Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Thermodynamic assessments of the Al–Th and Th–Zn systems

Z.S. Li [a], X.J. Liu [a], M.Z. Wen [a], C.P. Wang [a,*], A.T. Tang [b], F.S. Pan [b]

[a] Department of Materials Science and Engineering, College of Materials, and Research Center of Materials Design and Applications, Xiamen University, Xiamen 361005, PR China
[b] College of Materials Science and Engineering, Chongqing University, Chongqing 400045, PR China

ARTICLE INFO

ABSTRACT

The phase diagrams of the Al–Th and Th–Zn systems have been evaluated by using the Calculation of Phase Diagrams (CALPHAD) method with the experimental data including the phase equilibria and thermodynamic properties. The Gibbs free energies of the liquid, bcc and hcp phases were described by the subregular solution model with the Redlich–Kister equation, and those of the stoichiometric compounds of the Th_2Al, Th_3Al_2, $ThAl$, Th_2Al_3, $ThAl_2$, $ThAl_3$, Th_2Al_7, Th_2Zn, $ThZn_2$, $ThZn_4$ and Th_2Zn_{17} were described by the two-sublattice model. The calculated phase equilibria and thermodynamic properties are in good agreement with the experimental data.

1. Introduction

Nuclear energy is a new kind of important energy, and the nuclear materials are the important fundamental guarantee to develop a safe nuclear reactor with high efficiency [1–3]. Thorium (Th) is an abundant element in nature with multiple advantages as a nuclear fuel for future reactors of all types [4]. The traditional methods of materials researches with many experimental tries are unsuitable in the nuclear materials researches because of the rigorous experimental conditions. Thus, the investigation on the phase diagrams of nuclear materials systems is very important for development of new nuclear materials. Our goal is to develop the thermodynamic database of the phase diagrams in nuclear material system. The present authors have made some thermodynamic assessments of nuclear material system [5–11]. As a part of this thermodynamic database, the purpose of the present work is to carry out thermodynamic assessment of the phase diagrams in the Al–Th and Th–Zn systems based on the Calculation of Phase Diagrams (CALPHAD) method by means of the available experimental data.

2. Thermodynamic models

The information of the stable solid phases and the used models in the Al–Th and Th–Zn systems are presented in Table 1.

2.1. Solution phases

Gibbs free energies of the solution phases (liquid, hcp, fcc and bcc phases) in an A–B system, corresponding to the Al–Th, and Th–Zn systems, are described by the subregular solution model. The molar Gibbs free energy of each solution phase in A–B system is given as follows:

$$G_m^\phi = \sum_{i=A,B} {}^0 G_i^\phi x_i + RT \sum_{i=A,B} x_i \ln x_i + {}^E G_m^\phi, \qquad (1)$$

where ${}^0 G_i^\phi$ is the molar Gibbs free energy of pure component i in the respective reference state with the ϕ phase, which is taken from the SGTE pure element database [12]. R is the gas constant, and T is the absolute temperature. The x_i denotes the mole fraction of component i. The term ${}^E G_m^\phi$ is the excess Gibbs free energy, which is expressed in the Redlich–Kister polynomials [13] as:

$$ {}^E G_m^\phi = L_{A,B}^\phi x_A x_B, \qquad (2) $$

where $L_{A,B}^\phi$ is the interaction energies in a hypothetical binary system denoted by A–B, which is expressed in the following forms:

$$
\begin{aligned}
L_{A,B}^\phi &= {}^0 L_{A,B}^\phi + {}^1 L_{A,B}^\phi (x_A - x_B) + {}^2 L_{A,B}^\phi (x_A - x_B)^2 + \cdots \\
&= \sum_{m=0}^{n} {}^m L_{A,B}^\phi (x_A - x_B)^m,
\end{aligned} \qquad (3)
$$

$$ {}^m L_{A,B}^\phi = a + bT, \qquad (4) $$

where the parameters of a and b were evaluated based on the experimental data in binary systems, respectively.

* Corresponding author. Tel.: +86 592 2180606; fax: +86 592 2187966.
E-mail address: wangcp@xmu.edu.cn (C.P. Wang).

Table 1
The stable solid phases and the used models in the Al–Th and Th–Zn systems.

