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Chapter 17

Calorimetric Determination of Heat Capacity, Entropy and Enthalpy of Mixed Oxides in the System CaO–SrO–Bi$_2$O$_3$–Nb$_2$O$_5$–Ta$_2$O$_5$

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Additional information is available at the end of the chapter

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1. Introduction

Mixed oxides in the system CaO–SrO–Bi$_2$O$_3$–Nb$_2$O$_5$–Ta$_2$O$_5$ possess many extraordinary electric, magnetic and optical properties for which they are used in fabrication of various electronic components. For example Sr$_2$(Nb,Ta)$_2$O$_7$, Sr$_2$Ta$_2$O$_7$ and (Sr,Ca)Bi$_2$(Nb,Ta)$_2$O$_9$ are used for ferroelectric memory devices, CaNb$_2$O$_6$, Sr$_5$(Nb$_{1-x}$Ta$_x$)$_4$O$_{15}$ and Bi(Nb,Ta)O$_x$ for microwave dielectric resonators and Ca$_2$Nb$_2$O$_7$ as non-linear optical materials and hosts for rare-earth ions in solid-state lasers. Ternary strontium bismuth oxides SrBi$_2$O$_4$, Sr$_2$Bi$_2$O$_5$, and Sr$_6$Bi$_2$O$_9$ are of considerable interest due to a visible light driven photocatalytic activity.

To assess the thermodynamic stability and reactivity of these oxides under various conditions during their preparation, processing and operation, a complete set of consistent thermodynamic data, including heat capacity, entropy and enthalpy of formation, is necessary. Some of these data are available in literature. Akishige et al. [1] have been measured the heat capacities of Sr$_2$Nb$_2$O$_7$ and Sr$_2$Ta$_2$O$_7$ single crystals in the temperature range 2-600 K. The results have been only plotted and the values of $S^\circ_m$(298) have not been calculated. A commensurate transformation of Sr$_2$Nb$_2$O$_7$ at $T_{INC} = 495$ K has been observed accompanied by changes in enthalpy and entropy of $\Delta H = 291$ J mol$^{-1}$ and $\Delta S = 0.587$ J K$^{-1}$ mol$^{-1}$. The heat capacity of Sr$_2$Nb$_2$O$_7$ has been also measured by Shabbir et al. [2] in the temperature range 375-575 K. They have observed a phase transition at $T_{INC} = 487 \pm 2$ K connected with $\Delta H = 147 \pm 14$ J mol$^{-1}$ and $\Delta S = 0.71 \pm 0.10$ J K$^{-1}$ mol$^{-1}$. The heat capacities of polycrystalline and monocristalline SrBi$_2$Ta$_2$O$_9$ and Sr$_{0.85}$Bi$_{2.1}$Ta$_2$O$_9$ have been measured by Onodera et al. [3–5] at 80-800 K. Morimoto et al. [6] have reported the results of the heat capacity measurements of SrBi$_2$(Nb$_{1-x}$Ta$_x$)$_2$O$_9$ (x = 0, 1/3, 2/3 a 1). The temperature dependences of heat capacities show lambda-transitions with maxima at the Currie temperature $T_c = 570 \pm 1$ K, 585 $\pm 2$ K, 625 $\pm 3$ K a 690 $\pm 2$ K for x = 0, 1/3, 2/3 and 1,
respectively. Using EMF (electromotive force) measurements, Raghavan has obtained the values of the Gibbs energy of formation from binary oxides, $\Delta_{\text{ox}}G$, for some niobates [7,8] and tantalates [9,10] of calcium. His results are summarized in Table 1. The same technique has been employed by Dneprova et al. [11] for $\Delta_{\text{ox}}G$ measurement for CaNb$_2$O$_6$ and CaNb$_2$O$_7$. Their results presented in Table 1 are not significantly different from the results of Raghavan. Using the CALPHAD approach [13], Yang et al. [14] have assessed thermodynamic data for various mixed oxides in the SrO-Nb$_2$O$_5$ system. The same approach has been used by Hallstedt et al. for the assessment of thermodynamic data of mixed oxides in the systems CaO–Bi$_2$O$_3$ [14] and SrO–Bi$_2$O$_3$ [15]. Besides equilibrium data, values of the enthalpy of formation [16] of mixed oxide have been considered. Later on, these systems have been studied by EMF method by Jacob and Jayadevan [17,18] and temperature dependences of $\Delta_{\text{ox}}G$ for various mixed oxides have been derived. These data have been included into the thermodynamic re-assessment of the CaO-SrO-Bi$_2$O$_3$ system [19].

<table>
<thead>
<tr>
<th>Oxide</th>
<th>$\Delta_{\text{ox}}G$ (kJ mol$^{-1}$)</th>
<th>$T$ (K)</th>
<th>$\Delta_{\text{ox}}H$ (kJ mol$^{-1}$)</th>
<th>$\Delta_{\text{ox}}S$ (J K$^{-1}$ mol$^{-1}$)</th>
<th>Ref.</th>
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<td>–1125.69</td>
<td>–350.69</td>
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</tr>
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<td>–58.65</td>
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</tr>
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<td>–118.75</td>
<td>–24.0</td>
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</tr>
<tr>
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<td>–109.60</td>
<td>–2.4</td>
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Table 1. Published values of $\Delta_{\text{ox}}G$, $\Delta_{\text{ox}}H$ and $\Delta_{\text{ox}}S$ for some mixed oxides in the system CaO-SrO-Bi$_2$O$_3$-Nb$_2$O$_5$-Ta$_2$O$_5$. 

Applications of Calorimetry in a Wide Context – Differential Scanning Calorimetry, Isothermal Titration Calorimetry and Microcalorimetry
This review brings a summary of our results [20–30] focused on calorimetric determination of heat capacity, entropy and enthalpy of mixed oxides in the system CaO–SrO–Bi_2O_3–Nb_2O_5–Ta_2O_5. Temperature dependences of molar heat capacity in a broad temperature range were evaluated from the experimental heat capacity and relative enthalpy data. Molar entropies at T = 298.15 K were calculated from low temperature heat capacity measurements. Furthermore, the results of calorimetric measurements of the enthalpies of drop-solution in a sodium oxide-molybdenum oxide melt for several stoichiometric mixed oxides in the above mentioned system are reported from which the values of enthalpy of formation from constituent binary oxides were derived. Finally, some empirical estimation and correlation methods (the Neumann-Kopp’s rule, entropy-volume correlation and electronegativity-differences method) for evaluation of thermodynamic data of mixed oxides are tested and assessed.

