

# Gas-Phase Energetics of Actinide Oxides: An Assessment of Neutral and Cationic Monoxides and Dioxides from Thorium to Curium<sup>†</sup>

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An assessment of the gas-phase energetics of neutral and singly and doubly charged cationic actinide monoxides and dioxides of thorium, protactinium, uranium, neptunium, plutonium, americium, and curium is presented. A consistent set of metal–oxygen bond dissociation enthalpies, ionization energies, and enthalpies of formation, including new or revised values, is proposed, mainly based on recent experimental data and on correlations with the electronic energetics of the atoms or cations and with condensed-phase thermochemistry.

## Introduction

The thermodynamic properties of actinide (An) oxides are of paramount importance to nuclear science at both the fundamental and applied levels. In the most recent comprehensive overview of the thermodynamics of actinides and actinide compounds,<sup>1</sup> the history of the field and the most reliable current data can be found. As concerns the actinide oxides, that work appropriately indicates that, while a significant number of studies of the solid compounds have been undertaken, gas-phase data are still incomplete. An earlier compilation devoted to the gas-phase thermochemistry of the actinides,<sup>2</sup> as well as others of a more general nature,<sup>3</sup> are now more than twenty years old and do not reflect the experimental data gathered since then. For instance, recent high-quality spectroscopic studies of thorium and uranium oxides<sup>4</sup> have afforded exceedingly reliable values for the ionization energies IE[ThO], IE[UO], and IE[UO<sub>2</sub>], which showed significant differences relative to the older accepted values included in the compilations.

In recent years, we have carried out a systematic study of the gas-phase thermochemistry of neutral and cationic actinide oxides from thorium to curium using Fourier transform ion cyclotron resonance mass spectrometry (FTICR/MS).<sup>5,6</sup> This experimental work was based on the observation of exothermic reactions of An metal or metal-oxide cations with various inorganic and organic molecules. Reactions of singly or doubly charged An cations with oxidizing reagents with a large range of oxygen dissociation energies provided metal–oxygen bond dissociation enthalpies,  $D[\text{An}^+-\text{O}]$ ,  $D[\text{OAn}^+-\text{O}]$ ,  $D[\text{An}^{2+}-\text{O}]$ , and  $D[\text{OAn}^{2+}-\text{O}]$ . Reactions of singly or doubly charged An monoxide and dioxide cations, produced via the oxidation reactions, yielded ionization energies of the corresponding neutral and monpositive monoxides and dioxides, IE[AnO], IE[AnO<sub>2</sub>], IE[AnO<sup>+</sup>], and IE[AnO<sub>2</sub><sup>+</sup>]. The values of  $D$  and IE determined by these procedures were either unknown or could be used to verify or correct literature values obtained by other methods.

The gas-phase data acquired from these studies justifies an overall assessment of gas-phase actinide oxide energetics.

Besides evaluating the consistency of the data from our experimental work,<sup>5,6</sup> which were obtained in several stages, this assessment compares them with corresponding values from the standard literature sources.<sup>1–3</sup> This assessment also tests the evaluation of the bond dissociation energies of neutral and singly charged actinide monoxides carried out not long ago by one of us,<sup>7</sup> based on correlations with the electronic structures and energetics of the isolated metal atoms and ions. Therefore, in the present work, we perform an assessment of the gas-phase energetics of neutral, and singly and doubly charged cationic actinide monoxides and dioxides from thorium to curium based on experimental data and on correlations with the electronic energetics of the atoms or cations and with condensed-phase thermochemistry. A prospective outcome of the assessment is the unraveling of variations across the actinide series that can be of value for evaluating or predicting the properties of other actinide oxides.

## Methodology

The approach used in this assessment is the following:

1. Identification of the more reliable experimental data from existing sources.
2. In the absence of data of confidence, selection of existing estimates as a starting point for the analysis.
3. Evaluation of the data based on the Hess's law eqs 1 to 4.

$$D[\text{An}^+-\text{O}] = D[\text{An}-\text{O}] + \text{IE}[\text{An}] - \text{IE}[\text{AnO}] \quad (1)$$

$$D[\text{OAn}^+-\text{O}] = D[\text{OAn}-\text{O}] + \text{IE}[\text{AnO}] - \text{IE}[\text{AnO}_2] \quad (2)$$

$$D[\text{An}^{2+}-\text{O}] = D[\text{An}^+-\text{O}] + \text{IE}[\text{An}^+] - \text{IE}[\text{AnO}^+] \quad (3)$$

$$D[\text{OAn}^{2+}-\text{O}] = D[\text{OAn}^+-\text{O}] + \text{IE}[\text{AnO}^+] - \text{IE}[\text{AnO}_2^+] \quad (4)$$

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4. Trial-and-error adjustment of the less reliable values based on experimental restraints and on correlations with independent data.

5. Estimation of the uncertainties of the final values based on experimental restraints, and on the uncertainties of the selected data.

A detailed explanation of each step of the procedure is presented in the following sections; additional data can be found in the Supporting Information.

### Key Data

The main sources of the An data selected as key for the evaluation are those indicated in the Introduction;<sup>1–6</sup> other sources of An data are cited when needed. Ancillary thermodynamic values are from the NIST Chemistry WebBook<sup>8</sup> (see Supporting Information, Table S1). The source for condensed-phase (solution and solid) thermodynamic data, used in correlations with the gas-phase data during the evaluation, was also Konings et al.<sup>1</sup> Values at 298.15 K have been used throughout the work with the exception of spectroscopically determined IEs which correspond to 0 K values; no thermal corrections were applied when combining 298.15 and 0 K values as the differences of a few  $\text{kJ mol}^{-1}$  are significantly smaller than the uncertainties involved.

**An Metals.** The enthalpies of formation of the gaseous An metals were retrieved from the review of Konings et al.<sup>1</sup> (see Supporting Information, Table S2). The first ionization energies of the An metals were obtained from the review of Worden et al.<sup>9</sup> (see Supporting Information, Table S2); with the exception of Pa, all the values are from highly reliable spectroscopic determinations.