System	Phase	Prototype	Crystal system	Modeling phase	Used models
Th–Al	αTh	Cu	fcc	(Al, Th)	SSM
	βTh	W	bcc	(Al, Th)	SSM
	(Al)	Cu	fcc	(Al, Th)	SSM
	Th_2Al	Al_2Cu	bct	$(Th)_{0.667}(Al)_{0.333}$	SM
	Th_3Al_2	U_3Si_2	Tetragonal	$(Th)_{0.6}(Al)_{0.4}$	SM
	ThAl	CrB	Orthorhombic	$(Th)_{0.5}(Al)_{0.5}$	SM
	Th_2Al_3	–	Tetragonal	$(Th)_{0.4}(Al)_{0.6}$	SM
	$ThAl_2$	AlB_2	Hexagonal	$(Th)_{0.333}(Al)_{0.667}$	SM
	$ThAl_3$	$SnNi_3$	Hexagonal	$(Th)_{0.25}(Al)_{0.75}$	SM
	Th_2Al_7	–	Orthorhombic	$(Th)_{0.222}(Al)_{0.778}$	SM
Th–Zn	αTh	Cu	fcc	(Th, Zn)	SSM
	βTh	W	bcc	(Th, Zn)	SSM
	(Zn)	Mg	hcp	(Th, Zn)	SSM
	Th_2Zn	Al_2Cu	bct	$(Th)_{0.667}(Zn)_{0.333}$	SM
	$ThZn_2$	–	Hexagonal	$(Th)_{0.333}(Zn)_{0.667}$	SM
	$ThZn_4$	$BaAl_4$	bct	$(Th)_{0.2}(Zn)_{0.8}$	SM
	Th_2Zn_{17}	Th_2Zn_{17}	Rhombohedral	$(Th)_{0.105}(Zn)_{0.895}$	SM

SSM: subregular solution model and SM: sublattice model.

2.2. Stoichiometric intermetallic compounds

In the Th–Me (Me: Al or Zn) system, the intermetallic compounds (Th_2Al, Th_3Al_2, ThAl, Th_2Al_3, $ThAl_2$, $ThAl_3$, Th_2Al_7, Th_2Zn, $ThZn_2$, $ThZn_4$ and Th_2Zn_{17}) are stoichiometric compounds. The Gibbs free energy for per mole of formula unit Th_pMe_q can be expressed as:
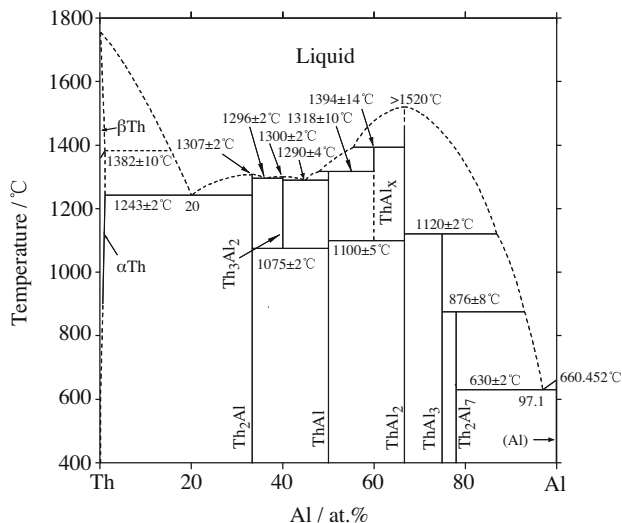
$$\Delta^0 G_f^{Th_pMe_q} = G_m^{Th_pMe_q} - p^0 G_{Th}^{ref} - q^0 G_{Me}^{ref} = a' + b'T, \qquad (5)$$

where the $\Delta^0 G_f^{Th_pMe_q}$ indicates the standard Gibbs free energy for the formation of the stoichiometric compound from pure elements, and the parameters of a' and b' were evaluated in the present paper.

3. Experimental information

3.1. The Al–Th binary system

The phase diagram in the Al–Th system consists of four solution phases (liquid, αTh, βTh, (Al) phases), and seven intermetallic compounds (Th_2Al, Th_3Al_2, ThAl, Th_2Al_3, $ThAl_3$, $ThAl_2$, Th_2Al_7 phases). The phase diagram in the Al–Th system has been investigated by many researchers [14–19]. Murray [17] studied the phase diagram

in the Al–Th system by thermal analysis, X-ray diffraction and metallographic methods, and found that the Th_2Al, Th_3Al_2 and $ThAl_2$ compounds are directly formed from the liquid phase, while the ThAl, Th_2Al_3 and $ThAl_3$ compounds are formed by the peritectic reactions ($Th_2Al_3 + L \leftrightarrow ThAl$, $L + ThAl_2 \leftrightarrow Th_2Al_3$ or $L + ThAl_2 \leftrightarrow ThAl_3$). Murray [17] reported that the Th_3Al_2 and Th_2Al_3 compounds eutectoidally decompose at 1075 °C and 1100 °C, respectively, and the solid solubilities of Al in the αTh and βTh phases are 0.4 at.% at 1000 °C and 0.85 at.% at 1300 °C. However, the liquidus of the Al–Th binary system around the Th-corner has not been determined. The phase diagram in the Al–Th system reviewed by Kassner et al. [20] is shown in Fig. 1.