2. Experimental

Nineteen mixed oxides in the system CaO–SrO–Bi_2O_3–Nb_2O_5–Ta_2O_5 with stoichiometry CaBi_2O_4, Ca_4Bi_6O_13, Ca_2Bi_2O_5, SrBi_2O_4, Sr_2Bi_2O_5, CaNb_2O_6, Ca_2Nb_2O_7, SrNb_2O_7, Sr_2NbO_15, BiNbO_4, BiNb_2O_14, BiTaO_3, BiTa_3O_9, BiTa_2O_7, SrBiNbO_9 and SrBiTaO_9 were prepared, characterized and examined. The samples were prepared by conventional solid state reactions from high purity precursors (CaCO_3, SrCO_3, Bi_2O_3, Nb_2O_5 and Ta_2O_5). A three step procedure was used consisting of an initial calcination run of mixed powder precursors and subsequent double firing of prereacted mixtures pressed into pellets. The phase composition of the prepared samples was checked by X-ray powder diffraction (XRD). XRD data were collected at room temperature with an X’Pert PRO (PANalytical, the Netherlands) θ-θ powder diffractometer with parafocusing Bragg-Brentano geometry using CuKα radiation (λ = 1.5418 nm). Data were scanned over the angular range 5–60° (2θ) with an increment of 0.02° (2θ) and a counting time of 0.3 s step⁻¹.

Data evaluation was performed by means of the HighScore Plus software.

The PPMS equipment 14 T-type (Quantum Design, USA) was used for the heat capacity measurements in the low temperature region [31-35]. The measurements were performed by the relaxation method [36] with fully automatic procedure under high vacuum (pressure ~10⁻² Pa) to avoid heat loss through the exchange gas. The samples were compressed powder pellets. The densities of the samples were about 65 % of the theoretical ones.

The samples were mounted to the calorimeter platform with cryogenic grease Apiezon N (supplied by Quantum Design). The procedure was as follows: First, a blank sample holder with the Apiezon only was measured in the temperature range approx. 2–280 K to obtain background data, then the sample plate was attached to the calorimeter platform and the measurement was repeated in the same temperature range with the same temperature steps. The sample heat capacity was then obtained as a difference between the two data sets. The sample was applied, because the heat capacity of Apiezon is not negligible in comparison with the sample heat capacity (~8 % at room temperature) and exhibits a peak-shaped transition below room temperature [37]. The manufacturer claims the precision of this
measurement better than 2 % [38]; the control measurement of the copper sample (99.999 % purity) confirmed this precision in the temperature range 50–250 K. However, the precision of the measurement strongly depends on the thermal coupling between the sample and the calorimeter platform. Due to unavoidable porosity of the sample plate this coupling is rapidly getting worse as the temperature raises above 270 K and Apiezon diffuses into the porous sample. Consequently, the uncertainty of the obtained data tends to be larger.

A Micro DSC III calorimeter (Setaram, France) was used for the heat capacity determination in the temperature range of 253–352 K. First, the samples were preheated in a continuous mode from room temperature up to 352 K (heating rate 0.5 K min\(^{-1}\)). Then the heat capacity was measured in the incremental temperature scanning mode consisting of a number of 5–10 K steps (heating rate 0.2 K min\(^{-1}\)) followed by isothermal delays of 9000 s. Two subsequent step-by-step heating were recorded for each sample. Synthetic sapphire, NIST Standard reference material No. 720, was used as the reference. The uncertainty of heat capacity measurements is estimated to be better than ±1 %.

Enthalpy increment determinations were carried out by drop method using high-temperature calorimeter, Multi HTC 96 (Setaram, France). All measurements were performed in air by alternating dropping of the reference material (small pieces of synthetic sapphire, NIST Standard reference material No. 720) and of the sample (pressed pellets 5 mm in diameter) being initially held at room temperature, through a lock into the working cell of the preheated calorimeter. Endothermic effects are detected and the relevant peak area is proportional to the heat content of the dropped specimen. The delays between two subsequent drops were 25–30 min. To check the accuracy of measurement, the enthalpy increments of platinum in the temperature range 770–1370 K were measured first and compared with published reference values [39]. The standard deviation of 22 runs was 0.47 kJ mol\(^{-1}\), the average relative error was 2.0 %. Estimated overall accuracy of the drop measurements is ±3 %.

The heats of drop-solution were determined using a Multi HTC 96 high-temperature calorimeter (Setaram, France). A sodium oxide-molybdenum oxide melt of the stoichiometry \(3\text{Na}_2\text{O} + 4\text{MoO}_3\) was used as the solvent. The ratio of solute/solvent varied from 1/250 up to 1/500. The measurements were performed at temperatures of 973 and 1073 K in argon or air atmosphere. The method consists in alternating dropping of the reference material (small spherules of pure platinum) and of the sample (small pieces of pressed tablets 10–40 mg), being initially held near room temperature \(T_0\), through a lock into the working cell (a platinum crucible with the solvent) of the preheated calorimeter at temperature \(T\). Two or three samples were examined during one experimental run. The delays between two subsequent drops were 30–60 min. The total heat effect \(\Delta H\) includes the heat of solution \(\Delta_{\text{sol}}H\), the heat content of the sample \(\Delta T\), and, for the carbonates, the heat of decomposition \(\Delta_{\text{decomp}}H\) to form solid CaO or SrO and gaseous CO\(_2\). Using appropriate thermochemical cycles, the values of the enthalpy of formation of mixed oxides from the binary oxides and from the elements at 298 K were evaluated. The temperature dependence of the heat capacity of platinum [39] was used for the calculation of the sensitivity of the calorimeters.
2.1. Characterization of prepared samples

The XRD analysis revealed that the prepared samples were without any observable diffraction lines from unreacted precursors or other phases. The lattice parameters of the oxides were evaluated by Rietveld refinement [40] and are summarized in Table 2 together with the values of theoretical density calculated from the lattice parameters.