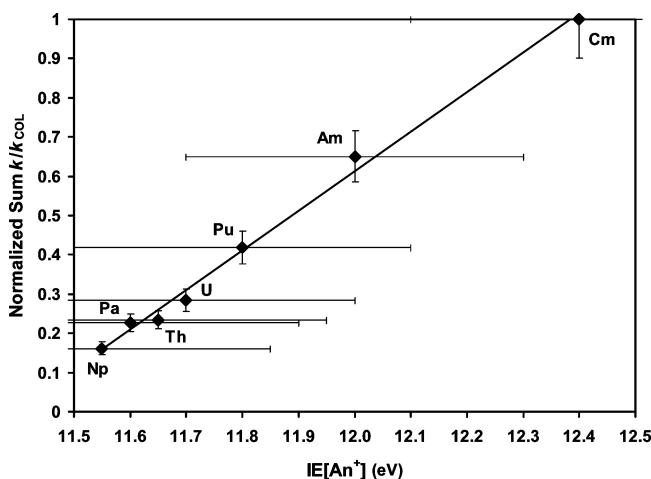
For the second ionization energies of the An metals there are no commonly accepted values. There are scattered values obtained from spectroscopic data<sup>10</sup> but more complete sets were only derived from estimates<sup>2,11</sup> or theoretical calculations.<sup>12</sup> The estimates made by Sugar (see Supporting Information, Table S3), as cited by Hildenbrand et al.<sup>2</sup> and also by Morss,<sup>13</sup> seemed to be reliable (as typical of Sugar's estimates) and we have used them in previous studies.<sup>5d–f</sup>

Recent work in our laboratories in which we have examined the gas-phase reactions of hydrocarbons with  $\text{Ln}^{2+}$ <sup>14</sup> have indicated that a correlation exists between the aggregate rates of electron transfer from hydrocarbons and the  $\text{IE}[\text{Ln}^{2+}]$ ; the same type of correlation was observed in reactions of other  $\text{M}^{2+}$  ions with different reagents (see Supporting Information, Figures S1 and S2 for details). However, our recent examination of the gas-phase reactions of hydrocarbons with  $\text{An}^{2+}$ <sup>15</sup> has shown that a poor correlation is obtained between the aggregate rates of electron transfer from hydrocarbons and the  $\text{IE}[\text{An}^{2+}]$  estimated by Sugar (see Supporting Information, Figure S3). Therefore, our first suggestion here is that an adjustment of the set of  $\text{IE}[\text{An}^{2+}]$  estimated by Sugar be made. For this, an anchor value within Sugar's set is needed. Known systematics of the ionization energies of the metallic elements tells us that, depending on the ground-state configuration of the  $\text{M}^{0/+2+}$  and the electron being removed,  $\text{IE}[\text{M}^{+}]/\text{IE}[\text{M}]$  is in many instances close to 2.<sup>16</sup> This is rather clear in the case of the lanthanides and we suggest here that for the more "lanthanide-like" actinides the same relationship applies. The more common ground state configurations of the lanthanides are  $4f^n 6s^2$  for the element,  $4f^n 6s^1$  for the singly charged cation, and  $4f^n$  for the doubly charged.<sup>17</sup> Considering Am and also Bk, Cf, and Es, which all have ground states similar to those of the more typical lanthanides, and also very reliable  $\text{IE}[\text{An}]$ <sup>9</sup> (see Supporting Information, Table S4 for the  $\text{IE}[\text{An}]$  for Bk, Cf, and Es), we can multiply these  $\text{IE}[\text{An}]$  by 2, obtaining  $\text{IE}[\text{Am}^{2+}] = 11.95$  eV; extrapolating linearly the values of  $\text{IE}[\text{An}^{2+}]$  for Bk, Cf,

**TABLE 1: Second Ionization Energies of An Elements<sup>a</sup>**

An	$\text{IE}[\text{An}^{2+}]$
Th	$11.65 \pm 0.3$
Pa	$11.6 \pm 0.3$
U	$11.7 \pm 0.3$
Np	$11.55 \pm 0.3$
Pu	$11.8 \pm 0.3$
Am	$12.0 \pm 0.3$
Cm	$12.4 \pm 0.3$

<sup>a</sup> This work; in eV.



**Figure 1.** Plot of the normalized sum of the fraction of the reaction efficiency ( $k/k_{\text{COL}}$ ) corresponding to electron transfer in reactions of  $\text{An}^{2+}$  with hydrocarbons,<sup>15</sup> as a function of the  $\text{IE}[\text{An}^{2+}]$  estimated in this work (sum normalized to  $\text{Cm}^{2+}$  which had the greatest electron-transfer efficiency;<sup>15</sup> for details of the procedure as applied to the case of the lanthanides see ref 14). (The linear fit has  $R^2 = 0.994$ .)

and Es back to Am, a value of  $\text{IE}[\text{Am}^{2+}] = 12.05$  eV is obtained. The two values for  $\text{IE}[\text{Am}^{2+}]$  derived here average to 12.0 eV which is also the value estimated by Sugar.<sup>2</sup>

Summarizing, in the present work we propose an adjustment to Sugar's estimates of the  $\text{IE}[\text{An}^{2+}]$  based on these considerations on the relationship between the  $\text{IE}[\text{M}]$  and the  $\text{IE}[\text{M}^{2+}]$ , taking  $\text{IE}[\text{Am}^{2+}] = 12.0$  eV as an anchor value, and on the experimental reactivity data obtained by us.<sup>14,15</sup> In Table 1, we present the new values of  $\text{IE}[\text{An}^{2+}]$  with our suggested uncertainty of  $\pm 0.3$  eV, and in Figure 1 a graphical representation is presented of the correlation of these new values with electron-transfer reaction efficiencies of the  $\text{An}^{2+}$  ions with hydrocarbons<sup>14,15</sup> (see Supporting Information, Figure S3 for the same representation when using Sugar's values). It should be noted that our new suggested values for  $\text{IE}[\text{An}^{2+}]$  are in general accord with Sugar's values when our rather large assigned uncertainty (i.e.,  $\pm 0.3$  eV) and the uncertainties in Sugar's values<sup>2</sup> (see Supporting Information, Table S3) are considered. A comparison of our new  $\text{IE}[\text{An}^{2+}]$  estimates with the high-level theoretical values from Dolg and co-workers<sup>12</sup> shows that the computed values are higher for Th, Pa, and U (particularly in the case of Th, 0.5 eV), are lower for Pu and Am, and are identical for Np and Cm. Similar trends can, however, be seen in a decrease of  $\text{IE}[\text{An}^{2+}]$  from Th to Np followed by an increase from Pu to Cm. These differences clearly indicate the need of reliable experimental determinations of the  $\text{IE}[\text{An}^{2+}]$ .

We use the new  $\text{IE}[\text{An}^{2+}]$  values (Table 1) in our assessment with the proviso that if reliable experimental values become available, a revision of this assessment will be necessary; corrections implied by new, reliable values of the  $\text{IE}[\text{An}^{2+}]$  would

require adjustment to the  $IE[AnO^+]$  which came out of this assessment with large uncertainties.

Other data pertaining to the An metals that will be used in this assessment are the promotion energies from the ground levels of the An,  $An^+$ , and  $An^{2+}$  species to relevant, low-lying excited configurations; these data were retrieved from the standard sources<sup>9,10a</sup> (the values are collected in Supporting Information, Tables S5, S6, and S7). It should be noted that the energies of the excited levels of the  $An^{2+}$ , other than for  $Th^{2+}$  and  $U^{2+}$ , have significant uncertainties.

