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ASD-TDR-63-846

AD-613040

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SURVEY OF THE THERMOCHEMISTRY OF HIGH-ENERGY REACTIONS

TECHNICAL DOCUMENTARY REPORT NO. ASD-TDR-63-846
August 1963

AF Avionics Laboratory
Research and Technology Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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(Prepared under Contract No. AF 33(616)-7835
by the IIT Research Institute, Chicago, Ill.,
Elliott Raisen, Sidney Katz, and Karl D. Franson, authors)

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FOREWORD



This report, Technical Report No. IITRI-C191-33, describes the thermodynamic and computational phases of a research program entitled "Study of New Materials Related to the Development of Radiant and Thermal Sources." The report covers the period from April 15, 1962, to August 14, 1963. The investigation was conducted at the IIT Research Institute and its predecessor organization, Armour Research Foundation, Technology Center, Chicago 16, Illinois, under the sponsorship of the Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. Mr. Jason W. Sarnow of the AF Avionics Laboratory served as Project Engineer. The work was performed under Contract AF 33(616)-7835 (IITRI Project C191).

Dr. Sidney Katz, Scientific Advisor, was the Project Leader. Dr. Elliott Raisen served as Group Leader of Thermochemistry and as Task Supervisor. Administrative direction was provided by Dr. J. I. Bregman, Assistant Director of Chemistry Research. Other participants in the work include Paul Ase, Robert H. Boes, Karl Franson, Richard Snow, Betty Isakson, Pat Llewellen, Roberta Patzer, Loretta Lucek, Gertrud Matuschkovitz, and Martha Williams.

ABSTRACT

SURVEY OF THE THERMOCHEMISTRY OF HIGH-ENERGY REACTIONS

This report describes the thermodynamic and computational phases of a survey of exothermic chemical reactions. The purpose of the survey was to ascertain the utility of these chemical reactions as radiation sources for a variety of applications.

All currently available thermochemical data were surveyed. Computer programs were prepared and enthalpies were obtained for all inorganic reactions for which data were adequate. Tabulations included reactions of metals with oxides, fluorides, chlorides, sulfides, phosphides, azides, nitrides, silicides, carbides, nitrates, nitrites, chlorates, perchlorates, chromates, and borides. Data for a total of about 20,000 reactions were obtained. The data for the individual reactions included a balanced chemical equation, and enthalpies and heats of reaction per unit weight and volume. Supplementary tabulations included listings in order of energies of the most energetic reactions in each class, graphical presentations of the reactions of all the metals with various oxidizing agents plotted against enthalpies, similar plots for the reactions of all the oxidants in different classes with various metals, and a total recapitulation of all the reactions in each category in grid form in descending order of energy per unit weight and per unit volume. An extension of this survey to include the detection of the free energies of the reactions is proposed.

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SURVEY OF THE THERMOCHEMISTRY OF HIGH-ENERGY REACTIONS

I. INTRODUCTION

The use of pyrotechnic reactions for the production of radiant and thermal energy has generated an interest in high-energy reactions in this laboratory. As a result, we have been conducting theoretical and experimental studies of high-energy reactions for the past several years. The theoretical studies were concerned with systematic examination of the reactions of metals with different oxidizer systems in order to establish logical criteria for choosing reactions to be studied experimentally. The experimental phases were concerned with the chemical and radiative properties of the reactions and included manipulative studies to establish control over the burning properties of the reactions, calorimetric studies to compare experimental enthalpies with theoretical values, burning-rate studies as a function of the ambient atmosphere, differential thermal analysis and thermogravimetric studies to aid in the interpretation of the kinetics and mechanisms of the reactions, and studies of the spectroradiative properties in the visible and infrared regions of the spectrum.

The most important property of the reaction is its enthalpy, which determines the maximum amount of heat available after the reaction occurs. If the reaction is carried out adiabatically, this heat will raise the temperature of the products to a value which is determined by their specific heats. If the reaction is carried out isothermally, the thermal energy can be used for processes involving energy absorption. The reactions exhibiting high negative enthalpies were therefore of most interest.

Much of the present study was concerned with calculating reaction enthalpies and correlating them with the properties of the reactants and the products and with relationships in the periodic table. The periodic table and the rapidly increasing body of thermochemical data on heat capacities, entropies, and heats and free energies of formation provide a framework for examining and correlating the theoretical behavior of thermochemical reactions. For our practical purposes it was most useful to compare the energy content of the reactions on a volumetric basis, because most of our applications are volume-limited. Since weight limitations are important too, the gravimetric enthalpies were also determined.

Manuscript released by authors in August 1963 for publication as an ASD Technical Documentary Report.

II. SCOPE OF THE STUDY

A. Reactions Surveyed

In earlier work 2600 reactions of metals with binary oxides and 50 reactions of metals with fluorides were examined by using manual computations. On the present program 60,000 high-energy reactions were examined by using a Remington-Rand Univac 1105 computer. Of these, about 20,000 reactions were printed by the computer and 10,000 of them were stored on magnetic tape for further operations. The remaining reactions were discarded either because they had positive enthalpies or because other reactions between the same reactants were found with greater negative enthalpy. In chlorate reactions, for example, each set of reactants may undergo several different stoichiometric reactions to produce different combinations of oxides and chlorides of the constituent metals.

The scope of the theoretical survey is summarized in Table 1. Sixteen classes of oxidizer systems were examined. The data for oxides, fluorides, and chlorides were the most numerous, being represented by 145, 105, and 102 compounds each. The others ranged from 68 for the sulfides to 5 for the chromates. The possible reactions of all these oxidizers with as many as 68 metals were examined.

The data compiled for the oxides were also used in the calculations involving ternary oxidants such as the nitrates, nitrites, chlorates, and perchlorates, in which oxides occur as a product. All the oxide reactions were examined by use of the computer to produce a more complete set of such reactions than those calculated previously; over 20,000 reactions were examined in 6 hours. It is estimated that the same task would take about 1 hour by using an IBM 7090 computer and about 7 man-years by using manual methods.

In general, the perchlorates, chlorates, oxides, and nitrates are the most energetic classes of reactions, followed by the fluorides, nitrites, silicides, nitrides, sulfides, and carbides. The enthalpy of the most energetic reaction in each of these classes is listed in Table 2. The results of this survey were used as a guide in choosing reactions to be studied in the laboratory.

Table 1

SCOPE AND SUMMARY OF THEORETICAL SURVEY
OF THERMOCHEMICAL REACTIONS

<u>Oxidizer Class</u>	<u>Number of Oxidizers</u>	<u>Number of Reactions Examined</u>	<u>Number of Reactions Printed</u>	<u>Enthalpy of the Most Energetic Reactions, cal/cc</u>
Oxides	145*	20,994	9,636	-8279 to -4949
Fluorides	105	n.r.	105	-5586 to -3000
Chlorides	102	10,545	3,061	-3336 to -2593
Sulfides	68	n.r.	2,145	-3169 to -2553
Nitrides	44	n.r.	1,575	-2478 to -1766
Azides	13	n.r.		-3346 to -1795
Silicides	36	n.r.	302	-5153 to -480
Carbides	30	n.r.	386	-2532 to -1102
Nitrates	18	n.r.	1,226	-7798 to -3468
Nitrites	8	n.r.		-4670 to -3476
Phosphides	25	n.r.	500	-1254 to -18
Chlorates	7			-7853 to -6100
Perchlorates	9	16,384	800	-9459 to -6099
Borides	8	n.r.	14	-2994 to -110
Chromates	5	2,920	114	-3845 to -1915
Organic fluorides	Examined on a limited basis manually			

* The data for 71 oxides were used in the nitrate and nitrite computations.

n.r. Not recorded.

Table 2

THE MOST ENERGETIC REACTION IN TERMS
OF VOLUMETRIC ENTHALPY IN EACH CLASS OF OXIDIZERS

Class	Reaction	Enthalpy, cal/cc
Perchlorates	$8\text{Be} + \text{MgClO}_4 = \text{MgCl}_2 + 8\text{BeO}$	-9459
Chlorates	$13\text{Be} + 4 \text{AgClO}_3 = 2\text{Ag}_2\text{Cl} + 12\text{BeO} + \text{BeCl}_2$	-8103
Oxides	$2\text{Be} + \text{RuO}_2 = \text{Ru} + 2\text{BeO}$	-8279
Nitrates	$5\text{Be} + 2\text{LiNO}_3 = \text{LiO} + 5\text{BeO} + \text{N}_2$	-7798
Fluorides	$3\text{Be} + \text{ReF}_6 = \text{Re} + 3\text{BeF}_2$	-5586
Nitrites	$3\text{Be} + 2\text{NaNO}_2 = \text{Na}_2\text{O} + 3\text{BeO} + \text{N}_2$	-4670
Silicides	$3\text{CoSi}_2 + 2\text{Ba} = 3\text{Co} + 2\text{BaSi}_3$	-5153
Chromates	$4\text{Be} + 2\text{PbCrO}_4 = \text{Pb}_2\text{O} + 4\text{BeO} + \text{Cr}_2\text{O}_3$	-3845
Azides	$9\text{Be} + \text{BaN}_6^* = \text{Ba} + 3\text{BeN}_2$	-3346
Nitrides	$2\text{U} + 3\text{Fe}_2\text{N} = 6\text{Fe} + \text{U}_2\text{N}_3$	-2478
Chlorides	$5\text{Ce} + \text{ReCl}_5 = 3\text{Re} + 5\text{CeCl}_3$	-3336
Sulfides	$8\text{Th} + 7\text{FeS}_2 = 7\text{Fe} + 2\text{Th}_4\text{S}_7$	-3169
Carbides	$2\text{Ta} + \text{Li}_2\text{C}_2 = 2\text{Li} + 2\text{TaC}$	-2533

* N_6 represents $(\text{N}_3)_2$

B. Computer Input and Output

All the data used for the computer input were obtained from the sources shown in Table 3 in the order of preference indicated. The National Bureau of Standards Circular 500¹ was used as the primary source whenever possible. In all cases, the heat of formation at 298°K was used.

Table 3

SOURCES OF DATA FOR THERMOCHEMICAL REACTIONS

<u>Property</u>	<u>Source, in Order of Preference</u>
Heat of formation at 298°K (ΔH_{298})	Reference 1, 2, 4, 5
Molecular weight	Reference 5
Density	Reference 5
Melting point	Reference 1, 3, 5
Boiling point	Reference 1, 3, 5

¹Rossini, F. D., Wagman, D. D., Evans, W. H., and Levine, S. Selected Values of Thermodynamic Tables, National Bureau of Standards Circular 500, 1952.

²Glassner, A. The Thermochemical Properties of Oxides, Fluorides and Chlorides to 2500°K, Argonne National Laboratories, No. 5750, 1957.

³Hodgman, C. D., ed., Handbook of Chemistry and Physics, Chemical Rubber Publishing Co., Cleveland, 1954-55.

⁴Quill, L. L., ed., The Chemistry and Metallurgy of Miscellaneous Materials, Thermodynamics, McGraw-Hill Book Co., 1950.

⁵Hodgman, C. D., ed., Handbook of Chemistry and Physics, Chemical Rubber Publishing Co., Cleveland, 1960-61.

The input data consisted of the reactants and products, their heats of formation, and various of their physical properties: molecular weight, melting point, boiling point, and density. Computer programs were designed which combined all the reducing agents (metals) and oxidizers (oxides, chlorides, perchlorates, etc.) into balanced equations and calculated the enthalpy of the stoichiometric reaction. Reactions with positive enthalpies were discarded. Those with negative enthalpies were subjected to further computations to determine the gravimetric and volumetric enthalpies* based on the reactants weight and volume. Then each reaction was printed together with the data for each component. This output was stored on magnetic tape for the further processing discussed later.

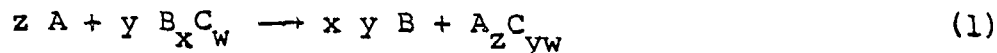
Much of the input data was printed, so that all the properties for each reaction were conveniently assembled in one place. Melting points and boiling points aid in determining practical uses for the reactions. Physical states of the reactants aid in determining the feasibility of formulating and storing the materials. Melting points and boiling points of the products indicate potentially useful properties of the reactions. For example, if the products undergo a phase transition at the temperature of maximum radiative energy, the reaction products will tend to liberate more of their energy at this temperature and thus increase the efficiency. Also, if gaseous products are desired for radiative or other purposes, reactions that have relatively low-boiling products can be selected. Conversely, if solid products are desired, reactions that have high-melting products can be selected. Assembling the input and calculated data in one place thus increases the versatility of the compilations.

The output consisted of the following input and derived data: a balanced equation, the reaction components, heats of formation at 298°K, the averaged densities of the components, the melting points of the components, the boiling points of the components, heat of the reaction on a molar basis, the reactants' averaged density, the heat of the reaction per unit weight of the reactants (the gravimetric enthalpy), the heat of the reaction per unit volume of reactants (the volumetric enthalpy), and the atomic numbers of the components. Output values were omitted when the data were too limited to allow the required calculation. For example, if the reactant density was unknown, the position for volumetric enthalpy was blank.

* In this work the "volumetric enthalpy" is used to designate the heat of the reaction based on a stoichiometric mixture of reactants occupying a theoretical volume of 1 cc. Similarly, the gravimetric enthalpy is the corresponding heat of reaction based on a gram of reactants.

C. Theory

A generalized equation for the reactions of a metal with a binary compound is:



where A and B are electropositive elements (metals); C is an electronegative element (O, F, Cl, S, C, B, N, H, etc.); and z, y, x, and w are the constants for the stoichiometric reaction after the coefficient of the last term is adjusted to unity. The metal A reduces the compound $B_x C_w$ to form the metal B and the compound of metal A. In order to calculate the energy per unit volume of reactants, the following equation is derived:

$$\Delta H_{cc} = - \frac{\Delta H_{A_z C_{yw}} - y \Delta H_{B_x C_w}}{z V_A + y V_{B_x C_w}} = \frac{\Delta H_{AO_x} - y \Delta H_{BO_x}}{z V_A + y V_{BO_x}} \quad (2)$$

where ΔH_{cc} is the heat of reaction per unit volume of reactants; V is the gram-atomic and gram-molecular volume of the respective reactants, i.e., the atomic or molecular weight divided by the density; and

$$\Delta H_{AO_x} \text{ and } \Delta H_{BO_x}$$

are the molar heats of formation of the products and the reactants, respectively.

To obtain a large energy per unit volume of reactants, it is evident that the heat of formation of the products

$$\Delta H_{A_z C_{yw}}$$

should be large, the heat of formation of reactants

$$\Delta H_{B_x C_w}$$

and the gram-atomic and the gram-molecular volumes of the reactants

$$V_A \text{ and } V_{B_x C_w}$$

should be small, and the coefficients y and z should also be small. According to the usual convention, a negative ΔH is considered as energy output. Thus, in this analysis a "large"

$$\Delta H_{A_z C_{yw}}$$

in reality signifies a large negative number and a "small"

$$\Delta H_{B_x C_w}$$

signifies a small negative number or even a positive number; hence a large negative value for $\Delta H/cc$ is desired.

The use of Equation 2 can be demonstrated by examples from the oxide systems. In general, the oxide of the reducing agent should have a heat of formation

$$\Delta H_{A_z C_{yw}}$$

exceeding -250 kcal and the reducing agent itself a gram-atomic volume less than 15 cc, while the oxidizing agent should have a heat of formation

$$\Delta H_{B_x C_w}$$

less than 100 kcal and a gram-molecular volume less than 35 cc. If the components of a reaction satisfy these four conditions, the reaction will be highly energetic, except when the combination of valences produces large values of y and z which nullify the other factors. The y term is especially significant because of its influence on the numerator. The value of y is not a constant for an oxide but is rather a function of the valence of element A in the reaction, and it can only be found by balancing the reaction and adjusting the coefficient of the $A_z C_{yw}$ term to unity. Various exceptions occur when one of the four factors is outside the specified range, but the extreme value of one or more of the other factors compensates.

The reducing agents Be, Mg, La, and Nd and the oxidizing agents WO_3 , Fe_2O_3 , OsO_4 , and Tl_2O_3 are examples of the various possibilities. For example, the low gram-atomic volumes of Be and Mg (4.96 and 14.0 cc, respectively) compensate for the rather low heats of formation of their oxides (-146.0 and -148.9 kcal, respectively), while the large heats of formation of the oxides of La and Nd (-433 and -436 kcal, respectively) compensate for the high gram-atomic volumes of the metals (50 and 46 cc, respectively). Similarly, the low gram-molecular volumes of WO_3 and Fe_2O_3 compensate for their rather high heats of formation. On the other hand, the low heats of formation of OsO_4 and Tl_2O_3 (-93.6 and -84 kcal, respectively) compensate for their relatively large gram-molecular volumes (51.8 and 44.8 cc, respectively).

D. Presentation of Data

Initially the computer was programmed to take each metal-oxidizer compound in alphabetical order and to treat it as the product of the reaction. When the oxidized metal exists in several valence states, each state was treated as a separate compound. All the other compounds were taken successively in alphabetical order and treated as reactants. A balanced equation was computed by using the appropriate metal from each of the compounds in the reaction. The enthalpy of the reaction was then computed by taking into account the coefficients in the balanced equation. If the enthalpy was negative, the gravimetric and volumetric* enthalpies were calculated and all the data for each reaction were printed. If the enthalpy was positive, the reaction was ignored** and the program went on alphabetically to the next compound. This was done for each metal. Later the order of choosing reactions was based on the reactant oxidizer.

Thus all the reactions of one metal with a series of reactants which yield the same product were printed. When the product exists in a higher valence form, the same process was repeated for the higher valence form. Then the next product was treated in alphabetical order. This type of output, represented by 1 in Table 4, was printed and also stored on magnetic tape. In order to make the data more readily available, the magnetic tape was processed many times with different programs to produce the other types of outputs shown in Table 4. These outputs all contain essentially the same data but arranged in different formats. All the outputs were obtained on volumetric and gravimetric bases.

It would be impractical to reproduce the prodigious amount of material available from the computer. The results are summarized and discussed in this report, and representative data sheets for each type of oxidizer system are included for illustrative purposes.

*The volumetric enthalpies were calculated from the density of condensed phases only.

**Reactions with positive enthalpies are not of interest here. If they were included, twice as many reactions would result.

Table 4

TYPES OF COMPUTER OUTPUTS

<u>Oxidizer Classes</u>	<u>Type</u>	<u>Description</u>	<u>Purpose</u>
<u>Programmed</u> Oxides Fluorides Chlorides Sulfides Nitrides Azides Silicides Carbides Nitrates Nitrites Phosphides Chlorates Perchlorates Borides Chromates	1	Compilation of balanced equations together with input and output data for each constituent.	Summarize all the data for each reaction in one place.
Oxides Fluorides Chlorides Chlorates Perchlorates Chromates	2	A list of all the reactions for each system in order of decreasing negative values of gravimetric enthalpy.	Rapid determination of the most energetic reactions of each oxidizer class on a gravimetric basis. This indicates the maximum energy for a unit weight of reactants.
Oxides Fluorides Chlorides Sulfides Nitrides Azides Silicides Carbides Nitrates Nitrites Phosphides Chlorates Perchlorates Borides Chromates	3	A list of all the reactions for each system in order of decreasing negative values of volumetric enthalpy.	Rapid determination of the most energetic reactions of each oxidizer class on a volumetric basis. This indicates the maximum energy for a unit volume of reactants.

Table 4 (cont.)

Oxidizer Classes Programmed	Type	Description	Purpose
Oxides Chlorides Chlorates Perchlorates Chromates	4	A list of all the data used for the graphs. Graphs of the gravimetric enthalpy of one metal versus the oxidizers for each metal.	Helpful in finding the best oxidizer with a particular metal or for examining the periodic behavior of a metal with the different oxidizers, based on a unit weight of reactants.
Oxides Nitrates Chlorides Chlorates Perchlorates Chromates	5	A list of all the data used for the graphs. Graphs of the volumetric enthalpy of one metal versus the oxidizers for each metal.	Helpful in finding the best oxidizer with a particular metal or for examining the periodic behavior of a metal with each oxidizer, based on a unit volume of reactants.
Oxides Chlorides Chlorates Perchlorates Chromates	6	A list of all the data used for the graphs. Graphs of the gravimetric enthalpy of one oxidizer versus the metals for each oxidizer.	Helpful in finding the best metal for a particular oxidizer, or for examining the periodic behavior of an oxidizer with the different metals, based on a unit weight of reactants.
Oxides Chlorides Chlorates Perchlorates Chromates	7	A list of all the data used for the graphs. Graphs of the volumetric enthalpy of one oxidizer versus the metals for each oxidizer.	Helpful in finding the best metal for a particular oxidizer, or for examining the periodic behavior of an oxidizer with the different metals, based on a unit volume of reactants.
Oxides Chlorides Chlorates Perchlorates Chromates	8	A chart of the gravimetric enthalpies of all the reactions for each system listed in general descending order from left to right, and from top to bottom.	The most concise summary of the enthalpies of all the reactions of each class. This table indicates the most energetic metals and oxidizers at a glance, based on a unit weight of reactants.
Oxides Chlorides Chlorates Perchlorates Chromates	9	A chart of the volumetric enthalpies of all the reactions for each system listed in general descending order from left to right, and from top to bottom.	The most concise summary of the enthalpies of all the reactions of each class. This table indicates the most energetic metals and oxidizers at a glance, based on a unit volume of reactants.

III. DISCUSSION OF THERMOCHEMICAL DATA

A. Fluoride Reactions

The molecular, gravimetric, and volumetric enthalpies of about 5000 reactions resulting from the combination of 50 metals with 105 fluorides were calculated and compiled on the computer. The reactions of beryllium with cobalt trifluoride, ferric fluoride, and stannic fluoride are particularly energetic; beryllium fluoride is formed in these reactions.

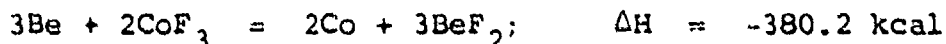
Table 5 is a list of fluoride reactions with negative enthalpies in excess of -3000 cal. The reactions are all of the form:



where BF and AF are the reactant and product fluorides, respectively, and A and B are the corresponding metals. Each reaction is identified by the reactant and product fluoride and their molecular coefficient; the metal reactants and products are omitted from the tabulation.

As a group, the fluorides are a highly energetic series of reactions. Experimental study of many of these reactions should prove interesting, especially those with very high enthalpies and those with products that have low melting or low boiling points. The reactions with the following products merit further study: mercury, cobalt, tin, iron, silver, bismuth, antimony, manganese, nickel, gallium, cadmium, chromium, beryllium fluoride, germanium fluoride, neodymium fluoride, praseodymium fluoride, and lithium fluoride.

Figure 1 illustrates the periodic behavior of the enthalpies of the fluoride reactions. The metals are plotted by atomic number along the abscissa, and the volumetric enthalpies of their reactions with cobalt trifluoride are shown on the ordinate. Cobalt fluoride was chosen as the reactant because most of its reactions are highly energetic. A representative reaction is:



Here, ΔH is the molar enthalpy. The enthalpy in Table 5 is the heat of the reaction on a volumetric basis in terms of calories per cubic centimeter of reacting material, in this case -5111 cal/cc.

All the available data are plotted in Figure 1, and the various points are connected by solid, dotted, or dashed lines to indicate their relationships within the periodic table. The solid lines connect metals with adjacent atomic numbers, the dotted lines connect members of the same group, and the dashed

lines connect the members of a B group (transition metals). The three subfigures 1A, B, and C emphasize each of these relationships.

Figure 1A, in which the adjacent atomic numbers are connected, illustrates the overall periodic behavior of the enthalpies. In general, the Group II elements (beryllium, magnesium, calcium, strontium, and barium) establish the peaks in the energy outputs (i.e., the largest negative enthalpies) and the Group I elements (lithium, sodium, potassium, rubidium, and cesium) establish the minima. The curve is irregular in the neighborhood of strontium and barium because the Group IIIB metals (yttrium, lanthanum, and the rare earths) and the Group IVB metals (titanium, zirconium, and hafnium) have unusually small atomic volumes and their fluorides have relatively high heats of formation.

The elements establishing the peaks in the energy curve are characterized by one or more of the following:

The electronic configuration of their valence orbitals. Their outermost orbital has two electrons, and the next-to-outermost orbital has either one or two electrons.

Their electronic configuration in the fluorides. They all have the rare gas configuration, s^2 or s^2p^6 .

The high heat of formation of the fluoride relative to the fluoride of their nearest neighbors.

Their low gram-atomic volumes.

Groups IIIB and IVB tend to react more energetically than Group II. The fluoride curve is similar to the analogous oxide and nitrate curves, with a few exceptions. Aluminum, for instance, is less energetic than magnesium in the fluoride system and more energetic in the oxygen system, because of the unusually high heat of formation of the oxide.

The relationship of the elements within Groups IA, IIA, IIIA, and IVA is shown in Figure 1B. Except for boron in Group IIIA, the energies of the reactions of cobalt trifluoride within the elements of a group diminish with increasing atomic number. A group relationship is also apparent. In decreasing order of energy, they follow the sequence Group IIA, IIIA, IVA, and IA.

Figure 1C shows the relationship of the elements within the transition metal groups. Groups IIB (zinc and cadmium), VB (vanadium, niobium, and tantalum), and VIB (chromium, molybdenum and tungsten) are similar to Groups IA, IIA, IIIA, and IVA in that the energy tends to decrease with increasing

Table 5

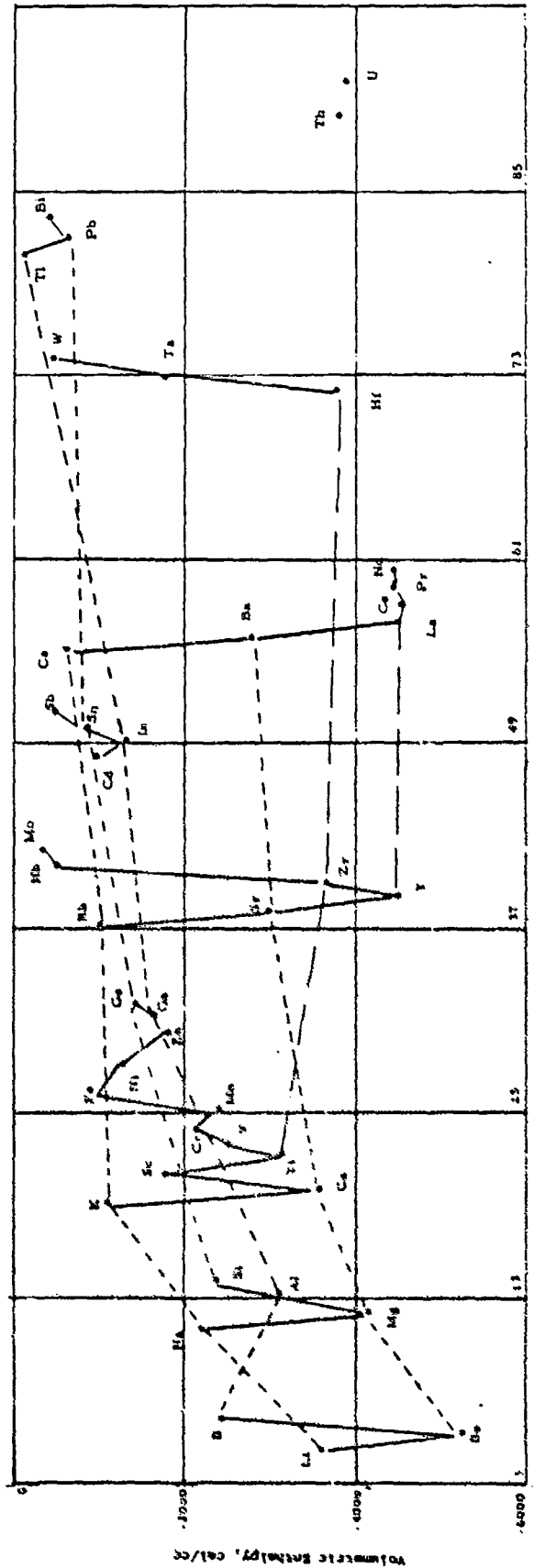
FLUORIDE REACTIONS* WITH HIGHEST NEGATIVE ENTHALPIES

Enthalpy, cal/cc	Reactant	Product	Metal		Fluoride	
			m.p., °C	b.p., °C	m.p., °C	b.p., °C
-5586	ReF ₆	3 BeF ₂	3147		800	
-5206	CF ₄	2 BeF ₂	4400			
-5112	2 CoF ₃	3 BeF ₂	1493	3100		
-5015	ReF ₆	3 YF ₃				
-4960	HgF ₂	BeF ₂	-39	357		
-4926	ReF ₆	2 CeF ₃			1460	
-4870	ReF ₆	2 LaF ₃				
-4830	SnF ₄	2 BeF ₂	232	2337		
-4820	ReF ₆	2 NdF ₃			1410	
-4809	ReF ₆	2 PrF ₃			1370	
-4765	NbF ₅	5 BeF ₂				
-4683	3 CF ₄	4 YF ₃				
-4648	FeF ₂	BeF ₂	1535	2800		
-4603	AgF ₂	BeF ₂	961	2193		
-4563	CoF ₃	YF ₃				
-4534	3 HgF ₂	2 YF ₃				
-4527	3 CF ₄	4 LaF ₃				
-4460	CoF ₃	LaF ₃				
-4450	3 HgF ₂	2 LaF ₃				
-4342	3 SnF ₄	4 YF ₃				
-4272	3 NbF ₃	5 YF ₃	2478	3700		
-4268	3 AgF ₂	2 YF ₃				
-4267	3 SnF ₄	4 LaF ₃				
-4216	3 AgF ₂	2 LaF ₂				
-4213	3 FeF ₂	2 YF ₃				
-4202	3 NbF ₅	5 LaF ₃				
-4156	3 FeF ₂	2 LaF ₃				
-3889	BiF ₃	YF ₃	271	1420		
-3869	BiF ₃	LaF ₃				
-3821	2 SbF ₅	5 BeF ₂	630	1440		
-3707	2 TaF ₅	5 BeF ₂				

Table 5 (cont.)

Enthalpy, cal/cc	Reactant	Product	Metal		Fluoride	
			m.p., °C	b.p., °C	m.p., °C	b.p., °C
-3704	2 VF ₅	5 BeF ₂	1730	3000		
-3611	AgF ₂	2 LiF			845	1681
-3601	3 SbF ₅	5 LaF ₃				
-3601	MoF ₆	3 BeF ₂	2610	4800		
-3589	3 SbF ₅	5 BeF ₂				
-3573	2 MnF ₃	3 BeF ₂	1244	2087		
-3568	NiF ₂	BeF ₂	1455	2800		
-3564	3 TaF ₅	5 LaF ₃				
-3544	3 TaF ₅	5 BeF ₂				
-3502	3 VF ₅	5 LaF ₃				
-3478	3 VF ₅	5 YF ₃				
-3427	MoF ₆	2 LaF ₃				
-3424	2 GaF ₃	3 BeF ₃	30	937		
-3394	MoF ₆	2 BeF ₂				
-3392	VF ₄	2 BeF ₂				
-3376	MnF ₃	LaF ₃				
-3323	3 NiF ₂	2 YF ₃				
-3329	MnF ₃	YF ₃				
-3322	2 SbF ₃	3 BeF ₂				
-3320	2 FeF ₃	3 BeF ₂				
-3259	GaF ₃	LaF ₃				
-3214	SbF ₃	LaF ₃				
-3202	FeF ₃	LaF ₃				
-3192	GaF ₃	YF ₃				
-3183	3 VF ₄	4 BeF ₂				
-3157	SbF ₃	YF ₃				
-3144	3 AgF	LaF ₃				
-3143	CdF ₂	BeF ₂	321	767		
-3109	3 CrF ₃	3 BeF ₂	1900	2480		
-3098	3 AgF	YF ₃				
-3070	3 CdF ₂	2 LaF ₃				
-3038	3 CrF ₃	LaF ₃				

* The first reaction, for example, is: $3 \text{ Be} + \text{ReF}_6 = \text{Re} + 3 \text{ BeF}_2$.



