

Effect of Environmental Lead on Human Health

Lead occurs naturally in all kinds of rocks in a wide range of concentrations. It is released during chemical weathering of minerals and is present in soil, water, and air. Lead is absorbed by plants from soil and thus enters the food chain. However, since Pb is toxic to most plants, its concentration in plants is generally low. Similarly, surface water and groundwater have low Pb concentrations because most compounds of Pb (e.g., PbCO_3 and PbSO_4) have low solubilities. Therefore, food, water, and air under natural environmental conditions are not a source of Pb contamination of humans.

However, the mining and smelting of Pb and its use in household implements have contaminated the surface of the Earth and jeopardized the health of humans, domestic animals, and even wildlife. The dispersal of large quantities of lead alkyls by the combustion of leaded gasoline has become the most pervasive form of Pb contamination. The resulting health effects in humans are difficult to recognize because all humans alive today carry an excessive burden of anthropogenic Pb.

The contamination of soil and dust in metropolitan areas and near smelters of Pb-bearing ores was demonstrated by Warren (1972). His data in Table 25.1 reveal that Pb, Cu, and Zn have been strongly enriched in such samples from metropolitan areas (e.g., Vancouver, Liverpool, and New York), from mining or smelting centers in Canada (e.g., Trail, Sudbury, and Noranda), and from industrial sites (e.g., Vancouver and Toronto). Contamination of the soil with Ni was detected only at Sudbury and Noranda where Ni-bearing ore was mined.

Lead is a neurotoxin and associates with the alkaline earths in the human body. Consequently, Pb is stored in bones together with Ca, Sr, and Ba. The biogeochemistry of Pb and its effects on human health were summarized in a two-volume set of books edited by Nriagu (1978). The occurrence of Pb and other trace metals in the environment was also treated by Cannon and Hopps (1971), Thornton (1983), Salomons and Förstner (1984), and Fuge et al. (1996). The biogeochemistry of trace metals in aquatic organisms was the subject of a book edited by Tessier and Turner (1995). The contamination of even the most remote sites on the Earth with Pb since the onset of the industrial revolution in the middle of the 19th century was thoroughly documented by C. C. Patterson and his collaborators at the California Institute of Technology (Patterson, 1981). A set of papers in honor of Dr. Patterson's retirement was published in 1994 in *Geochimica et Cosmochimica Acta*, 58(15).

25.1 Isotope Composition of Environmental Lead

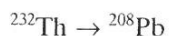
The study of Pb in the environment not only is based on the concentrations of this element in different kinds of samples, but relies also on its isotope composition. Lead in the environment may have a range of isotopic compositions because, in many cases, it is derived from different sources that have characteristic isotope compositions depending on the type of ore deposits from which the Pb originated. The isotope composition

Table 25.1 Enrichment Factors of Selected Metals in Contaminated Soils and Industrial Dust Compared to Those of Normal Soil^a (Warren, 1972)

Locality	Pb	Cu	Zn	Ni
Soil^a				
Vancouver, industrial	20.5	13.0	6.6	0.43
Vancouver, nonindustrial	24.0	2.7	6.0	0.63
Toronto, industrial	19.5	4.1	6.6	0.65
Liverpool, allotment gardens	27.5	3.1	3.7	0.68
Trail, British Columbia	65.0	2.1	10.6	0.48
Sudbury, Ontario	2.9	12.5	1.34	10.4
Noranda, Quebec	12.5	22.5	6.2	1.15
Dust				
Richmond, B.C. (contam.)	4000	47.5	23.2	—
Vancouver, industrial	1200	16.0	108	—
Vancouver, west end	600	31.3	33.6	—
New York, heavy traffic	2000	—	—	—
Toronto, industrial	6780	6.1	6.4	—

^aAverage soil in ppm: Pb = 10, Cu = 20, Zn = 50, Ni = 40 (Vinogradov, 1959).
(—, not determined.)

of Pb in ore deposits depends on the U/Pb and Th/Pb ratios and on the geologic ages of the source rocks from which Pb was removed during the ore-forming process (Faure, 1986). The ultimate cause for the variations of the isotope composition of Pb is that three of its four stable isotopes are decay products of isotopes of U and Th (Section 16.3e, Table 16.1):



Since ^{204}Pb is the only nonradiogenic stable isotope, the isotopic composition of Pb can be expressed in the form of atomic ratios: $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$, which can be combined in various ways for specific purposes. For example, the isotopic composition of environmental Pb is commonly expressed in terms of the

$^{206}\text{Pb}/^{204}\text{Pb}$, $^{206}\text{Pb}/^{207}\text{Pb}$, and $^{206}\text{Pb}/^{208}\text{Pb}$ ratios. The $^{206}\text{Pb}/^{207}\text{Pb}$ ratio can be calculated from:

$$\frac{^{206}\text{Pb}}{^{204}\text{Pb}} = \frac{^{206}\text{Pb}}{^{207}\text{Pb}} \times \frac{^{204}\text{Pb}}{^{207}\text{Pb}} = \frac{^{206}\text{Pb}}{^{207}\text{Pb}}$$

Automobile exhaust fumes became the most important source of environmental Pb after 1923 when tetraethyl Pb was added to gasoline. Chow and Johnstone (1965) measured the isotope composition of Pb in gasoline sold in May of 1964 in San Diego, California, in the hope that the results would help to identify the sources of Pb in the atmosphere. The results in Figure 25.1 indicate that the $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{207}\text{Pb}$ ratios of gasoline have characteristic values, except for gasoline sold by the Shell Oil Co.

The data in Figure 25.1 demonstrate that the Pb in aerosol collected by an electrostatic air filter

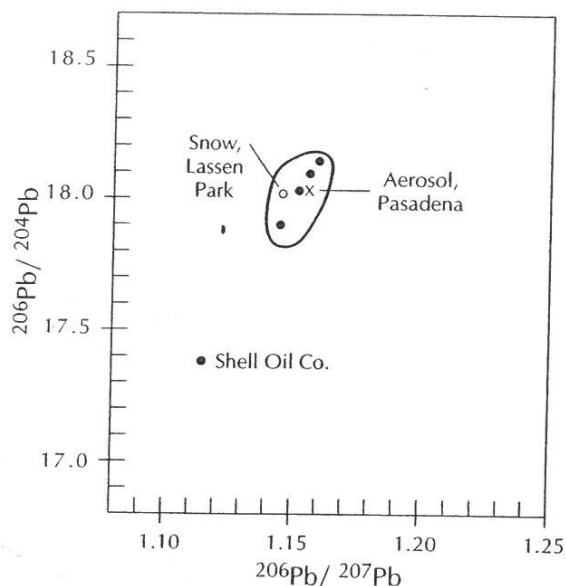


Figure 25.1 Isotope composition of Pb in leaded gasoline (solid circles) purchased in May 1964 in San Diego, California. The distribution of data points indicates that the Pb in aerosol particles on the Caltech campus in Pasadena (cross) and in snow of Lassen National Park (open circle) has virtually the same isotope composition as Pb in gasoline. This result reveals that automobile exhaust fumes were the dominant source of environmental Pb in 1963 and 1964 in California. The difference in the isotope composition of Pb in the gasoline sold by the Shell Oil Co. presumably indicates that the Pb originated from different ore deposits (from Chow and Johnstone, 1965).

at the geochemistry laboratory of the California Institute of Technology in the spring of 1964 originated from leaded gasoline. The concentration of Pb in the ash of the dust collected on the air filter was 5000 parts per million (ppm). In addition, the data show that the isotope composition of Pb in snow in Lassen National Park is also similar to that of Pb in gasoline. Therefore, the Pb in snow of Lassen Park could have originated by combustion of leaded gasoline like that sold in San Diego. The deviation of the Pb in gasoline sold by the Shell Oil Co. from the others in Figure 25.1 presumably indicates that the Pb originated from differ-

ent ore deposits. Nevertheless, these results reveal that in 1963 and 1964 automobile exhaust fumes were the dominant source of atmospheric Pb in California.

25.2 Lead in the Environment

The environmental Pb derived from natural sources has been overwhelmed by anthropogenic Pb, most of which is discharged into the atmosphere and is widely dispersed over the surface of the Earth. Therefore, the atmosphere plays an important role in the geochemistry of environmental Pb.

a. Sources of Atmospheric Lead

Natural sources of atmospheric Pb include (Nriagu, 1978):

1. Windblown dust (85%).
2. Plant exudates (10%).
3. Forest fires, volcanic eruptions, and meteorite impacts (3%).
4. Radioactive decay and seasalt spray (2%).

The total amount of Pb released annually into the atmosphere from these sources is about 18,600 tons or 1.86×10^{10} g, compared to about 44×10^{10} g released in 1974/75 from anthropogenic sources. In other words, natural sources contributed only about 4% of the total amount of Pb that was discharged annually into the atmosphere in the 1970s.

The principal sources of anthropogenic Pb are (Nriagu, 1978):

1. Combustion of leaded gasoline (61%).
2. Production of steel and base metals (23%).
3. Mining and smelting of Pb (8%).
4. Combustion of coal (5%) (Chow and Earl, 1972).

The amounts of anthropogenic Pb discharged into the atmosphere from these sources vary regionally around the world and change with time. For example, the use of leaded gasoline has been discontinued in the USA, Canada, and many European countries. Consequently, there has been a welcome reduction in the amount of

anthropogenic Pb deposited on the surface of the Earth from the atmosphere. In fact, Wu and Boyle (1997) reported that anthropogenic Pb has been virtually eliminated from the surface water of the North Atlantic Ocean.

Both natural and anthropogenic Pb in the atmosphere occur in the form of aerosol particles whose median diameters range from 0.12 μm (Los Angeles freeway) to 0.7 μm (Toronto). The particles have a variety of shapes including spheres, single crystals, and aggregates of smaller particles. In rural air, the particles consist of a large number of Pb compounds, such as PbCO_3 (30%), $(\text{PbO})_2 \text{PbCO}_3$ (28%), PbO (21%), PbCl_2 (5.4%), PbOPbSO_4 (4%), etc. (Ter Haar and Bayard, 1971). The compositions of aerosol particles in automobile exhaust are dominated by PbBrCl , but the particles also contain oxides, oxyhalides, sulfate, phosphate, and oxysulfate. The residence time of Pb-bearing aerosol particles in the troposphere ranges from 2 to 10 days.

Patterson (1965) estimated that the Pb concentration of pristine (preindustrial) air was about 0.6 nanogram per cubic meter (ng/m^3 ; 1 nanogram = 10^{-9}). Even lower values of 0.046 ng/m^3 have been reported for air over the North Atlantic (Nriagu, 1978). However, at most other sites on the Earth today the Pb concentrations of air are much higher than Patterson's value for pristine air, especially in metropolitan areas and near Pb smelters. The data tabulated by Nriagu (1978) include 0.63 ng/m^3 at the South Pole, 5.5 ng/m^3 at Mauna Loa, Hawaii, and 8.0 ng/m^3 at White Mountain, California.

The concentration of Pb in the air of large cities worldwide is up to three orders of magnitude greater than that of air at the remote locations cited above. A sampling of the data compiled by Nriagu (1978) indicates the following Pb concentrations in air on busy streets of European capitals:

		$\mu\text{g}/\text{m}^3$
Berlin, Germany	1966-67	3.8
Rome, Italy	1972-73	4.5
Paris, France	1964	4.6
London, England	1972	5.1

The situation in the USA was not much better:

New York	1960-65	4.1
Boston	1972	4.5
Detroit	1960-65	4.8
Los Angeles	1954-55	6.6

b. Snow and Ice

Atmospheric transport of anthropogenic Pb has caused the contamination of meteoric precipitation, soil, and surface water in the oceans. Records of the history of contamination of the surface of the Earth have been preserved in ice sheets of the polar regions and in lacustrine sediment.

The extent of contamination of remote sites by airborne Pb was originally demonstrated by Tatsumoto and Patterson (1963). Subsequently Chow and Johnstone (1965) reported that the isotope composition of Pb in snow collected in 1963 in Lassen State Park in California is indistinguishable from that of gasoline sold in San Diego and of aerosols in Los Angeles (Figure 25.1). In addition, they cited an estimate by Patterson that 2.7×10^{11} g of Pb was released annually by combustion of leaded gasoline in the northern hemisphere and used it to calculate that the Pb concentration of snow in Lassen Park from this source alone is 1.1 $\mu\text{g}/\text{kg}$. The predicted value is similar to the concentration of 1.6 $\mu\text{g}/\text{kg}$ measured by Tatsumoto and Patterson (1963) and thereby confirmed that most of the Pb in the snow at Lassen Park originated from automobile exhaust fumes.

The definitive study of Pb in snow and ice in Greenland and Antarctica was carried out by Murozumi et al. (1969). They took extreme precautions in the collection and subsequent analysis of snow and ice samples and reported much lower concentrations of Pb than had been observed in snow and ice at temperate regions. Their measured Pb and Ca concentrations in Figure 25.2 in ice at Camp Century (77°10'N, 61°08'W) in northern West Greenland reveal the history of anthropogenic emission of Pb into the atmosphere. The Pb concentrations generally increased from 0.011 $\mu\text{g}/\text{kg}$ in 1753 A.D. to about 0.068 $\mu\text{g}/\text{kg}$ at about 1945. Subsequently, the Pb concentrations

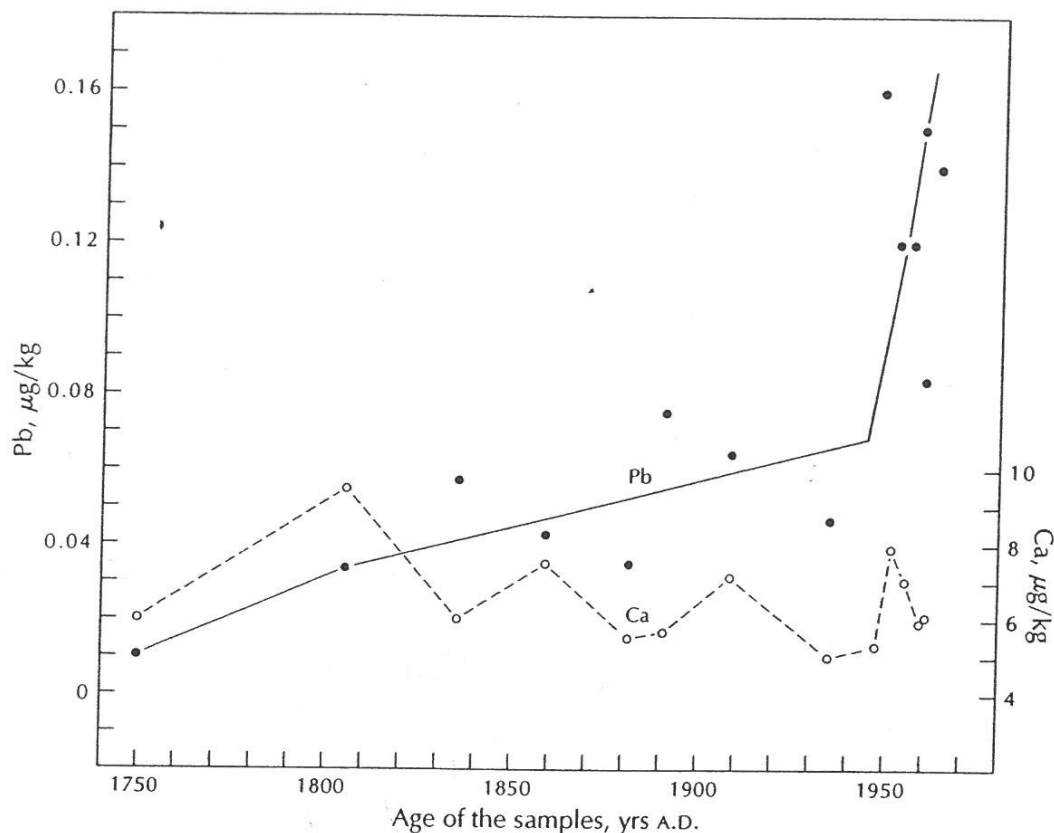


Figure 25.2 Evidence for anthropogenic contamination of the atmosphere with Pb recorded in ice and snow deposited between 1750 and 1963 A.D. at Camp Century ($77^{\circ}10'N$, $61^{\circ}08'W$) about 200 km east of Thule located on the west coast of North Greenland. The concentrations of Pb in ice and snow at this site rise from $0.011 \mu\text{g/kg}$ in 1753 A.D. to about $0.068 \mu\text{g/kg}$ in 1945 A.D. Subsequently, the Pb concentrations rise steeply to about $0.16 \mu\text{g/kg}$ in 1960. In contrast to the increasing Pb concentrations, the Ca concentrations of the ice at Camp Century remained constant at an average value of $6.4 \pm 0.7 \mu\text{g/kg}$, (data from Murozumi et al., 1969).

rose steeply to about $0.16 \mu\text{g/kg}$ by 1960. In contrast to Pb, the Ca concentrations did not change systematically in the same time interval and have an average value of $6.4 \pm 0.7 \mu\text{g/kg}$.

The increasing concentrations of Pb in ice and snow at Camp Century between 1750 and 1920 are attributable primarily to emissions from Pb smelters, with a minor contribution from combustion of coal. Starting in 1923, when tetraethyl Pb was introduced as an additive to gasoline, automobile exhaust fumes became a growing source of Pb contamination, whereas emission of

smelters declined starting about 1880 because of efforts to prevent the loss of Pb for economic reasons. The rapid increase in the concentrations of Pb after 1945 in the Camp Century ice core was caused almost entirely by automobile exhaust fumes (Murozumi et al., 1969).

In a recent review of the concentrations of Pb and other metals in snow and ice, Boutron et al. (1994) reported that the concentration of Pb in snow in Antarctica increased by a factor of about 10 from 1900 to 1980, whereas the Pb content of Greenland snow rose by a factor of more than 200

between 1750 and 1989 as a result of anthropogenic inputs of Pb to the troposphere. However, they also concluded that the Pb concentration of snow in Greenland has decreased significantly after the use of tetraethyl lead in gasoline declined in the USA and Canada. The decrease in Pb concentrations in the western North Atlantic Ocean was also reported by Wu and Boyle (1997).

The concentrations of Pb in snow in the interior of Antarctica are very low and range from 0.5 picogram/g (1 picogram = 10^{-12} /g) for ice at Dome C about 7500 years B.P. to about 5 pg/g for snow in 1980. In order to accurately determine such low concentrations of Pb, extreme precautions are required to prevent contamination of snow or ice during collection, transport, and analysis in the laboratory (Patterson and Settle, 1976; Boutron, 1990).

c. Lacustrine Sediment

The contamination of the Earth's surface with anthropogenic Pb was also demonstrated by Shirahata et al. (1980) who determined concentrations of Pb in sediment deposited in a remote pond in Thompson Canyon in Yosemite National Park, California. The data in Figure 25.3 reveal that the concentration of Pb increased from 9.6 $\mu\text{g/g}$ at about 1700 A.D. to $14.8 \pm 0.8 \mu\text{g/g}$ between 1853 and 1894 A.D. Subsequently, the Pb concentration increased to 42.4 $\mu\text{g/g}$ in sediment deposited between 1962 and 1968. The most recent sample, deposited between 1968 and 1976, contains about 10% less Pb than the sediment in the preceding interval.

The foregoing example suggests that the distribution of Pb in lacustrine sediment is a record of the industrial development of the surrounding area and therefore has archaeological value. This aspect of the environmental geochemistry of Pb is illustrated by the work of Ritson et al. (1994) on the concentrations and isotope composition of Pb in the sediment of Lake Erie. Their paper is the latest contribution to the study of the contamination of the Great Lakes of North America with heavy metals of anthropogenic origin (Flegal et al., 1989; Nriagu et al., 1979; Edgington and Robbins, 1976).

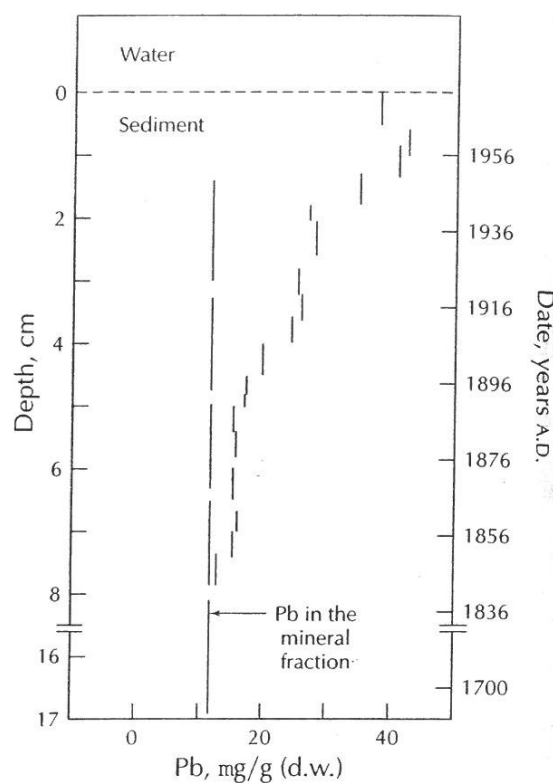


Figure 25.3 Concentrations of Pb in dry sediment in a core recovered from a remote pond in Thompson Canyon, Yosemite National Park, California. The sediment contains both anthropogenic Pb adsorbed on humus and Pb contained within the mineral grains. The average concentration of Pb in the mineral fraction of the sediment is $11.8 \pm 1.1 \mu\text{g/g}$ (2σ , $N = 7$). The diagram shows that the amount of anthropogenic Pb increased with time after about 1850 A.D. and reached a maximum between 1962 and 1968 A.D. (from Shirahata et al., 1980).

The data for the western basin of Lake Erie in Figure 25.4 reveal a sharp increase in the total concentration of Pb in sediment at a depth of 15 cm below the sediment-water interface. The sediment at that depth was deposited in 1963. Ritson et al. (1994) reported that the isotope ratios of Pb also changed at that time from $^{206}\text{Pb}/^{207}\text{Pb} = 1.243$ before 1963 to 1.202 after that year. The simultaneous change of both the concentration and the iso-

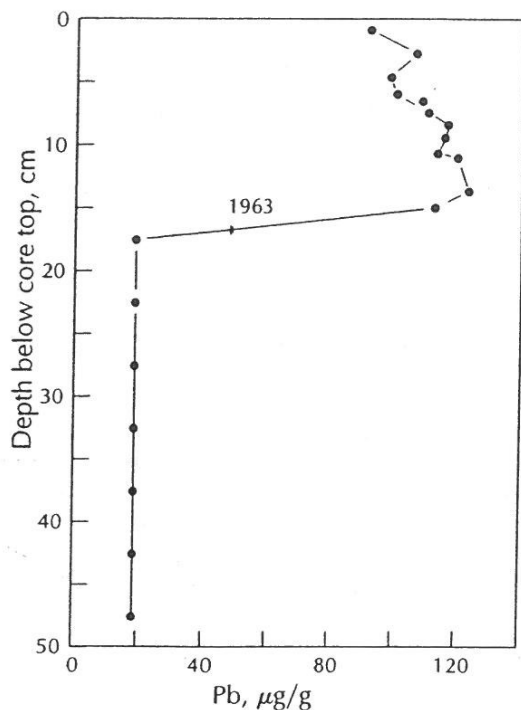


Figure 25.4 Profile of Pb concentrations of bulk sediment in a short core (0–50 cm) taken in the western basin of Lake Erie, USA and Canada. The increase of the Pb concentration from an average of $17.3 \pm 0.3 \mu\text{g/g}$ to $124.4 \pm 0.5 \mu\text{g/g}$ occurred at 1963 A.D. The $^{206}\text{Pb}/^{207}\text{Pb}$ ratios also changed from 1.243 ± 0.0006 to 1.202 ± 0.0001 . The sediment deposited prior to 1963 contains Pb derived from natural sources. The anthropogenic Pb in the more recent sediment is attributable to municipal wastewater as well as to the combustion of coal and leaded gasoline (data and interpretation from Ritson et al., 1994).

tope composition of Pb in the western basin of Lake Erie indicates a change in the sources of Pb.

According to Ritson et al. (1994), the dominant *natural* source of Pb in the western basin of Lake Erie is sediment derived from the Detroit River, the Maumee River, and from the erosion of shoreline bluffs. *Anthropogenic* Pb is contributed by combustion of coal and leaded gasoline as well as by discharge of municipal wastewater. In the

western basin, municipal wastewater is the dominant source of anthropogenic Pb because of the large populations of the cities of Detroit, Toledo, and Cleveland. The Pb in the central and eastern basins originated primarily by atmospheric deposition of Pb derived from combustion of coal and leaded gasoline, as well as by transport of sediment from the western basin. Anthropogenic Pb is detectable in sediment deposited in the western basin starting in 1963 and in the eastern basin starting in 1926. Prior to these dates, the average concentrations of Pb in sediment throughout the lake were fairly uniform, ranging from about $17.3 \pm 0.3 \mu\text{g/g}$ (western basin) to $17.6 \pm 0.5 \mu\text{g/g}$ (central basin) to $18.4 \pm 0.5 \mu\text{g/g}$ (eastern basin). The $^{206}\text{Pb}/^{207}\text{Pb}$ ratios were also similar, ranging from 1.242 ± 0.0006 (west) to 1.228 ± 0.0013 (central) to 1.228 ± 0.0020 (east). In addition, the $^{206}\text{Pb}/^{207}\text{Pb}$ ratio of sediment from long cores (1.80–10.25 m) in Lake Erie have an average value of 1.229 ± 0.004 , which is indistinguishable from the Pb in the short cores. For these and other reasons Ritson et al. (1994) concluded that these concentrations and isotope ratios represent Pb derived from natural sources.

d. Mixing of Lead in Lake Erie Sediment

The data of Ritson et al. (1994) indicate that the recently deposited sediment in Lake Erie contains mixtures of natural and anthropogenic Pb. Therefore, the concentrations and isotope ratios of the Pb are related to the end members by equations 18.19 and 18.20 (Section 18.5), restated here for convenience in terms of Pb concentrations and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios:

$$\text{Pb}_M = \text{Pb}_A f_A + \text{Pb}_B (1 - f_A) \quad (25.1)$$

$$\left(\frac{^{206}\text{Pb}}{^{204}\text{Pb}} \right)_M = \left(\frac{^{206}\text{Pb}}{^{204}\text{Pb}} \right)_A \frac{\text{Pb}_A}{\text{Pb}_M} f_A + \left(\frac{^{206}\text{Pb}}{^{204}\text{Pb}} \right)_B \frac{\text{Pb}_B}{\text{Pb}_M} (1 - f_A) \quad (25.2)$$

where Pb is the concentration, f is the weight fraction, and the subscripts A, B, and M refer to the components A and B and the mixture M,

respectively. These equations can be used to construct mixing hyperbolas in coordinates of the Pb concentration (x-coordinate) and the $^{206}\text{Pb}/^{204}\text{Pb}$ ratio (y-coordinate) for any two end-member components A and B. Equations 25.1 and 25.2 can be combined to yield the equation of the mixing hyperbola:

$$\left(\frac{^{206}\text{Pb}}{^{204}\text{Pb}}\right)_M = \frac{a}{\text{Pb}_M} + b \quad (25.3)$$

where a and b are constants whose values are derived from the isotope ratios and concentrations of Pb in the end-member components (Section 18.5). The significance of equation 25.3 arises from the fact that it is a straight line when the isotope ratios are plotted versus the reciprocal concentrations of Pb.

For this reason, the data reported by Ritson et al. (1994) for short cores from the western, central, and eastern basins of Lake Erie form a linear array of points in Figure 25.5. The fit of the data points to a straight line is not perfect because the isotope ratios and concentrations of Pb in sediment containing primarily anthropogenic or natural Pb vary in terms of time and space. Nevertheless, the sediment samples deposited after 1948 in the eastern and western basins cluster within narrow limits and have average values approaching those of sediment containing only the anthropogenic component:

	Western basin	Eastern Basin
Pb, $\mu\text{g/g}$	110.5 ± 5.5	68.5 ± 6.9
$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	18.79 ± 0.04	18.81 ± 0.03

The isotope compositions and concentrations do not represent Pb of purely anthropogenic origin because even the sediment deposited after 1948 contains some Pb derived from natural sources. The $^{206}\text{Pb}/^{204}\text{Pb}$ ratio of anthropogenic Pb lies on the extension of the mixing line and must have a value greater than about 18.6 when the concentration of Pb in the sediment becomes very large.

Sediment samples deposited in the eastern basin between 1926 and 1946 form a separate

array in Figure 25.5 and approach the cluster of data points representing sediment deposited after 1948. The source of Pb deposited between 1926 and 1948 in the eastern basin of Lake Erie is presently unknown.

The sediment in the central basin contains Pb whose isotope ratios encompass the entire range of values from nearly pure anthropogenic to natural Pb. However, anthropogenic Pb is less abundant in the central basin than in the eastern and western basins.

The sediment deposited in Lake Erie prior to the introduction of large amounts of anthropogenic Pb is characterized by high $^{206}\text{Pb}/^{204}\text{Pb}$ ratios and low concentrations. The sediment deposited prior to 1968 in the western basin forms a separate array. Nevertheless, the average isotope ratios and concentrations of Pb from *natural* sources are:

	Western basin	Eastern basin
Pb, $\mu\text{g/g}$	17.3 ± 0.3	18.4 ± 0.5
$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	19.45 ± 0.05	19.21 ± 0.11

The combination of isotope ratios and concentrations of Pb in the sediment of Lake Erie in Figure 25.5 reveals that the Pb deposited in the lake is a mixture derived primarily from two sources in varying proportions. Therefore, mixing theory applied to closely spaced samples of lacustrine sediment of known age can recover information about the history of industrial activity in the area.

25.3 Lead in Plants

The growth of plants depends on the availability of certain essential nutrients:

C, H, O, N, P, S, K, Ca, Mg, Fe, as well as B, Cl, Cu, Mn, Mo, Zn.

In addition, small concentrations of other elements appear to be beneficial to plants, including Se, Co, Si, and V. However, plant tissue may contain many other elements that do not necessarily have a useful function.

Chemical elements enter plants either from soil through the roots or by absorption from the

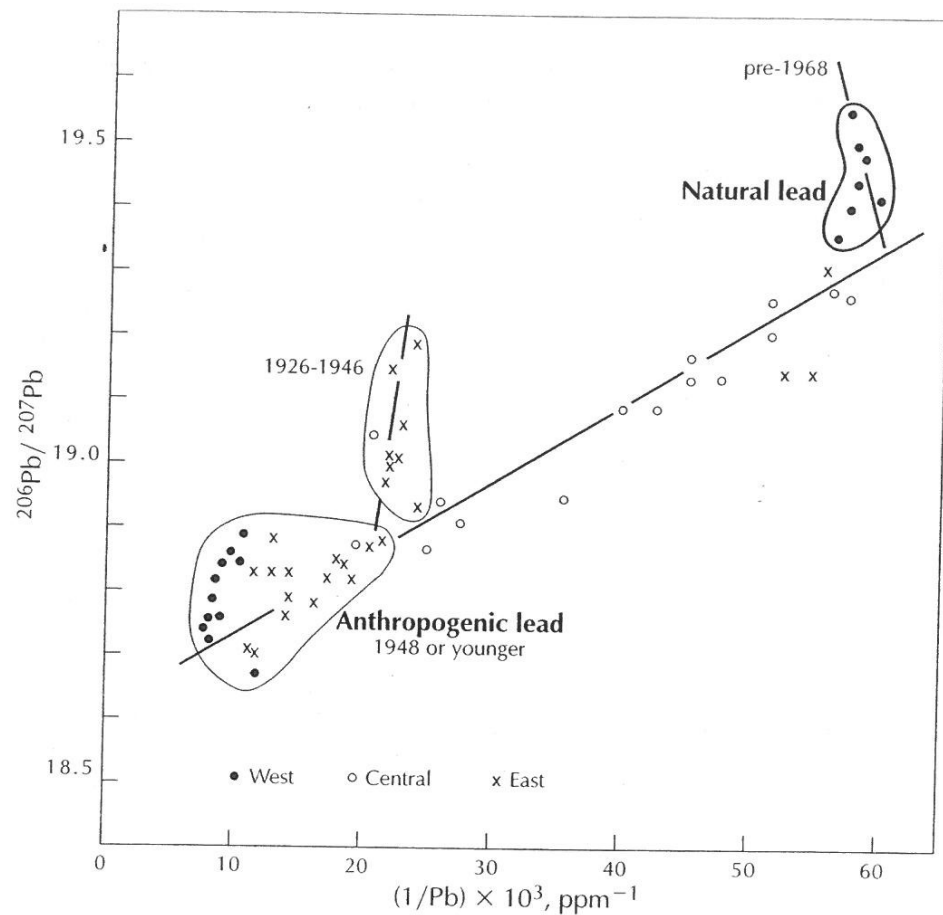


Figure 25.5 Mixing diagram for Pb in sediment samples derived from short cores recovered from the western, central, and eastern basins of Lake Erie. Sediment deposited after 1968 in the western and, after 1946, in the eastern basins contains primarily anthropogenic Pb, whereas sediment deposited before 1968 in the western basin and before 1926 in the eastern basin is dominated by Pb derived from natural sources. The sediment in the central basin contains mixtures of anthropogenic and natural Pb in varying proportions. The isotope compositions of the anthropogenic and natural Pb changed significantly in the time intervals represented by sediment samples that form separate arrays of data points (data from Ritson et al., 1994).

atmosphere by leaves. Plants can absorb only those elements from soil that occur in aqueous solution or are adsorbed on the surfaces of solid particles composed of minerals, amorphous oxides and hydroxides, or organic matter. Ions in solution can diffuse directly into the cells of root tips. Cations that are adsorbed on the surfaces of soil particles must be replaced by H^+ released by the roots as a result of dissociation of carbonic acid

formed from CO_2 . The H^+ ions release nutrients (Ca^{2+} , Mg^{2+} , K^+ , etc.) from exchangeable sites on the surfaces of clay minerals and other types of soil particles. The cations then diffuse to the root tip where they are exchanged for H^+ ions that move into the soil to release additional nutrients.

Consequently, plants are selective in the absorption of elements from soil and exclude those elements that are toxic. However, the exclusion

mechanisms fails when the concentration of the toxic element exceeds a certain threshold level. For example, the data of Nicolls et al. (1965) in Figure 25.6 indicate that *Triodia pungens* maintains a constant concentration of Pb of about 10 ppm (plant ash) until the Pb concentration of the soil within about 15 cm of the plant approaches the

threshold value of about 580 ppm. Above this threshold, the concentration of Pb in the plant increases rapidly to a toxic level of more than 150 ppm (plant ash). The exclusion of Cu by *Triodia pungens* is less effective than that for Pb, and Zn is assimilated without exclusion up to 10,000 ppm (plant ash). Therefore, *Triodia pungens*

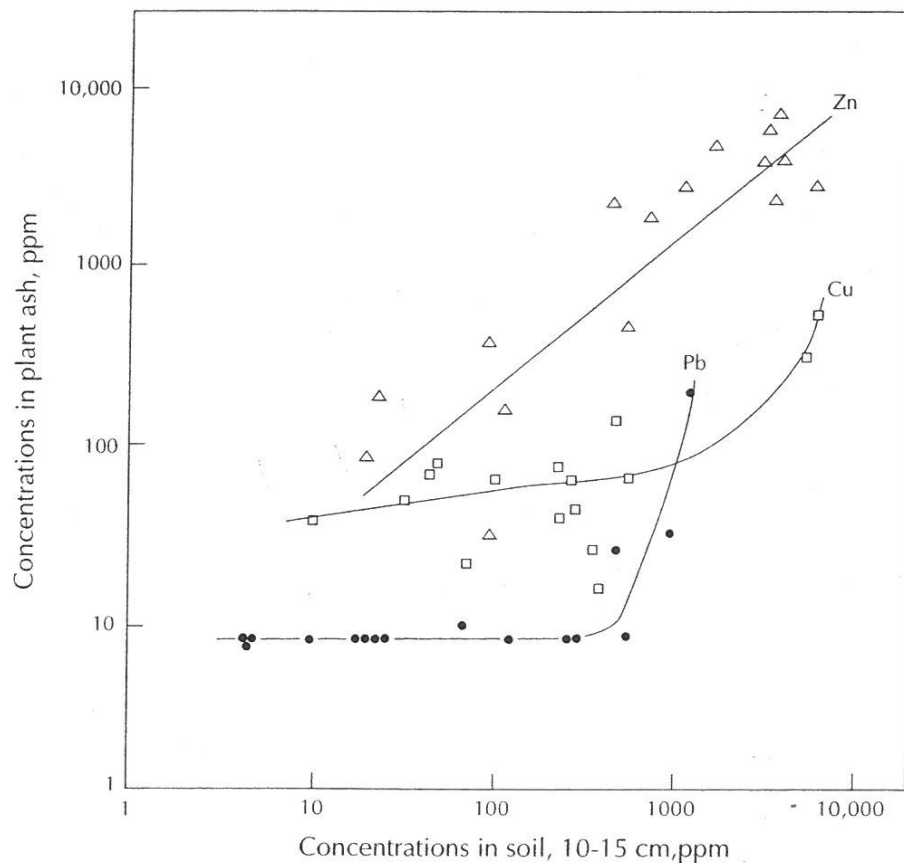


Figure 25.6 Concentrations of Pb, Cu, and Zn in the ash of *Triodia pungens* growing in soil containing a range of concentrations of these metals. The plant maintains a constant Pb concentration of <10 ppm until the Pb concentration of the soil within 10–15 cm of the plant increases to the threshold value of about 580 ppm. At higher soil concentrations, the Pb concentration of the plant rises to toxic levels at about 170 ppm. The data show that the threshold for Cu is higher than that for Pb and that the plant admits Zn without discrimination up to almost 10,000 ppm (from Brooks, 1972; after Nicolls et al., 1965).

tends to exclude Pb and Cu, but admits Zn up to high levels of concentration. In general, different types of plants growing in the same soil may contain different concentrations of metals depending on the nutritional requirements of each species and on the depth of penetration of their roots (Peterson, 1978).