**Neutral An Oxides.** The gas-phase thermodynamics of neutral An oxides has been recently reviewed by Konings et al.<sup>1</sup> who present evaluated values of the enthalpies of formation of AnO for An = Th, U, Np, Pu, Cm, and  $AnO_2$  for An = Th, U, Np, Pu (see Supporting Information, Table S8). The Th oxide gas-phase thermodynamic data in Konings et al.<sup>1</sup> are virtually identical to those in a very recent, comprehensive compilation of the thermochemistry of Th.<sup>18</sup> In the case of Pa, the sole experimental study by Kleinschmidt and Ward<sup>19</sup> that provided values for the enthalpies of formation of gaseous PaO and  $PaO_2$  is cited (also included in Supporting Information, Table S8). The value in ref 1 for  $\Delta_f H^\circ[CmO.g]$  relies on a previous evaluation of the thermodynamic properties of Cm and its oxides by Konings.<sup>20</sup> (See Supporting Information, Table S9 for a compilation of the previously available bond dissociation enthalpies of neutral An oxides.)

Konings et al.<sup>1</sup> also discuss and adjust the model put forward by Haire<sup>21</sup> for the  $D[An-O]$  in which the energetics of the  $6d^17s^1$  configurations of the An atoms were used to assess and estimate values along the An series. The  $D[An-O]$  values presented by Konings et al. in their Figure 19.18,<sup>1</sup> following Haire's work, apparently parallel the  $D[Ln-O]$  values; among the adjustments to these dissociation energies is our recent new experimentally derived value for  $D[Cm-O]$ ,<sup>5f</sup> which suggests that  $D[Gd-O]$  is comparable to, or somewhat higher than  $D[Cm-O]$ . Konings et al.<sup>1</sup> appropriately indicate that more recent work by one of us<sup>7</sup> has shown that a  $6d^2$  configuration in the AnO (and also in the LnO) appears to be more consistent with the existing experimental data. This correlation of the  $D[An-O]$  with the electronic energetics of the An atoms was tested in the present assessment.

The thermodynamics for the more studied (for reasons of availability and technological relevance) oxides of Th, U, and Pu are to be the most reliable among the actinide oxides and were selected as key values in the present assessment. In our previous studies of  $Pa^{5e}$  and  $Cm^{5f}$  we have already addressed the existing values for these two An and suggested some changes which we retain in the present work. In the case of Np, we came across some inconsistencies in the data, including in those from our previous work<sup>5a-c</sup> and, therefore, we have particularly focused on evaluating the Np data in the present assessment.

**Cationic An Oxides.** The energetics of cationic An oxides is less well established. For singly charged AnO and  $AnO_2$  species, most of the available experimental ionization energy (IE) determinations of AnO and  $AnO_2$ <sup>2,3a</sup> are based on electron-impact measurements whose reliability is known to be variable and unpredictable.<sup>22</sup> Highly reliable spectroscopic data for IEs are only available for ThO, UO, and  $UO_2$  from recent determinations by Heaven and co-workers<sup>4</sup> and their IEs are considered key values in our assessment. (See Supporting Information, Table S9 for a compilation of the previously available bond dissociation enthalpies of singly charged An oxides, and Supporting Information, Table S10 for the previously available ionization energies of the neutral An oxides.)

In our previous experimental work, we have determined  $IE[AnO]$  values for Np,<sup>5b,c</sup> Pu,<sup>5b,c</sup> Am,<sup>5b,c</sup> and Cm,<sup>5f</sup> anchored on the  $IE[UO]$  value of Heaven and co-workers,<sup>4c-e</sup> and these were also considered key values for the present evaluation. In the case of Pa, we have previously addressed the energetics of the  $PaO^+$  ion<sup>5e</sup> and here we have retained the estimate of  $IE[PaO]$  made therein.

In the case of  $IE[AnO_2]$ , we have no doubt as to the validity of the value of  $IE[UO_2]$  from Heaven and co-workers<sup>4c,d,f</sup> indicated above; we additionally consider that our experimental determinations of  $IE[AnO_2]$  for Np,<sup>5c</sup> Pu,<sup>5a</sup> and Am<sup>5b</sup> are valid to within the assigned uncertainties; furthermore, our estimate of  $IE[PaO_2]$ <sup>5e</sup> is also considered as reliable. It should be noted that our  $IE[PuO_2] = 7.03 \pm 0.12$  eV was lower by ca. 2.5–3 eV than the previous literature values.<sup>2,23</sup> The value for  $IE[PuO_2]$  previously reported by Capone et al.<sup>23</sup> ( $10.1 \pm 0.1$  eV) was recently redetermined by the same authors<sup>24</sup> ( $\sim 6.6$  eV); their revised value is in fair agreement with our value but this work<sup>24</sup> was the object of controversy related to the experimental approach.<sup>25</sup> A contribution from a theoretical study was very recently added<sup>26</sup> in which the experimental range  $\sim 6.6$ – $7.0$  eV for  $IE[PuO_2]$  is confirmed as compared to the previous range  $\sim 9$ – $10$  eV, although a value of 6.2 eV is considered the best computed estimate. The particular case of  $IE[PuO_2]$  illustrates the challenges associated with obtaining reliable thermodynamic data for transuranium actinides, and the need for both high-quality spectroscopic measurements and the development of reliable theoretical methodologies for transuranium actinide molecules. The commonly cited value of  $IE[ThO_2]$ <sup>2,3a</sup> was used as a starting point in the evaluation with the caveat that it was derived from inherently suspect high-temperature electron impact experiments.

A complementary contribution to the energetics of singly charged An oxide ions came from the  $D[An^+-O]$  and  $D[OAn^+-O]$  estimated in our studies of the reactions of  $An^+$  and  $AnO^+$  with oxidants with a large spectrum of oxidizing abilities<sup>5a,b,e,f</sup> (see Supporting Information, Table S11). In these type of studies, if the reactant ions are properly thermalized, the reactions that are observed are either exothermic or thermoneutral. Although the existence of kinetic barriers may prevent the observation of some exothermic reactions, in carefully analyzed cases the comparative rate constants can be used to improve the estimates of the bond dissociation enthalpies. The constraints imposed on the  $D[An^+-O]$  and  $D[OAn^+-O]$  by the experimental observations were taken into account throughout the present assessment (see Supporting Information, Table S12); specifically, observation of an oxidation reaction establishes a lower limit for the actinide-oxygen bond energy.

While the energetics of singly charged An oxides may be considered to some extent established, albeit in many cases tentatively, from previous work, there was an almost complete lack of data on doubly charged An oxides before our experimental studies of these species.<sup>5d-f</sup> (See Supporting Information, Table S9 for a compilation of the previously available bond dissociation enthalpies of doubly charged An oxides, and Supporting Information, Table S10 for the previously available ionization energies of the singly charged An oxides.)