2.2. Evaluation of temperature dependence of heat capacity at low temperatures

The fit of the low-temperature heat capacity data (LT fit) consists of two steps. Assuming the validity of the phenomenological formula $C_m = \beta T^3 + \gamma_{el} T$, at $T \to 0$ where $\beta$ is proportional to the inverse cube root of the Debye temperature $\Theta_D$ and $\gamma_{el} T$ is the Sommerfeld term, we plotted the $C_m/T$ vs. $T^2$ dependence for $T < 8$ K to estimate the $\Theta_D$ and $\gamma_{el}$ values. Since all compounds under study are semiconductors with a sufficiently large band gap, the non-zero $\gamma_{el}$ values are supposed to be either due to some metallic impurities or to a series of Schottky-like transitions resulting from structure defects. Nevertheless, they are negligible in most cases (typically < 0.5 mJ K$^{-2}$ mol$^{-1}$) and can be ignored in further analysis. As an example, the results of heat capacity measurements on CaNb$_2$O$_6$ and LT fit for $T < 10$ K is shown in Fig. 1.

<table>
<thead>
<tr>
<th>Oxide</th>
<th>a (nm)</th>
<th>b (nm)</th>
<th>c (nm)</th>
<th>α (°)</th>
<th>β (°)</th>
<th>γ (°)</th>
<th>d (g cm$^{-3}$)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
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<td>1.39915</td>
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<td>134.03</td>
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<td>6.631</td>
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<td>1.73512</td>
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<td>90</td>
<td>90</td>
<td>6.540</td>
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</tr>
<tr>
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<td>1.01249</td>
<td>1.04618</td>
<td>116.88</td>
<td>107.16</td>
<td>92.98</td>
<td>6.468</td>
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<td>95.50</td>
<td>90</td>
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<td>0.56576</td>
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<td>0.54711</td>
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<td>90</td>
<td>90</td>
<td>8.801</td>
<td>[22]</td>
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</table>

*Quoted according to JCPDS 035-1220.

b) Quoted according to JCPDS 048-0986

Table 2. Structural characterization of prepared samples
In the second step of the LT fit, both sets of the $C_{pm}$ data (relaxation time + DSC) were considered. Analysis of the phonon heat capacity was performed as an additive combination of Debye and Einstein models. Both models include corrections for anharmonicity, which is responsible for a small, but not negligible, additive term at higher temperatures and which accounts for the difference between isobaric and isochoric heat capacity. According to literature [41], the term $1/(1 - \alpha T)$ is considered as a correction factor.

The acoustic part of the phonon heat capacity is described using the Debye model

$$C_{phD} = \frac{9R}{1 - \alpha_D T} \left( \frac{T}{\Theta_D} \int_0^{\Theta_D} x^4 \exp(x) \frac{1}{\exp(x) - 1} dx \right)^3$$

where $R$ is the gas constant, $\Theta_D$ is the Debye characteristic temperature, $\alpha_D$ is the coefficient of anharmonicity of acoustic branches and $x_D = \Theta_D / T$. Here the three acoustic branches are taken as one triply degenerate branch. Similarly, the individual optical branches are described by the Einstein model

$$C_{phE} = \frac{R}{1 - \alpha_E T} \left( \int_0^{\Theta_E} x^3 \exp(x) \frac{1}{\exp(x) - 1} dx \right)^3$$

where $\alpha_E$ and $x_E = \Theta_E / T$ have analogous meanings as in the previous case. Several optical branches are again grouped into one degenerate multiple branch with the same Einstein characteristic temperature and anharmonicity coefficient. The phonon heat capacity then reads

![Figure 1. Temperature dependence of $C_{pm}/T$ function for CaNb$_2$O$_7$ at low temperatures](image)
Calorimetric Determination of Heat Capacity, Entropy and Enthalpy of Mixed Oxides in the System CaO–SrO–Bi₂O₃–Nb₂O₅–Ta₂O₅

\[ C_{ph} = C_{phD} + \sum_{i=1}^{3} C_{phE_i} \] (3)

All the estimated values were further treated by a simplex routine and a full non-linear fit was performed on all adjustable parameters.

The values of relative enthalpies at 298.15 K, \( H_m(298) - H_m(0) \), were evaluated from the low-temperature \( C_p \) data (LT fit) by numerical integration of the \( C_p(T) \) dependences from zero to 298.15 K. Standard deviations (2σ) were calculated using the error propagation law.

The values of standard molar entropies at 298.15 K, \( S_m(298) \), were derived from the low-temperature \( C_p \) data (LT fit) by numerical integration of the \( C_p(T)/T \) dependences from zero to 298.15 K. A numerical integration was used with the boundary conditions \( S_m = 0 \) and \( C_p = 0 \) at \( T = 0 \) K. Standard deviations (2σ) were calculated using the error propagation law.

All calculated values are summarized in Table 3.

