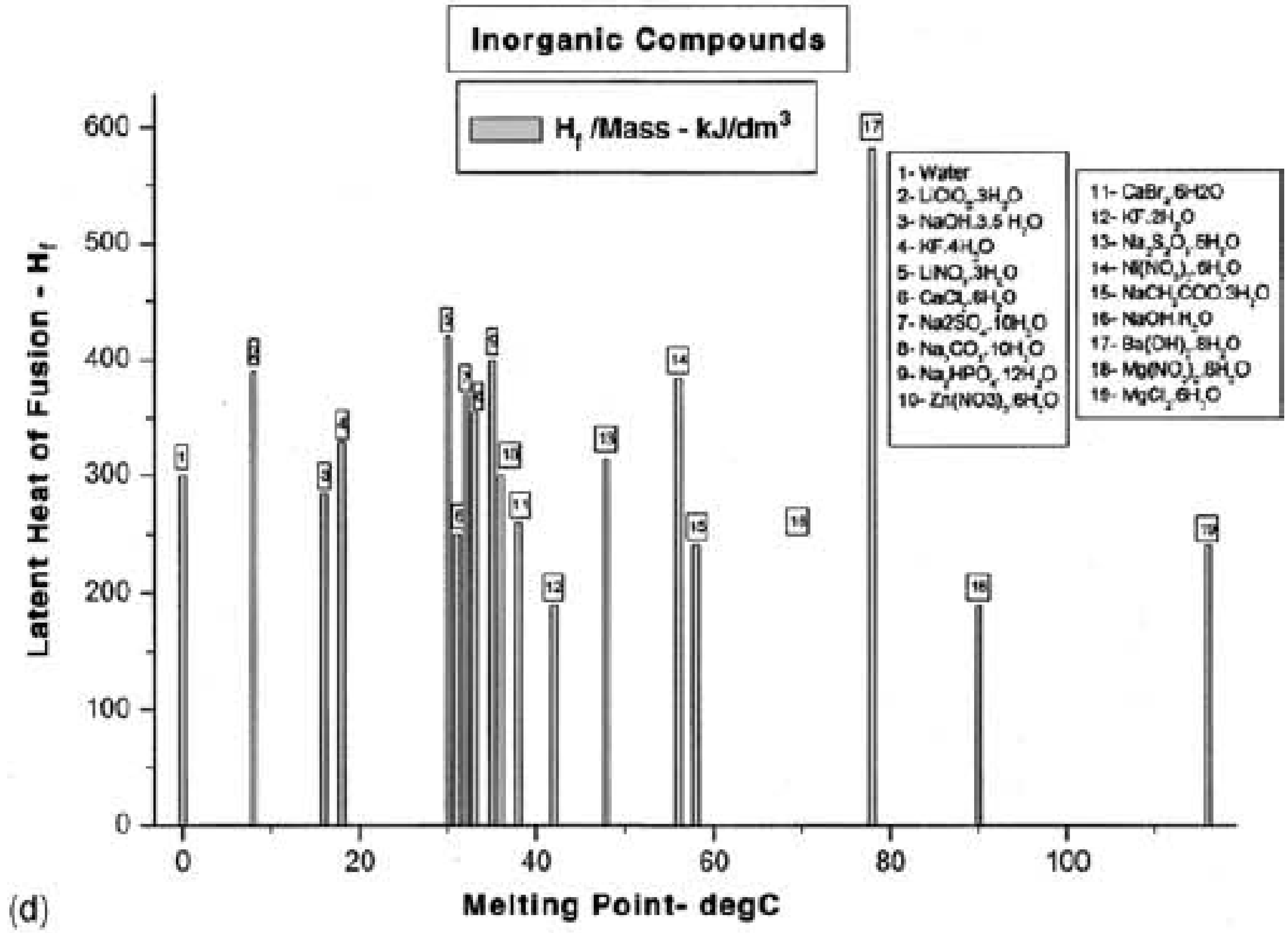

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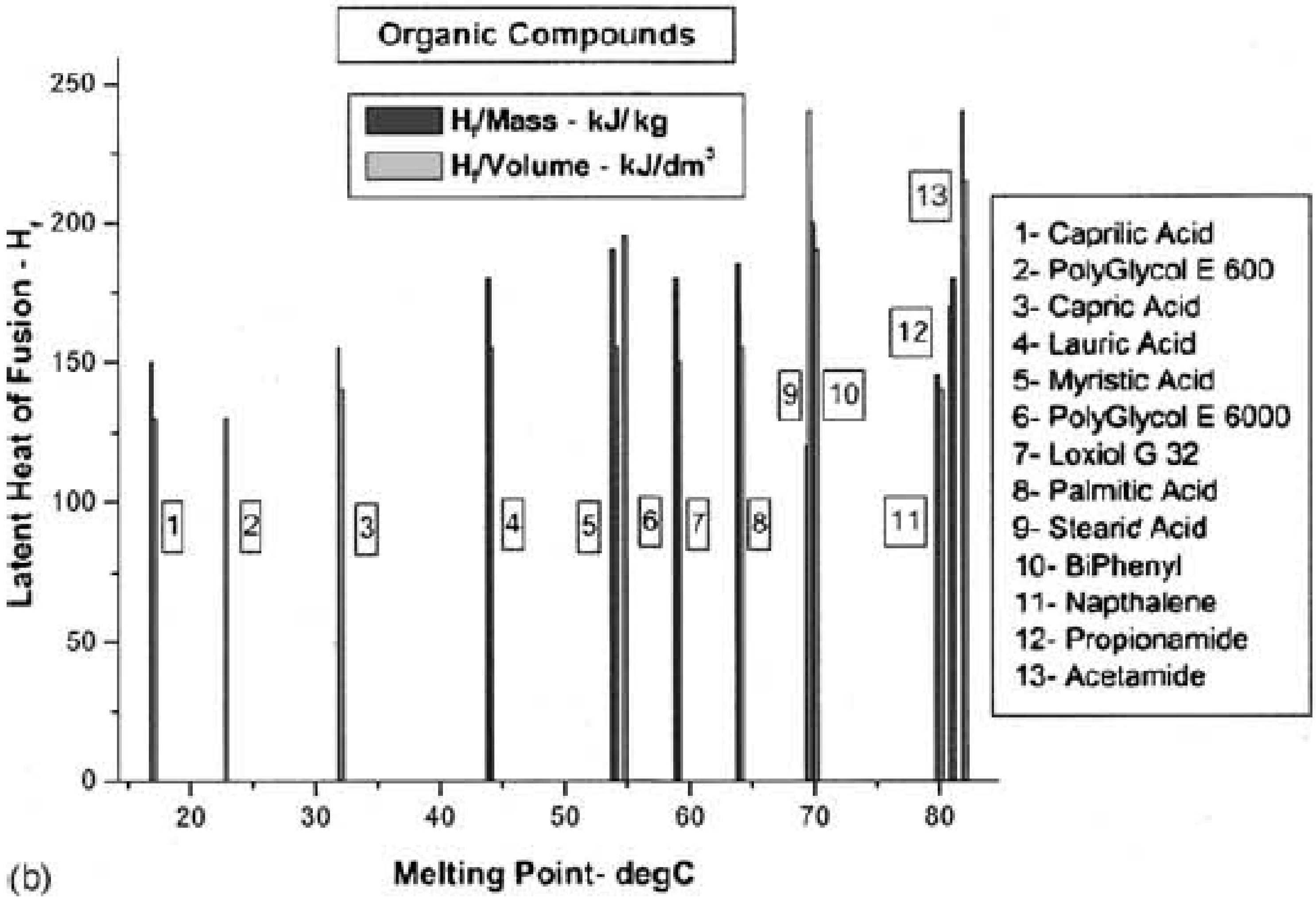

Mohammed M Farid, Amar M Khudhair, Siddique Ali K Razack, Said Al-Hallaj, A review on phase change energy storage: materials and applications, Energy Conversion and Management, Volume 45, Issues 9–10, June 2004, Pages 1597-1615, ISSN 0196-8904, 10.1016/j.enconman.2003.09.015. (http://www.sciencedirect.com/science/article/pii/S0196890403002668)