In addition, the enthalpies and entropies of formation of the Th_2Al_7 and $ThAl_3$ compounds in the temperature range from 673 °C to 807 °C were determined by Poyarkov et al. [19] on the basis of Electromotive Force (EMF) measurements. And the enthalpy formation of $ThAl_2$ was measured calorimetically by Wang et al. [21].

3.2. The Th–Zn binary system

The phase diagram in the Th–Zn system consists of four solution phases (liquid, αTh, βTh, (Zn) phases), and four intermetallic

Fig. 1. The phase diagram of the Al–Th system reviewed by Kassner [20].
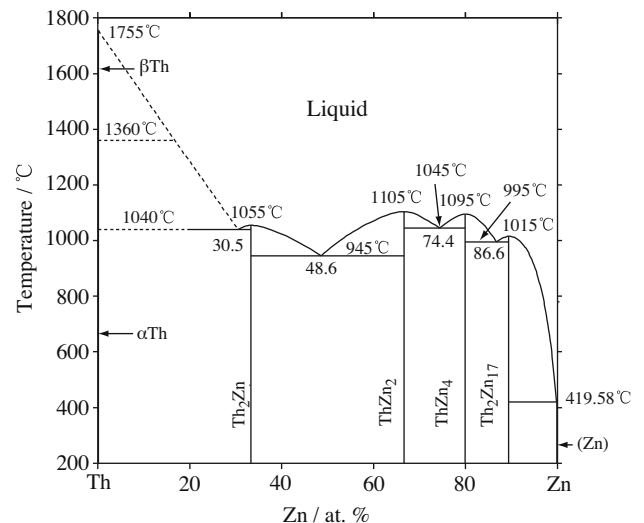
Fig. 2. The phase diagram of the Th–Zn system reviewed by Okamoto [27].

compounds (Th_2Zn, $ThZn_2$, $ThZn_4$, Th_2Zn_{17} phases). The phase diagram in the Th–Zn system was investigated by many researchers [22–26]. Chiotti and Gill [26] determined the phase diagram in the Th–Zn system by thermal analysis, metallographic method

and vapor pressure method, and found that the melting points of these compounds (Th_2Zn, $ThZn_2$, $ThZn_4$ and Th_2Zn_{17}) under constrained vapor conditions were 1055 °C, 1105 °C, 1095 °C and 1015 °C, respectively. Five eutectic reactions of the L $\leftrightarrow$ αTh + Th_2Zn, L $\leftrightarrow$ $ThZn_2$ + $ThZn_4$, L $\leftrightarrow$ $ThZn_4$ + Th_2Zn_{17}, L $\leftrightarrow$ Th_2Zn + $ThZn_2$ and L $\leftrightarrow$ Th_2Zn_{17} + Zn exist in this system with the following eutectic temperatures and Zn atom percentages: 1040 °C and 30.5 at.% Zn, 945 °C and 48.6 at.% Zn, 1045 °C and 74.4 at.% Zn, 995 °C and 86.8 at.% Zn, 419.58 °C and 0 at.% Zn. However, the relation between the liquid and Th-rich phases (including αTh and βTh phases) was only estimated by Chiotti and Gill [26] without enough experimental data. The phase diagram in the Th–Zn system reviewed by Okamoto [27] is shown in Fig. 2.

In addition, the standard enthalpy and entropy of formation for the compounds in the Th–Zn system were determined by many researchers [26,28–30] using vapor pressure measurement or EMF method. Based on these experimental data, Chiotti et al. [31] calculated these thermodynamic properties of the Th_2Zn_{17}, $ThZn_4$, $ThZn_2$ and Th_2Zn compounds.
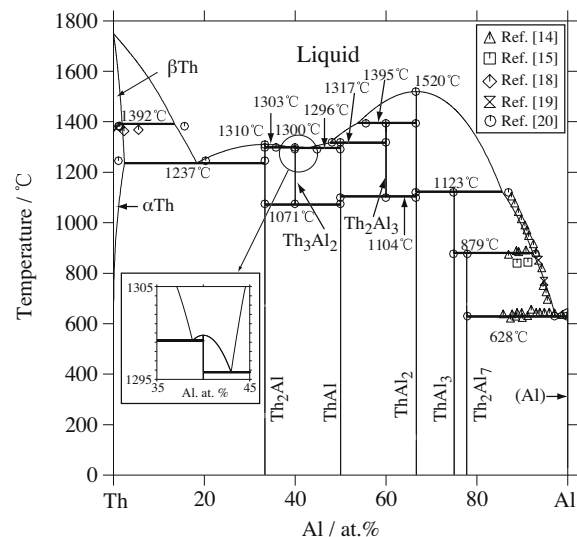
4. Optimized results and discussion