Atomic Number of Metal Reactants

Figure 1

VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS WITH CoF_3

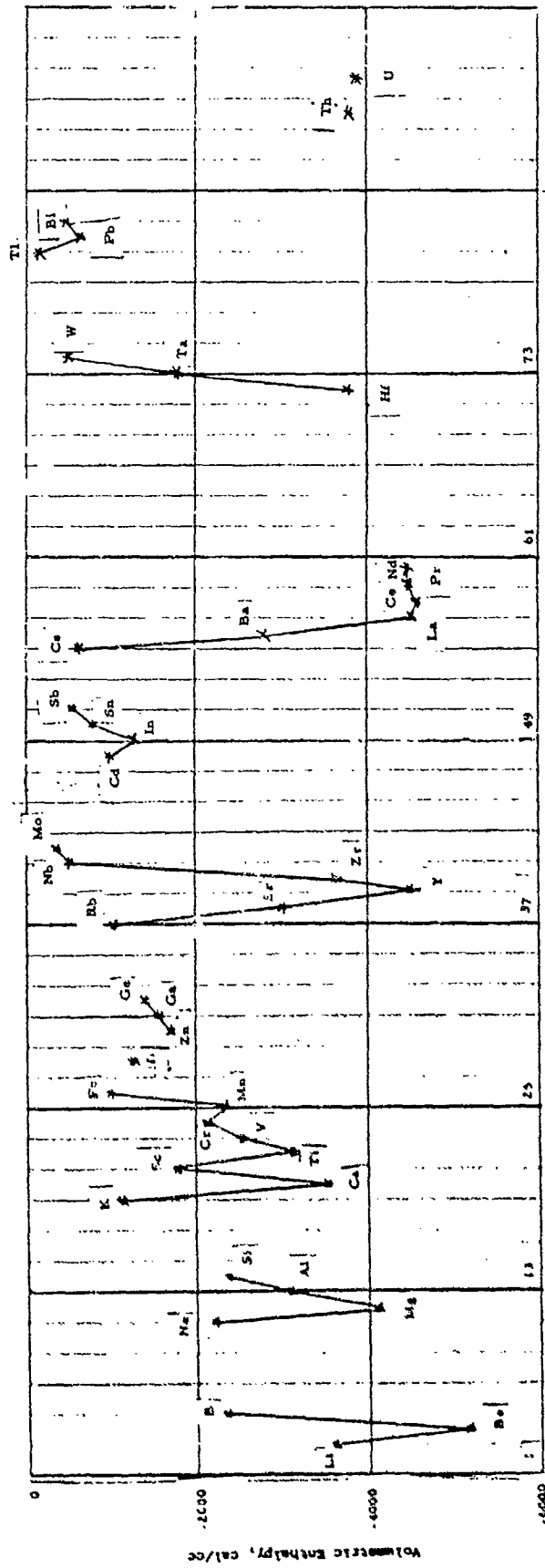
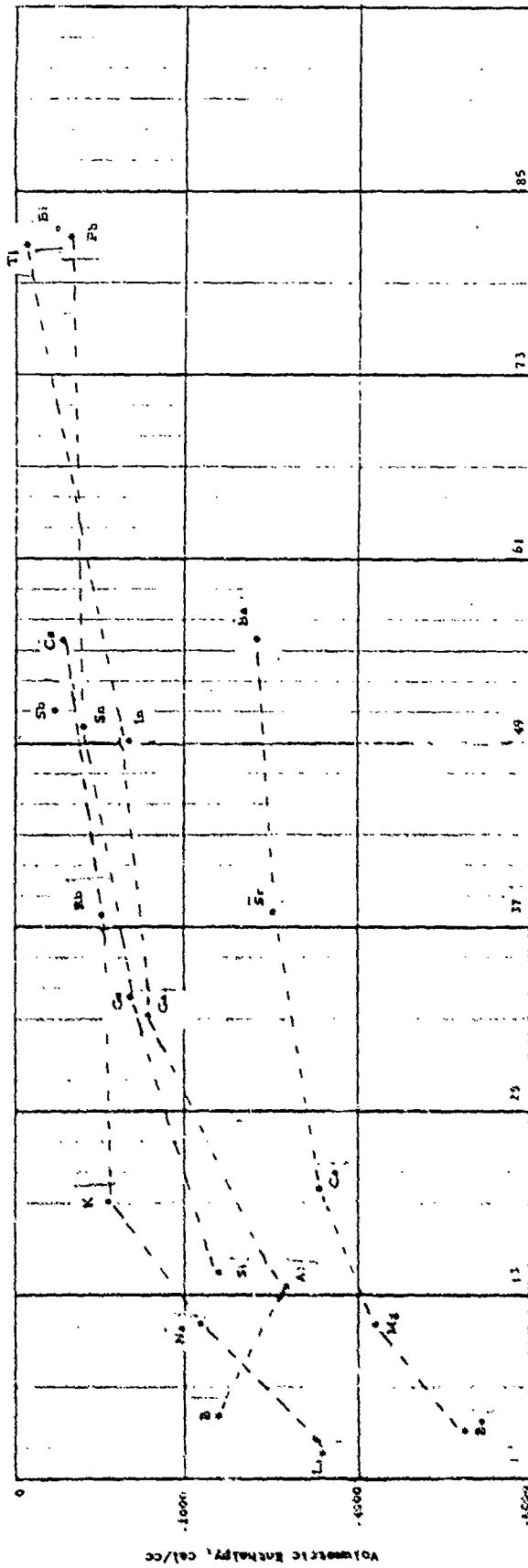
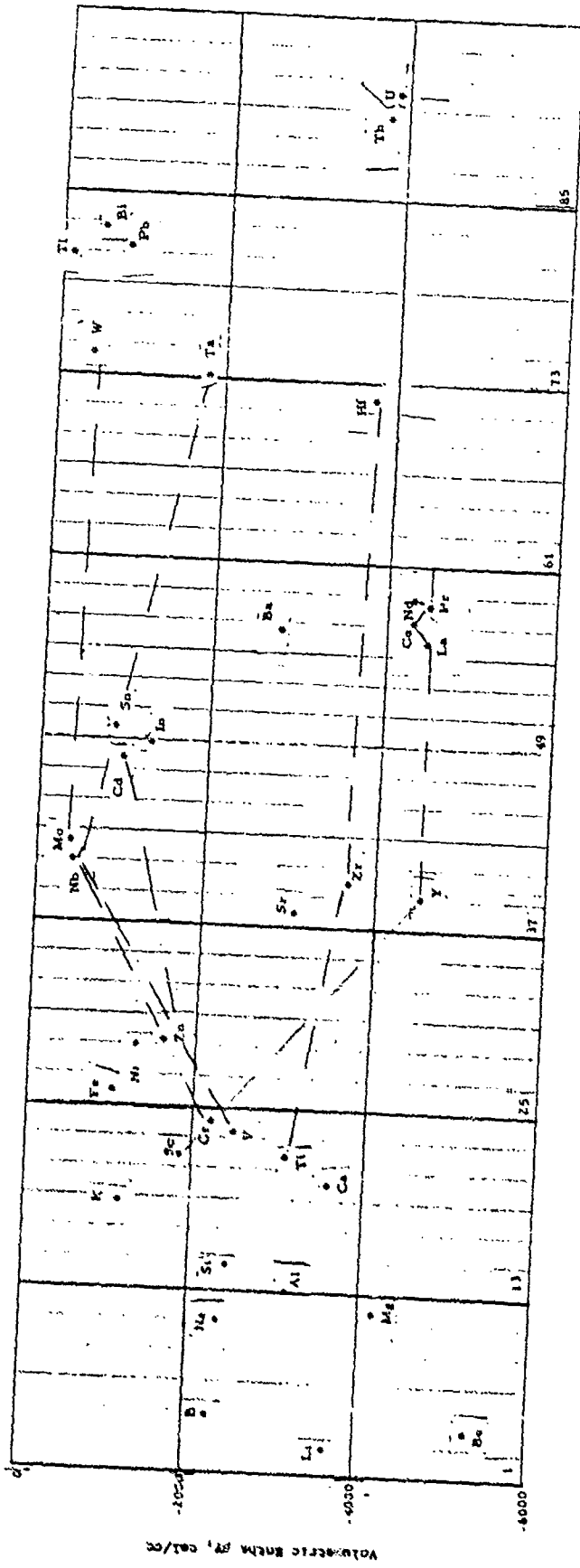


Figure 1A
 VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS WITH CoF_3



Atomic Number of Metal Reactants

Figure 1a
VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS WITH CoF_3



Atomic Number of Metal Reactants

Figure 1C1

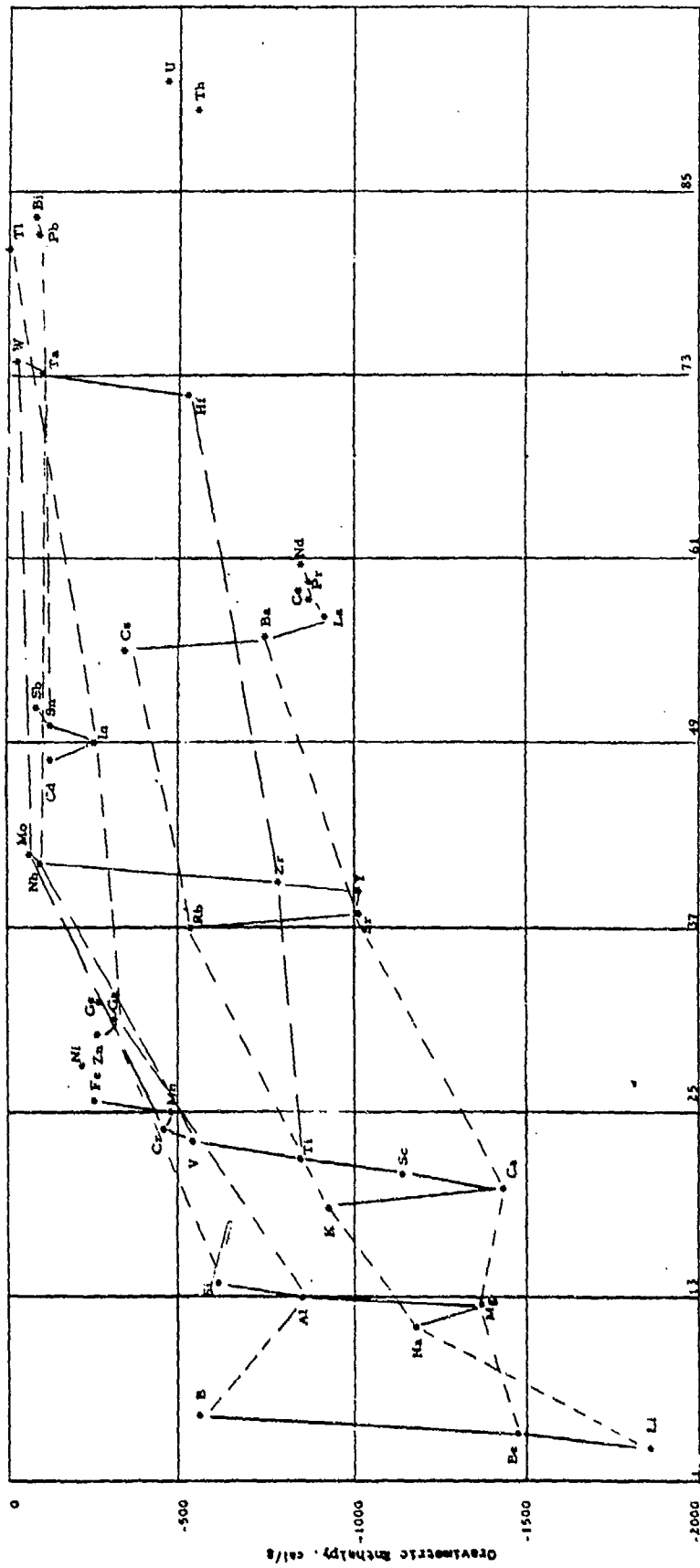
VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS WITH CoF_3

atomic number. Groups IIIB (scandium, yttrium, and lanthanum, and the rare earth elements) and IVB (titanium, zirconium, and hafnium) exhibit the opposite behavior and increase in energy with increasing atomic number. This behavior is due primarily to the small increase, or even decrease, in the atomic volume of the elements in these groups with increasing atomic number, caused by the lanthanide contraction. Groups IIIB and IVB are the most energetic, and Groups IIB, VB, and VIB are the least energetic.

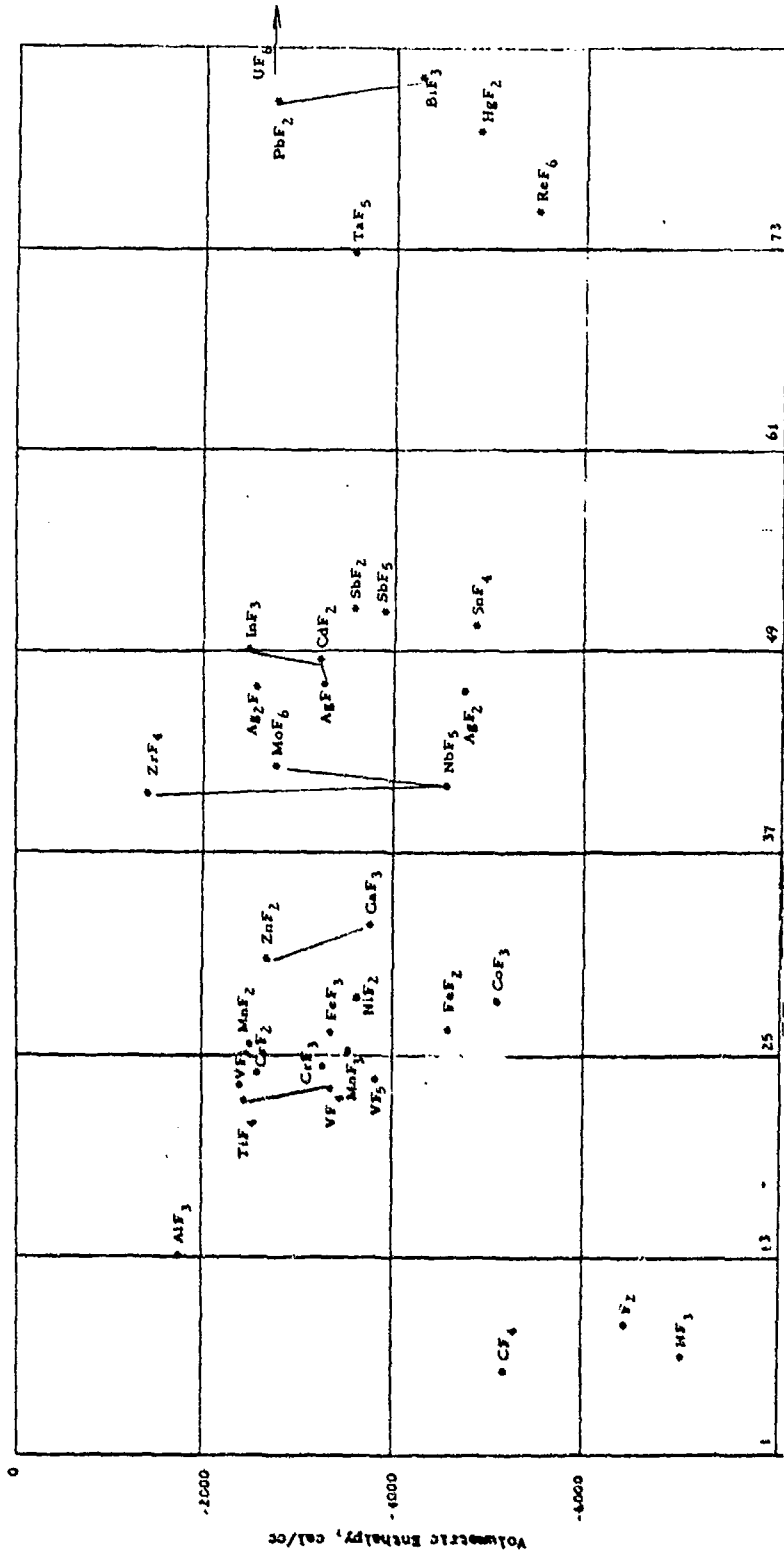
Similar relationships for the gravimetric enthalpies (heat output per gram of reactants) are illustrated in Figure 2. A few differences are observed because densities of the reactants vary. Since the volume is not considered, the effect of the lanthanide contraction is not evident, and Groups IIIB and IVB exhibit a normal behavior, with their energy decreasing with increasing atomic number. On the gravimetric basis, lithium is more energetic than beryllium, scandium more energetic than titanium, and Group I more energetic than Group III. The gravimetric enthalpies are lower than the volumetric ones because the densities of the reactants are more than unity in all cases.

Although the volumetric enthalpies were considered more significant for the present studies, because the establishment of a maximum energy in a fixed volume is usually desired, the gravimetric enthalpies were also considered in choosing the reactions to be studied experimentally. Less information is available on volumetric enthalpies because the densities of the reactants are often not known.

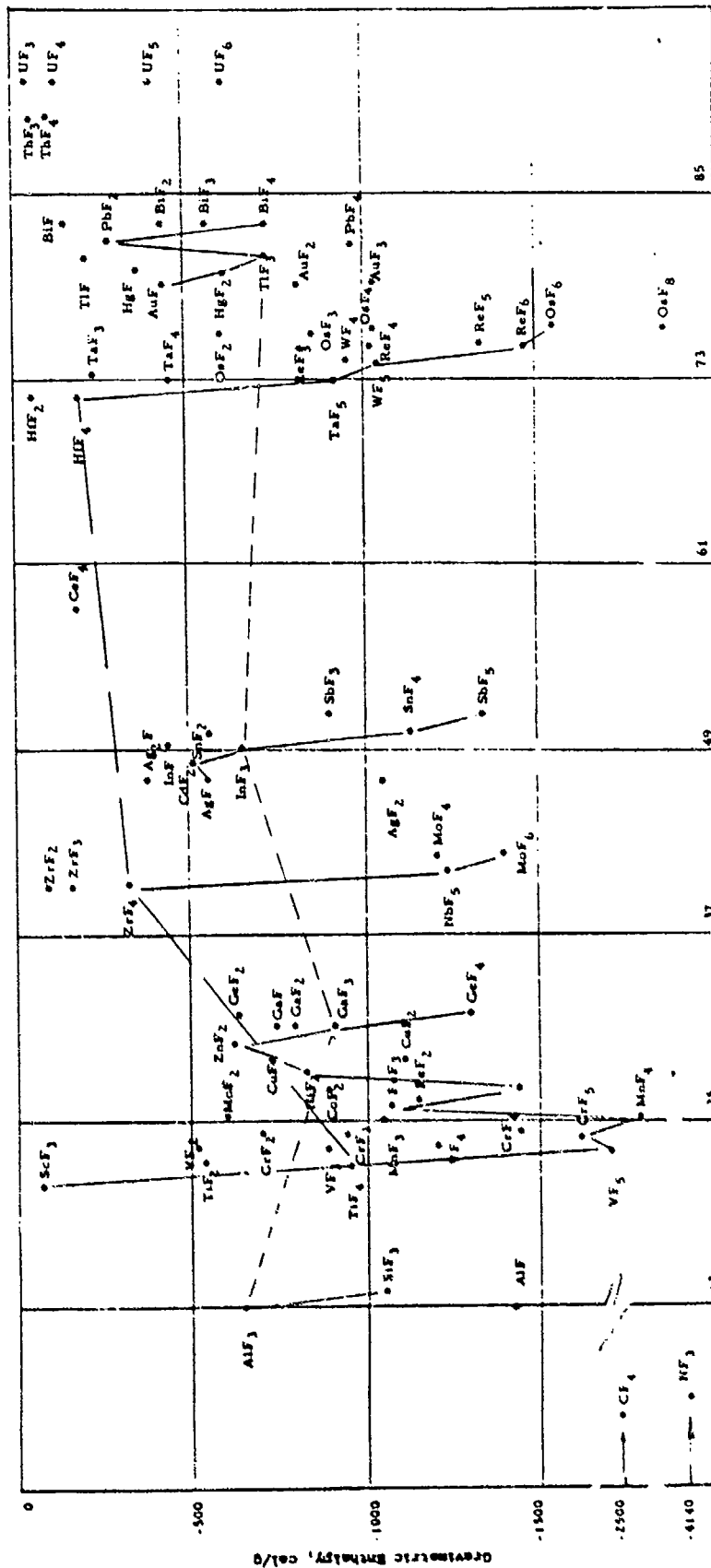
Figures 1 and 2 emphasized the effect of the metal on the enthalpy of the reactions. Figures 3 and 4 emphasize the effect of the fluoride. The volumetric and gravimetric enthalpies of the reactions of the fluorides with beryllium are plotted in Figures 3 and 4 on the ordinate, with the atomic number of the metal in the fluoride shown on the abscissa. A periodic behavior is apparent but is difficult to specify because fluorides of each metal can exist in different valence states. In general, within a group the energy decreases with increasing atomic number; since the metals are in the oxidized form, the order of the groups is reversed. Thus Groups IIIB and IVB are the least energetic when the metal fluoride, rather than the metal, is used as the reactant. Groups V, VI, VII, and VIII, represented by vanadium, chromium, manganese, iron, cobalt, molybdenum, tungsten, rhenium, and osmium fluorides, are the most energetic. When a metal forms more than one fluoride, the one with the greatest number of fluorine atoms is usually the most energetic. The iron fluorides are exceptions, FeF_2 being more energetic than FeF_3 . The trends illustrated in the figures are similar for the other fluorides and metals, except for displacement of the vertical scale.



Atomic Number of Metal Reactants
 Figure 2
 GRAVIMETRIC ENTHALPIES OF REACTIONS OF METALS WITH CO₂



Atomic Number of Metal in the Fluorides
 Figure 1
 VOLUMETRIC ENTHALPIES OF REACTIONS OF FLUORIDES WITH B.



Atomic Number of Metal in the Fluoride
 Figure 4
 GRAVIMETRIC ENTHALPIES OF FLUORIDES WITH Be

B. Oxide Reactions

A total of 20,994 reactions involving 145 oxides was examined, and the data for 9636 reactions were printed. Of the 9636 reactions, about half were pertinent to the present study; reactions with positive and negative enthalpies were inadvertently included in the output. The oxides form a highly energetic class of reactions, with volumetric enthalpies up to -8279 cal/cc. The oxide systems, including the perchlorates, chlorates, and nitrates, are the most energetic of all the classes of reactions examined. The oxide parameters tend to dominate and, as a result, the trends in perchlorate, chlorate, and nitrate reactions are similar to those in the oxide reactions.

Representative computer outputs, including some of the more energetic reactions, are shown in Table 6. In this format all the data for each reaction are assembled in one place. Several reactions with positive enthalpies are shown. On a molar or gravimetric basis, they are the same as the reverse reaction with a negative enthalpy. On a volumetric basis, the results for the reverse reaction are slightly different, since the reactants and products have different densities. This is illustrated by the reaction of silver with cobalt monoxide and the reverse reaction of cobalt with silver oxide. It is also demonstrated by the fact that the reaction between cobalt and silver oxide is more energetic when the cobalt monoxide, rather than the dicobalt trioxide, is produced. This is not obvious from Table 6 because only the reaction with the greatest thermal output is printed when more than one reaction is possible between any two reactants.

The most energetic oxide reactions are shown in Tables 7 and 8 on volumetric and gravimetric bases, respectively. On the volumetric basis, the best reducing metals are the lower members of Groups IIA and IIIA (beryllium, magnesium, aluminum, and boron), the Group IVB elements (titanium, zirconium, and hafnium), and the IVF and VF elements (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, gadolinium, etc., and thorium and uranium). On the gravimetric basis, the same elements are the best reducing metals, with a few notable exceptions. Lithium is one of the best metals on a gravimetric basis but is very poor on a volumetric basis because of its extremely low density. On the other hand, the extremely high densities of thorium and uranium cause them to be much more effective on a volumetric than on a gravimetric basis.

The most effective oxidizers on a volumetric basis are the oxides of ruthenium, nitrogen, rhenium, sulfur, silver, osmium, selenium, manganese, carbon, cobalt, arsenic, lead, and copper. The most effective oxidizers on a gravimetric basis are the oxides of nitrogen, carbon, sodium, sulfur, ruthenium, molybdenum, indium, potassium, and chromium.

Table 6

DATA ON REACTIONS OF VARIOUS METALS WITH OXIDES

	Cd	+ Ag ₂ O	= 2 Ag	+ CdO
Heat of formation		-7.31	107.87	-60.86
Molecular weight	112.41	231.76	10.50	128.41
Density	8.64	7.14	960.80	8.15
Melting point, °C	320.90	300.00	2193.00	900.00
Boiling point, °C	767.00			900.00
Heat of reaction, kcal	-53.55			
Reactants' density	7.57			
Gravimetric enthalpy, cal/g	-155.60			
Volumetric enthalpy, cal/cc	-1178.15			
	2 Ce	+ 3 Ag ₂ O	= 8 Ag	+ Ce ₂ O ₃
Heat of formation		-7.31	107.87	-435.00
Molecular weight	140.13	231.76	10.50	328.26
Density	6.70	7.14	960.80	6.90
Melting point, °C	775.00	300.00	2193.00	1692.00
Boiling point, °C	2900.00			
Heat of reaction, kcal	-413.08			
Reactants' density	7.01			
Gravimetric enthalpy, cal/g	-423.44			
Volumetric enthalpy, cal/cc	-2968.24			
	Co	+ Ag ₂ O	= 2 Ag	+ CoO
Heat of formation		-7.31	107.87	-57.20
Molecular weight	58.94	231.76	10.50	74.94
Density	8.90	7.14	960.80	5.70
Melting point, °C	1493.00	300.00	2193.00	1800.00
Boiling point, °C	3100.00			
Heat of reaction, kcal	-49.89			
Reactants' density	7.44			
Gravimetric enthalpy, cal/g	-171.63			
Volumetric enthalpy, cal/cc	-1277.10			

Table 6 (cont.)

	2 Ag	+	CoO	=	Co	+	Ag ₂ O
Heat of formation			-57.20		58.94		-7.31
Molecular weight	107.87		74.94		8.90		231.76
Density	10.50		5.70		1493.00		7.14
Melting point, °C	960.80		1800.00		3100.00		300.00
Boiling point, °C	2193.00						
Heat of reaction, kcal	49.89						
Reactants' density	8.63						
Gravimetric enthalpy, cal/g	171.64						
Volumetric enthalpy, cal/cc	1480.77						
	2 Al	+	3 CoO	=	3 Co	+	Al ₂ O ₃
Heat of formation			-57.20		58.94		-399.09
Molecular weight	26.98		74.94		8.90		101.94
Density	2.70		5.70		1493.00		3.97
Melting point, °C	660.00		1800.00		3100.00		2015.00
Boiling point, °C	2327.00						3500.00
Heat of reaction, kcal	-227.49						
Reactants' density	4.69						
Gravimetric enthalpy, cal/g	-816.02						
Volumetric enthalpy, cal/cc	-3828.99						
	2 As	+	3 CoO	=	3 Co	+	As ₂ O ₃
Heat of formation			-57.20		58.94		-156.15
Molecular weight	74.92		74.94		8.90		197.82
Density	5.73		5.70		1493.00		4.13
Melting point, °C	817.00		1800.00		3100.00		313.00
Boiling point, °C	817.00						460.00
Heat of reaction, kcal	15.45						
Reactants' density	5.71						
Gravimetric enthalpy, cal/g	41.24						
Volumetric enthalpy, cal/cc	235.50						

Table 6 (cont.)

	6 Ag	+	Co ₂ O ₃	=	2 Co	+	3 Ag ₂ O
Heat of formation			-140.00				-7.31
Molecular weight	107.87		165.88		58.94		231.76
Density	10.50		5.18		8.90		7.14
Melting point, °C	960.80		895.00		1493.00		300.00
Boiling point, °C	2193.00				3100.00		
Heat of reaction, kcal	118.08						
Reactants' density	8.68						
Gravimetric enthalpy, cal/g	145.22						
Volumetric enthalpy, cal/cc	1260.69						
	2 Al	+	Co ₂ O ₃	=	2 Co	+	Al ₂ O ₃
Heat of formation			-140.00				-399.09
Molecular weight	26.98		165.88		58.94		101.94
Density	2.70		5.18		8.90		3.97
Melting point, °C	660.00		895.00		1493.00		2015.00
Boiling point, °C	2327.00				3100.00		3500.00
Heat of reaction, kcal	-259.09						
Reactants' density	4.23						
Gravimetric enthalpy, cal/g	-1178.54						
Volumetric enthalpy, cal/cc	-4983.12						
	2 As	+	Co ₂ O ₃	=	2 Co	+	As ₂ O ₃
Heat of formation			-140.00				-156.15
Molecular weight	74.92		165.88		58.94		197.82
Density	5.73		5.18		8.90		4.15
Melting point, °C	817.00		895.00		1493.00		313.00
Boiling point, °C	817.00				3100.00		460.00
Heat of reaction, kcal	-16.15						
Reactants' density	5.43						
Gravimetric enthalpy, cal/g	-51.15						
Volumetric enthalpy, cal/cc	-277.55						

Table 6 (cont.)

	6 Li	+	Co ₂ O ₃	=	2 Co	+	3 Li ₂ O
Heat of formation			-140.00				-142.40
Molecular weight	6.94		165.88		58.94		29.88
Density	.52		5.18		8.90		2.01
Melting point, °C	180.00		895.00		1493.00		1700.00
Boiling point, °C	1326.00				3100.00		
Heat of reaction, kcal	-287.20						
Reactants' density	1.89						
Gravimetric enthalpy, cal/g	-1383.96						
Volumetric enthalpy, cal/cc	-2610.89						
	3 Mg	+	Co ₂ O ₃	=	2 Co	+	3 MgO
Heat of formation			-140.00				-143.84
Molecular weight	24.32		165.88		58.94		40.32
Density	1.74		5.18		8.90		3.58
Melting point, °C	650.00		895.00		1493.00		2800.00
Boiling point, °C	1120.00				3100.00		
Heat of reaction, kcal	-291.52						
Reactants' density	3.23						
Gravimetric enthalpy, cal/g	-1220.57						
Volumetric enthalpy, cal/cc	-3941.90						
	3 Mn	+	Co ₂ O ₃	=	2 Co	+	3 MnO
Heat of formation			-140.00				-92.00
Molecular weight	54.94		165.88		58.94		70.93
Density	7.20		5.18		8.90		5.43
Melting point, °C	1244.00		895.00		1493.00		1650.00
Boiling point, °C	2087.00				3100.00		
Heat of reaction, kcal	-136.00						
Reactants' density	6.02						
Gravimetric enthalpy, cal/g	-411.25						
Volumetric enthalpy, cal/cc	-2476.56						

Table 6 (cont.)

	4 Ag	+	MnO ₂	=	Mn	+	2 Ag ₂ O
Heat of formation			-124.50				-7.31
Molecular weight	107.87		86.93		54.94		231.76
Density	10.50		5.03		7.20		7.14
Melting point, °C	960.80		535.00		1244.00		300.00
Boiling point, °C	2193.00				2087.00		
Heat of reaction, kcal	109.89						
Reactants' density	8.88						
Gravimetric enthalpy, cal/g	211.97						
Volumetric enthalpy, cal/cc	1881.95						
	4 Al	+	3 MnO ₂	=	3 Mn	+	2 Al ₂ O ₃
Heat of formation			-124.50				-399.09
Molecular weight	26.98		86.93		54.94		101.94
Density	2.70		5.03		7.20		3.97
Melting point, °C	660.00		535.00		1244.00		2015.00
Boiling point, °C	2327.00				2087.00		3500.00
Heat of reaction, kcal	-424.68						
Reactants' density	4.02						
Gravimetric enthalpy, cal/g	-1151.80						
Volumetric enthalpy, cal/cc	-4624.68						
	4 As	+	3 MnO ₂	=	3 Mn	+	2 As ₂ O ₃
Heat of formation			-124.50				-156.15
Molecular weight	74.92		86.93		54.94		197.82
Density	5.73		5.03		7.20		4.15
Melting point, °C	817.00		535.00		1244.00		313.00
Boiling point, °C	817.00				2087.00		460.00
Heat of reaction, kcal	61.20						
Reactants' density	5.38						
Gravimetric enthalpy, cal/g	109.19						
Volumetric enthalpy, cal/cc	587.24						

Table 6 (cont.)

	2 Be	+	MnO ₂	=	Mn	+	2 BeO
Heat of formation			-124.50				-146.00
Molecular weight	9.01		86.93		54.94		25.01
Density	1.85		5.03		7.20		3.01
Melting point, °C	1283.00		535.00		1244.00		2530.00
Boiling point, °C	2970.00				2087.00		3900.00
Heat of reaction, kcal	-167.50						
Reactants' density	3.88						
Gravimetric enthalpy, cal/g	-1595.91						
Volumetric enthalpy, cal/cc	-6194.56						
	4 Bi	+ <td>3 MnO₂</td> <td>= <td>3 Mn</td> <td>+ <td>2 Bi₂O₃</td> </td></td>	3 MnO ₂	= <td>3 Mn</td> <td>+ <td>2 Bi₂O₃</td> </td>	3 Mn	+ <td>2 Bi₂O₃</td>	2 Bi ₂ O ₃
Heat of formation			-124.50				-137.90
Molecular weight	208.99		86.93		54.94		466.00
Density	9.80		5.03		7.20		8.90
Melting point, °C	271.00		535.00		1244.00		820.00
Boiling point, °C	1420.00				2087.00		1890.00
Heat of reaction, kcal	97.70						
Reactants' density	7.99						
Gravimetric enthalpy, cal/g	89.08						
Volumetric enthalpy, cal/cc	712.15						
	C	+ <td>MnO₂</td> <td>= <td>Mn</td> <td>+ <td>CO₂</td> </td></td>	MnO ₂	= <td>Mn</td> <td>+ <td>CO₂</td> </td>	Mn	+ <td>CO₂</td>	CO ₂
Heat of formation			-124.50				-94.05
Molecular weight	12.01		86.93		54.94		44.01
Density	2.25		5.03		7.20		1.98
Melting point, °C	25.00		535.00		1244.00		-56.20
Boiling point, °C	4347.00				2087.00		-78.50
Heat of reaction, kcal	30.45						
Reactants' density	4.37						
Gravimetric enthalpy, cal/g	307.76						
Volumetric enthalpy, cal/cc	1345.30						

Table 6 (cont.)

	8 Ag	+	N ₂ O ₄	=	2 N	+	4 Ag ₂ O
Heat of formation			2.31				-7.31
Molecular weight	107.87		92.00		14.01		231.76
Density	10.50		1.49		.81		7.14
Melting point, °C	960.80		61.60				300.00
Boiling point, °C	2193.00						
Heat of reaction, kcal	-31.53						
Reactants' density	6 64						
Gravimetric enthalpy, cal/g	-33.02						
Volumetric enthalpy, cal/cc	-219.14						
	8 Al	+ <td>3 N₂O₄ <td>= <td>6 N <td>+ <td>4 Al₂O₃</td> </td></td></td></td>	3 N ₂ O ₄ <td>= <td>6 N <td>+ <td>4 Al₂O₃</td> </td></td></td>	= <td>6 N <td>+ <td>4 Al₂O₃</td> </td></td>	6 N <td>+ <td>4 Al₂O₃</td> </td>	+ <td>4 Al₂O₃</td>	4 Al ₂ O ₃
Heat of formation			2.31				-399.09
Molecular weight	26.98		92.00		14.01		101.94
Density	2.70		1.49		.81		3.97
Melting point, °C	660.00		61.60				2015.00
Boiling point, °C	2327.00						3500.00
Heat of reaction, kcal	-1603.29						
Reactants' density	1.86						
Gravimetric enthalpy, cal/g	-3259.77						
Volumetric enthalpy, cal/cc	-6050.32						
	8 As	+ <td>3 N₂O₄ <td>= <td>6 N <td>+ <td>4 As₂O₃</td> </td></td></td></td>	3 N ₂ O ₄ <td>= <td>6 N <td>+ <td>4 As₂O₃</td> </td></td></td>	= <td>6 N <td>+ <td>4 As₂O₃</td> </td></td>	6 N <td>+ <td>4 As₂O₃</td> </td>	+ <td>4 As₂O₃</td>	4 As ₂ O ₃
Heat of formation			2.31				-156.15
Molecular weight	74.92		92.00		14.01		197.82
Density	5.73		1.49		.81		4.15
Melting point, °C	817.00		61.60				313.00
Boiling point, °C	817.00						460.00
Heat of reaction, kcal	-631.53						
Reactants' density	3.02						
Gravimetric enthalpy, cal/g	-721.45						
Volumetric enthalpy, cal/cc	-2179.44						

Table 6 (cont.)

	4 Be	+	N ₂ O ₄	=	2 N	+	4 BeO
Heat of formation			2.31		14.01		-146.00
Molecular weight	9.01		92.00		.81		25.01
Density	1.85		1.49				3.01
Melting point, °C	1283.00		61.60				2530.00
Boiling point, °C	2970.00						3900.00
Heat of reaction, kcal	-586.31						
Reactants' density	1.58						
Gravimetric enthalpy, cal/g	-4578.68						
Volumetric enthalpy, cal/cc	-7221.34						
	8 Bi	+ <td>3 N₂O₄ <td>= <td>6 N <td>+ <td>4 Bi₂O₃</td> </td></td></td></td>	3 N ₂ O ₄ <td>= <td>6 N <td>+ <td>4 Bi₂O₃</td> </td></td></td>	= <td>6 N <td>+ <td>4 Bi₂O₃</td> </td></td>	6 N <td>+ <td>4 Bi₂O₃</td> </td>	+ <td>4 Bi₂O₃</td>	4 Bi ₂ O ₃
Heat of formation			2.31		14.01		-137.90
Molecular weight	208.99		92.00		.81		466.00
Density	9.80		1.49				8.90
Melting point, °C	271.00		61.60				280.00
Boiling point, °C	1420.00						1890.00
Heat of reaction, kcal	-558.53						
Reactants' density	5.48						
Gravimetric enthalpy, cal/g	-286.73						
Volumetric enthalpy, cal/cc	-1570.15						
	2 C	+ <td>N₂O₄ <td>= <td>2 N <td>+ <td>2 CO₂</td> </td></td></td></td>	N ₂ O ₄ <td>= <td>2 N <td>+ <td>2 CO₂</td> </td></td></td>	= <td>2 N <td>+ <td>2 CO₂</td> </td></td>	2 N <td>+ <td>2 CO₂</td> </td>	+ <td>2 CO₂</td>	2 CO ₂
Heat of formation			2.31		14.01		-94.05
Molecular weight	12.01		92.00		.81		44.01
Density	2.25		1.49				1.98
Melting point, °C	25.00		61.60				-56.20
Boiling point, °C	4347.00						-78.50
Heat of reaction, kcal	-190.41						
Reactants' density	1.60						
Gravimetric enthalpy, cal/g	-1641.15						
Volumetric enthalpy, cal/cc	-2630.69						

Table 6 (cont.)

	4 Ag	+	PbO ₂	=	Pb	+	2 Ag ₂ O
Heat of formation			-66.12				-7.31
Molecular weight	107.87		239.21		207.21		231.76
Density	10.50		9.38		11.34		7.14
Melting point, °C	960.80		290.00		327.40		300.00
Boiling point, °C	2193.00				1750.00		
Heat of reaction, kcal	51.51						
Reactants' density	10.07						
Gravimetric enthalpy, cal/g	76.80						
Volumetric enthalpy, cal/cc	773.27						
	4 Al	+	3 PbO ₂	=	3 Pb	+	2 Al ₂ O ₃
Heat of formation			-66.12				-399.09
Molecular weight	26.98		439.21		207.21		101.94
Density	2.70		9.38		11.34		3.97
Melting point, °C	660.00		290.00		327.40		2015.00
Boiling point, °C	2327.00				1750.00		3500.00
Heat of reaction, kcal	-599.82						
Reactants' density	7.09						
Gravimetric enthalpy, cal/g	-726.57						
Volumetric enthalpy, cal/cc	-5149.20						
	4 As	+	3 PbO ₂	=	3 Pb	+	2 As ₂ O ₃
Heat of formation			-66.12				-156.15
Molecular weight	74.92		239.21		207.21		197.82
Density	5.73		9.38		11.34		4.15
Melting point, °C	817.00		290.00		327.40		313.00
Boiling point, °C	817.00				1750.00		460.00
Heat of reaction, kcal	-113.94						
Reactants' density	7.89						
Gravimetric enthalpy, cal/g	-112.00						
Volumetric enthalpy, cal/cc	-884.11						

Table 6 (cont.)

	2 Be	+	PbO ₂	=	Pb	+	2 BeO
Heat of formation			-66.12				-146.00
Molecular weight	9.01		239.21		207.21		25.01
Density	1.85		9.38		11.34		3.01
Melting point, °C	1283.00		290.00		327.40		2530.00
Boiling point, °C	2970.00				1750.00		3900.00
Heat of reaction, kcal	-225.88						
Reactants' density	7.30						
Gravimetric enthalpy, cal/g	-878.10						
Volumetric enthalpy, cal/cc	-6406.21						
	2 Bi	+ <td>PbO₂</td> <td>= <td>Pb</td> <td>+ <td>2 BiO</td> </td></td>	PbO ₂	= <td>Pb</td> <td>+ <td>2 BiO</td> </td>	Pb	+ <td>2 BiO</td>	2 BiO
Heat of formation			-66.12				-49.95
Molecular weight	208.99		239.21		207.21		224.99
Density	9.80		9.38		11.34		
Melting point, °C	271.00		290.00		327.40		
Boiling point, °C	1420.00				1750.00		
Heat of reaction, kcal	-33.78						
Reactants' density	9.64						
Gravimetric enthalpy, cal/g	-51.40						
Volumetric enthalpy, cal/cc	-495.55						
	C	+ <td>PbO₂</td> <td>= <td>Pb</td> <td>+ <td>CO₂</td> </td></td>	PbO ₂	= <td>Pb</td> <td>+ <td>CO₂</td> </td>	Pb	+ <td>CO₂</td>	CO ₂
Heat of formation			-66.12				-94.05
Molecular weight	12.01		239.21		207.21		44.01
Density	2.25		9.38		11.34		1.98
Melting point, °C	25.00		290.00		327.40		-56.20
Boiling point, °C	4347.00				1750.00		-78.50
Heat of reaction, kcal	-27.93						
Reactants' density	8.14						
Gravimetric enthalpy, cal/g	-111.18						
Volumetric enthalpy, cal/cc	-905.23						

Table 6 (cont.)