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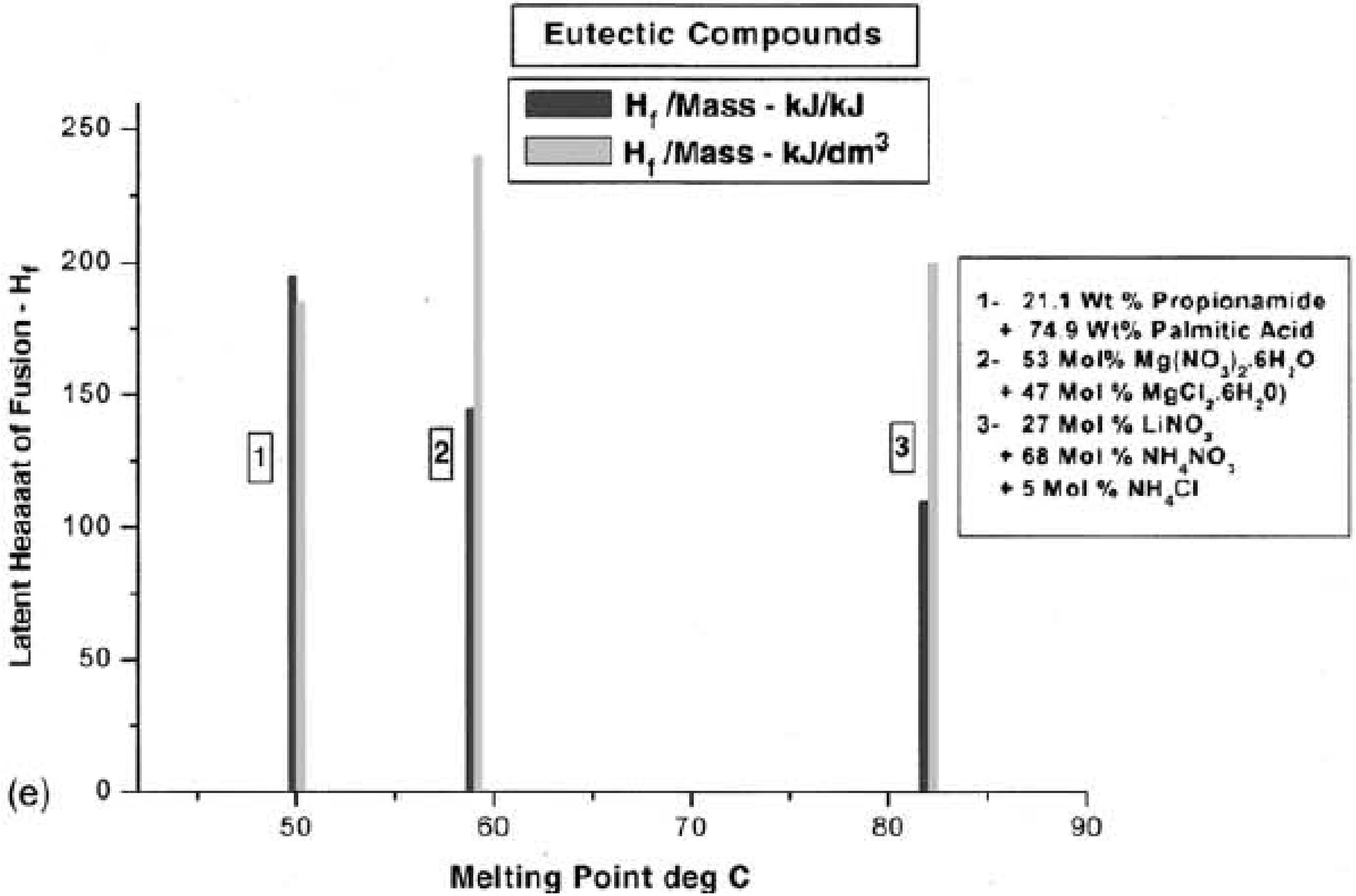

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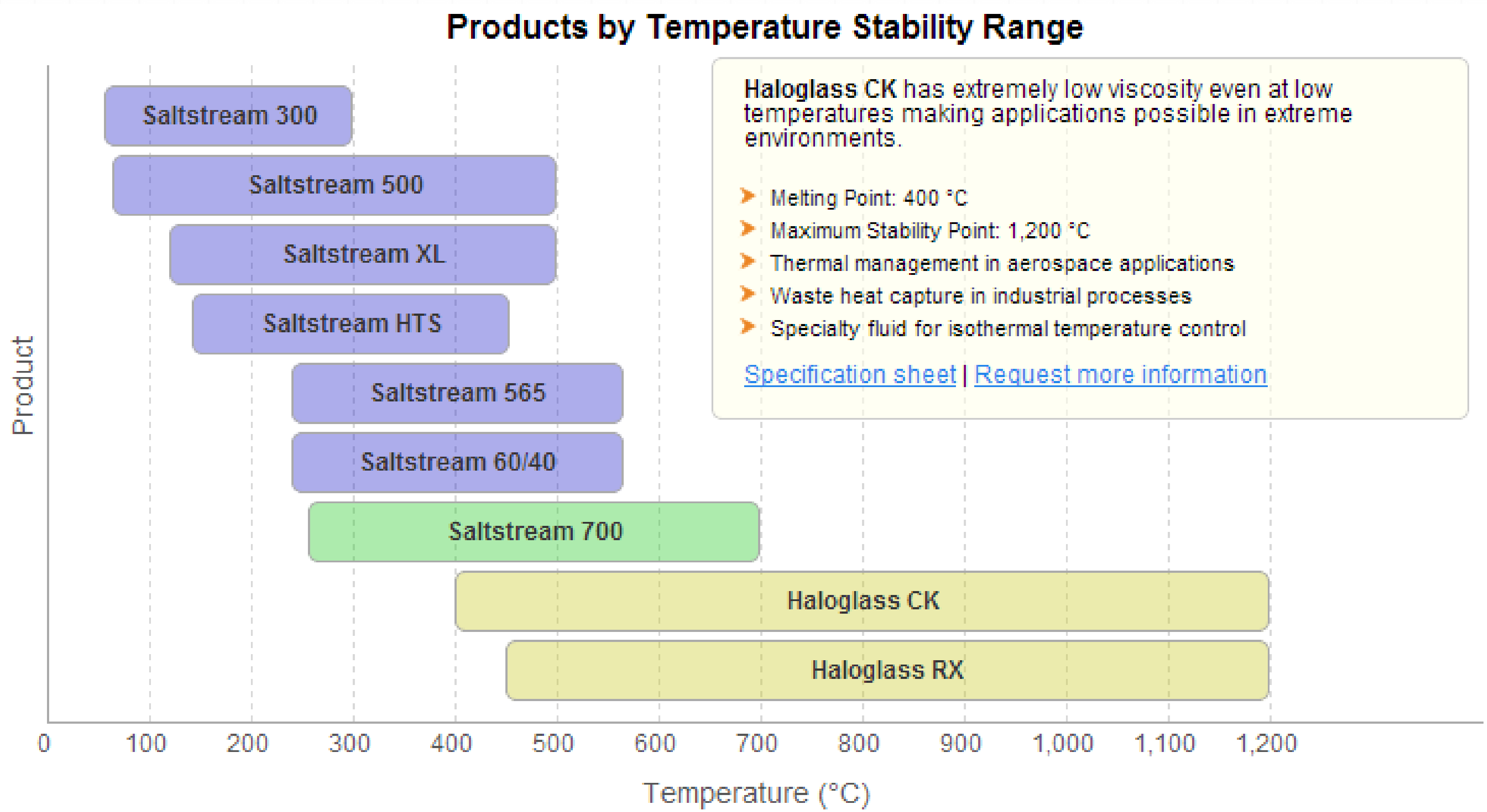
Halotechnics Products



http://www.halotechnics.com/products/

Approach

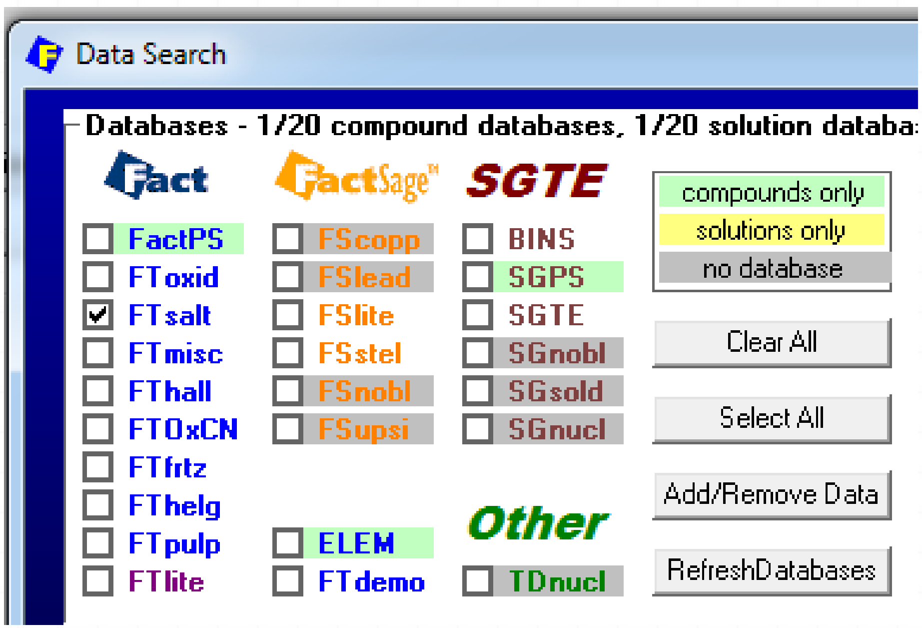
- $NaNO_3$ and KNO_3 most mentioned in literature and in industry
- Compare $CsNO_3$, $LiNO_3$, $RbNO_3$ with:
  - $NaNO_3$ only
  - KNO_3 only
  - $NaNO_3$ and KNO_3

Approach

- Calculated the phase diagram for each system
  - Noted the eutectic temperature of melting
  - Noted the eutectic composition
- For ternary systems, used 30%mol KNO_3
- Ruled out mixtures operating at too ↓ T because
  - Want to take into account heat loss during storage
  - Concentrate sunbeam temperature is ~150-350C
- Did equilibrium calculations at eutectic comp.
- Pick 2 mixtures with ↑ latent heat of melting

Database Selection

- FTsalt
  - -ALKN (HT solid solution NaNO3, KNO3; dilute Rbno3, CsNO3)
  - -CRKN (HT solid solution RbNO3, CsNO3; dilute KNO3)
  - -CsKN (LT solid binary solution CsNO3: dilute KNO3)
  - -NKNA (LT, high KNO3 content solid binary solution KNO3; dilute NaNO3)



Phase Selection

- Select all stable phases in accordance to phase diagram results
- Always picked Ftsalt-SALTE for liquid phase
- Omitted some Base-Phases at times because…

Solution species

*	+	Base-Phase	Full Name
	+	FTsalt-ALKN	Na,K,[Rb,Cs]//NO3(ss)
	+	FTsalt-CRKN	Rb,Cs,[K]//NO3(ss)
	+	FTsalt-CsKN	CsNO3-[KNO3](ss)
	+	FTsalt-NKNA	KNO3-[NaNO3](LT)
		FTsalt-SALTD	DSalt-liquid
	I	FTsalt-SALTE	ESalt-liquid
		FTsalt-SALT?	?Salt-liquid