Average concentrations of Pb in plants growing in uncontaminated soil range from about 26 to 85 $\mu\text{g/g}$ (ash). Plants growing in Pb-rich soil may contain up to 100 times more Pb. Mosses, liverworts, and lichens are especially efficient in collecting Pb from the atmosphere and from dilute aqueous solutions. Peterson (1978) cited data from the literature indicating extremely high Pb concentrations in these kinds of plants (e.g., 11,611 $\mu\text{g/g}$ in mosses; 15,900 $\mu\text{g/g}$ in liverworts; and 12,045 $\mu\text{g/g}$ in lichens).

The contamination of plants with Pb occurs naturally in areas where soils have formed from Pb-rich rocks. However, in most cases plants are contaminated with Pb released by mine dumps, landfills, and aerosol particles deposited by smelter plumes, and by combustion of leaded gasoline. As a result, wildlife as well as domestic animals feeding on contaminated vegetation may be adversely affected.

25.4 Lead Poisoning of Cows and Horses

Plants discriminate against Pb such that the Pb/Ca ratios of plants are lower than those of the soil in which they grow. Similarly, herbivorous and carnivorous animals preferentially excrete Pb in relation to Ca. This process of *biopurification* causes the Pb/Ca ratios of successive members of the food chain to decline.

Lead poisoning of domestic animals generally results from the ingestion of plants containing excessive concentrations of anthropogenic Pb. Cattle are especially vulnerable because of their indiscriminate eating habits. Forbes and Sanderson (1978) listed the symptoms of acute lead poisoning

in cattle: diarrhea, colic, disorders of the central nervous system, excitement or stupor or depression, loss of coordination, and blindness. However, not all of the symptoms may be present and some cattle have died of Pb poisoning without displaying any of the symptoms. The internal organs of cattle that died from Pb poisoning generally have high concentrations of this element (e.g., livers: 43 ppm, from 0 to 1300; kidneys: 137 ppm, from 2 to 2355). The livers and kidneys of healthy cattle contain only 0.3 to 1.5 ppm of Pb.

A case of Pb poisoning of horses on two pastures near Benicia, California, was investigated by Rabinowitz and Wetherill (1972). They reported that the principal source of anthropogenic Pb in this area was a Pb smelter at Benicia that daily discharged about 45 kg of Pb into the atmosphere. Automobile exhaust contributed an additional 15 kg of Pb per day. Grass collected about 500 meters from the smelter had a Pb concentration of 9645 $\mu\text{g/g}$. Grass along the local freeways also had high lead concentrations, ranging from 275 to 6141 $\mu\text{g/g}$.

The data in Figure 25.7 demonstrate that the concentrations of Pb in grass near Benicia, California, decreased with increasing distance from the smelter, but remained anomalously high (268 $\mu\text{g/g}$) for at least 50 km downwind from the smelter. Grass at a remote location about 100 km downwind of the smelter was found to have a Pb concentration of 36 $\mu\text{g/g}$. However, even that value exceeds the average concentrations of Pb in different vegetables reported by Warren and Delavault (1971). The grass on the horse pastures had very high Pb concentrations of 5975 $\mu\text{g/g}$ at 3.7 km and 680 $\mu\text{g/g}$ at 8.5 km downwind from the smelter.

The symptoms displayed by the horses in the contaminated area included anemia, nucleated red blood cells, peripheral neuritis, and poor health. The cause of death was identified as respiratory complications of chronic Pb poisoning. The Pb concentrations of the kidneys of two horses that had been pastured at 3.7 and 8.5 km downwind from the smelter were found to be 16 and 9.4 $\mu\text{g/g}$, respectively, compared to concentrations

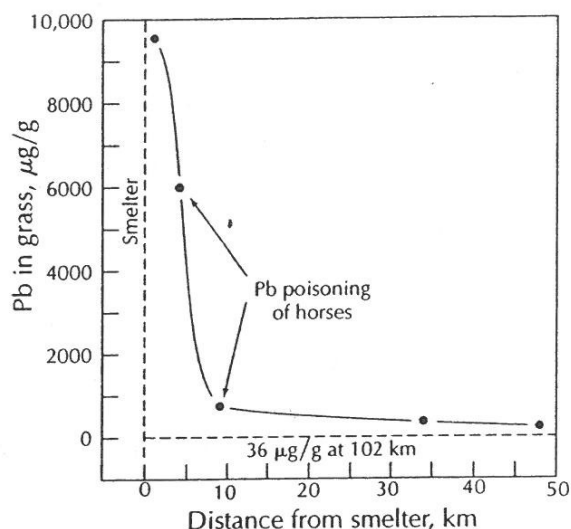


Figure 25.7 Concentrations of Pb in grass at increasing distances downwind from a smelter at Benicia, north of San Francisco, California. The Pb concentrations decrease with increasing distance downwind from the smelter. However, horses pastured in the smelter plume up to 10 km downwind died of chronic Pb poisoning (from Rabinowitz and Wetherill, 1972).

of 1–5 µg/g in the kidneys of horses in the Los Angeles basin that died of other causes. Rabinowitz and Wetherill (1972) concluded that the smelter was the dominant source of Pb in grass growing up to 35 km downwind of it. At greater distances, gasoline became a significant source, reflected in a different isotopic composition of the Pb.

The isotope ratios of Pb in the grass of the horse pastures in Figure 25.8 is similar to that of aerosols collected at the pastures and elsewhere within the plume emitted by the smelter. The Pb in grass growing along the local freeways and in curbside scrapings and aerosols in Berkeley originated primarily from automobile emissions and has a distinctly different isotope composition than the smelter Pb. The kidneys, livers, and bones of horses that died of Pb poisoning on the pastures in the smelter plume contain Pb of intermediate isotopic composition. Evidently, the horses

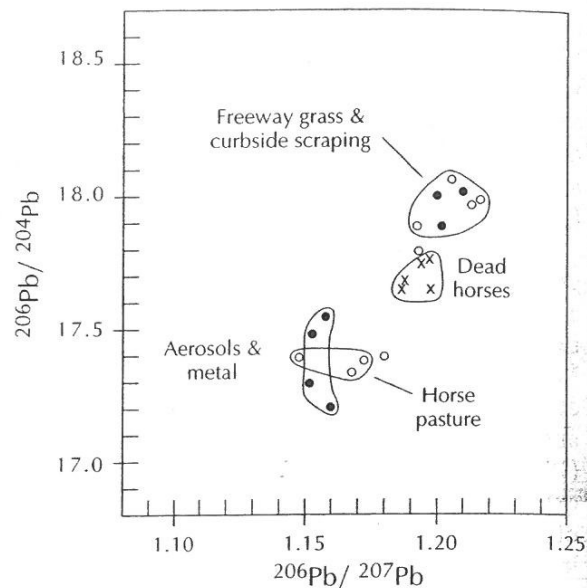


Figure 25.8 Isotope composition of Pb in grass (open circles), aerosols and curbside scrapings (solid circles), and internal organs of horses that died of Pb poisoning (crosses) near Benicia, north of San Francisco, California. The isotope composition of Pb in grass in the horse pastures is similar to that of aerosols derived from a nearby Pb smelter. The Pb in grass along local freeways and curbside scrapings has a distinctly different isotope composition than the smelter Pb in the aerosols. The isotope composition of Pb in kidneys, livers, and bones of horses that died of Pb poisoning is intermediate between those of the pasture grass and in gasoline emissions. Evidently, the horses assimilated not only smelter Pb in the grass they ate but also Pb from automobile exhaust (from Rabinowitz and Wetherill, 1972).

ingested not only smelter Pb in the grass but also freeway Pb in the air they breathed.

Ironically, Hippocrates (460–377 B.C.) reported 2400 years ago that cows and horses could not be pastured near the mines of Laurion near Athens in classical Greece because they became sick and died (Lessler, 1988). It is now known that farm animals have a low tolerance for Pb compared to humans. For example, Zmudski et al. (1983) reported that horses receiving only 3–4 mg of Pb per kg of feed per day died in a few weeks.

25.5 Human Bones and Tissues

In 1965 Patterson published an invited paper in the Archives of Environmental Health in which he estimated that the natural concentration of Pb in human bones is about $0.85 \mu\text{g/g}$ and that the present Pb content of humans is about 200 times *higher* than expected on geochemical grounds. He concluded that the present Pb content of most humans in developed countries is a toxic burden that jeopardizes their health. Patterson and his research group later demonstrated that 1600-year-old human bones from South America actually do contain less Pb by several orders of magnitude than the bones of present-day humans (Ericson et al., 1979).

The outward symptoms of Pb poisoning in humans were described by Hippocrates (460–377 B.C.) as loss of appetite, colic, palor, weight loss, fatigue, and irritability (Lessler, 1988). A more recent review of the effects of Pb on human health by Posner et al. (1983) included the same symptoms and discussed the specific effects on the digestive, renal, muscular, nervous, and vascular systems.

Lead poisoning of humans generally results from the use of this metal in the home and from occupational exposures. Sources of Pb in the home include paint (white and red), water pipes made from Pb, litharge (glazing compound), solder, leaded gasoline, ammunition, storage batteries used in automobiles, lead-bearing glaze in pottery, etc. Occupational exposure to Pb is associated with mining and smelting of ores of Pb and related chalcophile metals, printing with Pb type, ship and bridge repair releasing flakes of Pb paint, manufacture of Pb compounds, etc.

The use of Pb in the home has been greatly reduced in many countries following the recognition of the harmful effects of this metal, especially for children. In the USA and Canada the manufacture and sale of leaded gasoline, Pb-based paint, and Pb-bearing glazes on pottery have been discontinued. As a result, the incidence of acute Pb poisoning has declined, but the effect of low-level Pb exposures on the mental development of pre-natal children is still a subject of concern.

a. Bones

Most of the Pb in the human body is stored in bones where it accumulates throughout life starting before birth. Soft tissues (e.g., liver, kidney, aorta, pancreas) have different but lower concentrations of Pb than bones. In general, the bones of adult males in the UK contain between about 91.6 and 96.0% of the total body burden of Pb. The amount of Pb in the bones of adult males in the UK is larger than that of females, but both increase with age. This conclusion is illustrated in Figure 25.9 based on the data of Barry (1975, 1976).

The soft tissues contain less Pb than bones and the amount is dependent of age (Figure 25.9). The amount of Pb in the soft tissue is balanced between the uptake of this element in food and water and from the air and its excretion or storage in the bones. The Pb in the vital organs, in blood, and in muscle tissue interferes with metabolic processes and therefore gives rise to the symptoms of Pb poisoning.

The concentration of Pb in bones of modern residents of the USA varies with age, according to data by Schroeder and Tipton (1968). The bones of adults between the ages of 30 and 69 have an average Pb concentration of $39.0 \mu\text{g/g}$ (ash) based on a sample of 50 individuals. The increase in the concentration of bone Pb with age in Figure 25.10 indicates that the intake of this element exceeded the ability of the body to excrete it. The low concentrations of Pb in the bones of individuals more than 70 years of age was attributed by Schroeder and Tipton (1968) to the survival of those person who had the lowest concentrations of Pb. Alternatively, these person may have had low Pb-exposures in their youth prior to the introduction of leaded gasoline in 1923.

b. Hair

Lead and other trace elements also occur in human hair, which can be preserved for hundreds of years. Weis et al. (1972) reported that the hair of children living in the USA between 1871 and 1923 A.D. contained almost twice as much Pb as the hair of adults, and that the Pb concentrations of both

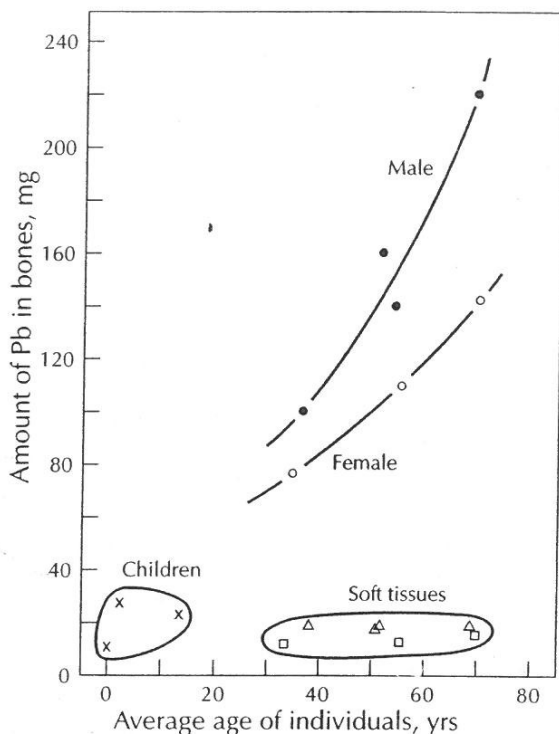


Figure 25.9 Accumulation of Pb in bones of adult humans (male and female) and children with average age of the individuals represented by each data point in the UK. The evidence indicates that Pb accumulates in the bones with increasing age, starting before birth, and that males carry more Pb in their bones than females. However, the amount of Pb in soft tissues is only about 6% of the total amount and is independent of age. The Pb in soft tissues represents a balance between intake and excretion. All amounts are relative to a standard body weight of 70 kg including the data for children (from Barry, 1975, 1976).

children and adults living in 1971 were significantly *lower* than those of the antique population. Weis et al. (1972) attributed the high Pb levels in the hair of the antique population to contamination with Pb in the homes of that period (water collected from leaded roofs, use of Pb-bearing glaze on pottery, Pb-based paint, etc.). They also suggested that the reduction of the Pb content of hair in the modern population (1971) resulted from increased

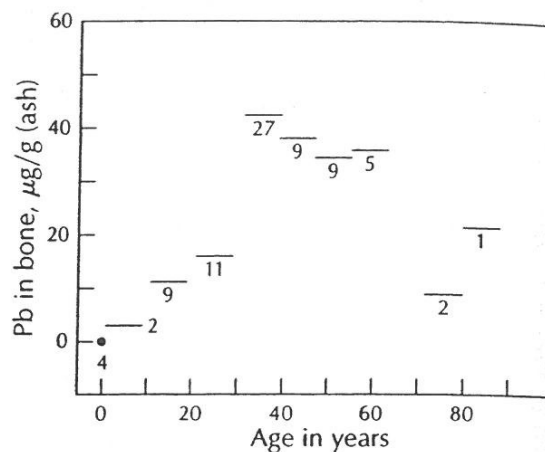


Figure 25.10 Average concentrations of Pb in bones of Americans of different ages, 1952-1957. The number of individuals included in each age group is indicated. The data reveal that Pb accumulated in the bones of Americans with age because the intake exceeded their ability to excrete it. The relatively low concentration of bone Pb of humans more than 70 years of age is attributable to the survival of individuals having low body burdens of Pb, perhaps because they grew up before leaded gasoline was introduced in 1923. However, individuals with high Pb levels did not display symptoms of Pb intoxication, nor were they chronically ill (data and interpretation by Schroeder and Tipton, 1968).

awareness of the danger of Pb contamination in the home.

A worldwide survey by Barry (1978) of human hair of individuals who were not exposed to high levels of environmental Pb indicated average values between 39.6 ppm (39 individuals, India) to 6.6 ppm (28 individuals, USA; 33 individuals, UK). The weighted mean Pb concentration of hair of 1055 individuals in the 20th century worldwide is about 24 ppm.

c. Effect of Lead on Children

The evidence that children are especially susceptible to Pb is cause for concern because Davis and Svendsgaard (1987) reported that even low concentrations of this element affect their mental

development. Although the maximum permissible Pb concentration of whole blood has been lowered from 600 to 250 $\mu\text{g/L}$ (Anonymous, 1986), the present limit may still be too high. The effect of Pb on young children is difficult to ascertain because of the large number of variables that affect their physical health and mental development (e.g., nutrition, heredity, home environment, use of tobacco and alcohol by the mother). The Pb concentrations of the blood of prenatal and postnatal children in the studies cited by Davis and Svendsgaard (1987) were less than 150 $\mu\text{g/L}$ and therefore considerably less than the maximum permissible concentration. Nevertheless, the data demonstrated several adverse effects.

1. The risk of premature birth increased significantly for mothers whose blood contained between 80 and 140 $\mu\text{g/L}$ of Pb.
2. Children whose blood in the umbilical cord contained an average of 140 $\mu\text{g/L}$ of Pb were measurably impaired in their mental development at the age of six months.
3. High prenatal blood levels in children are associated with low birth weight and a decrease in their length.
4. The adverse effects of high Pb content in the blood of prenatal children are detectable up to at least 12 months after birth.

The authors noted that in 1980 alone nearly one million children were born with sufficiently high Pb concentrations in their blood to adversely affect their mental and physical development.

25.6 Lead in the Bones of Ancient Peoples

The use of Pb among the peoples of Europe probably increased with time and therefore may be reflected by increasing Pb concentrations of human bones of decreasing historical age. The data of Grandjean and Holma (1973) in Figure 25.11 actually suggest such a relationship.

a. Denmark

The bones of humans who lived in what is now Denmark from 1500 B.C. to about 1400 A.D. contain less than 1 $\mu\text{g/g}$ of Pb (Grandjean and Holma, 1973). Subsequently, the concentrations increased significantly and reached levels of about 7 $\mu\text{g/g}$ in the 18th century A.D. In marked contrast, Romans who lived in York (UK) up to about 320 A.D. had high concentrations of Pb in their bones because the food they ate was contaminated by kitchen utensils containing high concentrations of Pb. The concentrations of Pb in bones of the Anasazi people in Utah and of ancient Peruvians (Ghazi, 1994) are consistent with the pattern of increasing concentrations of Pb in the former inhabitants of Denmark in Figure 25.11.

The lowest concentrations of Pb, ranging from 0.11 to 2.7 $\mu\text{g/g}$, were reported by Ericson et al. (1979) for bones of ancient Peruvians who died between 4500 and 1400 years ago. The average Pb concentration of these bones is $1.0 \pm 0.9 \mu\text{g/g}$ (2σ , $N = 5$). The same authors also measured a Pb concentration of 1.1 $\mu\text{g/g}$ in the vertebra of a 2200-year-old Egyptian mummy. These values are similar to the Pb concentrations of ancient bones from Denmark (4000 B.C. to 1000 A.D.) analyzed by Grandjean and Holma (1973).

Another example of historical changes of Pb in human bones was reported by Jaworowski (1968). His data demonstrate that the concentration of Pb in human bones in Poland increased from an average of $2.3 \pm 0.6 \mu\text{g/g}$ in the 3rd century A.D. to about $60 \pm 25 \mu\text{g/g}$ in the 19th century. He attributed the increase in Pb concentrations to the use of Pb-bearing kitchen utensils and noted that the concentration of Pb in the bones of modern residents of Poland has declined in spite of the evidence of a rise in atmospheric Pb contamination recorded in the glaciers of the Tatra Mountains.

In summary, the data suggest that the bones of humans who lived in uncontaminated environments have Pb concentrations of no more than 1 or 2 $\mu\text{g/g}$. Higher concentrations indicate either that the individuals ingested excess amounts of Pb or that the bones were contaminated after burial.

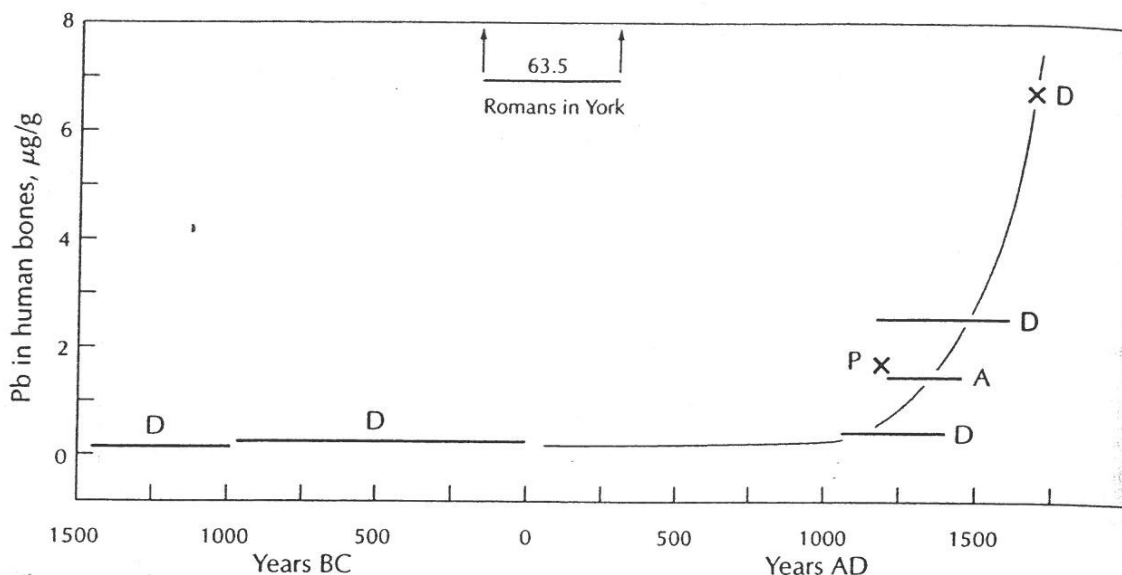


Figure 25.11 Average Pb concentrations of human bones ($\mu\text{g/g}$ dry weight) as a function of historical time (D = Denmark, A = Anasazi, Utah, P = Chiribaya, Peru). The data suggest that the Pb concentration of human bones increased as this metal became more widely used in household articles. The Romans are known to have used Pb both in metallic form and as a food additive (sapa). Consequently, they became significantly contaminated with Pb and experienced ill health as a result of its toxicity (from Grandjean and Holma, 1975, Denmark; Ghazi, 1994, Anasazi and Peruvians; Mackie et al., 1975, Romans, York, UK).

by diagenetic alteration or after subsequent exposure and transport to the analytical laboratory.

b. Lead Poisoning Among the Romans

The contamination of humans with Pb started long before the industrial revolution and the introduction of tetraethyl lead as an additive to gasoline. Lead was used in water pipes by the Romans, in drinking cups, and in other household implements, as well as in cosmetics. A significant cause of Pb poisoning in the Roman Empire (Figure 25.11) was the custom of adding "sapa" containing Pb acetate to wine in order to sweeten it and to prevent spoilage. Sapa was prepared by boiling acidic wine in lead-lined pots and therefore contained approximately 240 mg of Pb per liter (Lessler, 1988).

Mackie et al. (1975) reported that the bones of Romans who lived in York (UK) have excessively high concentrations of Pb averaging $60.2 \mu\text{g/g}$ for males and $85.2 \mu\text{g/g}$ for females (dry weight). The higher concentration of Pb in

the bones of females is remarkable and is consistent with the assumption that the Pb contamination occurred during the preparation of food.

The use of Pb in household articles and of sapa by the Roman aristocrats may have adversely affected their health and thereby contributed to the disintegration of the Roman Empire (Lessler, 1988; Nriagu, 1983a,b; Gilfillan, 1965).

c. The Omaha Indians of Nebraska

High concentrations of Pb ranging from 4.8 to $2570 \mu\text{g/g}$ were reported in bones of the Omaha tribe of American Indians who lived in northeastern Nebraska near the town of Homer between 1780 and 1820 A.D. (Ghazi, 1994). The data indicate that the bones of children under the age of eight had an average Pb concentration of $663 \pm 518 \mu\text{g/g}$ (range: 4.8–2570 $\mu\text{g/g}$), whereas the bones of adults more than 18 years of age contained $97.5 \pm 80 \mu\text{g/g}$ of Pb (range: 13.7–271). The data of Ghazi (1994) strongly suggest that the highest Pb concentrations occur in the bones of

children, even though not all of the children were significantly contaminated with Pb.

The chemical composition of bones buried in soil may be altered during diagenesis by the transfer of elements from the soil to the bone. For this reason, Ghazi (1994) analyzed soil and animal bones from the burial site of the Omaha Indians. The results demonstrate that the soil (total dissolution) has an average Pb concentration of $19.9 \pm 2.1 \mu\text{g/g}$ and that the animal bones recovered at the burial site contain only $1.4 \pm 1.2 \mu\text{g/g}$. Ghazi (1994) concluded that the Pb in the human bones is not of diagenetic origin because:

1. The total Pb concentration of the soil is less than that of most of the human bones that were buried in it.
2. The animal bones that were in contact with the same soil have much lower Pb concentrations than the human bones.
3. The human bones have a wide range of Pb concentrations, indicating that additions of Pb from the soil were insignificant.

Therefore, the high concentration of Pb in the human bones, compared to the animal bones at the same site, indicates that the individuals of the Omaha tribe buried near Homer, Nebraska, suffered from Pb poisoning and that some of the children may have died of this condition.

The excess Pb in the bones of the Omaha Indians may have originated from musket balls, ornamental coils of metallic Pb, cosmetic pigments containing Pb and Hg, and Pb-bearing alloys used in belt buckles and other household implements. In order to relate these artifacts to the Pb in the human bones, Ghazi (1994) determined the isotope compositions of the Pb. The resulting $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios of the artifacts used by the Omaha Indians and the Pb in their bones form a straight line in Figure 25.12. This relationship not only confirms that the excess Pb in the bones originated from the artifacts and pigments used by the Omahas, but also suggests that the Pb originated from deposits of galena (PbS) in Missouri, Oklahoma, and Arkansas (Heyl et al., 1974). Isotope compositions of Pb in ancient

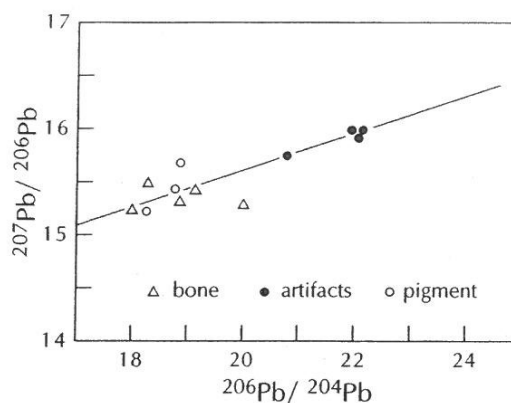


Figure 25.12 Isotope ratios of Pb in the bones of Omaha Indians at a burial site near Homer, Nebraska, and in pigment and Pb artifacts they used. The linear relationship of the isotope ratios suggests that the skeletal Pb originated primarily from Pb artifacts and pigments used by the Omaha tribe and that the Pb originated from deposits in the Tri-State District of Missouri, Oklahoma, and Arkansas (adapted from Ghazi, 1989).

objects have also been reported by Brill (1970), Brill and Wampler (1967), Gale (1989), and Gale and Stos-Gale (1989).

In marked contrast to the Omaha Indians of Nebraska, the bones of the Anasazi people from the Poly Secret burial site in Moab, Utah, (1225–1405 A.D.) have low Pb concentrations with an average of $1.52 \pm 0.45 \mu\text{g/g}$ and a range from 0.6 to $2.7 \mu\text{g/g}$. Similarly, the bones of Alta people who lived at about 1200 A.D. near Chiribaya, Peru, have a low average Pb concentration of $1.70 \pm 0.70 \mu\text{g/g}$.

Since neither the Anasazi nor the Alta people used Pb artifacts or pigments like those of the Omaha Indians, the Pb of their bones is presumably derived from the natural environment. The bones of the herbivorous animals recovered from the burial site of the Omaha Indians presumably also contain only natural environmental Pb derived from the soil by ingestion of plants and water. If that is true, then the Pb content of bones of herbivorous animals at Tonwantonga village is lower than that of the soil by a factor of about

0.07. In addition, the bones of adult Omaha Indians contain about 70 times as much Pb on the average as herbivorous animals, whereas children's bones are enriched in Pb by factors ranging from 3.4 to 1835 with a mean of about 475.

d. The Franklin Expedition of 1845

One of the worst cases of Pb poisoning occurred between 1845 and 1847 in the Canadian Arctic. Sir John Franklin, who had led two previous expeditions to the Canadian Arctic from 1819 to 1822 and from 1825 to 1827, was ordered to explore a northern route from the Atlantic to the Pacific Ocean. He departed from England in the spring of 1845 in two ships (*Erebus* and *Terror*) and a crew of 129 officers and men. They were last seen by a Scottish whaler in the waters north of Baffin Island and then disappeared forever. After twelve years of fruitless searches by several relief expeditions, the skeletons of some of the crew and a diary with a final entry dated April 25, 1848, were found on King William Island.

The expedition had spent the winter of 1845–1846 on Beechey Island off the southern coast of Devon Island. During the following summer the ships moved south through Peel Sound and Franklin Strait, but became trapped in the ice near King William Island. During the following winter Franklin and 24 of his men died. On April 22, 1848, the survivors abandoned the ships and attempted to reach the Canadian mainland by walking south across King William Island. All of them died during that attempt. The skull of one of Franklin's men was discovered 133 years later on June 29, 1981, on the south coast of King William Island along Simpson Strait, which separates it from the Canadian mainland (Beattie and Geiger, 1987).

Subsequent research by anthropologists from the University of Alberta eventually led to the discovery of three graves on Beechey Island (Beattie and Savelle, 1983). The bodies in these graves were exhumed and autopsied. Samples of hair, bone, and internal organs were found to have anomalously high concentrations of Pb (Kowal et al., 1989).

Hair samples collected from the bodies of John Torrington, John Hartnell, and William

Braine contained high concentrations of Pb (Beattie and Geiger, 1987):

Torrington: 413–657 ppm

Hartnell: 138–313 ppm

Braine: 145–280 ppm

Because of the rapid growth of hair, the Pb must have entered the bodies of these men after the start of the expedition. It could have originated from several sources, including Pb foil used to wrap tea, pewterware, pottery covered with Pb-bearing glaze, and the solder of the tin cans in which most of the food was stored.

The solder used to seal the metal cans contained more than 90% Pb. The cans were soldered not only on the outside but also on the inside. Kowal et al. (1989) demonstrated that the isotope composition of the Pb in the solder is identical to that in the soft tissues and bones of Franklin's men. Therefore, the solder was probably the principal source of Pb ingested by all members of the expedition.

Franklin's expedition ended tragically not only because of the harsh climatic conditions and bad luck but also because acute Pb intoxication of the officers and crewmen caused anorexia, fatigue, and colic as well as neurotic behavior leading to inappropriate decisions. As a result, all 129 men perished.

Much later, men like Fridtjof Nansen (1861–1930) and Roald Amundsen (1872–1928) adopted the life style of the Inuits by hunting and eating game and wearing fur clothing. Their success in polar exploration demonstrates the wisdom of living in harmony with the polar environment instead of attempting to maintain the life style appropriate to a much more temperate climate.

25.7 Summary

Lead and many other industrial metals have been widely dispersed over the surface of the Earth. The sources of anthropogenic Pb include combustion of leaded gasoline, mining and smelting of Pb-bearing ores, and the use of Pb in household articles such as solder, paint, glazing compound,

storage batteries, pottery covered with Pb-bearing glaze, etc. Many of these sources of Pb have been eliminated and acute Pb poisoning among humans is not as common as it used to be. However, Pb continues to be a hazard in certain occupations related to mining and smelting of Pb-bearing ores and to the use of Pb in the manufacturing and chemical industries.

In spite of precautions against the ingestion of Pb, most humans alive today contain significant amounts of Pb in their bones and soft tissues. The amounts increase with age because the rate of intake exceeds the body's ability to excrete it. The health effects caused by the accumulation of Pb are difficult to evaluate because everybody is contaminated.

The lead enters the human body primarily in contaminated food, water, and air. For example, vegetables grown in the vicinity of smelters or other industries that use Pb contain significantly more Pb than vegetables grown elsewhere. Even air con-

tains Pb-bearing aerosol particles that may release Pb into the bloodstream after they enter the lungs.

The growing burden of Pb and other metals may adversely affect the life expectancy of humans by making them more vulnerable to other kinds of illnesses. The evidence that the bones of humans over 70 years of age contain less Pb than those of persons who died in their prime is an ominous sign that the chances for survival to old age are reduced by the accumulation of lead and other metals in bones and internal organs.

Children appear to be especially at risk because Pb affects not only their physical growth but also their mental development. Consequently, children who are exposed to anthropogenic Pb in their environment may never reach their full potential. The tragic deaths of the officers and crew of the Franklin Expedition are a reminder that even adults can suffer loss of good judgment in stressful situations as a result of Pb poisoning.

Problems

1. Calculate the concentration of Pb in gasoline sold in the USA in 1964 given that it contained 1.82 mL of tetraethyl lead (TEL) per gallon and that 1 mL of tetraethyl lead contained 1.057 g of Pb (1 gallon, US = 3.785 L).

2. Calculate the concentration of Pb in sediment that is a mixture of two components labeled A and B. Assume that the sediment mixture contains 35% of component B and that the Pb concentrations of the components are $Pb_A = 110$ ppm, $Pb_B = 18$ ppm.

3. Given that the Pb concentration of a mixture of two components A and B is 75 ppm, calculate the abundance of component A assuming that $Pb_A = 125$ ppm, and $Pb_B = 30$ ppm.

4. Calculate the $^{206}\text{Pb}/^{204}\text{Pb}$ ratio of Pb in a mixture of two components in which the abundance of component A is 35%, given that $(^{206}\text{Pb}/^{204}\text{Pb})_A = 18.60$, $Pb_A = 175$ ppm, $(^{206}\text{Pb}/^{204}\text{Pb})_B = 19.50$, and $Pb_B = 28$ ppm.

5. Plot a mixing hyperbola for a series of two-component mixtures such that the abundance of component A has values of 0.1, 0.2, 0.4, 0.6, 0.8, and 0.9.

Assume that $(^{206}\text{Pb}/^{204}\text{Pb})_A = 18.60$, $Pb_A = 175$ ppm, $(^{206}\text{Pb}/^{204}\text{Pb})_B = 19.50$, $Pb_B = 28$ ppm.

6. Use the results of problem 5 to convert the mixing hyperbola into a straight line by plotting the $^{206}\text{Pb}/^{204}\text{Pb}$ ratios versus the reciprocal concentrations of Pb.

7. Calculate the $^{207}\text{Pb}/^{206}\text{Pb}$ ratio of a mixture of aerosol particles derived from two sources A and B having different isotope ratios of Pb but identical concentrations. The abundance of component B is 65% and the isotope ratios are $(^{207}\text{Pb}/^{206}\text{Pb})_A = 0.859$, $(^{207}\text{Pb}/^{206}\text{Pb})_B = 0.832$.

8. The average $^{206}\text{Pb}/^{204}\text{Pb}$ ratio of Pb in the internal organs and bones of horses that died of Pb poisoning on the pastures near Benicia, California, is 17.62 ± 0.18 . Assume that the Pb was derived from the nearby Pb smelter ($^{206}\text{Pb}/^{204}\text{Pb} = 17.33$) and by combustion of leaded gasoline ($^{206}\text{Pb}/^{204}\text{Pb} = 18.09$) and that it was transported in aerosol particles having equal concentrations of Pb. What fraction of the Pb in the internal organs of horses originated from the Pb smelter? State the error limits of the result based on the error of the average $^{206}\text{Pb}/^{204}\text{Pb}$ ratio of the Pb in the horses.