<table>
<thead>
<tr>
<th>Oxide</th>
<th>( C_p(298) ) (J K(^{-1}) mol(^{-1}))</th>
<th>( H_m(298) - H_m(0) ) (J mol(^{-1}))</th>
<th>( S_m(298) ) (J K(^{-1}) mol(^{-1}))</th>
<th>( \Delta mS ) (J K(^{-1}) mol(^{-1}))</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaBi₂O₄</td>
<td>151.3</td>
<td>26470 ± 158</td>
<td>188.5 ± 3.3</td>
<td>1.9</td>
<td>[20]</td>
</tr>
<tr>
<td>CaBi₂O₃</td>
<td>504.1</td>
<td>85079 ± 507</td>
<td>574.1 ± 8.8</td>
<td>–23.8</td>
<td>[20]</td>
</tr>
<tr>
<td>CaBi₂O₅</td>
<td>197.4</td>
<td>33735 ± 201</td>
<td>231.3 ± 2.9</td>
<td>6.6</td>
<td>[20]</td>
</tr>
<tr>
<td>SrBi₂O₅</td>
<td>155.6</td>
<td>29601 ± 169</td>
<td>206.1 ± 1.1</td>
<td>4.0</td>
<td>[29]</td>
</tr>
<tr>
<td>SrBi₂O₇</td>
<td>201.9</td>
<td>38199 ± 219</td>
<td>261.2 ± 1.4</td>
<td>5.5</td>
<td>[29]</td>
</tr>
<tr>
<td>CaNb₂O₆</td>
<td>171.8</td>
<td>28159 ± 170</td>
<td>167.3 ± 0.9</td>
<td>–8.1</td>
<td>[26]</td>
</tr>
<tr>
<td>CaNb₂O₇</td>
<td>218.1</td>
<td>35631 ± 215</td>
<td>212.4 ± 1.2</td>
<td>–1.1</td>
<td>[26]</td>
</tr>
<tr>
<td>SrNb₂O₆</td>
<td>170.2</td>
<td>28722 ± 174</td>
<td>173.9 ± 0.9</td>
<td>–17.0</td>
<td>[24]</td>
</tr>
<tr>
<td>SrNb₂O₇</td>
<td>216.6</td>
<td>37977 ± 266</td>
<td>238.5 ± 1.3</td>
<td>–5.9</td>
<td>[26]</td>
</tr>
<tr>
<td>SrNb₂O₉</td>
<td>746.8</td>
<td>124150 ± 740</td>
<td>759.7 ± 4.1</td>
<td>–33.9</td>
<td>[27]</td>
</tr>
<tr>
<td>SrNb₂O₁₁</td>
<td>477.2</td>
<td>83340 ± 490</td>
<td>524.5 ± 2.8</td>
<td>–18.4</td>
<td>[27]</td>
</tr>
<tr>
<td>BiNbO₄</td>
<td>121.3</td>
<td>22120 ± 134</td>
<td>147.9 ± 0.8</td>
<td>5.0</td>
<td>[21]</td>
</tr>
<tr>
<td>BiNbO₄</td>
<td>386.8</td>
<td>62639 ± 362</td>
<td>397.2 ± 2.1</td>
<td>–25.8</td>
<td>[23]</td>
</tr>
<tr>
<td>BiTaO₄</td>
<td>119.3</td>
<td>22021 ± 132</td>
<td>149.1 ± 0.8</td>
<td>3.3</td>
<td>[21]</td>
</tr>
<tr>
<td>BiTaO₄</td>
<td>363.2</td>
<td>66566 ± 384</td>
<td>449.6 ± 2.3</td>
<td>9.5</td>
<td>[28]</td>
</tr>
<tr>
<td>BiTaO₈</td>
<td>602.7</td>
<td>109760 ± 634</td>
<td>743.0 ± 3.8</td>
<td>8.6</td>
<td>[28]</td>
</tr>
<tr>
<td>BiTaO₉</td>
<td>235.2</td>
<td>44265 ± 254</td>
<td>304.3 ± 1.6</td>
<td>10.0</td>
<td>[28]</td>
</tr>
<tr>
<td>SrBi₂Nb₂O₅</td>
<td>286.4</td>
<td>49230 ± 292</td>
<td>327.2 ± 1.7</td>
<td>–12.2</td>
<td>[22]</td>
</tr>
<tr>
<td>SrBi₂TaO₅</td>
<td>286.6</td>
<td>49060 ± 289</td>
<td>339.2 ± 1.8</td>
<td>–5.9</td>
<td>[22]</td>
</tr>
</tbody>
</table>

Table 3. Heat capacity, relative enthalpy, entropy and entropy of formation from binary oxides at temperature 298.15 K of various mixed oxides in the system CaO–SrO–Bi₂O₃–Nb₂O₅–Ta₂O₅.
A comparison is given in Table 4 of the values of entropy of formation from binary oxides $\Delta_{ox}S$ at 298 K calculated from our results and those from literature. The values of $\Delta_{ox}S$ are calculated using the relation

$$\Delta_{ox}S = S_m(MO) - \sum_i b_i S_m(BO_i)$$

(4)

where $S_m(MO)$ and $S_m(BO_i)$ stand for the molar entropies of a mixed oxide and a binary oxide $i$, respectively, and $b_i$ is a constitution coefficient representing the number of formula units of a binary oxide $i$ per formula unit of the mixed oxide. The following values were used for calculation:

- $S_m(CaO,298.15 K) = 38.1 \text{ J K}^{-1} \text{ mol}^{-1}$ [42],
- $S_m(SrO,298.15 K) = 53.58 \text{ J K}^{-1} \text{ mol}^{-1}$ [43],
- $S_m(Bi_2O_3,298.15 K) = 148.5 \text{ J K}^{-1} \text{ mol}^{-1}$ [44],
- $S_m(Nb_2O_5,298.15) = 137.30 \text{ J K}^{-1} \text{ mol}^{-1}$ [45],
- $S_m(Ta_2O_5,298.15) = 143.09 \text{ J K}^{-1} \text{ mol}^{-1}$ [45].

Furthermore, $S_m(Sr_2Nb_2O_7,298.15) = 238.5 \text{ J K}^{-1} \text{ mol}^{-1}$ from this work can be directly compared with the value 232.37 J K$^{-1}$ mol$^{-1}$ obtained by numeric integration of the $C_p(T)/T$ dependences from zero to 298.15 K given in Ref. [1]. It should be noted that the values of entropy assessed by thermodynamic optimization of phase equilibrium data are generally considered as less reliable as the values derived from low temperature heat capacity measurements. It is due to possible strong correlation between the enthalpy and entropy contributions to the Gibbs energy. So the obvious discrepancies between our values and data from assessments [12,19] could be explain in this way.

<table>
<thead>
<tr>
<th>Oxide</th>
<th>$\Delta_{ox}S$ a) (J K$^{-1}$ mol$^{-1}$)</th>
<th>$\Delta_{ox}S$ (J K$^{-1}$ mol$^{-1}$)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaNb$_2$O$_6$</td>
<td>$-8.1$</td>
<td>33.45</td>
<td>[7]</td>
</tr>
<tr>
<td>CaNb$_2$O$_7$</td>
<td>$-1.1$</td>
<td>22.18</td>
<td>[11]</td>
</tr>
<tr>
<td>SrNb$_2$O$_7$</td>
<td>$-34.0$</td>
<td>$-350.69$</td>
<td>[12]</td>
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<tr>
<td>SrNb$_2$O$_6$</td>
<td>$-17.0$</td>
<td>$-58.65$</td>
<td>[12]</td>
</tr>
<tr>
<td>SrNb$_2$O$_7$</td>
<td>$-6.0$</td>
<td>$-39.93$</td>
<td>[12]</td>
</tr>
<tr>
<td>SrNb$_2$O$_7$</td>
<td>$-18.0$</td>
<td>$-51.01$</td>
<td>[12]</td>
</tr>
<tr>
<td>CaBi$_2$O$_6$</td>
<td>$1.9$</td>
<td>3.0</td>
<td>[19]</td>
</tr>
<tr>
<td>CaBi$_2$O$_7$</td>
<td>$-23.8$</td>
<td>8.0</td>
<td>[19]</td>
</tr>
<tr>
<td>CaBi$_2$O$_6$</td>
<td>$6.6$</td>
<td>3.0</td>
<td>[19]</td>
</tr>
<tr>
<td>SrBi$_2$O$_5$</td>
<td>$4.0$</td>
<td>1.8</td>
<td>[19]</td>
</tr>
<tr>
<td>SrBi$_2$O$_5$</td>
<td>$5.5$</td>
<td>$-24.0$</td>
<td>[19]</td>
</tr>
</tbody>
</table>

a) This work

Table 4. The values of entropy of formation from binary oxides at 298.15 K: a comparison of our results and data from literature