Selected: 3/3 FTsalt-SALTE

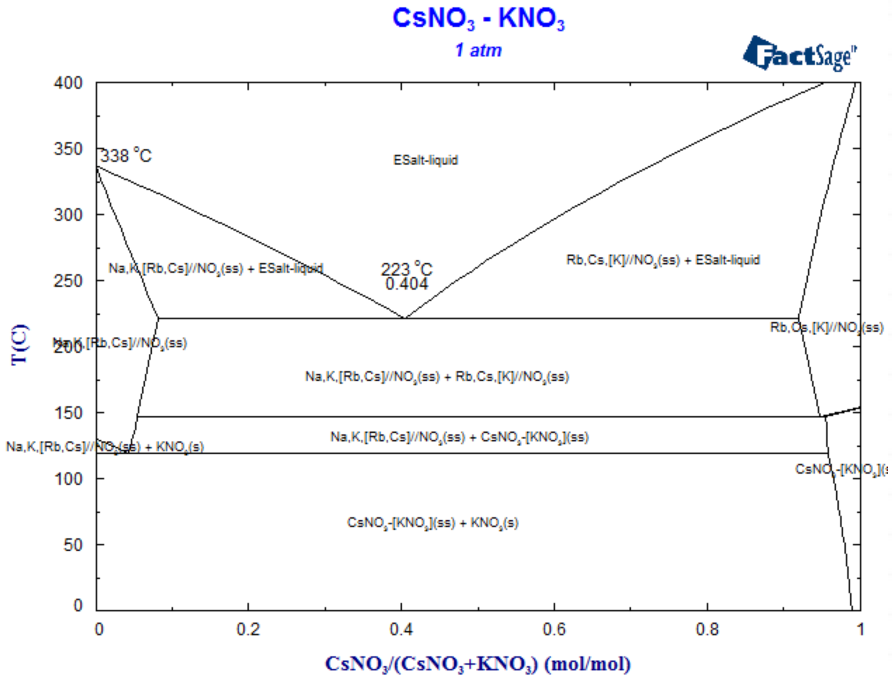
+	Code	Species	Data	Phase
I	24	CsNO3(SALTE)	FTsalt	FTsalt-SALTE
I	23	KNO3(SALTE)	FTsalt	FTsalt-SALTE
I	22	NaNO3(SALTE)	FTsalt	FTsalt-SALTE

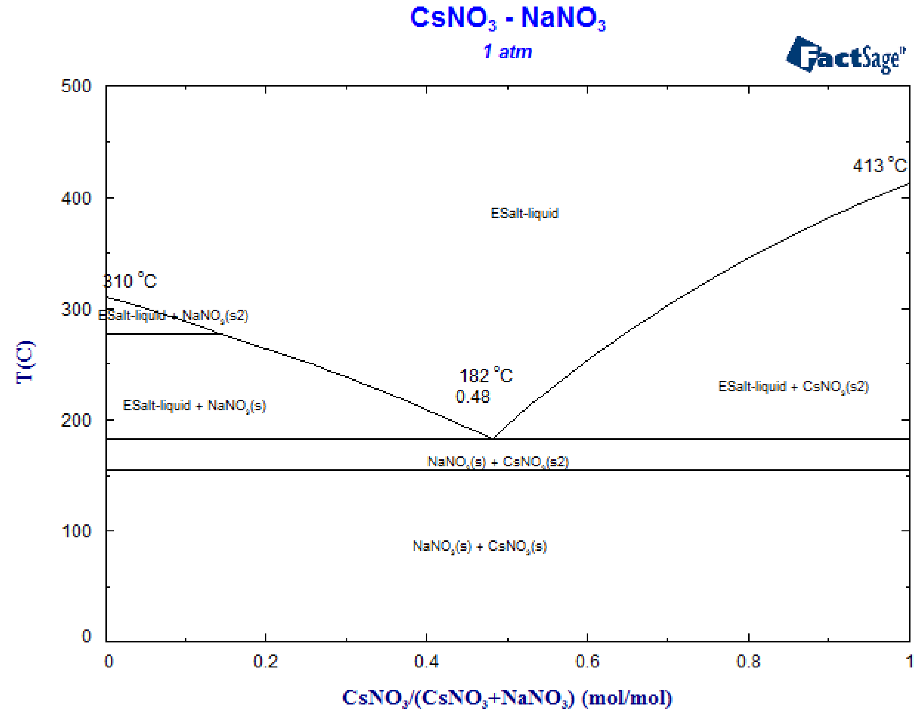
Selected: 0/3 FTsalt-SALTD

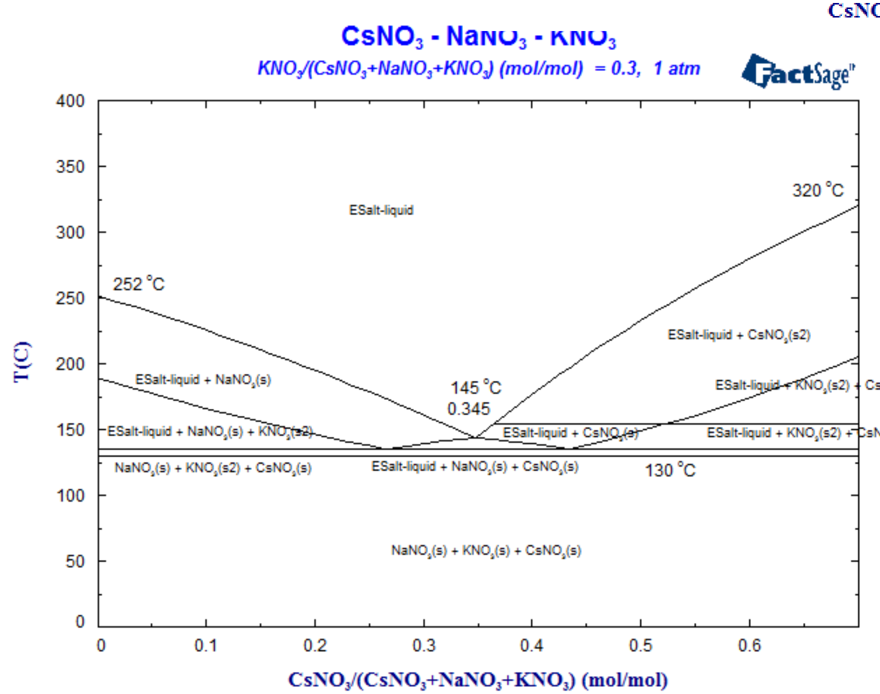
+	Code	Species	Data	Phase
	21	Cs2O(SALTD)	FTsalt	FTsalt-SALTD
	20	K2O(SALTD)	FTsalt	FTsalt-SALTD
	19	Na2O(SALTD)	FTsalt	FTsalt-SALTD