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Appendix A

COMPILATIONS OF GEOCHEMICAL DATA

Table A.1 Abundances of the Chemical Elements in the Sun in Units of Atoms per 10^6 Si Atoms

<i>Z</i>	<i>Symbol</i>	<i>Abundance</i> ^a		<i>Z</i>	<i>Symbol</i>	<i>Abundance</i> ^a	
1	H	2.2×10^{10}		41	Nb	1.8	(D ⁻)
2	He	1.4×10^9	(C)	42	Mo	3.2	(D ⁻)
3	Li	2.2×10^{-1}	(B)	44	Ru	1.5	(D ⁻)
4	Be	3.1×10^{-1}	(B)	45	Rh	5.6×10^{-1}	(D ⁻)
5	B	<2.8		46	Pd	7.1×10^{-1}	(D ⁻)
6	C	9.3×10^6	(B)	47	Ag	1.6×10^{-1}	(C)
7	N	1.9×10^6	(B)	48	Cd	1.58	(B)
8	O	1.5×10^7	(A)	49	In	1.0	(C)
9	F	8.1×10^2	(C)	50	Sn	2.2	(C ⁻)
10	Ne	8.3×10^5	(B)	51	Sb	2.2×10^{-1}	(D)
11	Na	4.2×10^4	(A)	55	Cs	<1.8	
12	Mg	8.9×10^5	(C)	56	Ba	2.75	(B)
13	Al	7.4×10^4	(C)	57	La	3.0×10^{-1}	(C)
14	Si	1.0×10^6	(C)	58	Ce	7.9×10^{-1}	(C)
15	P	7.1×10^3	(C)	59	Pr	1.0×10^{-1}	(C)
16	S	3.5×10^5	(C)	60	Nd	3.8×10^{-1}	(C)
17	Cl	7.1×10^3	(D)	62	Sm	1.2×10^{-1}	(C)
18	Ar	2.2×10^4	(C)	63	Eu	1.1×10^{-1}	(D)
19	K	3.2×10^3	(B)	64	Gd	2.9×10^{-1}	(D)
20	Ca	5.0×10^4	(B)	66	Dy	2.6×10^{-1}	(D)
21	Sc	2.4×10^1	(B)	68	Er	1.3×10^{-1}	(D)
22	Ti	2.5×10^4	(B)	69	Tm	4.1×10^{-2}	(C)
23	V	2.3×10^2	(C)	70	Yb	1.8×10^{-1}	(D)
24	Cr	1.1×10^4	(C)	71	Lu	1.3×10^{-1}	(C ⁻)
25	Mn	5.9×10^3	(C)	72	Hf	1.4×10^{-1}	(C)
26	Fe	7.1×10^5	(B?)	74	W	1.1	(D ⁻)
27	Co	1.8×10^3	(C ⁻)	75	Re	$<1.1 \times 10^{-2}$	
28	Ni	4.3×10^4	(B)	76	Os	1.1×10^{-1}	(D)
29	Cu	2.6×10^2	(B)	77	Ir	1.6×10^{-1}	(C)
30	Zn	6.3×10^2	(C)	78	Pt	1.25	(C)
31	Ga	1.4×10^1	(C)	79	Au	1.3×10^{-1}	(C ⁻)
32	Ge	7.1×10^1	(C)	80	Hg	<2.8	
37	Rb	8.9	(B)	81	Tl	1.8×10^{-1}	(C)
38	Sr	1.8×10^1	(B)	82	Pb	1.90	(B)
39	Y	2.8	(D)	83	Bi	<1.8	
40	Zr	1.3×10^1	(D)	90	Th	3.5×10^{-2}	
				92	U	$<8.9 \times 10^{-2}$	

^aRating of the quality of the determination. A = abundance known to an accuracy of about 10%; B = reasonably good determination; C = fair determination; and D = poor determination.

Recalculated from Ross and Aller (1976).

Table A.2 Representative Chemical Compositions of Meteorites in Weight Percent^a

	<i>Carbonaceous chondrite</i> ⁽¹⁾	<i>Enstatite chondrite</i> ⁽²⁾	<i>Ca-poor achondrites</i> ⁽³⁾	<i>Ca-rich achondrites</i> ⁽⁴⁾	<i>Average iron meteorites</i> ⁽⁵⁾
Fe	—	20.04	2.92	0.80	90.6
Ni	—	1.96	0.17	—	7.9
Co	—	0.07	—	—	0.5
P	—	—	—	—	0.2
S	—	—	—	—	0.7
FeS	15.07	7.27	1.25	0.41	—
SiO ₂	22.56	41.53	54.01	48.17	—
TiO ₂	0.07	—	0.06	0.51	—
Al ₂ O ₃	1.65	1.55	0.67	13.91	—
MnO	0.19	—	0.14	0.46	—
FeO	11.39	0.34	0.97	15.99	—
MgO	15.81	23.23	35.92	7.10	—
CaO	1.22	0.74	0.91	10.94	—
Na ₂ O	0.74	1.26	1.32	0.67	—
K ₂ O	0.07	0.32	0.10	0.13	—
P ₂ O ₅	0.28	0.8	0.22	0.11	—
H ₂ O	19.89	—	1.14	0.44	—
Cr ₂ O ₃	0.36	0.56	0.06	0.39	—
NiO	1.23	—	0.26	—	—
CoO	0.06	—	—	—	—
C	3.10	—	—	—	0.04
LOI ^b	6.96	0.86(CaS)	0.51(CaS)	—	—
Sum	100.65	99.91	100.00	100.3	99.94

^aA dash (—) means “not reported and probably zero,” although in some cases the element in question was reported in different form.

^bLoss on ignition.

SOURCES: (1) Orgueil, type I, from Henderson (1982, Table 1.3); (2) Hvittis, from Henderson (1982, Table 1.3); (3) average aubrite, from Henderson (1982, Table 1.3); (4) average eucrites, from Henderson (1982, Table 1.3); (5) average iron meteorite from Glass (1982, Table 4.3).

Table A.3 Abundance of the Chemical Elements in Chondrite Meteorites in Number of Atoms per 10^6 Si Atoms

<i>Z</i>	<i>Element</i>	<i>Abundance</i>	<i>Z</i>	<i>Element</i>	<i>Abundance</i>
1	H	—	44	Ru	1.5
2	He	1.1×10^{-1}	45	Rh	2.5×10^{-1}
3	Li	$\sim 5.0 \times 10$	46	Pd	$\sim 9 \times 10^{-1}$
4	Be	6.9×10^{-1}	47	Ag	$\sim 9 \times 10^{-2}$
5	B	6.2	48	Cd	7.9×10^{-2}
6	C	2.0×10^3	49	In	1.0×10^{-2}
7	N	9.0×10	50	Sn	5.6×10^{-1}
8	O	3.7×10^6	51	Sb	1.1×10^{-1}
9	F	$\sim 7.0 \times 10^2$	52	Te	6.0×10^{-1}
10	Ne	1.5×10^{-3}	53	I	5.1×10^{-2}
11	Na	4.6×10^4	54	Xe	7×10^{-6}
12	Mg	9.4×10^5	55	Cs	1.4×10^{-1}
13	Al	6.0×10^4	56	Ba	5.0
14	Si	1.0×10^6	57	La	3.9×10^{-1}
15	P	5.3×10^3	58	Ce	1.2
16	S	1.1×10^5	59	Pr	1.4×10^{-1}
17	Cl	7.0×10^2	60	Nd	6.4×10^{-1}
18	Ar	4.0×10^{-1}	62	Sm	2.3×10^{-1}
19	K	3.5×10^3	63	Eu	8.2×10^{-1}
20	Ca	4.9×10^4	64	Gd	3.4×10^{-1}
21	Sc	2.9×10	65	Tb	5.1×10^{-2}
22	Ti	$\sim 2.6 \times 10^3$	66	Dy	3.3×10^{-1}
23	V	2.0×10^2	67	Ho	7.6×10^{-2}
24	Cr	6.6×10^3	68	Er	2.3×10^{-1}
25	Mn	7.4×10^3	69	Tm	3.1×10^{-2}
26	Fe	6.9×10^5	70	Yb	1.8×10^{-1}
27	Co	1.3×10^3	71	Lu	3.1×10^{-2}
28	Ni	4×10^4	72	Hf	1.7×10^{-1}
29	Cu	2.5×10^2	73	Ta	1.6×10^{-2}
30	Zn	1.3×10^2	74	W	1.2×10^{-1}
31	Ga	1.2×10	75	Re	4.6×10^{-2}
32	Ge	2.0×10	76	Os	5.4×10^{-1}
33	As	4.6	77	Ir	3.5×10^{-1}
34	Se	1.9×10	78	Pt	1.30
35	Br	5	79	Au	1.8×10^{-1}
36	Kr	—	80	Hg	1.0×10^{-1}
37	Rb	~ 5	81	Tl	1.0×10^{-3}
38	Sr	2.0×10	82	Pb	1.4×10^{-1}
39	Y	3.4	83	Bi	2.0×10^{-3}
40	Zr	$\sim 3.7 \times 10$	90	Th	2.7×10^{-2}
41	Nb	1.0	92	U	9.0×10^{-3}
42	Mo	2.5			

SOURCE: Brownlow (1979)

Table A.4 Average Chemical Composition of Selected Lunar Rocks

	1 ^a	2 ^b	3 ^c	4 ^d	5 ^e	6 ^f	7 ^g
SiO ₂	40.67	40.37	44.32	47.88	44.08	45.40	47.04
TiO ₂	10.18	11.77	2.65	1.82	0.02	0.32	1.21
Al ₂ O ₃	10.40	8.84	8.03	9.46	35.49	28.63	18.69
FeO	18.68	19.28	21.11	20.13	0.23	4.25	9.45
MnO	0.27	0.24	0.28	0.28	0.00	0.06	0.11
MgO	6.92	7.56	14.07	8.74	0.09	4.38	10.14
CaO	11.70	10.59	8.61	10.54	19.68	16.39	11.52
Na ₂ O	0.41	0.52	0.22	0.31	0.34	0.41	0.48
K ₂ O	0.07	0.31	0.06	0.06	<0.01	0.06	0.34
Cr ₂ O ₃	0.29	0.36	0.63	0.47	—	—	0.20
Total	99.59	99.52	99.98	99.69	99.94	99.9	99.18

^aLow K basalt, Mare Tranquillitatis, Apollo 11, average of eight analyses.^bHigh K basalt, Mare Tranquillitatis, Apollo 11, average of six analyses.^cOlivine basalt, Oceanus Procellarum, Apollo 12, average of nine analyses.^dPigeonite basalt, Hadley-Apennine, Apollo 15 Mare Imbrium, average of 13 analyses.^eAnorthosite, lunar highlands, Hadley-Apennine, Apollo 15, 15415, Lunar Sample Preliminary Examination Team (1972).^fGabbroic anorthosite, lunar highlands, Descartes Crater, Southern Highlands, Apollo 16, 68415, Lunar Sample Preliminary Examination Team (1972).^gKREEP basalt, Fra Mauro Crater, Apollo 14, Philpotts et al. (1972).

SOURCE: Glass (1982).

Table A.5 Abundance of Chemical Elements in the Moon
Based on 10⁶ Si Atoms

Z	Element	Abundance	Z	Element	Abundance
3	Li ^a	1.7 × 10 ²	27	Co ^a	5.6 × 10 ²
6	C ^a	1.1 × 10 ²	28	Ni	1.2
8	O ^a	3.5 × 10 ⁶	37	Rb	4.6 × 10 ⁻¹
9	F ^a	2.1 × 10 ²	38	Sr	6.5 × 10 ¹
11	Na ^a	5.3 × 10 ³	39	Y	1.2 × 10 ¹
12	Mg	1.0 × 10 ⁶	40	Zr	4.3 × 10 ¹
13	Al	2.2 × 10 ⁵	41	Nb	3.1
14	Si	1.0 × 10 ⁶	55	Cs	1.3 × 10 ¹
15	P ^a	2.3 × 10 ³	56	Ba	1.7 × 10 ¹
16	S ^a	1.6 × 10 ⁴	57	La	1.1
19	K	3.5 × 10 ²	62	Sm	9.1 × 10 ⁻¹
20	Ca	1.5 × 10 ⁵	63	Eu	2.4 × 10 ⁻¹
21	Sc	6.1 × 10 ¹	65	Tb	1.5 × 10 ⁻¹
22	Ti	5.1 × 10 ³	70	Yb	5.6 × 10 ⁻¹
23	V	1.3 × 10 ²	71	Lu	8.3 × 10 ⁻²
24	Cr	3.5 × 10 ³	72	Hf	4.9 × 10 ⁻¹
25	Mn	2.5 × 10 ³	90	Th	1.3 × 10 ⁻¹
26	Fe	2.0 × 10 ⁵	92	U	3.4 × 10 ⁻²

^aFrom Ganapathy and Anders (1974).

Recalculated from Taylor (1975) except as noted.

Table A.6 Chemical Compositions of the Atmospheres of Mars and Earth

<i>Component</i>	<i>Mars</i>		<i>Earth</i>	
	%	ppm	%	ppm
CO ₂	95.32		0.033	
N ₂	2.7		78.084	
Ar	1.6		0.934	
O ₂	0.13		20.946	
CO	0.07			
H ₂ O ^a	0.03			
Ne		2.5		18.2
Kr		0.3		1.2
Xe		0.08		0.9
O ₃ ^a		0.03		

^aVariable.

SOURCE: Owen et al. (1977); Glass (1982).

Table A.7 Chemical Composition of Martian Soil at the Landing Sites of Viking 1 and 2 in Weight Percent

	<i>Viking 1</i>			<i>Viking 2</i>
	<i>1</i>	<i>2</i>	<i>3</i>	<i>1</i>
SiO ₂	44.7	44.5	43.9	42.8
Al ₂ O ₃	5.7	—	5.5	—
Fe ₂ O ₃	18.2	18.0	18.7	20.3
MgO	8.3	—	8.6	—
CaO	5.6	5.3	5.6	5.0
K ₂ O	<0.3	<0.3	<0.3	<0.3
TiO ₂	0.9	0.9	0.9	1.0
SO ₃	7.7	9.5	9.5	6.5
Cl	0.7	0.8	0.9	0.6
Sum	92.1	incomplete	93.9	incomplete

SOURCE: Toulmin et al. (1977).

Table A.8 Chemical Composition of Surface Material at the Landing Sites of Venera 13 and 14 on Venus in Weight Percent

	<i>Venera 13</i>	<i>Venera 14</i>	<i>Average terrestrial oceanic basalt</i>
MgO	10 ± 6	8 ± 4	7.56
Al ₂ O ₃	16 ± 4	18 ± 4	16.5
SiO ₂	45 ± 3	49 ± 4	51.4
K ₂ O	4 ± 0.8	0.2 ± 0.1	1.0
CaO	7 ± 1.5	10 ± 1.5	9.4
TiO ₂	1.5 ± 0.6	1.2 ± 0.4	1.5
MnO	0.2 ± 0.1	0.16 ± 0.08	0.26
FeO	9 ± 3	9 ± 2	12.24
Total	92.7	95.56	99.86

SOURCE: Data from Barsukov quoted by Carr et al. (1984).

Table A.9 Chemical Composition of the Atmosphere of Venus

<i>Component</i>	<i>Concentration^a</i>	
	<i>%</i>	<i>ppm</i>
CO ₂	96.4 ± 1.03	
N ₂	3.4 ± 0.02	
H ₂ O	0.14 ± 0.01	
O ₂		69.3 ± 1.3
Ar		18.6 ± 2.4
Ne		4.3 ^{+5.5} _{-3.9}
SO ₂		186 ⁺³⁴⁹ ₋₁₅₆

^aAnalysis by gas chromatograph on Pioneer Venus.

SOURCE: Oyama et al. (1979).

Table A.10 Average Chemical Composition of the Continental Crust of the Earth

Element	Units		Elements	Units	
	$\mu\text{g/g}$	atoms/ 10^6 Si atoms		$\mu\text{g/g}$	atoms/ 10^6 Si atoms
Li	13	2.0×10^2	Cd	9.8×10^{-2}	9.1×10^{-2}
Be	1.5	1.7×10^1	In	5.0×10^{-2}	4.6×10^{-2}
B	10	9.7×10^1	Sn	2.5	2.2
O	45.5×10^4	3.08×10^6	Sb	0.2	2×10^{-1}
Na	2.3×10^4	1.05×10^5	Cs	1.0	8×10^{-1}
Mg	3.2×10^4	1.38×10^5	Ba	250	1.9×10^2
Al	8.40×10^4	3.27×10^5	La	16	1.2×10^1
Si	26.8×10^4	1.00×10^6	Ce	33	2.5×10^1
K	0.90×10^4	2.44×10^4	Pr	3.9	2.9
Ca	5.3×10^4	1.38×10^5	Nd	16	1.2×10^1
Sc	30	7.0×10^1	Sm	3.5	2.4
Ti	5.3×10^3	1.18×10^4	Eu	1.1	7.6×10^{-1}
V	2.3×10^2	4.74×10^2	Gd	3.3	2.2
Cr	1.85×10^2	3.73×10^2	Tb	0.60	4.0×10^{-1}
Mn	1.40×10^3	2.67×10^3	Dy	3.7	2.4
Fe	7.06×10^3	1.32×10^5	Ho	0.78	5.0×10^{-1}
Co	29	5.2×10^1	Er	2.2	1.4
Ni	105	1.88×10^2	Tm	0.32	2.0×10^{-1}
Cu	75	1.2×10^2	Yb	2.2	1.3
Zn	80	1.3×10^2	Lu	0.30	1.8×10^{-1}
Ga	18	2.7×10^1	Hf	3.0	1.8
Ge	1.6	2.3	Ta	1.0	5.8×10^{-1}
As	1.0	1.4	W	1.0	5.7×10^{-1}
Se	5×10^{-2}	7×10^{-2}	Re	5×10^{-4}	3×10^{-4}
Rb	32	3.9×10^1	Ir	1×10^{-4}	5×10^{-5}
Sr	260	3.1×10^2	Au	3×10^{-3}	2×10^{-3}
Y	20	2.4×10^1	Tl	0.36	1.8×10^{-1}
Zr	100	1.15×10^2	Pb	8.0	4.1
Nb	11	1.2×10^1	Bi	6×10^{-2}	3×10^{-2}
Mo	1.0	1.1	Th	3.5	1.6
Pd	1×10^{-3}	1×10^{-3}	U	0.91	4.0×10^{-1}
Ag	8.0×10^{-2}	8×10^{-2}			

SOURCE: Taylor and McLennan (1985).

Table A.11 Chemical Composition of Igneous and Sedimentary Rocks (in parts per million unless otherwise indicated)

<i>Element, Z</i>	<i>Ultramafic^a</i>	<i>Basalt^a</i>	<i>High-Ca granites^b</i>	<i>Low-Ca granites^b</i>	<i>Shale^b</i>	<i>Sandstone^b</i>	<i>Carbonate rocks^b</i>	<i>Deep-sea clay^b</i>
3 Li	0.5	16	24	40	66	15	5	57
4 Be	0.2	0.7	2	3	3	—	—	2.6
5 B	2	5	9	10	100	35	20	230
9 F	100	385	520	850	740	270	330	1300
11 Na (%)	0.49	1.87	2.84	2.58	0.96	0.33	0.04	4
12 Mg (%)	23.2	4.55	0.94	0.16	1.50	0.70	4.70	2.10
13 Al (%)	1.2	8.28	8.20	7.20	8	2.50	0.42	8.40
14 Si (%)	19.8	23.5	31.40	34.70	7.30	36.80	2.40	25
15 P	195	1130	920	600	700	170	400	1500
16 S	200	300	300	300	2400	240	1200	1300
17 Cl	45	55	130	200	180	10	150	21000
19 K (%)	0.017	0.83	2.52	4.20	2.66	1.07	0.27	2.50
20 Ca (%)	1.6	7.2	2.53	0.51	2.21	3.91	30.23	2.90
21 Sc	10	27	14	7	13	1	1	19
22 Ti	300	11400	3400	1200	4600	1500	400	4600
23 V	40	225	88	44	130	20	20	120
24 Cr	1800	185	22	4.1	90	35	11	90
25 Mn	1560	1750	540	390	850	—	1100	6700
26 Fe (%)	9.64	8.60	2.96	1.42	4.72	0.98	0.33	6.50
27 Co	175	47	7	1	19	0.3	0.1	74
28 Ni	2000	145	15	4.5	68	2	20	225
29 Cu	15	94	30	10	45	—	4	250
30 Zn	40	118	60	39	95	16	20	165
31 Ga	1.8	18	17	17	19	12	4	20
32 Ge	1.3	1.4	1.3	1.3	1.6	0.8	0.2	2
33 As	0.8	2.2	1.9	1.5	13	1	1	13
34 Se	0.05	0.05	0.05	0.05	0.6	0.05	0.08	0.17
35 Br	0.8	3.3	4.5	1.3	4	1	6.2	70
37 Rb	1.1	38	110	170	140	60	3	100
38 Sr	5.5	452	440	100	300	20	610	180
39 Y	—	21	35	40	26	40	30	90
40 Zr	38	120	140	175	160	220	19	150
41 Nb	9	20	20	21	11	—	0.3	14
42 Mo	0.3	1.5	1	1.3	2.6	0.2	0.4	27
47 Ag	0.05	0.11	0.051	0.037	0.07	0.01	0.01	0.11
48 Cd	0.05	0.21	0.13	0.13	0.3	—	0.035	0.42
49 In	0.012	0.22	—	0.26	0.1	—	—	0.08
50 Sn	0.5	1.5	1.5	3	6	0.1	0.1	1.5
51 Sb	0.1	0.6	0.2	0.2	1.5	0.01	0.2	1
53 I	0.3	0.5	0.5	0.5	2.2	1.7	1.2	0.05
55 Cs	0.1	1.1	2	4	5	0.1	0.1	6
56 Ba	0.7	315	420	840	580	10	10	2300
57 La	1.3 ^c	6.1 ^d	45	55	92	30	1	115
58 Ce	3.5 ^c	16 ^d	81	92	59	92	11.5	345

Table A.11 (continued)

<i>Element, Z</i>	<i>Ultramafic^a</i>	<i>Basalt^a</i>	<i>High-Ca granites^b</i>	<i>Low-Ca granites^b</i>	<i>Shale^b</i>	<i>Sandstone^b</i>	<i>Carbonate rocks^b</i>	<i>Deep-sea clay^b</i>
59 Pr	0.49 ^c	2.7 ^d	7.7	8.8	5.6	8.8	1.1	33
60 Nd	1.9 ^c	14 ^d	33	37	24	37	4.7	140
62 Sm	0.42 ^c	4.3 ^d	8.8	10	6.4	10	1.3	38
63 Eu	0.14 ^c	1.5 ^d	1.4	1.6	1	1.6	0.2	6
64 Gd	0.54 ^c	6.2 ^d	8.8	10	6.4	10	1.3	38
65 Tb	0.12 ^c	1.1 ^d	1.4	1.6	1	1.6	0.2	6
66 Dy	0.77 ^c	5.9 ^d	6.3	7.2	4.6	7.2	0.9	27
67 Ho	0.12 ^c	1.4 ^d	1.8	2	1.2	2	0.3	7.5
68 Er	0.30 ^c	3.6 ^d	3.5	4	2.5	4	0.5	15
69 Tm	0.041 ^c	0.60 ^d	0.3	0.3	0.2	0.3	0.04	1.2
70 Yb	0.38 ^c	3.2 ^d	3.5	4	2.6	4	0.5	15
71 Lu	0.036 ^c	0.55 ^d	1.1	1.2	0.7	1.2	0.2	4.5
72 Hf	0.4	1.5	2.3	3.9	2.8	3.9	0.3	4.1
73 Ta	0.5	0.8	3.6	4.2	0.8	0.01	0.01	0.1
74 W	0.5	0.9	1.3	2.2	1.8	1.5	0.6	1
79 Au	0.006	0.004	0.004	0.004	—	—	—	—
80 Hg	0.01	0.09	0.08	0.08	0.4	0.03	0.04	0.1
81 Tl	0.04	0.21	0.72	2.3	1.4	0.82	0.01	0.8
82 Pb	0.5	7	15	19	20	7	9	80
90 Th	0.0045	3.5	8.5	17	12	1.7	1.7	7
92 U	0.002	0.75	3	3	3.7	0.45	2.2	1.3

^aAverage of Turekian and Wedepohl (1961) and Vinogradov (1962).^bTurekian and Wedepohl (1961).^cCalculated from data listed by Herrmann (1970).^dAverage values calculated by Herrmann (1970).

Table A.12 Average Composition of Water in Streams and in the Oceans in micrograms per gram

<i>Element</i>	<i>Classification^a</i>	<i>Stream water</i>	<i>Seawater</i>	<i>Seawater enrichment</i>	<i>MORT^b</i>
Li	I	3×10^{-3}	1.7×10^{-1}	56.7	2.5×10^6
Be	IV	1×10^{-5}	2×10^{-7}	0.02	6.3×10^1
B	I	1×10^{-2}	4.5	450	1.6×10^7
F	I	1×10^{-3}	1.3	1300	7.9×10^5
Na	I	6.3	1.08×10^4	1714	2.0×10^8
Mg	I	4.1	1.29×10^3	315	5.0×10^7
Al	IV	5×10^{-2}	8×10^{-4}	0.016	7.0
Si	II	6.5	2.8	0.43	7.9×10^3
P	II	2×10^{-2}	7.1×10^{-2}	3.6	4.0×10^4
S	I	3.7	9.0×10^2	243	5.0×10^8
Cl	I	7.8	1.95×10^4	2500	6.3×10^8
K	I	2.3	3.99×10^2	173	1.3×10^7
Ca	I	15	4.13×10^2	27.5	1.3×10^6
Sc	IV	4×10^{-6}	6.7×10^{-7}	0.17	2.5×10^1
Ti	IV	3×10^{-3}	$<9.6 \times 10^{-4}$	0.32	$<1.6 \times 10^2$
V	IV	9×10^{-4}	1.2×10^{-3}	1.3	7.9×10^3
Cr	IV	1×10^{-3}	2×10^{-4}	0.2	1.6×10^3
Mn	III	7×10^{-3}	3×10^{-4}	0.04	3.2×10^1
Fe	IV	4×10^{-2}	6×10^{-5}	0.0015	6.9×10^{-1}
Co	III	1×10^{-4}	2×10^{-6}	0.02	2.0×10^1
Ni	III	3×10^{-4}	5×10^{-4}	1.7	1.6×10^3
Cu	III	7×10^{-3}	3×10^{-4}	0.04	1.0×10^3
Zn	III	2×10^{-2}	4×10^{-4}	0.02	1.3×10^3
Ga	IV	9×10^{-5}	2×10^{-5}	0.2	7.9×10^2
Ge	IV	5×10^{-6}	5×10^{-6}	1	2.0×10^3
As	IV	2×10^{-3}	1.7×10^{-3}	0.85	1.0×10^5
Se	III	6×10^{-5}	1.3×10^{-4}	2.2	6.3×10^5
Br	I	2×10^{-2}	6.7×10^1	3350	7.9×10^8
Rb	I	1×10^{-3}	1.2×10^{-1}	120	7.9×10^5
Sr	I	7×10^{-2}	7.6	109	5.0×10^6
Y	III	4×10^{-5}	7×10^{-6}	0.18	1.3×10^2
Zr	IV	—	3×10^{-5}	—	1.6×10^2
Nb	IV	—	$<5 \times 10^{-6}$	—	$<2.5 \times 10^2$
Mo	I	6×10^{-4}	1.1×10^{-2}	18.3	3.2×10^5
Ag	III	3×10^{-4}	2.7×10^{-6}	0.009	2.0×10^4
Cd	IV	1×10^{-5}	8×10^{-5}	8	7.9×10^4
In	IV	—	1×10^{-7}	—	1.0×10^3
Sn	IV	4×10^{-5}	5×10^{-7}	0.013	1.3×10^2
Sb	III	7×10^{-5}	1.5×10^{-4}	2.1	1.3×10^5
I	I	7×10^{-3}	5.6×10^{-2}	8	$<4.0 \times 10^6$
Cs	I	2×10^{-5}	2.9×10^{-4}	14.5	4.0×10^4
Ba	III	2×10^{-2}	1.4×10^{-2}	0.7	5.0×10^3
La	III	4.8×10^{-5}	4.5×10^{-6}	0.094	7.9×10^1
Cl	III	7.9×10^{-5}	3.5×10^{-6}	0.044	3.2×10^1

Table A.12 (continued)

<i>Element</i>	<i>Classification^a</i>	<i>Stream water</i>	<i>Seawater</i>	<i>Seawater enrichment</i>	<i>MORT^b</i>
Pr	III	7.3×10^{-6}	1.0×10^{-6}	0.14	7.9×10^1
Nd	III	3.8×10^{-5}	4.2×10^{-6}	0.11	7.9×10^1
Sm	III	7.8×10^{-6}	8.0×10^{-7}	0.10	7.9×10^1
Eu	III	1.5×10^{-6}	1.5×10^{-7}	0.10	6.3×10^1
Gd	III	8.5×10^{-6}	1.0×10^{-6}	0.11	1.0×10^2
Tb	III	1.2×10^{-6}	1.7×10^{-7}	0.14	1.0×10^2
Dy	III	7.2×10^{-6}	1.1×10^{-6}	0.15	1.0×10^2
Ho	III	1.4×10^{-6}	2.8×10^{-7}	0.20	1.3×10^2
Er	III	4.2×10^{-6}	9.2×10^{-7}	0.22	1.6×10^2
Tm	III	6.1×10^{-7}	1.3×10^{-7}	0.21	1.6×10^2
Yb	IV	3.6×10^{-6}	9.0×10^{-7}	0.25	2.0×10^2
Lu	IV	6.4×10^{-7}	1.4×10^{-7}	0.22	2.0×10^2
Hf	IV	—	$<7 \times 10^{-6}$	—	$<1.3 \times 10^3$
Ta	IV	—	$<2.5 \times 10^{-6}$	—	$<2.0 \times 10^3$
W	IV	3×10^{-5}	1×10^{-4}	3.3	7.9×10^4
Re	IV	—	4×10^{-6}	—	3.2×10^6
Au	III	2×10^{-6}	4.9×10^{-6}	2.5	1.6×10^6
Hg	III	7×10^{-5}	1×10^{-6}	0.14	7.9×10^3
Tl	IV	—	1×10^{-5}	—	6.3×10^3
Pb	III	1×10^{-3}	2×10^{-6}	0.002	5.0×10^1
Bi	IV	—	2×10^{-5}	—	2.5×10^4
Th	IV	$<1 \times 10^{-4}$	6×10^{-8}	~ 0.0006	3.4
U	I	4×10^{-5}	3.1×10^{-3}	2.7	1×10^6

^aI. Conservative element whose concentration is directly related to the salinity of seawater.

II. Nonconservative element whose concentration varies with depth or regionally within the oceans, or both, generally because of involvement in biological activity.

III. Nonconservative element whose concentration varies irregularly and is not related to salinity, depth, or geographic factors.

IV. Unclassified, but probably nonconservative.

^bMean oceanic residence time in years.

SOURCE: Taylor and McLennan (1985).

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Appendix B

STANDARD GIBBS FREE ENERGIES (G_f°) AND STANDARD ENTHALPIES OF FORMATION (H_f°)

The elements are listed in alphabetical order by their chemical symbols, except the REEs that follow La and the transuranium elements that follow U. All charged ionic species are considered to be in aqueous solution. The superscript 0 means neutral molecule in aqueous solution, (g) = gas, (l) = liquid, (c) = crystalline, (amorph.) = amorphous. Compounds identified by their mineral names are crystalline. The conversion from kilocalories to kilojoules is 1 kcal = 4.184 kJ. The standard state is $T = 25^\circ\text{C}$, $P = 1\text{ atm}$, activity of ions and molecules = 1.

The data are from compilations of the literature by (1) Woods and Garrels (1987); (2) Weast et al., (1986); (3) Drever (1982); (4) Brookins, (1988); (5) Lindsay (1979); (6) Krauskopf (1979); (7) Garrels and Christ (1965); and (8) Tardy and Garrels (1974) and are expressed in kcal/mol. In cases where several sources are indicated, the stated value is the *average* of the data given by those sources. The calculations in the text are based on data from 2, 3, 4, 5, 6, and 7. Brookins (1988) primarily cited data from Wagman et al. (1982). The values compiled by Woods and Garrels (1987) were averaged when the range of values is less than about 1% but stated as ranges

when the data vary beyond reasonable estimates of analytical errors. These values are stated here to confirm the older data compilations where possible, to detect significant discrepancies in the values of the thermodynamic parameters, and to suggest the magnitude of these discrepancies by the range of values that have been reported in the literature.

The range of thermodynamic parameters compiled from the literature by Woods and Garrels (1987) reminds us that the values of these parameters are *measurements* that have both random and systematic errors. Therefore, the correct values must be *selected* by a review of the analytical data for other solids and ions based on chemical reactions. Such a critical evaluation of the thermodynamic properties of the rock-forming minerals was not attempted in this book but was made by Helgeson et al. (1978). However, many new measurements have since been reported. When calculations are made for research purposes, the original sources should be consulted to assure the accuracy of the data. The values listed by Weast et al. (1986) are from *Technical Notes* 270-3, 270-4, 270-5, 270-6, 270-7 and 270-8 of the National Bureau of Standards.