In the present work, for the doubly charged An monoxides we rely on our revised values of the  $IE[An^+]$  described above (see Table 1), our estimates of the  $D[An^{2+}-O]$ <sup>5d-f</sup> (see Supporting Information, Tables S11 and S12), and our somewhat approximate estimates of the  $IE[AnO^+]$ <sup>5d-f</sup> with the sole exception of  $IE[CmO^+]$ , which was the object of a more direct



**TABLE 2: Bond Dissociation Enthalpies of An Oxides<sup>a</sup>**

An	$D[\text{An}-\text{O}]$	$D[\text{An}^+-\text{O}]$	$D[\text{An}^{2+}-\text{O}]$	$D[\text{OAn}-\text{O}]$	$D[\text{OAn}^+-\text{O}]$	$D[\text{OAn}^{2+}-\text{O}]$
Th	872 ± 25	843 ± 25	829 ± 80	684 ± 14	462 ± 36	0 ± 170 <sup>b</sup>
Pa	801 ± 59	800 ± 50	781 ± 30	780 ± 48	780 ± 29	317 ± 110
U	758 ± 13	774 ± 13	706 ± 45	750 ± 14	741 ± 14	529 ± 31
Np	744 ± 21	760 ± 10	524 ± 26	632 ± 43	610 ± 22	504 ± 10
Pu	658 ± 10	651 ± 19	439 ± 49	599 ± 22	509 ± 38	403 ± 95
Am	582 ± 34	560 ± 28	367 ± 13	509 ± 65	410 ± 56	256 ± 129
Cm	709 ± 43	670 ± 38	342 ± 12	405 ± 70	202 ± 60	0 ± 150 <sup>b</sup>

<sup>a</sup> The values are from the evaluation in this work; 298.15 K, in kJ mol<sup>-1</sup>. See Supporting Information, Table S9 for previously available values and references. <sup>b</sup> Rough estimate.

**TABLE 3: Ionization Energies of An Oxides<sup>a</sup>**

An	IE[AnO]	IE[AnO <sup>+</sup> ]	IE[AnO <sub>2</sub> ]	IE[AnO <sub>2</sub> <sup>+</sup> ]
Th	6.60242 ± 0.00002	11.8 ± 0.7	8.9 ± 0.4	16.6 ± 1 <sup>b</sup>
Pa	5.9 ± 0.2	11.8 ± 0.7	5.9 ± 0.2	16.6 ± 0.4
U	6.0313 ± 0.0006	12.4 ± 0.6	6.128 ± 0.003	14.6 ± 0.4
Np	6.1 ± 0.2	14.0 ± 0.6	6.33 ± 0.18	15.1 ± 0.4
Pu	6.1 ± 0.2	14.0 ± 0.6	7.03 ± 0.12	15.1 ± 0.4
Am	6.2 ± 0.2	14.0 ± 0.6	7.23 ± 0.15	15.7 ± 0.6
Cm	6.4 ± 0.2	15.8 ± 0.4	8.5 ± 1	17.9 ± 1 <sup>b</sup>

<sup>a</sup> The values are from the evaluation in this work; in eV. See Supporting Information, Table S10 for previously available values and references. <sup>b</sup> Rough estimate.

experimental determination.<sup>5f</sup> With the exception of IE[CmO<sup>+</sup>], our previous estimates for IE[AnO<sup>+</sup>] were adjusted in this work.

The second ionization energies of the AnO<sub>2</sub> for the cases of PaO<sub>2</sub><sup>5e</sup> and UO<sub>2</sub>, NpO<sub>2</sub>, and PuO<sub>2</sub><sup>5d</sup> were experimentally determined by us, and in the case of AmO<sub>2</sub> an estimate was obtained in our previous work;<sup>5d</sup> we have used all of these values in the present assessment. The IE[UO<sub>2</sub><sup>+</sup>] had previously been the object of a rough experimental determination.<sup>27</sup> It should be highlighted that our experimental determination of IE[PaO<sub>2</sub><sup>+</sup>] was accompanied by a theoretical study performed by Pitzer and Tyagi that, besides providing insights into the nature of the intriguing protactinyl species PaO<sub>2</sub><sup>2+</sup>, provided remarkably good agreement with the experimental value of IE[PaO<sub>2</sub><sup>+</sup>].<sup>5e</sup> For the doubly charged An dioxides, we relied on our estimates of  $D[\text{OAn}^{2+}-\text{O}]$ <sup>5d,e</sup> to carry out the evaluation (see Supporting Information, Tables S11 and S12).

### Evaluation of the Energetics of Actinide Oxides

As stated in the section where we summarized our methodology, we have evaluated the selected key data by means of the eqs 1 to 4, performed a trial-and-error adjustment of the less reliable values based on experimental restraints and on correlations with independent data, and made estimates of the uncertainties of the final values. In Tables 2 and 3, we present the results of this analysis for the An monoxides and dioxides as evaluated bond dissociation enthalpies (Table 2) and ionization energies (Table 3).

To clarify the procedure, we will now describe a few representative examples. In the simpler cases of U and Pu for which  $D[\text{An}-\text{O}]$  and IE[AnO] were key values, the  $D[\text{An}^+-\text{O}]$  were easily obtained from eq 1; as  $D[\text{OAn}-\text{O}]$  and IE[AnO<sub>2</sub>] were also key values, the  $D[\text{OAn}^+-\text{O}]$  were therefore obtained through eq 2. With the  $D[\text{An}^+-\text{O}]$  and  $D[\text{OAn}^+-\text{O}]$  from above, the IE[An<sup>+</sup>] from this work, and the key IE[AnO<sub>2</sub><sup>+</sup>], the  $D[\text{An}^{2+}-\text{O}]$ , IE[AnO<sup>+</sup>], and  $D[\text{OAn}^{2+}-\text{O}]$  were adjusted using as starting points the estimates from previous work (see Supporting Information, Tables S9 and S10) and the eqs 3 and 4.

In the cases of Np and Am, the IE[AnO] and IE[AnO<sub>2</sub>] were the key values and therefore the  $D[\text{An}-\text{O}]$  and  $D[\text{An}^+-\text{O}]$  were adjusted using eq 1 and the previously available  $D[\text{An}^+-\text{O}]$  (see Supporting Information, Table S9) as starting points, together with the  $D[\text{OAn}-\text{O}]$  and  $D[\text{OAn}^+-\text{O}]$  via eq 2 and the previously available values (see Supporting Information, Table S9) as starting points; for the doubly charged species, the procedure was the same as described above for U and Pu.