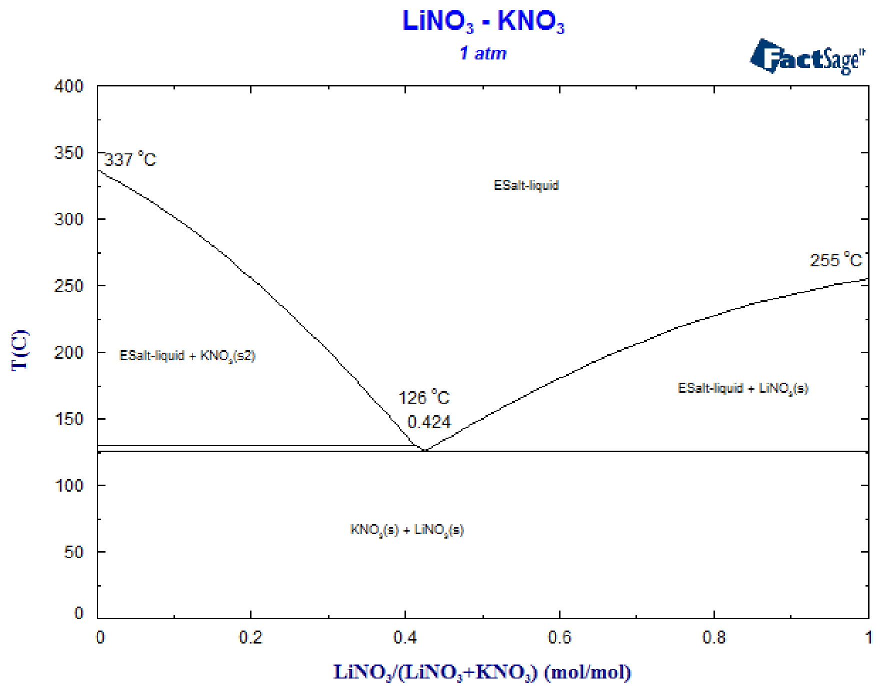
Results

Phase Diagrams

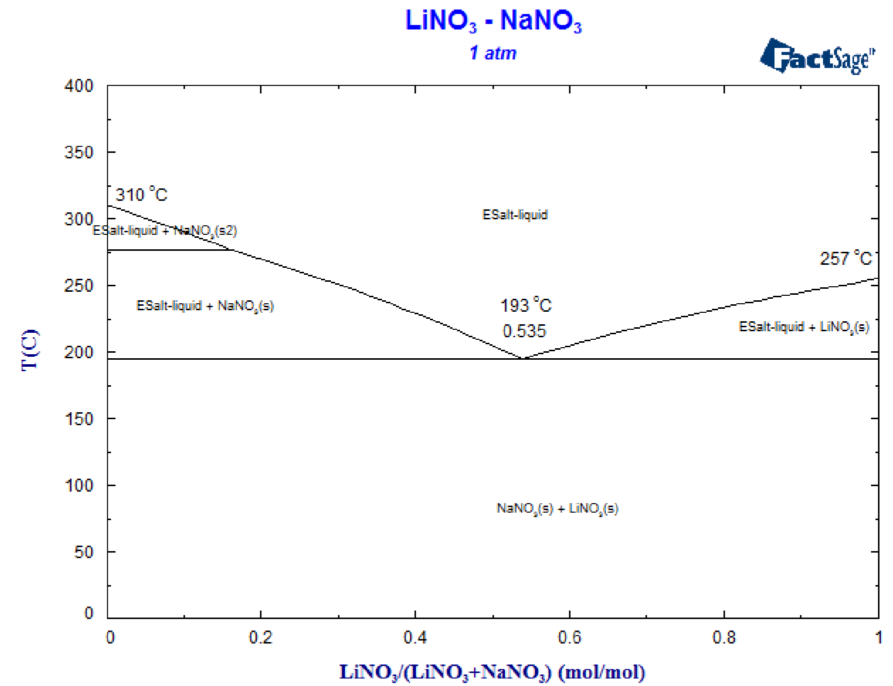

CsNO3 - KNO3
1 atm
FactSage
400
350
300
250
200
150
100
50
0
338 °C
ESalt-liquid
Na,K,[Rb,Cs]//NO3(ss) + ESalt-liquid
223 °C
0.404
Rb,Cs,[K]//NO3(ss) + ESalt-liquid
Rb,Cs,[K]//NO3(ss)
Na,K,[Rb,Cs]//NO3(ss)
Na,K,[Rb,Cs]//NO3(ss) + Rb,Cs,[K]//NO3(ss)
Na,K,[Rb,Cs]//NO3(ss) + CsNO3-[KNO3](ss)
Na,K,[Rb,Cs]//NO3(ss) + KNO3(s)
CsNO3-[KNO3](ss) + KNO3(s)
T(C)
0
0.2
0.4
0.6
0.8
1
CsNO3/(CsNO3+KNO3) (mol/mol)


CsNO3 - NaNO3
1 atm
FactSage
500
400
300
200
100
0
413 °C
ESalt-liquid
310 °C
ESalt-liquid + NaNO3(s2)
182 °C
0.48
ESalt-liquid + CsNO3(s2)
ESalt-liquid + NaNO3(s)
NaNO3(s) + CsNO3(s2)
NaNO3(s) + CsNO3(s)
T(C)
0
0.2
0.4
0.6
0.8
1
CsNO3/(CsNO3+NaNO3) (mol/mol)

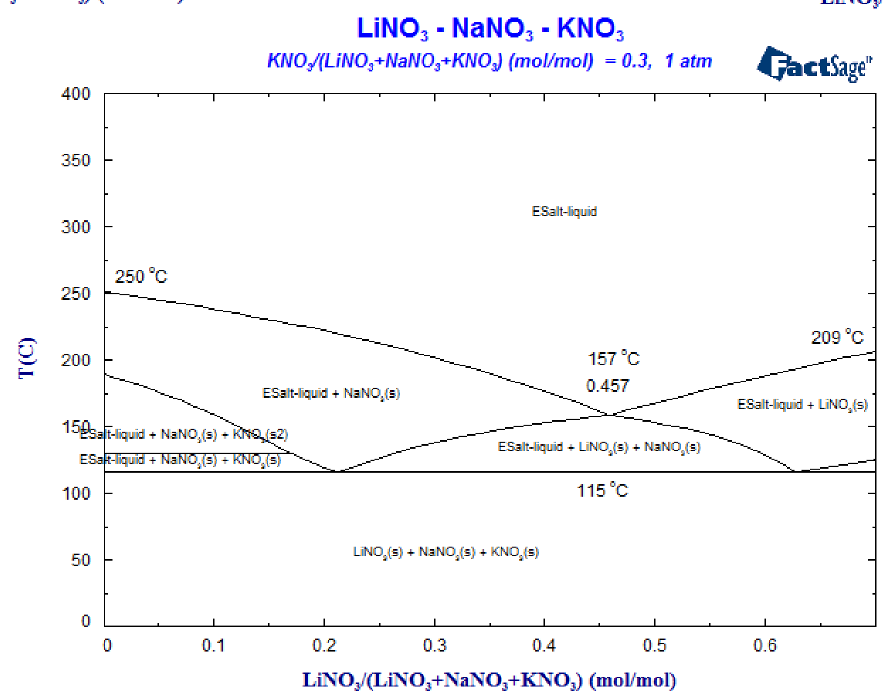

CsNO3 - NaNO3 - KNO3
KNO3/(CsNO3+NaNO3+KNO3) (mol/mol) = 0.3, 1 atm
FactSage
400
350
300
250
200
150
100
50
0
ESalt-liquid
320 °C
252 °C
ESalt-liquid + CsNO3(s2)
ESalt-liquid + NaNO3(s)
145 °C
0.345
ESalt-liquid + NaNO3(s) + KNO3(s2)
ESalt-liquid + CsNO3(s)
NaNO3(s) + KNO3(s2) + CsNO3(s)
ESalt-liquid + NaNO3(s) + CsNO3(s)
130 °C
NaNO3(s) + KNO3(s) + CsNO3(s)
T(C)
0
0.1
0.2
0.3
0.4
0.5
0.6
CsNO3/(CsNO3+NaNO3+KNO3) (mol/mol)



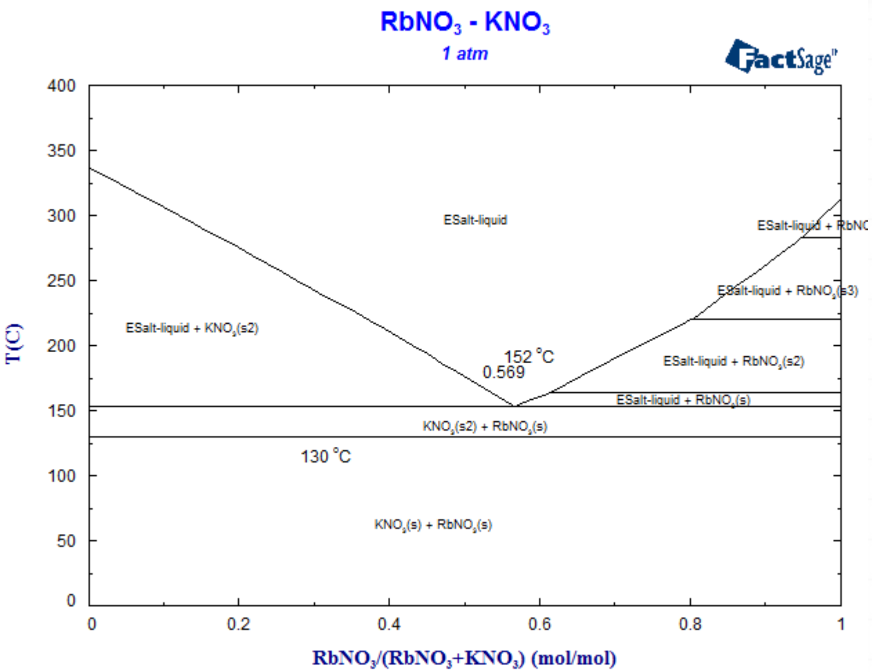
LiNO3 - KNO3
1 atm
FactSage
337 °C
ESalt-liquid
255 °C
ESalt-liquid + KNO3(s2)
126 °C
0.424
ESalt-liquid + LiNO3(s)
KNO3(s) + LiNO3(s)
T(C)
400
350
300
250
200
150
100
50
0
0
0.2
0.4
0.6
0.8
1
LiNO3/(LiNO3+KNO3) (mol/mol)