Contents

(The elements are listed in alphabetical order by name)

Aluminum	522	Osmium	557
Antimony	562	Oxygen	557
Arsenic	525	Palladium	560
Barium	527	Phosphorus	557
Beryllium	528	Platinum	560
Bismuth	529	Polonium	560
Bromine	529	Potassium	544
Cadmium	533	Radium	561
Calcium	530	Rare Earths	545
Carbon	529	Rhenium	561
Cesium	536	Rhodium	561
Chlorine	534	Rubidium	561
Chromium	536	Ruthenium	561
Cobalt	535	Scandium	563
Copper	537	Selenium	563
Fluorine	539	Silicon	564
Gallium	542	Silver	521
Germanium	542	Sodium	554
Gold	526	Strontium	565
Hafnium	542	Sulfur	562
Hydrogen	542	Tantalum	566
Indium	544	Tellurium	566
Iridium	544	Thallium	568
Iron	539	Thorium	567
Iodine	544	Tin	564
Lead	558	Titanium	567
Lithium	548	Transuranium	569
Magnesium	549	Tungsten	571
Manganese	551	Uranium	568
Mercury	543	Vanadium	570
Nickel	556	Yttrium	571
Nitrogen	553	Zinc	572
Niobium	556	Zirconium	574

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
Ag (silver)			
Ag(c)		0.00	0.00
Ag ⁺		+18.433 ^(2,4-7)	+25.234 ^(2,6,7)
Ag ²⁺		+64.20 ^(5,7)	+64.20 ⁽¹⁾
		+64.29 ⁽⁴⁾	
AgO(c)		+2.61 ⁽¹⁾	-6.0 ⁽¹⁾
Ag ₂ O(c)		-2.68 ^(2,4)	-7.42 ⁽²⁾
Ag ₂ O ₂ (c)		+6.60 ^(1,4)	-5.81 ⁽¹⁾
Ag ₂ O ₃ (c)		+29.01 ^(2,4)	+8.1 ⁽²⁾
AgCl ⁰		-12.939 ⁽²⁾	-14.718 ⁽²⁾
		-17.43 ⁽¹⁾	-17.47 ⁽¹⁾
AgCl	chlorargyrite	-26.244 ^(2,5-7)	-30.37 ^(2,6,7)
AgCl ₂ ⁻		-51.48 ^(1,4)	-58.56 ⁽¹⁾
AgCl ₃ ²⁻		-82.67 ⁽¹⁾	-58.56 ⁽¹⁾
AgF ⁰		-48.21 ^(2,5)	-54.27 ⁽²⁾
AgF	fluorargyrite	-50.03 ⁽⁵⁾	-48.9 ^(2,6)
		-44.2 ⁽⁶⁾	
AgBr	bromargyrite	-23.1 ⁽¹⁾	-24.0 ⁽¹⁾
AgI ⁰		-2.94 ⁽⁵⁾	
AgI(c)	iodargyrite	-15.87 ^(5,7)	-14.91 ⁽⁷⁾
			-14.77 ⁽¹⁾
AgNO ₃ ⁰		-8.18 ⁽²⁾	-24.33 ⁽²⁾
AgNO ₃ (c)		-8.00 ⁽²⁾	-29.73 ⁽²⁾
Ag(NH ₃) ₂ ⁺		-4.12 ⁽¹⁾	-26.66 ⁽¹⁾
Ag(CN) ₂ ⁻		+72.53 ⁽¹⁾	+64.55 ⁽¹⁾
Ag(OH) ⁰		-21.84 ⁽⁵⁾	
Ag(OH) ₂ ⁻		-62.20 ^(4,5)	
Ag(OH) ₃ ²⁻		-85.91 ⁽⁵⁾	
Ag ₃ (OH) ₄ ⁻		-120.78 ⁽⁵⁾	
AgOH(c)		-29.69 ⁽⁵⁾	
		-21.98 ⁽¹⁾	
Ag(OH) ₂ (c)		-45.86 ⁽⁵⁾	
AgMoO ₄ (c)		-196.4 ⁽¹⁾	
Ag ₂ MoO ₄ (c)		-179.2 ⁽¹⁾	-200.5 ⁽¹⁾
Ag ₂ CO ₃ (c)		-104.47 ^(5,7)	-120.97 ⁽⁷⁾
AgHS ⁰		+2.19 ⁽⁵⁾	
Ag(HS) ₂ ⁻		-3.08 ⁽⁵⁾	
α-Ag ₂ S	acanthite	-9.63 ^(2,5,6,7)	-7.73 ^(2,6,7)
		-9.72 ⁽⁴⁾	
β-Ag ₂ S(c)	argentite	-9.41 ^(2,5,7)	-7.02 ^(2,7)
Ag ₂ SO ₄ (c)		-147.82 ⁽²⁾	-171.10 ⁽²⁾
		-147.53 ⁽¹⁾	-170.8 ⁽¹⁾
AgSO ₄ ⁻		-161.30 ⁽⁵⁾	
Ag ₂ SO ₄ ⁰		-141.10 ^(2,5)	-166.85 ⁽²⁾

<i>Compound or species</i>	<i>Mineral name</i>	G_f° , kcal/mol	H_f° , kcal/mol
$\text{Ag}(\text{SO}_3)_2^{3-}$		-225.4 ⁽¹⁾	
$\text{Ag}(\text{S}_2\text{O}_3)_2^{3-}$		-246.5 ⁽¹⁾	-295.5 ⁽¹⁾
Al (aluminum) (additional silicates are listed with Ca, Mg, Fe)			
$\text{Al}(\text{c})$		0.00	0.00
Al^{+3}		-117.33 ⁽⁵⁾	-127.0 ⁽²⁾
		-116.9 ⁽¹⁾	-126.5 ⁽¹⁾
		-115.92 ⁽⁴⁾	
AlO_2^-		-196.7 ⁽²⁾	-219.6 ⁽²⁾
		-198.59 ⁽⁴⁾	
$\text{Al}(\text{OH})^{2+}$		-167.17 ⁽⁵⁾	-182.8 ⁽¹⁾
		-165.89 ⁽⁴⁾	
		-166.3 ⁽¹⁾	
$\text{Al}(\text{OH})_2^+$		-218.02 ⁽⁵⁾	
		-216.9 ⁽¹⁾	
$\text{Al}(\text{OH})_3^0$		-266.94 ⁽⁵⁾	
$\text{Al}(\text{OH})_4^-$		-312.25 ⁽⁵⁾	-356.2 ⁽⁶⁾
		-312.0 ⁽¹⁾	-357.0 ⁽¹⁾
$\text{Al}(\text{OH})_5^{2-}$		-354.06 ⁽⁵⁾	
$\text{Al}_2(\text{OH})_2^{4+}$		-337.54 ⁽⁵⁾	
$\text{Al}(\text{OH})_3(\text{amorph.})$		-271.9 ^(6,7)	-305.0 ⁽²⁾
		-272.4 ⁽¹⁾	
$\alpha\text{-Al}(\text{OH})_3$	bayerite	-275.78 ⁽⁵⁾	308.0 ⁽²⁾
		-274.9 ⁽¹⁾	
$\gamma\text{-Al}(\text{OH})_3$	gibbsite	-276.1 ^(3,4,5)	-306.25 ⁽²⁾
		-275.9 ⁽¹⁾	-308.9 ⁽¹⁾
$\text{Al}(\text{OH})_3$	nordstrandite	-276.3 ⁽⁵⁾	
$\alpha\text{-AlOOH}$	diaspore	-219.2 ^(2,3,5,7)	-238.4 ^(2,3)
		-219.5 ⁽¹⁾	-238.6 ⁽¹⁾
$\gamma\text{-AlOOH}$	boehmite	-218.36 ^(2,3,5,6,7)	-236.0 ^(2,3,6,7)
		-218.5 ⁽¹⁾	-236.2 ⁽¹⁾
$\alpha\text{-Al}_2\text{O}_3$	corundum	-378.2 ^(2,3,5,6)	-398.6 ^(2,3,6,7)
		-377.9 ⁽¹⁾	-399.3 ⁽¹⁾
$\gamma\text{-Al}_2\text{O}_3(\text{c})$		-373.38 ⁽⁵⁾	
AlPO_4	berlinite	-387.6 ^(2,5)	-414.4 ⁽²⁾
		-386.1 ⁽¹⁾	
$\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$	variscite	-505.97 ⁽⁵⁾	-562.4 ⁽¹⁾
		-501.7 ⁽¹⁾	
$\text{AlPO}_4(\text{OH})_3$	augelite	-660.9 ⁽¹⁾	
$\text{Al}_3(\text{PO}_4)_2(\text{OH})_3(\text{H}_2\text{O})_4 \cdot \text{H}_2\text{O}$	wavelite	-1330.0 ⁽¹⁾	
$\text{H}_6\text{K}_3\text{Al}_5(\text{PO}_4)_8 \cdot 18\text{H}_2\text{O}$	K-taranakite	-4014.76 ⁽⁵⁾	-4520.5 ⁽¹⁾
		-4005.9 to 4162.8 ⁽¹⁾	
$\text{H}_6(\text{NH}_4)_3\text{Al}_5(\text{PO}_4)_8 \cdot 18\text{H}_2\text{O}$	NH_4 -taranakite	-3864.84 ⁽⁵⁾	
AlSO_4^+		-299.64 ⁽⁵⁾	

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
$\text{Al}(\text{SO}_4)_2^-$		-475.82 ⁽⁵⁾	
$\text{Al}_2(\text{SO}_4)_3^0$		-765.94 ⁽⁵⁾	
$\text{Al}_2(\text{SO}_4)_3(\text{c})$		-740.51 ^(2,5)	-822.38 ⁽²⁾
		-740.4 ⁽¹⁾	-822.0 ⁽¹⁾
$\text{Al}_2(\text{SO}_4)_3 \cdot 6\text{H}_2\text{O}(\text{c})$		-1104.38 ^(2,5)	-1269.53 ⁽²⁾
$\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$	alunite	-1111.38 ⁽⁵⁾	-1235.6 ⁽¹⁾
		-1113.6 ⁽¹⁾	
$\text{NH}_4\text{Al}(\text{SO}_4)_2(\text{c})$		-487.2 ⁽²⁾	-562.2 ⁽²⁾
$\text{NH}_4\text{Al}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}(\text{c})$		-1180.21 ⁽²⁾	-1420.26 ⁽²⁾
$\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}(\text{c})$		-1228.9 ⁽²⁾	-1448.8 ⁽²⁾
$\text{KAl}(\text{SO}_4)_2 \cdot 3\text{H}_2\text{O}(\text{c})$		-711.0 ⁽²⁾	-808.1 ⁽²⁾
$\text{KAl}(\text{SO}_4)_2(\text{c})$		-535.4 ^(1,2)	-590.4 ^(1,2)
$\text{AlF}_3(\text{c})$		-341.6 ⁽¹⁾	-360.5 ⁽¹⁾
$\text{Al}_2\text{SiO}_4(\text{OH})_2$	hydroxyl-topaz	-643.7 ⁽¹⁾	
$\text{Al}_2\text{SiO}_4\text{F}_2$	fluor-topaz	-695.7 ⁽¹⁾	-737.2 ⁽¹⁾
Al_2SiO_5	andalusite	-584.25 ⁽⁵⁾	-562.2 ⁽²⁾
		-583.5 ⁽¹⁾	-618.7 ⁽¹⁾
Al_2SiO_5	kyanite	-583.38 ⁽⁵⁾	-619.5 ⁽¹⁾
		-583.8 ⁽¹⁾	
Al_2SiO_5	sillimanite	-582.81 ⁽⁵⁾	-618.0 ⁽¹⁾
		-582.9 ⁽¹⁾	
$\text{Al}_6\text{Si}_2\text{O}_{13}$	mullite	-1541.2 ⁽²⁾	-1632.8 ⁽²⁾
		-1537.7 ⁽¹⁾	-1628.9 ⁽¹⁾
$\text{CaAl}_2\text{SiO}_6$	pyroxene	-745.13 ⁽⁵⁾	-787.0 ⁽¹⁾
		-746.1 ⁽¹⁾	
$\text{CaAl}_2\text{Si}_2\text{O}_8$	anorthite	-960.4 ^(3,5)	-1010.1 ^(2,3,6)
	(triclinic)	-954.3 to 961.5 ⁽¹⁾	-1007.8 to 1014.1 ⁽¹⁾
$\text{CaAl}_2\text{Si}_2\text{O}_8$	Ca-glass	-946.24 ⁽⁵⁾	-993.1 to -997.0 ⁽¹⁾
		-941.9 to 945.7 ⁽¹⁾	
$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	wairakite	-1447.65 ⁽³⁾	-1579.55 ⁽³⁾
		-1477.7 to 1483.0 ⁽¹⁾	-1579.5 to -1586.4 ⁽¹⁾
$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 4\text{H}_2\text{O}$	laumontite	-1597.04 ⁽³⁾	-1728.88 ⁽³⁾
		-1597.0 to 1603.0 ⁽¹⁾	-1729.8 to 1733.0 ⁽¹⁾
$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 2\text{H}_2\text{O}$	lawsonite	-1081.95 ⁽⁵⁾	-1162.6 ⁽¹⁾
		-1073.6 to -1082.3 ⁽¹⁾	
$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 7\text{H}_2\text{O}$	leonhardite	-3155.37 ⁽⁵⁾	(see also Ca)
$\text{CaAl}_2\text{Si}_3\text{O}_{10} \cdot 3\text{H}_2\text{O}$	scolecite	-1337.9 ⁽¹⁾	-1445.7 ⁽¹⁾
KAlSiO_4	kaliophilite	-479.70 ⁽⁵⁾	-507.1 ⁽¹⁾
		-479.4 ⁽¹⁾	
KAlSiO_4	kalsilite	-471.3 to 481.7 ⁽¹⁾	-498.9 to 509.5 ⁽¹⁾
KAlSi_2O_6	leucite	-681.6 ⁽⁶⁾	-721.7 ⁽⁶⁾
		-681.8 to -687.4 ⁽¹⁾	-721.0 to -726.3 ⁽¹⁾
KAlSi_3O_8	K-glass	-885.34 ⁽⁵⁾	
KAlSi_3O_8	microcline	-892.8 ⁽⁶⁾	-946.3 ⁽⁶⁾
		893.6 ⁽¹⁾	-947.3 ⁽¹⁾

<i>Compound or species</i>	<i>Mineral name</i>	<i>G_f^o, kcal/mol</i>	<i>H_f^o, kcal/mol</i>
KAlSi ₃ O ₈	sanidine	-892.9 ⁽¹⁾	-945.2 ⁽¹⁾
KAlSi ₃ O ₈	high sanidine	-894.16 ⁽⁵⁾	-946.5 ⁽¹⁾
		-893.8 ⁽¹⁾	
NaAlSiO ₄	nepheline	-472.8 ⁽²⁾	-500.2 ⁽²⁾
		-463.6 to -477.0 ⁽¹⁾	-491.1 to -504.3 ⁽¹⁾
NaAlSi ₃ O ₈	Na-glass	-876.32 ⁽⁵⁾	-922.6 to -926.3 ⁽¹⁾
NaAlSi ₃ O ₈	albite	-884.8 ⁽¹⁾	-938.1 ⁽¹⁾
NaAlSi ₃ O ₈	high albite	-886.5 ^(3,5)	-940.1 ⁽³⁾
		-882.0 to -884.5 ⁽¹⁾	-933.9 to -937.0 ⁽¹⁾
NaAlSi ₃ O ₈	low albite	-844.0 ⁽⁶⁾	-937.1 ⁽⁶⁾
		-883.3 to -887.1 ⁽¹⁾	-936.5 to 940.5 ⁽¹⁾
NaAlSi ₂ O ₆	jadeite	-681.7 ⁽²⁾	-724.4 ⁽²⁾
		-676.6 to -681.7 ⁽¹⁾	-719.3 to -724.4 ⁽¹⁾
NaAlSi ₂ O ₆ · H ₂ O	analcime	-738.16 ^(3,5)	-790.63 ⁽³⁾
		-734.4 to -738.9 ⁽¹⁾	-786.6 to -791.1 ⁽¹⁾
NaAlSi ₂ O ₆	dehydrated		
	analcime	-671.3 to -675 ⁽¹⁾	-711.0 to -714.7 ⁽¹⁾
NaAlSi ₂ O ₅ · 2H ₂ O	analcime	-733.3 ⁽¹⁾	-785.9 ⁽¹⁾
Na ₂ Al ₃ Si ₃ O ₁₀ · 2H ₂ O	natrolite	-1270.7 ⁽¹⁾	-1366.7 ⁽¹⁾
4NaAlSi ₃ O ₈ · CaAl ₂ Si ₂ O ₈	oligoclase	-897.3 ⁽¹⁾	-950.6 ⁽¹⁾
3NaAlSi ₃ O ₈ · 2CaAl ₂ Si ₂ O ₈	andesine	-912.6 ⁽¹⁾	-966.0 ⁽¹⁾
2.5NaAlSi ₃ O ₈ · 2.5CaAl ₂ Si ₂ O ₈	labradorite	-919.9 ⁽¹⁾	-973.3 ⁽¹⁾
Na ₂ Mg ₃ Al ₂ Si ₈ O ₂₂ (OH) ₂	glaucofane	-2710.1 ⁽¹⁾	-2885.4 ⁽¹⁾
NaCa ₂ Mg ₄ Al ₃ Si ₆ O ₂₂ (OH) ₂	pargasite	-2848.8 ⁽¹⁾	-3021.7 ⁽¹⁾
NaCa ₂ Fe ₄ ²⁺ Al ₃ Si ₆ O ₂₂ (OH) ₂	ferropargasite	-2518.8 ⁽¹⁾	-2685.8 ⁽¹⁾
Al ₂ Si ₂ O ₅ (OH) ₄	dickite	-908.55 ⁽⁵⁾	-984.1 ⁽¹⁾
		-906.2 ⁽¹⁾	
Al ₂ Si ₂ O ₅ (OH) ₄	halloysite	-904.2 ^(3,5)	-980.28 ⁽³⁾
		-902.3 ⁽¹⁾	-979.9 ⁽¹⁾
Al ₂ Si ₂ O ₅ (OH) ₄	kaolinite	-906.84 ⁽³⁾	-983.5 ⁽³⁾
		-905.7 ⁽¹⁾	-983.5 ⁽¹⁾
Al ₂ Si ₄ O ₁₀ (OH) ₂	pyrophyllite	-1256.00 ⁽³⁾	-1345.31 ⁽³⁾
		-1258.3 ⁽¹⁾	-1347.4 ⁽¹⁾
KAl ₂ (AlSi ₃ O ₁₀)(OH) ₂	muscovite	-1337.45 ⁽³⁾	-1427.9 ⁽³⁾
		-1330.0 to -1340.6 ⁽¹⁾	-1421.4 to -1430.3 ⁽¹⁾
CaAl ₄ Si ₂ O ₁₀ (OH) ₂	margarite	-1398.0 ⁽¹⁾	-1489.8 ⁽¹⁾
KMg _{0.5} Al ₂ Si _{3.5} O ₁₀ (OH) ₂	phengite	-1321.5 ⁽¹⁾	-1412.6 ⁽¹⁾
K _{0.6} Mg _{0.25} Al _{2.3} Si _{3.5} O ₁₀ (OH) ₂	illite	-1307.49 ⁽⁸⁾	
KMg ₃ AlSi ₃ O ₁₀ (OH) ₂	phlogopite	-1396.19 ⁽³⁾	-1488.07 ⁽³⁾
		-1389.5 to -1410.9 ⁽¹⁾	-1412.6 to -1568.5 ⁽¹⁾
KMg ₃ (AlSi ₃ O ₁₀)F ₂	fluorphlogopite	-1461.63 ⁽⁵⁾	-1522.8 ⁽¹⁾ -1527.9 ⁽¹⁾
		-1440.3 to -1446.7 ⁽¹⁾	
KFe ₃ AlSi ₃ O ₁₀ (OH) ₂	annite	-1147.16 ⁽³⁾	-1232.20 ⁽³⁾
		-1145.8 to 1159.2 ⁽¹⁾	-1232.2 to -1301.1 ⁽¹⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
$\text{NaAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$	paragonite	-1327.42 ^(3,5)	-1416.96 ⁽³⁾
$\text{NaSi}_7\text{O}_{13}(\text{OH}) \cdot 3\text{H}_2\text{O}$	magadiite	-1762.2 ⁽¹⁾	
$\text{NaSi}_7\text{O}_{13}(\text{OH})_3$	magadiite	-1589.85 ⁽³⁾	
$\text{K}_{0.33}\text{Al}_{2.33}\text{Si}_{3.67}\text{O}_{10}(\text{OH})_2$	K-montmorillonite	-1279.9 ⁽¹⁾	-1369.3 ⁽¹⁾
$\text{Na}_{0.33}\text{Al}_{2.33}\text{Si}_{3.67}\text{O}_{10}(\text{OH})_2$	beidellite	-1277.76 ⁽³⁾	
$\text{Ca}_{0.167}\text{Al}_{2.33}\text{Si}_{3.67}\text{O}_{10}(\text{OH})_2$	Ca-montmorillonite	-1279.24 ^(1,2)	-1368.4 ⁽¹⁾
$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	Mg-cordierite	-2075.26 ⁽⁵⁾	
$\text{Mg}_{0.2}(\text{Si}_{3.81}\text{Al}_{1.71}\text{Fe}_{0.22}^{3+}\text{Mg}_{0.29})\text{O}_{10}(\text{OH})_2$	Mg-montmorillonite	-1258.84 ⁽⁵⁾	
$(\text{Al}_{1.29}\text{Mg}_{0.445}\text{Fe}_{0.335}^{3+})(\text{Si}_{3.82}\text{Al}_{0.18})\text{O}_{10}(\text{OH})_2$	Aberdeen montmorillonite (charges unbalanced)	-1227.7 ⁽¹⁾	
$(\text{Al}_{1.515}\text{Mg}_{0.29}\text{Fe}_{0.225}^{3+})(\text{Si}_{3.935}\text{Al}_{0.065})\text{O}_{10}(\text{OH})_2$	Spur montmorillonite (charges unbalanced)	-1237.1 ⁽¹⁾	
$(\text{Mg}_{2.71}\text{Fe}_{0.02}^{2+}\text{Fe}_{0.46}^{3+}\text{Ca}_{0.06}\text{K}_{0.1})(\text{Si}_{2.91}\text{Al}_{1.14})\text{O}_{10}(\text{OH})_2$	vermiculite	-1324.38 ⁽⁵⁾	
$\text{Mg}_5\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_8$	chlorite (clinochlore)	-1961.70 ⁽³⁾ -1975.56 ⁽⁵⁾	
As (arsenic) (see also Fe)			
$\alpha\text{-As}$ (grey, metallic)		0.00	0.00
As(g)		+50.7 to +62.4 ⁽¹⁾	+60.6 to +72.3 ⁽¹⁾
$\text{As}_2(\text{g})$		+17.5 ⁽⁷⁾	+29.6 ⁽⁷⁾
		+17.5 to +41.1 ⁽¹⁾	+29.6 to +53.1 ⁽¹⁾
$\text{As}_4(\text{g})$		+20.9 to +25.2 ⁽¹⁾	+34.3 to +35.1 ⁽¹⁾
AsO^+		-39.15 ⁽²⁾ -38.3 ⁽¹⁾	
AsO_2^-		-83.66 ^(1,2)	-102.54 ^(1,2)
AsO_4^{3-}		-155.0 ^(2,6) -154.97 ⁽⁴⁾ -154.7 ⁽¹⁾	-212.27 ^(2,6) -211.7 ⁽¹⁾
HAsO_4^{2-}		-170.82 ⁽²⁾ -170.69 ⁽⁴⁾ -170.7 ⁽¹⁾	-216.62 ⁽²⁾ -216.7 ⁽¹⁾
H_2AsO_4^-		-180.04 ⁽²⁾ -180.01 ⁽⁴⁾ -180.2 ⁽¹⁾	-217.39 ⁽²⁾ -217.6 ⁽¹⁾
H_3AsO_4^0		-183.1 ⁽⁶⁾ -183.06 ⁽⁴⁾ -183.7 ⁽¹⁾	-216.2 ⁽²⁾ -216.0 ⁽¹⁾
H_3AsO_3^0		-152.9 ^(4,6,7) -153.6 ⁽¹⁾	-177.4 ^(6,7) -178.1 ⁽¹⁾
HAsO_3^{2-}		-125.31 ⁽⁴⁾	
H_2AsO_3^-		-140.35 ^(2,4) -125.3 to 141.8 ⁽¹⁾	-170.84 ⁽²⁾ -164.7 to -172.3 ⁽¹⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
AsO_3^{3-}		-107.00 ⁽⁴⁾	
HAsO_2^0		-96.25 ⁽²⁾	-109.1 ⁽²⁾
$\text{As}_2\text{O}_3, \alpha$	arsenolite, (octahedral)	-138.4 ⁽¹⁾	-157.6 ⁽¹⁾
$\text{As}_2\text{O}_3, \beta$	claudetite, (monoclinic)	-137.9 ⁽⁶⁾ -137.66 ⁽⁴⁾ -138.7 ⁽¹⁾	-156.5 ⁽⁶⁾ -157.2 ⁽¹⁾
$\text{As}_2\text{O}_5(\text{c})$		-187.0 ⁽²⁾ -186.2 ⁽¹⁾	-221.05 ⁽²⁾ -220.2 ⁽¹⁾
$\text{As}_2\text{O}_5 \cdot 4\text{H}_2\text{O}$		-411.1 ⁽⁷⁾ -411.1 ⁽¹⁾	-503.0 ⁽²⁾ -501.6 ⁽¹⁾
AsS	realgar	-16.80 ⁽⁴⁾	
As_2S_2		-32.15 ⁽⁷⁾ -33.1 ⁽¹⁾	-34.1 ⁽²⁾ -33.6 ⁽¹⁾
As_2S_3	orpiment	-40.3 ^(2,4) -22.8 to -40.3 ⁽¹⁾	-40.4 ⁽²⁾ -23.0 to -40.4 ⁽¹⁾
Au (gold)			
$\text{Au}(\text{c})$		0.00	0.00
Au^+		+39.0 ^(6,7) +41.4 ⁽¹⁾	+53.1 ⁽¹⁾
Au^{3+}		+103.6 ^(1,6,7)	
AuCl_2^-		-36.13 ^(2,4) -36.1 ⁽¹⁾	-41.7 ⁽¹⁾
AuCl_4^-		-56.22 ⁽²⁾ -56.2 ^(1,4)	-77.0 ⁽²⁾ -77.4 ⁽¹⁾
HAuCl_4^0		-56.22 ^(2,4)	-77.0 ⁽²⁾
$\text{AuCl}(\text{c})$		-3.6 ⁽⁶⁾	-8.3 ⁽²⁾
$\text{AuCl}_3(\text{c})$		-10.8 ⁽⁶⁾	-28.1 ⁽²⁾
$\text{AuO}_2(\text{c})$		+48.0 ^(1,7)	
$\text{Au}(\text{CN})_2^-$		-68.31 ⁽⁴⁾	
$\text{Au}(\text{SCN})_2^-$		-60.21 ⁽⁴⁾	
$\text{Au}_2\text{O}_3(\text{c})$		+39.0 ^(1,7)	+19.3 ^(1,7)
H_3AuO_3^0		-61.8 ^(1,7)	
H_2AuO_3^-		-52.2 ^(2,4) -45.8 to -61.8 ⁽¹⁾	
HAuO_3^{2-}		-34.0 ^(2,4) -27.6 to -34.0 ⁽¹⁾	
AuO_3^{3-}		-12.4 ^(2,4) -5.8 to -12.4 ⁽¹⁾	
$\text{Au}(\text{OH})_3(\text{c})$		-75.77 ^(2,4) -69.3 to 83.4 ⁽¹⁾	-101.5 ⁽²⁾ -100.0 to -114.3 ⁽¹⁾
$\text{Au}(\text{OH})_3^0$		-67.7 to 75.9 ⁽¹⁾	

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
B (boron) (see also Na)			
B(c), β		0.00	0.00
B ₂ O ₃ (glass)		-282.6 ⁽²⁾	-299.84 ⁽²⁾
		-281.8 ⁽¹⁾	-299.1 ⁽¹⁾
B ₂ O ₃ (c)		-285.30 ^(2,4)	-304.20 ⁽²⁾
		-284.7 ⁽¹⁾	-303.7 ⁽¹⁾
H ₃ BO ₃ (c)		-231.60 ⁽²⁾	-261.55 ⁽²⁾
		-230.9 ⁽¹⁾	-260.9 ⁽¹⁾
H ₃ BO ₃ ⁰		-231.56 ^(2,4)	-256.29 ⁽²⁾
		-231.2 ⁽¹⁾	-256.1 ⁽¹⁾
H ₂ BO ₃ ⁻		-271.60 ^(1,4,7)	-251.8 ^(1,7)
HBO ₃ ²⁻		-200.2 ⁽⁷⁾	
		-200.3 ^(1,4)	
BO ₃ ³⁻		-181.48 ^(7,4)	
		-181.5 ⁽¹⁾	
B(OH) ₄ ⁻		-275.65 ⁽²⁾	-321.23 ⁽²⁾
		-275.61 ⁽⁴⁾	-321.1 ⁽¹⁾
		-275.7 ⁽¹⁾	
BO ₂ ⁻		-162.27 ^(2,4)	-184.60 ⁽²⁾
		-162.3 to -181.5 ⁽¹⁾	-184.1 ⁽¹⁾
HB ₄ O ₇ ⁻		-628.3 ⁽¹⁾	
B ₄ O ₇ ²⁻		-622.56 ⁽⁴⁾	
		-615.0 to -622.6 ⁽¹⁾	
BF ₄ ⁻		-352.8 ⁽¹⁾	-372.5 ⁽¹⁾
BH ₄ ⁻		+27.33 ⁽⁴⁾	
Ba (barium)			
Ba(c)		0.00	0.00
Ba ²⁺		-134.02 ^(2,4)	-128.50 ⁽²⁾
		-132.7 ⁽¹⁾	-127.2 ⁽¹⁾
BaO(c)		-132.0 ⁽⁶⁾	-139.1 ⁽⁶⁾
		-124.5 ⁽¹⁾	-131.3 ⁽¹⁾
		-125.50 ⁽⁴⁾	
BaO ₂ (c)		-135.8 ^(1,7)	-151.6 ⁽²⁾
			-151.0 ⁽¹⁾
BaO ₂ · H ₂ O(c)		-195.0 ^(1,7)	-222.3 ⁽²⁾
			-222.9 ⁽¹⁾
BaF ₂ (c)		-276.5 ⁽²⁾	-288.5 ⁽²⁾
		-273.9 ⁽¹⁾	-286.5 ⁽¹⁾
BaF ₂ ⁰		-267.30 ⁽²⁾	-287.50 ⁽²⁾
BaS(c)		-109 ⁽²⁾	-110 ⁽²⁾
		-104.5 to -109.0 ⁽¹⁾	-106.0 to -109.9 ⁽¹⁾
BaSO ₄	barite	-325.6 ^(2,4)	-352.1 ⁽²⁾
		-324.2 ⁽¹⁾	-351.0 ⁽¹⁾

<i>Compound or species</i>	<i>Mineral name</i>	<i>G_f^o, kcal/mol</i>	<i>H_f^o, kcal/mol</i>
BaSO ₄ ⁰		-311.99 ⁽²⁾	-345.82 ⁽²⁾
BaCO ₃	witherite	-271.9 ^(2,4)	290.7 ⁽²⁾
		-272.3 ⁽¹⁾	291.2 ⁽¹⁾
BaCO ₃ ⁰		-260.19 ⁽²⁾	-290.34 ⁽²⁾
BaSiO ₃ (c)		-368.1 ⁽⁶⁾	-388.7 ⁽⁶⁾
		-338.7 to -369.1 ⁽¹⁾	-359.5 to -389.2 ⁽¹⁾
Ba ₂ SiO ₄ (c)		-519.8 ⁽²⁾	-546.8 ⁽²⁾
		-518.1 ⁽¹⁾	-544.8 ⁽¹⁾
Ba(OH) ₂ (c)		-204.7 ⁽⁷⁾	-225.8 ⁽²⁾
		-204.8 ⁽¹⁾	-226.2 ⁽¹⁾
Ba(OH) ₂ ·8H ₂ O(c)		-667.6 ⁽²⁾	-798.8 ⁽²⁾
		-667.1 ⁽¹⁾	-799.1 ⁽¹⁾
Ba ₃ (PO ₄) ₂ (c)		-944.4 ^(1,7)	-998.0 ⁽⁷⁾
			-998.1 ⁽¹⁾
BaCl ₂ (c)		-193.7 ⁽²⁾	-205.2 ⁽²⁾
		-192.7 ⁽¹⁾	-204.2 ⁽¹⁾
BaCl ₂ ⁰		-196.76 ⁽²⁾	-208.40 ⁽²⁾
Ba(NO ₃) ₂	nitrobarite	-190.42 ⁽²⁾	-237.11 ⁽²⁾
		-189.5 ⁽¹⁾	-236.3 ⁽¹⁾
Ba(NO ₃) ₂ ⁰		-187.24 ⁽²⁾	-227.62 ⁽²⁾
Be (beryllium)			
Be(c)		0.00	0.00
Be ²⁺		-90.75 ^(2,4)	-91.5 ⁽²⁾
		-85.2 to -91.1 ⁽¹⁾	-91.5 to -96.5 ⁽¹⁾
BeO(c)	bromellite	-138.7 ^(2,4)	-145.7 ⁽²⁾
		-136.1 to -139.01	-143.1 to -146.0 ⁽¹⁾
BeO ₂ ²⁻		-153.0 ^(2,4)	-189.0 ⁽²⁾
		-153.0 to -155.3 ⁽¹⁾	-187.8 to -189.0 ⁽¹⁾
Be ₂ O ₃ ²⁻		-298.0 ⁽¹⁾	
BeCl ₂ , α(c)		-106.5 to -118.9 ⁽¹⁾	-117.2 to -122.3 ⁽¹⁾
BeCl ₂ , β(c)		-107.3 ⁽¹⁾	-115.7 to -118.5 ⁽¹⁾
BeAl ₂ O ₄	chrysoberyl	-520.7 ⁽²⁾	-549.9 ⁽²⁾
		-520.6 ⁽¹⁾	-549.8 ⁽¹⁾
Be ₂ SiO ₄	phenacite	-485.3 to -488.6 ⁽¹⁾	-512.6 to -515.9 ⁽¹⁾
BeSiO ₃ (c)		-347.5 ⁽¹⁾	-368.0 ⁽¹⁾
Be(OH) ₂ , α(c)		-194.8 ^(2,4)	-215.7 ⁽²⁾
		-194.8 to -196.2 ⁽¹⁾	-215.7 to -216.8 ⁽¹⁾
Be(OH) ₂ , β(c)		-195.4 ⁽²⁾	-216.5 ⁽²⁾
		-195.5 ⁽¹⁾	-216.4 ⁽¹⁾
Be ₃ ·(OH) ₃ ³⁺		-430.6 ⁽²⁾	
		-431.0 ⁽¹⁾	
BeS(c)		-55.9 ^(1,7)	-56.0 ^(1,2)
BeSO ₄ , α(c)		-261.44 ⁽²⁾	-288.05 ⁽²⁾
		-260.6 ⁽¹⁾	-286.0 to -288.1 ⁽¹⁾

<i>Compound or species</i>	<i>Mineral name</i>	<i>G_f^o, kcal/mol</i>	<i>H_f^o, kcal/mol</i>
BeSO ₄ ⁰		-268.72 ⁽²⁾	-308.8 ⁽²⁾
BeSO ₄ · 2H ₂ O(c)		-381.99 ⁽²⁾	-435.74 ⁽²⁾
BeSO ₄ · 4H ₂ O(c)		-497.29 ⁽²⁾	-579.29 ⁽²⁾
Bi (bismuth)			
Bi(c)		0.00	0.00
Bi ₂ (g)		+48.0 ^(1,7)	+52.5 ⁽²⁾
			+52.5 to +59.4 ⁽¹⁾
Bi ³⁺		+19.8 ^(2,4)	+19.3 ⁽¹⁾
		+14.8 to +21.9 ⁽¹⁾	
BiO ⁺		-34.8 ⁽¹⁾	
		-34.99 ⁽⁴⁾	
Bi(OH) ²⁺		-39.13 ⁽⁷⁾	
		-34.99 ⁽⁴⁾	
		-32.6 to -39.13 ⁽¹⁾	
BiO(c)		-43.5 ^(1,7)	-49.85 ^(1,7)
Bi ₂ O ₃ (c)	bismite	-118.0 ⁽²⁾	-137.16 ⁽²⁾
		-118.2 ⁽¹⁾	-137.4 ⁽¹⁾
Bi ₂ O ₄ (c)		-109.0 ^(1,7)	
Bi ₂ O ₅ (c)		-91.57 ^(1,7)	
Bi ₄ O ₇ (c)		-232.75 ^(1,4)	
Bi(OH) ₃ (amorph.)		-137.0 ^(1,7)	-169.6 ^(1,7)
Bi ₆ O ₆ ⁶⁺		-221.80 ⁽⁴⁾	
Bi(OH) ₃ (c)		-139.3 ⁽¹⁾	-170.8 ⁽¹⁾
BiCl ₃ (c)		-76.23 ⁽⁷⁾	-90.61 ^(7,1)
		-74.8 to -76.2 ⁽¹⁾	
BiOCl	bismoclite	-77.6 ⁽¹⁾	-87.8 ⁽¹⁾
Bi ₂ S ₃	bismuthinite	-33.6 ^(2,4)	-34.2 ⁽²⁾
		-33.6 to -39.4 ⁽¹⁾	-34.2 to -43.8 ⁽¹⁾
Br (bromine)			
Br ₂ (l)		0.00	0.00
Br ⁻		-24.85 ⁽²⁾	-25.05 ⁽²⁾
		-24.8 ⁽¹⁾	-29.0 ⁽¹⁾
HBr(g)		-12.77 ⁽²⁾	-8.70 ^(1,2)
		-12.7 ⁽¹⁾	
HBr ⁰		-24.85 ⁽²⁾	-29.05 ⁽²⁾
Br ₂ (g)		+0.751 ^(5,7)	+7.34 ⁽⁷⁾
		+0.74 ⁽¹⁾	+7.37 ⁽¹⁾
Br ₂ ⁰		+0.977 ⁽⁷⁾	-1.1 ⁽⁷⁾
		+0.96 ⁽¹⁾	-0.19 to -1.10 ⁽¹⁾
C (carbon)			
C	graphite	0.00	0.00
C	diamond	+0.693 ^(1,2)	+0.454 ^(1,2)
CO(g)	carbon monoxide	-32.780 ^(1,2)	-26.416 ^(1,2)