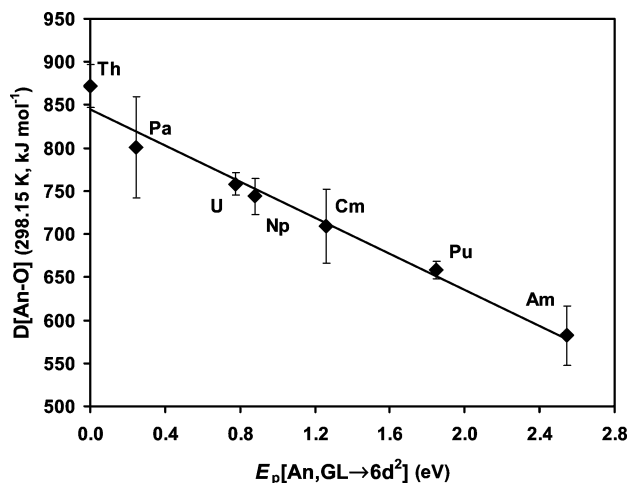
Differences to the previously available values (Supporting Information, Tables S9 and S10) of the adjusted  $D$  and IE values (Tables 2 and 3) were typically around or below 30 kJ mol<sup>-1</sup>.

Correlations with external data were used to assess the evaluated  $D$  and IE values as described in the sections below. The correlations of the more straightforwardly evaluated bond dissociation enthalpies of neutral and cationic An monoxides with the electronic energetics of the atoms and cations were only used as consistency checks. For the An dioxides, the correlations with condensed-phase data were also mainly used as consistency checks, although in the cases where less key data was available they were used in the adjustment of  $D$  and IE values.

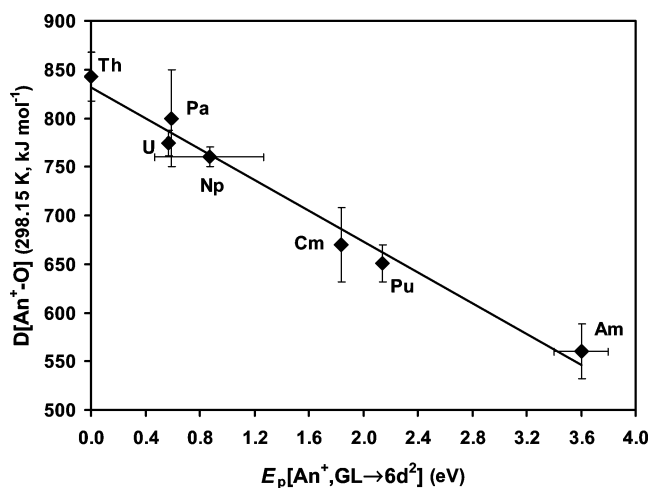
In the cases of ThO<sub>2</sub><sup>2+</sup>, CmO<sub>2</sub>, CmO<sub>2</sub><sup>+</sup>, and CmO<sub>2</sub><sup>2+</sup>, for the sake of completeness we have made rough estimates of the corresponding values with accordingly large assigned uncertainties. For the estimates on the neutral and singly charged Cm dioxide, we took as a reference available data on MO<sub>2</sub><sup>28</sup> for M = Sc, Y, and La, that like Cm are trivalent metals. For the most reliable case of Y, the existing data lead to  $D[\text{OY}-\text{O}] = 399 \pm 21$  kJ mol<sup>-1</sup>,  $D[\text{OY}^+-\text{O}] = 170 \pm 15$  kJ mol<sup>-1</sup>, and IE[YO<sub>2</sub>] = 8.49 ± 0.16 eV, and these were used as a primary basis for estimating Cm values.

**An Monoxides.** To assess the consistency of our assigned bond dissociation enthalpies of the An monoxides, we have followed the recent evaluation of neutral AnO and singly charged AnO<sup>+</sup> based on correlations with the electronic structures and energetics of the isolated metal atoms and ions<sup>7</sup> and have extended that analysis to the doubly charged AnO<sup>2+</sup> in the present work. The correlations are presented in Figures 2, 3, and 4 for the  $D[\text{An}-\text{O}]$ ,  $D[\text{An}^+-\text{O}]$ , and  $D[\text{An}^{2+}-\text{O}]$ , respectively, and in all three cases the fits are quite good.

It should be pointed out that in the case of the An<sup>2+</sup>, the promotion energies from the ground levels to 6d<sup>2</sup> and to 6d<sup>1</sup>7s<sup>1</sup> configurations, besides displaying significant uncertainties (see Supporting Information, Table S7), follow a parallel trend (see Supporting Information, Figure S4), and therefore the validity of the specific pertinent electronic configuration—6d<sup>2</sup> or 6d<sup>1</sup>7s<sup>1</sup>—in the model for the An<sup>2+</sup> cannot be ascertained. Nevertheless, in terms of verifying the  $D[\text{An}^{2+}-\text{O}]$  values proposed in this work there appears to be reasonable consistency regardless of which electronic configuration is employed. Also of note are the slight upward deviation of  $D[\text{Th}-\text{O}]$  and/or the slight downward deviation of  $D[\text{Pa}-\text{O}]$  from the fit in Figure 2, which



**Figure 2.** Plot of the  $D[\text{An}-\text{O}]$  obtained in this work (Table 2) as a function of the promotion energy ( $E_p$ ) of the An atoms from the ground level to the lowest  $6d^2$  configuration (Supporting Information, Table S3). (The linear fit has  $R^2 = 0.977$ .)

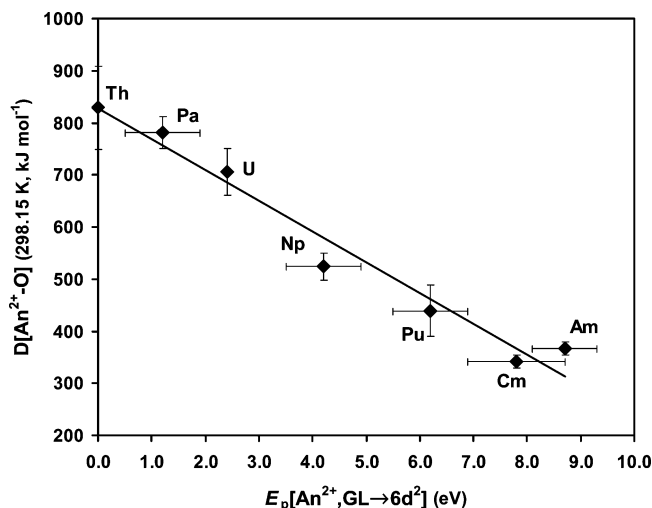


**Figure 3.** Plot of the  $D[\text{An}^+-\text{O}]$  obtained in this work (Table 2) as a function of the promotion energy ( $E_p$ ) of the  $\text{An}^+$  cations from the ground level to the lowest  $6d^2$  configuration (Supporting Information, Table S4). (The linear fit has  $R^2 = 0.982$ .)