	4 La	+ 3 PbO ₂	=	3 Pb	+ 2 La ₂ O ₃
Heat of formation		-66.12		207.21	-458.00
Molecular weight	138.92	239.21		11.34	325.84
Density	6.15	9.38		327.40	6.51
Melting point, °C	880.00	290.00		1750.00	2315.00
Boiling point, °C	1800.00				4200.00
Heat of reaction, kcal	-717.64				
Heat of reaction, density	7.63				
Reactants' density	-563.60				
Gravimetric enthalpy, cal/g	-4299.78				
Volumetric enthalpy, cal/cc					
	4 Li	+ PbO ₂	=	Pb	+ 2 Li ₂ O
Heat of formation		-66.12		207.21	-142.40
Molecular weight	6.94	239.21		11.34	29.88
Density	.53	9.38		327.40	2.01
Melting point, °C	180.00	290.00		1750.00	1700.00
Boiling point, °C	1326.00				
Heat of reaction, kcal	-218.68				
Heat of reaction, density	3.44				
Reactants' density	-819.12				
Gravimetric enthalpy, cal/g	-2821.65				
Volumetric enthalpy, cal/cc					
	2 Mg	+ PbO ₂	=	Pb	+ 2 MgO
Heat of formation		-66.12		207.21	-143.84
Molecular weight	24.32	239.21		11.34	40.32
Density	1.74	9.38		327.40	3.58
Melting point, °C	650.00	290.00		1750.00	2800.00
Boiling point, °C	1120.00				
Heat of reaction, kcal	-221.56				
Heat of reaction, density	5.38				
Reactants' density	-769.71				
Gravimetric enthalpy, cal/g	-4143.65				
Volumetric enthalpy, cal/cc					

Table 7

MOST ENERGETIC REACTIONS OF METALS WITH OXIDES,
IN TERMS OF VOLUMETRIC ENTHALPY

Reaction						Enthalpy, cal/cc
2	Be	+	RuO ₂	=	Ru + 2 BeO	-8279
5	Be	+	N ₂ O ₅	=	2 N [*] + 5 BeO	-7987
7	Be	+	Re ₂ O ₇	=	2 Re + 7 BeO	-7773
4	Be	+	RuO ₄	=	Ru + 4 BeO	-7616
2	Be	+	NO ₂	=	N + 2 BeO	-7390
4	Be	+	N ₂ O ₄	=	2 N + 4 BeO	-7221
2	Be	+	SO ₂	=	S + 2 BeO	-6987
4	Be	+	10 SO ₄	=	10 S + 4 BeO	-6880
3	Be	+	N ₂ O ₃	=	2 N + 3 BeO	-6820
	U	+	RuO ₂	=	Ru + UO ₂	-6815
5	U	+	2 N ₂ O ₅	=	4 N + 5 UO ₂	-6812
5	Hf	+	2 N ₂ O ₅	=	4 N + 5 HfO ₂	-6732
	Hf	+	RuO ₂	=	Ru + HfO ₂	-6717
2	Be	+	Ag ₂ O ₂	=	2 Ag + 2 BeO	-6637
10	Al	+	3 N ₂ O ₅	=	6 N + 5 Al ₂ O ₃	-6613
4	Al	+	3 RuO ₂	=	3 Ru + 2 Al ₂ O ₃	-6571
	Hf	+	NO ₂	=	N + HfO ₂	-6314
5	Zr	+	2 N ₂ O ₅	=	4 N + 5 ZrO ₂	-6266
7	U	+	2 Re ₂ O ₇	=	4 Re + 7 UO ₂	-6246
8	Al	+	3 RuO ₄	=	3 Ru + 4 Al ₂ O ₃	-6235
2	Be	+	SeO ₂	=	Se + 2 BeO	-6227
2	U	+	N ₂ O ₄	=	2 N + 2 UO ₂	-6221
4	Al	+	3 NO ₂	=	3 N + 2 Al ₂ O ₃	-6206
2	Be	+	MnO ₂	=	Mn + 2 BeO	-6194
2	Be	+	CO ₂	=	C + 2 BeO	-6185
2	Hf	+	N ₂ O ₄	=	2 N + 2 HfO ₂	-6158
7	Hf	+	2 Re ₂ O ₇	=	4 Re + 7 HfO ₂	-6153
	Zr	+	RuO ₂	=	Ru + ZrO ₂	-6152
	Be	+	NO	=	N + BeO	-6147
2	U	+	RuO ₄	=	Ru + 2 RuO ₂	-6435

Table 7 (cont.)

Reaction						Enthalpy, cal/cc
2 Be	+	PbO ₂	=	Pb	+ 2 BeO	-6406
3 Be	+	CO ₂ O ₃	=	2 CO	+ 3 BeO	-6389
U	+	NO ₂	=	N	+ UO ₂	-6379
2 Hf	+	RuO ₄	=	Ru	+ 2 HfO ₂	-6359
5 Be	+	As ₂ O ₅	=	2 As	+ 5 BeO	-6345
Be	+	CuO	=	Cu	+ BeO	-6330
4 Be	+	Co ₃ O ₄	=	3 Co	+ 4 BeO	-6321
Hf	+	NO ₂	=	N	+ HfO ₂	-6314
5 Zr	+	2 N ₂ O ₅	=	4 N	+ 5 ZrO ₂	-6266
7 U	+	2 Re ₂ O ₇	=	4 Re	+ 7 UO ₂	-6246
8 Al	+	3 RuO ₄	=	3 Ru	+ 4 Al ₂ O ₃	-6235
2 Be	+	SeO ₂	=	Se	+ 2 BeO	-6227
2 U	+	N ₂ O ₄	=	2 N	+ 2 UO ₂	-6221
4 Al	+	3 NO ₂	=	3 N	+ 2 Al ₂ O ₃	-6206
2 Be	+	MnO ₂	=	Mn	+ 2 BeO	-6194
2 Be	+	CO ₂	=	C	+ 2 BeO	-6185
2 Hf	+	N ₂ O ₄	=	2 N	+ 2 HfO ₂	-6158
Be	+	NO	=	N	+ BeO	-6147
5 Th	+	2 N ₂ O ₅	=	4 N	+ 5 ThO ₂	-6123
Be	+	N ₂ O	=	2 N	+ BeO	-6098
5 Np	+	2 N ₂ O ₅	=	4 N	+ 5 NpO ₂	-6083
8 Al	+	3 N ₂ O ₄	=	6 N	+ 4 Al ₂ O ₃	-6050
Th	+	RuO ₄	=	Ru	+ ThO ₂	-6003
14 Al	+	3 Re ₂ O ₇	=	6 Re	+ 7 Al ₂ O ₃	-5995
10 Ti	+	3 N ₂ O ₅	=	6 N	+ 5 Ti ₂ O ₃	-5941
3 U	+	2 N ₂ O ₃	=	4 N	+ 3 UO ₂	-5933
Np	+	RuO ₂	=	Ru	+ NpO ₂	-5926
Zr	+	NO ₂	=	N	+ ZrO ₂	-5902
4 B	+	3 RuO ₂	=	3 Ru	+ 2 B ₂ O ₃	-5889
2 Zr	+	RuO ₄	=	Ru	+ 2 ZrO ₂	-5888
Be	+	NiO	=	Ni	+ BeO	-5880
3 Hf	+	2 N ₂ O ₃	=	4 N	+ 3 HfO ₂	-5879

Table 7 (cont.)

Reaction						Enthalpy, cal/cc
2 Be	+	TeO ₂	=	Te	+ 2 BeO	-5831
Th	+	NO ₂	=	N	+ ThO ₂	-5818
3 Be	+	CrO ₃	=	Cr	+ 3 BeO	-5799
2 Th	+	RuO ₄	=	Ru	+ 2 ThO ₂	-5795
2 Al	+	N ₂ O ₃	=	2 N	+ Al ₂ O ₃	-5780
2 U	+	10 SO ₄	=	10 S	+ 2 UO ₂	-5779
4 Ti	+	3 RuO ₂	=	3 Ru	+ 2 Ti ₂ O ₃	-5757
10 Ho	+	3 N ₂ O ₅	=	6 N	+ 5 Ho ₂ O ₃	-5751
2 Zr	+	N ₂ O ₄	=	2 N	+ 2 ZrO ₂	-5750
U	+	SO ₂	=	S	+ UO ₂	-5749
Np	+	NO ₂	=	N	+ NpO ₂	-5732
U	+	Ag ₂ O ₂	=	2 Ag	+ UO ₂	-5728
2 Hf	+	10 SO ₄	=	10 S	+ 2 HfO ₂	-5716
2 Np	+	RuO ₄	=	Ru	+ 2 NpO ₂	-5692
2 Th	+	N ₂ O ₄	=	2 N	+ 2 ThO ₂	-5685
Hf	+	SO ₂	=	S	+ HfO ₂	-5679
Hf	+	Ag ₂ O ₂	=	2 Ag	+ HfO ₂	-5676
4 B	+	3 NO ₂	=	3 N	+ 2 B ₂ O ₃	-5668
2 Be	+	WO ₂	=	W	+ 2 BeO	-5646
4 Ti	+	3 NO ₂	=	3 N	+ 2 Ti ₂ O ₃	-5610
8 B	+	3 RuO ₄	=	3 Ru	+ 4 B ₂ O ₃	-5607
2 Ta	+	N ₂ O ₅	=	2 N	+ Ta ₂ O ₅	-5593
8 Al	+	3 OsO ₄	=	3 Os	+ 4 Al ₂ O ₃	-5592
4 Ho	+	3 RuO ₂	=	3 Ru	+ 2 Ho ₂ O ₃	-5582
2 Np	+	N ₂ O ₄	=	2 N	+ 2 NpO ₂	-5576
4 Al	+	3 Ag ₂ O ₂	=	6 Ag	+ 2 Al ₂ O ₃	-5572
7 Zr	+	2 Re ₂ O ₇	=	4 Re	+ 7 ZrO ₂	-5562
8 Ti	+	3 RuO ₄	=	3 Ru	+ 4 Ti ₂ O ₃	-5553
10 Tb	+	3 N ₂ O ₅	=	6 N	+ 5 Tb ₂ O ₃	-5549
4 Al	+	3 SO ₂	=	3 S	+ 2 Al ₂ O ₃	-5542
3 Be	+	MoO ₃	=	Mo	+ 3 BeO	-5528

Table 7 (cont.)

Reaction						Enthalpy, cal/cc	
3 Zr	+	2 N ₂ O ₃	=	4 N	+	3 ZrO ₂	-5510
7 Th	+	2 Re ₂ O ₇	=	4 Re	+	7 ThO ₂	-5505
4 Ho	+	3 NO ₂	=	3 N	+	2 Ho ₂ O ₃	-5500
2 Be	+	MoO ₂	=	Mo	+	2 BeO	-5487
8 B	+	3 N ₂ O ₄	=	6 N	+	4 B ₂ O ₃	-5481
3 Th	+	2 N ₂ O ₃	=	4 N	+	3 ThO ₂	-5477
8 Ti	+	3 N ₂ O ₄	=	6 N	+	4 Ti ₂ O ₃	-5457
10 Sm	+	3 N ₂ O ₅	=	6 N	+	5 Sm ₂ O ₃	-5449
U	+	2 NO	=	2 N	+	UO ₂	-5445
8 Ho	+	3 RuO ₄	=	3 Ru	+	4 Ho ₂ O ₃	-5443
10 Gd	+	3 N ₂ O ₅	=	6 N	+	5 Gd ₂ O ₃	-5412
Hf	+	2 NO	=	2 N	+	HfO ₂	-5406
U	+	2 N ₂ O	=	4 N	+	UO ₂	-5395
8 Ho	+	3 N ₂ O ₄	=	6 N	+	4 Ho ₂ O ₃	-5377
10 Sc	+	3 N ₂ O ₅	=	6 N	+	5 Sc ₂ O ₃	-5368
10 Nd	+	3 N ₂ O ₅	=	6 N	+	5 Nd ₂ O ₃	-5363
Hf	+	2 N ₂ O	=	4 N	+	HfO ₂	-5357
3 Be	+	Fe ₂ O ₃	=	2 Fe	+	3 BeO	-5355
4 Tb	+	3 RuO ₂	=	3 Ru	+	2 Tb ₂ O ₃	-5349
3 Np	+	2 N ₂ O ₃	=	4 N	+	3 NpO ₂	-5348
10 La	+	3 N ₂ O ₅	=	6 N	+	5 La ₂ O ₃	-5339
U	+	PbO ₂	=	Pb	+	UO ₂	-5330
2 Al	+	3 NO	=	3 N	+	Al ₂ O ₃	-5323
4 Tb	+	3 NO ₂	=	3 N	+	2 Tb ₂ O ₃	-5316
7 Np	+	2 Re ₂ O ₇	=	4 Re	+	7 NpO ₂	-5304
5 Si	+	2 N ₂ O ₅	=	4 N	+	5 SiO ₂	-5297
Zr	+	Ag ₂ O ₂	=	2 Ag	+	ZrO ₂	-5297
10 Pr	+	3 N ₂ O ₅	=	6 N	+	5 Pr ₂ O ₃	-5293
Th	+	Ag ₂ O ₂	=	2 Ag	+	ThO ₂	-5289
4 Ta	+	5 RuO ₂	=	5 Ru	+	2 Ta ₂ O ₅	-5284
10 Ce	+	3 N ₂ O ₅	=	6 N	+	5 Ce ₂ O ₃	-5276

Table 7 (cont.)

Reaction						Enthalpy, cal/cc	
Hf	+	PbO ₂	=	Pb	+	HfO ₂	-5274
2 Al	+	3 N ₂ O	=	6 N	+	Al ₂ O ₃	-5273
2 Zr	+	10 SO ₄	=	10 S	+	2 ZrO ₂	-5266
2 Th	+	10 SO ₄	=	10 S	+	2 ThO ₂	-5261
4 Ta	+	5 NO ₂	=	5 N	+	2 Ta ₂ O ₅	-5256
2 Ti	+	N ₂ O ₃	=	2 N	+	Ti ₂ O ₃	-5242
8 Tb	+	3 RuO ₄	=	3 Ru	+	4 Tb ₂ O ₃	-5238
4 Sm	+	3 RuO ₂	=	3 Ru	+	2 Sm ₂ O ₃	-5236
U	+	2 CuO	=	2 Cu	+	UO ₂	-5236
U	+	SeO ₂	=	Se	+	UO ₂	-5232
5 Mg	+	N ₂ O ₅	=	2 N	+	5 MgO	-5227
4 Sm	+	3 NO ₂	=	3 N	+	2 Sm ₂ O ₃	-5226
2 B	+	N ₂ O ₃	=	2 N	+	B ₂ O ₃	-5221
2 Ho	+	N ₂ O ₃	=	2 N	+	Ho ₂ O ₃	-5206
4 Gd	+	3 RuO ₂	=	3 Ru	+	2 Gd ₂ O ₃	-5194
4 Gd	+	3 NO ₂	=	3 N	+	2 Gd ₂ O ₃	-5193
8 Tb	+	3 N ₂ O ₄	=	6 N	+	4 Tb ₂ O ₃	-5193
Th	+	SO ₂	=	S	+	ThO ₂	-5188
3 U	+	2 Co ₂ O ₃	=	4 Co	+	3 UO ₂	-5183
5 U	+	2 As ₂ O ₅	=	4 As	+	5 UO ₂	-5183
Hf	+	SeO ₂	=	Se	+	HfO ₂	-5181
Zr	+	SO ₂	=	S	+	ZrO ₂	-5180
Hf	+	2 CuO	=	2 Cu	+	HfO ₂	-5180
2 Nb	+	N ₂ O ₅	=	2 N	+	Nb ₂ O ₅	-5178
4 Nd	+	3 NO ₂	=	3 N	+	2 Nd ₂ O ₃	-5154
4 Al	+	3 PbO ₂	=	3 Pb	+	2 Al ₂ O ₃	-5149
4 Nd	+	3 RuO ₂	=	3 Ru	+	2 Nd ₂ O ₃	-5145
4 Sc	+	3 NO ₂	=	3 N	+	2 Sc ₂ O ₃	-5144
8 Sm	+	3 RuO ₄	=	3 Ru	+	4 Sm ₂ O ₃	-5140
4 La	+	3 NO ₂	=	3 N	+	2 La ₂ O ₃	-5140
14 Ti	+	3 Re ₂ O ₇	=	6 Re	+	7 Ti ₂ O ₃	-5137

Table 7 (cont.)

Reaction						Enthalpy, cal/cc
4	Sc	+	3 RuO ₂	=	3 Ru + 2 Sc ₂ O ₃	-5131
8	Ta	+	5 RuO ₄	=	5 Ru + 4 Ta ₂ O ₅	-5131
4	La	+	3 RuO ₂	=	3 Ru + 2 La ₂ O ₃	-5128
	Np	+	Ag ₂ O ₂	=	2 Ag + NpO ₂	-5125
5	Hf	+	2 As ₂ O ₅	=	4 As + 5 HfO ₂	-5125
3	Hf	+	2 Co ₂ O ₃	=	4 Co + 3 HfO ₂	-5124
2	Be	+	GeO ₂	=	Ge + 2 BeO	-5118
	Th	+	2 NO	=	2 N + ThO ₂	-5117
14	Ho	+	3 Re ₂ O ₇	=	8 Re + 7 Ho ₂ O ₃	-5113
	Be	+	HgO	=	Hg + BeO	-5112
	Zr	+	2 NO	=	2 N + ZrO ₂	-5105
8	Sm	+	3 N ₂ O ₄	=	6 N + 4 Sm ₂ O ₃	-5105
8	Gd	+	3 RuO ₄	=	3 Ru + 4 Gd ₂ O ₃	-5104
	U	+	10 SO ₂	=	10 S + UO ₂	-5095
4	Pr	+	3 NO ₂	=	3 N + 2 Pr ₂ O ₃	-5093
8	Ta	+	5 N ₂ O ₄	=	10 N + 4 Ta ₂ O ₅	-5082
4	Ce	+	3 NO ₂	=	3 N + 2 Ce ₂ O ₃	-5074
8	Gd	+	3 N ₂ O ₄	=	6 N + 4 Gd ₂ O ₃	-5073
	Th	+	2 N ₂ O	=	4 N + ThO ₂	-5072
4	Pr	+	3 RuO ₂	=	3 Ru + 2 Pr ₂ O ₃	-5070
2	U	+	Co ₃ O ₄	=	3 Co + 2 UO ₂	-5066
8	Nd	+	3 RuO ₄	=	3 Ru + 4 Nd ₂ O ₃	-5063
14	B	+	3 Re ₂ O ₇	=	6 Re + 7 B ₂ O ₃	-5063
4	Al	+	3 SeO ₂	=	3 Se + 2 Al ₂ O ₃	-5063
2	Np	+	10 SO ₄	=	10 S + 2 NpO ₂	-5061
	Zr	+	2 N ₂ O	=	4 N + ZrO ₂	-5055
8	La	+	3 RuO ₄	=	3 Ru + 4 La ₂ O ₃	-5051
2	Al	+	3 CuO	=	3 Cu + Al ₂ O ₃	-5051
	Hf	+	10 SO ₂	=	10 S + HfO ₂	-5046
3	Be	+	WO ₃	=	W + 3 BeO	-5045
4	Ce	+	3 RuO ₂	=	3 Ru + 2 Ce ₂ O ₃	-5045

Table 7 (cont.)

Reaction						Enthalpy, cal/cc	
8 Sc	+	3 RuO ₄	=	3 Ru	+	4 Sc ₂ O ₃	-5044
2 Tb	+	N ₂ O ₃	=	2 N	+	Tb ₂ O ₃	-5036
8 Nd	+	3 N ₂ O ₄	=	6 N	+	4 Nd ₂ O ₃	-5036
2 Mg	+	NO ₂	=	N	+	2 MgO	-5029
U	+	CO ₂	=	C	+	UO ₂	-5028
8 La	+	3 N ₂ O ₄	=	6 N	+	4 La ₂ O ₃	-5026
4 Ho	+	3 Ag ₂ O ₂	=	6 Ag	+	2 Ho ₂ O ₃	-5024
10 V	+	3 N ₂ O ₅	=	6 N	+	5 V ₂ O ₃	-5020
8 Sc	+	3 N ₂ O ₄	=	6 N	+	4 Sc ₂ O ₃	-5018
4 Ti	+	3 Ag ₂ O ₂	=	6 Ag	+	2 Ti ₂ O ₃	-5018
Si	+	NO ₂	=	N	+	SiO ₂	-5015
2 Hf	+	Co ₃ O ₄	=	3 Co	+	2 HfO ₂	-5006
8 Pr	+	3 RuO ₄	=	3 Ru	+	4 Pr ₂ O ₃	-4997
2 Mg	+	RuO ₂	=	Ru	+	2 MgO	-4989
10 Al	+	3 As ₂ O ₅	=	6 As	+	5 Al ₂ O ₃	-4988
2 Al	+	Co ₂ O ₃	=	2 Co	+	Al ₂ O ₃	-4983
8 Pr	+	3 N ₂ O ₄	=	6 N	+	4 Pr ₂ O ₃	-4978
8 Ce	+	3 RuO ₄	=	3 Ru	+	4 Ce ₂ O ₃	-4974
Hf	+	CO ₂	=	C	+	HfO ₂	-4973
Np	+	2 NO	=	2 N	+	NpO ₂	-4964
8 Ho	+	3 OsO ₄	=	3 Os	+	4 Ho ₂ O ₃	-4960
8 Ce	+	3 N ₂ O ₄	=	6 N	+	4 Ce ₂ O ₃	-4956
2 Sm	+	N ₂ O ₃	=	2 N	+	Sm ₂ O ₃	-4955
Np	+	SO ₂	=	S	+	NpO ₂	-4951
4 B	+	3 Ag ₂ O ₂	=	6 Ag	+	2 B ₂ O ₃	-4951
Si	+	RuO ₂	=	Ru	+	SiO ₂	-4950
3 U	+	2 SO ₃	=	2 S	+	3 UO ₂	-4949

* N refers to molecular nitrogen and is thus 1/2 N₂.

Table 8

MOST ENERGETIC REACTIONS OF METALS WITH OXIDES,
IN TERMS OF GRAVIMETRIC ENTHALPY

Reaction						Enthalpy, cal/g
3 Be	+	NO ₃	=	N*	+ 3 BeO	-5064
5 Be	+	N ₂ O ₅	=	2 N	+ 5 BeO	-4703
2 Be	+	NO ₂	=	N	+ 2 BeO	-4686
4 Be	+	N ₂ O ₄	=	2 N	+ 4 BeO	-4578
3 Be	+	N ₂ O ₃	=	2 N	+ 3 BeO	-4444
1 Be	+	NO	=	N	+ BeO	-4294
6 Li	+	NO ₃	=	N	+ 3 Li ₂ O	-4246
4 Li	+	NO ₂	=	N	+ 2 Li ₂ O	-3970
10 Li	+	N ₂ O ₅	=	2 N	+ 5 Li ₂ O	-3956
8 Li	+	N ₂ O ₄	=	2 N	+ 4 Li ₂ O	-3876
6 Li	+	N ₂ O ₃	=	2 N	+ 3 Li ₂ O	-3800
2 B	+	NO ₃	=	N	+ B ₂ O ₃	-3765
2 Li	+	NO	=	N	+ Li ₂ O	-3736
2 Al	+	NO ₃	=	N	+ Al ₂ O ₃	-3553
4 B	+	3 NO ₂	=	3 N	+ 2 B ₂ O ₃	-3465
10 B	+	3 N ₂ O ₅	=	3 N	+ 5 B ₂ O ₃	-3423
8 B	+	3 N ₂ O ₄	=	6 N	+ 4 B ₂ O ₃	-3350
4 Al	+	3 NO ₂	=	3 N	+ 2 Al ₂ O ₃	-3343
10 Al	+	3 N ₂ O ₅	=	6 N	+ 5 Al ₂ O ₃	-3309
2 B	+	N ₂ O ₃	=	2 N	+ B ₂ O ₃	-3297
3 Mg	+	NO ₃	=	N	+ 3 MgO	-3293
2 B	+	3 NO	=	3 N	+ B ₂ O ₃	-3284
8 Al	+	3 N ₂ O ₄	=	6 N	+ 4 Al ₂ O ₃	-3259
Be	+	CO	=	C	+ BeO	-3230
2 Al	+	N ₂ O ₃	=	2 N	+ Al ₂ O ₃	-3224
2 Al	+	3 NO	=	3 N	+ Al ₂ O ₃	-3221
2 Be	+	CO ₂	=	C	+ 2 BeO	-3190
2 Be	+	Na ₂	=	Na	+ 2 BeO	-3151
2 Mg	+	NO ₂	=	N	+ 2 MgO	-3124

Table 8 (cont.)

Reaction						Enthalpy, cal/g	
Be	+	N ₂ O	=	2 N	+	BeO	-3120
3 Si	+	2 NO ₃	=	2 N	-	3 SiO ₂	-3083
4 Mg	+	N ₂ O ₄	=	2 N	+	4 MgO	-3051
Mg	+	NO	=	N	+	MgO	-3045
3 Mg	+	N ₂ O ₃	=	2 N	+	3 MgO	-3030
Si	+	NO ₂	=	N	+	SiO ₂	-2881
5 Si	+	2 N ₂ O ₅	=	N	+	5 SiO ₂	-2824
Si	+	2 NO	=	2 N	+	SiO ₂	-2821
2 Li	+	N ₂ O	=	2 N	+	Li ₂ O	-2796
2 Sc	+	NO ₃	=	N	+	Sc ₂ O ₃	-2790
2 Si	+	N ₂ O ₄	=	2 N	+	2 SiO ₂	-2787
3 Si	+	2 N ₂ O ₃	=	2 N	+	3 SiO ₂	-2776
2 Li	+	CO	=	C	+	Li ₂ O	-2769
4 Li	+	NaO ₂	=	Na	+	2 Li ₂ O	-2693
2 Be	+	SO ₂	=	2 S	+	2 BeO	-2692
4 Sc	+	3 NO ₂	=	3 N	+	2 Sc ₂ O ₃	-2662
4 Li	+	CO ₂	=	C	+	2 Li ₂ O	-2657
6 Li	+	SO ₃	=	S	+	3 Li ₂ O	-2650
2 Sc	+	3 NO	=	3 N	+	Sc ₂ O ₃	-2644
4 Be	+	RuO ₄	=	Ru	+	4 BeO	-2636
10 Sc	+	3 N ₂ O ₅	=	6 N	+	5 Sc ₂ O ₃	-2617
5 Be	+	MoO ₅	=	Mo	+	5 BeO	-2601
2 Sc	+	N ₂ O ₃	=	2 N	+	Sc ₂ O ₃	-2597
8 Sc	+	3 N ₂ O ₄	=	6 N	+	4 Sc ₂ O ₃	-2597
3 Ca	+	NO ₃	=	N	+	3 CaO	-2571
4 Be	+	K ₂ O ₄	=	2 K	+	4 BeO	-2524
Ca	+	NO	=	N	+	CaO	-2475
2 Ca	+	NO ₂	=	N	+	2 CaO	-2471
2 Al	+	3 N ₂ O	=	3 N	+	Al ₂ O ₃	-2459
Be	+	SO	=	S	+	BeO	-2452
5 Ca	+	N ₂ O ₅	=	2 N	+	5 CaO	-2430

Table 8 (cont.)

Reaction						Enthalpy, cal/g	
3 Ca	+	N_2O_3	=	2 N	+	3 CaO	-2423
4 Ca	+	N_2O_4	=	2 N	+	4 CaO	-2417
Mg	+	N_2O	=	2 N	+	MgO	-2389
3 Be	+	CrO_3	=	Cr	+	3 BeO	-2358
2 B	+	3 N_2O	=	6 N	+	1 B_2O_3	-2345
8 Li	+	RuO_4	=	Ru	+	4 Li_2O	-2339
Be	+	SiO	=	Si	+	BeO	-2331
4 Li	+	SO_2	=	S	+	2 Li_2O	-2328
2 Ti	+	3 NO	=	3 N	+	Ti_2O_3	-2323
2 Al	+	3 CO	=	3 C	+	Al_2O_3	-2318
4 Ti	+	3 NO_2	=	6 N	+	2 Ti_2O_3	-2300
4 Be	+	Nb_2O_4	=	2 Nb	+	4 BeO	-2284
2 P	+	NO_3	=	N	+	P_2O_3	-2282
10 Li	+	MoO_5	=	Mo	+	5 Li_2O	-2269
2 Ti	+	N_2O_3	=	2 N	+	Ti_2O_3	-2252
10 Ti	+	3 N_2O_5	=	6 N	+	5 Ti_2O_3	-2247
4 Al	+	3 NaO_2	=	3 Na	+	2 Al_2O_3	-2244
Mg	+	CO	=	C	+	MgO	-2244
8 Ti	+	3 N_2O_4	=	6 N	+	4 Ti_2O_3	-2237
8 Li	+	K_2O_4	=	2 K	+	4 Li_2O	-2203
2 P	+	3 NO	=	3 N	+	P_2O_3	-2202
2 Li	+	SO	=	S	+	Li_2O	-2201
2 Al	+	SC_3	=	S	+	Al_2O_3	-2197
2 Be	+	Li_2O_2	=	2 Li	+	2 BeO	-2195
2 Mg	+	NaO_2	=	Na	+	2 MgO	-2178
4 P	+	3 NO_2	=	3 N	+	2 P_2O_3	-2154
4 Al	+	3 CO_2	=	3 C	+	2 Al_2O_3	-2150
3 Mg	+	SO_3	=	S	+	3 MgO	-2136
2 Sc	+	3 N_2O	=	6 N	+	Sc_2O_3	-2114
2 B	+	3 CO	=	3 C	+	B_2O_3	-2108
Si	+	2 N_2O	=	4 N	+	SiO_2	-2104

Table 8 (cont.)

Reaction						Enthalpy, cal/g	
2 P	+	N ₂ O ₃	=	2 N	+	P ₂ O ₃	-2101
4 Be	+	MoO ₄	=	Mo	+	4 BeO	-2094
2 Mg	+	CO ₂	=	C	+	2 MgO	-2089
10 P	+	3 N ₂ O ₃	=	6 N	+	5 P ₂ O ₃	-2082
8 P	+	3 N ₂ O ₄	=	6 N	+	4 P ₂ O ₃	-2075
2 Li	+	SiO	=	Si	+	Li ₂ O	-2073
3 Be	+	K ₂ O ₃	=	2 K	+	3 BeO	-2042
6 Li	+	CrO ₃	=	Cr	+	3 Li ₂ O	-2038
Ca	+	N ₂ O	=	2 N	+	CaO	-2037
7 Be	+	Tc ₂ O ₇	=	2 Tc	+	7 BeO	-2026
8 Al	+	3 RuO ₄	=	3 Ru	+	4 Al ₂ O ₃	-2020
3 Zr	+	2 NO ₃	=	2 N	+	3 ZrO ₂	-2013
4 B	+	3 NaC ₂	=	3 Na	+	2 B ₂ O ₃	-2008
Zr	+	2 NO	=	2 N	+	ZrO ₂	-1992
4 Mg	+	RuO ₄	=	Ru	+	4 MgO	-1990
4 Al	+	3 SO ₂	=	3 S	+	2 Al ₂ O ₃	-1950
2 B	+	SO ₃	=	S	+	B ₂ O ₃	-1940
Zr	+	NO ₂	=	N	+	ZrO ₂	-1940
3 C	+	2 NO ₃	=	2 N	+	3 CO ₂	-1925
2 Be	+	MgO ₂	=	Mg	+	2 BeO	-1924
2 Al	+	3 SO	=	3 S	+	Al ₂ O ₃	-1923
2 Mg	+	SO ₂	=	S	+	2 MgO	-1922
10 Al	+	3 MoO ₅	=	3 Mo	+	5 Al ₂ O ₃	-1918
3 Zr	+	2 N ₂ O ₅	=	4 N	+	3 ZrO ₂	-1913
2 Sc	+	3 CO	=	3 C	+	Sc ₂ O ₃	-1907
C	+	2 NO	=	2 N	+	CO ₂	-1905
Mg	+	SO	=	S	+	MgO	-1904
5 Mg	+	MoO ₅	=	Mo	+	5 MgO	-1895
2 Zr	+	N ₂ O ₄	=	2 N	+	2 ZrO ₂	-1890
5 Zr	+	2 N ₂ C ₅	=	4 N	+	5 ZrO ₂	-1890
3 Ti	+	NO ₃	=	N	+	3 TiO	-1870
2 Ti	+	3 N ₂ O	=	6 N	+	Ti ₂ O ₃	-1867

Table 8 (cont.)

Reaction						Enthalpy, cal/g	
5 Be	+	As ₂ O ₅	=	2 As	+	5 BeO	-1860
8 Al	+	3 K ₂ O ₄	=	6 K	+	4 Al ₂ O ₃	-1859
2 V	+	3 NO	=	3 N	+	V ₂ O ₃	-1848
2 V	+	NO ₃	=	N	+	V ₂ O ₃	-1848
4 Sc	+	3 NaO ₂	=	3 Na	+	2 Sc ₂ O ₃	-1845
Ca	+	CO	=	C	+	CaO	-1843
4 Mg	+	K ₂ O ₄	=	2 K	+	4 MgO	-1842
8 Li	+	MoO ₄	=	Mo	+	4 Li ₂ O	-1838
4 B	+	3 CO ₂	=	3 C	+	2 B ₂ O ₃	-1835
2 Be	+	SeO ₂	=	Se	+	2 BeO	-1826
Si	+	2 CO	=	2 C	+	SiO ₂	-1814
8 B	+	3 RuO ₄	=	3 Ru	+	4 B ₂ O ₃	-1802
2 Sc	+	SO ₃	=	S	+	Sc ₂ O ₃	-1802
6 Li	+	K ₂ O ₃	=	2 K	+	3 Li ₂ O	-1800
14 Li	+	Tc ₂ O ₇	=	Tc	+	7 Li ₂ O	-1794
2 Ca	+	NaO ₂	=	Na	+	2 CaO	-1789
2 Al	+	3 SiO	=	3 Si	+	Al ₂ O ₃	-1785
2 Be	+	Na ₂ O ₂	=	2 Na	+	2 BeO	-1785
8 Be	+	Re ₂ C ₈	=	2 Re	+	8 BeO	-1780
Mg	+	SiO	=	Si	+	MgO	-1778
3 Be	+	TcO ₃	=	Tc	+	3 BeO	-1775
4 V	+	3 NO ₂	=	3 N	+	2 V ₂ O ₃	-1767
C	+	NO ₂	=	N	+	CO ₂	-1760
3 Ca	+	SO ₃	=	S	+	3 CaO	-1752
2 V	+	N ₂ O ₃	=	2 N	+	V ₂ O ₃	-1742
8 Sc	+	3 RuO ₄	=	3 Ru	+	4 Sc ₂ O ₃	-1736
4 Sc	+	3 CO ₂	=	3 C	+	2 Sc ₂ O ₃	-1731
8 Li	+	Nb ₂ O ₄	=	2 Nb	+	4 Li ₂ O	-1725
2 Cr	+	3 NO	=	3 N	+	Cr ₂ O ₃	-1723
2 B	+	3 SO	=	3 S	+	B ₂ O ₃	-1712
3 C	+	2 N ₂ O ₃	=	4 N	+	3 CO ₂	-1712
8 V	+	3 N ₂ O ₄	=	6 N	+	4 V ₂ O ₃	-1707
4 Ca	+	RuO ₄	=	Ru	+	4 CaO	-1704

Table 8 (cont.)

Reaction							Enthalpy, cal/g
10 V	+	3 N ₂ O ₅	=	6 N	+	5 V ₂ O ₃	-1703
2 Cr	+	NO ₃	=	N	+	Cr ₂ O ₃	-1702
2 Nb	+	5 NO	=	5 N	+	Nb ₂ O ₅	-1700
Be	+	InO	=	In	+	BeO	-1695
3 Mg	+	CrO ₃	=	Cr	+	3 MgO	-1694
2 P	+	3 N ₂ O	=	6 N	+	P ₂ O ₃	-1693
2 Al	+	CrO ₃	=	Cr	+	Al ₂ O ₃	-1693
4 Be	+	OsO ₄	=	Os	+	4 BeO	-1690
4 Be	+	Rb ₂ O ₄	=	2 Rb	+	4 BeO	-1689
2 Ca	+	CO ₂	=	C	+	2 CaO	-1689
2 Sc	+	3 SO	=	3 S	+	Sc ₂ O ₃	-1678
6 Nb	+	5 NO ₃	=	5 N	+	3 Nb ₂ O ₅	-1676
3 Si	+	2 SO ₃	=	2 S	+	3 SiO ₂	-1665
4 B	+	3 SO ₂	=	3 S	+	2 B ₂ O ₃	-1661
Zr	+	2 N ₂ O	=	4 N	+	ZrO ₂	-1657
Ca	+	SO	=	S	+	CaO	-1655
10 Li	+	As ₂ O ₅	=	2 As	+	5 Li ₂ O	-1649
4 Li	+	SeO ₂	=	Se	+	2 Li ₂ O	-1646
10 B	+	3 MoO ₅	=	3 Mo	+	5 B ₂ O ₃	-1642
2 C	+	N ₂ O ₄	=	2 N	+	2 CO ₂	-1641
4 Sc	+	3 SO ₂	=	3 S	+	2 Sc ₂ O ₃	-1637
5 C	+	2 N ₂ O ₅	=	4 N	+	5 CO ₂	-1630
4 Cr	+	3 NO ₂	=	3 N	+	2 Cr ₂ O ₃	-1628
10 Sc	+	3 MoO ₅	=	3 Mo	+	5 Sc ₂ O ₃	-1626
16 Li	+	Re ₂ O ₈	=	2 Re	+	8 Li ₂ O	-1620
2 Si	+	RuO ₄	=	Ru	+	2 SiO ₂	-1617
4 Li	+	MgO ₂	=	Mg	+	2 Li ₂ O	-1616
2 Ca	+	SO ₂	=	S	+	2 CaO	-1614
2 Li	+	InO	=	In	+	Li ₂ O	-1613
2 Cr	+	N ₂ O ₃	=	2 N	+	Cr ₂ O ₃	-1609
4 Nb	+	5 NO ₂	=	5 N	+	2 Nb ₂ O ₅	-1606
5 Ca	+	MoO ₅	=	Mo	+	5 CaO	-1605
2 Ti	+	3 CO	=	3 C	+	Ti ₂ O ₃	-1600
2 Be	+	MnO ₂	=	Mn	+	2 BeO	-1595
6 Nb	+	5 N ₂ O ₃	=	10 N	+	3 Nb ₂ O ₅	-1588

* Refers to molecular nitrogen and is thus 1/2 N₂.