Optimization of thermodynamic parameters describing the Gibbs free energy of each phase is carried out by using PARROT module in the Thermo-Calc software [32], a computer program that can accept different types of data, such as any specific thermodynamic quantities and phase equilibria, in the same operation. Each piece of the selected data is given a certain weight and the weight can be changed until a satisfactory description for most of the selected data is achieved.

All the parameters were finally evaluated together and adjustments were made to give the best description of the binary Al–Th and Th–Zn systems. All evaluated parameters are listed in Tables 2 and 3.

4.1. Al–Th system

Fig. 3 shows the calculated phase diagram in the Al–Th system compared with the experimental data [14,15,18,19], and all the invariant reactions in the Al–Th system are listed in Table 4, where good agreement between calculated results and experimental data is obtained. The deviation between the calculated liquidus and the

Table 2
Thermodynamic parameters in the Al–Th system.

System	Parameters in each phase (J/mol)
Th–Al	Liquid phase, format $(Al, Th)_1$
	$^0L_{Al,Th}^{Liq} = -93725 + 4.523T$
	$^1L_{Al,Th}^{Liq} = -30000$
	$^2L_{Al,Th}^{Liq} = -20156 + 9.264T$
	Fcc phase (A1), format $(Al, Th)_1(Va)_1$
	$^0L_{Al,Th}^{fcc} = 6670$
	$^1L_{Al,Th}^{fcc} = 10557 + 7.000T$
	$^2L_{Al,Th}^{fcc} = -27932$
	Bcc phase (A2), format $(Al, Th)_1(Va)_3$
	$^0L_{Al,Th}^{bcc} = -32510$
	$^1L_{Al,Th}^{bcc} = 26059$
	$^2L_{Al,Th}^{bcc} = 20000$
	Th_2Al phase, format $(Th)_{0.6667}(Al)_{0.3333}$
	$G_{Al:Th}^{Th_2Al} = -44333 + 11.491T + 0.6667\,^0G_{Th}^{fcc} + 0.3333\,^0G_{Al}^{fcc}$
	Th_3Al_2 phase, format $(Th)_{0.6}(Al)_{0.4}$
	$G_{Al:Th}^{Th_3Al_2} = -41970 + 7.999T + 0.6\,^0G_{Th}^{fcc} + 0.4\,^0G_{Al}^{fcc}$
	$ThAl$ phase, format $(Th)_{0.5}(Al)_{0.5}$
	$G_{Al:Th}^{ThAl} = -42950 + 6.127T + 0.5\,^0G_{Th}^{fcc} + 0.5\,^0G_{Al}^{fcc}$
	Th_2Al_3 phase, format $(Th)_{0.4}(Al)_{0.6}$
	$G_{Al:Th}^{Th_2Al_3} = -38940 + 1.719T + 0.4\,^0G_{Th}^{fcc} + 0.6\,^0G_{Al}^{fcc}$
	$ThAl_2$ phase, format $(Th)_{0.3333}(Al)_{0.6667}$
	$G_{Al:Th}^{ThAl_2} = -41518 + 2.593T + 0.3333\,^0G_{Th}^{fcc} + 0.6667\,^0G_{Al}^{fcc}$
	$ThAl_3$ phase, format $(Th)_{0.25}(Al)_{0.75}$
	$G_{Al:Th}^{ThAl_3} = -37826 + 4.805T + 0.25\,^0G_{Th}^{fcc} + 0.75\,^0G_{Al}^{fcc}$
	Th_2Al_7 phase, format $(Th)_{0.2222}(Al)_{0.7778}$
	$G_{Al:Th}^{Th_2Al_7} = -36911 + 6.698T + 0.2222\,^0G_{Th}^{fcc} + 0.7778\,^0G_{Al}^{fcc}$

Table 3
Thermodynamic parameters in the Th–Zn system.