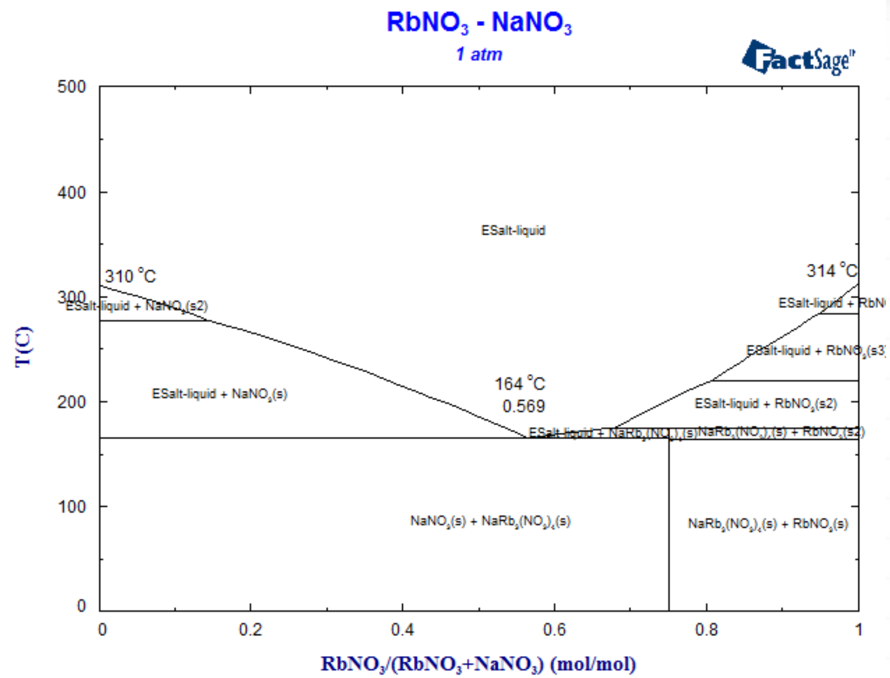


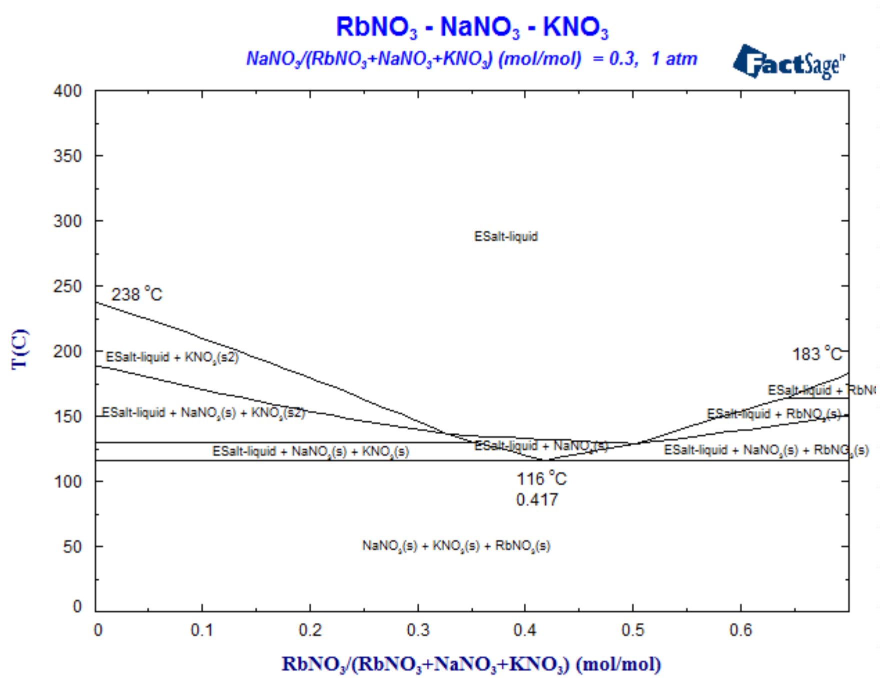
LiNO3 - NaNO3
1 atm
FactSage
310 °C
ESalt-liquid + NaNO3(s2)
ESalt-liquid
257 °C
ESalt-liquid + NaNO3(s)
193 °C
0.535
ESalt-liquid + LiNO3(s)
NaNO3(s) + LiNO3(s)
T(C)
400
350
300
250
200
150
100
50
0
0
0.2
0.4
0.6
0.8
1
LiNO3/(LiNO3+NaNO3) (mol/mol)

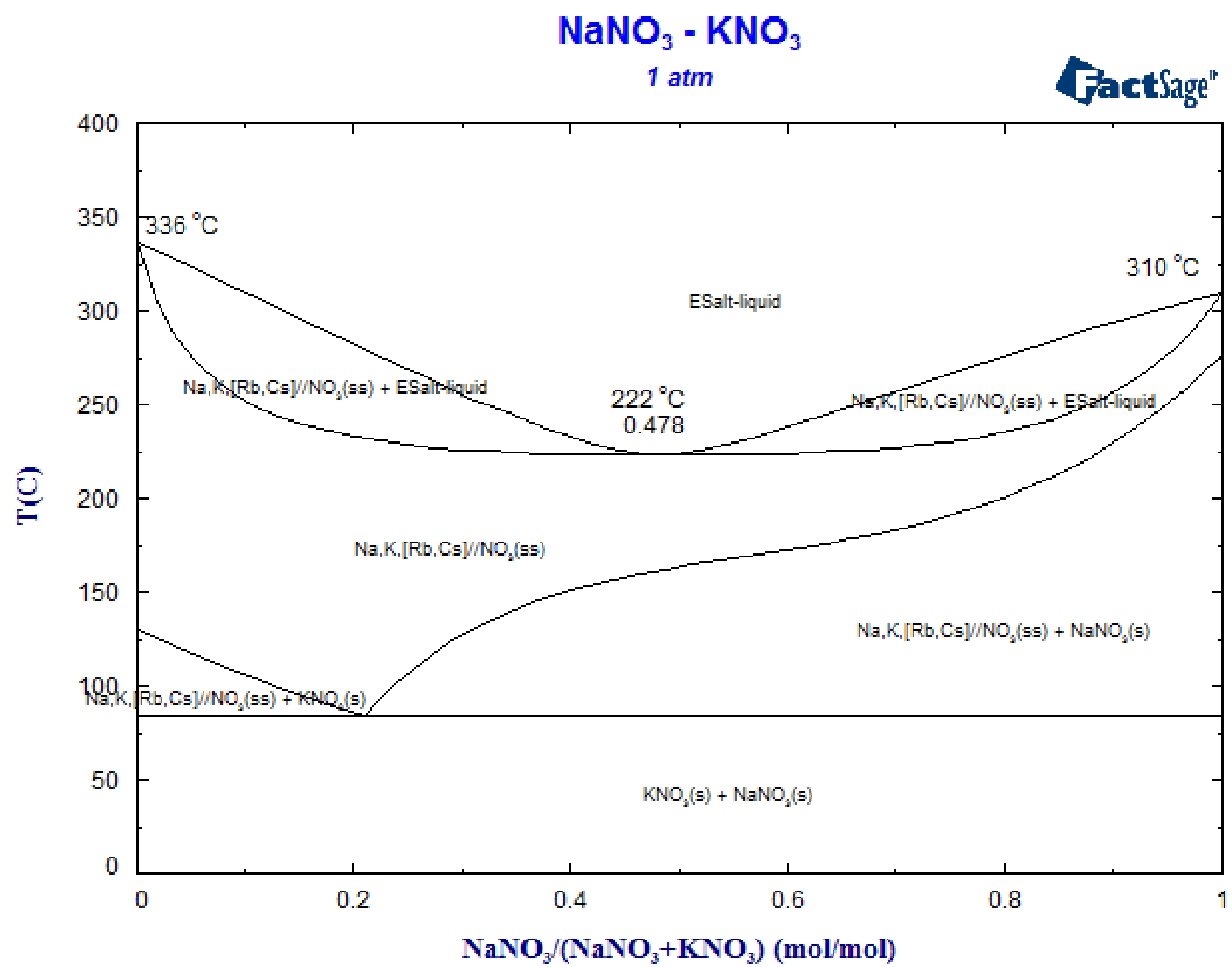


LiNO3 - NaNO3 - KNO3
KNO3/(LiNO3+NaNO3+KNO3) (mol/mol) = 0.3, 1 atm
FactSage
ESalt-liquid
250 °C
209 °C
157 °C
0.457
ESalt-liquid + NaNO3(s)
ESalt-liquid + LiNO3(s)
ESalt-liquid + NaNO3(s) + KNO3(s2)
ESalt-liquid + NaNO3(s) + KNO3(s)
ESalt-liquid + LiNO3(s) + NaNO3(s)
115 °C
LiNO3(s) + NaNO3(s) + KNO3(s)
T(C)
400
350
300
250
200
150
100
50
0
0
0.1
0.2
0.3
0.4
0.5
0.6
LiNO3/(LiNO3+NaNO3+KNO3) (mol/mol)


RbNO3 - KNO3
1 atm
FactSage
ESalt-liquid
ESalt-liquid + KNO3(s2)
ESalt-liquid + RbNO3(s3)
ESalt-liquid + RbNO3(s2)
ESalt-liquid + RbNO3(s)
152 °C
0.569
KNO3(s2) + RbNO3(s)
130 °C
KNO3(s) + RbNO3(s)
T(C)
RbNO3/(RbNO3+KNO3) (mol/mol)

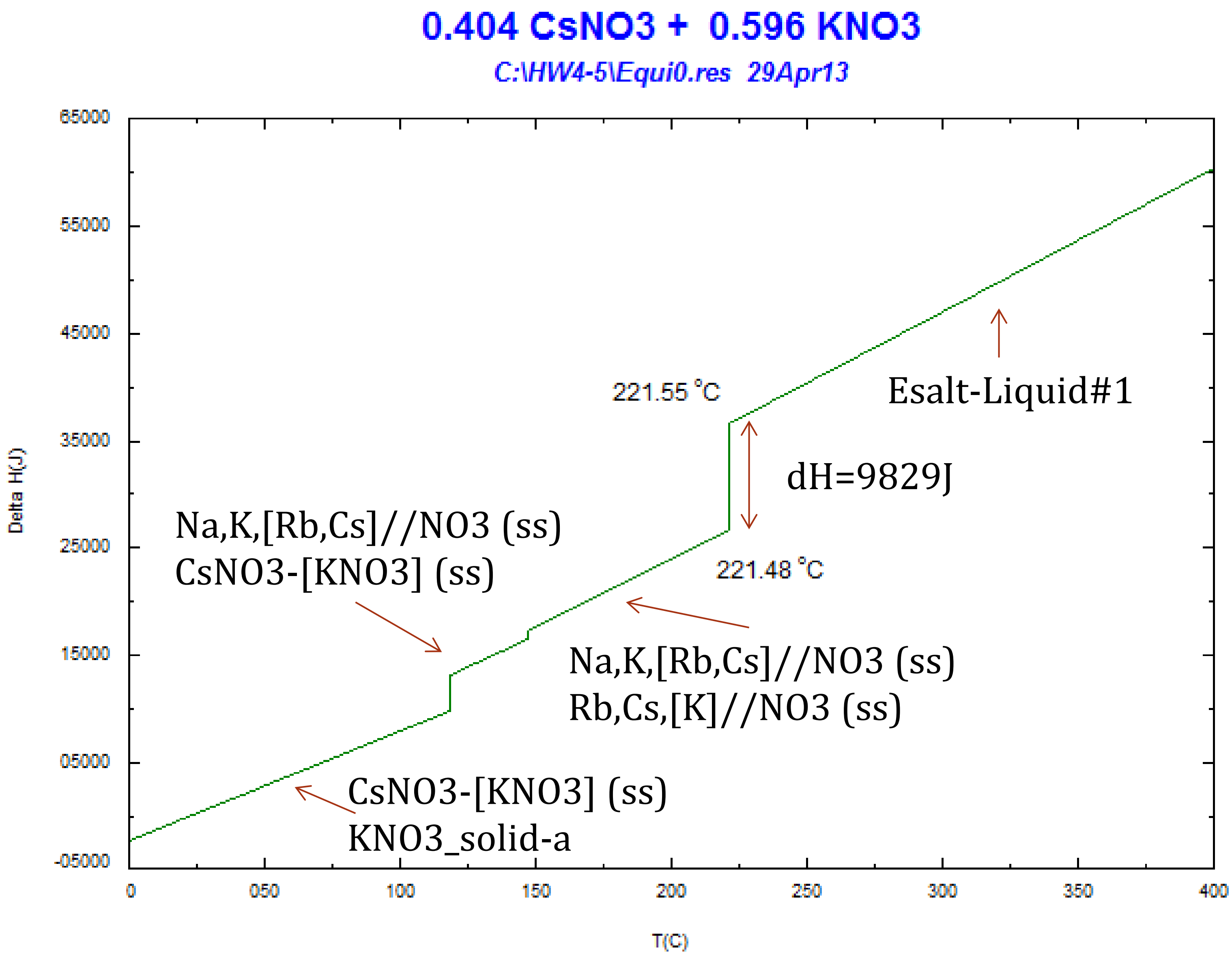

RbNO3 - NaNO3
1 atm
FactSage
ESalt-liquid
310 °C
ESalt-liquid + NaNO3(s2)
314 °C
ESalt-liquid + RbNO3(s2)
ESalt-liquid + NaNO3(s)
164 °C
0.569
NaNO3(s) + NaRb3(NO3)4(s)
NaRb3(NO3)4(s) + RbNO3(s)
T(C)
RbNO3/(RbNO3+NaNO3) (mol/mol)