The oxides of nitrogen are excellent oxidizers because they uniquely combine the characteristics of a slightly positive heat of formation, a small gram-atomic volume, and small values of z and y in their stoichiometric equations. In addition to the unusually large thermal outputs, their reactions are unique in other respects. For instance, with many metals either gaseous nitrogen or a metal nitride is produced:

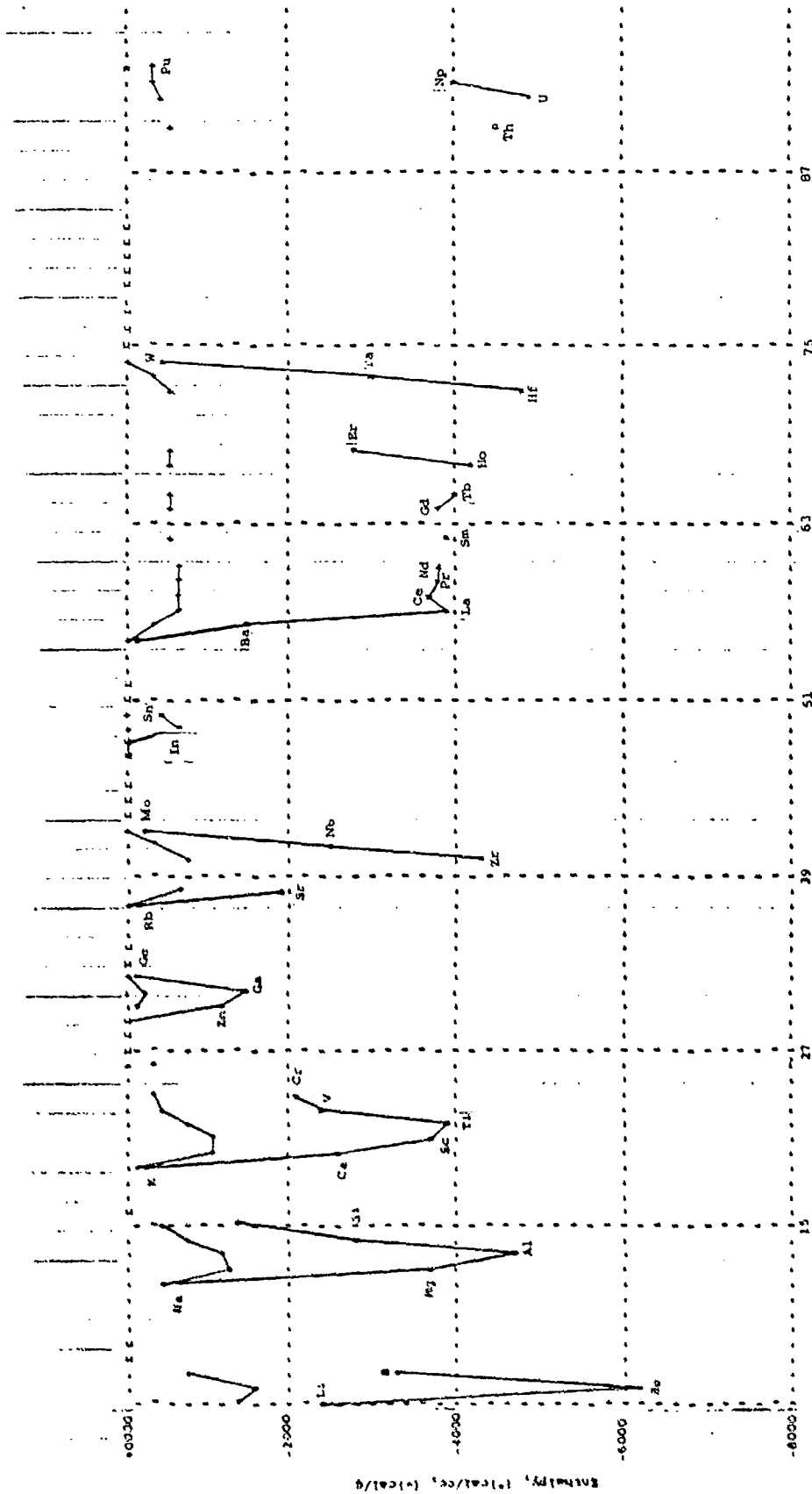


Only the reactions producing gaseous nitrogen were considered here.

The periodicity of the enthalpies is illustrated in Figures 5, 6, and 7. The periodic behavior demonstrated by the oxides is somewhat different from that of the fluorides. Energy peaks (actually minima in the curves) occur at every ninth atomic number, forming the series beryllium, aluminum, titanium, gallium, zirconium, indium, and hafnium. Except for beryllium, these elements comprise Groups IIIA and IVB. In this analysis the elements from lanthanum to lutetium are considered as one unit. The rare earth elements, lanthanum to holmium and probably thorium to element 103, also form a broad energy peak within the peaks separated by nine units. The elements at the energy peaks are characterized by the electronic configuration of their valence orbitals. The electronic configuration in the oxides is the rare gas s^2 or s^2p^6 or the pseudo rare gas $s^2p^6d^{10}$. Other characterizing features of the energy peaks are the high heats of formation of their oxides relative to the oxides of their immediate neighbors, their low gram-atomic volumes, and their low values of z and y due to the stoichiometry of their oxidation states.

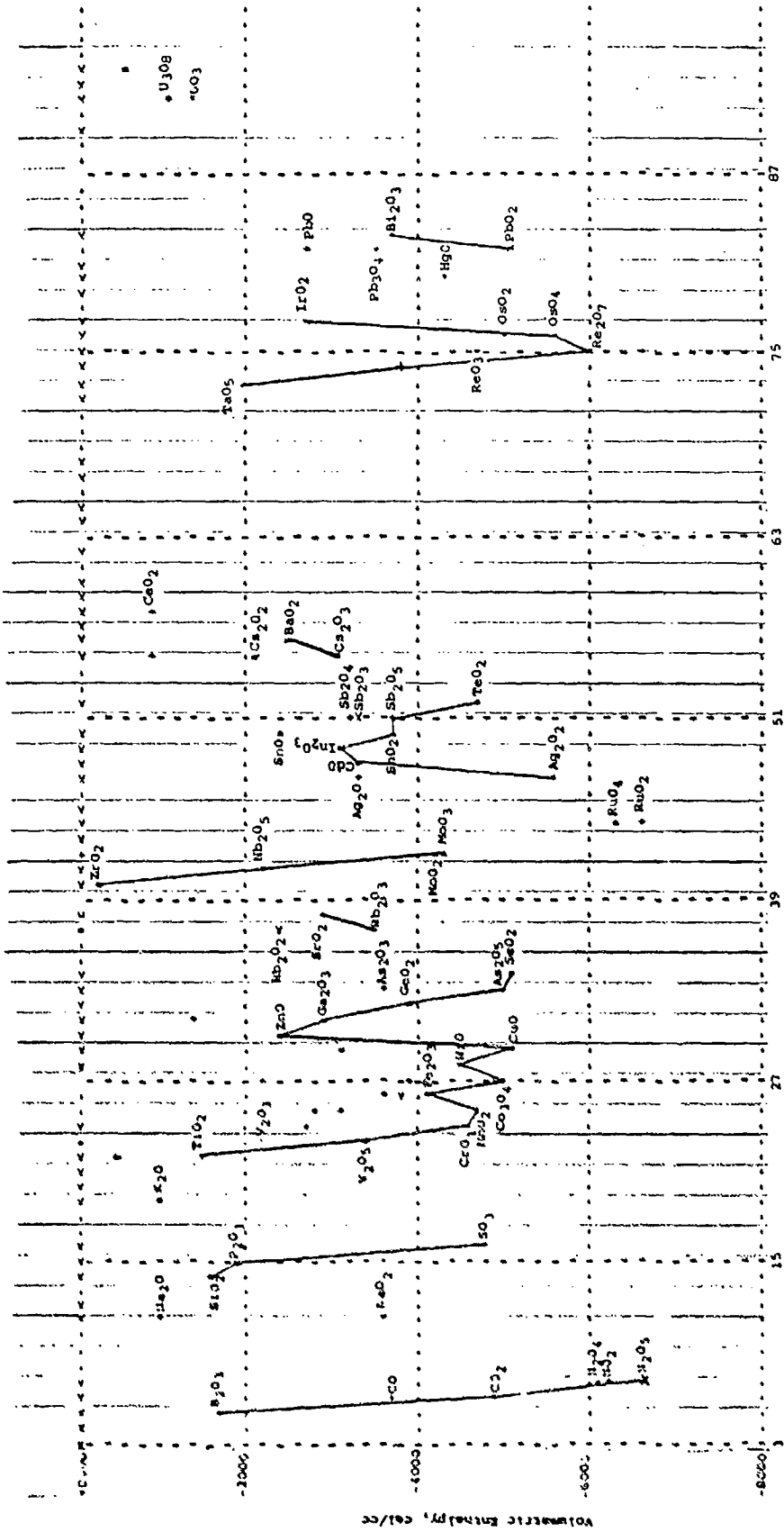
The high volumetric energy outputs exhibited by the reactions with beryllium are due to the extremely low atomic volume of the metal. It also exhibits a high gravimetric energy output because its atomic weight is low. Because of these factors, the heat of formation of the oxide per unit volume and per unit weight is comparatively high. The heat of formation of magnesium oxide is about the same as that of beryllium oxide, but the atomic volume and the atomic weight of the metal are greater. Magnesium reactions are therefore not as energetic as beryllium reactions.

A similar situation exists between boron and aluminum. The smaller atomic volume and atomic weight of boron tend to increase the volumetric and gravimetric energies of its reactions. But aluminum reactions are much more energetic because aluminum oxide has a much higher heat of formation than boric oxide. These factors are discussed more thoroughly under nitrate reactions.



Atomic Number of Metal Reactants

Figure 5
GRAVIMETRIC AND VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS WITH MnO_2



Atomic Number of Metal in the Oxide

Figure 6

VOLUMETRIC ENTHALPIES OF REACTIONS OF OXIDES WITH AL

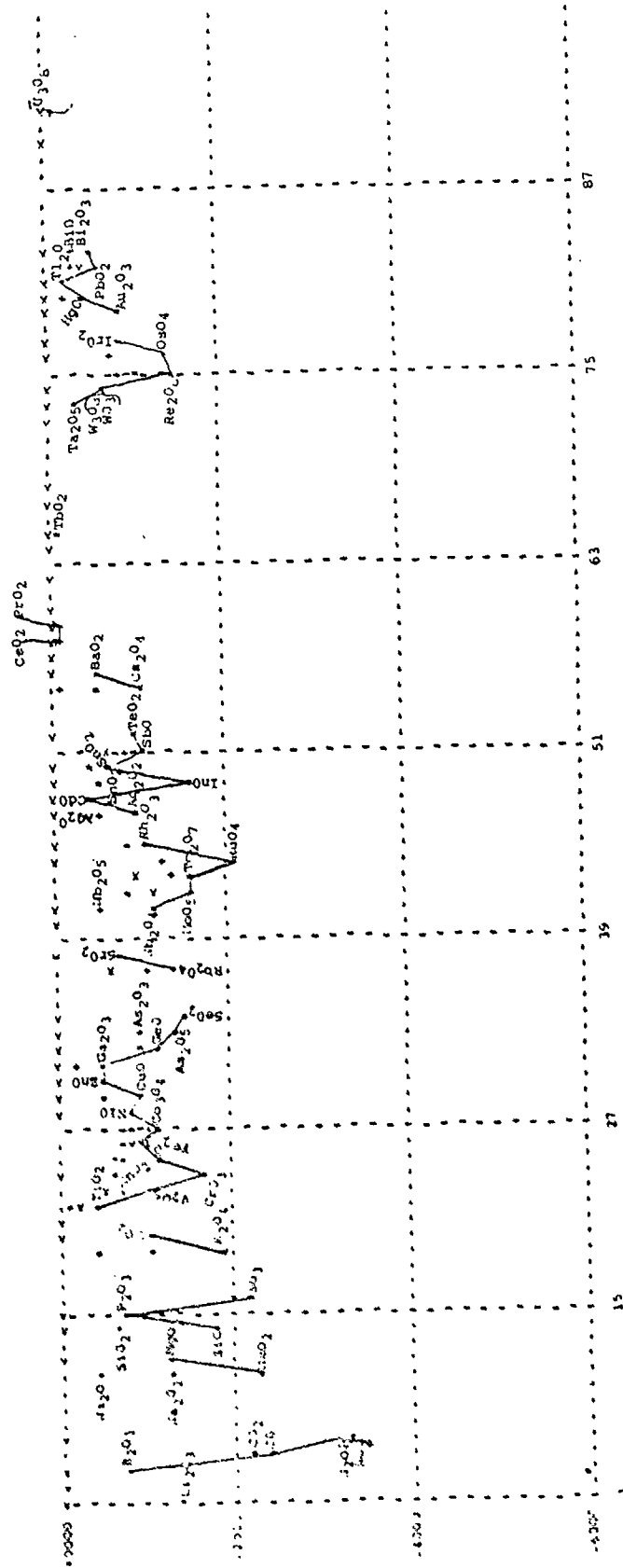


Figure 7
GRAVIMETRIC ENTHALPIES OF REACTIONS OF OXIDES WITH AL

GRAVIMETRIC ENTHALPIES, kcal/mole

Titanium, zirconium, and hafnium occupy peak positions because their gram-atomic volumes are relatively low and the heats of formation of their oxides are relatively high. Although gallium and indium have very low energy outputs, they are higher than their immediate neighbors because of their lower gram-atomic volumes and because of the higher heats of formation of their oxides relative to those of their neighbors. The extremely low gram-atomic volume of beryllium placed it in a peak position, in spite of the relatively low heat of formation of its oxide.

The peak positions of the rare earths lanthanum to holmium are due to the reverse phenomenon. Their relatively large gram-atomic volumes are compensated by the extremely high heats of formation of their oxides. Although data are not available, it seems that the energy outputs of all the members of the rare earth series should be comparable and therefore they will establish a horizontal position in the curve between lanthanum and lutetium. The volumetric energy for erbium is based on a questionable value for the density of the metal--4.77 g/cc.⁵ The anomalous position it occupies in the volumetric curve indicates that this density is probably in error. The interposition of the rare earth elements between zirconium and hafnium plus the lanthanide contraction cause hafnium to have a gram-atomic value comparable to that of zirconium even though its atomic weight is much greater.

The trend of the enthalpies within the various groups of the periodic table is similar to that of the fluorides (Figure 1B). The energy decreases from lithium to cesium. Group IIA energies also decrease from beryllium to barium. The Group II values are higher than the Group I values because all the factors -- ΔH_{AO_x} , gram-atomic volume, z, and y -- are more favorable. Group III elements exhibit a similar trend, but their outputs are lower, because the less favorable z and y values predominate even though their ΔH_{AO_x} 's and gram-atomic volumes are more favorable. This relationship is best illustrated by comparing calcium and gallium, which have gram-atomic volumes of 25.8 and 11.8 cc and ΔH_{AO_x} 's of 152 and 259 kcal, respectively. In spite of these decided advantages, the thermal release of calcium is superior to that of gallium because of the more favorable z and y values. Because of the unusually high heat of formation of its oxide, aluminum occupies an anomalous position above magnesium.

The trend in enthalpies within the transition metal groups in the periodic table is also similar to that of the fluorides (Figure 1C). The first two groups, copper, silver, gold,* and zinc, cadmium, mercury, exhibit a decrease in enthalpy with

* Copper, silver, and gold are not shown on the plot in Figure 5 because their reactions yield positive enthalpies.

increasing atomic number. Their enthalpies are all very low because of their low ΔH_{AO_x} 's. The energies decrease both because the ΔH_{AO_x} 's decrease and because the gram-atomic volumes increase with increasing atomic number.

Within Group IVB (titanium, zirconium, and hafnium), Group VB (vanadium, niobium, and tantalum,) and Group VIB (chromium, molybdenum, and tungsten) the enthalpies increase with atomic number because their gram-atomic volumes and the heats of formation of their oxides become more favorable. In comparing one group with another, however, the normalized enthalpies decrease with increasing group number. The reasons for this differ between Groups IV and V and between Groups V and VI. Even though the gram-atomic volumes and ΔH_{AO_x} 's of Group V are more favorable than those of Group IV, their energies are lower because of the predominant effect of the unfavorable z and y values. Whereas the gram-atomic volumes and the z and y values of Group VI are more favorable, the unfavorable ΔH_{AO_x} 's cause Group VI energies to be even lower than those of Group V.

Curves of the type shown in Figure 5 were drawn for the other oxides. Similar trends were exhibited, but the curves were displaced vertically because of the differences in the parameters of each oxide.

The volumetric and gravimetric enthalpies of the reactions of the various oxides with aluminum metal are shown in Figures 6 and 7, respectively. These curves appear as an inverted version of the curves in Figure 5 because the metals that act as effective reducing agents form oxides that are poor oxidizing agents and vice versa. Thus the maximum volumetric energy outputs occur with the oxides of nitrogen, arsenic, sulfur, selenium, tellurium, the transition metals (chromium, manganese, iron, cobalt, nickel, copper, molybdenum, ruthenium, silver, rhenium, and osmium), and lead. The gravimetric behavior is similar, with the notable exception of the alkali metals. They exhibit relatively high gravimetric outputs, but their volumetric outputs are relatively low because of their very low densities. These curves enable one to determine the best oxide that can be used with aluminum metal for applications involving different parameters. Similar curves were drawn for all the metals.

The volumetric and gravimetric enthalpies of 9636 reactions of the oxides are summarized in Tables 9 and 10, respectively. The most energetic reactions are in the upper left portion of the tables. The most effective oxidizers are on the left and the most effective reducing agents are on the top. The orders of efficacy mentioned previously are confirmed here.

Table 10

GRAVIMETRIC ENTHALPIES OF REACTIONS OF METALS WITH OXIDES
(in descending order from top to bottom and left to right)

	MO ₃	H ₂ O ₅	H ₂ O ₄	H ₂ O ₃	H ₂ O ₂	H ₂ O	B ₂ O ₃	CO	H ₂ O	SO ₂	CO ₂	RuO ₄	SO ₂	MoO ₅	InO	SO	SiO ₂	K ₂ O	CrO ₃	Li ₂ O	MoO ₄	K ₂ O
Be	4549	-6703	6044	-4574	-4484	-4290	-312	-1006	3230	-3151	-3112	-3190	-2635	-2492	-1695	-2452	-2331	-2824	-2458	-2195	-2094	-2042
B	-224	-3054	-2974	-3474	-3823	-3740	-2762	-1124	-2762	-2673	-2450	-2457	-2337	-2278	-2269	-1615	-1921	-1785	-1851	-1397	-1494	-1591
C	-484	-3094	-3036	-3540	-3931	-3823	-2850	-785	-3310	-3244	-3107	-3150	-3020	-2950	-1514	-1904	-1728	-1842	-1434	-1484	-1542	-1591
Ni	-1265	-2940	-3130	-3541	-3930	-3795	-2280	-809	-2244	-2178	-2116	-2089	-1990	-1922	-1892	-1514	-1904	-1728	-1842	-1434	-1484	-1542
Mg	-674	-3483	-3424	-3940	-4327	-4204	-2304	-1210	-2108	-2008	-1940	-1831	-1802	-1743	-1645	-1570	-1570	-1570	-1434	-1154	-1334	-1333
Al	-3740	-2617	-2667	-3207	-3607	-3468	-2118	-693	-1837	-1845	-1802	-1731	-1714	-1628	-1537	-1454	-1454	-1394	-1154	-725	-1007	-1047
Si	-454	-3494	-3541	-4054	-4471	-4337	-3037	-1095	-2491	-2434	-2382	-2314	-2245	-2176	-2085	-1994	-1994	-1934	-1684	-1254	-1434	-1434
Ca	-1874	-2297	-2300	-2827	-3243	-3123	-1647	-992	-3100	-3037	-2986	-2928	-2870	-2812	-2743	-2674	-2614	-2554	-2494	-2064	-244	-311
Fe	-2345	-2792	-2834	-3357	-3783	-3657	-2282	-1674	-4413	-4337	-4266	-4207	-4148	-4089	-4020	-3951	-3891	-3831	-3771	-3341	-372	-487
Sr	-3643	-3400	-3400	-3923	-4346	-4220	-2857	-2245	-5113	-5037	-4971	-4902	-4833	-4764	-4695	-4626	-4557	-4488	-4419	-4089	-446	-511
Zn	-484	-3494	-3541	-4054	-4471	-4337	-3037	-1095	-2491	-2434	-2382	-2314	-2245	-2176	-2085	-1994	-1994	-1934	-1684	-1254	-1434	-1434
Y	-1702	-2141	-2141	-2664	-3087	-2961	-1672	-1066	-3103	-3037	-2986	-2928	-2870	-2812	-2743	-2674	-2614	-2554	-2494	-2064	-244	-311
Ce	-3302	-3100	-3100	-3623	-4046	-3920	-2533	-1921	-4848	-4782	-4731	-4672	-4613	-4554	-4495	-4436	-4376	-4316	-4256	-3826	-424	-491
La	-3544	-3342	-3342	-3865	-4288	-4162	-2746	-2134	-5116	-5040	-4984	-4925	-4866	-4807	-4748	-4689	-4629	-4569	-4409	-4079	-449	-516
C	-1025	-1840	-1740	-2263	-2686	-2560	-1294	-682	-3340	-3274	-3223	-3164	-3105	-3046	-2987	-2928	-2869	-2809	-2749	-2319	-274	-341
Pr	-3544	-3342	-3342	-3865	-4288	-4162	-2746	-2134	-5116	-5040	-4984	-4925	-4866	-4807	-4748	-4689	-4629	-4569	-4409	-4079	-449	-516
Pa	-3544	-3342	-3342	-3865	-4288	-4162	-2746	-2134	-5116	-5040	-4984	-4925	-4866	-4807	-4748	-4689	-4629	-4569	-4409	-4079	-449	-516
Ac	-1374	-1794	-1801	-2324	-2747	-2621	-1357	-745	-3840	-3774	-3723	-3664	-3605	-3546	-3487	-3428	-3369	-3309	-3249	-2819	-324	-391
Th	-1274	-1694	-1701	-2224	-2647	-2521	-1257	-645	-3740	-3674	-3623	-3564	-3505	-3446	-3387	-3328	-3269	-3209	-3149	-2719	-314	-381
U	-1374	-1794	-1801	-2324	-2747	-2621	-1357	-745	-3840	-3774	-3723	-3664	-3605	-3546	-3487	-3428	-3369	-3309	-3249	-2819	-324	-391
Ac	-1374	-1794	-1801	-2324	-2747	-2621	-1357	-745	-3840	-3774	-3723	-3664	-3605	-3546	-3487	-3428	-3369	-3309	-3249	-2819	-324	-391
Sc	-671	-812	-804	-885	-966	-958	-504	-254	-442	-442	-442	-442	-442	-442	-442	-442	-442	-442	-442	-442	-442	-442
Ti	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
V	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Cr	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Mn	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Co	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Ni	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Cu	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Zn	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Fe	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Co	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Ni	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Cu	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Zn	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Fe	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Co	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Ni	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Cu	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Zn	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Fe	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Co	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Ni	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842
Cu	-1071	-1212	-1204	-1285	-1366	-1358	-812	-462	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842	-842

Table 10 (cont.)

Table with 28 columns: Li2O, UO2, B2O3, B2O, Sc2O3, TiO2, HfO2, Pr2O3, MgO, CaO, MgO, HfO2, La2O3, UO2, Pr2O3, Ho2O3, ErO3, Gd2O3, Tb2O3, Ce2O3, Cs2O, Pr2O3, P2O5, SrO, ThO2. Rows list various chemical elements and their corresponding values.

C. Nitrate and Nitrite Reactions

The interactions of 18 nitrates and 8 nitrites with metals were examined, and 1226 reactions resulted. The groups of reactions embodying the nitrates and nitrites are highly energetic. In general, the nitrates are more energetic than the nitrites.

The data for a few of the more energetic reactions are shown in Table 11. These data were abstracted from the series of reactions of elements with lead nitrate listed on the computer data sheets. Reactions with lead nitrate can produce several oxides. For aluminum, boron, beryllium, calcium, and cesium, the most energetic reaction produces Pb_2O . For barium, bismuth, carbon, and cadmium, the most energetic reaction produces PbO . The reactions producing Pb_2O are generally more energetic.

Table 12 lists the 199 most energetic nitrate and nitrite reactions. Beryllium, uranium, hafnium, aluminum, zirconium, thorium, boron, titanium, tantalum, neodymium, lanthanum, scandium, praseodymium, cerium, magnesium, silicon, vanadium, chromium, niobium, gallium, and calcium are the best reducing metals, in that order. Lithium nitrate, lead nitrate, calcium nitrate, strontium nitrate, silver nitrate, sodium nitrate, barium nitrate, potassium nitrate, rubidium nitrate, barium nitrite, silver nitrite, sodium nitrite, and cesium nitrate are the best oxidizing agents, in that order. These relationships are depicted graphically in Figures 8, 9, and 10.

The periodicity of the data is apparent in Figure 8. These curves are similar to those depicting the behavior of oxides with metals, and the same rules seem to be applicable. The "rule of nine" that was observed in the oxide reactions is still valid: the minima in the curve, corresponding to maximum thermal outputs, occur at every ninth atomic number starting with beryllium, aluminum, titanium, gallium, zirconium, indium (no data), lanthanum, and hafnium.

The dotted lines connect the members of a periodic group with five or more members. Thus, the members of Groups IA (lithium, sodium, potassium, rubidium, and cesium) and IIA (beryllium, magnesium, calcium, strontium, and barium) are connected. The energy of the reaction decreases with increasing atomic number of the members of a group. This is generally true for the other "long" groups (IIIA and VIA), except for anomalies evident at aluminum and carbon.

These anomalies are related to the volumetric enthalpy, which is highly dependent upon the heats of formation of the products and reactants, on the volume of the reactants, and on the coefficients of the terms in the balanced equation. Aluminum and boron have the same stoichiometric coefficients, and

Table 11

DATA ON REACTIONS OF VARIOUS METALS WITH LEAD NITRATE

	22 Al	+ 6 Pb(NO ₃) ₂	= 3 Pb ₂ O	+ 11 Al ₂ O ₃	+ 6 N ₂
Heat of formation		-107.35	-51.20	-399.09	28.02
Molecular weight	26.98	331.23	430.42	101.94	
Density	2.70	4.53	8.34	3.97	
Melting point, °C	660.00	470.00		2015.00	-209.86
Boiling point, °C	2327.00			3500.00	-195.80
Heat of reaction, kcal	-3899.49				
Reactants' density	3.92				
Gravimetric enthalpy, cal/g	-1501.88				
Volumetric enthalpy, cal/cc	-5922.77				
	22 B	+ 6 Pb(NO ₃) ₂	= 3 Pb ₂ O	+ 11 B ₂ O ₃	+ 6 N ₂
Heat of formation		-107.35	-51.20	-302.00	28.02
Molecular weight	10.82	331.23	430.42	69.64	
Density	2.37	4.53	8.34	1.84	
Melting point, °C	2040.00	470.00		450.00	-209.86
Boiling point, °C	2550.00			1500.00	-195.00
Heat of reaction, kcal	-2831.50				
Reactants' density	4.13				
Gravimetric enthalpy, cal/g	-1272.34				
Volumetric enthalpy, cal/cc	-5251.75				
	5 Ba	+ Pb(NO ₃) ₂	= PbO	+ 5 BaO	+ N ₂
Heat of formation		-107.35	-52.40	133.40	28.02
Molecular weight	-137.36	331.23	223.21	153.36	
Density	3.50	4.53	8.00	5.72	
Melting point, °C	704.00	470.00		1923.00	-209.86
Boiling point, °C	1638.00			2000.00	-195.80
Heat of reaction, kcal	-612.05				
Reactants' density	3.78				
Gravimetric enthalpy, cal/g	-601.21				
Volumetric enthalpy, cal/cc	-2272.34				

Table 11 (cont.)

	11 Be	+ 2 Pb(NO ₃) ₂	=	Pb ₂ O	+ 11 BeO	+ 2 N ₂
Heat of formation		-107.35		-51.20	-146.00	
Molecular weight	9.01	331.23		430.42	25.01	28.02
Density	1.85	4.53		8.34	3.01	
Melting point, °C	1283.00	470.00			2530.00	-209.86
Boiling point, °C	2970.00				3900.00	-195.80
Heat of reaction, kcal	-1442.50					
Reactants' density	3.81					
Gravimetric enthalpy, cal/g	-1894.03					
Volumetric enthalpy, cal/cc	-7218.66					
	10 Bi	+ 3 Pb(NO ₃) ₂	=	3 PbO	+ 5 Bi ₂ O ₃	+ 3 N ₂
Heat of formation		-107.35		-52.40	-137.90	
Molecular weight	208.99	331.23		223.21	466.00	28.02
Density	9.80	4.53		8.00	8.90	
Melting point, °C	271.00	470.00			820.00	-209.86
Boiling point, °C	1420.00				1890.00	-195.80
Heat of reaction, kcal	-524.65					
Reactants' density	7.13					
Gravimetric enthalpy, cal/g	-170.14					
Volumetric enthalpy, cal/cc	-1212.75					
	5 C	+ 2 Pb(NO ₃) ₂	=	2 PbO	+ 5 CO ₂	+ 2 N ₂
Heat of formation		-107.35		-52.40	-94.05	
Molecular weight	12.01	331.23		223.21	44.01	28.02
Density	2.25	4.53		8.00	1.98	
Melting point, °C	25.00	470.00			-56.20	-209.86
Boiling point, °C	4347.00				-78.50	-195.80
Heat of reaction, kcal	-360.35					
Reactants' density	4.18					
Gravimetric enthalpy, cal/g	-498.74					
Volumetric enthalpy, cal/cc	-2083.80					

Table 11 (cont.)

	11 Ca	+ 2 Pb(NO ₃) ₂	=	Pb ₂ O	+ 11 CaO	+ 2 N ₂
Heat of formation		-107.35		-51.20	-151.90	
Molecular weight	40.08	331.23		430.42	56.08	28.02
Density	1.55	4.53		8.34	3.35	
Melting point, °C	850.00	470.00			2580.00	209.86
Boiling point, °C	1240.00				2850.00	-195.80
Heat of reaction, kcal	-1507.40					
Reactants' density	2.56					
Gravimetric enthalpy, cal/g	-1366.22					
Volumetric enthalpy, cal/cc	-3500.07					
	5 Cd	+ Pb(NO ₃) ₂	=	PbO	+ 5 CaO	+ N ₂
Heat of formation		-107.35		-52.40	-60.86	
Molecular weight	112.41	331.23		223.21	128.41	28.02
Density	8.64	4.53		8.00	8.15	
Melting point, °C	320.90	470.00			900.00	209.86
Boiling point, °C	767.00					-195.80
Heat of reaction, kcal	-249.35					
Reactants' density	6.47					
Gravimetric enthalpy, cal/g	-279.14					
Volumetric enthalpy, cal/cc	-1804.64					
	22 Ce	+ 6 Pb(NO ₃) ₂	=	3 Pb ₂ O	+ 11 Ce ₂ O ₃	+ 6 N ₂
Heat of formation		-107.35		-51.20	-435.00	
Molecular weight	140.13	331.23		430.42	328.26	28.02
Density	6.70	4.53		8.34	6.90	
Melting point, °C	775.00	470.00			1692.00	209.86
Boiling point, °C	2900.00					-195.80
Heat of reaction, kcal	-4294.50					
Reactants' density	5.64					
Gravimetric enthalpy, cal/g	-847.00					
Volumetric enthalpy, cal/cc	-4777.81					

Table 12

MOST ENERGETIC NITRATE AND NITRITE REACTIONS WITH METALS,
IN TERMS OF VOLUMETRIC ENTHALPY

Reaction						Enthalpy, cal/cc
5 Be +	2 Li(NO ₃)	=	Li ₂ O	+ 5 BeO	+ N ₂	-7798
11 Be +	2 Pb(NO ₃) ₂	=	Pb ₂ O	+ 11 BeO	+ 2 N ₂	-7218
5 Be +	Ca(NO ₃) ₂	=	CaO	+ 5 BeO	+ N ₂	-7006
5 Be +	Sr(NO ₃) ₂	=	SrO	+ 5 BeO	+ N ₂	-6697
5 Be +	2 Ag(NO ₃)	=	Ag ₂ O	+ 5 BeO	+ N ₂	-6623
5 U +	4 Li(NO ₃)	=	2 Li ₂ O	+ 5 UO ₂	+ 2 N ₂	-6537
5 Hf +	4 Li(NO ₃)	=	2 Li ₂ O	+ 5 HfO ₂	+ 2 N ₂	-6454
10 Al +	6 Li(NO ₃)	=	3 Li ₂ O	+ 5 Al ₂ O ₃	+ 3 N ₂	-6324
11 U +	4 Pb(NO ₃) ₂	=	2 Pb ₂ O	+ 11 UO ₂	+ 4 N ₂	-6110
5 Be +	2 Na(NO ₃)	=	Na ₂ O	+ 5 BeO	+ N ₂	-6090
11 Hf +	4 Pb(NO ₃) ₂	=	2 Pb ₂ O	+ 11 HfO ₂	+ 4 N ₂	-6042
5 Be +	Ba(NO ₃) ₂	=	BaO	+ 5 BeO	+ N ₂	-5963
5 Zr +	4 Li(NO ₃)	=	2 Li ₂ O	+ 5 ZrO ₂	+ 2 N ₂	-5956
5 U +	2 Ca(NO ₃) ₂	=	2 CaO	+ 5 UO ₂	+ 2 N ₂	-5948
22 Al +	6 Pb(NO ₃) ₂	=	3 Pb ₂ O	+ 11 Al ₂ O ₃	+ 6 N ₂	-5922
5 Hf +	2 Ca(NO ₃) ₂	=	2 CaO	+ 5 HfO ₂	+ 2 N ₂	-5884
5 Th +	4 Li(NO ₃)	=	2 Li ₂ O	+ 5 ThO ₂	+ 2 N ₂	-5849
10 Al +	3 Ca(NO ₃) ₂	=	3 CaO	+ 5 Al ₂ O ₃	+ 3 N ₂	-5767
10 B +	6 Li(NO ₃)	=	3 Li ₂ O	+ 5 B ₂ O ₃	+ 2 N ₂	-5674
5 U +	2 Sr(NO ₃) ₂	=	2 SrO	+ 5 UO ₂	+ 2 N ₂	-5674
5 U +	4 Ag(NO ₃)	=	2 Ag ₂ O	+ 5 UO ₂	+ 2 N ₂	-5672
5 Hf +	4 Ag(NO ₃)	=	2 Ag ₂ O	+ 5 HfO ₂	+ 2 N ₂	-5618
5 Hf +	2 Sr(NO ₃) ₂	=	2 SrO	+ 5 HfO ₂	+ 2 N ₂	-5616
10 Ti +	6 Li(NO ₃)	=	3 Li ₂ O	+ 5 Ti ₂ O ₃	+ 3 N ₂	-5603
11 Zr +	4 Pb(NO ₃) ₂	=	2 Pb ₂ O	+ 11 ZrO ₂	+ 4 N ₂	-5594
11 Th +	4 Pb(NO ₃) ₂	=	2 Pb ₂ O	+ 11 ThO ₂	+ 4 N ₂	-5544
10 Al +	6 Ag(NO ₃)	=	3 Ag ₂ O	+ 5 Al ₂ O ₃	+ 3 N ₂	-5510
10 Al +	3 Sr(NO ₃) ₂	=	3 SrO	+ 5 Al ₂ O ₃	+ 3 N ₂	-5500
5 Zr +	2 Ca(NO ₃) ₂	=	2 CaO	+ 5 ZrO ₂	+ 2 N ₂	-5452

Table 12 (cont.)