System	Parameters in each phase (J/mol)
Th–Zn	Liquid phase, format $(Th, Zn)_1$
	$^0L_{Th,Zn}^{Liq} = -85000 + 17.000T$
	$^1L_{Th,Zn}^{Liq} = 50000$
	$^2L_{Th,Zn}^{Liq} = -50000 + 15.000T$
	Fcc phase (A1), format $(Th, Zn)_1(Va)_1$
	$^0L_{Th,Zn}^{fcc} = 20000$
	Bcc phase (A2), format $(Th, Zn)_1(Va)_3$
	$^0L_{Th,Zn}^{bcc} = 20000$
	Hcp phase (A3), format $(Th, Zn)_1(Va)_{0.5}$
	$G_{Th}^{hcp} = 5000 + G_{Th}^{fcc}$
	$^0L_{Th,Zn}^{hcp} = 0$
	Th_2Zn phase, format $(Th)_{0.6667}(Zn)_{0.3333}$
	$G_{Th:Zn}^{Th_2Zn} = -18800 + 1.250T + 0.6667\,^0G_{Th}^{fcc} + 0.3333\,^0G_{Zn}^{hcp}$
	$ThZn_2$ phase, format $(Th)_{0.3333}(Zn)_{0.6667}$
	$G_{Th:Zn}^{ThZn_2} = -32180 + 2.400T + 0.3333\,^0G_{Th}^{fcc} + 0.6667\,^0G_{Zn}^{hcp}$
	$ThZn_4$ phase, format $(Th)_{0.2}(Zn)_{0.8}$
	$G_{Th:Zn}^{ThZn_4} = -28700 + 1.200T + 0.2\,^0G_{Th}^{fcc} + 0.8\,^0G_{Zn}^{hcp}$
	Th_2Zn_{17} phase, format $(Th)_{0.105}(Zn)_{0.895}$
	$G_{Th:Zn}^{Th_2Zn_{17}} = -26550 + 4.900T + 0.105\,^0G_{Th}^{fcc} + 0.895\,^0G_{Zn}^{hcp}$

Fig. 3. The calculated phase diagram of the Al–Th system with the experimental data [14,15,18–20].

Table 4
Experimental and calculated invariant reactions in the Al–Th system.

| Reaction type	Reaction	Al (at.%)			T (°C)	Reference
Peritetic reaction	L + ThAl$_2$ ↔ Th$_2$Al$_3$	56	66.7	60	1394 ± 14	[20]
		53.8	66.7	60	1394.8	This work
Peritetic reaction	L + βTh ↔ αTh	15	1	~1	1382 ± 10	[20]
		13.4	1.91	1.93	1391.8	This work
Peritetic reaction	Th$_2$Al$_3$ + L ↔ ThAl	60	48	50	1318 ± 10	[20]
		60	47.6	50	1317.3	This work
Eutectic reaction	L ↔ Th$_3$Al$_2$ + Th$_2$Al	35	40	33.3	1296 ± 2	[20]
		38.8	40	33.3	1299.2	This work
Eutectic reaction	L ↔ ThAl + Th$_3$Al$_2$	43	50	40	1290 ± 4	[20]
		43	50	40	1295.8	This work
Eutectic reaction	L ↔ Th$_2$Al + αTh	20	33.3	0.85	1243 ± 2	[20]
		18.3	33.3	2.4	1236.5	This work
Peritetic reaction	L + ThAl$_2$ ↔ ThAl$_3$	84	66.7	75	1120 ± 2	[20]
		85.6	66.7	75	1122.6	This work
Eutectoid reaction	Th$_2$Al$_3$ ↔ ThAl$_2$ + ThAl	60	66.7	50	1100 ± 5	[20]
		60	66.7	50	1104.1	This work
Eutectoid reaction	Th$_3$Al$_2$ ↔ ThAl + Th$_2$Al	40	50	33.3	1075 ± 2	[20]
		40	50	33.3	1070.9	This work
Peritetic reaction	L + ThAl$_3$ ↔ Th$_2$Al$_7$	92.9	75	77.8	876 ± 8	[20]
		92.4	75	77.8	879.2	This work
Eutectic reaction	L ↔ (Al) + Th$_2$Al$_7$	97.1	0	77.8	630 ± 2	[20]
		97.3	0	77.8	628.4	This work
Congruent reaction	L ↔ Th$_2$Al		33.3		1307 ± 2	[20]
			33.3		1310	This work
Congruent reaction	L ↔ Th$_3$Al$_2$		40		1301 ± 2	[20]
			40		1300	This work
Congruent reaction	L ↔ ThAl$_2$		66.7		>1520	[20]
			66.7		1520	This work

estimated values by Kassner et al. [20] is smaller than 4 at.% Al. Since there is no enough experimental data on the liquidus, this calculated result is acceptable and can provide information for the further experiment. The calculated solid solubilities of Al in the βTh and αTh phases are respectively less than 1.5 at.% and 2 at.%, which are close to Murray's result [17].