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
CO^0		-28.66 ⁽²⁾	-28.91 ⁽²⁾
$\text{CO}_2(\text{g})$	carbon dioxide	-94.254 ⁽²⁾	-94.051 ⁽²⁾
		-92.27 ⁽¹⁾	-98.85 ⁽¹⁾
CO_2^0		-92.26 ⁽²⁾	-98.90 ⁽²⁾
HCN^0		+28.6 ⁽¹⁾	+25.6 ⁽¹⁾
CN^-		-41.2 ⁽¹⁾	+36.0 ⁽¹⁾
CH_2O^0		-31.00 ⁽⁷⁾	
CO_3^{2-}		-126.17 ^(1,2,4)	-161.8 ^(1,2)
HCO_3^-		-140.26 ^(1,2,4)	-165.39 ^(1,2)
H_2CO_3^0	carbonic acid	-148.94 ^(1,2)	-167.22 ^(1,2)
		-149.00 ⁽⁴⁾	
$\text{CH}_4(\text{g})$	methane	-12.13 ^(1,2)	-17.88 ^(1,2)
CH_4^0		-8.22 ^(1,2)	-21.28 ^(1,2)
		-8.28 ⁽⁴⁾	
CH_3COO^-		-88.29 ^(1,2)	-116.16 ^(1,2)
$\text{CH}_3\text{COOH}(\text{l})$		-93.2 ⁽²⁾	-115.8 ⁽²⁾
CH_3COOH^0	acetic acid	-94.8 ⁽²⁾	-116.10 ⁽²⁾
$\text{C}_2\text{O}_4^{2-}$		-161.1 ⁽⁵⁾	-195.7 ⁽⁷⁾
		-159.5 ⁽¹⁾	-193.2 to -195.0 ⁽¹⁾
HC_2O_4^-		-166.93 ⁽⁵⁾	-195.7 ^(1,7)
		-165.1 ⁽¹⁾	
$\text{H}_2\text{C}_2\text{O}_4^0$	oxalic acid	-166.8 ⁽¹⁾	-197.2 ⁽²⁾
			-195.6 ⁽¹⁾
Ca (calcium)			
$\text{Ca}(\text{c})$		0.00	0.00
Ca^{2+}		-132.30 ^(2,4)	-129.74 ^(1,2)
		-132.2 ⁽¹⁾	
CaHCO_3^+		-274.33 ^(3,5)	
		-273.7 ⁽¹⁾	
CaCO_3^0		-258.47 ⁽²⁾	-291.58 ⁽²⁾
		-262.7 ⁽¹⁾	
CaCO_3	aragonite	-269.55 ^(2,4)	-288.51 ⁽²⁾
		-269.7 ⁽¹⁾	-288.6 ⁽¹⁾
CaCO_3	calcite	-269.80 ^(2,4)	-288.46 ⁽²⁾
		-269.9 ⁽¹⁾	-288.6 ⁽¹⁾
CaCO_3	vaterite (hexag.)	-269.0 ⁽¹⁾	
$\text{CaCO}_3 \cdot \text{H}_2\text{O}(\text{c})$		-325.4 ⁽¹⁾	-258.1 ⁽¹⁾
$\text{CaMg}(\text{CO}_3)_2$	dolomite	-517.1 ⁽²⁾	-556.0 ⁽²⁾
		-514.3 to -520.5 ⁽¹⁾	-553.2 to -557.5 ⁽¹⁾
$\text{CaMg}_3(\text{CO}_3)_4$	huntite	-1007.7 ⁽⁷⁾	-1082.6 ⁽¹⁾
		-1004.6 to -1007.7 ⁽¹⁾	
$\text{CaBa}(\text{CO}_3)_2$	alstonite	-543.0 ^(1,7)	
$\text{CaBa}(\text{CO}_3)_2$	barytocalcite	-542.9 ^(1,7)	

<i>Compound or species</i>	<i>Mineral name</i>	<i>G_f^o, kcal/mol</i>	<i>H_f^o, kcal/mol</i>
CaMn(CO ₃) ₂	kutnahorite	-466.2 ^(1,7)	
CaCl ⁺		-162.53 ⁽⁵⁾	
CaCl ₂ ⁰		-195.04 ⁽²⁾	-209.64 ⁽²⁾
CaCl ₂	hydrophilite	-178.8 ⁽²⁾	-190.2 ⁽²⁾
		-179.0 ⁽¹⁾	-190.0 ⁽¹⁾
CaF ₂	fluorite	-279.0 ⁽²⁾	-291.5 ⁽²⁾
		-277.7 to -281.3 ⁽¹⁾	-290.3 to -293.8 ⁽¹⁾
CaF ₂ ⁰		-265.58 ⁽²⁾	-288.74 ⁽²⁾
CaMoO ₄	powellite	-342.9 ⁽²⁾	-368.4 ⁽²⁾
		-342.9 to -346.6 ⁽¹⁾	-368.4 to -372.3 ⁽¹⁾
CaMoO ₄ ⁰		-332.2 ⁽²⁾	-368.2 ⁽²⁾
CaWO ₄	scheelite	-367.1 ⁽²⁾	-393.2 ⁽²⁾
		-357.0 to -367.7 ⁽¹⁾	-381.1 to -393.2 ⁽¹⁾
CaNO ₃ ⁺		-152.61 ⁽⁵⁾	
Ca(NO ₃) ₂ ⁰		-185.52 ⁽²⁾	-228.86 ⁽²⁾
Ca(NO ₃) ₂ (c)		-177.63 ^(1,2)	-224.28 ^(1,2)
CaOH ⁺		-171.7 ⁽²⁾	-182.7 ⁽¹⁾
		-171.4 ⁽¹⁾	
Ca(OH) ₂ ⁰		-207.49 ⁽²⁾	-239.68 ⁽²⁾
CaO(c)	lime	-144.37 ^(1,2,4)	-151.79 ⁽²⁾
			-151.8 ⁽¹⁾
Ca(OH) ₂	portlandite	-214.76 ^(2,4)	-235.68 ⁽²⁾
		-214.5 ⁽¹⁾	-235.6 ⁽¹⁾
CaPO ₄ ⁻		-386.51 ⁽⁵⁾	
CaHPO ₄ ⁰		-398.29 ⁽⁵⁾	
CaH ₂ PO ₄ ⁺		-406.28 ⁽⁵⁾	
CaHPO ₄ ⁰		-392.64 ⁽²⁾	-438.57 ⁽²⁾
CaHPO ₄	monetite	-401.5 ⁽²⁾	-433.65 ⁽²⁾
		-401.6 ⁽¹⁾	-433.4 to -435.2 ⁽¹⁾
CaHPO ₄ · 2H ₂ O	brushite	-515.00 ⁽²⁾	-574.47 ⁽²⁾
		-514.8 ⁽¹⁾	-574.3 to -576.0 ⁽¹⁾
Ca(H ₂ PO ₄) ₂ (amorph.)		-672 ^(1,7)	-742.04 ⁽²⁾
			-744.4 ⁽¹⁾
Ca(H ₂ PO ₄) ₂ (c)		-675.1 ⁽¹⁾	-741.9 to -744.2 ⁽¹⁾
Ca(H ₂ PO ₄) ₂ ⁰		-672.64 ⁽²⁾	-749.38 ⁽²⁾
Ca(H ₂ PO ₄) ₂ · H ₂ O(c)		-730.98 ⁽²⁾	-814.93 ⁽²⁾
α-Ca ₃ (PO ₄) ₂ (c)	high temp.	-926.3 ⁽²⁾	-982.3 ⁽²⁾
		-925.0 to -929.7 ⁽¹⁾	-981.0 to -986.2 ⁽¹⁾
β-Ca ₃ (PO ₄) ₂ (c)		-928.5 ⁽²⁾	-984.9 ⁽²⁾
		-928.5 to -932.0 ⁽¹⁾	-984.9 to -988.9 ⁽¹⁾
Ca ₃ (PO ₄) ₂ ⁰		-883.9 ⁽²⁾	-999.8 ⁽²⁾
Ca ₈ H ₂ (PO ₄) ₆ · 5H ₂ O	octacalcium phosphate	-2942.62 ⁽³⁾	

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
$\text{Ca}_{10}\text{F}_2(\text{PO}_4)_6$	fluorapatite	-3094.73 ⁽⁵⁾ -3108.2 ⁽¹⁾	-3287.4 ⁽¹⁾
$\text{Ca}_{10}(\text{OH})_2(\text{PO}_4)_6$	hydroxyapatite	-3030.0 ^(3,5) -3030.4 ⁽¹⁾	-3211.0 ⁽³⁾ -3218.9 ⁽¹⁾
$\text{CaAl}_3(\text{PO}_4)_2(\text{OH})_5 \cdot \text{H}_2\text{O}$	crandallite	-1336.7 ⁽¹⁾	
CaS	oldhamite	-114.1 ⁽²⁾ -112.3 to -114.1 ⁽¹⁾	-115.3 ⁽²⁾ -113.5 to -115.3 ⁽¹⁾
CaSO_4^0		-310.27 ⁽²⁾ -313.0 ⁽¹⁾	-347.06 ⁽²⁾
CaSO_4	anhydrite	-315.93 ^(1,2,4)	-342.76 ^(1,2)
$\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}, \alpha$	bassanite	-343.41 ⁽²⁾ -343.0 to -349.3 ⁽¹⁾	-376.85 ⁽²⁾ -376.6 ⁽¹⁾
$\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}, \beta(\text{c})$		-342.8 to -349.0 ⁽¹⁾	-376.1 ⁽¹⁾
$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	gypsum	-429.60 ⁽²⁾ -429.56 ⁽⁴⁾ -429.5 ⁽¹⁾	-483.42 ⁽²⁾ -483.3 ⁽¹⁾
$\alpha\text{-CaSO}_4(\text{soluble})(\text{c})$		-313.93 ⁽²⁾ -313.7 ⁽¹⁾	-340.64 ⁽²⁾ -340.4 ⁽¹⁾
$\beta\text{-CaSO}_4(\text{soluble})(\text{c})$		-312.87 ⁽²⁾ -312.7 ⁽¹⁾	-339.58 ⁽²⁾ -339.4 ⁽¹⁾
CaSiO_3	wollastonite	-358.2 to -370.5 ⁽¹⁾	-378.6 to -390.8 ⁽¹⁾
CaSiO_3	α -wollastonite	-369.7 ⁽¹⁾	-389.7 ⁽¹⁾
CaSiO_3	β -wollastonite	-370.39 ⁽²⁾ -370.6 ⁽¹⁾	-390.76 ⁽²⁾ -390.9 ⁽¹⁾
CaSiO_3	pseudowollastonite	-369.2 ⁽²⁾ -357.4 to -370.0 ⁽¹⁾	-389.2 ⁽²⁾ -377.4 to -390.0 ⁽¹⁾
Ca_2SiO_4	larnite	-524.1 ⁽²⁾ -512.7 to -524.3 ⁽¹⁾	-551.5 ⁽²⁾ -538.0 to -551.7 ⁽¹⁾
Ca_2SiO_4	Ca-olivine	-526.1 ⁽²⁾ -525.8 ⁽¹⁾	-554.0 ⁽²⁾ -553.7 ⁽¹⁾
$\text{Ca}_2\text{SiO}_4, \gamma$	bredigite	-526.1 ⁽¹⁾	-554.0 ⁽¹⁾
$\text{Ca}_3\text{Si}_2\text{O}_7$	rankinite	-899.0 ⁽²⁾ -890.8 to -902.3 ⁽¹⁾	-946.7 ⁽²⁾ -938.7 to -952.5 ⁽¹⁾
$\text{CaMg}(\text{SiO}_3)_2$	diopside	-724.00 ⁽³⁾ -724.6 ⁽¹⁾	-765.60 ⁽³⁾ -766.3 ⁽¹⁾
$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	tremolite	-2780 ⁽²⁾ -2776.7 ⁽¹⁾	-2954 ⁽²⁾ -2951.5 ⁽¹⁾
$\text{Ca}_2\text{Fe}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	actinolite	-2352.1 to -2625.5 ⁽¹⁾	-2515.2 ⁽¹⁾
Ca_3SiO_5	hatrurite	-665.6 ⁽¹⁾	-700.6 ⁽¹⁾
$\text{Ca}_3\text{Fe}_2\text{Si}_3\text{O}_{12}$	andradite	-1294.4 ⁽¹⁾	-1376.8 ⁽¹⁾
$\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	grossular	-1500.2 ⁽¹⁾	-1583.8 ⁽¹⁾
$\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	almandine	see Fe	
$\text{Ca}_2\text{Al}_2\text{SiO}_7$	gehlenite	-906.1 ⁽¹⁾	-953.4 ⁽¹⁾
$\text{Ca}_2\text{MgSi}_2\text{O}_7$	akermanite	-879.1 ⁽¹⁾	-926.3 ⁽¹⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
$\text{Ca}_2\text{Al}_3\text{Si}_3\text{O}_{12}(\text{OH})$	clinozoisite	-1549.7 ⁽¹⁾	-1644.2 ⁽¹⁾
$\text{Ca}_2\text{Al}_3\text{Si}_3\text{O}_{12}(\text{OH})$	zoisite	-1293.7 ⁽¹⁾	-1644.2 ⁽¹⁾
$\text{Ca}_2\text{Fe}^{3+}\text{Al}_2\text{Si}_3\text{O}_{12}(\text{OH})$	epidote	-1451.3 ⁽¹⁾	-1544.4 ⁽¹⁾
$\text{Ca}_2\text{Fe}^{3+}\text{Si}_3\text{O}_{12}(\text{OH})$	epidote	-1244.2 ⁽¹⁾	
$\text{Ca}_2\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_2$	prehnite	-1390.8 ⁽¹⁾	-1480.2 ⁽¹⁾
$\text{Ca}_2\text{Al}_2\text{SiO}_6(\text{OH})_2$	bicchucite	-973.0 ⁽¹⁾	-1036.6 ⁽¹⁾
$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 7\text{H}_2\text{O}$	leonhardite (see Al)	-3150.1 ⁽¹⁾	-3400.9 ⁽¹⁾
$\text{CaAl}_2\text{Si}_7\text{O}_{18} \cdot 6\text{H}_2\text{O}$	heulandite	-2331.4 ⁽¹⁾	-2527.6 ⁽¹⁾
$\text{CaFeSi}_2\text{O}_6$	hedenbergite	-639.6 ⁽¹⁾	-678.9 ⁽¹⁾
CaMgSiO_4	monticellite	-512.2 ⁽¹⁾	-540.6 ⁽¹⁾
$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	merwinite	-829.0 ⁽¹⁾	-1090.8 ⁽¹⁾
$\text{Ca}_4\text{MgAl}_5(\text{H}_2\text{O})\text{Si}_6\text{O}_{23}(\text{OH})_3$	pumpellyite	-3194.0 ⁽¹⁾	-3403.4 ⁽¹⁾
CaTiO_3	perovskite	-376.6 ⁽¹⁾	-397.0 ⁽¹⁾
CaTiSiO_5	sphene	-586.7 ⁽¹⁾	-619.0 ⁽¹⁾
$\text{Ca}_5(\text{SiO}_4)_2(\text{CO}_3)$	spurrite	-1331.0 ⁽¹⁾	-1410.1 ⁽¹⁾
$\text{Ca}_5\text{Si}_2\text{O}_7(\text{CO}_3)_2$	tilleyite	-1436.4 ⁽¹⁾	-1522.8 ⁽¹⁾
$\text{Ca}_4\text{Al}_6\text{Si}_6\text{O}_{24}(\text{CO}_3)$	meiyonite	-3141.2 ⁽¹⁾	-3321.6 ⁽¹⁾
Cd (cadmium)			
$\alpha\text{-Cd(c)}$		0.00	0.00
Cd^{2+}		-18.6 ^(1,2)	-18.0 ^(1,2)
		-18.55 ⁽⁴⁾	
HCdO_2^-		-86.7 ⁽¹⁾	
CdO_2^{2-}		-67.97 ⁽⁴⁾	
CdCO_3^0		-150.38 ⁽⁵⁾	
CdHCO_3^+		-161.74 ⁽⁵⁾	
CdCO_3	otavite	-160.0 ^(2,4)	-179.4 ^(1,2)
		-160.3 ⁽¹⁾	
CdCl^+		-52.68 ⁽⁵⁾	-57.5 ⁽¹⁾
		-51.8 to -53.6 ⁽¹⁾	
$\text{CdBr}_2(\text{c})$		-70.6 ⁽¹⁾	-75.4 ⁽¹⁾
$\text{CdCl}_2(\text{c})$		-82.21 ⁽²⁾	-93.57 ⁽²⁾
		-82.1 ⁽¹⁾	-93.4 ⁽¹⁾
CdCl_2^0		-81.286 ⁽²⁾	-98.04 ⁽²⁾
		-84.3 to -85.9 ⁽¹⁾	-96.8 ⁽¹⁾
CdCl_3^-		-116.00 ^(1,5,7)	-134.0 ⁽¹⁾
CdCl_4^{2-}		-147.50 ⁽⁵⁾	
$\text{CdF}_2(\text{c})$		-154.8 ⁽²⁾	-167.4 ⁽²⁾
		-155.1 ⁽¹⁾	-166.6 ⁽¹⁾
CdF_2^0		-151.82 ⁽²⁾	-177.14 ⁽²⁾
CdNO_3^+		-45.67 ⁽⁵⁾	
$\text{Cd}(\text{NO}_3)_2^0$		-71.76 ⁽²⁾	-117.26 ⁽²⁾
$\text{Cd}(\text{OH})^+$		-61.52 ⁽¹⁾	
		-62.4 to -64.9 ⁽¹⁾	

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
$\text{Cd}(\text{OH})_2^0$		-93.73 ⁽²⁾	-128.08 ⁽²⁾
$\text{Cd}(\text{OH})_3^-$		-105.8 to -106.7 ⁽¹⁾	
$\text{Cd}(\text{OH})_4^{2-}$		-143.64 ⁽⁵⁾	
		-143.6 to -144.6 ⁽¹⁾	
$\text{Cd}(\text{OH})_5^{3-}$		-180.85 ⁽⁵⁾	
$\text{Cd}(\text{OH})_6^{4-}$		-181.5 ⁽¹⁾	
$\text{Cd}_2\text{OH}^{3+}$		-217.57 ⁽⁵⁾	
$\text{Cd}_4(\text{OH})_4^{4+}$		-253.96 ⁽⁵⁾	
CdO	monteponite	-85.18 ⁽⁵⁾	
		-263.10 ⁽⁵⁾	
		-54.6 ^(2,4)	-61.7 ⁽²⁾
		-54.4 ⁽¹⁾	-61.5 ⁽¹⁾
$\text{Cd}(\text{OH})_2(\text{c})$		-113.26 ⁽²⁾	-134.06 ⁽²⁾
		-113.19 ⁽⁴⁾	
		-113.4 ⁽¹⁾	-134.7 ⁽¹⁾
CdHPO_4^0		-285.00 ⁽⁵⁾	
$\text{Cd}_3(\text{PO}_4)_2(\text{c})$		-598.16 ⁽⁵⁾	
CdS	greenockite	-37.4 ^(2,4)	-38.7 ⁽²⁾
		-33.6 to -37.4 ⁽¹⁾	-34.5 to -38.7 ⁽¹⁾
$\text{CdSO}_4(\text{c})$		-196.65 ⁽²⁾	-223.06 ⁽²⁾
		-196.33 ⁽⁴⁾	
		-196.4 ⁽¹⁾	-222.5 ⁽¹⁾
CdSO_4^0		-196.51 ⁽²⁾	-235.46 ⁽²⁾
$\text{CdSO}_4 \cdot \text{H}_2\text{O}(\text{c})$		-255.46 ⁽²⁾	-296.26 ⁽²⁾
		-255.2 ⁽¹⁾	-295.6 ⁽¹⁾
$\text{CdSO}_4 \cdot \frac{8}{3}\text{H}_2\text{O}(\text{c})$		-350.224 ⁽²⁾	-413.33 ⁽²⁾
		-350.0 ⁽¹⁾	-412.8 ⁽¹⁾
CdTe		-23.1 ⁽¹⁾	-23.5 ⁽¹⁾
$\text{CdSO}_4 \cdot 2\text{Cd}(\text{OH})_2(\text{c})$		-429.63 ⁽⁵⁾	
$2\text{CdSO}_4 \cdot \text{Cd}(\text{OH})_2(\text{c})$		-519.93 ⁽⁵⁾	
$\text{CdSiO}_3(\text{c})$		-264.0 ⁽²⁾	-284.20 ⁽²⁾
		-263.9 ⁽¹⁾	-283.9 ⁽¹⁾
Cl (chlorine)			
$\text{Cl}_2(\text{g})$		0.00	0.00
Cl^-		-31.3 ^(1,2)	-39.9 ^(1,2)
Cl_2^0		+1.65 ^(1,2)	-5.6 ^(1,2)
$\text{HCl}(\text{g})$		-22.77 ^(1,2)	-22.06 ^(1,2)
HCl^0		-31.35 ^(1,2)	-40.0 ^(1,2)
HClO^0		-19.1 ⁽¹⁾	-28.6 ⁽¹⁾
ClO^-		-8.82 ⁽¹⁾	-25.6 ⁽¹⁾
HClO_2^0		+0.07 to +6.8 ⁽¹⁾	-12.7 ⁽¹⁾
ClO_2^-		+2.74 to +4.1 ⁽¹⁾	-15.9 to -17.2 ⁽¹⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
HClO_3^0		-0.62 ⁽¹⁾	-23.5 ⁽¹⁾
ClO_3^-		-0.62 to -2.0 ⁽¹⁾	-23.5 to -24.9 ⁽¹⁾
HClO_4^0		-2.47 ^(1,7)	-31.41 ^(1,7)
ClO_4^-		-2.57 ⁽⁷⁾	-31.41 ⁽⁷⁾
		-2.0 to -2.6 ⁽¹⁾	-31.0 ⁽¹⁾
Co (cobalt)			
Co(c)		0.00	0.00
Co^{2+}		-13.0 ^(2,4)	-13.9 ^(1,2)
		-13.1 ⁽¹⁾	
Co^{3+}		+32.03 ^(2,4)	+22 ⁽²⁾
		+18.7 to +32.0 ⁽¹⁾	+6.0 to +22.0 ⁽¹⁾
CoO(c)		-49.0 ⁽⁷⁾	-55.2 ⁽⁷⁾
		-51.20 ⁽⁴⁾	
		-49.0 to -51.4 ⁽¹⁾	-55.2 to -56.9 ⁽¹⁾
Co_3O_4	cobalt spinel	-184.9 ^(1,2,4,7)	-213 ^(1,2)
HCoO_2^-		-82.97 ⁽⁷⁾	
		-83.0 to -97.4 ⁽¹⁾	
$\text{Co(OH)}_2(\text{c, blue, ppt})$		-107.6 ^(1,2)	-129.3 ⁽⁷⁾
		-107.53 ⁽⁴⁾	
Co(OH)_2	transvaalite	-109.8 ⁽¹⁾	
$\text{Co(OH)}_2(\text{c, pink, ppt})$		-108.6 ^(1,2)	-129.0 ^(1,2)
Co(OH)_2^0		-88.2 ⁽²⁾	-123.8 ⁽²⁾
		-101.0 ⁽¹⁾	
CoOH^+		-56.7 ⁽¹⁾	
$\text{Co(OH)}_3(\text{c})$		-142.6 ^(1,2,7)	-171.3 ⁽²⁾
			-174.6 ⁽¹⁾
Co(OH)_3^-		-140.5 ⁽¹⁾	
$\alpha\text{-CoS(c)}$		-19.8 ^(1,7)	-19.8 ⁽²⁾
			-19.3 ⁽¹⁾
$\beta\text{-CoS(c)}$		-20.2 ⁽¹⁾	-19.8 ⁽¹⁾
$\text{CoSO}_4(\text{c})$		-187.0 ⁽²⁾	-212.3 ⁽²⁾
		-180.1 to -187.3 ⁽¹⁾	-205.5 to -212.6 ⁽¹⁾
CoSO_4^0		191.0 ⁽²⁾	231.2 ⁽²⁾
CoCO_3	sphaerocobaltite	-155.57 ⁽⁷⁾	-170.8 ⁽¹⁾
		-154.8 ⁽¹⁾	
$\text{Co(NO}_3)_2(\text{c})$		-55.1 ^(1,7)	-100.5 ^(1,2)
$\text{Co(NO}_3)_2^0$		-66.2 ⁽²⁾	-113.0 ⁽²⁾
$\text{CoSO}_4 \cdot 6\text{H}_2\text{O(c)}$		-534.35 ⁽²⁾	-641.4 ⁽²⁾
$\text{CoSO}_4 \cdot 7\text{H}_2\text{O(c)}$		-591.26 ⁽²⁾	-712.22 ⁽²⁾
$\text{Co}_3(\text{AsO}_4)_2$		-387.4 ⁽²⁾	
CoS_2	cattierite	-32.8 ⁽¹⁾	-32.1 ⁽¹⁾
Co_3S_3	linnaeite	-77.3 ⁽¹⁾	-73.4 ⁽¹⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
Cr (chromium)			
Cr(c)		0.00	0.00
Cr ²⁺		-42.1 ⁽⁷⁾	-34.3 ⁽²⁾
		-39.3 to -42.1 ⁽¹⁾	-33.2 to -34.4 ⁽¹⁾
Cr ³⁺		-51.5 ^(4,7)	-50.6 to -56.4 ⁽¹⁾
		-48.7 to -53.3 ⁽¹⁾	
Cr(OH) ²⁺		-103.0 ^(7,4)	-113.5 ⁽⁷⁾
		-100.0 ⁽¹⁾	-106.6 ⁽¹⁾
Cr(OH) ₂ ⁺		-151.2 ⁽⁷⁾	
		-149.1 to -151.2 ⁽¹⁾	
Cr(OH) ₃ (c)		-215.3 ⁽⁷⁾	-254.3 ⁽²⁾
		-202.4 to -215.3 ⁽¹⁾	-233.2 to -247.1 ⁽¹⁾
Cr(OH) ₂ (c)		-140.5 ^(1,7)	
Cr(OH) ₄ (c)		-242.4 ^(1,7)	
CrO ₂ ⁻		-128.00 ⁽⁷⁾	
		-123.9 to -128.1 ⁽¹⁾	
CrO ₃ ³⁻		-144.2 ⁽¹⁾	
CrO ₄ ²⁻		-173.94 ⁽⁴⁾	
		-172.3 to -176.1 ⁽¹⁾	-209.2 to -213.7 ⁽¹⁾
Cr ₂ O ₇ ²⁻		-311.0 ^(2,4)	-356.2 ⁽²⁾
		-307.7 to -315.4 ⁽¹⁾	-353.4 to -364.0 ⁽¹⁾
CrO ₂ (c)			-142.9 ⁽¹⁾
CrO ₃ (c)			-140.9 ⁽¹⁾
Cr ₂ O ₃	eskolaite	-259.9 ⁽²⁾	-272.4 ⁽²⁾
		-252.89 ⁽⁴⁾	
		-252.0 ⁽¹⁾	-271.5 ⁽¹⁾
H ₂ CrO ₄ ⁰		-185.92 ⁽⁷⁾	-201.7 ⁽¹⁾
		-179.8 to -185.9 ⁽¹⁾	
HCrO ₄ ⁻		-182.8 ^(2,4)	-209.9 ⁽²⁾
		-181.2 to -184.9 ⁽¹⁾	-208.5 to -220.2 ⁽¹⁾
FeCr ₂ O ₄	chromite	-321.2 ⁽²⁾	-345.3 ⁽²⁾
		-324.5 ⁽¹⁾	-348.6 ⁽¹⁾
Cs (cesium)			
Cs(c)		0.00	0.00
Cs ⁺		-69.79 ⁽²⁾	-61.73 ⁽²⁾
		-67.4 to -69.8 ⁽¹⁾	-59.2 to -61.7 ⁽¹⁾
CsOH(c)		-84.9 ⁽⁷⁾	-97.72 ⁽²⁾
		-84.9 to -88.6 ⁽¹⁾	-97.2 to -99.7 ⁽¹⁾
Cs ₂ O(c)		-65.6 ⁽⁷⁾	-68.4 ⁽²⁾
		-65.6 to -73.6 ⁽¹⁾	-79.9 to -82.6 ⁽¹⁾
CsF(c)		-125.6 ⁽²⁾	-132.3 ⁽²⁾
CsCl(c)		-99.08 ⁽²⁾	-105.89 ⁽²⁾
Cs ₂ SO ₄ (c)		-316.36 ⁽²⁾	-344.89 ⁽²⁾
Cs ₂ SO ₄ ⁰		-317.55 ⁽²⁾	-340.78 ⁽²⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
CsNO ₃ (c)		97.18 ⁽²⁾	-120.93 ⁽²⁾
Cs ₂ UO ₄ (c)		-429.6 ⁽¹⁾	-458.9 ⁽¹⁾
Cu (copper)			
Cu(c)		0.00	0.00
Cu ⁺	cuprous ion	+11.95 ^(2,4)	+17.13 ⁽²⁾
		+12.0 ⁽¹⁾	+12.4 to +17.2 ⁽¹⁾
Cu ²⁺	cupric ion	+15.65 ^(1,2,4)	+15.48 ⁽²⁾
			+15.6 ⁽¹⁾
CuCO ₃ ⁰		-119.69 ⁽⁵⁾	
		-120.0 ⁽¹⁾	
Cu(CO ₃) ₂ ²⁻		-250.10 ⁽⁵⁾	
		-250.6 ⁽¹⁾	
CuHCO ₃ ⁺		-127.46 ⁽⁵⁾	
CuCO ₃ (c)		-123.65 ⁽⁵⁾	-142.2 ^(1,7)
		-123.8 ⁽¹⁾	
CuCO ₃ · Cu(OH) ₂	malachite	-216.44 ⁽⁷⁾	-251.3 ⁽²⁾
		-213.58 ⁽⁴⁾	
		-213.6 to -216.4 ⁽¹⁾	-250.6 to -251.9 ⁽¹⁾
2CuCO ₃ · Cu(OH) ₂	azurite	-345.8 ⁽⁷⁾	-390.1 ⁽²⁾
		-314.29 ⁽⁴⁾	
		-314.4 to -343.7 ⁽¹⁾	-389.0 to -390.1 ⁽¹⁾
CuCl	nantokite	-28.65 ⁽²⁾	-32.8 ⁽²⁾
		-28.5 ⁽¹⁾	-32.2 to -32.8 ⁽¹⁾
CuCO ₃ (OH) ₂ ²⁻		-206.0 ⁽¹⁾	
CuCl ⁰		-22.95 ⁽⁵⁾	
CuCl ⁺		-16.3 ⁽²⁾	
		-15.8 to -17.1 ⁽¹⁾	
CuCl ₂ ⁰		-57.4 ⁽²⁾	
		-45.2 to -47.3 ⁽¹⁾	
CuCl ₂ (c)		-42.0 ⁽²⁾	-52.6 ⁽²⁾
		-41.1 to -42.1 ⁽¹⁾	-51.6 to -52.6 ⁽¹⁾
CuCl ₂ · 2H ₂ O(c)		-156.8 ⁽²⁾	-196.3 ⁽²⁾
CuCl ₂ ⁻		-58.16 ^(5,6)	-66.3 ⁽⁶⁾
		-57.4 to -58.4 ⁽¹⁾	
CuCl ₃ ⁻		-76.30 ⁽⁵⁾	
CuCl ₃ ²⁻		-89.79 ⁽⁵⁾	
		-85.5 to -90.0 ⁽¹⁾	
CuCl ₄ ²⁻		-103.6 ⁽¹⁾	
Cu ₂ Cl ₄ ²⁻		-119.15 ⁽⁵⁾	
α-CuFe ₂ O ₄	cupric ferrite	-205.3 ⁽⁵⁾	
α-Cu ₂ Fe ₂ O ₄	cuprous ferrite	-229.04 ⁽⁵⁾	
CuMoO ₄ (c)		-193.01 ⁽⁵⁾	
CuNO ₃ ⁺		-11.65 ⁽⁵⁾	

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
$\text{Cu}(\text{NO}_3)_2^0$		-37.06 ⁽⁵⁾	
CuOH^+		-30.52 ⁽⁵⁾	
		-31.1 ⁽¹⁾	
$\text{Cu}(\text{OH})_2^0$		-59.53 ⁽²⁾	-94.46 ⁽²⁾
$\text{Cu}(\text{OH})_2(\text{c})$		-85.3 ^(1,6,7)	-106.8 ^(2,6)
			-106.1 to -107.5 ⁽¹⁾
$\text{Cu}(\text{OH})_3^-$		-117.90 ⁽⁵⁾	
$\text{Cu}(\text{OH})_4^{2-}$		-157.08 ⁽⁵⁾	
$\text{Cu}_2(\text{OH})_2^{2+}$		-67.47 ⁽⁵⁾	
CuO_2^{2-}		-43.3 ⁽⁷⁾	
		-43.88 ⁽⁴⁾	
		-43.6 ⁽¹⁾	
HCuO_2^-		-61.42 ⁽⁷⁾	
		-61.8 ⁽¹⁾	
CuO	tenorite	-30.7 ^(2,5,7)	-37.4 ^(2,6,7)
		-31.00 ⁽⁴⁾	
		-30.4 ⁽¹⁾	-37.3 ⁽¹⁾
$\text{CuOH}(\text{c})$		-45.54 ⁽⁵⁾	
		-43.5 ⁽¹⁾	
$\text{Cu}_4\text{Cl}_2(\text{OH})_6$	atacamite	-320.5 ⁽¹⁾	-396.2 ⁽¹⁾
$\text{Cu}_4\text{Cl}_2(\text{OH})_6$	paratacamite	-320.3 ⁽¹⁾	
Cu_2O	cuprite	-35.1 ^(1,2,5,6,7)	-40.3 ^(2,6,7)
			-40.4 ⁽¹⁾
CuHPO_4^0		-250.72 ⁽⁵⁾	
$\text{CuH}_2\text{PO}_4^+$		-258.35 ⁽⁵⁾	
$\text{Cu}_3(\text{PO}_4)_2(\text{c})$		-493.63 ⁽⁵⁾	-533.3 ⁽¹⁾
		-490.3 to -493.9 ⁽¹⁾	
$\text{Cu}_3(\text{PO}_4)_2 \cdot 2\text{H}_2\text{O}(\text{c})$		-609.60 ⁽⁵⁾	
CuSe	klockmannite	-7.9 to -9.9 ⁽¹⁾	-6.6 to -9.4 ⁽¹⁾
CuS	covellite	-12.81 ^(2,4,6)	-12.7 ^(2,6)
		-11.7 to -12.9 ⁽¹⁾	-11.6 to -12.7 ⁽¹⁾
Cu_2S	chalcocite	-20.6 ^(1,2,4,6,7)	-19.0 ^(1,2,6,7)
CuFeS_2	chalcopyrite	-42.7 to -45.6 ⁽¹⁾	-42.3 to -45.5 ⁽¹⁾
Cu_5FeS_4	bornite	-86.7 to -93.9 ⁽¹⁾	-79.9 to -90.9 ⁽¹⁾
CuSO_4	chalcocyanite	-158.2 ^(1,2)	-184.36 ⁽²⁾
			-184.2 ⁽¹⁾
CuSO_4^0		-162.31 ⁽²⁾	-201.84 ⁽²⁾
		-165.3 ⁽¹⁾	-200.4 ⁽¹⁾
$\text{Cu}_2\text{SO}_4(\text{c})$		-156.41 ^(5,7)	-179.6 ⁽²⁾
		-156.0 ⁽¹⁾	-179.4 ⁽¹⁾
$\text{CuO} \cdot \text{CuSO}_4(\text{c})$		-187.61 ⁽⁵⁾	-223.8 ⁽²⁾
$\text{CuSO}_4 \cdot 3\text{Cu}(\text{OH})_2$	brochantite	-434.5 ^(1,2)	-525.4 ⁽¹⁾
$\text{CuSO}_4 \cdot 3\text{Cu}(\text{OH})_2 \cdot \text{H}_2\text{O}$	langite	-488.6 ⁽²⁾	-594 ^(1,2)
		-488.5 ⁽¹⁾	