Reaction		Enthalpy, cal/cc
5 Th + 2 Ca(NO ₃) ₂ = 2 CaO	+ 5 ThO ₂ + 2 N ₂	-5422
22 Ti + 6 Pb(NO ₃) ₂ = 3 Pb ₂ O	+ 11 Ti ₂ O ₃ + 6 N ₂	-5270
22 B + 6 Pb(NO ₃) ₂ = 3 Pb ₂ O	+ 11 B ₂ O ₃ + 5 N ₂	-5251
5 Th + 4 Ag(NO ₃) = 2 Ag ₂ O	+ 5 ThO ₂ + 2 N ₂	-5224
5 Zr + 4 Ag(NO ₃) = 2 Ag ₂ O	+ 5 ZrO ₂ + 2 N ₂	-5223
5 Th + 2 Sr(NO ₃) ₂ = 2 SrO	+ 5 ThO ₂ + 2 N ₂	-5199
5 Zr + 2 Sr(NO ₃) ₂ = 2 SrO	+ 5 ZrO ₂ + 2 N ₂	-5195
5 Ta + 2 Li(NO ₃) = Li ₂ O	+ Ta ₂ O ₅ + N ₂	-5163
5 U + 4 Na(NO ₃) = 2 Na ₂ O	+ 5 UO ₂ + 2 N ₂	-5151
10 Ti + 3 Ca(NO ₃) ₂ = 3 CaO	+ 5 Ti ₂ O ₃ + 3 N ₂	-5137
5 Hf + 4 Na(NO ₃) = 2 Na ₂ O	+ 5 HfO ₂ + 2 N ₂	-5104
10 B + 3 Ca(NO ₃) ₂ = 3 CaO	+ 5 B ₂ O ₃ + 3 N ₂	-5088
10 Nd + 6 Li(NO ₃) = 3 Li ₂ O	+ 5 Nd ₂ O ₃ + 3 N ₂	-5080
5 U + 2 Ba(NO ₃) ₂ = 2 BaO	+ 5 UO ₂ + 2 N ₂	-5078
10 La + 6 Li(NO ₃) = 3 Li ₂ O	+ 5 La ₂ O ₃ + 3 N ₂	-5067
3 Be + 2 Ag(NO ₂) = Ag ₂ O	+ 3 BeO + N ₂	-5064
10 Sc + 6 Li(NO ₃) = 3 Li ₂ O	+ 5 Sc ₂ O ₃ + 3 N ₂	-5062
5 Hf + 2 Ba(NO ₃) ₂ = 2 BaO	+ 5 HfO ₂ + 2 N ₂	-5034
10 Pr + 6 Li(NO ₃) = 3 Li ₂ O	+ 5 Pr ₂ O ₃ + 3 N ₂	-5012
10 Al + 6 Na(NO ₃) = 3 Na ₂ O	+ 5 Al ₂ O ₃ + 3 N ₂	-4991
10 Ce + 6 Li(NO ₃) = 3 Li ₂ O	+ 5 Ce ₂ O ₃ + 3 N ₂	-4988
5 Mg + 2 Li(NO ₃) = Li ₂ O	+ 5 MgO + N ₂	-4936
10 Ti + 6 Ag(NO ₃) = 3 Ag ₂ O	+ 5 Ti ₂ O ₃ + 3 N ₂	-4932
10 Al + 3 Ba(NO ₃) ₂ = 3 BaO	+ 5 Al ₂ O ₃ + 3 N ₂	-4927
10 Ti + 3 Sr(NO ₃) ₂ = 3 SrO	+ 5 Ti ₂ O ₃ + 3 N ₂	-4884
5 Si + 4 Li(NO ₃) = 2 Li ₂ O	+ 5 SiO ₂ + 2 N ₂	-4877
22 Nd + 6 Pb(NO ₃) ₂ = 3 Pb ₂ O	+ 11 Nd ₂ O ₃ + 6 N ₂	-4864
22 La + 6 Pb(NO ₃) ₂ = 3 Pb ₂ O	+ 11 La ₂ O ₃ + 6 N ₂	-4860
10 B + 6 Ag(NO ₃) = 3 Ag ₂ O	+ 5 B ₂ O ₃ + 3 N ₂	-4842
5 Be + 2 K(NO ₃) = K ₂ O	+ 5 BeO + N ₂	-4831

Table 12 (cont.)

Reaction		Enthalpy, cal/cc
22 Sc + 6 Pb(NO ₃) ₂	= 3 Pb ₂ O + 11 Sc ₂ O ₃ + 6 N ₂	-4830
5 Be + 2 Rb(NO ₃)	= Rb ₂ O + 5 BeO + N ₂	-4821
22 Ta + 10 Pb(NO ₃) ₂	= 5 Pb ₂ O + 11 Ta ₂ O ₅ + 10 N ₂	-4821
22 Pr + 6 Pb(NO ₃) ₂	= 3 Pb ₂ O + 11 Pr ₂ O ₃ + 6 N ₂	-4804
22 Ce + 6 Pb(NO ₃) ₂	= 3 Pb ₂ O + 11 Ce ₂ O ₃ + 6 N ₂	-4777
10 B + 3 Sr(NO ₃) ₂	= 5 SrO + 5 B ₂ O ₃ + 3 N ₂	-4775
5 Th + 4 Na(NO ₃)	= 2 Na ₂ O + 5 ThO ₂ + 2 N ₂	-4774
10 Nd + 3 Ca(NO ₃) ₂	= 3 CaO + 5 Nd ₂ O ₃ + 3 N ₂	-4773
10 La + 3 Ca(NO ₃) ₂	= 3 CaO + 5 La ₂ O ₃ + 3 N ₂	-4772
10 Sc + 3 Ca(NO ₃) ₂	= 3 CaO + 5 Sc ₂ O ₃ + 3 N ₂	-4733
11 Mg + 2 Pb(NO ₃) ₂	= Pb ₂ O + 11 MgO + 2 N ₂	-4729
5 Th + 2 Ba(NO ₃) ₂	= 2 BaO + 5 ThO ₂ + 2 N ₂	-4728
10 Pr + 3 Ca(NO ₃) ₂	= 3 CaO + 5 Pr ₂ O ₃ + 3 N ₂	-4716
5 Zr + 1 Na(NO ₃)	= 2 Na ₂ O + 5 ZrO ₂ + 2 N ₂	-4708
2 Nb + 2 Li(NO ₃)	= Li ₂ O + Nb ₂ O ₅ + N ₂	-4707
10 Ce + 3 Ca(NO ₃) ₂	= 3 CaO + 5 Ce ₂ O ₃ + 3 N ₂	-4688
2 Ta + Ca(NO ₃) ₂	= CaO + Ta ₂ O ₅ + N ₂	-4683
3 Be + 2 Na(NO ₂)	= Na ₂ O + 3 BeO + N ₂	-4670
5 Zr + 2 Ba(NO ₃) ₂	= 2 BaO + 5 ZrO ₂ + 2 N ₂	-4658
5 Mg + Ca(NO ₃) ₂	= CaO + 5 MgO + N ₂	-4641
10 La + 6 Ag(NO ₃)	= 3 Ag ₂ O + 5 La ₂ O ₃ + 3 N ₂	-4640
3 Be + Ba(NO ₂) ₂	= BaO + 3 BeO + N ₂	-4640
10 La + 3 Sr(NO ₃) ₂	= 3 SrO + 5 La ₂ O ₃ + 3 N ₂	-4591
10 Sc + 6 Ag(NO ₃)	= 3 Ag ₂ O + 5 Sc ₂ O ₃ + 3 N ₂	-4589
11 Si + 4 Pb(NO ₃) ₂	= 2 Pb ₂ O + 11 SiO ₂ + 4 N ₂	-4587
10 Nd + 3 Sr(NO ₃) ₂	= 3 SrO + 5 Nd ₂ O ₃ + 3 N ₂	-4584
10 Pr + 6 Ag(NO ₃)	= 3 Ag ₂ O + 5 Pr ₂ O ₃ + 3 N ₂	-4584
10 V + 6 Li(NO ₃)	= 3 Li ₂ O + 5 V ₂ O ₃ + 3 N ₂	-4571
10 Ce + 6 Ag(NO ₃)	= 3 Ag ₂ O + 5 Ce ₂ O ₃ + 3 N ₂	-4556
10 Pr + 3 Sr(NO ₃) ₂	= 3 SrO + 5 Pr ₂ O ₃ + 3 N ₂	-4531

Table 12 (cont.)

Reaction		Enthalpy, cal/cc
10 Sc + 3 Sr(NO ₃) ₂	= 3SrO + 5 Sc ₂ O ₃ + 3 N ₂	-4531
5 Mg + 2 Ag(NO ₃) ₂	= Ag ₂ O + 5 MgO + N ₂	-4512
10 Ce + 3 Sr(NO ₃) ₂	= 3 SrO + 5 Ce ₂ O ₃ + 3 N ₂	-4501
2 Ta + 2 Ag(NO ₃) ₂	= Ag ₂ O + Ta ₂ O ₅ + N ₂	-4489
5 Si + 2 Ca(NO ₃) ₂	= 2 CaO + 5 SiO ₂ + 2 N ₂	-4467
5 Mg + Sr(NO ₃) ₂	= SrO + 5 MgO + N ₂	-4454
3 U + 4 Ag(NO ₂) ₂	= 2 Ag ₂ O + 3 UO ₂ + 2 N ₂	-4433
10 Ti + 6 Na(NO ₃) ₂	= 3 Na ₂ O + 5 Ti ₂ O ₃ + 3 N ₂	-4409
22 Nb + 10 Pb(NO ₃) ₂	= 5 Pb ₂ O + 11 Nb ₂ O ₅ + 10 N ₂	-4408
3 HF + 4 Ag(NO ₂) ₂	= 2 Ag ₂ O + 3 HfO ₂ + 2 N ₂	-4407
10 Cr + 6 Li(NO ₃) ₂	= 3 Li ₂ O + 5 Cr ₂ O ₃ + 3 N ₂	-4405
2 Ta + Sr(NO ₃) ₂	= SrO + Ta ₂ O ₅ + N ₂	-4399
5 Be + 2 Cs(NO ₃) ₂	= Cs ₂ O + 5 BeO + N ₂	-4377
10 Ti + 3 Ba(NO ₃) ₂	= 3 BaO + 5 Ti ₂ O ₃ + 3 N ₂	-4373
2 Al + 2 Ag(NO ₂) ₂	= Ag ₂ O + Al ₂ O ₃ + N ₂	-4323
22 V + 6 Pb(NO ₃) ₂	= 3 Pb ₂ O + 11 V ₂ O ₃ + 6 N ₂	-4306
5 Si + 4 Ag(NO ₃) ₂	= 2 Ag ₂ O + 5 SiO ₂ + 2 N ₂	-4303
2 Nb + Ca(NO ₃) ₂	= CaO + Nb ₂ O ₃ + N ₂	-4285
10 La + 6 Na(NO ₃) ₂	= 3 Na ₂ O + 5 La ₂ O ₃ + 3 N ₂	-4250
3 Th + 4 Ag(NO ₂) ₂	= 2 Ag ₂ O + 3 ThO ₂ + 2 N ₂	-4232
10 Nd + 6 Na(NO ₃) ₂	= 3 Na ₂ O + 5 Nd ₂ O ₃ + 3 N ₂	-4230
10 La + 3 Ba(NO ₃) ₂	= 3 BaO + 5 La ₂ O ₃ + 3 N ₂	-4229
10 Nd + 3 Ba(NO ₃) ₂	= 3 BaO + 5 Nd ₂ O ₃ + 3 N ₂	-4209
5 Si + 2 Sr(NO ₃) ₂	= 2 SrO + 5 SiO ₂ + 2 N ₂	-4207
10 B + 6 Na(NO ₃) ₂	= 3 Na ₂ O + 5 B ₂ O ₃ + 3 N ₂	-4199
10 V + 3 Ca(NO ₃) ₂	= 3 CaO + 5 V ₂ O ₃ + 3 N ₂	-4195
10 Pr + 6 Na(NO ₃) ₂	= 3 Na ₂ O + 5 Pr ₂ O ₄ + 3 N ₂	-4185
10 B + 3 Ba(NO ₃) ₂	= 3 BaO + 5 B ₂ O ₃ + 3 N ₂	-4168
10 Pr + 3 Ba(NO ₃) ₂	= 3 BaO + 5 Pr ₂ O ₃ + 3 N ₂	-4166
10 Sc + 6 Na(NO ₃) ₂	= 3 Na ₂ O + 5 Sc ₂ O ₃ + 3 N ₂	-4153

Table 12 (cont.)

Reaction		Enthalpy, cal/cc
10 Ce + 6 Na(NO ₃)	= 3 Na ₂ O + 5 Ce ₂ O ₃ + 3 N ₂	-4149
22 Cr + 6 Pb(NO ₃) ₂	= 3 Pb ₂ O + 11 Cr ₂ O ₃ + 6 N ₂	-4143
10 Sc + 3 Ba(NO ₃) ₂	= 3 BaO + 5 Sc ₂ O ₃ + 3 N ₂	-4143
10 Ce + 3 Ba(NO ₃) ₂	= 3 BaO + 5 Ce ₂ O ₃ + 3 N ₂	-4131
3 Zr + 4 Ag(NO ₂)	= 2 Ag ₂ O + 3 ZrO ₂ + 2 N ₂	-4126
2 Nb + 2 Ag(NO ₃)	= Ag ₂ O + Nb ₂ O ₃ + N ₂	-4124
5 U + 4 K(NO ₃)	= 2 K ₂ O + 5 UO ₂ + 2 N ₂	-4118
5 Mg + 2 Na(NO ₃)	= Na ₂ O + 5 MgO + N ₂	-4104
5 U + 4 Rb(NO ₃)	= 2 Rb ₂ O + 5 UO ₂ + 2 N ₂	-4103
5 Hf + 4 K(NO ₃)	= 2 K ₂ O + 5 HfO ₂ + 2 N ₂	-4092
5 Mg + Ba(NO ₃) ₂	= BaO + 5 MgO + N ₂	-4088
5 Hf + 4 Rb(NO ₃)	= 2 Rb ₂ O + 5 HfO ₂ + 2 N ₂	-4077
10 V + 6 Ag(NO ₃)	= 3 Ag ₂ O + 5 V ₂ O ₃ + 3 N ₂	-4051
3 U + 2 Ba(NO ₂) ₂	= 2 BaO + 3 UO ₂ + 2 N ₂	-4043
10 Cr + 3 Ca(NO ₃) ₂	= 3 CaO + 5 Cr ₂ O ₃ + 3 N ₂	-4031
3 Hf + 2 Ba(NO ₂) ₂	= 2 BaO + 3 HfO ₂ + 2 N ₂	-4022
3 U + 4 Na(NO ₂)	= 2 Na ₂ O + 3 UO ₂ + 2 N ₂	-4018
2 Nb + Sr(NO ₃) ₂	= SrO + Nb ₂ O ₅ + N ₂	-4006
3 Hf + 4 Na(NO ₂)	= 2 Na ₂ O + 3 HfO ₂ + 2 N ₂	-3996
10 Al + 6 K(NO ₃)	= 3 K ₂ O + 5 Al ₂ O ₃ + 3 N ₂	-3995
10 Al + 6 Rb(NO ₃)	= 3 Rb ₂ O + 5 Al ₂ O ₃ + 3 N ₂	-3980
2 Al + Ba(NO ₂) ₂	= BaO + Al ₂ O ₃ + N ₂	-3940
10 V + 3 Sr(NO ₃) ₂	= 3 SrO + 5 V ₂ O ₃ + 3 N ₂	-3936
5 Th + 4 K(NO ₃)	= 2 K ₂ O + 5 ThO ₂ + 2 N ₂	-3933
5 Th + 4 Rb(NO ₃)	= 2 Rb ₂ O + 5 ThO ₂ + 2 N ₂	-3920
2 Al + 2 Na(NO ₂)	= Na ₂ O + Al ₂ O ₃ + N ₂	-3906
2 Ti + 2 Ag(NO ₂)	= Ag ₂ O + Ti ₂ O ₃ + N ₂	-3905
10 Cr + 6 Ag(NO ₃)	= 3 Ag ₂ O + 5 Cr ₂ O ₃ + 3 N ₂	-3895
3 Th + 2 Ba(NO ₂) ₂	= 2 BaO + 3 ThO ₂ + 2 N ₂	-3892
2 La + 2 Ag(NO ₂)	= Ag ₂ O + La ₂ O ₃ + N ₂	-3885

Table 12 (cont.)

Reaction						Enthalpy, cal/cc
2 Ta +	2 Na(NO ₃)	=	Na ₂ O	+	Ta ₂ O ₅ + N ₂	-3873
5 Mn +	2 Li(NO ₃)	=	Li ₂ O	+	5 MnO + N ₂	-3869
2 Ta +	Ba(NO ₃) ₂	=	BaO	+	Ta ₂ O ₅ + N ₂	-3866
3 Th +	4 Na(NO ₂)	=	2 Na ₂ O	+	3 ThO ₂ + 2 N ₂	-3859
2 Nd +	2 Ag(NO ₂)	=	Ag ₂ O	+	Nd ₂ O ₃ + N ₂	-3858
2 Pr +	2 Ag(NO ₂)	=	Ag ₂ O	+	Pr ₂ O ₃ + N ₂	-3828
2 Ce +	2 Ag(NO ₂)	=	Ag ₂ O	+	Ce ₂ O ₃ + N ₂	-3793
2 Sc +	2 Ag(NO ₂)	=	Ag ₂ O	+	Sc ₂ O ₃ + N ₂	-3778
5 Zr +	4 K(NO ₃)	=	2 K ₂ O	+	5 ZrO ₂ + 2 N ₂	-3774
10 Cr +	3 Sr(NO ₃) ₂	=	3 SrO	+	5 Cr ₂ O ₃ + 3 N ₂	-3763
3 Mg +	2 Ag(NO ₂)	=	Ag ₂ O	+	3 MgO + N ₂	-3760
5 Zr +	4 Rb(NO ₃)	=	2 Rb ₂ O	+	5 ZrO ₂ + 2 N ₂	-3757
3 Zr +	2 Ba(NO ₂) ₂	=	2 BaO	+	3 ZrO ₂ + 2 N ₂	-3752
5 U +	4 Cs(NO ₃)	=	2 Cs ₂ O	+	5 UO ₂ + 2 N ₂	-3739
5 Si +	4 Na(NO ₃)	=	2 Na ₂ O	+	5 SiO ₂ + 2 N ₂	-3731
5 Si +	2 Ba(NO ₃) ₂	=	2 BaO	+	5 SiO ₂ + 2 N ₂	-3728
5 Hf +	4 Cs(NO ₃)	=	2 Cs ₂ O	+	5 HfO ₂ + 2 N ₂	-3720
3 Zr +	4 Na(NO ₂)	=	2 Na ₂ O	+	3 ZrO ₂ + 2 N ₂	-3702
11 Mn +	2 Pb(NO ₃) ₂	=	Pb ₂ O	+	11 MnO + 2 N ₂	-3686
2 B +	2 Ag(NO ₂)	=	Ag ₂ O	+	B ₂ O ₃ + N ₂	-3681
10 Al +	6 Cs(NO ₃)	=	3 Cs ₂ O	+	5 Al ₂ O ₃ + 3 N ₂	-3629
5 Th +	4 Cs(NO ₃)	=	2 Cs ₂ O	+	5 ThO ₂ + 2 N ₂	-3615
5 Mn +	Ca(NO ₃) ₂	=	CaO	+	5 MnO + N ₂	-3602
2 La +	Ba(NO ₂) ₂	=	BaO	+	La ₂ O ₃ + N ₂	-3592
10 La +	6 K(NO ₃)	=	3 K ₂ O	+	5 La ₂ O ₃ + 3 N ₂	-3588
5 Ca +	2 Li(NO ₃)	=	Li ₂ O	+	5 CaO + N ₂	-3585
10 La +	6 Rb(NO ₃)	=	3 Rb ₂ O	+	5 La ₂ O ₃ + 3 N ₂	-3574
2 Nd +	Ba(NO ₂) ₂	=	BaO	+	Nd ₂ O ₃ + N ₂	-3557
10 Nd +	6 K(NO ₃)	=	3 K ₂ O	+	5 Nd ₂ O ₃ + 3 N ₂	-3548
2 La +	2 Na(NO ₂)	=	Na ₂ O	+	La ₂ O ₃ + N ₂	-3542

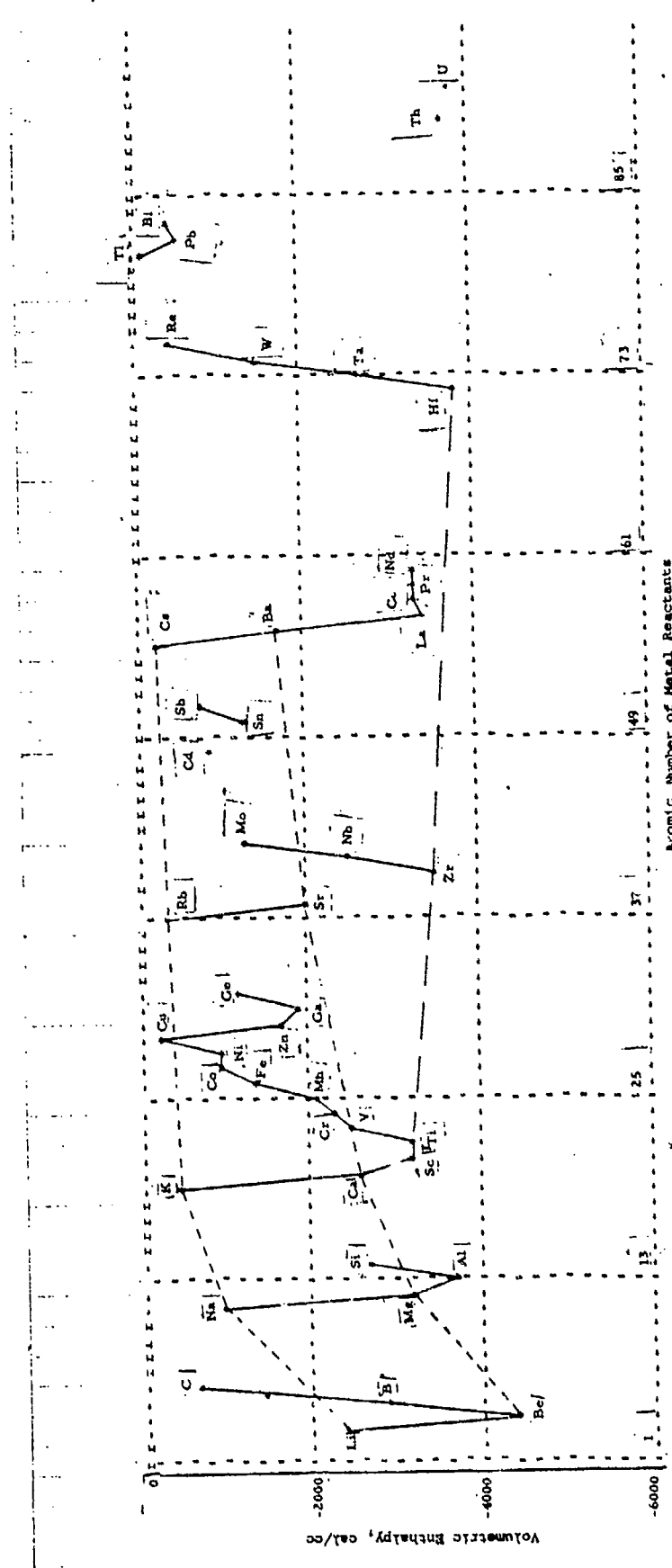


Figure 8
 VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS WITH CaNO_3

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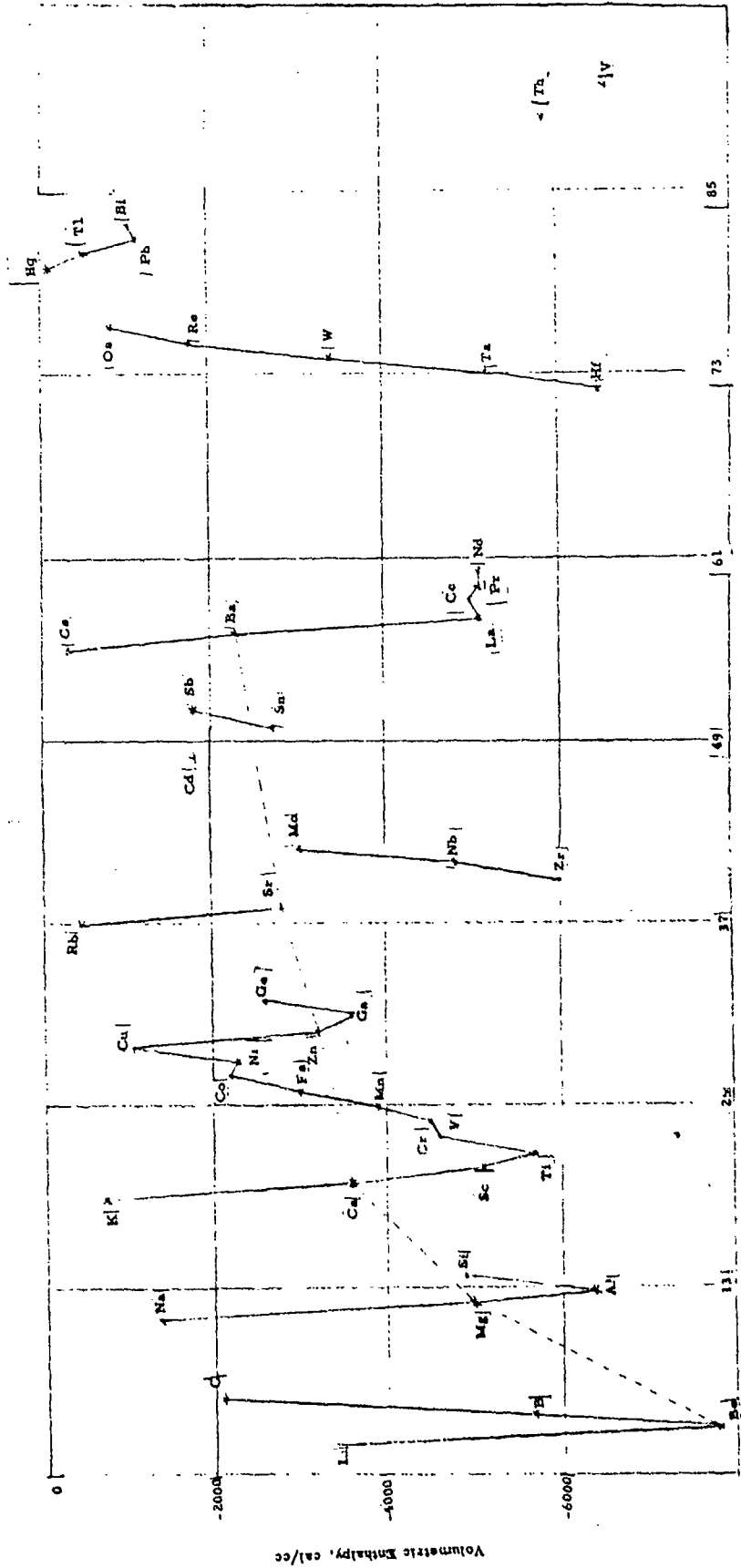
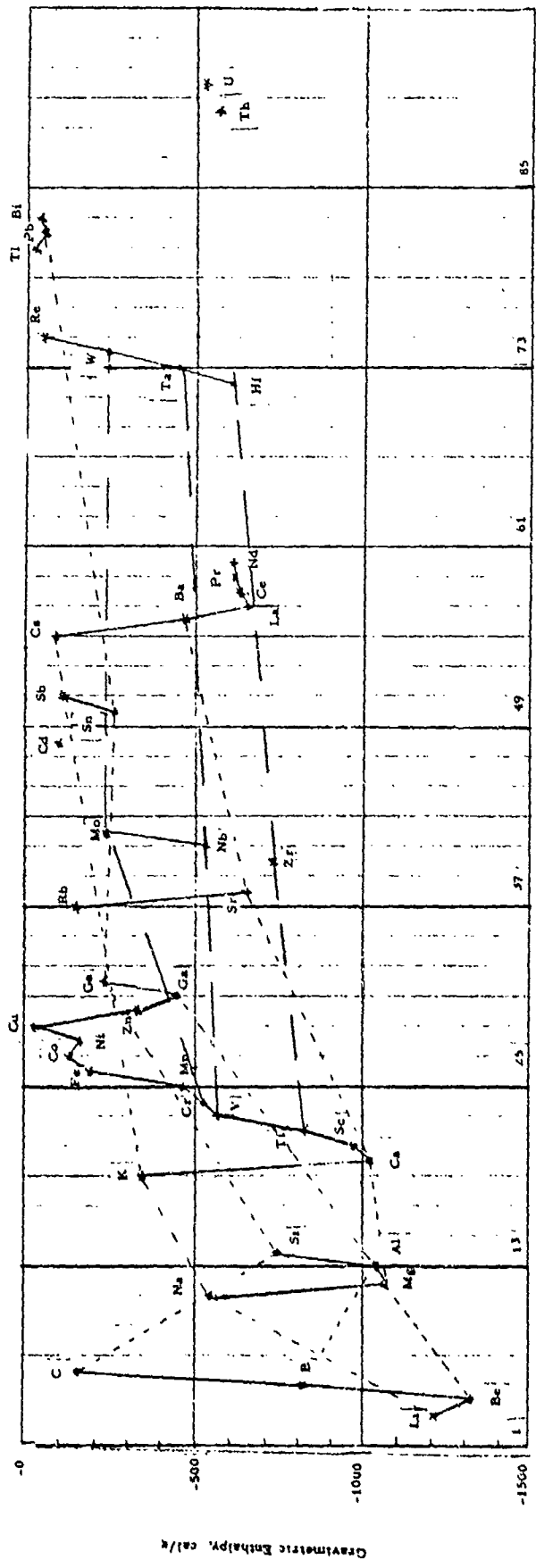


Figure 9
 VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS WITH LiNO₃



Atomic Number of Metal Reactants

Figure 10

GRAVIMETRIC ENTHALPIES OF REACTIONS OF METALS WITH CaNO_3

the products and reactants are the same except for boric oxide and aluminum oxide. Thus the coefficients of the reaction, the heat of formation, the volume of the nitrate, and the volume of the resultant oxide are not involved in the fact that aluminum reactions are more energetic than boron reactions. The remaining factors contributing to the reaction enthalpy are the atomic volumes of boron and aluminum and the heats of formation of boric oxide and aluminum oxide. Since boron's atomic volume, 4.57 cc, is much less than that of aluminum, 9.99 cc, its reactions would be expected to be more energetic. However, the unusually high heat of formation of aluminum oxide compared with that of boric oxide, -399 and -302 kcal, respectively, causes the aluminum reactions to be especially energetic. The effect of the heat of formation is enhanced by the stoichiometric coefficient of these oxides in the balanced equation because these factors multiply the difference between the heats of formation.

Comparison of beryllium and magnesium illustrates this further. Beryllium has a much lower atomic volume than magnesium, 4.94 compared with 13.95 cc. But unlike aluminum and boron, the heat of formation of magnesium oxide is slightly less than that of beryllium oxide, -144 compared with -146 kcal, so that beryllium reactions are more energetic than magnesium reactions. A similar situation in reverse exists with carbon. Its reaction energies are low compared with those of silicon because of the low heat of formation of carbon dioxide compared with that of silicon dioxide, -94 compared with -205 kcal.

Except for these anomalies, the reactions in a group become less energetic with increasing atomic number of the metal reactant. Group I has the least energetic reactions and Group II the most energetic. Group I reactions are not energetic because of the large atomic volumes of the metals and the low heats of formation of the oxides. The Group II and VI reactions are intermediate between the Group I and II extremes.

The dashed lines in Figure 8 connect members of the "short" groups in the periodic table. These groups also have an interesting behavior. In the first three groups in the series, Group IIIB (scandium, yttrium, and lanthanum), Group IVB (titanium, zirconium, and hafnium), and Group VB (vanadium, niobium, and tantalum), the reaction energy increases with increasing atomic number. The remaining groups, Group VIB (chromium, molybdenum, and tungsten), Group VIIB (manganese, technetium, and rhenium), Group VIII (iron, ruthenium, dysprosium, cobalt, rhodium, iridium, nickel, palladium, and platinum), Group IB (copper, silver, and gold), and Group IIB (zinc, cadmium, and mercury), exhibit a decrease in energy with increasing atomic number. The members of Group VIII are not

evident because their reactions in general have a positive enthalpy and are not recorded. As drawn in Figure 8, the dashed lines (only one is drawn in for reference) connecting the members in Groups IIB, IVB, VB, VIB, VIIB, and IIB start with a negative slope for Group IIB and become more positive for each group in the above order. Some of the reasons for this behavior have been discussed previously with respect to the lanthanide contraction.

Figures 9, 10, and 11 illustrate that the reactions of metals with other nitrates or nitrites exhibit the same behavior except for vertical displacement of the ordinate scale. The two nitrates chosen represent the extremes of reaction energy with any particular metal, lithium nitrate (Figure 9) being the most energetic and cesium nitrate (Figure 10) the least energetic of those included in this study.

The gravimetric relationships are essentially the same as the volumetric ones (Figures 9 and 11 versus Figure 10) except for reversal of the magnesium and aluminum energies. Magnesium is more energetic on the gravimetric basis because the small atomic volume of aluminum is not involved. The energy decreases with increasing atomic number of the Group IIB and IVB elements. These elements behave normally on a gravimetric basis because the lanthanide contraction is not involved.

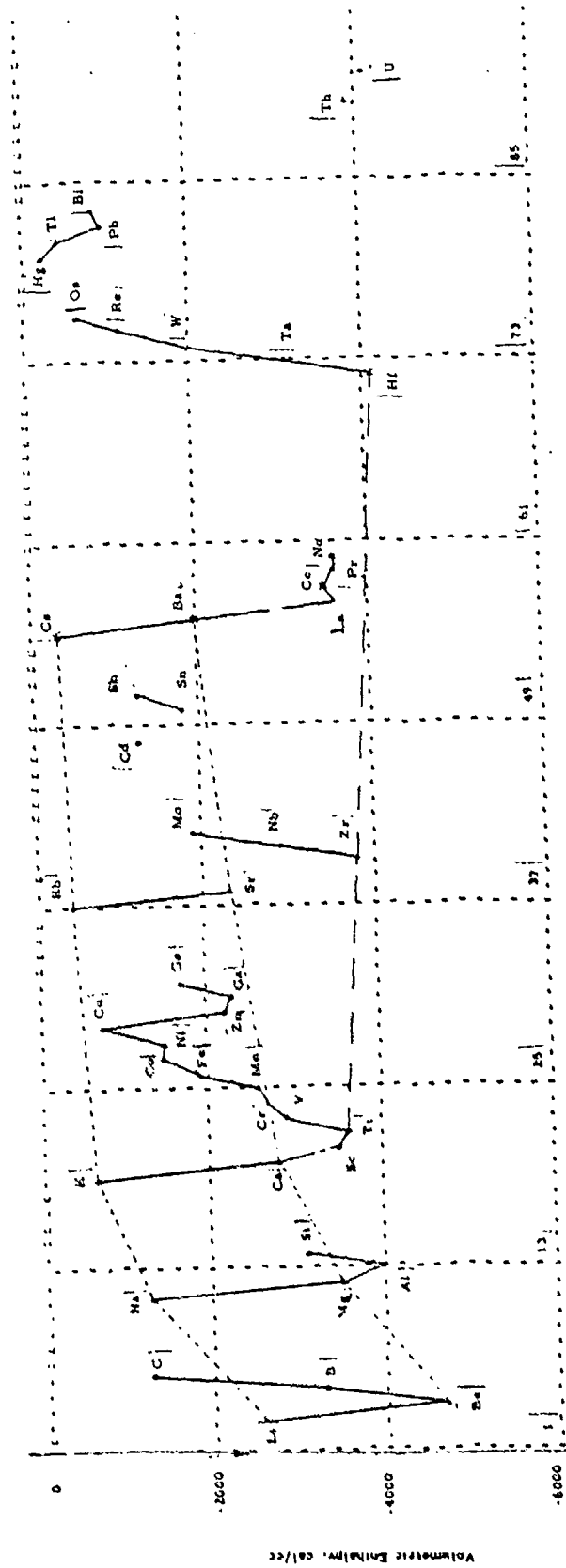


Figure 11
 VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS WITH $B(NO_2)_2$

D. Silicide Reactions

The reactions of various metals with 36 silicides are represented by 302 reactions in the present study. Six typical reactions are shown in Table 13 and the 50 most energetic reactions are shown in Table 14. Table 14 shows that the silicide reactions with barium metal are the most energetic. This is because $BaSi_3$ has an unusually high heat of formation, -407 kcal. When barium is the reactant, Ba_2Si_2 may also form and result in a less energetic reaction. Strontium also produces moderately energetic reactions because the heats of formation of $SrSi_2$ and $SrSi$ are -150 and -113 kcal respectively. With the exception of these four silicides, the heats of formation of the silicides for which data are available are very low. In fact, the remainder serve preferentially as reactants because of their low heats of formation.

The periodic behavior of enthalpies of these reactions as typified by the cobalt disilicide reactions is shown in Figure 12. Because of the paucity of data, only the Group II metal reactions are available for comparative purposes. The behavior of the Group II silicides is the reverse of that exhibited by the nitrates and oxides; i.e., magnesium is least energetic and barium is most energetic. This occurs because barium silicide has a much higher heat of formation than magnesium silicide, whereas barium oxide has a lower heat of formation and a larger molecular volume than magnesium oxide.

The gravimetric behavior is shown in Figure 13. It is essentially the same as the volumetric behavior. The energy of the Group II elements increases with increasing atomic number.

Although experimental studies of silicide reactions are of great interest, they would be time-consuming because very few of the reactants are available and would have to be synthesized individually.