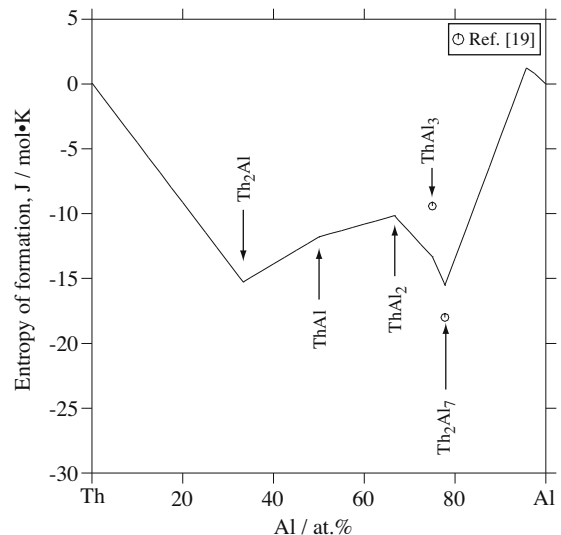The calculated enthalpy and entropy of formation in the whole compositional region at 1000 K based on the present assessed ther-modynamic parameters are shown in Figs. 4 and 5, which are in good agreement with the experimental data [19,21].

4.2. The Th–Zn system

The calculated phase diagram in the Th–Zn system with exper-imental data [26] is shown in Fig. 6. The calculated phase diagram
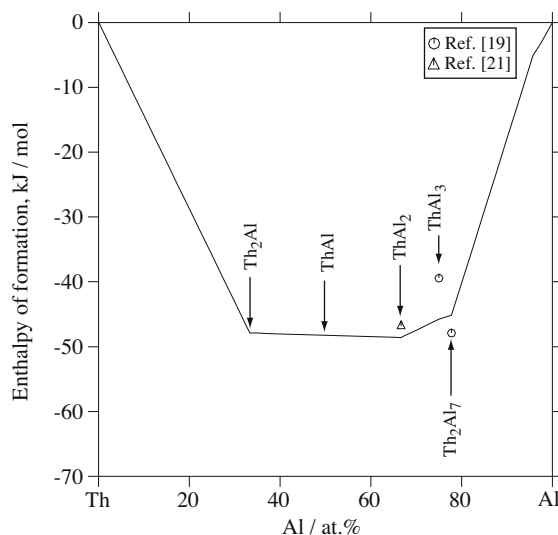
Fig. 4. The calculated enthalpy of formation at 1000 K in the Al–Th system compared with the experimental data [19,21]. (The reference states of pure elements of Th and Al are αTh and liquid phases, respectively.)

Fig. 5. The calculated entropy of formation at 1000 K in the Al–Th system compared with the experimental data [19]. (The reference states of pure elements of Th and Al are αTh and liquid phases, respectively.)
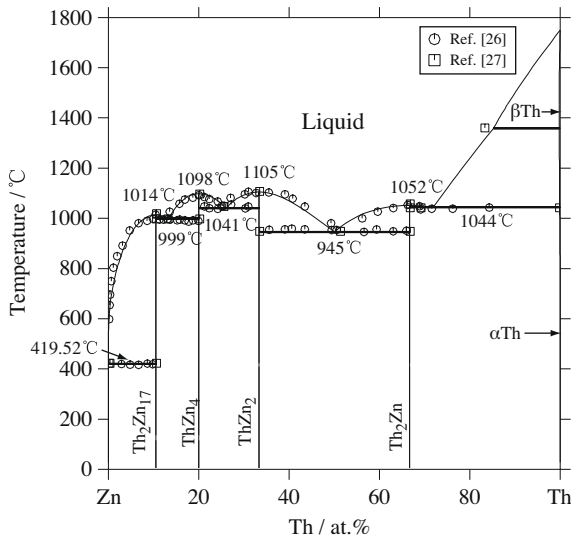
Fig. 6. The calculated phase diagram of the Th–Zn system with the experimental data [26,27].
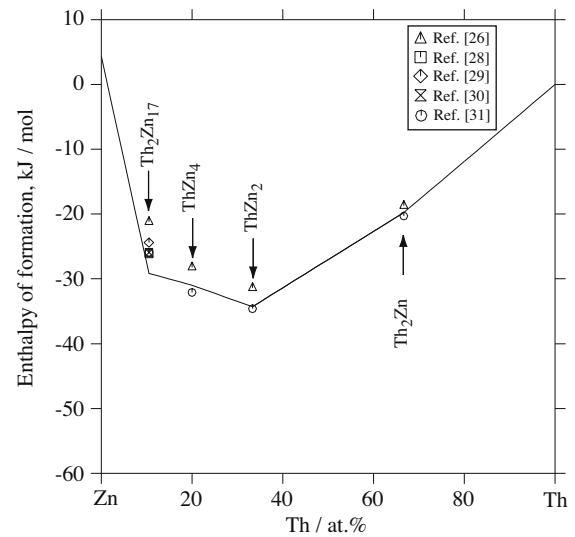