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
$\text{CuSO}_4 \cdot \text{H}_2\text{O}(\text{c})$		-219.46 ⁽²⁾ -219.2 ⁽¹⁾	-259.52 ⁽²⁾ -259.2 ⁽¹⁾
$\text{CuSO}_4 \cdot 3\text{H}_2\text{O}(\text{c})$		-334.6 ^(1,2)	-402.56 ⁽²⁾ -402.4 ⁽¹⁾
$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}(\text{c})$	chalcantite	-449.3 ^(1,2)	-544.85 ⁽²⁾ -544.7 ⁽¹⁾
$\text{CuSO}_4 \cdot 2\text{Cu}(\text{OH})_2$	antlerite	-345.8 ⁽²⁾ -345.6 ⁽¹⁾	
$\text{CuSiO}_3 \cdot \text{H}_2\text{O}$	diopase	-288.6 ⁽¹⁾	-324.8 ⁽¹⁾
$\text{CuSiO}_3 \cdot 2\text{H}_2\text{O}$	chrysocolla (amorph.)	-345.1 ⁽¹⁾	
F (fluorine) (see also Ag, Ba, Ca, etc.)			
$\text{F}_2(\text{g})$		0.00	0.00
F^-		-66.4 ⁽²⁾ -66.8 ⁽¹⁾	-79.5 ⁽²⁾ -79.6 ⁽¹⁾
$\text{HF}(\text{g})$		-65.3 ⁽²⁾ -64.7 to -65.8 ⁽¹⁾	-64.8 ⁽²⁾ -64.2 to -65.3 ⁽¹⁾
HF^0		-66.64 ⁽²⁾ -71.0 ⁽¹⁾	-79.50 ⁽²⁾ -77.1 ⁽¹⁾
Fe (iron) (see also Ca)			
$\text{Fe}(\text{c})$		0.00	0.00
Fe^{2+}		-18.85 ^(2,3,4,6) -18.9 to -22.0 ⁽¹⁾	-21.3 ^(2,3,6) -21.0 to -22.1 ⁽¹⁾
Fe^{3+}	ferric ion	-1.12 ^(2,3,4,6) -1.1 to -4.3 ⁽¹⁾	-11.6 ^(2,6) -11.1 to -12.1 ⁽¹⁾
FeO_2^-		-70.58 ⁽⁴⁾	
Fe_3C	cohenite	+4.3 to +4.7 ⁽¹⁾	+5.9 ⁽¹⁾
FeCO_3	siderite	-160.3 ^(2,3,5,6,7) -159.34 ⁽⁴⁾ -159.3 to -162.6 ⁽¹⁾	-177.3 ^(2,3,6,7) -176.1 to -180.0 ⁽¹⁾
FeCl_2	lawrencite	-72.3 ^(1,2)	-81.7 ^(1,2)
FeCl_2^0		-81.59 ⁽²⁾	-101.2 ⁽²⁾
FeCl_3	molysite	-79.8 ^(1,2)	-95.48 ⁽²⁾ -95.8 ⁽¹⁾
FeCl_3^0		-95.2 ⁽²⁾	-131.5 ⁽²⁾
FeCl^{2+}		-34.4 to -37.7 ⁽¹⁾	-42.9 to -46.5 ⁽¹⁾
$\text{Fe}_{0.95}\text{O}$	wüstite	-58.7 ^(2,5,6,7) -58.6 ⁽¹⁾	-63.6 ^(1,2,6,7)
$\text{FeO}(\text{c})$		-60.1 ^(1,5)	-65.0 ^(1,2)
$\alpha\text{-Fe}_2\text{O}_3$	hematite	-177.6 ^(3,5,6,7) -177.39 ⁽⁴⁾ -177.5 ⁽¹⁾	-197.3 ^(2,3,6) -197.0 ⁽¹⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
$\gamma\text{-Fe}_2\text{O}_3$	maghemite	-173.75 ⁽⁵⁾	
Fe_3O_4	magnetite	-242.69 ^(2,3,4,5,6,7)	-267.1 ^(2,3,6,7)
		-241.6 to -243.1 ⁽¹⁾	-265.9 to -267.3 ⁽¹⁾
$\alpha\text{-FeOOH}$	goethite	-116.86 ^(3,5,6)	-133.6 ^(2,3,6)
		-116.77 ⁽⁴⁾	
		-117.0 ⁽¹⁾	-133.7 ⁽¹⁾
$\gamma\text{-FeOOH}$	lepidocrocite	-115.50 ⁽⁵⁾	
		-112.7 ⁽¹⁾	
$\text{FePO}_4(\text{c})$	heterosite	-283.19 ⁽⁵⁾	-299.6 ⁽⁷⁾
		-272.0 to -283.2 ⁽¹⁾	-299.6 to -310.1 ⁽¹⁾
$\text{FePO}_4 \cdot 2\text{H}_2\text{O}$	strengite	-396.2 ⁽²⁾	-451.3 ^(1,2)
		-396.2 to -397.4 ⁽¹⁾	
$\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$	vivianite	-1058.36 ⁽⁵⁾	
		-1046.2 ⁽¹⁾	
$\text{FeSO}_4(\text{c})$		-196.2 ⁽²⁾	-221.9 ⁽²⁾
		-196.2 to -198.3 ⁽¹⁾	-220.5 to -221.9 ⁽¹⁾
FeSO_4^0		-196.82 ⁽²⁾	-238.6 ⁽²⁾
FeSO_4^+		-187.63 ⁽⁵⁾	
$\text{Fe}_2(\text{SO}_4)_3(\text{c})$		-537.4 ⁽¹⁾	-616.7 ⁽¹⁾
$\text{Fe}(\text{SO}_4)_2^-$		-367.26 ⁽⁵⁾	
$\text{FeS}(\text{amorph.})$		-21.3 ⁽³⁾	
FeS	Fe-rich pyrrhotite	-24.0 ^(1,2)	-23.9 ^(1,2)
$\text{Fe}_{0.877}\text{S}$	pyrrhotite	-25.6 ⁽¹⁾	-25.2 ⁽¹⁾
FeS	mackinawite(synthet.)	-22.3 ^(1,3)	
FeS	troilite, α	-23.87 ^(3,5,6)	-24.0 ^(3,6)
		-24.0 ^(1,4)	-23.9 ⁽¹⁾
FeS_2	pyrite	-39.0 ^(2,3,5)	-41.8 ^(2,3,6)
		-39.89 ⁽⁴⁾	
		-36.0 to -39.9 ⁽¹⁾	-41.0 to -42.6 ⁽¹⁾
FeS_2	marcasite	-37.4 ^(2,5)	
		-37.9 ⁽¹⁾	
FeOH^+		-66.3 ⁽³⁾	-77.6 ⁽³⁾
		-64.2 to -69.6 ⁽¹⁾	-77.6 to -78.4 ⁽¹⁾
$\text{Fe}(\text{OH})_2^0$		-113.29 ⁽⁵⁾	
		-109.5 ⁽¹⁾	
$\text{Fe}(\text{OH})_2$	amakinite	-116.3 ^(2,4)	-136.0 ⁽²⁾
		-115.6 to -117.8 ⁽¹⁾	-135.8 to -137.0 ⁽¹⁾
$\text{Fe}(\text{OH})_3^-$		-147.0 ⁽³⁾	
		-147.9 to -148.5 ⁽¹⁾	
$\text{Fe}(\text{OH})_4^{2-}$		-185.27 ⁽⁵⁾	
		-184.0 to -185.5 ⁽¹⁾	
$\text{Fe}_3(\text{OH})_4^{2-}$		-230.23 ⁽⁵⁾	
$\text{Fe}(\text{OH})^{2+}$		-54.83 ⁽³⁾	-69.5 ⁽³⁾
		-54.8 to -58.0 ⁽¹⁾	-69.7 ⁽¹⁾

<i>Compound or species</i>	<i>Mineral name</i>	$G_f^\circ, \text{kcal/mol}$	$H_f^\circ, \text{kcal/mol}$
$\text{Fe}(\text{OH})_2^+$		-104.7 ⁽³⁾ -104.7 to -109.3 ⁽¹⁾	-131.8 ⁽¹⁾
$\text{Fe}(\text{OH})_3(\text{c})$		-166.5 ^(2,4) -166.0 to -171.7 ⁽¹⁾	-196.7 ⁽²⁾ -197.0 to -201.8 ⁽¹⁾
$\text{Fe}(\text{OH})_3^0$		-156.6 ⁽²⁾ -157.6 to -161.9 ⁽¹⁾	
$\text{Fe}(\text{OH})_4^-$		-201.32 ⁽⁵⁾ -201.4 ⁽¹⁾	
$\text{Fe}_2(\text{OH})_2^{4+}$		-117.46 ⁽⁵⁾ -111.7 ⁽¹⁾	-146.3 ⁽¹⁾
$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$	melanterite	-599.9 ^(1,2)	-720.5 ^(1,2)
$\text{FeSO}_4 \cdot \text{H}_2\text{O}$	szomolnokite		-297.3 ⁽¹⁾
$\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$	jarosite	-792.66 ⁽⁵⁾	
FeSiO_3	ferrosilite	-267.16 ^(3,4) -256.9 to -268.5 ⁽¹⁾	-285.63 ⁽³⁾ -276.1 to -288.2 ⁽¹⁾
$\text{FeS}_3\text{O}_3(\text{OH})_8^0$		-898.00 ⁽⁴⁾	
FeSiO_3	clinoferrosilite	-267.5 ⁽¹⁾	-286.0 ⁽¹⁾
FeSiO_3	orthoferrosilite	-266.4 ⁽¹⁾	-285.0 ⁽¹⁾
Fe_2SiO_4	fayalite	-329.6 ⁽²⁾ -319.8 to -330.7 ⁽¹⁾	-353.7 ⁽²⁾ -343.7 to -354.8 ⁽¹⁾
$\text{FeMgSi}_2\text{O}_6$	hypersthene	-619.7 ⁽¹⁾	-658.6 ⁽¹⁾
$\text{FeMoO}_4(\text{c})$		-232.14 ⁽⁵⁾ -232.9 to -234.8 ⁽¹⁾	-257.5 ⁽⁷⁾ -257.1 ⁽¹⁾
$\text{FeWO}_4(\text{c})$	ferberite	-250.4 ⁽⁷⁾ -250.4 to -259.8 ⁽¹⁾	-274.1 ⁽⁷⁾ -274.1 to -283.9 ⁽¹⁾
FeAsS	arsenopyrite	-12.0 to -26.2 ⁽¹⁾	-10.0 to -25.2 ⁽¹⁾
FeAl_2O_4	hercynite	-442.3 to -449.3 ⁽¹⁾	-470.0 to -476.9 ⁽¹⁾
Fe_2SiO_4	fayalitic spinel	-327.1 ⁽¹⁾	-351.9 ⁽¹⁾
FeTiO_3	ilmenite	-277.9 ⁽¹⁾	-295.5 ⁽¹⁾
$\text{Fe}_3\text{Si}_2\text{O}_5(\text{OH})_4$	greenalite	-720.0 ⁽⁸⁾ -719.9 ⁽¹⁾	
$\text{Fe}_2^{3+}\text{Si}_4\text{O}_{10}(\text{OH})_2$	minnesotaite	-1055.0 ⁽⁸⁾ -1069.9 ⁽¹⁾	-1152.6 ⁽¹⁾
$\text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$	grunerite	-2141.0 ⁽¹⁾	-2294.0 ⁽¹⁾
$\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	almandine	-1187.8 ⁽¹⁾	-1267.2 ⁽¹⁾
	pyrope	see Mg	
	andradite	see Ca	
	grossular	see Ca	
$\text{Fe}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	ferrocordierite	-1902.7 ⁽¹⁾	-2019.7 ⁽¹⁾
	cordierite	see Mg	
$\text{FeAl}_2\text{SiO}_5(\text{OH})_2$	chloritoid	-709.8 ⁽¹⁾	-762.7 ⁽¹⁾
$\text{Fe}_5\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_8$	Fe-clinocllore	-1801.2 ⁽¹⁾	
$\text{Fe}_4\text{Al}_4\text{Si}_2\text{O}_{10}(\text{OH})_8$	daphnite	-1678.4 ⁽¹⁾	-1823.7 ⁽¹⁾
$\text{Fe}_2\text{Al}_3\text{Si}_4\text{O}_{23}(\text{OH})$	staurolite	-2674.8 ⁽¹⁾	-2882.1 ⁽¹⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
Ga (gallium)			
Ga(c)		0.00	0.00
Ga ³⁺		-38.00 ⁽⁴⁾	
GaO ₃ ³⁻		-147.94 ⁽⁴⁾	
Ga(OH) ²⁺		-90.89 ⁽⁴⁾	
Ga(OH) ₂ ⁺		-142.78 ⁽⁴⁾	
Ga(OH) ₃ (c)		-198.69 ⁽⁴⁾	
Ga ₂ O ₃ (c)		-238.52 ⁽⁴⁾	
Ge (germanium)			
Ge(c)		0.00	0.00
Ge ²⁺		-8.8 ⁽¹⁾	
Ge ⁴⁺		-6.6 ⁽¹⁾	
GeO ₃ ²⁻		-157.9 ^(1,4)	
HGeO ₃ ⁻		-175.2 ^(1,4)	
H ₂ GeO ₃ ⁰		-186.8 ^(1,4)	
HGeO ₂		-92.1 ⁽¹⁾	
GeO(brown, c)		-57.7 ^(2,4)	-62.6 ⁽²⁾
		-50.7 to -56.7 ⁽¹⁾	-56.7 to -62.6 ⁽¹⁾
GeO(yellow, c)		-49.5 ^(1,2)	
GeS(c)		-17.09 ⁽⁴⁾	
GeO(hydrated, a,c)		-69.1 ⁽¹⁾	
GeO(hydrated, b,c)		-62.7 ⁽¹⁾	
GeO ₂ (hexagonal)		-119.7 ⁽¹⁾	-132.6 ⁽¹⁾
GeO ₂ (quartz type)		-118.8 ⁽¹⁾	-131.7 ⁽¹⁾
		-118.79 ⁽⁴⁾	
GeO ₂ (c)		-124.7 ⁽¹⁾	-138.7 ⁽¹⁾
GeO ₂ (tetragonal)		-136.1 ⁽¹⁾	
GeO ₂ (amorph.)		-113.6 ⁽¹⁾	-125.8 to -129.1 ⁽¹⁾
H (hydrogen)			
H ₂ (g)		0.00	0.00
H ₂ ⁰		+4.2 ^(1,2)	-1.0 ^(1,2)
H ⁺		0.00	0.00
OH ⁻		-37.594 ⁽²⁾	-54.970 ⁽²⁾
		-37.595 ⁽¹⁾	-54.971 ⁽¹⁾
H ₂ O(l)		-56.687 ⁽²⁾	-68.315 ⁽²⁾
		-56.684 ⁽¹⁾	-68.307 ⁽¹⁾
H ₂ O(g)		-54.636 ^(1,2)	-57.791 ^(1,2)
H ₂ O ₂ ⁰		-31.5 to -32.0 ⁽¹⁾	-45.7 ⁽¹⁾
H ₂ O ₂ (l)		-28.8 ⁽¹⁾	-44.9 ⁽¹⁾
Hf (hafnium)			
Hf(c)		0.00	0.00
HfO ₂ (c)		-260.09 ⁽⁴⁾	
Hf ⁴⁺		-156.80 ⁽⁴⁾	

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
Hg (mercury)			
Hg(l)		0.00	0.00
Hg(g)		+7.6 ^(1,2)	+14.6 ^(1,2)
Hg ²⁺		+39.3 ^(1,2,4)	+40.9 ⁽²⁾
			+41.0 ⁽¹⁾
Hg ₂ ²⁺		+36.70 ^(2,4)	+41.2 ^(1,2)
		+36.6 ⁽¹⁾	
Hg(NO ₃) ⁺		-12.72 ⁽⁵⁾	
Hg(NO ₃) ₂ ⁰		-12.06 ⁽⁵⁾	
HgOH ⁺		-12.69 ⁽⁵⁾	-20.2 ⁽¹⁾
		-12.5 ⁽¹⁾	
Hg(OH) ₂ ⁰		-65.7 ^(1,2)	-84.9 ^(1,2)
Hg(OH) ⁺		-12.50 ⁽⁴⁾	
Hg(OH) ₂ (c)		-70.47 ⁽⁵⁾	
Hg(OH) ₃ ⁻		-101.92 ⁽⁵⁾	
HgO(red)	montroydite	-13.995 ⁽²⁾	-21.71 ⁽²⁾
		-14.0 ⁽¹⁾	-21.7 ⁽¹⁾
HgO(red, hexagonal)		-13.92 ⁽²⁾	-21.4 ^(1,2)
		-13.9 ⁽¹⁾	
HgO(c)		-58.56 ⁽⁴⁾	
HgO(yellow)		-13.964 ^(1,7)	-21.62 ⁽²⁾
		-14.0 ⁽¹⁾	-21.6 ⁽¹⁾
HHgO ₂ ⁻		-45.48 ⁽⁴⁾	
Hg ₂ (OH) ₂ (c)		-69.49 ⁽⁵⁾	
HgCO ₃ (c)		-117.62 ⁽⁵⁾	
Hg ₂ CO ₃ (c)		-111.9 ⁽²⁾	-132.3 ^(1,2)
		-105.8 to -111.9 ⁽¹⁾	
HgCl ₂ (c)		-42.7 ⁽²⁾	-53.6 ⁽²⁾
		-42.7 to -44.4 ⁽¹⁾	-53.6 to -55.0 ⁽¹⁾
Hg ₂ Cl ₂	calomel	-50.37 ^(1,2,4)	-63.39 ⁽²⁾
			-63.37 ⁽¹⁾
HgCl ⁺		-1.3 ⁽¹⁾	-4.5 ⁽¹⁾
HgCl ₂ ⁰		-41.4 ⁽¹⁾	-51.7 ⁽¹⁾
HgCl ₃ ⁻		-73.9 ⁽¹⁾	-92.9 ⁽¹⁾
HgCl ₄ ²⁻		-106.79 ⁽⁴⁾	
		-107.2 ⁽¹⁾	-132.4 ⁽¹⁾
HgCl(g)		+13.9 to +15.0 ⁽¹⁾	+18.9 to +20.1 ⁽¹⁾
HgBr ₂ (c)		-35.2 to -36.6 ⁽¹⁾	-40.6 ⁽¹⁾
Hg ₂ Br ₂ (c)		-43.1 ⁽¹⁾	-49.4 ⁽¹⁾
HgBr ₄ ²⁻		-88.3 ⁽¹⁾	-99.9 to -103.0 ⁽¹⁾
HgI ₂ (red)	coccinite	-24.4 ⁽¹⁾	-25.2 ⁽¹⁾
Hg ₂ I ₂ (yellow)		-26.6 ⁽¹⁾	-29.0 ⁽¹⁾
Hg ₂ HPO ₄ (c)		-242.23 ⁽⁵⁾	
HgS(red)	cinnabar	-12.1 ⁽²⁾	-13.9 ⁽²⁾

<i>Compound or species</i>	<i>Mineral name</i>	<i>G_f^o, kcal/mol</i>	<i>H_f^o, kcal/mol</i>
HgS(black)	metacinnabar	-10.9 to -12.1 ⁽¹⁾	-12.7 to -13.9 ⁽¹⁾
		-11.4 ⁽²⁾	-12.8 ⁽²⁾
Hg ₂ S(c)		-10.3 to -11.8 ⁽¹⁾	-10.4 to -12.9 ⁽¹⁾
HgS ₂ ²⁻		-17.49 ⁽⁵⁾	
		+45.90 ⁽⁴⁾	
HgSO ₄ (c)		+10.0 to +11.6 ⁽¹⁾	
		-143.14 ⁽⁵⁾	-168.3 ⁽⁷⁾
HgSO ₄ ⁰		-141.0 ⁽¹⁾	-168.3 to -169.1 ⁽¹⁾
Hg ₂ SO ₄ (c)		-140.51 ⁽²⁾	
		-149.589 ⁽²⁾	-177.61 ⁽²⁾
		-149.4 ⁽¹⁾	-177.5 ⁽¹⁾
Hg ₂ CrO ₄		-147.6 to -155.7 ⁽¹⁾	
I (iodine)			
I ₂ (c)		0.00	0.00
I ⁻		-12.33 ⁽²⁾	-13.19 ⁽²⁾
		-12.4 ⁽¹⁾	-13.5 ⁽¹⁾
HI(g)		+0.41 ⁽²⁾	+6.33 ⁽²⁾
HI ⁰		-12.33 ⁽²⁾	-13.19 ⁽²⁾
I ₂ ⁰		+3.92 ^(1,2)	+5.4 ⁽²⁾
			+5.2 ⁽¹⁾
In (indium)			
In(c)		0.00	0.00
In ²⁺		-12.12 ⁽⁴⁾	
In ³⁺		-23.42 ⁽⁴⁾	
In ₂ O ₃ (c)		-198.54 ⁽⁴⁾	
InOH ²⁺		-74.81 ⁽⁴⁾	
In(OH) ₂ ⁺		-125.48 ⁽⁴⁾	
InS(c)		-31.50 ⁽⁴⁾	
In ₂ S ₃ (c)		-98.59 ⁽⁴⁾	
InS(c)		-31.50 ⁽⁴⁾	
Ir (iridium)			
Ir(c)		0.00	0.00
Ir ₂ S ₃ (c)		-49.8 ⁽⁴⁾	
IrS ₂ (c)		-30.4 ⁽⁴⁾	
IrO ₂ (c)		-28.0 ⁽⁴⁾	
IrO ₄ ⁻		-47.0 ⁽⁴⁾	
K (potassium) (see also Al, Fe)			
K(c)		0.00	0.00
K ⁺		-67.70 ⁽²⁾	-60.32 ⁽²⁾
		-67.6 ⁽¹⁾	-60.2 ⁽¹⁾
KCl	sylvite	-97.79 ⁽²⁾	-104.385 ⁽²⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
KCl ⁰		-97.7 ⁽¹⁾	-104.3 ⁽¹⁾
K ₂ CO ₃ (c)		-99.07 ⁽¹⁾	-100.27 ⁽¹⁾
		-254.2 ^(1,2)	-275.1 ⁽²⁾
			-274.4 ⁽¹⁾
K ₂ CO ₃ ⁰		-261.18 ⁽⁵⁾	
KOH(c)		-90.61 ⁽²⁾	-101.521 ⁽²⁾
		-90.4 ⁽¹⁾	-101.6 ⁽¹⁾
KOH ⁰		-105.29 ⁽²⁾	-115.29 ⁽²⁾
KH ₂ PO ₄ (c)		-339.65 ⁽⁵⁾	
K ₂ HPO ₄ (c)		-392.14 ⁽⁵⁾	
KSO ₄ ⁻		-246.4 ^(1,3,5,7)	-276.6 ⁽¹⁾
K ₂ SO ₄	arcanite	-315.83 ⁽²⁾	-343.64 ^(1,2)
		-315.6 ⁽¹⁾	
K ₂ SiO ₃ (c)		-343.3 ⁽⁶⁾	-365.9 ⁽⁶⁾
		-350.1 ⁽¹⁾	-368.5 to -372.5 ⁽¹⁾
K ₂ O(c)		-76.2 ⁽⁷⁾	-86.4 ⁽⁷⁾
		-76.6 ⁽¹⁾	-86.5 ⁽¹⁾
K ₂ S(c)		-87.0 ⁽²⁾	-91.0 ⁽²⁾
		-87.0 to -96.6 ⁽¹⁾	-91.0 to -99.9 ⁽¹⁾
K ₂ S ⁰		-114.9 ⁽²⁾	-112.7 ⁽²⁾
KBr(c)		-90.9 ⁽¹⁾	-94.1 ⁽¹⁾
KI(c)		-77.4 ⁽¹⁾	-78.5 ⁽¹⁾
K ₂ SO ₄ ⁰		313.37 ⁽²⁾	-337.96 ⁽²⁾
KHSO ₄	mercallite	-246.5 ⁽²⁾	-277.4 ^(1,2)
		-246.5 to -247.4 ⁽¹⁾	
KNO ₃	niter	-94.39 ⁽²⁾	-118.22 ⁽²⁾
		-94.2 ⁽¹⁾	-118.1 ⁽¹⁾
KHSO ₄ ⁰		-248.39 ⁽²⁾	-272.40 ⁽²⁾
KNO ₃ ⁰		-94.31 ⁽²⁾	-109.88 ⁽²⁾

RARE EARTH ELEMENTS

La (lanthanum)

α -La(c)	0.00	0.00
La ³⁺	-163.4 ^(2,4)	-169.0 ⁽²⁾
	-163.4 to -174.5 ⁽¹⁾	-169.0 to -176.2 ⁽¹⁾
La ₂ O ₃ (c)	-407.7 ^(2,4)	-428.7 ⁽²⁾
	-407.6 to -426.9 ⁽¹⁾	-428.7 to -458.0 ⁽¹⁾
La(OH) ₃ (c)	-313.2 ^(1,7)	-337.0 ⁽²⁾
	-305.8 ⁽⁴⁾	-337.0 to -345.0 ⁽¹⁾
La ₂ (CO ₃) ₃ (c)	-750.9 ^(2,4)	
La ₂ S ₃ (c)	-301.2 ⁽¹⁾	-288.9 to -306.8 ⁽¹⁾

Ce (cerium)

Ce(c)	0.00	0.00
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Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
Ce^{3+}		-160.6 ^(2,4)	-166.4 ⁽²⁾
		-160.6 to -170.5 ⁽¹⁾	-166.4 to -173.8 ⁽¹⁾
Ce^{4+}		-120.9 ⁽¹⁾	-128.4 to -137.9 ⁽¹⁾
		-120.44 ⁽⁴⁾	
CeO_2	cerianite	-244.9 ⁽²⁾	-258.80 ⁽²⁾
		-244.4 ⁽⁴⁾	
		-219.0 to -245.1 ⁽¹⁾	-233.0 to -260.2 ⁽¹⁾
$Ce_2O_3(c)$		-407.8 ^(2,4)	-429.3 ^(1,2)
		-408.1 ⁽¹⁾	
$Ce(OH)^{3+}$		-187.7 ⁽⁷⁾	-194.1 ⁽¹⁾
		-179.1 to -187.7 ⁽¹⁾	
$Ce(OH)_2^{2+}$		-244.0 ^(1,7)	
$Ce_2(CO_3)_3(c)$		-744.1 ⁽⁴⁾	
$Ce(OH)_3(c)$		-311.63 ⁽⁷⁾	-336.2 ⁽¹⁾
		-303.2 to -311.6 ⁽¹⁾	
		-303.6 ⁽⁴⁾	
$CePO_4$	monazite	-434.0 ⁽¹⁾	-464.6 ⁽¹⁾
$CeSO_4^+$		-343.3 ⁽²⁾	-380.2 ⁽²⁾
$Ce(SO_4)_2^-$		-523.6 ⁽²⁾	-595.9 ⁽²⁾
$Ce_2(SO_4)_2 \cdot H_2O(c)$		-1320.6 ⁽²⁾	
$CeS(c)$		-107.9 ⁽¹⁾	-109.8 ⁽¹⁾
$CeS_2(c)$		-151.5 ⁽¹⁾	-146.3 to -153.9 ⁽¹⁾
$Ce_2S_3(c)$		-293.1 ⁽¹⁾	-298.7 ⁽¹⁾
Pr (praseodymium)			
$Pr(c)$		0.00	0.00
Pr^{3+}		-162.3 ⁽⁴⁾	
$Pr(OH)_3(c)$		-307.1 ⁽⁴⁾	
$Pr_2(CO_3)_3(c)$		-747.1 ⁽⁴⁾	
Nd (neodymium)			
$Nd(c)$		0.00	0.00
Nd^{3+}		-160.5 ⁽⁴⁾	
$Nd(OH)_3(c)$		-305.2 ⁽⁴⁾	
$Nd_2O_3(c)$		-411.3 ⁽⁴⁾	
$Nd_2(CO_3)_3$		-741.4 ⁽⁴⁾	
$Nd(OH)_4^-$		-336.7 ⁽⁴⁾	
Sm (samarium)			
$Sm(c)$		0.00	0.00
Sm^{3+}		-159.3 ⁽⁴⁾	
$Sm(OH)_3(c)$		-306.9 ⁽⁴⁾	
$Sm_2O_3(c)$		-414.6 ⁽⁴⁾	
$Sm_2(CO_3)_3$		-741.4 ⁽⁴⁾	

<i>Compound or species</i>	<i>Mineral name</i>	G_f° , kcal/mol	H_f° , kcal/mol
Eu (europium)			
Eu(c)		0.00	0.00
Eu ³⁺		-137.2 ⁽⁴⁾	
Eu ²⁺		-129.10 ⁽⁴⁾	
Eu(OH) ₃ (c)		-285.5 ⁽⁴⁾	
Eu ₂ O ₃ (c)		-372.2 ⁽⁴⁾	
Eu ₂ (CO ₃) ₃ (c)		-697.3 ⁽⁴⁾	
Gd (gadolinium)			
Gd(c)		0.00	0.00
Gd ³⁺		-158.0 ⁽⁴⁾	
Gd(OH) ₃ (c)		-306.9 ⁽⁴⁾	
Gd ₂ (CO ₃) ₂ (c)		-738.9 ⁽⁴⁾	
Gd(OH) ₄ ⁻		-338.0 ⁽⁴⁾	
Tb (terbium)			
Tb(c)		0.00	0.00
Tb ³⁺		-155.8 ⁽⁴⁾	
Tb(OH) ₃ (c)		-303.4 ⁽⁴⁾	
Tb ₂ (CO ₃) ₃ (c)		-734.5 ⁽⁴⁾	
Dy (dysprosium)			
Dy(c)		0.00	0.00
Dy ³⁺		-159.0 ⁽⁴⁾	
Dy(OH) ₃ (c)		-307.2 ⁽⁴⁾	
Dy ₂ O ₃ (c)		-423.4 ⁽⁴⁾	
Dy ₂ (CO ₃) ₃ (c)		-739.3 ⁽⁴⁾	
Dy(OH) ₄ ⁻		-339.9 ⁽⁴⁾	
Ho (holmium)			
Ho(c)		0.00	0.00
Ho ³⁺		-161.0 ⁽⁴⁾	
Ho(OH) ₃ (c)		-310.1 ⁽⁴⁾	
Ho ₂ O ₃ (c)		-428.1 ⁽⁴⁾	
Ho ₂ (CO ₃) ₃ (c)		-744.9 ⁽⁴⁾	
Er (erbium)			
Er(c)		0.00	0.00
Er ³⁺		-159.9 ⁽⁴⁾	
Er(OH) ₃ (c)		-309.5 ⁽⁴⁾	
Er ₂ O ₃ (c)		-432.3 ⁽⁴⁾	
Er ₂ (CO ₃) ₃ (c)		-742.7 ⁽⁴⁾	
Er(OH) ₄ ⁻		-342.2 ⁽⁴⁾	

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
Tm (thullium)			
Tm(c)		0.00	0.00
Tm ³⁺		-158.2 ⁽⁴⁾	
Tm(OH) ₃ (c)		-307.8 ⁽⁴⁾	
Tm ₂ O ₃ (c)		-428.9 ⁽⁴⁾	
Tm ₂ (CO ₃) ₃ (c)		-739.3 ⁽⁴⁾	
Yb (ytterbium)			
Yb(c)		0.00	0.00
Yb(OH) ₃ (c)		-301.7 ⁽⁷⁾	
		-303.9 ⁽⁴⁾	
		-301.7 to -310.3 ⁽¹⁾	
Yb(OH) ₄ ⁻		-336.0 ⁽⁴⁾	
Yb ²⁺		-126 ⁽²⁾	
		-129.0 ⁽¹⁾	
		-153.9 ^(2,4)	-161.2 ⁽²⁾
Yb ³⁺		-153.9 to -156.8 ⁽¹⁾	-160.9 ⁽¹⁾
Yb ₂ O ₃ (c)		-412.7 ^(1,2,4)	-433.7 ^(1,2)
Yb ₂ (CO ₃) ₃ (c)		-729.1 ⁽⁴⁾	
Lu (lutetium)			
Lu(c)		0.00	0.00
Lu ³⁺		-150.0 ⁽⁴⁾	
Lu(OH) ₃ (c)		-300.3 ⁽⁴⁾	
Lu ₂ O ₃ (c)		-427.6 ⁽⁴⁾	
Lu ₂ (CO ₃) ₃ (c)		-722.9 ⁽⁴⁾	

End of Rare Earths

Li (lithium)			
Li(c)		0.00	0.00
Li ⁺		-70.10 ⁽²⁾	-66.56 ^(1,2)
		-70.0 ⁽¹⁾	
LiOH(c)		-104.92 ⁽²⁾	-115.90 ⁽²⁾
		-105.4 ⁽¹⁾	-116.1 ⁽¹⁾
LiOH ⁰		-107.82 ⁽⁷⁾	-121.511 ⁽⁷⁾
		-104.9 ⁽¹⁾	-121.5 ⁽¹⁾
Li ₂ O(c)		-134.13 ⁽²⁾	-142.91 ⁽²⁾
		-134.2 ⁽¹⁾	-142.8 ⁽¹⁾
LiCl(c)		-91.87 ^(1,2)	-97.66 ⁽²⁾
			-97.7 ⁽¹⁾
LiCl ⁰		-101.48 ⁽²⁾	-106.51 ⁽²⁾
LiF(c)		-140.47 ⁽²⁾	-147.22 ⁽²⁾
Li ₂ SO ₄ (β, c)		-315.91 ⁽²⁾	-343.33 ⁽²⁾
		-316.1 ⁽¹⁾	-343.1 ⁽¹⁾

<i>Compound or species</i>	<i>Mineral name</i>	<i>G_f^o, kcal/mol</i>	<i>H_f^o, kcal/mol</i>
Mg ₃ Si ₂ O ₅ (OH) ₄	chrysotile	-965.1 ⁽²⁾	-1043.4 ⁽²⁾
		-962.0 to -965.1 ⁽¹⁾	-1042.5 to -1071.2 ⁽¹⁾
Mg ₃ Si ₄ O ₁₀ (OH) ₂	talc	-1320.38 ^(3,5)	-1410.92 ⁽³⁾
		-1318.1 to -1324.9 ⁽¹⁾	-1410.9 to 1481.9 ⁽¹⁾
Mg ₃ Si ₄ O ₁₀ (OH) ₂ · 2H ₂ O *	vermiculite	-1422.85 ⁽⁵⁾	
Mg ₆ Si ₄ O ₁₀ (OH) ₈	serpentine	-1933.85 ⁽⁵⁾	
Mg ₃ Si ₂ O ₅ (OH) ₄	serpentine	-964.87 ⁽³⁾	-1043.12 ⁽³⁾
		-966.0 ⁽¹⁾	-1044.0 ⁽¹⁾
Mg ₂ Al ₄ Si ₅ O ₁₈	cordierite	-2055 ⁽²⁾	-21.77 ⁽²⁾
		-2075.26 ⁽⁵⁾	-2177.0 to -2204.5 ⁽¹⁾
		-2055.0 to -2088.9 ⁽¹⁾	
Mg ₇ Si ₈ O ₂₂ (OH) ₂	anthophyllite	-2715.4 ⁽³⁾	-2888.75 ⁽³⁾
		-2708.6 to -2723.7 ⁽¹⁾	-2882.0 to -2898.1 ⁽¹⁾
Mg ₂ SiO ₄	forsteritic spinel	-483.4 ⁽¹⁾	-513.3 ⁽¹⁾
Mg ₂ Al ₄ SiO ₁₀	sapphirine	-1190.6 ⁽¹⁾	-1261.5 ⁽¹⁾
Mg ₃ Al ₂ Si ₃ O ₁₂	pyrope	-1415.1 to -1428.8 ⁽¹⁾	-1512.1 to -1520.6 ⁽¹⁾
Mg ₄ Al ₄ Si ₂ O ₁₀ (OH) ₈	amesite	-2013.0 ⁽¹⁾	-2167.1 ⁽¹⁾
Mg ₅ Al ₂ Si ₃ O ₁₀ (OH) ₈	7-Å clinochlore	-1957.1 ⁽¹⁾	-2113.2 ⁽¹⁾
Mg ₅ Al ₂ Si ₃ O ₁₀ (OH) ₈	14-Å clinochlore	-1961.70 ⁽³⁾	-2116.96 ⁽³⁾
		-1961.7 to -1968.9 ⁽¹⁾	-2117.0 to -2123.1 ⁽¹⁾
Mg ₅ Al ₂ Si ₃ O ₁₀ (OH) ₈	clinochlore	-1974.3 ⁽¹⁾	
Mg ₅ Al ₂ Si ₃ O ₁₀ (OH) ₈	chlorite	-1973.5 ⁽¹⁾	-2127.5 ⁽¹⁾
Mg ₄ Al ₁₀ Si ₇ O ₃₁ (OH) ₄	yoderite	-4016.5 ⁽¹⁾	-4271.2 ⁽¹⁾
Mg _{0.167} Al _{2.33} Si _{3.67} O ₁₀ (OH) ₂	montmorillonite	-1274.9 ⁽¹⁾	-1364.4 ⁽¹⁾
Mg _{0.49} Fe _{0.22} ³⁺ Al _{1.71} Si _{3.81} O ₁₀ (OH) ₂	montmorillonite	-1255.8 ⁽¹⁾	
Mn (manganese)			
α-Mn(c)		0.00	0.00
Mn ²⁺		-54.52 ^(2,4)	-52.76 ⁽²⁾
		-54.6 ⁽¹⁾	-52.9 ⁽¹⁾
Mn ³⁺		-20.26 ⁽⁵⁾	-27.0 ⁽⁷⁾
		-19.6 to -20.4 ⁽¹⁾	-24.0 ⁽¹⁾
MnO ₄ ⁻		-105.2 to -107.4 ⁽¹⁾	-127.4 to -129.7 ⁽¹⁾
MnO ₄ ²⁻		-118.1 to -120.4 ⁽¹⁾	-156.1 ⁽¹⁾
HMnO ₂ ⁻		-120.9 ⁽¹⁾	
MnHCO ₃ ⁺		-197.84 ⁽⁵⁾	
		-195.0 ⁽¹⁾	
MnCO ₃	rhodochrosite	-195.20 ^(2,4)	-213.7 ⁽²⁾
		-195.1 ⁽¹⁾	-212.9 ⁽¹⁾
MnCO ₃ ⁰		-179.96 ^(5,7)	-213.9 ^(1,7)
		-179.6 ⁽¹⁾	
Mn(OH) ⁺		-97.8 ^(3,5)	-107.7 ⁽³⁾
		-96.80 ⁽⁴⁾	
		-97.1 ⁽¹⁾	-107.0 ⁽¹⁾