Table 13

DATA ON REACTIONS OF VARIOUS METALS WITH SILICIDES

	Sr	+	Co ₂ Si	=	2 Co	+	SrSi
Heat of formation			-27.60				-113.00
Molecular weight	87.63		145.94		58.94		115.72
Density	2.60		7.28		8.90		
Melting point, °C	770.00		1325.00		1493.00		
Boiling point, °C	1384.00				3100.00		
Heat of reaction, kcal	-85.40						
Reactants' density	4.35						
Gravimetric enthalpy, cal/g	-365.63						
Volumetric enthalpy, cal/cc	-1588.82						
	Sr	+	CoSi	=	Co	+	SrSi
Heat of formation			-24.00				-113.00
Molecular weight	87.63		87.00		58.94		115.72
Density	2.60		6.30		8.90		
Melting point, °C	770.00		1390.00		1493.00		
Boiling point, °C	1384.00				3100.00		
Heat of reaction, kcal	-89.00						
Reactants' density	3.68						
Gravimetric enthalpy, cal/g	-509.65						
Volumetric enthalpy, cal/cc	-1873.16						
	2 Sr	+	CoSi ₂	=	Co	+	2 SrSi
Heat of formation			-24.60				-113.00
Molecular weight	87.63		115.06		58.94		115.72
Density	2.60		5.30		8.90		
Melting point, °C	770.00		1275.00		1493.00		
Boiling point, °C	1384.00				3100.00		
Heat of reaction, kcal	-201.40						
Reactants' density	3.26						
Gravimetric enthalpy, cal/g	-693.72						
Volumetric enthalpy, cal/cc	-2259.95						

Table 13 (cont.)

	2 Ba	+ 3 CoSi ₂	= 3 Co	+ 2 BaSi ₃
Heat of formation		-24.60		-407.00
Molecular weight	137.36	115.06	58.94	221.63
Density	3.50	5.30	8.90	
Melting point, °C	704.00	1275.00	1493.00	3100.00
Boiling point, °C	1638.00			
Heat of reaction, kcal	-740.20			
Reactants' density	4.32			
Gravimetric enthalpy, cal/g	-1194.06			
Volumetric enthalpy, cal/cc	-5153.89			
	Ba	+ CoSi ₃	= Co	+ BaSi ₃
Heat of formation		-25.60		-407.00
Molecular weight	137.36	143.21	58.94	221.63
Density	3.50		8.90	
Melting point, °C	704.00	1305.00	1493.00	3100.00
Boiling point, °C	1638.00			
Heat of reaction, kcal	-381.40			
Reactants' density				
Gravimetric enthalpy, cal/g	-1359.38			
Volumetric enthalpy, cal/cc				
	Ba	+ 3 FeSi	= 3 Fe	+ BaSi ₃
Heat of formation		-19.20		-407.00
Molecular weight	137.36	83.91	55.85	221.63
Density	3.50	6.10	7.86	
Melting point, °C	704.00	1430.00	1535.00	2800.00
Boiling point, °C	1638.00			
Heat of reaction, kcal	-349.40			
Reactants' density	4.83			
Gravimetric enthalpy, cal/g	-897.99			
Volumetric enthalpy, cal/cc	-4339.68			

Table 14

MOST ENERGETIC SILICIDE REACTIONS* WITH METALS,
IN TERMS OF VOLUMETRIC ENTHALPY

<u>Reactant</u>	<u>Product</u>	<u>Enthalpy, cal/cc</u>
3 CoSi ₂	2 BaSi ₃	-5153
3 FeSi	BaSi ₃	-4339
3 ZrSi ₂	2 BaSi ₃	-4174
3 CoSi	BaSi ₃	-4152
3 CaSi ₂	2 BaSi ₃	-3639
CoSi ₂	Ba ₂ Si ₂	-3417
3 Co ₂ Si	BaSi ₃	-3262
2 FeSi	Ba ₂ Si ₂	-3099
3 Ni ₂ Si	BaSi ₃	-3065
ZrSi ₂	Ba ₂ Si ₂	-3045
2 CoSi	Ba ₂ Si ₂	-3006
CaSi ₂	Ba ₂ Si ₂	-2829
2 Cu ₂ Si	Ba ₂ Si ₂	-2629
2 Ni ₂ Si	Ba ₂ Si ₂	-2521
CoSi ₂	SrSi ₂	-2263
CoSi ₂	2 SrSi	-2259
FeSi	SrSi	-1976
ZrSi ₂	2 SrSi	-1946
CoSi	SrSi	-1873
2 FeSi	SrSi ₂	-1823
CaSi ₂	2 SrSi	-1793
ZrSi ₂	SrSi ₂	-1783
2 CoSi	SrSi ₂	-1663
Co ₂ Si	SrSi	-1588
CaSi ₂	SrSi ₂	-1578
Ni ₂ Si	SrSi	-1472

Table 14 (cont.)

<u>Reactant</u>	<u>Product</u>	<u>Enthalpy, cal/cc</u>
2 Co ₂ Si	SrSi ₂	-1284
2 Ni ₂ Si	SrSi ₂	-1117
3 CoSi ₂	2 Zr ₅ Si ₃	-1055
CoSi ₂	2 Zr ₂ Si	- 957
CoSi ₂	2 ZrSi	- 916
CoSi ₂	2 Ni ₂ Si	- 885
3 FeSi	Zr ₅ Si ₃	- 789
CoSi ₂	2 Ni ₃ Si	- 757
FeSi	Zr ₂ Si	- 728
3 CaSi ₂	2 Zr ₅ Si ₃	- 716
CaSi ₂	2 Zr ₂ Si	- 670
3 CoSi	Zr ₅ Si ₃	- 661
CoSi ₂	Ca ₂ Si ₂	- 645
CoSi ₂	2 CaSi	- 645
CoSi	Zr ₂ Si	- 614
CoSi ₂	2 Ca ₂ Si	- 602
FeSi	ZrSi	- 574
ZrSi ₂	2 Ni ₂ Si	- 551
FeSi	Ni ₂ Si	- 534
CaSi ₂	2 ZrSi	- 516
ZrSi ₂	2 Ni ₃ Si	- 501
FeSi	Ni ₃ Si	- 485
3 Co ₂ Si	Zr ₅ Si ₃	- 484
CaSi ₂	2 Ni ₂ Si	- 480

*The first reaction, for example, is:
 $2 \text{Ba} + 3 \text{CoSi}_2 = 3 \text{Co} + 2 \text{BaSi}_3$.

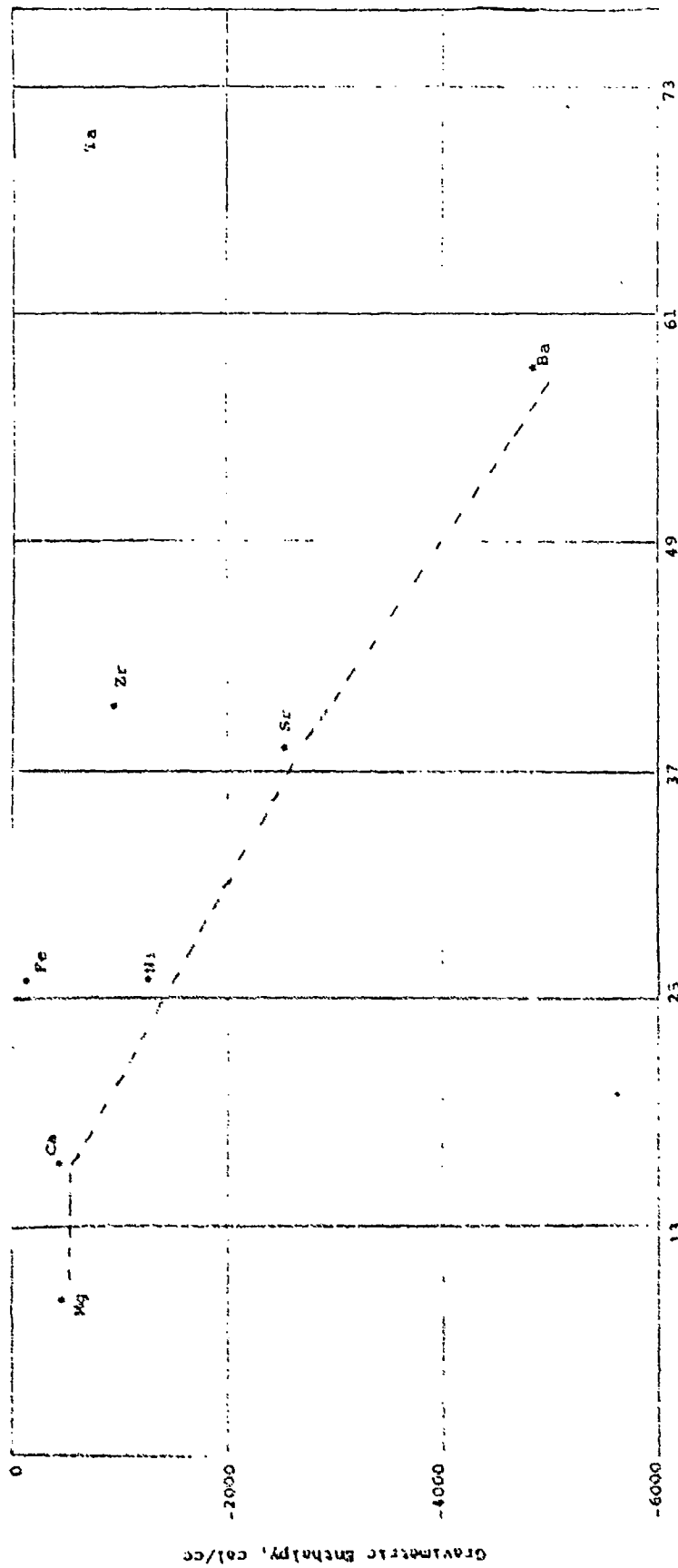
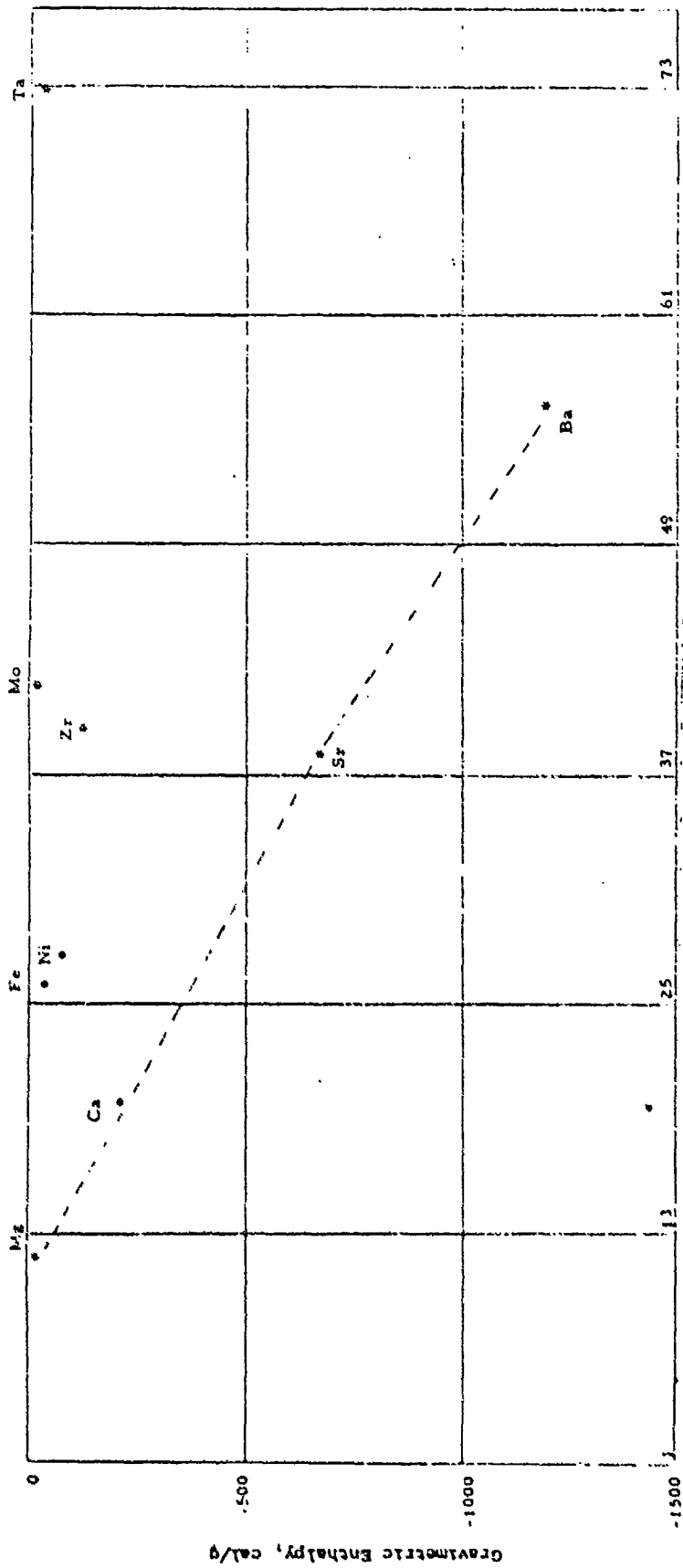


Figure 12
 VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS WITH CoSi_2



Atomic Number of Metal Reactants

Figure 13

GRAVIMETRIC ENTHALPIES OF REACTIONS OF METALS WITH $CoSi_2$

E. Carbide Reactions

Based on the data available for 30 carbides, 386 reactions were analyzed. The carbide reactions are not a very energetic class. The most energetic reactions are listed in Table 15. Tantalum, titanium, and zirconium are the most energetic metal reactants, forming tantalum carbide, titanium carbide, and zirconium carbide, respectively. Many different carbides, e.g., lithium carbide, vanadium carbide, tungsten carbide, calcium carbide, and trichromium dicarbide, perform as useful reactants. Three representative reactions are shown in Table 16.

The reactions of a few of the metals with lithium carbide are shown in Figure 14. Although no useful correlations can be made because of the lack of data, Figure 14 does show that tantalum, titanium, and zirconium are the most energetic metals in these systems.

Table 15

MOST ENERGETIC CARBIDE REACTIONS* WITH METALS,
IN TERMS OF VOLUMETRIC ENTHALPY

<u>Reactant</u>	<u>Product</u>	<u>Enthalpy, cal/cc</u>
Li ₂ C ₂	2 TaC	-2532
VC	TaC	-2351
WC	TaC	-2334
CaC ₂	2 TaC	-2222
Cr ₃ C ₂	2 TaC	-2186
Ni ₃ C	TaC	-2165
Li ₂ C ₂	2 TiC	-2119
Mo ₂ C	TaC	-2056
Na ₂ C ₂	2 TaC	-1987
Fe ₃ C	TaC	-1956
WC	TiC	-1937
VC	TiC	-1925
UC ₂	2 TaC	-1900
Ni ₃ C	TiC	-1896
CaC ₂	2 TiC	-1853
Cr ₃ C ₂	2 TiC	-1803
Mo ₂ C	TiC	-1774
Mn ₃ C	TaC	-1717
Al ₄ C ₃	3 TaC	-1713
Na ₂ C ₂	2 TiC	-1705
Fe ₃ C	TiC	-1690
ThC ₂	2 TaC	-1639
SiC	TaC	-1588

Table 15 (cont.)

<u>Reactant</u>	<u>Product</u>	<u>Enthalpy, cal/cc</u>
B ₄ C	TaC	-1508
UC ₂	2 TiC	-1482
Ni ₃ C	ZrC	-1477
Li ₂ C ₂	2 ZrC	-1472
Mn ₃ C	TiC	-1459
Al ₄ C ₃	3 TiC	-1411
Ni ₃ C	UC	-1402
Li ₂ C ₂	2 UC	-1358
Mo ₂ C	ZrC	-1351
WC	ZrC	-1340
CaC ₂	2 ZrC	-1307
Fe ₃ C	ZrC	-1298
VC	ZrC	-1291
Na ₂ C ₂	2 ZrC	-1289
Mo ₂ C	UC	-1267
ThC ₂	2 TiC	-1263
Cr ₃ C ₂	2 ZrC	-1244
NbC	TaC	-1237
WC	UC	-1223
B ₄ C	TiC	-1220
Fe ₃ C	UC	-1216
Na ₂ C ₂	2 UC	-1202
CaC ₂	2 UC	-1196
SiC	TiC	-1181
VC	UC	-1163
Cr ₃ C ₂	2 UC	-1125
Mn ₃ C	ZrC	-1102

* The first reaction, for example, is:
 $2 \text{ Ta} + \text{Li}_2\text{C}_2 = 2 \text{ Li} + 2 \text{ TaC}.$

Table 16

DATA ON REACTIONS OF VARIOUS METALS WITH CARBIDES

	2 Ta	+ Li ₂ C ₂	=	2 Li	+	2 TaC
Heat of formation		-14.20				-63.80
Molecular weight	180.95	37.90		6.94		192.87
Density	16.60	1.65		0.53		14.65
Melting point, °C	2977.00			180.00		3827.00
Boiling point, °C	4100.00			1326.00		5500.00
Heat of reaction, kcal	-113.40					
Reactants' density	8.93					
Gravimetric enthalpy, cal/g	-283.64					
Volumetric enthalpy, cal/cc	-2532.90					
	3 Ta	+ Mg ₂ C ₃	=	2 Mg	+	3 TaC
Heat of formation		19.00				-63.80
Molecular weight	180.95	84.67		24.32		192.87
Density	16.60			1.74		14.65
Melting point, °C	2977.00			650.00		3827.00
Boiling point, °C	4100.00			1120.00		5500.00
Heat of reaction, kcal	-210.40					
Reactants' density						
Gravimetric enthalpy, cal/g	-335.29					
Volumetric enthalpy, cal/cc						
	2 Ta	+ MgC ₂	=	Mg	+	2 TaC
Heat of formation		21.00				-63.80
Molecular weight	180.95	48.34		24.32		192.87
Density	16.60			1.74		14.65
Melting point, °C	2977.00			650.00		3827.00
Boiling point, °C	4100.00			1120.00		5500.00
Heat of reaction, kcal	-148.60					
Reactants' density						
Gravimetric enthalpy, cal/g	-362.23					
Volumetric enthalpy						

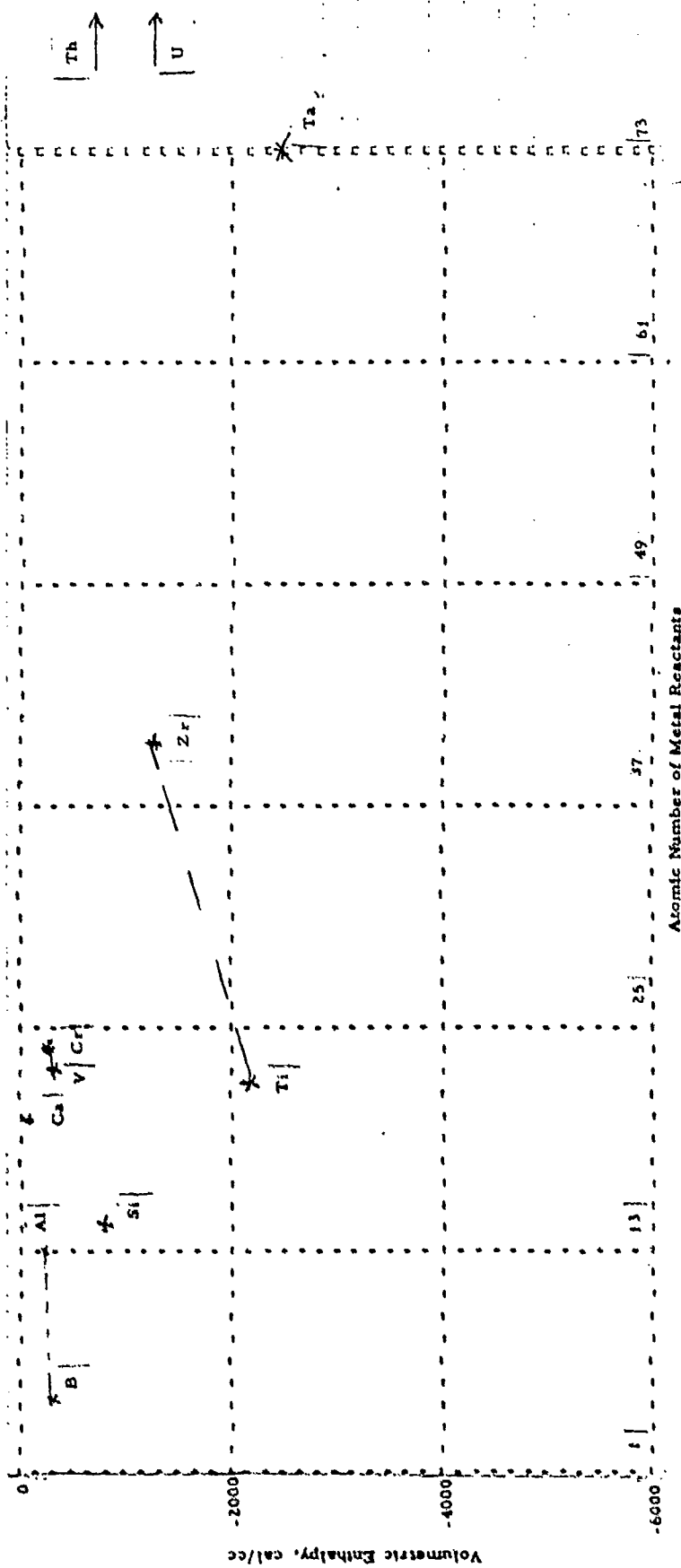


Figure 14
 VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS WITH LIC₂

F. Sulfide Reactions

The data for 68 sulfides were used to calculate the enthalpies of 2145 reactions of sulfides with metals. These reactions are, in general, only moderately energetic. The 50 most energetic reactions are shown in Table 17. The reactions of iron disulfide with thorium, cesium, and lanthanum are the most energetic. The energies of these reactions are not considered high for pyrotechnic materials but are high enough to warrant a modest experimental study. In most cases several sulfide products, involving different valences of the metals, form from the same two reactants. It would be interesting to determine which reactions predominate, since this will define the experimental reaction energy. This energy is a function of the kinetics of the reaction and the thermodynamic equilibrium based on free energies. A few representative reactions are shown in Table 18.

Figure 15 illustrates the periodic relationships between the reactions of metals with iron disulfide. The relationship is essentially the same as that among the nitrate reactions except for some differences with the low-atomic number metals. For instance, in the sulfide systems the Group II metals exhibit a maximum energy output at calcium, whereas in the nitrate systems beryllium and magnesium are more energetic than calcium. In the nitrate systems, the energy output based on the volume of reactants decreases in going from beryllium to barium because the product oxides all have approximately the same heats of formation, -133 to -152 kcal, and the reactant metals increase in atomic volume, 4.74 to 39.2 cc. In the sulfide systems, the effect of the reactant volumes is the same, but the heats of formation vary widely, with a pronounced maximum (-115 kcal) at calcium sulfide and a minimum (-56 kcal) at beryllium sulfide. In this case, the effect of the heats of formation predominates and the energy outputs also have a maximum at calcium. Another interesting difference between the sulfide and nitrate systems is that in the former aluminum is less energetic than magnesium and in the latter the reverse is true. This phenomenon results from the unusually high heat of formation of aluminum oxide, -399 kcal.

Table 17

MOST ENERGETIC SULFIDE REACTIONS* WITH METALS,
IN TERMS OF VOLUMETRIC ENTHALPY

<u>Reactant</u>	<u>Product</u>	<u>Enthalpy, cal/cc</u>
7 FeS ₂	2 Th ₄ S ₇	-3169
2 FeS ₂	Ce ₃ S ₄	-3104
7 FeS ₂	2 Th ₄ S ₇	-3093
3 FeS ₂	2 Ce ₂ S ₃	-3089
FeS ₂	2 ThS	-3074
3 FeS ₂	2 La ₂ S ₃	-3061
2 FeS ₂	Ce ₃ S ₄	-3038
3 FeS ₂	2 Ce ₂ S ₃	-3018
FeS ₂	2 ThS	-3018
FeS ₂	2 CeS	-2995
3 FeS ₂	2 La ₂ S ₃	-2993
FeS ₂	2 CeS	-2939
FeS ₂	ThS ₂	-2935
7 Co ₂ S ₃	3 Th ₄ S ₇	-2920
Co ₂ S ₃	3 ThS	-2894
4 Ce ₂ S ₃	3 Ce ₃ S ₄	-2892
Co ₂ S ₃	Ce ₂ S ₃	-2865
FeS ₂	ThS ₂	-2851
Ce ₂ S ₃	La ₂ S ₃	-2849
Co ₂ S ₃	3 CeS	-2822
Co ₃ S ₄	4 ThS	-2781
7 Co ₃ S ₄	4 Th ₄ S ₇	-2769
Co ₃ S ₄	Ce ₃ S ₄	-2760
3 Co ₃ S ₄	4 Ce ₂ S ₃	-2726
3 Co ₃ S ₄	4 La ₂ S ₃	-2715
Co ₃ S ₄	4 CeS	-2711

Table 17 (cont.)

<u>Reactant</u>	<u>Product</u>	<u>Enthalpy, cal/cc</u>
NiS	ThS	-2708
2 Co ₂ S ₃	3 ThS ₂	-2695
4 NiS	Ce ₃ S ₄	-2678
7 NiS	Th ₄ S ₇	-2675
CoS	ThS	-2667
NiS	CeS	-2641
3 NiS	Ce ₂ S ₃	-2641
3 FeS ₂	2 Th ₂ S ₃	-2636
3 NiS	La ₂ S ₃	-2633
4 CoS	Ce ₃ S ₄	-2630
7 CoS	Th ₄ S ₇	-2621
ReS ₂	2 ThS	-2615
CuS	ThS	-2612
CoS	CeS	-2600
WS ₂	2 ThS	-2599
3 CoS	Ce ₂ S ₃	-2590
3 CoS	La ₂ S ₃	-2584
4 CuS	Ce ₃ S ₄	-2571
2 ReS ₂	Ce ₃ S ₄	-2570
FeS ₂	CeS ₂	-2568
CS ₂	2 ThS	-2563
3 FeS ₂	2 Th ₂ S ₃	-2560
7 CuS	Th ₄ S ₇	-2556
7 ReS ₂	2 Th ₄ S ₇	-2553

*The first reaction, for example, is:
 $8 \text{ Th} + 7 \text{ FeS}_2 = 7 \text{ Fe} + 2 \text{ Th}_4\text{S}_7$.

Table 18

DATA ON REACTIONS OF VARIOUS METALS WITH SULFIDES

	3 Ce	+ 2 FeS ₂	= 2 Fe	+ Ce ₃ S ₄
Heat of formation		-36.88		-421.50
Molecular weight	140.13	119.98	55.85	548.65
Density	6.70	4.87	7.86	
Melting point, °C	775.00	450.00	1535.00	2050.00
Boiling point, °C	2900.00		2800.00	
Heat of reaction, kcal	-347.74			
Reactants' density	5.90			
Gravimetric enthalpy, cal/g	-526.60			
Volumetric enthalpy, cal/cc	-3104.33			
	3 Ce	+ 2 FeS ₂	= 2 Fe	+ Ce ₃ S ₄
Heat of formation		-42.52		-421.50
Molecular weight	140.13	119.98	55.85	548.65
Density	6.70	5.00	7.86	
Melting point, °C	775.00	1171.00	1535.00	2050.00
Boiling point, °C	2900.00		2800.00	
Heat of reaction, kcal	-336.46			
Reactants' density	5.96			
Gravimetric enthalpy, cal/g	-509.52			
Volumetric enthalpy, cal/cc	-3038.38			
	3 Ce	+ 4 GaS	= 4 Ga	+ Ce ₃ S ₄
Heat of formation		-46.40		-421.50
Molecular weight	140.13	101.79	69.72	548.65
Density	6.70	3.86	5.90	
Melting point, °C	775.00	965.00	29.78	2050.00
Boiling point, °C	2900.00		937.00	
Heat of reaction, kcal	-235.90			
Reactants' density	4.92			
Gravimetric enthalpy, cal/g	-285.06			
Volumetric enthalpy, cal/cc	-1402.27			

Table 18 (cont.)

	8 Th	+ 7 FeS ₂	= 7 Fe	+ 2 Th ₄ S ₇
Heat of formation		-36.88		-665.00
Molecular weight	232.00	119.98	55.85	1152.46
Density	11.20	4.87	7.86	
Melting point, °C	1840.00	450.00	1535.00	2027.00
Boiling point, °C	4500.00		2800.00	
Heat of reaction, kcal	-1071.84			
Reactants' density	7.97			
Gravimetric enthalpy, cal/g	-397.59			
Volumetric enthalpy, cal/cc	-3169.53			
	8 Th	+ 7 FeS ₂	= 7 Fe	+ 2 Th ₄ S ₇
Heat of formation		-42.52		-665.00
Molecular weight	232.00	119.98	55.85	1152.46
Density	11.20	5.00	7.86	
Melting point, °C	1840.00	1171.00	1535.00	2027.00
Boiling point, °C	4500.00		2800.00	
Heat of reaction, kcal	-1032.36			
Reactants' density	8.08			
Gravimetric enthalpy, cal/g	-382.94			
Volumetric enthalpy, cal/cc	-3093.80			
	4 Th	+ 7 GaS	= 7 Ga	+ Th ₄ S ₇
Heat of formation		-46.40		-665.00
Molecular weight	232.00	101.79	69.72	1152.46
Density	11.20	3.86	5.90	
Melting point, °C	1840.00	965.00	29.78	2027.00
Boiling point, °C	4500.00		937.00	
Heat of reaction, kcal	-340.20			
Reactants' density	6.13			
Gravimetric enthalpy, cal/g	-207.37			
Volumetric enthalpy, cal/cc	-1272.01			

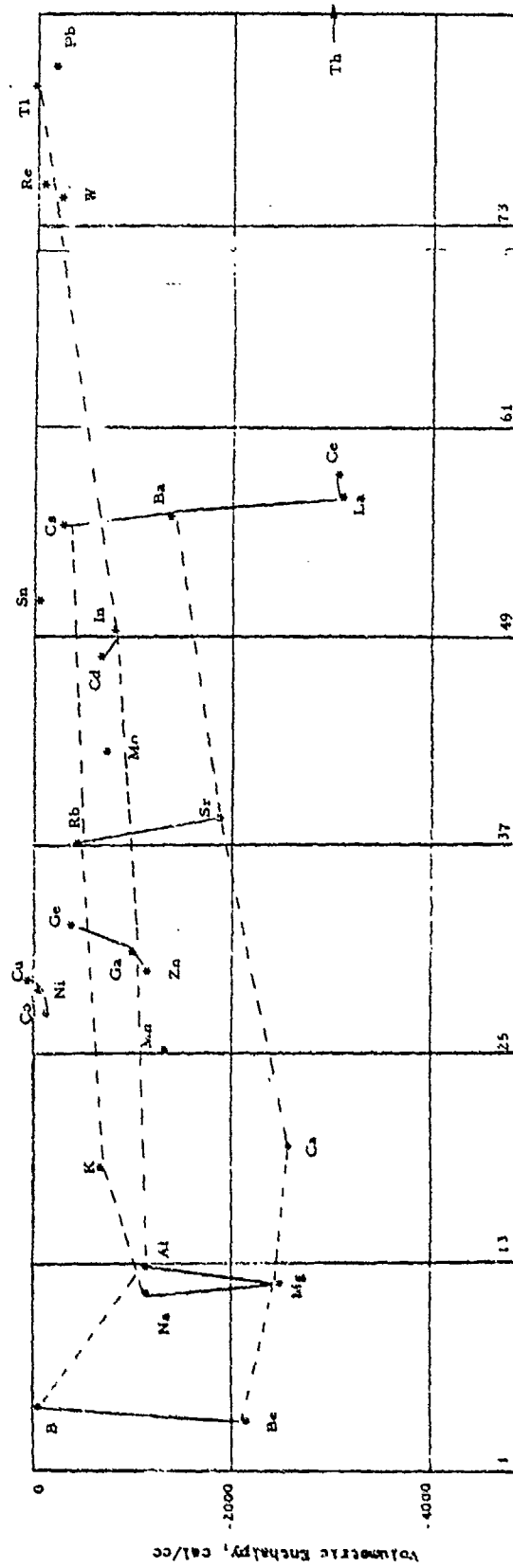


Figure 15
 VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS WITH FeS₂

G. Nitride and Azide Reactions

The data for 44 nitrides and 13 azides were used to compute the enthalpies of 1575 reactions. These reactions, like the sulfides, are only moderately energetic and appear to warrant only a modest experimental study. Caution must be exercised in experimental work because many of the azide compounds are very reactive. The 50 most energetic reactions are listed in Table 19. The reactions of barium azide (BaN_6 or $\text{Ba}(\text{N}_3)_2$) with beryllium, yttrium, titanium, zirconium, hafnium, thorium, and aluminum metal are the most energetic. The reactions of iron nitride with these metals are also fairly energetic.

Several representative reactions are shown in Table 20. Certain interesting relationships are apparent. For instance, the azide or nitride of barium can be used as the reactant. The azide is more energetic because it has a lower heat of formation. Copper can also be used as a nitride or azide, but not enough data are available to calculate the volumetric enthalpies. On a gravimetric basis, the reaction of copper azide with titanium is highly energetic. In some cases more than one nitride can be used as a reactant or is formed as a product from the same reactant metal. This is illustrated by the iron nitrides, Fe_2N and Fe_4N .

The periodic relationships of the reactions with barium azide and with the iron nitride Fe_2N are shown in Figures 16 and 17. Although all the possible lines have not been drawn, it is evident that except for minor deviations the behavior of these systems closely resembles that of the oxide and nitrate systems. This is especially apparent in Groups II and III: aluminum is more energetic than magnesium.

Table 19

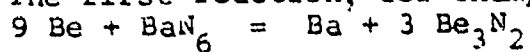
MOST ENERGETIC NITRIDE AND AZIDE REACTIONS* WITH METALS,
IN TERMS OF VOLUMETRIC ENTHALPY

<u>Reactant</u>	<u>Product</u>	<u>Enthalpy, cal/cc</u>
BaN ₆	3 Be ₃ N ₂	-3346
BaN ₆	2 U ₂ N ₃	-3308
BaN ₆	6 UN	-3109
BaN ₆	6 TiN	-3087
BaN ₆	6 ZrN	-3014
BaN ₆	6 HfN	-2961
2 BaN ₆	3 Th ₃ N ₄	-2692
BaN ₆	6 AlN	-2499
3 Fe ₂ N	U ₂ N ₃	-2478
2 Fe ₂ N	Be ₃ N ₂	-2470
BaN ₆	NbN ₆	-2460
BaN ₆	6 YN	-2444
Fe ₂ N	UN	-2431
BaN ₆	6 TaN	-2423
Fe ₂ N	ZrN	-2387
Fe ₂ N	TiN	-2368
Fe ₂ N	HfN	-2330
BaN ₆	6 CeN	-2298
BaN ₆	6 ScN	-2182
4 Fe ₂ N	Th ₃ N ₄	-2153
CrN	UN	-2096
3 CrN	U ₂ N ₃	-2093
GaN	UN	-2078
3 GaN	U ₂ N ₃	-2070
CrN	ZrN	-2059

Table 19 (cont.)

<u>Reactant</u>	<u>Product</u>	<u>Enthalpy, cal/cc</u>
2 CrN	Be ₃ N ₂	-2057
GaN	ZrN	-2044
2 BaN ₆	3 Si ₃ N ₄	-2037
2 GaN	Be ₃ N ₂	-2037
BaN ₆	6 LaN	-2012
BN	UN	-1994
CrN	TiN	-1978
CrN	HfN	-1970
GaN	TiN	-1969
3 BN	U ₂ N ₃	-1967
Fe ₂ N	YN	-1964
GaN	HfN	-1963
BN	ZrN	-1961
2 BN	Be ₃ N ₂	-1922
Fe ₂ N	AlN	-1907
Fe ₂ N	CeN	-1901
Fe ₂ N	NbN	-1894
BaN ₆	6 YN	-1878
BN	HfN	-1869
Fe ₂ N	TaN	-1866
BN	TiN	-1864
BaN ₆	6 BN	-1795
4 GaN	Th ₃ N ₄	-1777
Fe ₂ N	ScN	-1776
4 CrN	Th ₃ N ₄	-1766

* The first reaction, for example, is:



N₆ represents the azide (N₃)₂

Table 20

DATA ON REACTIONS OF VARIOUS METALS WITH NITRIDES AND AZIDES

	3 Be	+	2 AlN	=	2 Al	+	Be ₃ N ₂
Heat of formation			-57.70				-135.70
Molecular weight	9.01		40.98		26.98		55.06
Density	1.85		3.26		2.70		
Melting point, °C	1283.00		220.00		660.00		2200.00
Boiling point, °C	2970.00				2327.00		2240.00
Heat of reaction, kcal	-20.30						
Reactants' density	2.74						
Gravimetric enthalpy, cal/g	-186.24						
Volumetric enthalpy, cal/cc	-510.60						
	3 Be	+	2 BN	=	2 B	+	Be ₃ N ₂
Heat of formation			-32.10				-135.70
Molecular weight	9.01		24.83		10.82		55.06
Density	1.85		2.20		2.37		
Melting point, °C	1283.00				2040.00		2200.00
Boiling point, °C	2970.00				2550.00		2240.00
Heat of reaction, kcal	-71.50						
Reactants' density	2.06						
Gravimetric enthalpy, cal/g	-932.22						
Volumetric enthalpy, cal/cc	-1922.64						
	9 Be	+	BaN ₆	=	Ba	+	3 Be ₃ N ₂
Heat of formation			-8.00				-135.70
Molecular weight	9.01		221.41		137.36		55.06
Density	1.85		2.94		3.50		
Melting point, °C	1283.00				704.00		2200.00
Boiling point, °C	2970.00				1638.00		2240.00
Heat of reaction, kcal	399.10						
Reactants' density	2.54						
Gravimetric enthalpy, cal/g	-1319.22						
Volumetric enthalpy, cal/cc	-3346.49						

Table 20 (cont.)