It should be noted that the thorough analysis of the Debye and Einstein contributions to the heat capacities reveals that the different vibrational modes contribute to the total values of $\Delta_{ox}S$ to a different extent and partial compensation is possible in some cases.
2.3. Evaluation of heat capacity at temperatures above 298 K

For the assessment of temperature dependences of $C_p$ above room temperature, the heat capacity data from DSC and the enthalpy increment data from drop calorimetry were treated simultaneously by the linear least-squares method (HT fit). The temperature dependence of $C_p$ was considered in the form

$$C_p = A + BT + C/T^2$$

(5)

thus the related temperature dependence of $\Delta H_m(T) = H_m(T) - H_m(T_0)$ is given by equation

$$\Delta H_m(T) = H_m(T) - H_m(T_0) = \int_T^{T_0} C_p \, dT = A(T - T_0) + B(T^2 - T_0^2)/2 - C(1/T - 1/T_0)$$

(6)

The sum of squares which is minimized has the following form

$$F = \sum_{i=1}^{N(C)} w_i \left[ C_{p,m,i} - A - BT_i - C/T_i^2 \right]^2 + \sum_{j=1}^{N(\Delta H)} w_j \left[ \Delta H_{m,j} - A(T_j - T_0,j) - B(T_j^2 - T_0,j^2)/2 - C(1/T_j - 1/T_0,j) \right]^2 \to \text{min}$$

(7)

where the first sum runs over the $C_p$ experimental points while the second sum runs over the $\Delta H_m$ experimental points. Different weights $w_i$ ($w_j$) were assigned to individual points calculated as $w_i = 1/\delta_i$ ($w_j = 1/\delta_j$) where $\delta_i$ ($\delta_j$) is the absolute deviation of the measurement estimated from overall accuracies of measurements (1 % for DSC and 3 % for drop calorimetry). Both types of experimental data thus gain comparable significance during the regression analysis. To smoothly connect the LT fit and HT fit data the values of $C_p(298.15)$ from LT fit were used as constraints and so Eq. (7) is modified

$$F_{\text{const}} = F - \lambda \left[ C_p(298.15) - A - 298.15B - C/298.15^2 \right] \to \text{min}$$

(8)

The numerical values of parameters $A$, $B$ and $C$ are now obtained by solving a set of equations deduced as derivatives of $F_{\text{const}}$ with respect of these parameters and a multiplier $\lambda$ which are equal to zero at the minimum of $F_{\text{const}}$. Assessed values of parameters $A$, $B$ and $C$ of Eq. (4) for mixed oxides are presented in Table 5.

As an example, the results of heat capacity measurements and relative enthalpy measurements on Bi$_7$Ta$_3$O$_{18}$ [28] are shown in Fig. 2. Empirical estimation according to the Neumann-Kopp’s rule (NKR) is also plotted for comparison.

The empirical Neumann-Kopp’s rule (NKR) is frequently used for estimation of unknown values of the heat capacity of mixed oxides [46–48]. According to NKR, heat capacity of a mixed oxide is calculated as a sum of heat capacities of the constituent binary ones

$$C_p(MO) = \sum_i b_i C_p(BO,i)$$

(9)
It was concluded [47,48] that NKR predicts the heat capacities of mixed oxides remarkably well around room temperature but the deviations (mostly positive) from NKR become substantial at higher temperatures. Mean relative error of the estimated values of $C_p(298.15 \text{ K})$ is 1.4 %. Calculated temperature dependences of $\Delta_{\text{ox}}C_p = C_{\text{pm}}(\text{MO}) - \sum b_i C_{\text{pm}}(\text{BO},i)$ for various mixed oxides in the systems CaO–Nb$_2$O$_5$, SrO–Nb$_2$O$_5$, and BiO–Ta$_2$O$_5$ are shown in Fig. 3.

$$C_{\text{pm}} = A + B \cdot T + C/T^2 \text{ (J K}^{-1} \text{ mol}^{-1})$$

<table>
<thead>
<tr>
<th>Oxide</th>
<th>$\Delta_{\text{ox}}C_p$</th>
<th>Temperature range (K)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaBi$_2$O$_4$</td>
<td>157.161</td>
<td>38.750</td>
<td>$-1.546$</td>
</tr>
<tr>
<td>CaBi$_2$O$_3$</td>
<td>550.808</td>
<td>114.890</td>
<td>$-7.201$</td>
</tr>
<tr>
<td>CaBi$_2$O$_5$</td>
<td>226.096</td>
<td>33.374</td>
<td>$-3.432$</td>
</tr>
<tr>
<td>SrBi$_2$O$_4$</td>
<td>161.97</td>
<td>45.936</td>
<td>$-1.7832$</td>
</tr>
<tr>
<td>SrBi$_2$O$_5$</td>
<td>197.48</td>
<td>87.463</td>
<td>$-1.9282$</td>
</tr>
<tr>
<td>CaNb$_2$O$_5$</td>
<td>200.40</td>
<td>34.32</td>
<td>$-3.45$</td>
</tr>
<tr>
<td>Ca$_2$Nb$_2$O$_7$</td>
<td>257.20</td>
<td>36.21</td>
<td>$-4.435$</td>
</tr>
<tr>
<td>SrNb$_2$O$_5$</td>
<td>200.47</td>
<td>29.37</td>
<td>$-3.473$</td>
</tr>
<tr>
<td>Sr$_2$Nb$_2$O$_7$</td>
<td>248.00</td>
<td>43.50</td>
<td>$-3.948$</td>
</tr>
<tr>
<td>Sr$_2$Bi$_2$O$_4$</td>
<td>835.351</td>
<td>227.648</td>
<td>$-13.904$</td>
</tr>
<tr>
<td>Sr$_2$Bi$_2$O$_5$</td>
<td>504.796</td>
<td>147.981</td>
<td>$-6.376$</td>
</tr>
<tr>
<td>BiNb$_2$O$_5$</td>
<td>128.628</td>
<td>33.400</td>
<td>$-1.991$</td>
</tr>
<tr>
<td>BiNb$_5$O$_14$</td>
<td>455.840</td>
<td>60.160</td>
<td>$-7.734$</td>
</tr>
<tr>
<td>BiTa$_2$O$_5$</td>
<td>133.594</td>
<td>25.390</td>
<td>$-2.734$</td>
</tr>
<tr>
<td>Bi$_3$TaO$_7$</td>
<td>445.8</td>
<td>5.451</td>
<td>$-7.489$</td>
</tr>
<tr>
<td>Bi$_5$Ta$<em>3$O$</em>{11}$</td>
<td>699.0</td>
<td>52.762</td>
<td>$-9.956$</td>
</tr>
<tr>
<td>Bi$_2$TaO$_7$</td>
<td>251.6</td>
<td>67.05</td>
<td>$-3.237$</td>
</tr>
<tr>
<td>SrBi$_2$Nb$_2$O$_7$</td>
<td>324.470</td>
<td>63.710</td>
<td>$-5.076$</td>
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<tr>
<td>SrBi$_2$TaO$_6$</td>
<td>320.220</td>
<td>64.510</td>
<td>$-4.700$</td>
</tr>
</tbody>
</table>