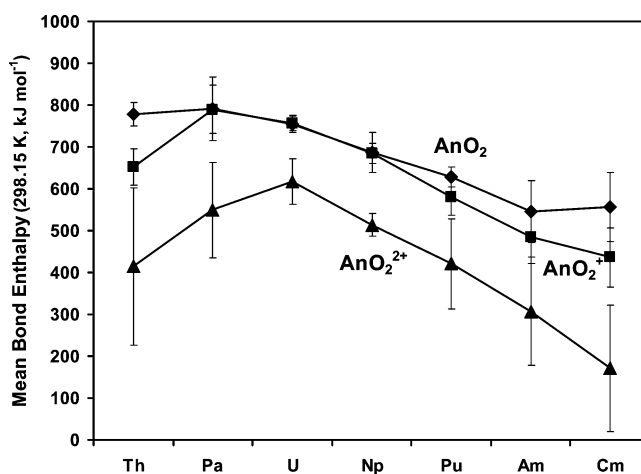
may indicate that one or both of these values need to be adjusted slightly, though in each case likely by  $<25 \text{ kJ mol}^{-1}$  (i.e.,  $<3\%$ ).

**An Dioxides.** To use a model equivalent to the one used for the An monoxides to test the consistency of the  $D[\text{OAn}-\text{O}]$ ,  $D[\text{OAn}^+-\text{O}]$ , and  $D[\text{OAn}^{2+}-\text{O}]$  data would require knowledge of the electronic structures and energetics of the  $\text{AnO}$ ,  $\text{AnO}^+$ , and  $\text{AnO}^{2+}$  species. Spectroscopic studies of gaseous An monoxides have been limited to neutral and singly charged Th and U monoxides.<sup>4</sup> A theoretical study of the electronic structure of  $\text{PaO}^+$  by R. M. Pitzer and co-workers is also available.<sup>28</sup> However, no generalized model can be tested with such a restricted set of data.

In the absence of the above test, we have first considered the mean bond enthalpies of the An dioxides, which we present in Figure 5. There, not unexpectedly, the mean bond enthalpy for the  $\text{AnO}_2^+$ , formally An(V), peaks at Pa, while for the  $\text{AnO}_2^{2+}$ , formally An(VI), the peak is at U. Moreover, there are approximately linear decays for both the  $\text{AnO}_2^+$  and  $\text{AnO}_2^{2+}$  when moving from U onward in the series. Interestingly, there is a plateau for Th and Pa in the case of the  $\text{AnO}_2$ , formally An(IV), with  $\text{PaO}_2$  perhaps being slightly higher. This may not



**Figure 4.** Plot of the  $D[\text{An}^{2+}-\text{O}]$  obtained in this work (Table 2) as a function of the promotion energy ( $E_p$ ) of the  $\text{An}^{2+}$  cations from the ground level to the lowest  $6d^2$  configuration (Supporting Information, Table S5). (The linear fit has  $R^2 = 0.967$ .)



**Figure 5.** Mean bond enthalpy of neutral and cationic An dioxides (calculated from data in Table 2).

be unanticipated if we take into account the available corresponding data for Zr and Nb,<sup>30</sup> which show clear similarities to the cases of Th and Pa, respectively:  $D[\text{Zr}-\text{O}] = 766 \pm 11 \text{ kJ mol}^{-1}$ ,  $D[\text{OZr}-\text{O}] = 633 \pm 28 \text{ kJ mol}^{-1}$ ,  $D[\text{Nb}-\text{O}] = 727 \pm 11 \text{ kJ mol}^{-1}$ , and  $D[\text{ONb}-\text{O}] = 724 \pm 24 \text{ kJ mol}^{-1}$ , leading to mean bond enthalpies of  $700 \pm 30 \text{ kJ mol}^{-1}$  for  $\text{ZrO}_2$  and  $725 \pm 26 \text{ kJ mol}^{-1}$  for  $\text{NbO}_2$ . Another salient feature of the  $\text{AnO}_2$  mean bond enthalpies is the leveling off at Am and Cm.

In the overview of An thermodynamics by Konings et al.,<sup>1</sup> there are significant amounts of thermodynamic data for the solid An compounds and also for cationic An and An oxide species in aqueous solution. These condensed-phase data show remarkable correlations with each other of which clear examples are summarized by the authors in their Figure 19.21,<sup>1</sup> where parallel trends in the enthalpies of formation of several solid An(IV) species and also of aqueous  $\text{An}^{4+}$  can be seen along the An series (see Supporting Information, Figure S5 for a partial reconstruction of Figure 19.21 from ref 1).

In order to try the same type of correlation with equivalent condensed-phase data, we have calculated the enthalpies of formation of the gaseous neutral and ionic An dioxides. These can be derived from the bond dissociation enthalpy values in Table 2 and the enthalpies of formation of the gaseous neutral

**TABLE 4: Enthalpies of Formation of Gaseous An Oxides<sup>a</sup>**

An	$\Delta_f H^\circ[\text{AnO}_2, \text{g}]$	$\Delta_f H^\circ[\text{AnO}^+, \text{g}]$	$\Delta_f H^\circ[\text{AnO}_2^{2+}, \text{g}]$	$\Delta_f H^\circ[\text{AnO}_2, \text{g}]$	$\Delta_f H^\circ[\text{AnO}_2^+, \text{g}]$	$\Delta_f H^\circ[\text{AnO}_2^{2+}, \text{g}]$
Th	$-21 \pm 26$	$617 \pm 26$	$1775 \pm 85$	$-456 \pm 19$	$404 \pm 38$	$2004 \pm 190$
Pa	$18 \pm 60$	$587 \pm 52$	$1726 \pm 44$	$-513 \pm 77$	$57 \pm 60$	$1658 \pm 119$
U	$24 \pm 15$	$606 \pm 15$	$1803 \pm 54$	$-477 \pm 21$	$114 \pm 21$	$1523 \pm 62$
Np	$-30 \pm 21$	$559 \pm 10$	$1909 \pm 39$	$-413 \pm 48$	$198 \pm 24$	$1654 \pm 40$
Pu	$-60 \pm 10$	$529 \pm 19$	$1879 \pm 57$	$-410 \pm 24$	$269 \pm 43$	$1725 \pm 111$
Am	$-49 \pm 34$	$549 \pm 28$	$1900 \pm 32$	$-309 \pm 73$	$389 \pm 63$	$1903 \pm 133$
Cm	$-76 \pm 44$	$541 \pm 39$	$2066 \pm 33$	$-232 \pm 83$	$588 \pm 72$	$2315 \pm 154$

<sup>a</sup> The values are derived from the bond dissociation enthalpies evaluated in this work; 298.15 K, in  $\text{kJ mol}^{-1}$ .

and cationic An (see Supporting Information, Table S2) via eqs 5 and 6.