	3 Be	+ 2 Fe ₂ N	= 4 Fe	+ Be ₃ N ₂
Heat of formation				-135.70
Molecular weight		99.90		55.06
Density	9.01	1.25.71	55.85	
Melting point, °C	1.85	6.35	7.86	
Boiling point, °C	1283.00		1535.00	2200.00
Heat of reaction, kcal	2970.00		2800.00	2240.00
Reactants' density	-133.90			
Gravimetric enthalpy, cal/g	5.14			
Volumetric enthalpy, cal/cc	-480.86			
	-2470.05			
	3 Be	+ 2 Fe ₄ N	= 8 Fe	+ Be ₃ N ₂
Heat of formation				-135.70
Molecular weight		-2.55	55.85	55.06
Density	9.01	237.41	7.86	
Melting point, °C	1.85	6.57	1535.00	2200.00
Boiling point, °C	1283.00		2800.00	2240.00
Heat of reaction, kcal	2970.00			
Reactants' density	-133.90			
Gravimetric enthalpy, cal/g	5.78			
Volumetric enthalpy, cal/cc	-260.23			
	-1503.11			
	3 Be	+ 2 GaN	= 2 Ga	+ Be ₃ N ₂
Heat of formation				-135.70
Molecular weight		-25.00	69.72	55.06
Density	9.01	83.73	5.90	
Melting point, °C	1.85	6.10	29.78	2200.00
Boiling point, °C	1283.00		937.00	2240.00
Heat of reaction, kcal	2970.00			
Reactants' density	-85.70			
Gravimetric enthalpy, cal/g	4.62			
Volumetric enthalpy, cal/cc	-440.62			
	-2037.17			

Table 20 (cont.)

	6 Ti	+	BaN ₆	=	Ba	+	6 TiN
Heat of formation			-8.00				-73.00
Molecular weight	47.90		221.41		137.36		61.91
Density	4.50		2.94		3.50		5.43
Melting point, °C	1812.00				704.00		2927.00
Boiling point, °C	3000.00				1638.00		
Heat of reaction, kcal	-430.00						
Reactants' density	3.65						
Gravimetric enthalpy, cal/g	-845.11						
Volumetric enthalpy, cal/cc	-3087.33						
	2 Ti	+	Ba ₃ N ₂	=	3 Ba	+	2 TiN
Heat of formation			-86.90				-73.00
Molecular weight	47.90		440.10		137.36		61.91
Density	4.50				3.50		5.43
Melting point, °C	1812.00		1000.00		704.00		2927.00
Boiling point, °C	3000.00				1638.00		
Heat of reaction, kcal	-59.10						
Reactants' density	-110.28						
Gravimetric enthalpy, cal/g							
Volumetric enthalpy, cal/cc							
	2 Ti	+	Be ₃ N ₂	=	3 Be	+	2 TiN
Heat of formation			-135.70				-73.00
Molecular weight	47.90		55.06		9.01		61.91
Density	4.50				1.85		5.43
Melting point, °C	1812.00		200.00		1283.00		2927.00
Boiling point, °C	3000.00		2240.00		2970.00		
Heat of reaction, kcal	-10.30						
Reactants' density	-68.28						
Gravimetric enthalpy, cal/g							
Volumetric enthalpy, cal/cc							

Table 20 (cont.)

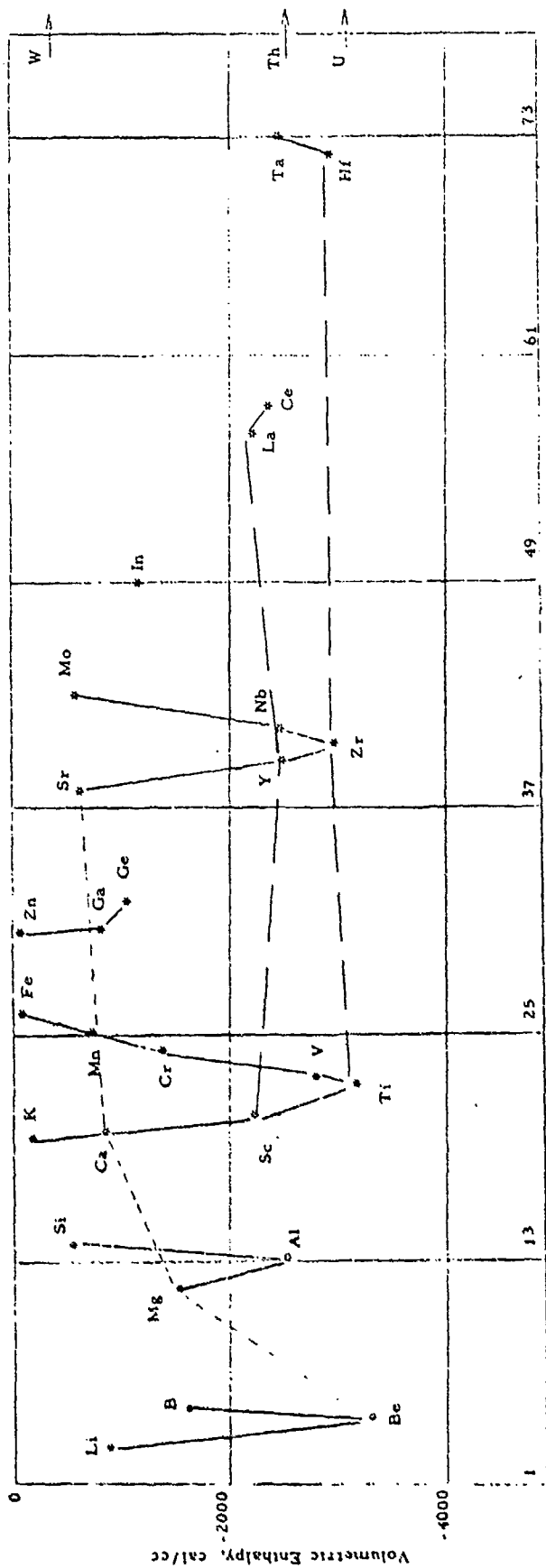
	Ti	+	Cu ₃ N	=	3 Cu	+	TiN
Heat of formation	47.90		17.80				-73.00
Molecular weight	4.50		204.63		63.54		61.91
Density					8.92		5.43
Melting point, °C	1812.00				1083.00		2927.00
Boiling point, °C	3000.00				2582.00		
Heat of reaction, kcal	-90.80						
Reactants' density							
Gravimetric enthalpy, cal/g	-359.56						
Volumetric enthalpy, cal/cc							
	3 Ti	+	CuN ₃	=	Cu	+	3 TiN
Heat of formation	47.90		60.50				-73.00
Molecular weight	4.50		105.56		63.54		61.91
Density					8.92		5.43
Melting point, °C	1812.00				1083.00		2927.00
Boiling point, °C	3000.00				2582.00		
Heat of reaction, kcal	-279.50						
Reactants' density							
Gravimetric enthalpy, cal/g	-1121.30						
Volumetric enthalpy, cal/cc							
	Ti	+	Fe ₂ N	=	2 Fe	+	TiN
Heat of formation	47.90		-90				-73.00
Molecular weight	4.50		125.71		55.85		61.91
Density			6.35		7.86		5.43
Melting point, °C	1812.00				1535.00		2927.00
Boiling point, °C	3000.00				2800.00		
Heat of reaction, kcal	-72.10						
Reactants' density	5.70						
Gravimetric enthalpy, cal/g	-415.30						
Volumetric enthalpy, cal/cc	-2368.49						

Table 20 (cont.)

	Zr	+	AlN	=	Al	+	ZrN
Heat of formation			-57.70				-82.20
Molecular weight	91.22		40.98		26.98		105.23
Density	6.40		3.26		2.70		7.09
Melting point, °C	1852.00		220.00		660.00		2952.00
Boiling point, °C	2900.00				2327.00		
Heat of reaction, kcal	-24.50						
Reactants' density	4.93						
Gravimetric enthalpy, cal/g	-185.22						
Volumetric enthalpy, cal/cc	-913.37						
<hr/>							
	Zr	+ <td>BN</td> <td>=</td> <td>B</td> <td>+ <td>ZrN</td> </td>	BN	=	B	+ <td>ZrN</td>	ZrN
Heat of formation			-32.10				-82.20
Molecular weight	91.22		24.83		10.82		105.23
Density	6.40		2.20		2.38		7.09
Melting point, °C	1852.00				2040.00		2952.00
Boiling point, °C	2900.00				2550.00		
Heat of reaction, kcal	-50.10						
Reactants' density	4.54						
Gravimetric enthalpy, cal/g	431.71						
Volumetric enthalpy, cal/cc	-1961.67						
<hr/>							
	6 Zr	+ <td>BaN₆</td> <td>=</td> <td>Ba</td> <td>+ <td>6 ZrN</td> </td>	BaN ₆	=	Ba	+ <td>6 ZrN</td>	6 ZrN
Heat of formation			-8.00				-82.20
Molecular weight	91.22		221.41		137.36		105.23
Density	6.40		2.94		3.50		7.09
Melting point, °C	1852.00				704.00		2952.00
Boiling point, °C	2900.00				1638.00		
Heat of reaction, kcal	-485.20						
Reactants' density	4.78						
Gravimetric enthalpy, cal/g	631.17						
Volumetric enthalpy, cal/cc	3014.96						

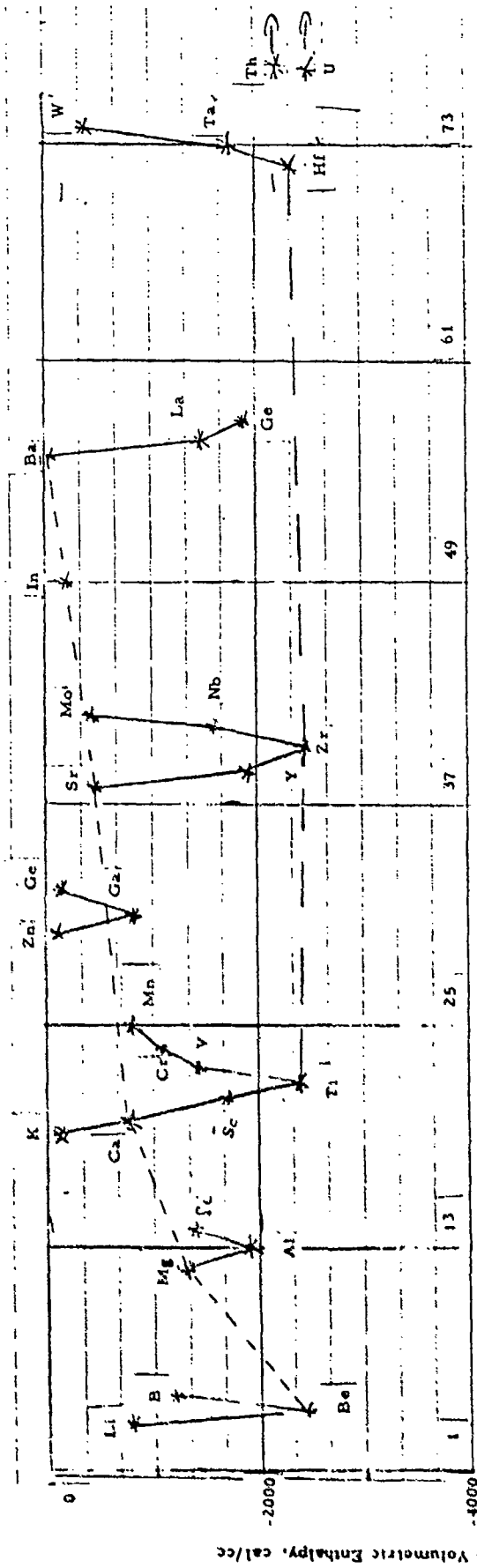
Table 20 (cont.)

	Zr	+	Cu ₃ N	=	3 Cu	+	ZrN
Heat of formation			17.80				-82.20
Molecular weight	91.22		204.63		63.54		105.23
Density	6.40				8.92		7.09
Melting point, °C	1852.00				1083.00		2952.00
Boiling point, °C	2900.00				2582.00		
Heat of reaction, kcal	-100.00						
Reactants' density							
Gravimetric enthalpy, cal/g	-338.01						
Volumetric enthalpy, cal/cc							
<hr/>							
	3 Zr	+	CuN ₃	=	Cu	+	3 ZrN
Heat of formation			60.50				-82.20
Molecular weight	91.22		105.56		63.54		105.23
Density	6.40				8.92		7.09
Melting point, °C	1852.00				1083.00		2952.00
Boiling point, °C	2900.00				2582.00		
Heat of reaction, kcal	-307.10						
Reactants' density							
Gravimetric enthalpy, cal/g	-809.81						
Volumetric enthalpy, cal/cc							
<hr/>							
	Zr	+	Fe ₂ N	=	2 Fe	+	ZrN
Heat of formation			-0.90				-82.20
Molecular weight	91.22		125.71		55.85		105.23
Density	6.40		6.35		7.96		7.09
Melting point, °C	1852.00				1535.00		2952.00
Boiling point, °C	2900.00				2800.00		
Heat of reaction, kcal	-81.30						
Reactants' density	6.37						
Gravimetric enthalpy, cal/g	-374.78						
Volumetric enthalpy, cal/cc	-2387.67						



Atomic Number of Metal Reactants

Figure 16
VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS WITH Ba(N₃)₂



Atomic Number of Metal Reactants

Figure 17

VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS WITH Fe₂N

H. Chlorate and Perchlorate Reactions

The possible reactions of 50 metals with 7 chlorates and 9 perchlorates resulted in the computation of 16,384 reactions. Only 801 of them were printed, because reactions with positive enthalpies were discarded, as were those with the lowest enthalpy from the possible combinations of each pair of reactants. Examples of the computer output for some of the more energetic reactions are shown in Table 21.

Chlorates and perchlorates are combinations of chlorine and oxygen systems. The chloride of the metal reactant is rarely produced, and when it is produced, it is in a very low ratio compared with its oxide. For example, note the reaction between beryllium and silver chlorate in Table 22. This occurs because the oxides of the highly reactant metals generally have higher negative heats of formation than the chlorides.

The chlorates and perchlorates are much more energetic than the comparable oxide systems. In fact, they are the most energetic systems examined. The 200 most energetic reactions are shown in Tables 22 and 23. The most energetic reaction, between beryllium and magnesium perchlorate, has a volumetric enthalpy of -9459 cal/cc, which is appreciably higher than the most energetic oxide and nitrate reactions: beryllium with ruthenium oxide, -7800 cal/cc; and beryllium with lithium nitrate, -7798 cal/cc. The beryllium-lithium perchlorate reaction, -9088 cal/cc, which is the next most energetic perchlorate reaction, compares with the beryllium-lithium nitrate reaction

The chlorates and perchlorates are listed in order of their effective energies in Table 24. In general, the perchlorate of a metal is more energetic than the chlorate. Silver is an exception because the chlorate has a much higher density than the perchlorate, and thus on a volumetric basis the chlorate is more energetic than the perchlorate.

The periodic trends in the gravimetric and volumetric enthalpies are shown in Figure 18 for reactions of all the metals with magnesium perchlorate. The trends are almost the same as those in the nitrate and oxide systems. The most energetic reactions occur with beryllium, aluminum, titanium, zirconium, hafnium, and the rare earths lanthanum, cerium, praseodymium, and neodymium. The alkali metals tend to have the lowest enthalpies. These trends are essentially the same for all the oxidizers in the oxide, nitrate, and chlorate-perchlorate systems, and for the gravimetric and volumetric bases. Thus, all the curves are similar except for vertical displacement of the ordinates. This type of plot allows one to choose a metal reactant for a particular oxidizer, magnesium perchlorate in this case.

Table 21

DATA ON REACTIONS OF VARIOUS METALS WITH CHLORATES AND PERCHLORATES

	13 Mg	+ 4 AgClO ₃	= 2 Ag ₂ Cl	+ 12 MgO	+ MgCl ₂
Heat of formation		5.73	-30.90	-143.84	-153.40
Molecular weight	24.32	191.34	251.20	40.32	95.23
Density	1.74	4.43	3.58	2.32	2.32
Melting point, °C	650.00	231.00	2800.00	714.00	714.00
Boiling point, °C	1120.00	270.00		1418.00	1418.00
Heat of reaction, kcal	-1918.36				
Reactants' density	3.05				
Gravimetric enthalpy, cal/g	-1773.76				
Volumetric enthalpy, cal/cc	-5411.93				
	13 Mn	+ 4 AgClO ₃	= 2 Ag ₂ Cl	+ 12 MnO	+ MnCl ₂
Heat of formation		-5.73	-30.90	-92.00	-115.30
Molecular weight	54.94	191.34	251.20	70.93	125.84
Density	7.20	4.43	5.43	2.98	2.98
Melting point, °C	1244.00	231.00	1650.00	650.00	650.00
Boiling point, °C	2087.00	270.00		1190.00	1190.00
Heat of reaction, kcal	-1258.18				
Reactants' density	5.44				
Gravimetric enthalpy, cal/g	-850.36				
Volumetric enthalpy, cal/cc	-4626.26				
	Mo	+ AgClO ₃	= AgCl	+ MoO ₃	
Heat of formation		-5.73	-30.36	-180.33	
Molecular weight	95.95	191.34	143.34	143.95	
Density	10.20	4.43	5.56	4.50	
Melting point, °C	2610.00	231.00	455.00	795.00	
Boiling point, °C	4800.00	270.00	1557.00	1155.00	
Heat of reaction, kcal	-204.96				
Reactants' density	5.46				
Gravimetric enthalpy, cal/g	-713.43				
Volumetric enthalpy, cal/cc	-3896.71				

Table 21 (cont.)

	13 Zn	+ 4 AgClO ₃	= 2 Ag ₂ Cl	+ 12 ZnO	+ ZnCl ₂
Heat of formation		-5.73	-30.90	-83.17	-99.40
Molecular weight	65.38	191.34	251.20	81.38	136.29
Density	7.14	4.43		5.47	2.91
Melting point, °C	419.50	231.00		1800.00	275.00
Boiling point, °C	907.00	270.00		1800.00	756.00
Heat of reaction, kcal	-1136.32				
Reactants' density	5.54				
Gravimetric enthalpy, cal/g	-703.47				
Volumetric enthalpy, cal/cc	-3894.08				
	10 Zr	+ 6 AgClO ₃	= 3 Ag ₂ Cl	+ 9 ZrO ₂	+ ZrCl ₃
Heat of formation		-5.73	-30.90	-258.20	-208.00
Molecular weight	91.22	191.34	251.20	123.22	197.59
Density	6.40	4.43		5.46	
Melting point, °C	1852.00	231.00		2700.00	350.00
Boiling point, °C	2900.00	270.00		4300.00	
Heat of reaction, kcal	-2590.12				
Reactants' density	5.13				
Gravimetric enthalpy, cal/g	-1257.10				
Volumetric enthalpy, cal/cc	-6448.18				
	16 Ag	+ 2 AgClO ₄	=	8 Ag ₂ O	+ 2 AgCl
Heat of formation		-7.75		-7.31	-30.36
Molecular weight	107.87	207.34		231.76	143.34
Density	10.50	2.81		7.14	5.56
Melting point, °C	960.80	486.00		300.00	455.00
Boiling point, °C	2193.00				1557.00
Heat of reaction, kcal	-103.67				
Reactants' density	6.86				
Gravimetric enthalpy, cal/g	-48.43				
Volumetric enthalpy, cal/cc	-332.11				

Table 21 (cont.)

	2 Zr +	LiClO ₄	=	LiCl + 2 ZrO ₂
Heat of formation		106.10		-97.70
Molecular weight	91.22	106.50		42.40
Density	6.40	2.43		2.07
Melting point, °C	1852.00	236.00		610.00
Boiling point, °C	2900.00	440.00		1382.00
Heat of reaction, kcal	-508.00			
Reactants' density	3.99			
Gravimetric enthalpy, cal/g	-1758.15			
Volumetric enthalpy, cal/cc	-7021.28			
	8 Ag +	Mg(ClO ₄) ₂	=	MgO ₂ + 3 Ag ₂ O ₂ + 2 AgCl
Heat of formation		-140.60		-148.90
Molecular weight	107.87	223.23		247.76
Density	10.50	2.60		7.44
Melting point, °C	960.80	251.00		100.00
Boiling point, °C	2193.00			
Heat of reaction, kcal	-87.92			
Reactants' density	6.46			
Gravimetric enthalpy, cal/g	-80.95			
Volumetric enthalpy, cal/cc	-523.21			
	16 Al + 3 Mg(ClO ₄) ₂	=	3 MgCl ₂ + 8 Al ₂ O ₃	
Heat of formation		-140.60		-153.40
Molecular weight	26.98	223.23		95.23
Density	2.70	2.60		2.32
Melting point, °C	660.00	251.00		714.00
Boiling point, °C	2327.00			1418.00
Heat of reaction, kcal	-3231.12			
Reactants' density	2.64			
Gravimetric enthalpy, cal/g	-2933.73			
Volumetric enthalpy, cal/cc	-7742.25			

Table 21 (cont.)

	4 Ge	+	Mg(ClO ₄) ₂	=	MgCl ₂	+ 4 GeO ₂
Heat of formation			-140.60		-153.40	-128.30
Molecular weight	72.60		223.23		95.23	104.60
Density	5.35		2.60		2.32	4.70
Melting point, °C	960.00		251.00		714.00	1000.00
Boiling point, °C	2700.00				1418.00	
Heat of reaction, kcal	-526.00					
Reactants' density	3.67					
Gravimetric enthalpy, cal/g	-1024.08					
Volumetric enthalpy, cal/cc	-3753.44					
	4 Hf	+	Mg(ClO ₄) ₂	=	MgCl ₂	+ 4 HfO ₂
Heat of formation			-140.60		-153.40	-271.50
Molecular weight	178.50		223.23		95.23	210.60
Density	13.30		2.60		2.32	9.63
Melting point, °C	2227.00		251.00		714.00	2810.00
Boiling point, °C	3200.00				1418.00	
Heat of reaction, kcal	-1098.80					
Reactants' density	6.72					
Gravimetric enthalpy, cal/g	-1172.39					
Volumetric enthalpy, cal/cc	-7874.34					
	8 Hg	+	Mg(ClO ₄) ₂	=	MgCl ₂	+ 8 HgO
Heat of formation			-140.60		-153.40	-21.68
Molecular weight	200.61		223.23		95.23	216.61
Density	13.55		2.60		2.32	11.14
Melting point, °C	-38.87		251.00		714.00	500.00
Boiling point, °C	356.57				1418.00	
Heat of reaction, kcal	186.24					
Reactants' density	8.95					
Gravimetric enthalpy, cal/g	-101.88					
Volumetric enthalpy, cal/cc	-911.45					

Table 22

MOST ENERGETIC CHLORATE AND PERCHLORATE REACTIONS WITH METALS,
IN TERMS OF VOLUMETRIC ENTHALPY

Reaction				Enthalpy, cal/cc
8 Be +	Mg(ClO ₄) ₂ =	MgCl ₂ + 8 BeO		-9459
4 Be +	Li(ClO ₄) =	LiCl + 4 BeO		-9088
13 Be +	4 Ag(ClO ₃) =	2 Ag ₂ Cl + 12 BeO + BeCl ₂		-8103
4 U +	Mg(ClO ₄) ₂ =	MgCl ₂ + 4 UO ₂		-7989
4 Hf +	Mg(ClO ₄) ₂ =	MgCl ₂ + 4 HfO ₂		-7874
3 Be +	Na(ClO ₃) =	NaCl + 3 BeO		-7853
4 Be +	K(ClO ₄) =	KCl + 4 BeO		-7850
16 Al +	3 Mg(ClO ₄) ₂ =	3 MgCl ₂ + 8 Al ₂ O ₃		-7742
2 U +	Li(ClO ₄) =	LiCl + 2 UO ₂		-7670
2 Hf +	Li(ClO ₄) =	LiCl + 2 HfO ₂		-7562
8 Al +	3 Li(ClO ₄) =	3 LiCl + 4 Al ₂ O ₃		-7431
16 B +	3 Mg(ClO ₄) ₂ =	3 MgCl ₂ + 8 B ₂ O ₃		-7423
4 Zr +	Mg(ClO ₄) ₂ =	MgCl ₂ + 4 ZrO ₂		-7318
8 Be +	Ba(ClO ₄) ₂ =	BaCl ₂ + 8 BeO		-7302
8 B +	3 Li(ClO ₄) =	3 LiCl + 4 B ₂ O ₃		-7038
2 Zr +	Li(ClO ₄) =	LiCl + 2 ZrO ₂		-7021
4 Be +	Rb(ClO ₄) =	RbCl + 4 BeO		-7002
4 Th +	Mg(ClO ₄) ₂ =	MgCl ₂ + 4 ThO ₂		-6998
10 U +	6 Ag(ClO ₃) =	3 Ag ₂ Cl + 9 UO ₂ + UCl ₃		-6989
16 Ti +	3 Mg(ClO ₄) ₂ =	3 MgCl ₂ + 8 Ti ₂ O ₃		-6951
13 Hf +	8 Ag(ClO ₃) =	4 Ag ₂ Cl + 12 HfO ₂ + HfCl ₄		-6905
2 Th +	Li(ClO ₄) =	LiCl + 2 ThO ₂		-6750
3 U +	2 Na(ClO ₃) =	2 NaCl + 3 UO ₂		-6750
13 Al +	6 Ag(ClO ₃) =	3 Ag ₂ Cl + 6 Al ₂ O ₃ + AlCl ₃		-6733
16 Ta +	5 Mg(ClO ₄) ₂ =	5 MgCl ₂ + 8 Ta ₂ O ₅		-6730
2 U +	K(ClO ₄) =	KCl + 2 UO ₂		-6720
3 Hf +	2 Na(ClO ₃) =	2 NaCl + 3 HfO ₂		-6675
8 Ti +	3 Li(ClO ₄) =	3 LiCl + 4 Ti ₂ O ₃		-6658

Table 22 (cont.)

Reaction				Enthalpy, cal/cc
3 Be +	K(ClO ₃)	=	KCl + 3 BeO	-6653
2 Hf +	K(ClO ₄)	=	KCl + 2 HfO ₂	-6643
3 Be +	Rb(ClO ₃)	=	RbCl + 3 BeO	-6616
17 Be +	4 Ag(ClO ₄)	=	2 Ag ₂ Cl + 16 BeO + BeCl ₂	-6573
2 Al +	Na(ClO ₃)	=	NaCl + Al ₂ O ₃	-6562
4 Be +	Cs(ClO ₄)	=	CsCl + 4 BeO	-6533
8 Al +	3 K(ClO ₄)	=	3 KCl + 4 Al ₂ O ₃	-6527
10 Zr +	6 Ag(ClO ₃)	=	3 Ag ₂ Cl + 9 ZrO ₂ + ZrCl ₃	-6448
8 Ta +	5 Li(ClO ₄)	=	5 LiCl + 4 Ta ₂ O ₅	-6388
4 U +	Ba(ClO ₄) ₂	=	BaCl ₂ + 4 UO ₂	-6292
4 Si +	Mg(ClO ₄) ₂	=	MgCl ₂ + 4 SiO ₂	-6289
13 Th +	8 Ag(ClO ₃)	=	4 Ag ₂ Cl + 12 ThO ₂ + ThCl ₄	-6289
16 Nb +	5 Mg(ClO ₄) ₂	=	5 MgCl ₂ + 8 Nb ₂ O ₅	-6249
2 B +	Ag(ClO ₃)	=	AgCl + B ₂ O ₃	-6242
3 Zr +	2 Na(ClO ₃)	=	2 NaCl + 3 ZrO ₂	-6234
4 Hf +	Ba(ClO ₄) ₂	=	BaCl ₂ + 4 HfO ₂	-6228
2 Zr +	K(ClO ₄)	=	KCl + 2 ZrO ₂	-6192
16 Al +	3 Ba(ClO ₄) ₂	=	3 BaCl ₂ + 8 Al ₂ O ₃	-6119
3 Th +	2 Na(ClO ₃)	=	2 NaCl + 3 Th O ₂	-6102
13 Ti +	6 Ag(ClO ₃)	=	3 Ag ₂ Cl + 6 Ti ₂ O ₃ + TiCl ₃	-6100
16 Sc +	3 Mg(ClO ₄) ₂	=	3 MgCl ₂ + 8 Sc ₂ O ₃	-6099
2 Th +	K(ClO ₄)	=	KCl + 2 ThO ₂	-6063
2 B +	Na(ClO ₃)	=	NaCl + B ₂ O ₃	-6061
2 U +	Rb(ClO ₄)	=	RbCl + 2 UO ₂	-6040
16 Nd +	3 Mg(ClO ₄) ₂	=	3 MgCl ₂ + 8 Nd ₂ O ₃	-6036
8 B +	3 K(ClO ₄)	=	3 KCl + 4 B ₂ O ₃	-6004
2 Si +	Li(ClO ₄)	=	LiCl + 2 SiO ₂	-5983
16 La +	3 Mg(ClO ₄) ₂	=	3 MgCl ₂ + 8 La ₂ O ₃	-5981
2 Hf +	Rb(ClO ₄)	=	RbCl + 2 HfO ₂	-5981
16 V +	3 Mg(ClO ₄) ₂	=	3 MgCl ₂ + 8 V ₂ O ₃	5980

Table 22 (cont.)

Reaction		Enthalpy, cal/cc
16 Pr + 3 Mg(ClO ₄) ₂	= 3 MgCl ₂ + 8 Pr ₂ O ₃	-5946
16 Ce + 3 Mg(ClO ₄) ₂	= 3 MgCl ₂ + 8 Ce ₂ O ₃	-5941
2 Ti + Na(ClO ₃)	= NaCl + Ti ₂ O ₃	-5926
8 Nb + 5 Li(ClO ₄)	= 5 LiCl + 4 Nb ₂ O ₅	-5914
8 Mg + Mg(ClO ₄) ₂	= MgCl ₂ + 8 MgO	-5886
16 Cr + 3 Mg(ClO ₄) ₂	= 3 MgCl ₂ + 8 Cr ₂ O ₃	-5885
8 Sc + 3 Li(ClO ₄)	= 3 LiCl + 4 Sc ₂ O ₃	-5877
8 Ti + 3 K(ClO ₄)	= 3 KCl + 4 Ti ₂ O ₃	-5876
8 Al + 3 Rb(ClO ₄)	= 3 RbCl + 4 Al ₂ O ₃	-5875
8 Nd + 3 Li(ClO ₄)	= 3 LiCl + 4 Nd ₂ O ₃	-5832
4 Zr + Ba(ClO ₄) ₂	= BaCl ₂ + 4 ZrO ₂	-5817
8 La + 3 Li(ClO ₄)	= 3 LiCl + 4 La ₂ O ₃	-5786
3 U + 2 K(ClO ₃)	= 2 KCl + 3 UO ₂	-5779
6 Ta + 5 Ag(ClO ₃)	= 5 AgCl + 3 Ta ₂ O ₅	-5767
8 Pr + 3 Li(ClO ₄)	= 3 LiCl + 4 Pr ₂ O ₃	-5747
3 U + 2 Rb(ClO ₃)	= 2 RbCl + 3 UO ₂	-5747
13 U + 6 Ag(ClO ₄)	= 3 Ag ₂ Cl + 12 UO ₂ + UCl ₃	-5747
4 Th + Ba(ClO ₄) ₂	= BaCl ₂ + 4 ThO ₂	-5743
8 Ce + 3 Li(ClO ₄)	= 3 LiCl + 4 Ce ₂ O ₃	-5737
3 Hf + 2 K(ClO ₃)	= 2 KCl + 3 HfO ₂	-5728
3 Hf + 2 Rb(ClO ₃)	= 2 RbCl + 3 HfO ₂	-5696
17 Hf + 8 Ag(ClO ₄)	= 4 Ag ₂ Cl + 16 HfO ₂ + HfCl ₄	-5688
4 Mg + Li(ClO ₄)	= LiCl + 4 MgO	-5683
8 V + 3 Li(ClO ₄)	= 3 LiCl + 4 V ₂ O ₃	-5676
2 U + Cs(ClO ₄)	= CsCl + 2 UO ₂	-5662
2 Al + K(ClO ₃)	= KCl + Al ₂ O ₃	-5629
2 Hf + Cs(ClO ₄)	= CsCl + 2 HfO ₂	-5612
2 Al + Rb(ClO ₃)	= RbCl + Al ₂ O ₃	-5597
6 Ta + 5 Na(ClO ₃)	= 5 NaCl + 3 Ta ₂ O ₅	-5596
16 Zr + 8 Rb(ClO ₄)	= 8 RbCl + 16 ZrO ₂	-5585

Table 22 (cont.)

Reaction						Enthalpy, cal/cc
13 Nd +	6 Ag(ClO ₃)	=	3 Ag ₂ Cl	+ 6 Nd ₂ O ₃ +	NdCl ₃	-5583
13 Sc +	6 Ag(ClO ₃)	=	3 Ag ₂ Cl	+ 6 Sc ₂ O ₃ +	ScCl ₃	-5568
8 Cr +	3 Li(ClO ₄)	=	3 LiCl	+ 4 Cr ₂ O ₃		-5565
16 B +	3 Ba(ClO ₄)	=	3 BaCl ₂	+ 8 B ₂ O ₃		-5562
13 La +	6 Ag(ClO ₃)	=	3 Ag ₂ Cl	+ 6 La ₂ O ₃ +	LaCl ₃	-5553
17 Al +	6 Ag(ClO ₄)	=	3 Ag ₂ Cl	+ 8 Al ₂ O ₃ +	AlCl ₃	-5553
2 Th +	Rb(ClO ₄)	=	RbCl	+ 2 ThO ₂		-5542
8 Ta +	5 K(ClO ₄)	=	5 KCl	+ 4 Ta ₂ O ₅		-5530
16 Ti +	3 Ba(ClO ₄) ₂	=	3 BaCl ₂	+ 8 Ti ₂ O ₃		-5523
13 Ce +	6 Ag(ClO ₃)	=	3 Ag ₂ Cl	+ 6 Ce ₂ O ₃ +	CeCl ₃	-5514
13 Pr +	6 Ag(ClO ₃)	=	3 Ag ₂ Cl	+ 6 Pr ₂ O ₃ +	PrCl ₃	-5514
8 Al +	3 Cs(ClO ₄)	=	3 CsCl	+ 4 Al ₂ O ₃		-5512
3 Si +	2 Ag(ClO ₃)	=	2 AgCl	+ 3 SiO ₂		-5477
13 Mg +	4 Ag(ClO ₃)	=	2 Ag ₂ Cl	+ 12 MgO +	MgCl ₂	-5411
6 Nb +	5 Ag(ClO ₃)	=	5 AgCl	+ 3 Nb ₂ O ₅		-5380
2 Sc +	Na(ClO ₃)	=	NaCl	+ Sc ₂ O ₃		-5379
2 Nd +	Na(ClO ₃)	=	NaCl	+ Nd ₂ O ₃		-5374
3 Zr +	2 K(ClO ₃)	=	2 KCl	+ 3 ZrO ₂		-5363
2 La +	Na(ClO ₃)	=	NaCl	+ La ₂ O ₃		-5350
3 Th +	2 K(ClO ₃)	=	2 KCl	+ 3 ThO ₂		-5348
13 Zr +	6 Ag(ClO ₄)	=	3 Ag ₂ Cl	+ 12 ZrO ₂ +	ZrCl ₃	-5333
3 Zr +	2 Rb(ClO ₃)	=	2 RbCl	+ 3 ZrO ₂		-5332
8 Sc +	3 K(ClO ₄)	=	3 KCl	+ 4 Sc ₂ O ₃		-5329
8 Nd +	3 K(ClO ₄)	=	3 KCl	+ 4 Nd ₂ O ₃		-5327
3 Th +	2 Rb(ClO ₃)	=	2 RbCl	+ 3 ThO ₂		-5320
17 Th +	8 Ag(ClO ₄)	=	4 Ag ₂ Cl	+ 16 ThO ₂ +	ThCl ₄	-5320
3 Si +	2 Na(ClO ₃)	=	2 NaCl	+ 3 SiO ₂		-5316
2 Pr +	Na(ClO ₃)	=	NaCl	+ Pr ₂ O ₃		-5307
8 La +	3 K(ClO ₄)	=	3 KCl	+ 4 La ₂ O ₃		-5305
8 Ti +	3 Rb(ClO ₄)	=	3 RbCl	+ 4 Ti ₂ O ₃		-5299

Table 22 (cont.)