*An extra term $1.363 \times 10^8/T^3$ was added.

*An extra term $2.360 \times 10^8/T^3$ was added.

Table 5. Parameters of temperature dependence of molar heat capacities of various mixed oxides in the system CaO–SrO–BiO–NbO–TaO.
Calorimetric Determination of Heat Capacity, Entropy and Enthalpy of Mixed Oxides in the System CaO–SrO–Bi₂O₃–Nb₂O₅–Ta₂O₅

Figure 2. Temperature dependence of heat capacity (a) and relative enthalpy (b) of BiTaO₆ (3NR means the Dulong-Petit limit).
2.4. Evaluation of enthalpy of formation

The heats of drop-solution for the calcium and strontium carbonates and for the bismuth and niobium oxides were measured first. These data are necessary for the evaluation of the $\Delta_{ds}H$ values for the mixed oxides, and furthermore, these data could be compared with the literature data [49–52]. For the AECO₃ carbonates, the measured heat effect consists of three contributions:

$$
\Delta_{ds}H(\text{AECO}_3, T) = \Delta_T H(\text{AECO}_3, T_0 \to T) + \Delta_{\text{decomp}} H(\text{AECO}_3, T) + \Delta_{\text{sol}} H(\text{AEO}, T)
$$

(10)

The measurements were performed at 973 K. The values of $\Delta_{ds}H(\text{AECO}_3, 973 K)$ are given in Table 6 along with the values of $\Delta_{ds}H(\text{AEO}, 973 K)$, which were derived based on the following thermochemical cycle ($T_0 \approx 298 K$):

$$
\text{AECO}_3(s, T_0) \to \text{AEO}(\text{melt}, T) + \text{CO}_2(g, T), \quad \Delta_{ds}H(\text{AECO}_3)
$$

(11)

$$
\text{AECO}_3(s, T_0) \to \text{AEO}(s, T_0) + \text{CO}_2(g, T), \quad \Delta_{\text{decomp}} H(\text{AECO}_3)
$$

(12)

$$
\text{CO}_2(g, T_0) \to \text{CO}_2(g, T), \quad \Delta_T H(\text{CO}_2)
$$

(13)

$$
\text{AEO}(s, T_0) \to \text{AEO}(\text{melt}, T), \quad \Delta_{ds}H(\text{AEO})
$$

(14)

$$
\Delta_{ds}H(\text{AEO}) = \Delta_{ds}H(\text{AECO}_3) - \Delta_{\text{decomp}} H(\text{AECO}_3) - \Delta_T H(\text{CO}_2)
$$

(15)

The values $\Delta_{\text{decomp}} H(\text{CaCO}_3, 298 K) = 178.8 \text{ kJ mol}^{-1}$, $\Delta_{\text{decomp}} H(\text{SrCO}_3, 298 K) = 233.9 \text{ kJ mol}^{-1}$ and $\Delta_T H(\text{CO}_2, 298 \to 973 K) = 32.0 \text{ kJ mol}^{-1}$ [53] were used for the calculations.

Next, the $\Delta_{ds}H$ values of the binary oxides Bi₂O₃ and Nb₂O₅ were measured. Because the dissolution of Nb₂O₅ and of the mixed oxides at 973 K proceeds rather slowly, the higher temperature of 1073 K was used. The measured values $\Delta_{ds}H$ are also given in Table 6.

The experimental values of $\Delta_{ds}H$ for SrCO₃ and CaCO₃ are in quite good agreement with the literature data [49–51]. On the other hand, our results and the published [52] values of $\Delta_{ds}H(\text{NbO}_2)$ are quite different. It should be noted that a more endothermic value $\Delta_{\text{decomp}} H(\text{SrCO}_3, 298 K) = 249.4 \text{ kJ mol}^{-1}$ is presented in the literature [45], which results in a more exothermic value for $\Delta_{ds}H(\text{SrO})$ by 15.5 kJ mol⁻¹.

$\Delta_{ds}H$ for the mixed oxides was measured at 1073 K. The following thermochemical cycle was used for the calculation of $\Delta_{ds}H$ for calcium and strontium niobates ($T_0 \approx 298 K$):

$$
\text{AE}_x\text{Nb}_2\text{O}_{5+x}(s, T_0) \to x\text{AEO}(\text{melt}, T) + \text{Nb}_2\text{O}_5(\text{melt}, T), \quad \Delta_{ds}H(\text{AEO})
$$

(16)

$$
\text{AEO}(s, T_0) \to \text{AEO}(\text{melt}, T), \quad \Delta_{ds}H(\text{AEO})
$$

(17)

$$
\text{Nb}_2\text{O}_5(s, T_0) \to \text{Nb}_2\text{O}_5(\text{melt}, T), \quad \Delta_{ds}H(\text{Nb}_2\text{O}_5)
$$

(18)

$$
\Delta_{ox}H(\text{AE}_x\text{Nb}_2\text{O}_{5+x})
$$

(19)
Calorimetric Determination of Heat Capacity, Entropy and Enthalpy of Mixed Oxides in the System CaO–SrO–Bi$_2$O$_3$–Nb$_2$O$_5$–Ta$_2$O$_5$

Figure 3. Temperature dependences of $\Delta_{\text{ox}}C_p$ for various mixed oxides in the systems CaO–Nb$_2$O$_5$, and SrO–Nb$_2$O$_5$ (a) and Bi$_2$O$_3$–Ta$_2$O$_5$ (b)
An analogous scheme was applied to calculate $\Delta^{\text{ox}}_{\text{H}}$(BiNbO$_4$). All of the experimental and calculated values are summarized in Table 7. The $\Delta^{\text{ox}}_{\text{H}}$(298 K) values derived from high-temperature EMN measurements [7,8,11] for the CaO-Nb$_2$O$_5$ oxides and the assessed values from the phase diagram for the SrO-Nb$_2$O$_5$ oxides [12] are also presented in Table 7.