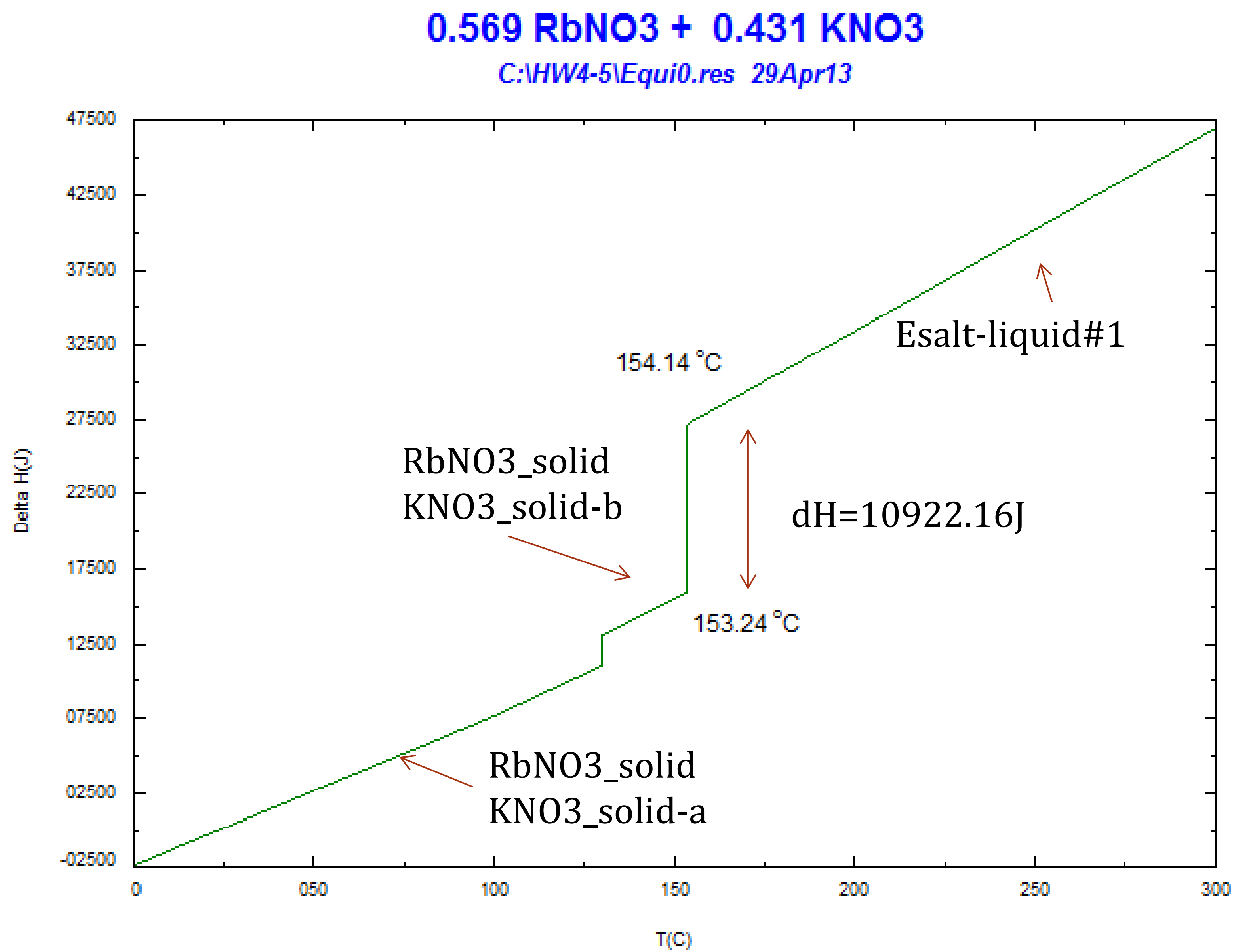

RbNO3 - NaNO3 - KNO3
NaNO3/(RbNO3+NaNO3+KNO3) (mol/mol) = 0.3, 1 atm
FactSage
ESalt-liquid
238 °C
ESalt-liquid + KNO3(s2)
ESalt-liquid + NaNO3(s) + KNO3(s2)
ESalt-liquid + NaNO3(s) + KNO3(s)
ESalt-liquid + NaNO3(s)
183 °C
ESalt-liquid + RbNO3(s)
ESalt-liquid + NaNO3(s) + RbNO3(s)
116 °C
0.417
NaNO3(s) + KNO3(s) + RbNO3(s)
T(C)
RbNO3/(RbNO3+NaNO3+KNO3) (mol/mol)


NaNO3 - KNO3
1 atm
FactSage
T(C)
NaNO3/(NaNO3+KNO3) (mol/mol)
336 °C
310 °C
222 °C
0.478
ESalt-liquid
Na,K,[Rb,Cs]//NO3(ss) + ESalt-liquid
Na,K,[Rb,Cs]//NO3(ss) + ESalt-liquid
Na,K,[Rb,Cs]//NO3(ss)
Na,K,[Rb,Cs]//NO3(ss) + NaNO3(s)
Na,K,[Rb,Cs]//NO3(ss) + KNO3(s)
KNO3(s) + NaNO3(s)
400
350
300
250
200
150
100
50
0
0
0.2
0.4
0.6
0.8
1

Selecting Mixtures by Operating Temperature

Mixture	Eutectic Melting Temperature (C)	Eutectic Composition (%mol)
CsNO3-KNO3	221	0.404
~~LiNO3-KNO3~~	~~126~~	~~0.424~~
RbNO3-KNO3	154	0.569
CsNO3-NaNO3	182	0.48
LiNO3-NaNO3	195	0.535
RbNO3-NaNO3	164	0.569
~~CsNO3-NaNO3-KNO3~~	~~145~~	~~0.345~~
LiNO3-NaNO3-KNO3	159	0.457
~~RbNO3-NaNO3-KNO3~~	~~116~~	~~0.417~~
NaNO3-KNO3	223	0.478