<i>Compound or species</i>	<i>Mineral name</i>	<i>G_f^o, kcal/mol</i>	<i>H_f^o, kcal/mol</i>
Mn(OH) ₂	pyrochroite	-147.76 ⁽⁵⁾ -146.99 ⁽⁴⁾ -147.2 ⁽¹⁾	-167.3 ⁽¹⁾
Mn(OH) ₂ (amorph.)		-147.0 ^(1,2)	-166.2 ^(1,2)
MnOH ²⁺		-77.49 ⁽⁵⁾	
Mn(OH) ₃ (c)		-181 ⁽⁷⁾	-212 ^(1,7)
		-180.9 ⁽¹⁾	
Mn(OH) ₃ ⁻		-178.35 ^(3,5) -177.87 ⁽⁴⁾	
Mn(OH) ₄ ²⁻		-215.99 ⁽⁵⁾	
Mn ₂ OH ³⁺		-152.45 ⁽⁵⁾	
Mn ₂ (OH) ₃ ⁺		-247.69 ⁽⁵⁾	
MnO	manganosite	-86.74 ^(2,4) -86.7 ⁽¹⁾	-92.0 ⁽¹⁾
MnO ₂ , γ	pyrolusite	-111.18 ^(2,4) -111.2 ⁽¹⁾	-124.29 ⁽²⁾ -124.3 ⁽¹⁾
δ-MnO _{1.8}	birnessite	-108.59 ^(3,5,7) -108.3 ⁽¹⁾	
γ-MnO _{1.9}	nsutite	-109.4 ^(-,7) -109.1 ⁽¹⁾	
Mn ₂ O ₃	bixbyite	-210.6 ^(2,4) -211.2 ⁽¹⁾	-229.2 ⁽²⁾ -228.9 to -232.1 ⁽¹⁾
Mn ₃ O ₄	hausmannite	-306.7 ^(2,4) -306.3 ⁽¹⁾	-331.7 ⁽²⁾ 331.5 ⁽¹⁾
γ-MnOOH	manganite	-133.2 ^(1,3,5,7) -332.5 ⁽²⁾	
MnHPO ₄ (c)		-683.1 ⁽¹⁾	-744.7 to -771.0 ⁽¹⁾
Mn ₃ (PO ₄) ₂ (precipitated)		-692.96 ⁽⁵⁾	-744.9 ⁽²⁾
Mn ₃ (PO ₄) ₂ (c)		-105.3 ⁽¹⁾	-113.0 to -115.0 ⁽¹⁾
MnCl ₂	scacchite	-52.2 ⁽²⁾	-51.2 ⁽²⁾
MnS(green)		-52.16 ^(3,5,6)	-51.15 ^(3,6)
MnS	alabandite	-52.20 ⁽⁴⁾ -49.9 to -52.2 ⁽¹⁾	-48.8 to -51.2 ⁽¹⁾
		-55.53 ⁽⁵⁾ -55.5 ⁽¹⁾	-58.5 ⁽¹⁾
MnS ₂	hauerite		
MnSO ₄ (c)		-228.83 ⁽²⁾ -228.8 ⁽¹⁾	-254.60 ⁽²⁾ -254.5 ⁽¹⁾
MnSO ₄ ⁰		-232.5 ⁽²⁾	-270.1 ⁽²⁾
α-MnSO ₄ ·H ₂ O(c)		-289.11 ⁽⁵⁾	-329.0 ⁽²⁾
Mn ₂ (SO ₄) ₃ (c)		-590.14 ⁽⁵⁾	
MnSiO ₃	rhodonite	-296.5 ⁽²⁾ -296.7 ⁽¹⁾	-315.7 ⁽²⁾ -315.6 ⁽¹⁾
Mn ₂ SiO ₄	tephroite	-390.1 ⁽²⁾ -389.8 ⁽¹⁾	-413.6 ⁽²⁾ -413.3 ⁽¹⁾
MnWO ₄	huebnerite	-287.8 ⁽¹⁾	-312.0 ⁽¹⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
Mo (molybdenum) (see also Ag, Ca, Fe, Pb)			
Mo(c)		0.00	0.00
Mo ³⁺		-13.8 ^(1,7)	
MoO ₂ ⁺		-122.80 ⁽⁴⁾	
H ₂ MoO ₄ ⁰		-227 ⁽⁷⁾	
MoO ₄ ²⁻		-199.90 ⁽²⁾	-238.5 ^(1,2)
HMoO ₄ ⁻		-199.9 to -205.4 ⁽¹⁾ -213.6 ⁽⁷⁾ -205.62 ⁽⁵⁾	
H ₂ MoO ₄ ⁰		-207.1 to -213.6 ⁽¹⁾ -211.08 ⁽⁵⁾	-240.8 ⁽¹⁾
H ₂ MoO ₄ (c)		-209.6 to -227.1 ⁽¹⁾ -218.08 ⁽⁵⁾	-250.0 ^(1,2)
MoO ₂ (c)		-283.7 ⁽¹⁾ -127.4 ^(2,4)	-140.76 ⁽²⁾
MoO ₃	molybdite	-120.0 to -127.4 ⁽¹⁾ -159.66 ^(2,4)	-140.7 ⁽¹⁾ -178.08 ⁽²⁾
MoS ₂	molybdenite	-159.6 to -162.0 ⁽¹⁾ -54.0 ^(2,4) -53.9 ⁽¹⁾	-178.1 to -180.3 ⁽¹⁾ -56.2 ⁽²⁾ -55.9 ⁽¹⁾
Mo ₃ O ₈ (c)		-480.00 ⁽⁴⁾	
MoO ₃ ·H ₂ O(c)		-283.7 ⁽¹⁾	
N (nitrogen)			
N ₂ (g)		0.00	0.00
N ₂ ⁰		+2.994 ⁽⁷⁾	-2.51 ⁽¹⁾
NH ₃ (g)	ammonia	+2.98 to +4.35 ⁽¹⁾ -3.94 ^(1,2) -3.98 ⁽⁴⁾	-11.02 ^(1,2)
NO ₂ ⁻		-0.88 to -8.2 ⁽¹⁾	-25.1 ⁽¹⁾
NHO ₂ ⁰		-12.1 ⁽¹⁾	-28.4 ⁽¹⁾
NH ₃ ⁰	aqueous ammonia	-6.35 ^(1,2)	-19.19 ⁽²⁾
NH ₄ ⁺		-18.97 ^(2,4) -18.9 ⁽¹⁾	-19.2 ⁽¹⁾ -31.67 ⁽²⁾
NH ₄ OH ⁰		-63.04 ⁽²⁾ -63.0 ⁽¹⁾	-31.7 ⁽¹⁾ -87.05 ⁽²⁾
NH ₄ OH(l)		-60.74 ⁽²⁾	-87.5 ⁽¹⁾
NO(g)		+20.69 ⁽²⁾ +20.7 ⁽¹⁾	-86.33 ⁽²⁾ +21.57 ⁽²⁾
NO ⁰		+24.41 ⁽⁵⁾	+21.6 ⁽¹⁾
NO ₂ (g)		+12.26 ⁽²⁾ +12.3 ⁽¹⁾	+7.93 ⁽²⁾ +7.99 ⁽¹⁾
NO ₃ (g)		+27.75 ⁽⁵⁾	

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
$N_2O_3(g)$		+33.32 ⁽²⁾	+20.01 ⁽²⁾
$N_2O_4(g)$		+23.38 ⁽²⁾	+2.19 ⁽²⁾
		+23.4 ⁽¹⁾	+2.26 ⁽¹⁾
$N_2O_5(g)$		+27.5 ⁽²⁾	+2.7 ⁽²⁾
$HNO_3(g)$		-17.87 ⁽²⁾	-32.28 ⁽²⁾
$HNO_3(l)$	nitric acid	-19.31 ⁽²⁾	-41.61 ⁽²⁾
		-19.2 ⁽¹⁾	-41.5 ⁽¹⁾
NO_3^-		-26.61 ⁽²⁾	-49.56 ⁽²⁾
		-26.5 ⁽¹⁾	-49.4 ⁽¹⁾
		-25.99 ⁽⁴⁾	
HNO_3^0	nitric acid	-26.46 ⁽²⁾	-49.56 ⁽²⁾
		-26.5 ⁽¹⁾	-49.5 ⁽¹⁾
$NH_4NO_3(c)$		-43.98 ⁽²⁾	-87.37 ⁽²⁾
		-43.9 ⁽¹⁾	-87.4 ⁽¹⁾
$NH_4NO_3^0$		-45.58 ⁽²⁾	-81.23 ⁽²⁾
N_2O^0		+24.90 ⁽²⁾	+19.61 ⁽²⁾
NH_4Cl	sal ammoniac	-48.51 ⁽²⁾	-75.15 ⁽²⁾
		-48.6 ⁽¹⁾	-75.2 ⁽¹⁾
NH_4Cl^0		-50.34 ⁽²⁾	-71.62 ⁽²⁾
$(NH_4)_2SO_4$	mascagnite	-215.56 ⁽²⁾	-282.23 ⁽²⁾
		-215.5 ⁽¹⁾	-282.2 ⁽¹⁾
$NH_4VO_3(c)$		-212.2 to -221.8 ⁽¹⁾	-251.7 ⁽¹⁾
Na (sodium) (see also Al)			
$Na(c)$		0.00	0.00
Na^+		-62.593 ⁽²⁾	-57.39 ⁽²⁾
		-62.6 ⁽¹⁾	-57.4 ⁽¹⁾
$NaCl^0$		-93.96 ^(5,7)	-97.302 ^(5,7)
$NaCl$	halite	-91.815 ⁽²⁾	-98.268 ⁽²⁾
		-91.8 ⁽²⁾	-98.3 ⁽¹⁾
$NaCO_3^-$		-190.50 ^(3,5,7)	-223.7 ⁽¹⁾
		-189.5 to -190.5 ⁽¹⁾	
$Na_2CO_3^0$		-251.36 ⁽²⁾	-276.62 ⁽²⁾
$Na_2CO_3(c)$		-249.64 ⁽²⁾	-270.24 ⁽²⁾
		-250.2 ⁽¹⁾	-270.3 ⁽¹⁾
$NaHCO_3^0$		-202.88 ^(3,5,7)	-222.5 ⁽⁷⁾
		-202.8 ⁽¹⁾	-222.5 to -225.6 ⁽¹⁾
$NaHCO_3$	nahcolite	-203.4 ⁽²⁾	-227.25 ⁽²⁾
		-195.0 to -203.6 ⁽¹⁾	-218.3 to -227.2 ⁽¹⁾
$NaOH^0$		-99.91 ⁽⁵⁾	-112.36 ⁽²⁾
$NaOH(c)$		-90.709 ⁽²⁾	-101.723 ⁽²⁾
		-90.6 ⁽¹⁾	-101.8 ⁽¹⁾
$NaOH \cdot H_2O(c)$		-149.0 ⁽⁷⁾	-175.17 ⁽⁷⁾
		-149.0 to -150.4 ⁽¹⁾	-175.4 ⁽¹⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
NaSO_4^-		-241.26 ^(3,5,7)	-273.6 ⁽¹⁾
$\text{Na}_2\text{SO}_4(\text{c})$	thenardite	-241.2 ⁽¹⁾ -303.59 ⁽²⁾	-331.52 ⁽²⁾
NaSO_4^0		-303.4 ⁽¹⁾	-331.5 ⁽¹⁾
$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}(\text{c})$		-303.16 ⁽²⁾	-332.10 ⁽²⁾
$\text{NaHSO}_4(\text{c})$		-871.75 ⁽²⁾	-1034.24 ⁽²⁾
$\text{Na}_2\text{SiO}_3(\text{c})$		-237.3 ⁽²⁾ -349.19 ⁽²⁾	-269.01 ⁽²⁾ -371.63 ⁽²⁾
NaNO_3^0		-341.1 to -353.2 ⁽¹⁾	-363.0 to -375.2 ⁽¹⁾
NaNO_3	soda niter	-89.20 ⁽²⁾ -87.73 ⁽²⁾	-106.95 ⁽²⁾ -111.82 ⁽²⁾
$\text{Na}_2\text{Si}_2\text{O}_5(\text{c})$		-87.7 ⁽¹⁾	-111.8 ⁽¹⁾
$\text{NaSi}_{11}\text{O}_{20.5}(\text{OH})_4 \cdot 3\text{H}_2\text{O}$	kenyaite	-555.0 ⁽²⁾ -2603.5 ⁽¹⁾	-589.8 ⁽²⁾
Na_2S^0		-104.7 ⁽²⁾	-106.9 ⁽²⁾
$\text{Na}_2\text{S}(\text{c})$		-83.6 ⁽²⁾	-87.2 ⁽²⁾
$\text{Na}_2\text{O}(\text{c})$		-83.6 to -86.6 ⁽¹⁾ -89.74 ⁽²⁾	-87.2 to -89.2 ⁽¹⁾ -99.00 ⁽²⁾
NaF	villiaumite	-90.0 ⁽¹⁾ -129.902 ⁽²⁾	-99.5 ⁽¹⁾ -137.105 ⁽²⁾
NaF^0		-129.3 to -130.6 ⁽¹⁾	-136.0 to -137.8 ⁽¹⁾
$\text{NaBr}(\text{c})$		-129.23 ⁽²⁾ -83.1 ⁽⁷⁾	-136.89 ⁽²⁾ -86.030 ⁽⁷⁾
$\text{NaI}(\text{c})$		-83.3 ⁽¹⁾ -56.7 ⁽⁷⁾	-86.2 ⁽¹⁾ -68.84 ⁽⁷⁾
$\text{Na}_2\text{CO}_3 \cdot \text{H}_2\text{O}$	thermonatrite	-56.7 to -68.7 ⁽¹⁾ -307.35 ^(2,7)	-69.0 ⁽¹⁾ -342.08 ⁽²⁾
Na_3AlF_6	cryolite	-307.5 ⁽¹⁾	-342.2 ⁽¹⁾
$\text{NaAlCO}_3(\text{OH})_2$	dawsonite	-751.6 ⁽¹⁾	-790.9 ⁽¹⁾
$\text{Na}_2\text{B}_4\text{O}_7 \cdot 4\text{H}_2\text{O}$	kernite	-426.9 ⁽¹⁾	-469.4 ⁽¹⁾
$\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$	borax		1077.3 ⁽¹⁾
$\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$	natron	-1318.4 ⁽¹⁾ -819.36 ^(2,7)	-1501.9 ⁽¹⁾ -975.46 ⁽²⁾
$\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$	mirabilite	-819.6 ⁽¹⁾ -871.5 ⁽³⁾	-975.5 ⁽¹⁾ -1034.2 ⁽³⁾
$\text{Na}_2\text{CO}_3 \cdot 7\text{H}_2\text{O}(\text{c})$		-871.6 ⁽¹⁾	-1034.3 ⁽¹⁾
$\text{NaHCO}_3 \cdot \text{Na}_2\text{CO}_3 \cdot 2\text{H}_2\text{O}$	trona	-648.8 ⁽²⁾ -570.40 ^(3,7)	-764.81 ⁽²⁾ -641.7 ⁽¹⁾
$\text{Na}_3\text{PO}_4(\text{c})$		-569.7 ⁽¹⁾ -427.55 ⁽²⁾	-458.27 ⁽²⁾
Na_3PO_4^0		-431.3 ⁽²⁾	-477.5 ⁽²⁾
$\text{Na}_2\text{UO}_4(\text{c})$			-500.9 ⁽¹⁾
$\text{Na}_2\text{UO}_4(\alpha, \text{c})$		-422.7 to -424.9 ⁽¹⁾	-451.0 to -452.5 ⁽¹⁾
$\text{Na}_3\text{UO}_4(\text{c})$		-453.9 ⁽¹⁾	-483.6 ⁽¹⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
Nb (niobium)			
Nb(c)		0.00	0.00
Nb ³⁺		-76.0 ^(1,4,7)	
NbO ₃ ⁻		-222.78 ⁽⁴⁾	
NbO(c)		-90.5 ^(2,4)	-97.0 ⁽²⁾
		-90.5 to -93.7 ⁽¹⁾	-97.0 to -100.3 ⁽¹⁾
NbO ₂ (c)		-177.0 ⁽²⁾	-190.3 ⁽²⁾
		-190.30 ⁽⁴⁾	
		-176.5 ⁽¹⁾	-190.2 ⁽¹⁾
Nb ₂ O ₄ (c)		-362.4 ^(1,7)	-387.8 ^(1,7)
Nb ₂ O ₅ (c)		-422.1 ⁽²⁾	-454.0 ⁽²⁾
		-453.99 ⁽⁴⁾	
		-421.9 ⁽¹⁾	-453.7 ⁽¹⁾
Ni (nickel)			
Ni(c)		0.00	0.00
Ni ²⁺		-10.9 ^(2,4)	-12.9 ⁽²⁾
		-11.0 ⁽¹⁾	-12.8 to -15.3 ⁽¹⁾
NiO	bunsenite	-50.6 ^(1,2,4)	-57.3 ^(1,2)
NiO ₂ (c)		-47.5 ^(1,7)	
Ni ₃ O ₄ (c)		-170.1 ⁽¹⁾	
Ni(OH) ₂ (c)		-106.9 ^(2,4)	-126.6 ⁽²⁾
		-106.9 to -109.7 ⁽¹⁾	-126.6 to -128.6 ⁽¹⁾
Ni(OH) ₂ ⁰		-86.1 ⁽²⁾	-122.8 ⁽²⁾
NiOH ⁺		-54.40 ⁽⁴⁾	
		-52.6 to -55.9 ⁽¹⁾	-68.8 ⁽¹⁾
HNiO ₂ ⁻		-83.46 ⁽⁷⁾	
		-83.5 ⁽¹⁾	
Ni(OH) ₃ (c)		-129.5 ^(1,7)	-160 ⁽²⁾
γ-NiS(c)		-27.3 ⁽¹⁾	-162.1 ⁽¹⁾
α-NiS(c)	millerite	-19.0 ^(2,4)	-19.6 ⁽²⁾
		-17.7 to -20.6 ⁽¹⁾	-19.6 to -20.3 ⁽¹⁾
Ni ₃ S ₂ (c)	heazlewoodite	-47.1 ^(1,2)	-48.5 ^(1,2)
NiCO ₃ (c)		-146.4 ^(2,4)	-158.7 ⁽⁷⁾
		-146.3 to -147.0 ⁽¹⁾	-158.7 to -164.7 ⁽¹⁾
Ni ₃ O ₄ · 2H ₂ O(c)		-283.5 ⁽¹⁾	
NiO ₂ · 2H ₂ O(c)		-164.8 ⁽¹⁾	
Ni ₂ O ₃ · H ₂ O(c)		-168.9 ⁽¹⁾	
NiSO ₄ (c)		-181.6 ^(2,4)	-208.63 ⁽²⁾
		-181.6 to -184.9 ⁽¹⁾	-208.6 to -213.0 ⁽¹⁾
NiSO ₄ ⁰		-188.9 ⁽²⁾	-230.2 ⁽²⁾
NiSO ₄ · 6H ₂ O(green, α)	retgersite (tetrag.)	-531.7 ^(1,2)	-641.21 ⁽²⁾
			-641.2 to -645.0 ⁽¹⁾
NiSO ₄ · 6H ₂ O(blue, β,c)	(monocl.)	-531.0 ^(1,7)	-638.7 ⁽²⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
NiCl ₂ (c)		-61.9 ⁽¹⁾	-638.7 to -642.5 ⁽¹⁾
NiSO ₄ · 7H ₂ O	morenosite	-588.4 ⁽¹⁾	-73.0 ⁽¹⁾
NiFe ₂ O ₄	trevorite	-232.2 ⁽¹⁾	-711.3 ⁽¹⁾
NiAl ₂ O ₄ (c)		-434.8 ⁽¹⁾	-258.1 ⁽¹⁾
NiSO ₃ (c)		-269.6 ⁽¹⁾	-457.9 to -463.6 ⁽¹⁾
Ni ₂ SiO ₄	olivine	-308.1 ⁽¹⁾	-333.8 ⁽¹⁾
Ni ₂ SiO ₄	spinel	-306.2 ⁽¹⁾	
Ni ₂ SiO ₄ (c)		-307.4 to -314.8 ⁽¹⁾	-334.3 to -341.7 ⁽¹⁾
O (oxygen)			
O ₂ (g)		0.00	0.00
O ₂ ⁰ (aqueous)		+3.91 ⁽¹⁾	-2.80 ⁽¹⁾
O ₂ ⁻		+12.9 ⁽¹⁾	
O ₃ (g)	ozone	+39.0 ⁽⁵⁾	
Os (osmium)			
Os(c)		0.00	0.00
OsS ₂		-27.49 ⁽⁴⁾	
Os(OH) ₄ (c)		-160.97 ⁽⁴⁾	
H ₂ OsO ₅ ⁰		-128.81 ⁽⁴⁾	
HOsO ₅ ⁻		-112.38 ⁽⁴⁾	
OsO ₄ ²⁻		-89.25 ⁽⁴⁾	
P (phosphorus) (see also Na, Al, Ca, Mg, K, Mn, Fe, etc.)			
α-P(white)		0.00	0.00
P ₂ (g)		+24.7 ⁽¹⁾	+34.2 ⁽¹⁾
HPO ₃ ⁰		-215.8 ⁽⁵⁾	-234.8 ⁽⁵⁾
HPO ₃ ²⁻		-191.07 ⁽⁵⁾	-233.8 ⁽⁷⁾
		-194.0 ⁽¹⁾	-231.6 to -233.8 ⁽¹⁾
H ₂ PO ₃ ⁻		-200.33 ⁽⁵⁾	-231.7 ⁽¹⁾
		-202.3 ⁽¹⁾	
H ₃ PO ₃ ⁰		-202.38 ⁽⁵⁾	-232.2 ⁽⁷⁾
		-204.8 ⁽¹⁾	-230.6 to -232.2 ⁽¹⁾
PO ₄ ³⁻		-245.18 ^(5,7)	-306.9 ⁽⁷⁾
		-243.5 ^(3,4)	-305.3 ⁽³⁾
		-243.8 ⁽¹⁾	-305.6 ⁽¹⁾
HPO ₄ ²⁻		-261.33 ^(3,5,7)	-308.83 ⁽³⁾
		-260.31 ⁽⁴⁾	
		-260.6 ⁽¹⁾	-309.2 ⁽¹⁾
H ₂ PO ₄ ⁻		-271.57 ^(3,5,7)	-310.6 ^(3,7)
		-270.14 ⁽⁴⁾	
		-270.4 ⁽¹⁾	-310.2 ⁽¹⁾
H ₃ PO ₄ ⁰	phosphoric acid	-274.0 ^(3,5,7)	-308.1 ^(3,7)
		-273.07 ⁽⁴⁾	

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
$H_3PO_4(c)$		-273.1 to -274.2 ⁽¹⁾	-307.9 to -308.2 ⁽¹⁾
		-267.5 ⁽²⁾	-305.7 ⁽²⁾
		-266.6 ⁽¹⁾	-304.7 ⁽¹⁾
$(H_2PO_4)_2^{2-}$		-543.22 ⁽⁵⁾	
PH_3^0		+6.06 ⁽⁴⁾	
$P_2O_5(orthorhomb.)$		-328.1 ⁽¹⁾	-359.7 to -363.5 ⁽¹⁾
$P_2O_5(hexagonal)$		-322.4 ⁽¹⁾	-356.6 ⁽¹⁾
Pb (lead)			
$Pb(c)$		0.00	0.00
Pb^{2+}		-5.85 ^(2,4,5,6,7)	-0.4 ^(2,6)
		-5.83 ⁽¹⁾	-0.38 ⁽¹⁾
PbO_3^{2-}		-66.3 ⁽¹⁾	
PbO_4^{4-}		-67.4 ⁽¹⁾	
$HPbO_2^-$		-80.9 ^(1,4)	
Pb^{4+}		+72.3 ^(1,7)	
$PbCO_3$	cerussite	-149.9 ^(1,2,6,7)	-167.2 ^(2,6,7)
		-149.5 ⁽⁴⁾	-167.5 ⁽¹⁾
$Pb_2CO_3Cl_2$	phosgenite	-227.94 ⁽⁵⁾	
$Pb_3(CO_3)_2(OH)_2$	hydrocerussite	-409.08 ⁽⁵⁾	-457.5 ⁽¹⁾
		-406.1 to -409.7 ⁽¹⁾	
$PbCl^+$		-39.45 ⁽⁵⁾	
		-39.4 ⁽¹⁾	
$PbCl_2^0$		-68.57 ⁽²⁾	-80.3 ⁽²⁾
		-71.0 to -71.9 ⁽¹⁾	
$PbCl_3^-$		-102.31 ⁽⁵⁾	
		-101.69 ⁽⁴⁾	
		-101.9 ⁽¹⁾	
$PbCl_4^{2-}$		-133.27 ⁽⁵⁾	
$PbCl_2$	cotunnite	-75.98 ⁽²⁾	-85.90 ^(1,2)
		-75.1 ⁽¹⁾	
$PbClOH$	laurionite	-93.5 ⁽¹⁾	-110.1 ⁽¹⁾
PbF^+		-75.86 ⁽⁵⁾	
PbF_2^0		-139.11 ⁽²⁾	-159.4 ⁽²⁾
		-144.86 ⁽⁵⁾	
PbF_3^-		-214.35 ⁽⁵⁾	
PbF_4^{2-}		-281.85 ⁽⁵⁾	
$PbF_2(c)$		-147.5 ⁽²⁾	-158.7 ⁽²⁾
		-147.5 to -150.0 ⁽¹⁾	-158.5 to -162.2 ⁽¹⁾
$Pb(OH)^+$		-52.09 ^(4,5)	
		-52.6 to -54.1 ⁽¹⁾	
$Pb(OH)_2^0$		-95.06 ⁽⁵⁾	
		-95.8 to -97.6 ⁽¹⁾	
$Pb(OH)_3^-$		-137.64 ^(5,6)	

<i>Compound or species</i>	<i>Mineral name</i>	<i>G_f^o, kcal/mol</i>	<i>H_f^o, kcal/mol</i>
Pb(OH) ₄ ²⁻		-137.6 ⁽¹⁾	
Pb ₂ (OH) ₃ ⁺		-178.78 ⁽⁵⁾	
Pb ₃ (OH) ₄ ²⁺		-59.76 ⁽⁵⁾	
Pb ₄ (OH) ₄ ⁴⁺		-211.86 ⁽⁵⁾	
Pb ₆ (OH) ₈ ⁴⁺		-211.85 ⁽⁵⁾	
Pb(OH) ₂ (c)		-429.45 ⁽⁵⁾	
		-108.1 ^(2,5)	-123.3 ⁽²⁾
		-100.6 to -108.1 ⁽¹⁾	-123.0 ⁽¹⁾
PbWO ₄	stolzite	-243.9 ⁽¹⁾	-268.1 ⁽¹⁾
PbCrO ₄	crocoite	-195.2 to -203.6 ⁽¹⁾	-218.7 to -225.2 ⁽¹⁾
PbMoO ₄	wulfenite	-227.62 ⁽⁵⁾	-265.8 ⁽⁷⁾
		-226.7 to -231.7 ⁽¹⁾	-250.7 to -265.8 ⁽¹⁾
Pb ₂ O ₃ (c)		-98.42 ^(1,7)	
PbO(yellow)	massicot	-45.00 ^(1,2,5,7)	-51.77 ^(2,7)
PbO(red)	litharge	-45.20 ^(1,2,5,6,7)	-52.37 ^(1,2,6,7)
		-45.16 ⁽⁴⁾	
PbO ₂	plattnerite	-51.95 ^(2,4,5,6,7)	-66.21 ^(2,6,7)
		-51.5 to -52.3 ⁽¹⁾	-66.0 ⁽¹⁾
Pb ₃ O ₄	minium	-143.75 ^(2,5)	-171.7 ⁽²⁾
		-143.69 ⁽⁴⁾	
		-143.6 to -147.6 ⁽¹⁾	-171.7 to -175.6 ⁽¹⁾
PbO · PbCO ₃ (c)		-195.72 ^(2,7)	-220.0 ⁽⁷⁾
		-195.4 ⁽¹⁾	-219.7 ⁽¹⁾
PbHPO ₄ ⁰		-272.16 ⁽⁵⁾	
PbH ₂ PO ₄ ⁺		-279.80 ⁽⁵⁾	
PbHPO ₄ (c)		-283.55 ⁽⁵⁾	-234.5 ⁽⁷⁾
Pb(H ₂ PO ₄) ₂ (c)		-563.04 ⁽⁵⁾	
Pb ₃ (PO ₄) ₂ (c)		-568.57 ⁽⁵⁾	-620.3 ^(1,7)
		-565.0 to -581.4 ⁽¹⁾	
Pb ₅ (PO ₄) ₃ Cl	chloropyromorphite	-910.59 ⁽⁵⁾	
		-838.1 to -906.2 ⁽¹⁾	
Pb ₅ (PO ₄) ₃ F	fluoropyromorphite	-930.68 ⁽⁵⁾	
Pb ₅ (PO ₄) ₃ OH	hydroxypyromorphite	-907.39 ⁽⁵⁾	
PbSO ₄ ⁰		-187.42 ⁽⁵⁾	
Pb(SO ₄) ₂ ²⁻		-366.53 ⁽⁵⁾	
PbS	galena	-22.9 ^(2,5,6,7)	-24.0 ^(2,6)
		-23.59 ⁽⁴⁾	
		-22.2 to -23.1 ⁽¹⁾	-22.5 to -24.0 ⁽¹⁾
PbSe	clausthalite	-24.3 ⁽¹⁾	-24.6 ⁽¹⁾
PbTe	altaite	-16.6 ⁽¹⁾	-16.7 ⁽¹⁾
PbSO ₄	anglesite	-194.42 ^(2,5,6)	-219.75 ^(1,2,6,7)
		-194.35 ⁽⁴⁾	
		-194.2 ⁽¹⁾	
PbSO ₄ · PbO	lanarkite	-246.70 ^(1,5)	-282.5 ⁽⁷⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
			-280.0 ⁽¹⁾
PbSO ₄ · 2PbO(c)		294.00 ⁽⁵⁾	
PbSO ₄ · 3PbO(c)		-341.2 ⁽⁵⁾	
PbSeO ₄ (c)		-120.7 ⁽¹⁾	-145.6 to -147.9 ⁽¹⁾
PbSiO ₃	alamosite	-253.86 ^(2,5,6)	-273.83 ^(2,6)
		-253.5 ⁽¹⁾	-273.5 ⁽¹⁾
Pb ₂ SiO ₄ (c)		-299.4 ^(1,2,5)	-325.8 ⁽²⁾
			-326.0 ⁽¹⁾
Pd (palladium)			
Pd(c)		0.00	0.00
Pd ²⁺		+42.2 ^(1,2)	+35.6 ^(1,2)
		+42.49 ⁽⁴⁾	
PdO(c)		-14.4 ^(1,7)	-20.4 ^(1,2)
		-15.31 ⁽⁴⁾	
PdO ₃ (c)		+24.1 ^(1,7)	
Pd(OH) ₂ (c)		-72.0 ^(1,7)	-94.4 ⁽⁴⁾
			-92.1 to -94.4 ⁽¹⁾
Pd(OH) ₄ (c)		-126.2 ^(1,7)	-171.1 ⁽²⁾
			-169.4 ⁽¹⁾
PdS(c)		-16.01 ^(2,4)	-18. ⁽²⁾
PdS ₂ (c)		-17.81 ^(2,4)	-19.4 ⁽²⁾
Pd ₄ S(c)		-16. ⁽²⁾	-16. ⁽²⁾
Po (polonium)			
Po(c)		0.00	0.00
Po ²⁺		+16.97 ⁽⁴⁾	
Po ⁴⁺		+70.00 ⁽⁴⁾	
Po(OH) ₄ (c)		-130.00 ⁽⁴⁾	
Po(OH) ₂ ⁴⁺		-113.05 ⁽⁴⁾	
PoS(c)		-0.96 ⁽⁴⁾	
PoO ₂ (c)		-46.60 ⁽⁴⁾	
Pt (platinum)			
Pt(c)		0.00	0.00
Pt ⁺		+60.9 ⁽²⁾	
Pt ²⁺		+54.8 ^(4,7)	
		+44.4 to +60.9 ⁽¹⁾	
Pt(OH) ₂ (c)		-68.2 ^(1,4,7)	-84.1 ⁽²⁾
			-84.1 to -87.2 ⁽¹⁾
PtS	cooperite	-18.2 ⁽²⁾	-19.5 ⁽²⁾
		-18.3 ⁽¹⁾	-19.6 ⁽¹⁾
		-21.6 ⁽⁴⁾	
PtS ₂ (c)		-23.8 ^(1,2)	-26.0 ^(1,2)
		-25.6 ⁽⁴⁾	
PtO ₂ (c)		-20.0 ⁽⁴⁾	

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
Ra (radium)			
Ra(c)		0.00	0.00
Ra ²⁺		-134.20 ⁽⁴⁾	
RaSO ₄ (c)		-326.39 ⁽⁴⁾	
RaCO ₃ (c)		-271.69 ⁽⁴⁾	
Rb (rubidium)			
Rb(c)		0.00	0.00
Rb ⁺		-67.87 ⁽²⁾	-60.03 ^(1,2)
		-67.4 to -69.7 ⁽¹⁾	
RbCl(c)		-97.47 ⁽²⁾	-104.05 ⁽²⁾
Rb ₂ SO ₄ (c)		-314.76 ⁽²⁾	-343.12 ⁽²⁾
Rb ₂ SO ₄ ⁰		-313.71 ⁽²⁾	-337.38 ⁽²⁾
RbNO ₃ (c)		-94.61 ⁽²⁾	-118.32 ⁽²⁾
RbNO ₃ ⁰		-94.48 ⁽²⁾	-109.59 ⁽²⁾
Rb ₂ CO ₃ (c)		-251.2 ⁽²⁾	-271.5 ⁽²⁾
		-250.0 ⁽¹⁾	-270.2 ⁽¹⁾
Rb ₂ CO ₃ ⁰		-261.9 ⁽²⁾	-281.90 ⁽²⁾
RbOH(c)		-87.1 ^(1,7)	-99.95 ^(1,2)
Rb(OH) ⁰		-105.05 ⁽⁷⁾	-113.9 ⁽⁷⁾
Rb ₂ O(c)		-69.5 ⁽⁷⁾	-81. ⁽²⁾
			-78.9 ⁽¹⁾
Rb ₂ S(c)		-80.6 ⁽¹⁾	-83.2 to -86.2 ⁽¹⁾
RbHCO ₃ (c)		-206.4 ⁽²⁾	-230.2 ⁽²⁾
RbHCO ₃ ⁰		-208.13 ⁽²⁾	-225.42 ⁽²⁾
Re (rhenium)			
Re(c)		0.00	0.00
Re ₂ O ₃ (c)		-138.64 ⁽⁴⁾	
ReO ₂ (c)		-87.95 ⁽⁴⁾	
ReO ₃ (c)		-127.96 ⁽⁴⁾	
ReO ₄ ⁻		-165.99 ⁽⁴⁾	
ReS ₂ (c)		-38.10 ⁽⁴⁾	
Rh (rhodium)			
Rh(c)		0.00	0.00
Rh ₂ O(c)		-20.0 ⁽⁴⁾	
Rh ₂ O ₃ (c)		-50.0 ⁽⁴⁾	
Rh ³⁺		+55.3 ⁽⁴⁾	
Ru (ruthenium)			
Ru(c)		0.00	0.00
RuS ₂ (c)		-45.03 ⁽⁴⁾	
RuO ₂ (c)		-60.49 ⁽⁴⁾	