![Table 6](image)

<table>
<thead>
<tr>
<th>Substance</th>
<th>$T$ (K)</th>
<th>$\Delta^{\text{ds}}_{\text{H}}$ (kJ mol$^{-1}$)</th>
<th>$\Delta^{\text{ox}}_{\text{H}}$(298 K) (kJ mol$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaCO$_3$</td>
<td>973</td>
<td>128.4 ± 10.1 (10)</td>
<td>119.70 ± 1.02</td>
</tr>
<tr>
<td>CaO</td>
<td>973</td>
<td>-82.39</td>
<td>-90.70 ± 1.69</td>
</tr>
<tr>
<td>SrCO$_3$</td>
<td>973</td>
<td>131.4 ± 9.1 (7)</td>
<td>130.16 ± 1.66</td>
</tr>
<tr>
<td>SrO</td>
<td>973</td>
<td>-134.47</td>
<td>-135.82 ± 2.48</td>
</tr>
<tr>
<td>SrO</td>
<td>1073</td>
<td>-129.25</td>
<td>-131.42 ± 1.89</td>
</tr>
<tr>
<td>BiO$_3$</td>
<td>973</td>
<td>26.0 ± 2.9 (12)</td>
<td></td>
</tr>
<tr>
<td>BiO$_3$</td>
<td>1073</td>
<td>39.6</td>
<td></td>
</tr>
<tr>
<td>Nb$_2$O$_5$</td>
<td>1073</td>
<td>141.8 ± 6.0 (11)</td>
<td>91.97 ± 0.78</td>
</tr>
</tbody>
</table>

$\Delta^{\text{ds}}_{\text{H}}$ Data from the present work. The uncertainty is two standard deviations of the mean (95% confidence level), the number in parentheses is the number of experiments performed, $^a$ From ref. [49], $^b$ The value $\Delta^{\text{H}}$(CaO, 973 → 1073 K) = 5.35 kJ mol$^{-1}$ [26] was used for the calculation, $^c$ From ref. [50], $^d$ From ref. [51], $^e$ From ref. [52], $^f$ The value $\Delta^{\text{H}}$(SrO, 973 → 1073 K) = 5.35 kJ mol$^{-1}$ [27] was used for the calculation, $^g$ From ref. [53], $^h$ The value $\Delta^{\text{H}}$(BiO$_3$, 973 → 1073 K) = 13.61 kJ mol$^{-1}$ [28] was used for the calculation, $\Delta^{\text{ox}}_{\text{H}}$ Data from the present work. The uncertainty was calculated according to the error propagation law, $^i$ From ref. [11], $^j$ From ref. [7], $^k$ From ref. [8], $^l$ From ref. [12].

![Table 7](image)

<table>
<thead>
<tr>
<th>Substance</th>
<th>$T$ (K)</th>
<th>$\Delta^{\text{ds}}_{\text{H}}$ (kJ mol$^{-1}$)</th>
<th>$\Delta^{\text{ox}}_{\text{H}}$(298 K) (kJ mol$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaNb$_2$O$_6$</td>
<td>1073</td>
<td>196.8 ± 20.7 (8)</td>
<td>-132.0 ± 23.8</td>
</tr>
<tr>
<td>CaNb$_2$O$_7$</td>
<td>1073</td>
<td>195.7 ± 27.8 (8)</td>
<td>-208.0 ± 31.9</td>
</tr>
<tr>
<td>SrNb$_2$O$_6$</td>
<td>1073</td>
<td>180.50 ± 15.7 (4)</td>
<td>-167.9 ± 19.1</td>
</tr>
<tr>
<td>SrNb$_2$O$_7$</td>
<td>1073</td>
<td>167.54 ± 34.7 (4)</td>
<td>-289.2 ± 37.5</td>
</tr>
<tr>
<td>BiNbO$_4$</td>
<td>1073</td>
<td>132.61 ± 8.9 (7)</td>
<td>-41.9 ± 11.1</td>
</tr>
</tbody>
</table>

$\Delta^{\text{ds}}_{\text{H}}$ Data from the present work. The uncertainty is two standard deviations of the mean (95% confidence level), the number in parentheses is the number of experiments performed, $^a$ The experimental data from the present work. The uncertainty was calculated according to the error propagation law, $^b$ From ref. [11], $^c$ From ref. [7], $^d$ From ref. [8], $^e$ From ref. [12].
Our values for the calcium niobates are in good agreement with Raghavan’s data [7,8], while the data from Dneprova et al. [11] are quite different. Moreover, a relation, \( \Delta_{\text{ox}}H(\text{CaNb}_2\text{O}_6) > \Delta_{\text{ox}}H(\text{CaNb}_2\text{O}_7) \), that holds for the values from the work of Dneprova et al. is rather unexpected. The \( \Delta_{\text{ox}}H \) values for strontium niobates obtained based on the binary SrO-Nb\(_2\)O\(_5\) phase diagram evaluation [12] are substantially more exothermic than our calorimetric data. These large differences in the \( \Delta_{\text{ox}}S \) values from the assessment [12] and those derived from low temperature dependences of the molar heat capacity of SrNb\(_2\)O\(_6\) and Sr\(_2\)Nb\(_2\)O\(_7\) [24,26].