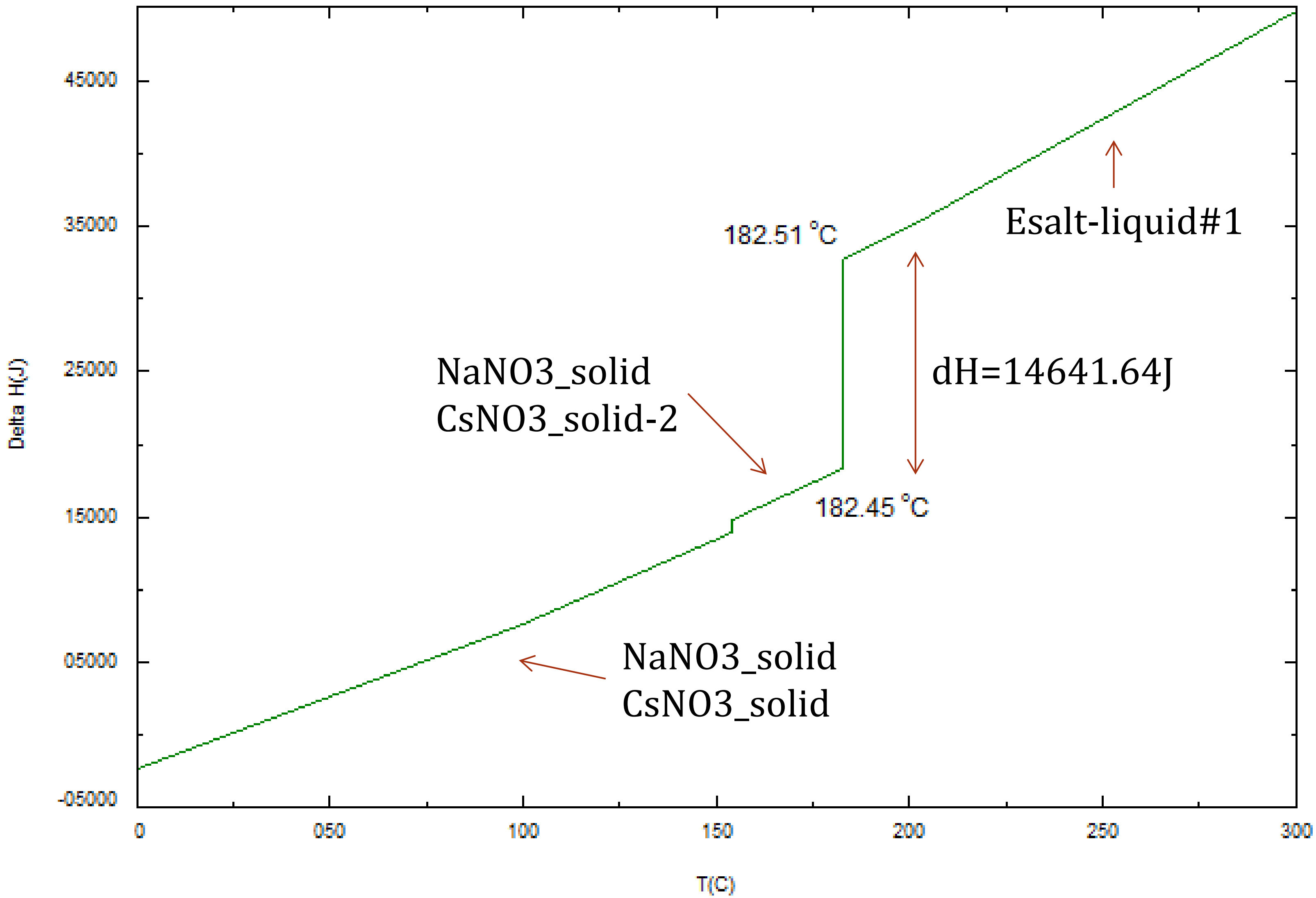

0.404 CsNO3 + 0.596 KNO3
C:\HW4-5\Equi0.res 29Apr13
Delta H(J)
T(C)
65000
55000
45000
35000
25000
15000
05000
-05000
0
050
100
150
200
250
300
350
400
221.55 °C
Esalt-Liquid#1
dH=9829J
221.48 °C
Na,K,[Rb,Cs]//NO3 (ss)
CsNO3-[KNO3] (ss)
Na,K,[Rb,Cs]//NO3 (ss)
Rb,Cs,[K]//NO3 (ss)
CsNO3-[KNO3] (ss)
KNO3_solid-a

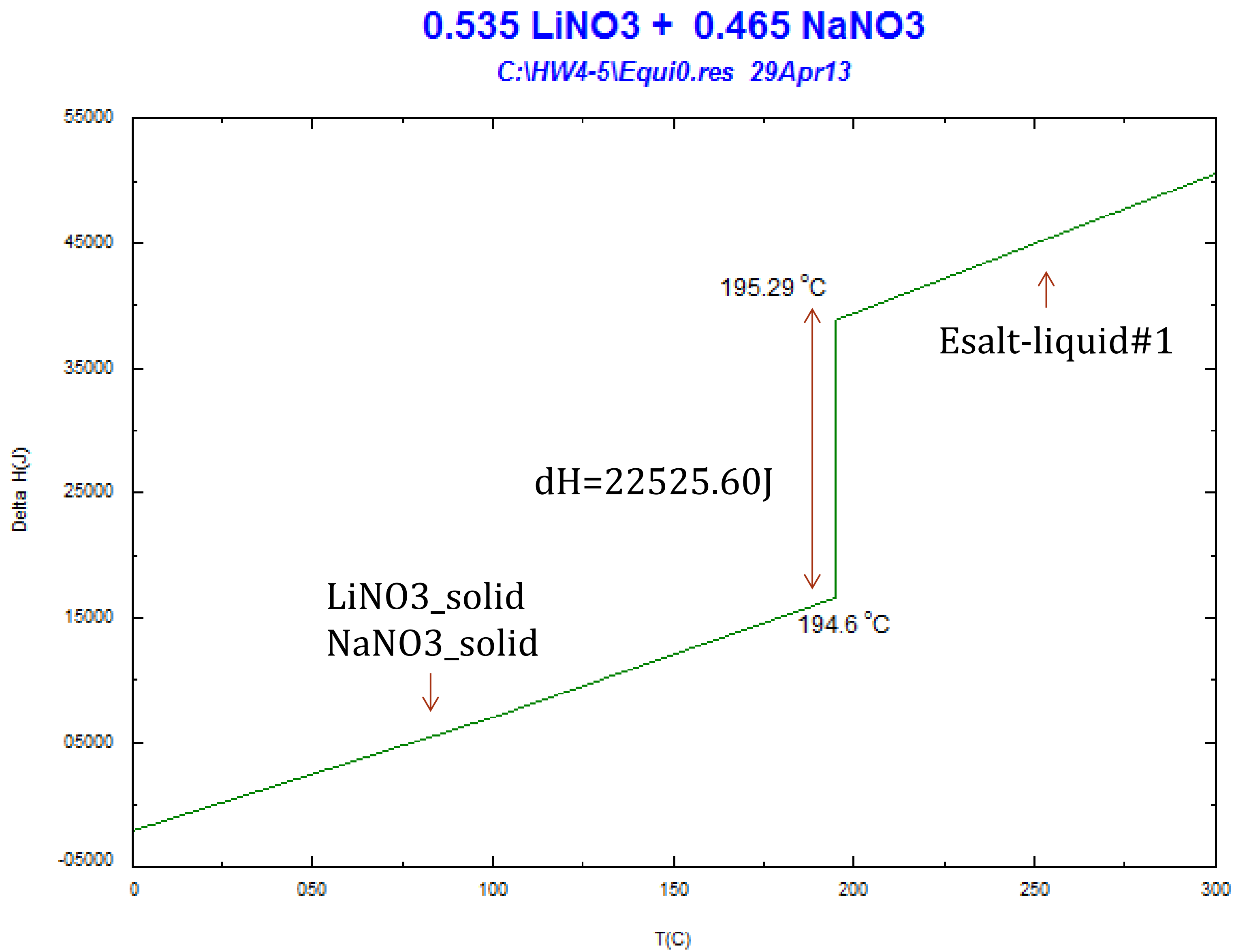


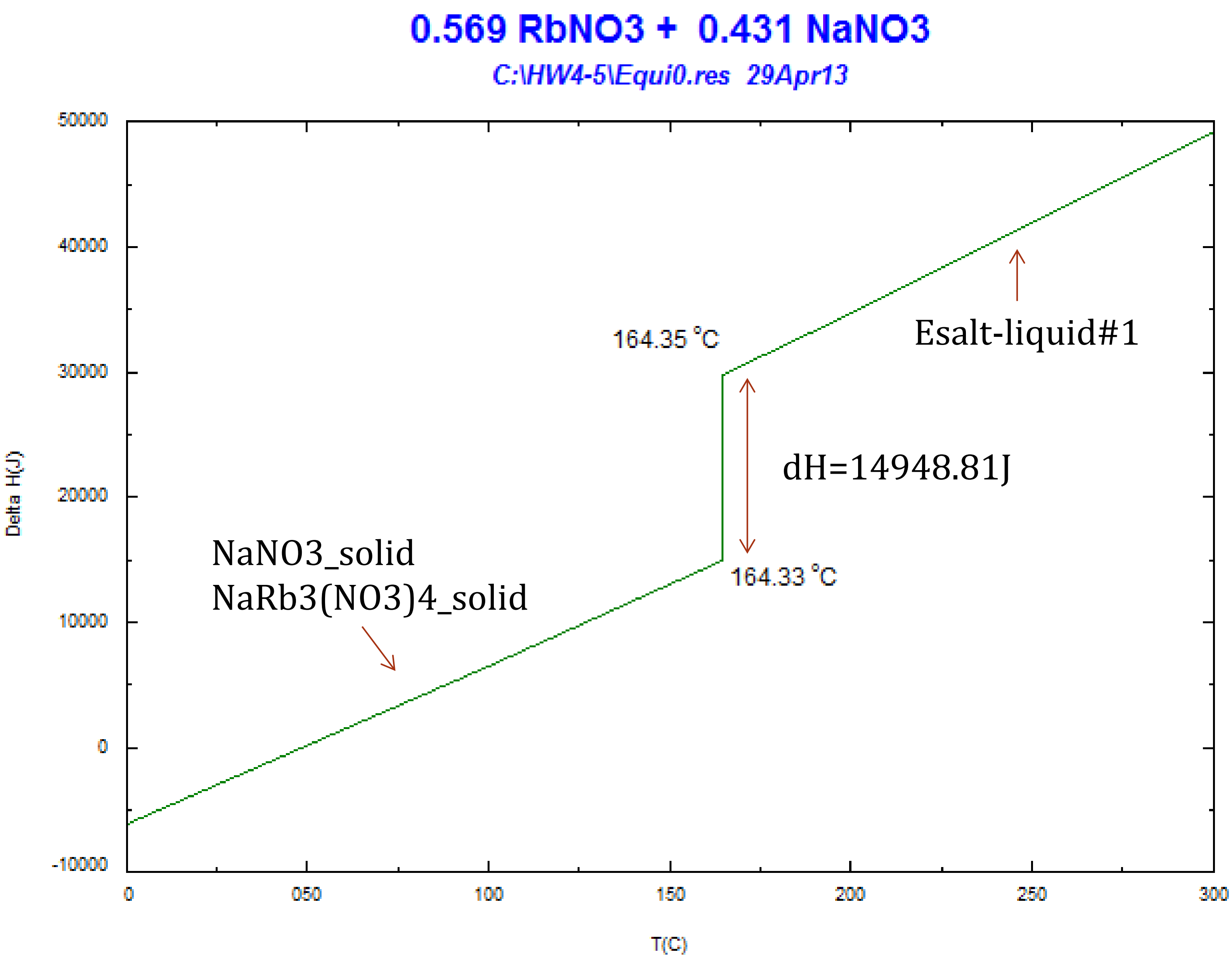
0.569 RbNO3 + 0.431 KNO3
C:\HW4-5\Equi0.res 29Apr13
Delta H(J)
47500
42500
37500
32500
27500
22500
17500
12500
07500
02500
-02500
0
050
100
150
200
250
300
T(C)
154.14 °C
153.24 °C
Esalt-liquid#1
RbNO3_solid
KNO3_solid-b
dH=10922.16J
RbNO3_solid
KNO3_solid-a