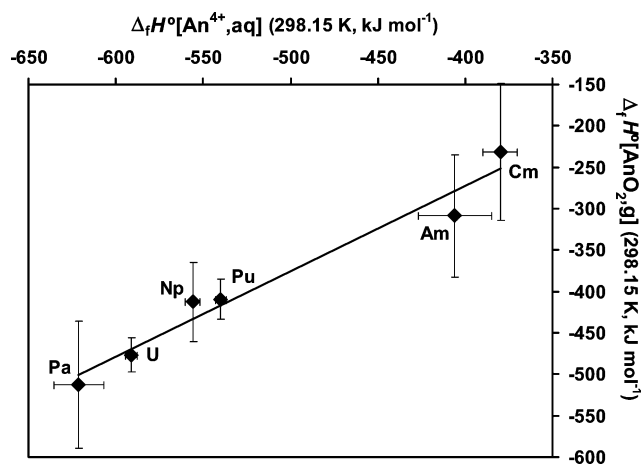
$$\Delta_f H^\circ[\text{AnO}_2^{0/+2+}, \text{g}] = \Delta_f H^\circ[\text{AnO}^{0/+2+}, \text{g}] + \Delta_f H^\circ[\text{O}, \text{g}] - D[\text{OAn}^{0/+2+} - \text{O}] \quad (5)$$

$$\Delta_f H^\circ[\text{AnO}^{0/+2+}, \text{g}] = \Delta_f H^\circ[\text{An}^{0/+2+}, \text{g}] + \Delta_f H^\circ[\text{O}, \text{g}] - D[\text{An}^{0/+2+} - \text{O}] \quad (6)$$

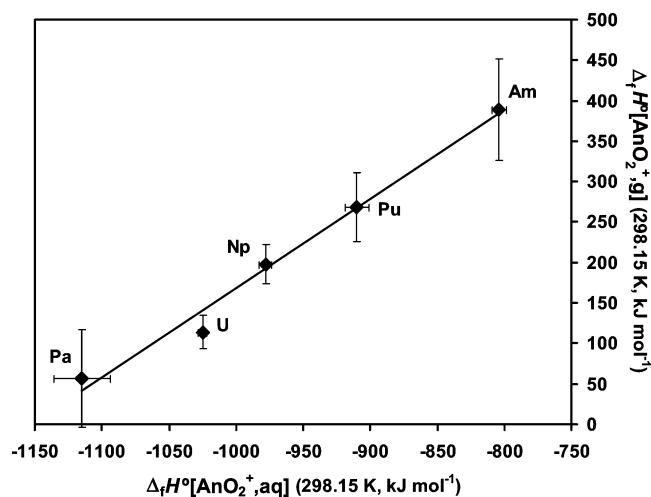
In Table 4, we present the calculated enthalpies of formation of the gaseous dioxides, as well as those of the gaseous monoxides.

In terms of relative stabilities for each oxidation state along the An series, relative to the metallic element, we can see from the values in Table 4 that  $\text{PaO}_2^+$  is the most stable An(V) species, while  $\text{UO}_2^{2+}$  is the most stable An(VI) species, with the stabilities of both oxidation states decreasing upon advancing across the series. Another issue that can be evaluated from the  $\Delta_f H^\circ$  values for the gaseous actinyls  $\text{AnO}_2^{2+}$  is their stability relative to “Coulombic explosion”,<sup>31</sup> that is, to their dissociation to two monopositive ions,  $\text{AnO}^+ + \text{O}^+$  or  $\text{An}^+ + \text{O}_2^+$ . We have previously addressed this issue for the cases of  $\text{Pa}^{5e}$  and U, Np, Pu, and Am,<sup>5d</sup> concluding that the corresponding actinyls are all stable toward Coulombic explosion, although this conclusion is somewhat doubtful in the case of Am because of uncertainties in the enthalpy of formation and potential entropic factors.<sup>5d</sup> The same conclusions still hold with the slightly modified  $\Delta_f H^\circ[\text{AnO}_2^{2+}, \text{g}]$  values obtained in the present work. The cases of  $\text{ThO}_2^{2+}$  and  $\text{CmO}_2^{2+}$ , not evaluated previously, are disparate; while “ $\text{CmO}_2^{2+}$ ”, if formed, would be unstable and would exothermically dissociate to  $\text{CmO}^+ + \text{O}^+$  and  $\text{Cm}^+ + \text{O}_2^+$ , “ $\text{ThO}_2^{2+}$ ”, if formed, would most probably be stable toward Coulombic explosion, but might spontaneously dissociate to  $\text{ThO}^{2+} + \text{O}$ , as indicated by our estimated  $D[\text{OTh}^{2+} - \text{O}] \approx 0$  (see Supporting Information, Table S13 for an analysis of Coulombic explosion of  $\text{AnO}_2^{2+}$ ).

With the  $\Delta_f H^\circ$  for the An dioxides from Table 4, we obtained the correlations with condensed phase thermochemistry that we present in Figures 6, 7, and 8, in which we can see reasonable correlations of the  $\Delta_f H^\circ[\text{AnO}_2, \text{g}]$  with  $\Delta_f H^\circ[\text{An}^{4+}, \text{aq}]$ ,  $\Delta_f H^\circ[\text{AnO}_2^+, \text{g}]$  with  $\Delta_f H^\circ[\text{AnO}_2^+, \text{aq}]$ , and  $\Delta_f H^\circ[\text{AnO}_2^{2+}, \text{g}]$  with  $\Delta_f H^\circ[\text{AnO}_2^{2+}, \text{aq}]$ , respectively (see Supporting Information, Table S12 for  $\Delta_f H^\circ$  values from condensed phases). Although not covering all the gas-phase data from Th to Cm, we used these relationships to adjust our evaluated  $D$  and IE values. A fair correlation was also obtained between  $\Delta_f H^\circ[\text{AnO}_2, \text{g}]$  and  $\Delta_f H^\circ[\text{AnO}_2, \text{c}]$ , which could be expected because, as indicated above,  $\Delta_f H^\circ[\text{An}^{4+}, \text{aq}]$  and  $\Delta_f H^\circ[\text{AnO}_2, \text{c}]$  show a good correlation.<sup>1</sup> Intriguingly, the  $\Delta_f H^\circ[\text{ThO}_2, \text{g}]$ , which we retained from Konings et al.<sup>1</sup> although with a larger assigned uncertainty, is