3. Empirical correlation \( S-V \)

A linear correlation between the standard molar entropy at 298.15 K and the formula unit volume \( V_{\text{f.u.}} \) has been proposed by Jenkins and Glauser [54–56]. This approach was used in this work for mixed oxides in the CaO–SrO–Bi\(_2\)O\(_3\)–Nb\(_2\)O\(_5\)–Ta\(_2\)O\(_5\) system. The linear relation is obvious (see Fig. 4) and the straight line almost naturally passes through the origin:

\[
S_m(\text{JK}^{-1}\text{mol}^{-1}) = 1680.5V_{\text{f.u.}}(\text{nm}^3\text{f.u.}^{-1})
\]  

(21)

The average relative error in entropy is 8.2%, the binary oxides CaO and Nb\(_2\)O\(_5\) show the deviations around 20%. It should be noted that, in this set of values, the simple analogy of NKR (Eq.(9)) provides a better prediction with an average relative error in entropy of 4.2%.

Eq. (21) can be used for estimation of missing data. So, the estimated value \( S_m(\text{Sr}_2\text{Ta}_2\text{O}_7) = 256.06 \text{ J K}^{-1}\text{mol}^{-1} \) can be compared with the value 245.41 J K\(^{-1}\) mol\(^{-1}\) obtained by numerical integration of the \( C_p^m(T)/T \) dependences from zero to 298.15 K given in Ref. [1] (relative deviation of ~4.3%). Simple calculation \( S_m(\text{Sr}_2\text{Ta}_2\text{O}_7) = 2S_m(\text{SrO}) + S_m(\text{Ta}_2\text{O}_5) = 250.25 \text{ J K}^{-1}\text{mol}^{-1} \) gives more reliable value (relative deviation 2.0%).

4. Empirical estimation of enthalpy of formation

There are other mixed oxides in the system CaO–SrO–Bi\(_2\)O\(_3\)–Nb\(_2\)O\(_5\)–Ta\(_2\)O\(_5\) for which the values of enthalpy of formation \( \Delta H \) or enthalpy of formation from binary oxides \( \Delta_{\text{ox}}H \) have not yet been determined. As a rough estimate, the values of \( \Delta_{\text{ox}}H \) calculated according to an empirical method proposed by the authors [56] can be used. In the case of Ca, Sr and Bi niobates the following relation holds for \( \Delta_{\text{ox}}H \):

\[
\frac{\Delta_{\text{ox}}H}{n_{\text{Nb}} + n_{\text{Me}}} = -2.965ayX_{\text{Nb}}\delta X_{\text{Me}}(X_{\text{Nb}} - X_{\text{Me}})^2
\]  

(22)

where \( X_{\text{Nb}} \) and \( X_{\text{Me}} \) (Me = Ca, Sr or Bi) are Pauling’s electronegativities of the relevant elements, \( \delta \) and \( \beta \) are the molar fractions of the oxide-forming elements (\( x_{\text{Nb}} = n_{\text{Nb}}/(n_{\text{Nb}} + n_{\text{Me}}) \) etc.), \( y \) is the number of oxygen atoms per one atom of oxide-forming elements and \( \alpha \)
and $\delta$ are the model parameters. Using Pauling’s electronegativities, $X_{\text{Nb}} = 1.60$, $X_{\text{Ca}} = 1.00$, $X_{\text{Sr}} = 0.95$, and $X_{\text{Bi}} = 2.02$, and the calorimetric values of $\Delta_m H$ obtained in this work, the values of $\alpha = 2.576$ and $\delta = 1.50$ were derived from the least-squares fit. The estimated $\Delta_m H$ values for calcium and strontium niobates are shown in Fig. 5. The values of $\Delta_m H$ that were calculated according to an empirical method proposed by Zhuang et al. [57] are displayed for comparison.

![Figure 4. Correlation between the standard molar entropy at 298.15 K and the formula unit volume $V_{\text{f.u.}}$ for various mixed oxides in the system CaO-SrO-Bi$_2$O$_3$-Nb$_2$O$_5$-Ta$_2$O$_5$ (data from Table 3)](image)

### 5. Conclusion

The above presented data derived from calorimetric measurements became the basis for thermodynamic database FS-FEROX [58] compatible with the FactSage software [59,60]. Missing data for other stoichiometric mixed oxides were estimated by the empirical methods described before: the Neumann-Kopp’s rule for heat capacities, the entropy-volume correlation for molar entropies and electronegativity-differences method for enthalpies of formation. At the same time, thermodynamic description of a multicomponent oxide melt was obtained analyzing relevant binary phase diagrams published in literature. The database and the FactSage software were subsequently used for various equilibrium calculations including binary $T$-$x$ phase diagrams and ternary phase diagrams in subsolidus region. Thermodynamic modeling of SrBi$_2$Ta$_2$O$_9$ and SrBi$_2$Nb$_2$O$_9$ thin layers deposition from the gaseous phase were also performed to optimize the deposition conditions.
Calorimetric Determination of Heat Capacity, Entropy and Enthalpy of Mixed Oxides in the System CaO–SrO–Bi$_2$O$_3$–Nb$_2$O$_5$–Ta$_2$O$_5$

Figure 5. Values of enthalpy of formation of the mixed oxides from constituent binary oxides in the CaO–Nb$_2$O$_5$ (a) and SrO–Nb$_2$O$_5$ (b) systems (lines serve only as a guide for the eyes)
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6. References
Calorimetric Determination of Heat Capacity, Entropy and Enthalpy of Mixed Oxides in the System CaO–SrO–Bi₂O₃–Nb₂O₅–Ta₂O₅


Applications of Calorimetry in a Wide Context –
Differential Scanning Calorimetry, Isothermal Titration Calorimetry and Microcalorimetry


Calorimetric Determination of Heat Capacity, Entropy and Enthalpy of Mixed Oxides in the System CaO–SrO–Bi$_2$O$_3$–Nb$_2$O$_5$–Ta$_2$O$_5$

[49] Helean KB, Navrotsky A, Vance ER, Carter ML, Ebbinghaus B, Krikorian O, Lian J, Wang LM, Catalano JG (2002) Enthalpies of formation of Ce-pyrochlore, Ca$_{0.93}$Ce$_{1.00}$Ti$_{2.03}$O$_{7.00}$, U-pyrochlore, Ca$_{1.46}$U$^{4+0.23}$U$^{6+0.46}$Ti$_{1.85}$O$_{7.00}$, and Gd-pyrochlore, Gd$_{2}$Ti$_{1}$O$_{7}$: three materials relevant to the proposed waste form for excess weapons plutonium. J. Nuclear Mater. 303: 226–239.