$0.48\ CsNO_3 + 0.52\ NaNO_3$

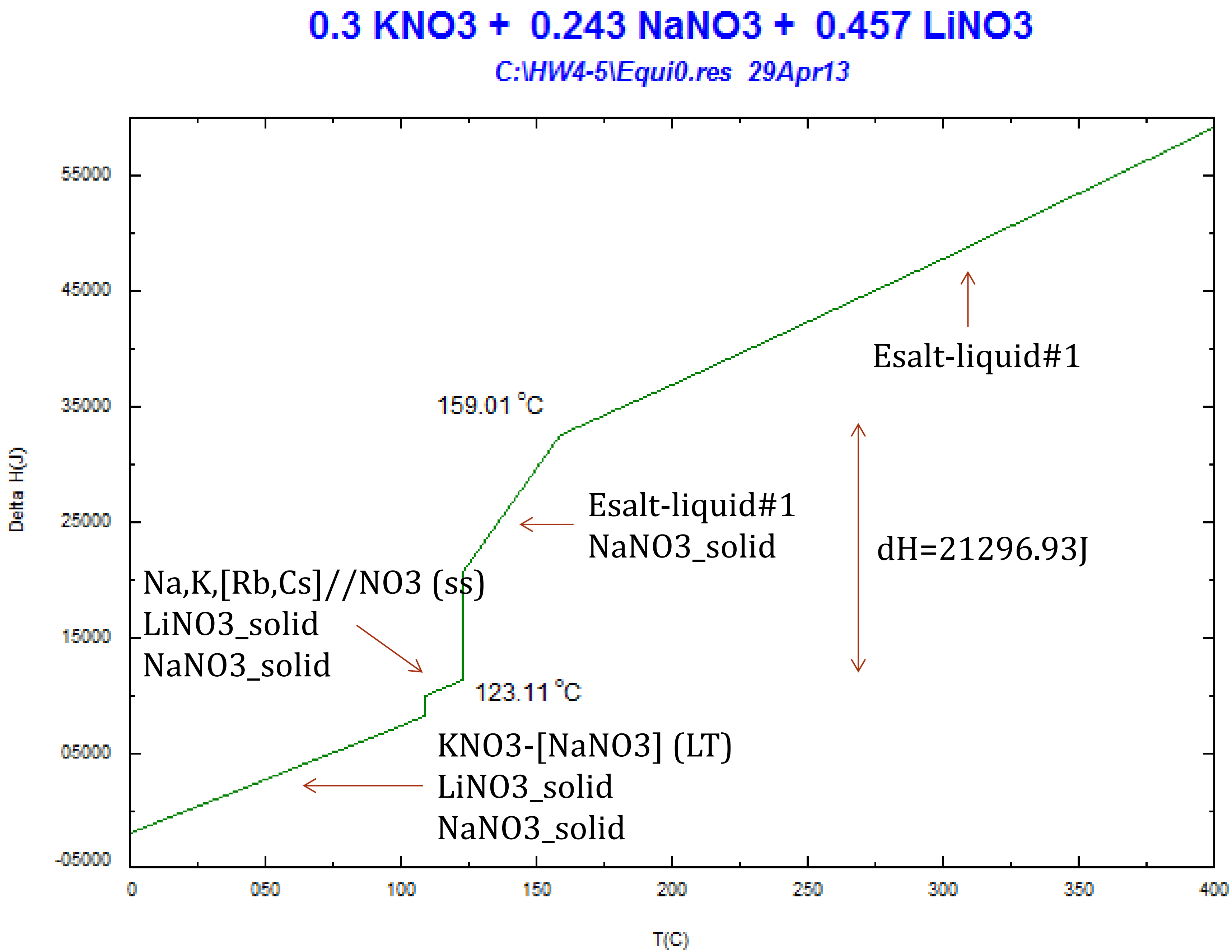
C:\HW4-5\Equi0.res 29Apr13

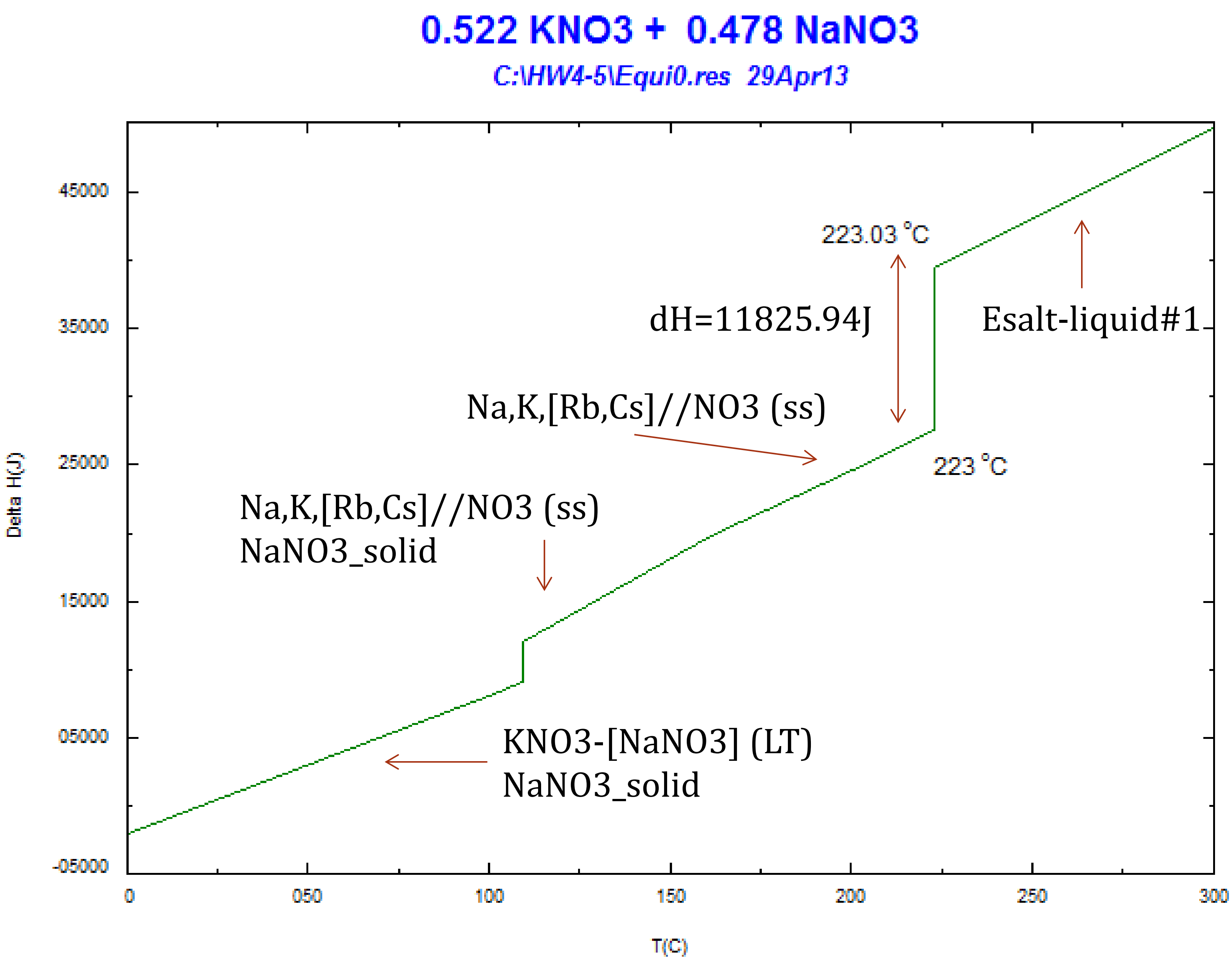



0.535 LiNO3 + 0.465 NaNO3
C:\HW4-5\Equi0.res 29Apr13
55000
45000
35000
25000
15000
05000
-05000
Delta H(J)
0
050
100
150
200
250
300
T(C)
195.29 °C
194.6 °C
dH=22525.60J
Esalt-liquid#1
LiNO3_solid
NaNO3_solid



0.569 RbNO3 + 0.431 NaNO3
C:\HW4-5\Equi0.res 29Apr13
Delta H(J)
T(C)
164.35 °C
164.33 °C
dH=14948.81J
Esalt-liquid#1
NaNO3_solid
NaRb3(NO3)4_solid


0.3 KNO3 + 0.243 NaNO3 + 0.457 LiNO3
C:\HW4-5\Equi0.res 29Apr13
Delta H(J)
T(C)
159.01 °C
123.11 °C
Esalt-liquid#1
Esalt-liquid#1
NaNO3_solid
dH=21296.93J
Na,K,[Rb,Cs]//NO3 (ss)
LiNO3_solid
NaNO3_solid
KNO3-[NaNO3] (LT)
LiNO3_solid
NaNO3_solid



0.522 KNO3 + 0.478 NaNO3
C:\HW4-5\Equi0.res 29Apr13
223.03 °C
dH=11825.94J
Esalt-liquid#1
Na,K,[Rb,Cs]//NO3 (ss)
223 °C
Na,K,[Rb,Cs]//NO3 (ss)
NaNO3_solid
KNO3-[NaNO3] (LT)
NaNO3_solid
Delta H(J)
T(C)
45000
35000
25000
15000
05000
-05000
0
050
100
150
200
250
300

Selecting Best Mixture based on Latent Heat

Mixture	Eutectic Melting Temperature (C)	Eutectic Composition (%mol)	Latent Heat of Melting (J)
CsNO3-KNO3	221	0.404	9829.352
~~LiNO3-KNO3~~	~~126~~	~~0.424~~	-
RbNO3-KNO3	154	0.569	10922.157
CsNO3-NaNO3	182	0.48	14641.638
LiNO3-NaNO3	195	0.535	22525.598
RbNO3-NaNO3	164	0.569	14948.805
~~CsNO3-NaNO3-KNO3~~	~~145~~	~~0.345~~	-
LiNO3-NaNO3-KNO3	159	0.457	21296.929
~~RbNO3-NaNO3-KNO3~~	~~116~~	~~0.417~~	-
NaNO3-KNO3	223	0.478	11825.938

References

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