Fig. 7. The calculated enthalpy of formation at 700 K in the Th–Zn system compared with the experimental data [26,28–31]. (The reference states of pure elements of Th and Zn are αTh and hcp phases, respectively.)

Table 5
Experimental and calculated invariant reactions in the Th–Zn system.

Reaction type	Reaction	Th (at.%)			T (°C)	Reference
Catatectic reaction	βTh ↔ αTh + L	100	100	–	1360	[27]
		99.78	99.8	85.2	1358.5	This work
Eutectic reaction	L ↔ αTh + Th₂Zn	69.5	100	66.7	1040	[27]
		71.9	99.86	66.7	1044	This work
Eutectic reaction	L ↔ ThZn₂ + ThZn₄	25.6	33.3	20	1045	[27]
		26	33.3	20	1041	This work
Eutectic reaction	L ↔ ThZn₄ + Th₂Zn₁₇	13.2	20	10.5	995	[27]
		13.3	20	10.5	999	This work
Eutectic reaction	L ↔ Th₂Zn + ThZn₂	51.4	66.7	33.3	945	[27]
		50.1	66.7	33.3	945	This work
Eutectic reaction	L ↔ Th₂Zn₁₇ + (Zn)	0	10.5	0	419.58	[27]
		0	10.5	0	419.52	This work
Congruent reaction	L ↔ Th₂Zn		66.7		1055	[27]
			66.7		1052	This work
Congruent reaction	L ↔ ThZn₂		33.3		1105	[27]
			33.3		1105	This work
Congruent reaction	L ↔ ThZn₄		20		1095	[27]
			20		1098	This work
Congruent reaction	L ↔ Th₂Zn₁₇		10.5		1015	[27]
			10.5		1014	This work

Fig. 8. The calculated entropy of formation at 700 K in the Th–Zn system compared with the experimental data [26,28–31]. (The reference states of pure elements of Th and Zn are αTh and hcp phases, respectively.)

5. Conclusions

The phase diagrams and thermodynamic properties in the Al–Th and Th–Zn binary systems were evaluated from the available experimental information in literature. A consistent set of optimized thermodynamic parameters has been derived for describing the Gibbs free energy of each solution phase and intermetallic compounds in the Al–Th and Th–Zn binary systems. Most of experimental information can be satisfactorily reproduced on the basis of the optimized thermodynamic parameters.

is in agreement with most of the experimental results reported by Chiotti and Gill [26]. In the Th-rich region, a smaller solubility of Zn in the αTh and βTh phases was given in this work, and the liquidus in the Th-rich region was predicted according to the assessment of Chiotti and Gill [26]. These results can provide information for the further experiment. All the invariant equilibria in the Th–Zn system are listed in Table 5.

Figs. 7 and 8 show the calculated enthalpy and entropy of formation in the whole compositional region at 700 K based on the present assessed thermodynamic parameters with the experimental data [26,28–31], where the reference states of pure elements of Th and Zn are fcc and hcp phases, respectively. Good agreement is obtained between the present calculated results and experimental data [26,28–31].
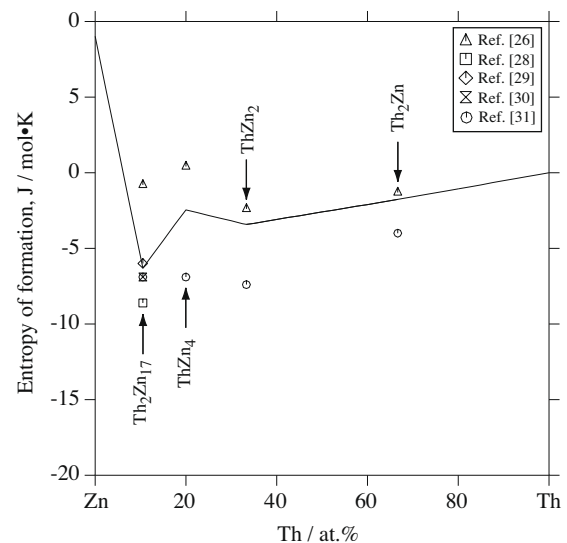
References