<i>Compound or species</i>	<i>Mineral name</i>	G_f° , kcal/mol	H_f° , kcal/mol
$\text{Ru}(\text{OH})_2^{2+}$		-53.01 ⁽⁴⁾	
RuO_4^{2-}		-73.28 ⁽⁴⁾	
RuO_4^-		-59.78 ⁽⁴⁾	
S (sulfur) (see also Ca, Fe, Mn, Ni, Co, etc.)			
S(c, rhombic)		0.00	0.00
$\text{S}_2(\text{g})$		+18.96 ^(2,6)	+30.68 ^(2,6)
		+19.0 ⁽¹⁾	+30.7 ⁽¹⁾
S^{2-}		+20.51 ^(3,4,5,6)	+7.9 ^(3,6)
		+20.6 ⁽¹⁾	+7.81 ⁽¹⁾
HS^-		+2.93 ^(3,5,6,7)	-4.2 ^(3,6,7)
		+2.89 ^(1,4)	-4.19 ⁽¹⁾
$\text{H}_2\text{S}(\text{g})$		-8.02 ^(2,5,6)	-4.93 ^(2,6)
		-8.00 ⁽¹⁾	-4.90 ⁽¹⁾
H_2S^0		-6.66 ^(2,3,5,6)	-9.5 ^(2,3,6)
		-6.65 ^(1,4)	-9.57 ⁽¹⁾
$\text{SO}(\text{g})$		-4.741 ⁽²⁾	+1.496 ⁽²⁾
		-4.73 to +12.8 ⁽¹⁾	-1.48 to +19.0 ⁽¹⁾
$\text{SO}_2(\text{g})$		-71.66 ^(2,3,5,6)	-70.94 ^(1,2,6,7)
		-71.8 ⁽¹⁾	
SO_2^0		-71.871 ^(2,5)	-77.194 ⁽²⁾
SO_3^{2-}		-116.24 ^(1,2,3,4,5,7)	-151.9 ^(1,2,3,7)
HSO_3^-		-126.05 ^(3,5,7)	-149.88 ^(3,7)
		-126.1 ^(1,4)	-149.8 ⁽¹⁾
H_2SO_3^0		-128.56 ^(2,5,7)	-145.51 ^(2,7)
		-128.6 ⁽¹⁾	-145.5 ⁽¹⁾
SO_4^{2-}		-177.75 ^(2,3,5,6,7)	-217.32 ^(2,3,6)
		-177.8 ⁽¹⁾	-217.3 ⁽¹⁾
		-177.95 ⁽⁴⁾	
HSO_4^-		-180.69 ^(2,3,4,5,6)	-212.08 ^(2,3,6)
		-180.4 ⁽¹⁾	-212.2 ⁽¹⁾
H_2SO_4^0		-177.75 ^(2,5,7)	-217.32 ⁽²⁾
$\text{H}_2\text{SO}_4(\text{l})$		-164.938 ⁽²⁾	-194.548 ⁽²⁾
		-164.9 ⁽¹⁾	-194.5 ⁽¹⁾
Sb (antimony)			
Sb(c)		0.00	0.00
$\text{Sb}_2(\text{g})$		+40. ⁽⁷⁾	+52. ⁽⁷⁾
		+39.9 to +44.7 ⁽¹⁾	+52.1 to 56.3 ⁽¹⁾
SbO^+		-42.33 ^(2,4)	
		-42.2 ⁽¹⁾	
SbO_2^-		-65.5 ^(1,7)	
SbO_3^-		-122.9 ⁽¹⁾	
SbO_2^-		-81.32 ^(2,4)	

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
		-81.3 to -82.5 ⁽¹⁾	
HSbO ₂ ⁰		-97.4 ^(1,2,4)	-116.6 ^(1,2)
Sb ₂ O ₄ (c)		-190.2 ^(2,4)	-216.9 ⁽²⁾
		-165.9 to -190.2 ⁽¹⁾	-193.3 to -216.9 ⁽¹⁾
Sb ₂ O ₅ (c)		-198.2 ^(2,4)	-232.3 ⁽²⁾
		-198.2 to -206.7 ⁽¹⁾	-232.3 to -240.8 ⁽¹⁾
Sb ₄ O ₆	cubic senarmontite	-298.0 ⁽⁷⁾	-336.8 ⁽⁷⁾
		-298.0 to -306.4 ⁽¹⁾	-336.8 to -334.4 ⁽¹⁾
Sb ₄ O ₆	ortho. valentinite	-294.0 ⁽⁷⁾	-338.7 ⁽¹⁾
		-294.0 to -302.0 ⁽¹⁾	
Sb(OH) ₃ (c)		-163.8 ^(2,4)	
Sb(OH) ₃ ⁰		-154.1 ⁽²⁾	-184.9 ⁽²⁾
SbCl ₃ (c)		-77.5 ⁽¹⁾	-91.3 ⁽¹⁾
SbF ₃ (c)		-199.8 ⁽¹⁾	-217.2 to -218.8 ⁽¹⁾
SbS ₃ ²⁻		-32.0 ^(1,7)	
Sb ₂ S ₃	stibnite	-41.5 ^(1,2,4)	-41.8 ^(1,2)
SbS ₂ ⁻		-13.0 ^(1,7)	
Sb ₂ S ₄ ²⁻		-11.9 ⁽¹⁾	-26.2 ⁽¹⁾
		-23.78 ⁽⁴⁾	
Sc (scandium)			
Sc(c)		0.00	0.00
Sc ³⁺		-140.2 ^(2,4)	-146.8 ⁽²⁾
		-143.7 ⁽¹⁾	-146.8 to -151.0 ⁽¹⁾
Sc ₂ O ₃ (c)		-434.85 ^(2,4)	-456.22 ^(1,2)
		-434.8 ⁽¹⁾	
Sc(OH) ²⁺		-193.7 ⁽⁷⁾	-205.9 ⁽¹⁾
		-191.49 ⁽⁴⁾	
		-193.9 ⁽¹⁾	
Sc(OH) ₃ (c)		-294.8 ^(2,4)	-325.9 ⁽²⁾
		-293.5 to -297.0 ⁽¹⁾	-325.9 to -328.7 ⁽¹⁾
Sc(OH) ₄ ⁻		-327.60 ⁽⁴⁾	
ScF ₃ (c)		-371.8 ⁽²⁾	-389.4 ⁽²⁾
Se (selenium)			
Se(c, hexagonal, black)		0.00	0.00
Se ₂ (g)		+23.0 ⁽²⁾	+34.9 ^(1,2)
		+21.2 to +23.0 ⁽¹⁾	
Se ²⁻		+30.9 ^(1,2,4)	+31.6 ^(1,7)
			+15.3 ⁽¹⁾
SeO ₂ (c)		-41.5 ⁽⁷⁾	-53.86 ^(1,2)
		-41.2 ⁽¹⁾	
H ₂ SeO ₃ ⁰		-101.8 ^(1,4,7)	-121.29 ^(1,2)
HSeO ₃ ⁻		-98.34 ^(1,4,7)	-123.5 ⁽⁷⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
			-123.1 ⁽¹⁾
SeO ₃ ²⁻		-89.33 ⁽⁷⁾	-122.39 ⁽⁷⁾
		-87.0 to -89.3 ⁽¹⁾	-121.7 ⁽¹⁾
		-88.38 ⁽⁴⁾	
H ₂ SeO ₄ ⁰		-105.42 ^(1,7)	-145.3 ^(1,7)
HSeO ₄ ⁻		-108.2 ⁽⁷⁾	-143.1 ⁽⁷⁾
		-107.9 ⁽¹⁾	-138.1 ⁽¹⁾
		-108.08 ⁽⁴⁾	
SeO ₄ ²⁻		-105.42 ⁽⁷⁾	-145.3 ⁽⁷⁾
		-105.5 ⁽¹⁾	-143.2 ⁽¹⁾
		-105.47 ⁽⁴⁾	
H ₂ Se(g)		+3.80 ⁽¹⁾	+7.10 ⁽¹⁾
H ₂ Se ⁻		+5.31 ⁽¹⁾	+4.59 ⁽¹⁾
		+3.80 ⁽⁴⁾	
HSe ⁻		+10.5 ^(1,4)	+3.80 ⁽¹⁾
Si (silicon) (see also Al, Ca, Fe, Mg, etc.)			
Si(c)		0.00	0.00
SiO ₂ · nH ₂ O(amorph.)		-202.9 ⁽¹⁾	-215.6 ⁽¹⁾
SiO ₂ (amorph.)		-203.33 ^(2,4)	-215.94 ⁽²⁾
		-203.1 ⁽¹⁾	-215.7 ⁽¹⁾
SiO ₂	chalcedony	-204.3 ⁽¹⁾	-217.3 ⁽¹⁾
SiO ₂	coesite	-203.44 ⁽⁵⁾	-216.4 ⁽¹⁾
		-203.3 ⁽¹⁾	
SiO ₂	cristobalite	-204.46 ⁽²⁾	-217.37 ⁽²⁾
		-204.2 ⁽¹⁾	-217.0 ⁽¹⁾
SiO ₂	quartz	-204.75 ⁽²⁾	-217.72 ⁽²⁾
		-204.7 ^(1,4)	-217.7 ⁽¹⁾
SiO ₂	tridymite	-204.42 ⁽²⁾	-217.27 ⁽²⁾
		-204.2 ⁽¹⁾	-217.1 ⁽¹⁾
SiO ₂	stishovite	-191.8 ⁽¹⁾	-205.8 ⁽¹⁾
SiO ₄ ⁴⁻		-249.99 ⁽⁵⁾	
HSiO ₄ ³⁻		-267.86 ⁽⁵⁾	
H ₂ SiO ₄ ²⁻		-283.1 ⁽³⁾	
H ₃ SiO ₄ ⁻		-299.1 ⁽³⁾	-342.1 ⁽³⁾
		-295.53 ⁽⁴⁾	
		-299.5 ⁽¹⁾	-340.7 ⁽¹⁾
H ₄ SiO ₄ ⁰		-312.66 ^(1,3,5)	-348.3 ⁽⁶⁾
		-314.53 ⁽⁴⁾	-349.0 ⁽¹⁾
SiF ₄ (g)		-375.9 ^(1,6)	-386.0 ^(1,6)
SiF ₆ ²⁻		-367.6 ⁽¹⁾	-572.0 ⁽¹⁾
Sn (tin)			
Sn(white, c)		0.00	0.00

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
Sn^{2+}		-6.5 ^(2,4)	-2.1 ⁽²⁾
		-6.49 ⁽¹⁾	-2.12 ⁽¹⁾
Sn^{4+}		+0.6 ^(4,6,7)	+7.3 ⁽⁶⁾
		+0.14 ⁽¹⁾	+7.29 ⁽¹⁾
SnO	romarchite	-61.4 ^(1,2,4)	-68.3 ⁽²⁾
			-68.4 ⁽¹⁾
SnO_2	cassiterite	-124.2 ^(1,2,4)	-138.8 ^(1,2)
HSnO_2^-		-98.0 ⁽¹⁾	
		-48.0 ⁽⁴⁾	
SnO_3^{2-}		-137.4 ^(1,4)	
$\text{Sn}_2\text{O}_3^{2-}$		-141.1 ⁽¹⁾	
$\text{SnO} \cdot \text{OH}^+$		-113.29 ⁽⁴⁾	
$\text{Sn}(\text{OH})^+$		-60.6 ⁽⁷⁾	-68.4 ⁽¹⁾
		-60.90 ⁽⁴⁾	
		-60.5 ⁽¹⁾	
$\text{Sn}(\text{OH})_2(\text{c})$		-117.5 ⁽²⁾	-134.1 ⁽²⁾
		-117.6 ⁽¹⁾	-138.3 ⁽¹⁾
$\text{Sn}(\text{OH})_4(\text{c})$		-227.5 ^(1,7)	-265.3 ⁽²⁾
			-270.5 ⁽¹⁾
$\text{SnCl}_4(\text{g})$		-105.2 ⁽²⁾	-112.2 ⁽²⁾
SnCl_4^0		-124.9 ⁽²⁾	-152.5 ⁽²⁾
$\text{SnCl}_2(\text{c})$		-72.2 ^(1,7)	-77.7 ^(1,2)
SnCl_2^0		-71.6 ⁽²⁾	-78.8 ⁽²⁾
SnS	herzenbergite	-23.5 ⁽²⁾	-24. ⁽²⁾
		-25.02 ⁽⁴⁾	
		-23.5 to -25.0 ⁽¹⁾	-23.9 to -25.5 ⁽¹⁾
SnS_2	berndtite	-38.0 ^(6,4)	-40.0 ⁽⁶⁾
		-34.7 ⁽¹⁾	-36.7 ⁽¹⁾
$\text{Sn}(\text{OH})_6^{2-}$		-310.5 ^(1,6,7)	
$\text{Sn}(\text{SO}_4)_2(\text{c})$		-346.8 ⁽⁷⁾	-393.4 ⁽⁷⁾
		-344.6 to -346.8 ⁽¹⁾	-389.4 to -393.4 ⁽¹⁾
SnF_6^{2-}		-419.9 ⁽¹⁾	-474.7 ⁽¹⁾
Sr (strontium)			
$\text{Sr}(\text{c})$		0.00	0.00
Sr^{2+}		-133.71 ^(2,4)	-130.45 ⁽²⁾
		-133.5 ⁽¹⁾	-130.4 ⁽¹⁾
$\text{Sr}(\text{NO}_3)_2(\text{c})$		-186.46 ⁽²⁾	-233.80 ^(1,2)
		-186.3 ⁽¹⁾	
$\text{Sr}(\text{NO}_3)_2^0$		-186.93 ⁽²⁾	-229.57 ⁽²⁾
$\text{SrO}(\text{c})$		-134.3 ^(2,4)	-141.5 ⁽²⁾
		-134.0 ⁽¹⁾	-141.2 ⁽¹⁾
SrSO_4	celestite	-320.5 ^(1,2,4)	-347.3 ^(1,2)

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
SrSO_4^0	strontianite	-311.68 ⁽²⁾	-347.77 ⁽²⁾
SrCO_3		-272.5 ^(2,4)	-291.6 ⁽²⁾
		-272.1 ⁽¹⁾	-291.4 ⁽¹⁾
SrCO_3^0		-259.88 ⁽²⁾	-292.29 ⁽²⁾
$\text{Sr}(\text{OH})_2(\text{c})$		-207.8 ^(1,4,7)	-229.2 ⁽²⁾
			-229.3 ⁽¹⁾
$\text{Sr}(\text{OH})^+$		-172.39 ⁽⁴⁾	
		-175.3 ⁽¹⁾	-186.8 ⁽¹⁾
$\text{SrCl}_2(\text{c})$		-186.7 ^(1,2)	-198.1 ^(1,2)
$\text{SrF}_2(\text{c})$		-278.4 ⁽²⁾	-290.7 ⁽²⁾
		-278.1 ⁽¹⁾	-290.5 ⁽¹⁾
$\text{Sr}_3(\text{PO}_4)_2(\text{c})$		-932.1 ^(1,7)	-985.4 ⁽²⁾
			-985.4 to -987.3 ⁽¹⁾
$\text{SrHPO}_4(\text{c})$		-403.6 ⁽²⁾	-435.4 ⁽²⁾
		-399.7 to -403.6 ⁽¹⁾	-431.3 to -435.4 ⁽¹⁾
$\text{SrBr}_2(\text{c})$		-166.5 ⁽¹⁾	-177.5 ⁽¹⁾
$\text{SrS}(\text{c})$		-97.4 to -111.8 ⁽¹⁾	-108.1 to -112.9 ⁽¹⁾
$\text{Sr}_3\text{SiO}_5(\text{c})$		-690.0 ⁽¹⁾	-709.9 to -724.4 ⁽¹⁾
$\text{SrSiO}_3(\text{c})$		-370.4 ⁽²⁾	-390.5 ⁽²⁾
		-372.9 ⁽¹⁾	-390.6 ⁽¹⁾
$\text{Sr}_2\text{SiO}_4(\text{c})$		-523.7 ⁽²⁾	-550.8 ⁽²⁾
		-523.7 to -532.4 ⁽¹⁾	-550.0 to -556.6 ⁽¹⁾
$\text{SrWO}_4(\text{c})$		-366. ⁽²⁾	-391.9 ⁽²⁾
		-366.2 ⁽¹⁾	-391.9 to -398.3 ⁽¹⁾
Ta (tantalum)			
$\text{Ta}(\text{c})$		0.00	0.00
TaO_2^+		-201.39 ⁽⁴⁾	
$\text{Ta}_2\text{O}_5(\text{c})$		-456.8 ^(2,4)	-489.0 ⁽²⁾
		-456.9 ⁽¹⁾	-489.1 ⁽¹⁾
Te (tellurium)			
$\text{Te}(\text{c})$		0.00	0.00
Te^{2-}		+42.6 ⁽¹⁾	+24.2 ⁽¹⁾
Te_2^{2-}		+38.9 ⁽¹⁾	
Te^{4+}		+52.38 ^(1,7)	
$\text{Te}_2(\text{g})$		+29.0 ⁽⁷⁾	+41.0 ⁽⁷⁾
		+28.1 ⁽¹⁾	+40.2 ⁽¹⁾
HTe^-		+37.7 ⁽⁷⁾	
$\text{H}_2\text{Te}(\text{g})$		+33.1 ⁽⁷⁾	+23.8 ⁽²⁾
H_2Te^0		+21.4 ⁽¹⁾	+18.6 ⁽¹⁾
	tellurite	+34.1 ^(4,7)	
TeO_2		-64.6 ^(2,4)	-77.1 ⁽²⁾
		-64.9 ⁽¹⁾	-77.0 ⁽¹⁾

<i>Compound or species</i>	<i>Mineral name</i>	G_f° , kcal/mol	H_f° , kcal/mol
$\text{UO}_2(\text{CO}_3)_3^{4-}$		-502.97 ⁽⁴⁾ -640.0 ⁽⁷⁾ -638.4 ⁽¹⁾ -635.57 ⁽⁴⁾	
$\text{UO}_2(\text{CO}_3)_2(\text{H}_2\text{O})_2^{2-}$		-622.0 ^(1,7)	
UO_2SO_4^0		-413.7 ⁽⁷⁾ -411.4 ⁽¹⁾	-467.3 ⁽⁷⁾ -456.6 ⁽¹⁾
UO_2	uraninite	-246.6 ^(1,2,4)	-259.3 ^(1,2)
$\text{UO}_3(\text{c})$		-273.0 ⁽¹⁾	
$\text{UO}_3(\alpha, \text{c})$			-291.4 ⁽¹⁾
$\text{UO}_3(\beta)$	orthorhomb.		
	orange-red	-273.0 ⁽¹⁾	-291.8 ⁽¹⁾
$\text{UO}_3(\gamma)$	orthorhomb.	-274.1 ⁽¹⁾	-292.6 ⁽¹⁾
$\text{UO}_3 \cdot \text{H}_2\text{O}(\alpha, \text{c})$			-365.2 ⁽¹⁾
$\text{UO}_3 \cdot \text{H}_2\text{O}(\beta, \text{c})$		-333.4 ⁽¹⁾	-366.6 ⁽¹⁾
$\text{UO}_3 \cdot \text{H}_2\text{O}(\epsilon, \text{c})$			-366.0 ⁽¹⁾
$\text{UO}_3 \cdot 2\text{H}_2\text{O}$		-389.8 ⁽¹⁾	-436.6 ⁽¹⁾
$\text{U}(\text{OH})^{3+}$		-193.5 ⁽⁷⁾ -182.7 to -193.5 ⁽¹⁾	-204.1 ⁽⁷⁾ -197.7 to -204.1 ⁽¹⁾
$\text{U}(\text{OH})_3(\text{c})$		-263.2 ^(1,7)	
$\text{U}(\text{OH})_4(\text{c})$		-351.6 ^(1,7)	
$\text{U}(\text{OH})_5^-$		-389.77 ⁽⁴⁾	
$\text{UO}_2(\text{OH})_2(\text{c})$		-322.6 to -334.7 ⁽¹⁾	-366.8 ⁽¹⁾
$\text{U}_3\text{O}_8(\text{c})$		-805.35 ⁽⁴⁾	
$\text{UO}_2(\text{OH})_2 \cdot \text{H}_2\text{O}$	schoepite	-390.6 ⁽¹⁾	-436.7 ⁽¹⁾
$\text{UCl}_3(\text{c})$		-191.0 to -197.0 ⁽¹⁾	-207.1 to -213.0 ⁽¹⁾
$\text{UCl}_4(\text{c})$		-222.1 ⁽¹⁾	-234.5 ⁽¹⁾
$\text{UF}_3(\text{c})$		-344.2 ⁽²⁾	-360.6 ⁽²⁾
UF_4	monoclinic	-437.4 ⁽²⁾ -435.8 to -438.3 ⁽¹⁾	-459.1 ⁽²⁾ -457.5 to -450.0 ⁽¹⁾
$\text{UF}_6(\text{c})$		-494.4 ⁽²⁾	-525.1 ⁽²⁾
$\text{UOF}_2(\text{c})$		-341.5 ⁽²⁾	-358.3 ⁽²⁾
$\text{UO}_2(\text{NO}_3)_2(\text{c})$		-264.1 ⁽²⁾	-322.5 ⁽²⁾
$\beta\text{-UO}_2\text{SO}_4(\text{c})$		-402.4 ⁽²⁾	-441.0 ⁽²⁾
UO_2CO_3	rutherfordine	-373.5 ^(2,4) -373.4 to -337.0 ⁽¹⁾	-404.2 ⁽²⁾ -404.2 to -405.4 ⁽¹⁾
USiO_4	coffinite	-452.0 ⁽¹⁾ -445.0 ⁽⁴⁾	-478.0 ⁽¹⁾
$\text{MgUO}_4(\text{c})$		-418.2 ⁽²⁾	-443.9 ⁽²⁾

TRANSURANIUM ELEMENTS

Np (neptunium)

Np(c)	0.00	0.00
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<i>Compound or species</i>	<i>Mineral name</i>	G_f° , kcal/mol	H_f° , kcal/mol
Np ³⁺		-123.59 ⁽⁴⁾	
Np ⁴⁺		-120.20 ⁽⁴⁾	
Np(OH) ₅ ⁻		-384.08 ⁽⁴⁾	
NpO ₂ (c)		-244.22 ⁽⁴⁾	
NpO ₂ ⁺		-218.69 ⁽⁴⁾	
NpO ₂ ²⁺		-190.20 ⁽⁴⁾	
NpO ₂ (OH)(amorph.)		-297.57 ⁽⁴⁾	
Np(CO ₃) ₂ (c)		-389.63 ⁽⁴⁾	
NpO ₂ (OH) ₂ CO ₃ ²⁻		-424.05 ⁽⁴⁾	
Np ₂ O ₃ (c)		-346.08 ⁽⁴⁾	
Np ₂ O ₅ (c)		-481.12 ⁽⁴⁾	
NpO ₂ (OH) ₂ (c)		-294.57 ⁽⁴⁾	
Pu (plutonium)			
Pu(c)		0.00	0.00
Pu ³⁺		-138.15 ⁽⁴⁾	
Pu ⁴⁺		-114.96 ⁽⁴⁾	
Pu ₂ S ₃ (c)		-233.99 ⁽⁴⁾	
PuO ₂ (c)		-238.53 ⁽⁴⁾	
Pu(OH) ₅ ⁻		-378.10 ⁽⁴⁾	
PuO ₂ ⁻		-203.10 ⁽⁴⁾	
PuO ₂ (OH) ₂ CO ₃ ²⁻		-413.99 ⁽⁴⁾	
Pu(OH) ₄ (c)		-340.82 ⁽⁴⁾	
Pu ₂ (CO ₃) ₃ (c)		-697.44 ⁽⁴⁾	
Am (americium)			
Am(c)		0.00	0.00
Am ³⁺		-143.19 ⁽⁴⁾	
Am ₂ (CO ₃) ₃ (c)		-716.11 ⁽⁴⁾	
Am(OH) ₃ (c)		-279.16 ⁽⁴⁾	
Am(OH) ₃ (amorph.)		-289.38 ⁽⁴⁾	
AmO ₂ (c)		-210.43 ⁽⁴⁾	
Am ⁴⁺		-89.20 ⁽⁴⁾	
Am ₂ O ₃ (c)		-385.97 ⁽⁴⁾	
Am(OH) ₅ ⁻		-356.58 ⁽⁴⁾	
Am(OH) ₂ ⁺		-189.65 ⁽⁴⁾	
<i>End of Transuranium Elements</i>			
V (vanadium) (see also N)			
V(c)		0.00	0.00
V ²⁺		-51.9 ⁽¹⁾	-54.3 ⁽¹⁾
V ³⁺		-57.8 ⁽¹⁾	-62.9 ⁽¹⁾
VO ²⁺		-106.7 ^(1,2,4)	-116.3 ⁽²⁾
			-116.6 ⁽¹⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
VO_2^+		-142.6 ⁽⁷⁾	-155.4 ⁽¹⁾
		-140.3 ^(1,4)	
VO_3^-		-137.28 ⁽⁴⁾	
$\text{V}_4\text{O}_9^{2-}$		-665.3 ⁽¹⁾	
$\text{V}_2\text{O}_7^{4-}$		-410.85 ⁽⁴⁾	
$\text{V}_{10}\text{O}_{28}^{6-}$		-1862.4 ⁽¹⁾	
$\text{HV}_{10}\text{O}_{28}^{5-}$		-1840.8 ⁽⁴⁾	
		-1840.8 to -1875.3 ⁽¹⁾	-2077.9 ⁽¹⁾
$\text{H}_2\text{V}_{10}\text{O}_{28}^{4-}$		-1845.84 ⁽⁴⁾	
		-1845.8 to -1875.2 ⁽¹⁾	
VO_4^{3-}		-214.87 ⁽⁴⁾	
HVO_4^{2-}		-233.0 ^(2,4)	-277.0 ⁽²⁾
H_2VO_4^-		-244.0 ^(2,4)	-280.6 ⁽²⁾
$\text{VO}(\text{c})$		-96.6 ^(1,2)	-103.2 ^(1,2)
$\text{V}_2\text{O}_2(\text{c})$		-189.0 ⁽¹⁾	
V_2O_3	karelianite	-272.3 ^(1,2,4)	-291.3 ^(1,2)
$\text{V}_2\text{O}_4(\text{c})$		-315.1 ^(1,2,4)	-341.1 ^(1,2)
$\text{V}_2\text{O}_5(\text{c})$		-339.3 ^(1,2,4)	-370.6 ^(1,2)
$\text{V}_3\text{O}_5(\text{c})$		-434. ⁽²⁾	-462. ⁽²⁾
$\text{V}(\text{OH})_3(\text{c})$		-218.0 ^(1,7)	
$\text{V}(\text{OH})^{2+}$		-112.8 ⁽⁷⁾	
		-110.5 to -112.8 ⁽¹⁾	
$\text{VO}(\text{OH})_2(\text{c})$		-213.6 ⁽⁷⁾	
		-212.8 ⁽¹⁾	
$\text{NH}_4\text{VO}_3(\text{c})$		-221.8 ⁽⁷⁾	
$\text{VCl}_2(\text{c})$		-97.0 ⁽¹⁾	-108.0 ⁽¹⁾
$\text{VCl}_3(\text{c})$		-122.2 ⁽¹⁾	-138.8 ⁽¹⁾
W (tungsten) (see also Ca, Fe, Mn, Pb)			
$\text{W}(\text{c})$		0.00	0.00
$\text{WO}_2(\text{c})$		-127.61 ^(1,2,4)	-140.94 ^(1,2)
$\text{WO}_3(\text{yellow, c})$		-182.67 ⁽²⁾	-201.45 ⁽²⁾
		-182.5 ⁽¹⁾	-200.8 ⁽¹⁾
$\text{WO}_3(\alpha, \text{c})$		-182.6 ^(1,4)	-201.5 ⁽¹⁾
$\text{W}_2\text{O}_5(\text{c})$		-360.9 ^(1,7)	-337.9 ^(1,7)
WO_4^{2-}		-220.00 ^(7,4)	-257.1 ⁽²⁾
		-222.6 ⁽¹⁾	-256.8 ⁽¹⁾
WS_2	tungstenite	-46.2 ⁽⁷⁾	-50. ⁽²⁾
		-71.20 ⁽⁴⁾	
		-46.2 to -71.2 ⁽¹⁾	-46.3 to -71.3 ⁽¹⁾
Y (yttrium)			
$\text{Y}(\text{c})$		0.00	0.00
Y^{3+}		-165.8 ^(2,4)	-172.9 ⁽²⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
$Y(OH)_3(c)$		-164.1 ⁽¹⁾	-167.8 ⁽¹⁾
		-307.1 ⁽⁷⁾	-339.5 ⁽⁷⁾
		-308.6 ⁽⁴⁾	
		-307.1 to -310.3 ⁽¹⁾	-339.5 to -342.0 ⁽¹⁾
$Y(OH)_4^-$		-341.2 ⁽⁴⁾	
$Y_2O_3(c)$		-434.19 ^(2,4)	-455.38 ⁽²⁾
		-434.2 ⁽¹⁾	-455.4 ⁽¹⁾
$Y_2O_3(cubic)$		-434.2 ⁽¹⁾	-455.4 ⁽¹⁾
$Y_2(SO_4)_3(c)$		-866.8 ⁽²⁾	
$Y_2(CO_3)_3(c)$		-752.4 ^(2,4)	
Zn (zinc)			
$Zn(c)$		0.00	0.00
Zn^{2+}		-35.14 ^(2,4)	-36.78 ⁽²⁾
		-35.2 ⁽¹⁾	-36.7 ⁽¹⁾
$ZnCO_3$	smithsonite	-174.85 ^(2,4)	-194.26 ⁽²⁾
		-174.9 ⁽¹⁾	-194.3 ⁽¹⁾
$ZnCl^+$		-67.14 ⁽⁵⁾	
		-65.8 ⁽¹⁾	
$ZnCl_2^0$		-97.88 ⁽²⁾	-116.68 ⁽²⁾
		-96.5 ⁽¹⁾	
$ZnCl_3^-$		-129.98 ⁽⁵⁾	
		-129.2 ⁽¹⁾	
$ZnCl_4^{2-}$		-160.94 ⁽⁵⁾	
		-159.2 ⁽¹⁾	
$ZnCl_2(c)$		-88.296 ⁽²⁾	-99.20 ⁽²⁾
		-88.3 ⁽¹⁾	-99.3 ⁽¹⁾
$ZnB_2(c)$		-74.5 ⁽¹⁾	-78.5 ⁽¹⁾
$ZnF_2(c)$		-170.5 ⁽²⁾	-182.7 ⁽²⁾
$ZnFe_2O_4$	franklinite	-256.54 ⁽⁵⁾	
$ZnMoO_4$	zinc molybdate	-241.15 ⁽⁵⁾	
$ZnNO_3^+$		-62.37 ⁽⁵⁾	
$Zn(NO_3)_2^0$		-88.36 ⁽²⁾	-135.90 ⁽²⁾
		-81.39 ⁽⁵⁾	
$Zn(OH)$		-78.90 ⁽⁴⁾	
		-79.2 ⁽¹⁾	
		-109.26 ⁽²⁾	
$HZnO_2^-$		-109.42 ⁽⁴⁾	
		-109.2 to -110.9 ⁽¹⁾	
ZnO_2^{2-}		-91.85 ^(2,4)	
		-91.8 to -93.0 ⁽¹⁾	
$Zn(OH)_2^0$		-110.33 ⁽²⁾	-146.72 ⁽²⁾
		-124.9 to -128.0 ⁽¹⁾	
$Zn(NH_3)_4^{2+}$		-72.2 to -73.5 ⁽¹⁾	-127.5 ⁽¹⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
$\text{Zn}(\text{OH})_3^-$		-167.49 ⁽⁵⁾	
$\text{Zn}(\text{OH})_4^{2-}$		-165.9 to -168.4 ⁽¹⁾	
		-205.23 ⁽²⁾	
		-205.2 to -208.2 ⁽¹⁾	
ZnO	zincite	-76.08 ^(2,4)	-83.24 ⁽²⁾
		-76.6 ⁽¹⁾	-83.7 ⁽¹⁾
$\text{Zn}(\text{OH})_2(\text{amorph.})$		-131.54 ⁽⁵⁾	-153.5 ⁽²⁾
		-131.7 ⁽¹⁾	
$\alpha\text{-Zn}(\text{OH})_2(\text{c})$		-131.93 ^(1,5,7)	
$\beta\text{-Zn}(\text{OH})_2(\text{c})$		-132.31 ⁽²⁾	-153.42 ^(1,2)
		-132.36 ⁽⁴⁾	
		-132.6 ⁽¹⁾	
$\gamma\text{-Zn}(\text{OH})_2(\text{c})$		-132.38 ⁽²⁾	
		-132.8 ⁽¹⁾	
$\varepsilon\text{-Zn}(\text{OH})_2(\text{c})$		-132.68 ⁽²⁾	-153.74 ^(1,2)
		-133.0 ⁽¹⁾	
$\text{Zn}_5(\text{OH})_6(\text{CO}_3)_2$	hydrozincite	-750.8 ⁽¹⁾	-828.3 ⁽¹⁾
ZnHPO_4^0		-301.72 ⁽⁵⁾	
$\text{ZnH}_2\text{PO}_4^+$		-309.22 ⁽⁵⁾	
$\text{Zn}_3(\text{PO}_4)_2 \cdot 4\text{H}_2\text{O}$	hopeite	-870.82 ⁽⁵⁾	
ZnSe	stilleite	-34.7 ⁽⁷⁾	-34.7 ⁽⁷⁾
		-39.6 ⁽¹⁾	-39.1 ⁽¹⁾
$\alpha\text{-ZnS}$	sphalerite	-48.11 ^(2,4)	-49.23 ⁽²⁾
		-48.3 ⁽¹⁾	-49.4 ⁽¹⁾
$\beta\text{-ZnS}$	wurtzite	-45.37 ⁽⁵⁾	-46.04 ⁽²⁾
		-44.2 to -46.2 ⁽¹⁾	-45.3 to -46.6 ⁽¹⁾
ZnSO_4	zinkosite	-209.0 ⁽²⁾	-234.9 ⁽²⁾
		-208.1 ⁽¹⁾	-234.5 ⁽¹⁾
ZnSO_4^0		-213.11 ⁽²⁾	-254.10 ⁽²⁾
$\text{ZnSO}_4 \cdot \text{H}_2\text{O}(\text{c})$		-270.58 ⁽²⁾	-311.78 ⁽²⁾
		-270.2 ⁽¹⁾	-311.2 ⁽¹⁾
$\text{ZnSO}_4 \cdot 6\text{H}_2\text{O}$	bianchite	-555.64 ⁽²⁾	-663.83 ⁽²⁾
		-555.1 ⁽¹⁾	-663.7 ⁽¹⁾
$\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$	goslarite	-612.59 ⁽²⁾	-735.6 ⁽²⁾
		-612.3 ⁽¹⁾	-735.4 ⁽¹⁾
$\text{ZnO} \cdot 2\text{ZnSO}_4(\text{c})$		-492.07 ⁽⁵⁾	
$\text{Zn}(\text{OH})_2 \cdot \text{ZnSO}_4(\text{c})$		-351.47 ⁽⁵⁾	
$\text{ZnSiO}_3(\text{c})$		-274.8 ⁽⁷⁾	-301.2 ⁽²⁾
		-287.1 ⁽¹⁾	-306.9 ⁽¹⁾
Zn_2SiO_4	willemite	-364.06 ^(1,2)	-391.19 ^(1,2)
ZnWO_4	sanmartinite	-268.6 ⁽¹⁾	-294.6 ⁽¹⁾
ZnAl_2O_4	gahnite		-493.6 ⁽¹⁾
$\text{ZnTiO}_4(\text{c})$		-366.7 ⁽¹⁾	-393.8 ⁽¹⁾

Compound or species	Mineral name	G_f° , kcal/mol	H_f° , kcal/mol
Zr (zirconium)			
Zr(c)		0.00	0.00
Zr ⁴⁺		-142.0 ⁽⁷⁾	
		-141.00 ⁽⁴⁾	
		-125.4 to -142.0 ⁽¹⁾	
ZrO ₂	baddeleyite	-249.24 ^(2,4)	-263.04 ⁽²⁾
		-248.6 ⁽¹⁾	-262.7 ⁽¹⁾
ZrO(OH) ₂ (c)		-311.5 ^(1,7)	-338.0 ^(1,7)
Zr(OH) ₄ (c)		-370.0 ^(1,4,7)	-411.2 ^(1,7)
ZrSiO ₄	zircon	-458.7 ⁽²⁾	-486.0 ⁽²⁾
		-456.7 to -458.7 ⁽¹⁾	-483.3 to -486.0 ⁽¹⁾
ZrO ²⁺		-201.5 ⁽¹⁾	
		-200.90 ⁽⁴⁾	
HZrO ₃ ⁻		-287.7 ^(1,4)	

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