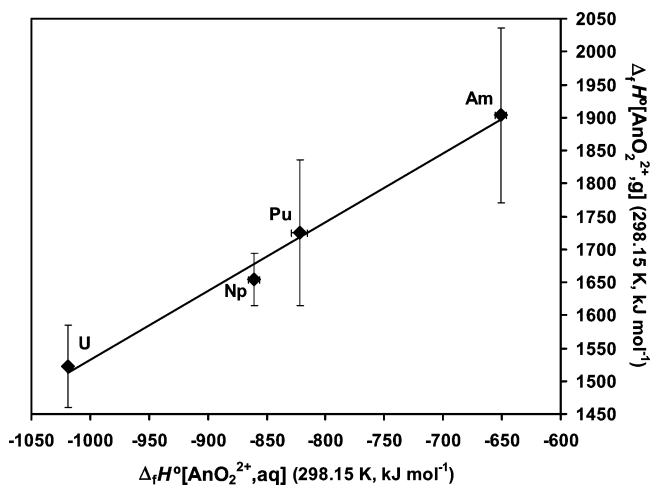


**Figure 6.** Plot of the  $\Delta_f H^\circ[\text{AnO}_2, \text{g}]$  obtained in this work (Table 4) as a function of the  $\Delta_f H^\circ[\text{An}^{4+}, \text{aq}]$  (Supporting Information, Table S12). (The linear fit has  $R^2 = 0.964$ ; the point for  $\text{ThO}_2, \text{g}/\text{Th}^{4+}, \text{aq}$  is not included in the plot, as discussed in the text.)



**Figure 7.** Plot of the  $\Delta_f H^\circ[\text{AnO}_2^+, \text{g}]$  obtained in this work (Table 4) as a function of the  $\Delta_f H^\circ[\text{AnO}_2^+, \text{aq}]$  (Supporting Information, Table S12). (The linear fit has  $R^2 = 0.985$ ; the Pa point corresponds not to  $\text{PaO}_2^+, \text{aq}$  but rather to the Pa(V) species that is stable in aqueous solution,  $\text{PaOOH}^{2+}$ .)

clearly out of the fit in Figure 6 (this data point at  $\Delta_f H^\circ[\text{ThO}_2, \text{g}] = -456 \text{ kJ mol}^{-1}$ ,  $\Delta_f H^\circ[\text{Th}^{4+}, \text{aq}] = -769 \text{ kJ mol}^{-1}$  does not appear in Figure 6). The remarkably high stability of condensed-phase Th(IV) species, which is evidently a special case in condensed-phase actinide chemistry, is also clearly seen in other correlations, such as is evident in Figure 19.21 of ref 1 (see Supporting Information, Figure S5). If the formation enthalpy for  $\text{ThO}_2, \text{g}$  is valid, it would appear that effects which result in an unusual stability of Th(IV) species in the condensed



**Figure 8.** Plot of the  $\Delta_f H^\circ[\text{AnO}_2^{2+}, \text{g}]$  obtained in this work (Table 4) as a function of the  $\Delta_f H^\circ[\text{AnO}_2^{2+}, \text{aq}]$  (Supporting Information, Table S12). (The linear fit has  $R^2 = 0.990$ .)

phase—specifically in ionic solids and as an ion in aqueous solutions—are not similarly manifested in the thorium dioxide molecule, which presumably exhibits more covalent character. It should be noted that in Figure 7 the Pa point corresponds not to  $\text{PaO}_2^+, \text{aq}$  but rather to the Pa(V) species that is stable in aqueous solution,  $\text{PaOOH}^{2+}$ .<sup>1</sup>

Other correlations of the data obtained for the An dioxides in the present assessment were attempted with fair results, namely  $D[\text{OAn}^+-\text{O}]$  versus  $D[\text{OAn}-\text{O}]$  and  $D[\text{OAn}^+-\text{O}]$  versus  $\text{IE}[\text{AnO}_2]$  (see Supporting Information, Figures S6 and S7). The correlation between  $D[\text{OAn}^+-\text{O}]$  and  $\text{IE}[\text{AnO}_2]$  may reflect the relative stabilities of the An(V). The significance of the correlation between  $D[\text{OAn}^+-\text{O}]$  and  $D[\text{OAn}-\text{O}]$  is not clear but it was also helpful in estimating the thermodynamic properties of curium dioxide (incidentally, a good correlation also exists between  $D[\text{An}^+-\text{O}]$  and  $D[\text{An}-\text{O}]$ , see Supporting Information, Figure S8). A fairly good correlation was also found between  $D[\text{OAn}-\text{O}]$  and the promotion energy from the ground level to a  $6d^2$  configuration of the  $\text{An}^{2+}$  atomic ions from Pa to Am (see Supporting Information, Figure S9). This correlation suggests that the An in  $\text{AnO}$  can be considered approximately as an  $\text{An}^{2+}$  ion, and the bonding to the second O atom in  $\text{OAn}-\text{O}$  involves a  $6d^2$  configuration at the An metal center. The several correlations we have identified evidently reflect a generalized gradual variation of the intrinsic properties of the An(IV) to An(VI) from Pa to Cm; Th is clearly an outlier.

**Comparisons with Theoretical Calculations.** As a final part of this section, we should mention that several recent theoretical calculations have examined the thermodynamics of a few An oxide species. As a first example of note, agreement of our values for the  $\Delta_f H^\circ[\text{AnO}_2^{2+}, \text{g}]$  in the cases of U and Pu with the calculated ones,<sup>32</sup>  $\Delta_f H^\circ_0[\text{UO}_2^{2+}, \text{g}] = 1527 \pm 42 \text{ kJ mol}^{-1}$  and  $\Delta_f H^\circ_0[\text{PuO}_2^{2+}, \text{g}] = 1749 \pm 63 \text{ kJ mol}^{-1}$ , is evident. Recent theoretical studies of the solvation of actinyls by water<sup>33</sup> have also showed a fair agreement between calculated free energies of hydration and the ones that can be derived from the enthalpies of formation for the gaseous actinyl ions from the present work (Table 4), in conjunction with the known enthalpies of formation of these species in aqueous phase (see Supporting Information, Table S14), as performed in our previous work.<sup>5d</sup> Other recent theoretical studies have led to disparate values for several

An oxide bond dissociation enthalpies and ionization energies,<sup>12a,26,34</sup> some of them showing reasonable agreement with the data evaluated in the present work.

## Conclusions

We have performed an assessment of the gas-phase energetics of neutral and singly and doubly charged cationic actinide monoxides and dioxides from thorium to curium based on experimental data and on correlations with the electronic energetics of the atoms or cations and with condensed-phase thermochemistry, and provide a consistent set of new or revised values of metal–oxygen bond dissociation enthalpies, ionization energies, and enthalpies of formation for these species. The assessment highlights the need for additional high-accuracy experimental measurements for elementary actinide molecules and even atoms, particularly for the transuranium actinides, and the development of advanced theoretical approaches to more reliably compute key thermodynamic properties of actinide molecules.

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**Supporting Information Available:** Tables S1–S14 and Figures S1–S9 provide thermodynamic data and correlations of data supplementary to the data in the manuscript. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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