[1] D.J. Hill, Nat. Mater. 7 (2008) 680.
[2] R.W. Grimes, R.J.M. Konings, L. Edwards, Nat. Mater. 7 (2008) 683.
[3] C. Guéneau, S. Chatain, S. Gossé, C. Rado, O. Rapaud, J. Lechelle, J.C. Dumas, C. Chatillon, J. Nucl. Mater. 344 (2005) 191.
[4] J. Stephen Herring, P.E. MacDonald, K.D. Weaver, Nucl. Eng. Des. 203 (2001) 65.
[5] J. Wang, C.P. Wang, X.J. Liu, J. Nucl. Mater. 374 (1–2) (2008) 79.
[6] C.P. Wang, P. Yu, X.J. Liu, I. Ohnuma, R. Kainuma, K. Ishida, J. Alloys Compd. 457 (1–2) (2008) 150.
[7] J. Wang, X.J. Liu, C.P. Wang, J. Nucl. Mater. 380 (1–3) (2008) 105.
[8] X.J. Liu, Z.S. Li, J. Wang, C.P. Wang, J. Nucl. Mater. 380 (1–3) (2008) 99.
[9] C.P. Wang, Y.F. Li, X.J. Liu, K. Ishida, J. Alloys Compd. 458 (1–2) (2008) 208.
[10] Z.S. Li, X.J. Liu, C.P. Wang, J. Alloys Compd. 476 (1–2) (2009) 193.
[11] C.P. Wang, W. Fang, Z.S. Li, X.J. Liu, J. Nucl. Mater. 392 (3) (2009) 525.
[12] A.T. Dinsdale, Calphad 15 (1991) 317.
[13] O. Redlich, A.T. Kister, Ind. Eng. Chem. 40 (1948) 345.
[14] A. Leber, Z. Anorg, Chem. 166 (1927) 16.
[15] G. Grube, L. Botzenhardt, Z. Elektrochem. 48 (1942) 418.
[16] H.A. Saller, F.A. Rough, Compilation of US and UK Uranium and Thorium Constitutional Diagrams. USAEC Rept., BMI-1000, 1955.
[17] J.R. Murray, J. Inst. Met. 87 (1958) 349.
[18] G.H. Bannister, J.R. Thomson, J. Nucl. Mater. 12 (1964) 16.
[19] A.M. Poyarkov, V.A. Lebedev, I.F. Nichkov, S.P. Raspopin, Sov. Atom. Energy 35 (1973) 1138.
[20] M.E. Kassner, D.E. Peterson, Bull. Alloy Phase Diag. 10 (1989) 466.
[21] J.W. Wang, Q.T. Guo, O.J. Kleppa, J. Alloys Compd. 313 (2000) 148.
[22] E.S. Makarov, S.I. Vinogradov, Kristallografiia 1 (6) (1956) 634.
[23] E.S. Makarov, L. Gudkov, Kristallografiia 1 (6) (1956) 650.
[24] N.C. Baenziger, R.E. Rundle, A.L. Snow, Acta Cryst. 9 (1956) 93.
[25] M.V. Smimov, N.G. Ilyushchenko, S.P. Detkov, L.E. Ivanovskii, Zhur. Fiz. Khim. 31 (1957) 1013.
[26] P. Chiotti, K.J. Gill, Trans. AIME 221 (1961) 573.
[27] H. Okamoto, Desk Handbook-Phase Diagrams for Binary Alloys, ASM International, 2000.
[28] Yu.P. Kanashin, V.A. Lebedev, I.F. Nichkov, S.P. Raspopin, Izv. Akad. Nauk. SSSR, Met. 3 (1972) 46.
[29] P. Chiotti, M. Koizumi, Report IS-193 (Ames Laboratory, Ames, IA), 1960, p. 32.
[30] P. Chiotti, C.H. Dock, J. Less-Common Met. 41 (1975) 225.
[31] P. Chiotti, V.V. Akhachinskij, I. Ansara, The Chemical Thermodynamics Of Actinide Elements Compounds, part 5: The Actinide Binary Alloys, in: V. Medvedev, M.H. Rand, E.F. Westrum Jr., F.L. Oetting (Eds.), International Atomic Energy Agency, Vienna, 1981.
[32] J.O. Andersson, T. Helander, L. Höglund, P.F. Shi, B. Sundman, Calphad 26 (2002) 273.