Reaction		Enthalpy, cal/cc
2 Ce + Na(ClO ₃)	= NaCl + Ce ₂ O ₃	-5290
8 B + 3 Rb(ClO ₄)	= 3 RbCl + 4 B ₂ O ₃	-5289
8 Pr + 3 K(ClO ₄)	= 3 KCl + 4 Pr ₂ O ₃	-5259
2 Si + K(ClO ₄)	= KCl + 2 SiO ₂	-5247
2 Zr + Cs(ClO ₄)	= CsCl + 2 ZrO ₂	-5246
2 Th + Cs(ClO ₄)	= CsCl + 2 ThO ₂	-5245
3 Mg + Na(ClO ₃)	= NaCl + 3 MgO	-5243
8 Ce + 3 K(ClO ₄)	= 3 KCl + 4 Ce ₂ O ₃	-5242
9 V + 4 Ag(ClO ₃)	= 2 Ag ₂ Cl + 4 V ₂ O ₃ + VCl ₂	-5233
6 Nb + 5 Na(ClO ₃)	= 5 NaCl + 3 Nb ₂ O ₅	-5205
4 Mg + K(ClO ₄)	= KCl + 4 MgO	-5193
16 Ta + 5 Ba(ClO ₄) ₂	= 5 BaCl ₂ + 8 Ta ₂ O ₅	-5155
6 Mn + Mg(ClO ₄) ₂	= MgCl ₂ + 2 Mn ₃ O ₄	-5132
13 Cr + 6 Ag(ClO ₃)	= 3 Ag ₂ Cl + 6 Cr ₂ O ₃ + CrCl ₃	-5129
8 Nb + 5 K(ClO ₄)	= 5 KCl + 4 Nb ₂ O ₅	-5128
2 Ti + K(ClO ₃)	= KCl + Ti ₂ O ₃	-5095
16 Nd + 3 Ba(ClO ₄) ₂	= 3 BaCl ₂ + 8 Nd ₂ O ₃	-5086
16 La + 3 Ba(ClO ₄) ₂	= 3 BaCl ₂ + 8 La ₂ O ₃	-5074
16 Sc + 3 Ba(ClO ₄) ₂	= 3 BaCl ₂ + 8 Sc ₂ O ₃	-5071
2 Ti + Rb(ClO ₃)	= RbCl + Ti ₂ O ₃	-5065
2 V + Na(ClO ₃)	= NaCl + V ₂ O ₃	-5054
2 B + K(ClO ₃)	= KCl + B ₂ O ₃	-5046
17 Ti + 6 Ag(ClO ₄)	= 3 Ag ₂ Cl + 8 Ti ₂ O ₃ + TiCl ₃	-5041
16 Pr + 3 Ba(ClO ₄) ₂	= 3 BaCl ₂ + 8 Pr ₂ O ₃	-5026
2 B + Rb(ClO ₃)	= RbCl + B ₂ O ₃	-5010
16 Ce + 3 Ba(ClO ₄) ₂	= 3 BaCl ₂ + 8 Ce ₂ O ₃	-5005
8 V + 3 K(ClO ₄)	= 3 KCl + 4 V ₂ O ₃	-4978
8 Ti + 3 Cs(ClO ₄)	= 3 CsCl + 4 Ti ₂ O ₃	-4977
8 Mg + Ba(ClO ₄) ₂	= BaCl ₂ + 8 MgO	-4960
8 B + 3 Ag(ClO ₄)	= 3 AgCl + 4 B ₂ O ₃	-4941

Table 22 (cont.)

Reaction				Enthalpy, cal/cc
2 Cr +	Na(ClO ₃)	=	NaCl + Cr ₂ O ₃	-4933
8 W +	3 Mg(ClO ₄) ₂	=	3 MgCl ₂ + 8 WO ₃	-4923
8 Nd +	3 Rb(ClO ₄)	=	3 RbCl + 4 Nd ₂ O ₃	-4922
4 Si +	Ba(ClO ₄) ₂	=	BaCl ₂ + 4 SiO ₂	-4921
8 La +	3 Rb(ClO ₄)	=	3 RbCl + 4 La ₂ O ₃	-4916
8 Ta +	5 Rb(ClO ₄)	=	5 RbCl + 4 Ta ₂ O ₅	-4912
8 B +	3 Cs(ClO ₄)	=	3 CsCl + 4 B ₂ O ₃	-4905
8 Sc +	3 Rb(ClO ₄)	=	3 RbCl + 4 Sc ₂ O ₃	-4896
8 Pr +	3 Rb(ClO ₄)	=	3 RbCl + 4 Pr ₂ O ₃	-4866
8 Cr +	3 K(ClO ₄)	=	3 KCl + 4 Cr ₂ O ₃	-4851
8 Ce +	3 Rb(ClO ₄)	=	3 RbCl + 4 Ce ₂ O ₃	-4843
3 Mn +	Li(ClO ₄)	=	LiCl + Mn ₃ O ₄	-4839
17 La +	6 Ag(ClO ₄)	=	3 Ag ₂ Cl + 8 La ₂ O ₃ + LaCl ₃	-4803
17 Nd +	6 Ag(ClO ₄)	=	3 Ag ₂ Cl + 8 Nd ₂ O ₃	-4802
4 Mg +	Rb(ClO ₄)	=	RbCl + 4 MgO	-4799
16 Nb +	5 Ba(ClO ₄) ₂	=	5 BaCl ₂ + 8 Nb ₂ O ₅	-4786
2 Nd +	K(ClO ₃)	=	KCl + Nd ₂ O ₃	-4783
2 La +	K(ClO ₃)	=	KCl + La ₂ O ₃	-4782
2 La +	Rb(ClO ₃)	=	RbCl + La ₂ O ₃	-4759
2 Nd +	Rb(ClO ₃)	=	RbCl + Nd ₂ O ₃	-4759
17 Pr +	6 Ag(ClO ₄)	=	3 Ag ₂ Cl + 8 Pr ₂ O ₃ + PrCl ₃	-4854
2 Sc +	K(ClO ₃)	=	KCl + Sc ₂ O ₃	-4749
17 Sc +	6 Ag(ClO ₄)	=	3 Ag ₂ Cl + 8 Sc ₂ O ₃ + ScCl ₃	-4745
17 Ce +	6 Ag(ClO ₄)	=	3 Ag ₂ Cl + 8 Ce ₂ O ₃ + CeCl ₃	-4739
2 Pr +	K(ClO ₃)	=	KCl + Pr ₂ O ₃	-4732
2 Sc +	Rb(ClO ₃)	=	RbCl + Sc ₂ O ₃	-4724
6 Ta +	5 K(ClO ₃)	=	5 KCl + 3 Ta ₂ O ₅	-4713
2 Pr +	Rb(ClO ₃)	=	RbCl + Pr ₂ O ₃	-4709
16 Ga +	3 Mg(ClO ₄) ₂	=	3 MgCl ₂ + 8 Ga ₂ O ₃	-4708
2 Ce +	K(ClO ₃)	=	KCl + Ce ₂ O ₃	-4708
2 Si +	Rb(ClO ₄)	=	RbCl + 2 SiO ₂	-4701

Table 22 (cont.)

		Reaction	Enthalpy, cal/cc
8 La +	3 Cs(ClO ₄)	= 3 CsCl + 4 La ₂ O ₃	-4691
8 Nd +	3 Cs(ClO ₄)	= 3 CsCl + 4 Nd ₂ O ₃	-4689
2 Ce +	Rb(ClO ₃)	= RbCl + Ce ₂ O ₃	-4685
6 Ta +	5 Rb(ClO ₃)	= 5 RbCl + 3 Ta ₂ O ₅	-4679
16 V +	3 Ba(ClO ₄) ₂	= 3 BaCl ₂ + 8 V ₂ O ₃	-4670
3 Mg +	K(ClO ₃)	= KCl + 3 MgO	-4666
17 Mg +	4 Ag(ClO ₄)	= 2 Ag ₂ Cl + 16 MgO + MgCl ₂	-4661
8 Sc +	3 Cs(ClO ₄)	= 3 CsCl + 4 Sc ₂ O ₃	-4648
3 Mg +	Rb(ClO ₃)	= RbCl + 3 MgO	-4643
8 Pr +	3 Cs(ClO ₄)	= 3 CsCl + 4 Pr ₂ O ₃	-4639
13 Mn +	4 Ag(ClO ₃)	= 2 Ag ₂ Cl + 12 MnO + MnCl ₂	-4626
8 Ta +	5 Ag(ClO ₄)	= 5 AgCl + 4 Ta ₂ O ₅	-4626
8 Ce +	3 Cs(ClO ₄)	= 3 CsCl + 4 Ce ₂ O ₃	-4614
4 W +	3 Li(ClO ₄)	= 3 LiCl + 4 WO ₃	-4587
8 Ta +	5 Cs(ClO ₄)	= 5 CsCl + 4 Ta ₂ O ₅	-4577
4 Mg +	Cs(ClO ₄)	= CsCl + 4 MgO	-4572
8 Nb +	5 Rb(ClO ₄)	= 5 RbCl + 4 Nb ₂ O ₅	-4554
16 Cr +	3 Ba(ClO ₄) ₂	= 3 BaCl ₂ + 8 Cr ₂ O ₃	-4539
3 Si +	2 K(ClO ₃)	= 2 KCl + 3 SiO ₂	-4529
3 Si +	2 Rb(ClO ₃)	= 2 RbCl + 3 SiO ₂	-4498
8 V +	3 Rb(ClO ₄)	= 3 RbCl + 4 V ₂ O ₃	-4455
8 Ga +	3 Li(ClO ₄)	= 3 LiCl + 4 Ga ₂ O ₃	-4454
2 Si +	Ag(ClO ₄)	= AgCl + 2 SiO ₂	-4454
8 Mo +	3 Mg(ClO ₄) ₂	= 3 MgCl ₂ + 8 MoO ₃	-4449

Table 23

MOST ENERGETIC CHLORATE AND PERCHLORATE REACTIONS WITH METALS,
IN TERMS OF GRAVIMETRIC ENTHALPY

Reaction			Enthalpy, cal/g
4 Be +	Li(ClO ₄)	= LiCl + 4 BeO	-4037
8 Be +	Mg(ClO ₄) ₂	= MgCl ₂ + 8 BeO	-3998
16 Li +	Mg(ClO ₄) ₂	= MgO + 7 Li ₂ O + 2 LiCl	-3576
3 Li +	Li(ClO ₄)	= LiCl + 4 Li ₂ O	-3463
3 Be +	Na(ClO ₃)	= NaCl + 3 BeO	-3374
4 Be +	K(ClO ₄)	= KCl + 4 BeO	-3348
34 Li +	2 Cu(ClO ₄) ₂	= Cu ₂ O + 15 Li ₂ O + 4 LiCl	-3323
12 Li +	2 Li(ClO ₃)	= Li ₂ O + 5 Li ₂ O + 2 LiCl	-3310
16 Li +	2 Na(ClO ₄)	= Na ₂ O + 7 Li ₂ O + 2 LiCl	-3110
26 Li +	2 Cu(ClO ₃) ₂	= Cu ₂ O + 11 Li ₂ O + 4 LiCl	-3015
3 Be +	K(ClO ₃)	= KCl + 3 BeO	-2999
6 Li +	Na(ClO ₃)	= NaCl + 3 Li ₂ O	-2969
8 Li +	K(ClO ₄)	= KCl + 4 Li ₂ O	-2937
3 Al +	3 Li(ClO ₄)	= 3 LiCl + 4 Al ₂ O ₃	-2934
16 Al +	3 Mg(ClO ₄) ₂	= 3 MgCl ₂ + 8 Al ₂ O ₃	-2933
8 B +	3 Li(ClO ₄)	= 3 LiCl + 4 B ₂ O ₃	-2912
16 B +	3 Mg(ClO ₄) ₂	= 3 MgCl ₂ + 8 B ₂ O ₃	-2912
3 Be +	Ba(ClO ₄) ₂	= BaCl ₂ + 8 BeO	-2891
8 Mg +	Mg(ClO ₄) ₂	= MgCl ₂ + 8 MgO	-2784
4 Mg +	Li(ClO ₄)	= LiCl + 4 MgO	-2782
6 Li +	K(ClO ₃)	= KCl + 3 Li ₂ O	-2666
4 Be +	Rb(ClO ₄)	= RbCl + 4 BeO	-2638
16 Li +	Ba(ClO ₄) ₂	= BaCl ₂ + 8 Li ₂ O	-2575
2 Al +	Na(ClO ₃)	= NaCl + Al ₂ O ₃	-2565
17 Be +	4 Ag(ClO ₄)	= 2 Ag ₂ Cl + 16 BeO + BeCl ₂	-2533
8 Al +	3 K(ClO ₄)	= 3 KCl + 4 Al ₂ O ₃	-2530
4 Si +	Mg(ClO ₄) ₂	= MgCl ₂ + 4 SiO ₂	-2486
3 Mg +	Na(ClO ₃)	= NaCl + 3 MgO	-2474
2 Si +	Li(ClO ₄)	= LiCl + 2 SiO ₂	-2473

Table 23 (cont.)

Reaction				Enthalpy, cal/g
2 B	+	Na(ClO ₃)	= NaCl + B ₂ O ₃	-2455
4 Mg	+	K(ClO ₄)	= KCl + 4 MgO	-2442
8 B	+	3 K(ClO ₄)	= 3 KCl + 4 B ₂ O ₃	-2408
16 Sc	+	3 Mg(ClO ₄) ₂	= 3 MgCl ₂ + 8 Sc ₂ O ₃	-2394
8 Sc	+	3 Li(ClO ₄)	= 3 LiCl + 4 Sc ₂ O ₃	-2383
8 Li	+	Rb(ClO ₄)	= RbCl + 4 Li ₂ O	-2364
17 Li	+	2 Ag(ClO ₄)	= Ag ₂ Cl + 8 Li ₂ O + LiCl	-2351
2 Al	+	K(ClO ₃)	= KCl + Al ₂ O ₃	-2321
3 Be	+	Rb(ClO ₃)	= RbCl + 3 BeO	-2281
3 Mg	+	K(ClO ₃)	= KCl + 3 MgO	-2261
8 Ca	+	Mg(ClO ₄) ₂	= MgCl ₂ + 8 CaO	-2257
4 Ca	+	Li(ClO ₄)	= LiCl + 4 CaO	-2245
16 Al	+	3 Ba(ClO ₄) ₂	= 3 BaCl ₂ + 8 Al ₂ O ₃	-2242
14 Al	+	2 Cu(ClO ₄) ₂	= Cu ₂ O + 5 Al ₂ O ₃ + 4 AlCl	-2234
12 Li	+	Ba(ClO ₃) ₂	= BaO + 5 Li ₂ O + 2 LiCl	-2217
8 Mg	+	Ba(ClO ₄) ₂	= BaCl ₂ + 8 MgO	-2191
4 Be	+	Cs(ClO ₄)	= CsCl + 4 BeO	-2174
2 B	+	K(ClO ₃)	= KCl + B ₂ O ₃	-2168
13 Be	+	4 Ag(ClO ₃)	= 2 Ag ₂ Cl + 12 BeO + BeCl ₂	-2167
3 Si	+	2 Na(ClO ₃)	= 2 NaCl + 3 SiO ₂	-2157
2 Sc	+	Na(ClO ₃)	= NaCl + Sc ₂ O ₃	-2156
8 Sc	+	3 K(ClO ₄)	= 3 KCl + 4 Sc ₂ O ₃	-2122
2 Si	+	K(ClO ₄)	= KCl + 2 SiO ₂	-2112
14 B	+	2 Cu(ClO ₄) ₂	= Cu ₂ O + 5 B ₂ O ₃	-2083
16 B	+	3 Ba(ClO ₄) ₂	= 5 BaCl ₂ + 8 B ₂ O ₃	-2076
16 Ti	+	3 Mg(ClO ₄) ₂	= 3 MgCl ₂ + 8 Ti ₂ O ₃	-2071
6 Li	+	Rb(ClO ₃)	= RbCl + 3 Li ₂ O	-2071
8 Al	+	3 Rb(ClO ₄)	= 3 RbCl + 4 Al ₂ O ₃	-2067
3 Ca	+	Na(ClO ₃)	= NaCl + 3 CaO	-2065
13 Li	+	2 Ag(ClO ₃)	= Ag ₂ Cl + 6 Li ₂ O + 1 LiCl	-2054
8 Ti	+	3 Li(ClO ₄)	= 3 LiCl + 4 Ti ₂ O ₃	-2053

Table 23 (cont.)

		Reaction	Enthalpy, cal/g
4 Mg +	Rb(ClO ₄)	= RbCl + 4 MgO	-2035
4 Ca +	K(ClO ₄)	= KCl + 4 CaO	-2034
20 Al +	6 Na(ClO ₄)	= 3 Na ₂ O + 7 Al ₂ O ₃ + 6 AlCl	-2015
17 Mg +	4 Ag(ClO ₄)	= 2 Ag ₂ Cl + 16 MgO + MgCl ₂	-2000
17 Al +	6 Ag(ClO ₄)	= 3 Ag ₂ Cl + 8 Al ₂ O ₃ + AlCl ₃	-1999
2 Sc +	K(ClO ₃)	= KCl + Sc ₂ O ₃	-1984
34 Be +	4 Cu(ClO ₄) ₂	= 2 Cu ₂ O + 15 BeO + 4 BeCl ₂	-1978
16 Al +	6 Li(ClO ₃)	= 3 Li ₂ O + 5 Al ₂ O ₃ + 6 AlCl	-1977
8 Li +	Cs(ClO ₄)	= CsCl + 4 Li ₂ O	-1977
12 Be +	4 Li(ClO ₃)	= 2 Li ₂ O + 5 BeO + 2 BeCl ₂	-1935
3 Si +	2 K(ClO ₃)	= 2 KCl + 3 SiO ₂	-1935
16 Sc +	3 Ba(ClO ₄) ₂	= 3 BaCl ₂ + 8 Sc ₂ O ₃	-1924
3 Ca +	K(ClO ₃)	= KCl + 3 CaO	-1920
34 Al +	6 Cu(ClO ₃) ₂	= 3 Cu ₂ O + 11 Al ₂ O ₃ + 12 AlCl	-1903
8 B +	3 Rb(ClO ₄)	= 3 RbCl + 4 B ₂ O ₃	-1878
2 Ti +	Na(ClO ₃)	= NaCl + Ti ₂ O ₃	-1876
8 Ca +	Ba(ClO ₄) ₂	= BaCl ₂ + 8 CaO	-1869
4 Si +	Ba(ClO ₄) ₂	= BaCl ₂ + 4 SiO ₂	-1859
8 Ti +	3 K(ClO ₄)	= 3 KCl + 4 Ti ₂ O ₃	-1839
2 Al +	Rb(ClO ₃)	= RbCl + Al ₂ O ₃	-1831
3 Mg +	Rb(ClO ₃)	= RbCl + 3 MgO	-1821
8 B +	3 Ag(ClO ₄)	= 3 AgCl + 4 B ₂ O ₃	-1800
8 Sc +	3 Rb(ClO ₄)	= 3 RbCl + 4 Sc ₂ O ₃	-1794
20 B +	6 Na(ClO ₄)	= 3 Na ₂ O + 7 B ₂ O ₃ + 6 BCl	-1793
4 Zr +	Mg(ClO ₄) ₂	= MgCl ₂ + 4 ZrO ₂	-1777
13 Mg +	4 Ag(ClO ₃)	= 2 Ag ₂ Cl + 12 MgO + MgCl ₂	-1773
26 Be +	4 Cu(ClO ₃) ₂	= 2 Cu ₂ O + 11 BeO + 4 BeCl ₂	-1771
17 Sc +	6 Ag(ClO ₄)	= 3 Ag ₂ Cl + 8 Sc ₂ O ₃ + Sc ₂ O ₃	-1770
16 B +	6 Li(ClO ₃)	= 3 Li ₂ O + 5 B ₂ O ₃ + 6 BCl	-1758
2 Zr +	Li(ClO ₄)	= LiCl + 2 ZrO ₂	-1758
4 Ca +	Rb(ClO ₄)	= RbCl + 4 CaO	-1757

Table 23 (cont.)

Reaction						Enthalpy, cal/g
17	Ca	+	4 Ag(ClO ₄)	=	2 Ag ₂ Cl + 16 CaO + CaCl ₂	-1754
13	Al	+	6 Ag(ClO ₃)	=	3 Ag ₂ Cl + 6 Al ₂ O ₃ + AlCl ₃	-1747
	8 Al	+	3 Cs(ClO ₄)	=	3 CsCl + 4 Al ₂ O ₃	-1747
	4 Mg	+	Cs(ClO ₄)	=	CsCl + 4 MgO	-1744
16	Be	+	4 Na(ClO ₄)	=	2 Na ₂ O + 7 BeO + 2 BeCl ₂	-1729
	2 Ti	+	K(ClO ₃)	=	KCl + Ti ₂ O ₃	-1729
	2 Si	+	Rb(ClO ₄)	=	RbCl + 2 SiO ₂	-1699
34	B	+	6 Cu(ClO ₃) ₂	=	3 Cu ₂ O + 11 B ₂ O ₃ + 12 BCl	-1682
16	Ti	+	3 Ba(ClO ₄) ₂	=	3 BaCl ₂ + 8 Ti ₂ O ₃	-1675
	2 Si	+	Ag(ClO ₄)	=	AgCl + 2 SiO ₂	-1644
	3 Zr	+	2 Na(ClO ₃)	=	2 NaCl + 3 ZrO ₂	-1643
	2 B	+	Rb(ClO ₃)	=	RbCl + B ₂ O ₃	-1632
	2 Sc	+	Rb(ClO ₃)	=	RbCl + Sc ₂ O ₃	-1622
	2 Zr	+	K(ClO ₄)	=	KCl + 2 ZrO ₂	-1610
	3 Ca	+	Rb(ClO ₃)	=	RbCl + 3 CaO	-1607
13	Ca	+	4 Ag(ClO ₃)	=	2 Ag ₂ Cl + 12 CaO + CaCl ₂	-1594
16	V	+	3 Mg(ClO ₄) ₂	=	3 MgCl ₂ + 8 V ₂ O ₃	-1588
13	Sc	+	6 Ag(ClO ₃)	=	3 Ag ₂ Cl + 6 Sc ₂ O ₃ + ScCl ₃	-1584
	8 Ti	+	3 Rb(ClO ₄)	=	3 RbCl + 4 Ti ₂ O ₃	-1561
	8 V	+	3 Li(ClO ₄)	=	3 LiCl + 4 V ₂ O ₃	-1560
	8 Sc	+	3 Cs(ClO ₄)	=	3 CsCl + 4 Sc ₂ O ₃	-1554
	4 Ca	+	Cs(ClO ₄)	=	CsCl + 4 CaO	-1546
	8 B	+	3 Cs(ClO ₄)	=	3 CsCl + 4 B ₂ O ₃	-1540
	3 Zr	+	2 K(ClO ₃)	=	2 KCl + 3 ZrO ₂	-1534
	2 B	+	Ag(ClO ₃)	=	AgCl + B ₂ O ₃	-1533
17	Ti	+	6 Ag(ClO ₄)	=	3 Ag ₂ Cl + 8 Ti ₂ O ₃ + TiCl ₃	-1528
	3 Si	+	2 Rb(ClO ₃)	=	2 RbCl + 3 SiO ₂	-1502
	4 Zr	+	Ba(ClO ₄) ₂	=	BaCl ₂ + 4 ZrO ₂	-1491
34	Mg	+	4 Cu(ClO ₄) ₂	=	2 Cu ₂ O + 30 MgO + 4 MgCl ₂	-1478
12	Mg	+	4 Li(ClO ₃)	=	2 Li ₂ O + 10 MgO + 2 MgCl ₂	-1470

Table 23 (cont.)

Reaction		Enthalpy, cal/g
16 Cr + 3 Mg(ClO ₄) ₂	= 3 MgCl ₂ + 8 Cr ₂ O ₃	-1462
2 V + Na(ClO ₃)	= NaCl + V ₂ O ₃	-1451
16 Nb + 5 Mg(ClO ₄) ₂	= 5 MgCl ₂ + 8 Nb ₂ O ₅	-1448
12 Na + 2 Li(ClO ₃)	= Li ₂ O + 5 Na ₂ O + 2 NaCl	-1446
18 Na + 2 Mg(ClO ₄) ₂	= 2 MgO + 7 Na ₂ O ₂ + 4 NaCl	-1445
34 Na + 2 Cu(ClO ₄) ₂	= Cu ₂ O + 15 Na ₂ O + 4 NaCl	-1443
4 C + Mg(ClO ₄) ₂	= MgCl ₂ + 4 CO ₂	-1433
8 Cr + 3 Li(ClO ₄)	= 3 LiCl + 4 Cr ₂ O ₃	-1432
3 Si + 2 Ag(ClO ₃)	= 2 AgCl + 3 SiO ₂	-1425
2 Si + Cs(ClO ₄)	= CsCl + 2 SiO ₂	-1422
2 Ti + Rb(ClO ₃)	= RbCl + Ti ₂ O ₃	-1420
8 Nb + 5 Li(ClO ₄)	= 5 LiCl + 4 Nb ₂ O ₅	-1419
8 V + 3 K(ClO ₄)	= 3 KCl + 4 V ₂ O ₃	-1411
16 Zr + 8 Rb(ClO ₄)	= 8 RbCl + 16 ZrO ₂	-1403
16 Al + 3 Ba(ClO ₃) ₂	= 3 BaO + 5 Al ₂ O ₃ + 6 AlCl	-1398
26 Mg + 4 Cu(ClO ₃) ₂	= 2 Cu ₂ O + 22 MgO + 4 MgCl ₂	-1382
26 Na + 2 Cu(ClO ₃) ₂	= Cu ₂ O + 11 Na ₂ O + 4 NaCl	-1381
13 Zr + 6 Ag(ClO ₄)	= 3 Ag ₂ Cl + 12 ZrO ₂ + ZrCl ₃	-1379
2 C + Li(ClO ₄)	= LiCl + 2 CO ₂	-1376
13 Ti + 6 Ag(ClO ₃)	= 3 Ag ₂ Cl + 6 Ti ₂ O ₃ + TiCl ₃	-1369
8 Ti + 3 Cs(ClO ₄)	= 3 CsCl + 4 Ti ₂ O ₃	-1357
2 Cr + Na(ClO ₃)	= NaCl + Cr ₂ O ₃	-1340
2 V + K(ClO ₃)	= KCl + V ₂ O ₃	-1339
6 Nb + 5 Na(ClO ₃)	= 5 NaCl + 3 Nb ₂ O ₅	-1332
16 Na + 2 Na(ClO ₄)	= Na ₂ O + 7 Na ₂ O + 2 NaCl	-1317
18 Na + 4 Li(ClO ₄)	= 2 Li ₂ O + 7 Na ₂ O ₂ + 4 NaCl	-1306
16 Mg + 4 Na(ClO ₄)	= 2 Na ₂ O + 14 MgO + 2 MgCl ₂	-1301
8 Cr + 3 K(ClO ₄)	= 3 KCl + 4 Cr ₂ O ₃	-1299
3 Zr + 2 Rb(ClO ₃)	= 2 RbCl + 3 ZrO ₂	-1296
8 Nb + 5 K(ClO ₄)	= 5 KCl + 4 Nb ₂ O ₅	-1292

Table 23 (cont.)

Reaction		Enthalpy, cal/g
16 V + 3 Ba(ClO ₄) ₂	= 3 BaCl ₂ + 8 V ₂ O ₃	-1292
16 La + 3 Mg(ClO ₄) ₂	= 3 MgCl ₂ + 8 La ₂ O ₃	-1280
12 Ca + 4 Li(ClO ₃)	= 2 Li ₂ O + 10 CaO + 2 CaCl ₂	-1274
8 La + 3 Li(ClO ₄)	= 3 LiCl + 4 La ₂ O ₃	-1262
34 Ca + 4 Cu(ClO ₄) ₂	= 2 Cu ₂ O + 30 CaO + 4 CaCl ₂	-1260
10 Zr + 6 Ag(ClO ₃)	= 3 Ag ₂ Cl + 9 ZrO ₂ + ZrCl ₃	-1257
2 Zr + Cs(ClO ₄)	= CsCl + 2 ZrO ₂	-1244
2 Cr + K(ClO ₃)	= KCl + Cr ₂ O ₃	-1237
8 Sr + Mg(ClO ₄) ₂	= MgCl ₂ + 8 SrO	-1235
8 Na + K(ClO ₄)	= KCl + 4 Na ₂ O	-1234
3 C + 2 Na(ClO ₃)	= 2 NaCl + 3 CO ₂	-1233
6 Nb + 5 K(ClO ₃)	= 5 KCl + 3 Nb ₂ O ₅	-1233
16 Pr + 3 Mg(ClO ₄) ₂	= 3 MgCl ₂ + 8 Pr ₂ O ₃	-1229
12 Be + 2 Ba(ClO ₃) ₂	= 2 BaO + 5 BeO + 2 BeCl ₂	-1225
2 La + Na(ClO ₃)	= NaCl + La ₂ O ₃	-1224
6 Mn + Mg(ClO ₄) ₂	= MgCl ₂ + 2 Mn ₃ O ₄	-1221
4 Sr + Li(ClO ₄)	= LiCl + 4 SrO	-1216
26 Ca + 4 Cu(ClO ₃) ₂	= 2 Cu ₂ O + 22 CaO + 4 CaCl ₂	-1214
8 Pr + 3 Li(ClO ₄)	= 3 LiCl + 4 Pr ₂ O ₃	-1211
16 Ce + 3 Mg(ClO ₄) ₂	= 3 MgCl ₂ + 8 Ce ₂ O ₃	-1208
8 V + 3 Rb(ClO ₄)	= 3 RbCl + 4 V ₂ O ₃	-1202
16 Nd + 3 Mg(ClO ₄) ₂	= 3 MgCl ₂ + 8 Nd ₂ O ₃	-1200
8 La + 3 K(ClO ₄)	= 3 KCl + 4 La ₂ O ₃	-1200
16 Cr + 3 Ba(ClO ₄) ₂	= 3 BaCl ₂ + 8 Cr ₂ O ₃	-1192
8 Ce + 3 Li(ClO ₄)	= 3 LiCl + 4 Ce ₂ O ₃	-1190
3 Mn + Li(ClO ₄)	= LiCl + Mn ₃ O ₄	-1190
16 Nb + 5 Ba(ClO ₄) ₂	= 5 BaCl ₂ + 8 Nb ₂ O ₅	-1189
6 Na + K(ClO ₃)	= KCl + 3 Na ₂ O	-1185
35 V + 12 Ag(ClO ₄)	= 6 Ag ₂ Cl + 16 V ₂ O ₃ + 3 VCl ₂	-1183
8 Nd + 3 Li(ClO ₄)	= 3 LiCl + 4 Nd ₂ O ₃	-1182
3 Sr + Na(ClO ₃)	= NaCl + 3 SrO	-1179

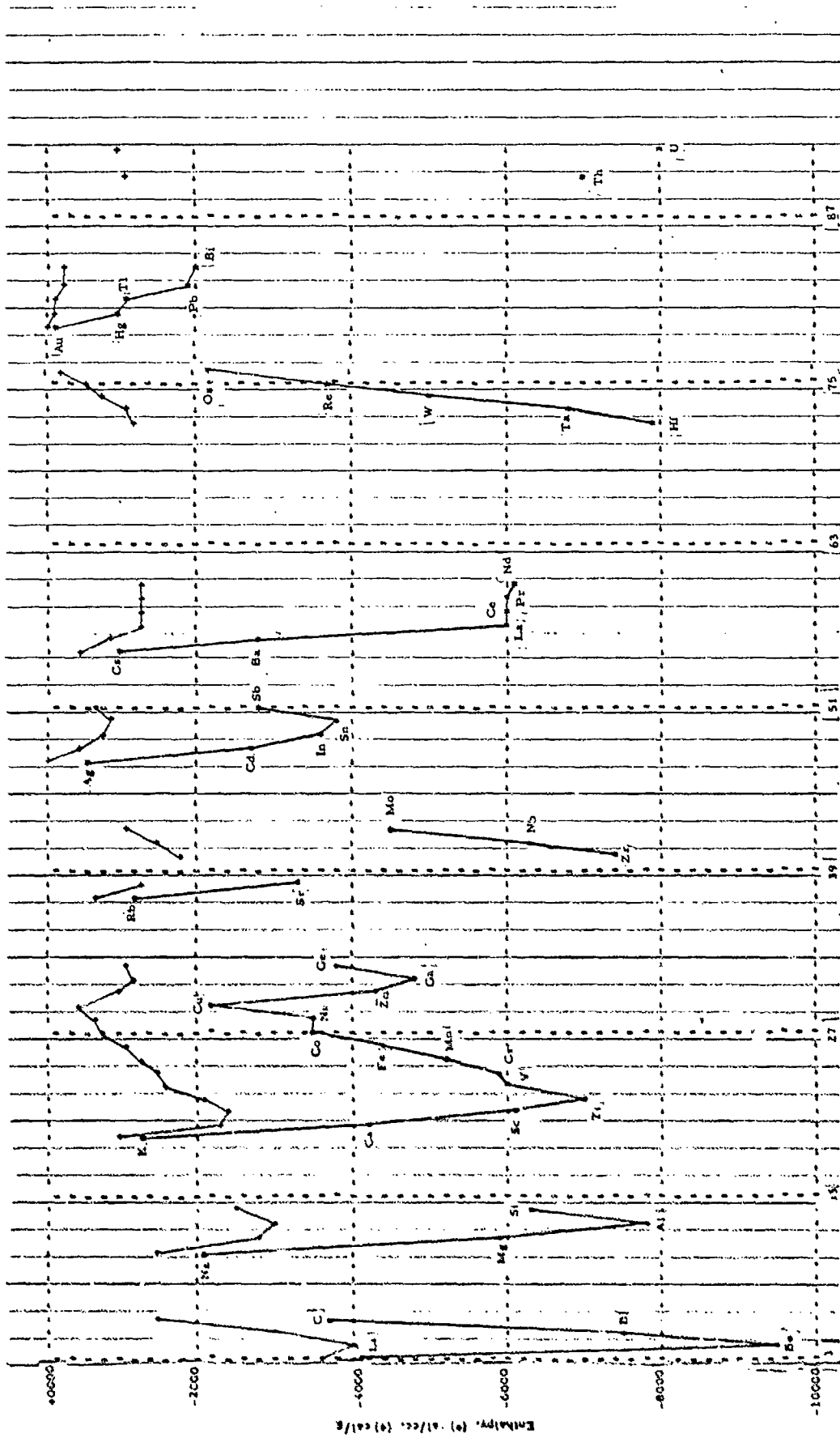
Table 23 (cont.)

		Reaction	Enthalpy, cal/g
16 Ga +	3 Mg(ClO ₄) ₂	= 3 MgCl ₂ + 8 Ga ₂ O ₃	-1177
2 Pr +	Na(ClO ₃)	= NaCl + Pr ₂ O ₃	-1176
4 Hf +	Mg(ClO ₄) ₂	= MgCl ₂ + 4 HfO ₂	-1172
2 La +	K(ClO ₃)	= KCl + La ₂ O ₃	-1170
2 C +	K(ClO ₄)	= KCl + 2 CO ₂	-1160
2 Ce +	Na(ClO ₃)	= NaCl + Ce ₂ O ₃	-1157
4 Sr +	K(ClO ₄)	= KCl + 4 SrO	-1155
2 Hf +	Li(ClO ₄)	= LiCl + 2 HfO ₂	-1153
8 Pr +	3 K(ClO ₄)	= 3 KCl + 4 Pr ₂ O ₃	-1153
2 Nd +	Na(ClO ₃)	= NaCl + Nd ₂ O ₃	-1150
8 Ga +	3 Li(ClO ₄)	= 3 LiCl + 4 Ga ₂ O ₃	-1147
16 La +	3 Ba(ClO ₄) ₂	= 3 BaCl ₂ + 8 La ₂ O ₃	-1145
8 Ce +	3 K(ClO ₄)	= 3 KCl + 4 Ce ₂ O ₃	-1133
8 Nd +	3 K(ClO ₄)	= 3 KCl + 4 Nd ₂ O ₃	-1127
16 Ca +	4 Na(ClO ₄)	= 2 Na ₂ O + 7 CaO + 2 CaCl ₂	-1125
2 Pr +	K(ClO ₃)	= KCl + Pr ₂ O ₃	-1125
3 Sr +	K(ClO ₃)	= KCl + 3 SrO	-1125
3 Hf +	2 Na(ClO ₃)	= 2 NaCl + 3 HfO ₂	-1121
16 B +	3 Ba(ClO ₃) ₂	= 3 BaO + 5 B ₂ O ₃ + 6 BCl	-1116
12 Na +	Ba(ClO ₃) ₂	= BaO + 5 Na ₂ O + 2 NaCl	-1112
8 Cr +	3 Rb(ClO ₄)	= 3 RbCl + 4 Cr ₂ O ₃	-1108
8 Nb +	5 Rb(ClO ₄)	= 5 RbCl + 4 Nb ₂ O ₅	-1107

Table 24

CHLORATES AND PERCHLORATES
IN DESCENDING ORDER OF HEAT OF REACTION

<u>Volumetric Heat of Reaction</u>	<u>Gravimetric Heat of Reaction</u>
Mg(ClO ₄) ₂	Mg(ClO ₄) ₂
LiClO ₄	LiClO ₄
AgClO ₃	NaClO ₃
NaClO ₃	KClO ₄
KClO ₄	KClO ₃
Ba(ClO ₄) ₂	Ba(ClO ₄) ₂
RbClO ₄	RbClO ₄
KClO ₃	AgClO ₄
RbClO ₃	RbClO ₃
AgClO ₄	AgClO ₃
CsClO ₄	CsClO ₄
	Cu(ClO ₄) ₂
	Cu(ClO ₃) ₂
	LiClO ₃
	Ba(ClO ₃) ₂



Atomic Number of Metal Reactance

Figure 18

CALYMETRIC AND VOLUNMETRIC ENTHALPIES OF REACTIONS OF METALS WITH $Hg(ClO_4)_2$

The plot in Figure 19 presents the data in a different manner. The volumetric enthalpies for the reactions of all the chlorates and perchlorates with beryllium are plotted. This allows one to choose an oxidizer for a particular metal reactant, beryllium in this case. Lithium perchlorate is the best oxidizer, and the alkali metal perchlorates follow a decreasing trend in enthalpy in progressing to cesium perchlorate. The gravimetric enthalpies, shown in Figure 20, exhibit similar trends.

The volumetric and gravimetric enthalpies of all 801 chlorate and perchlorate reactions are summarized in Tables 25 and 26, respectively. The same trends noted previously are apparent here.

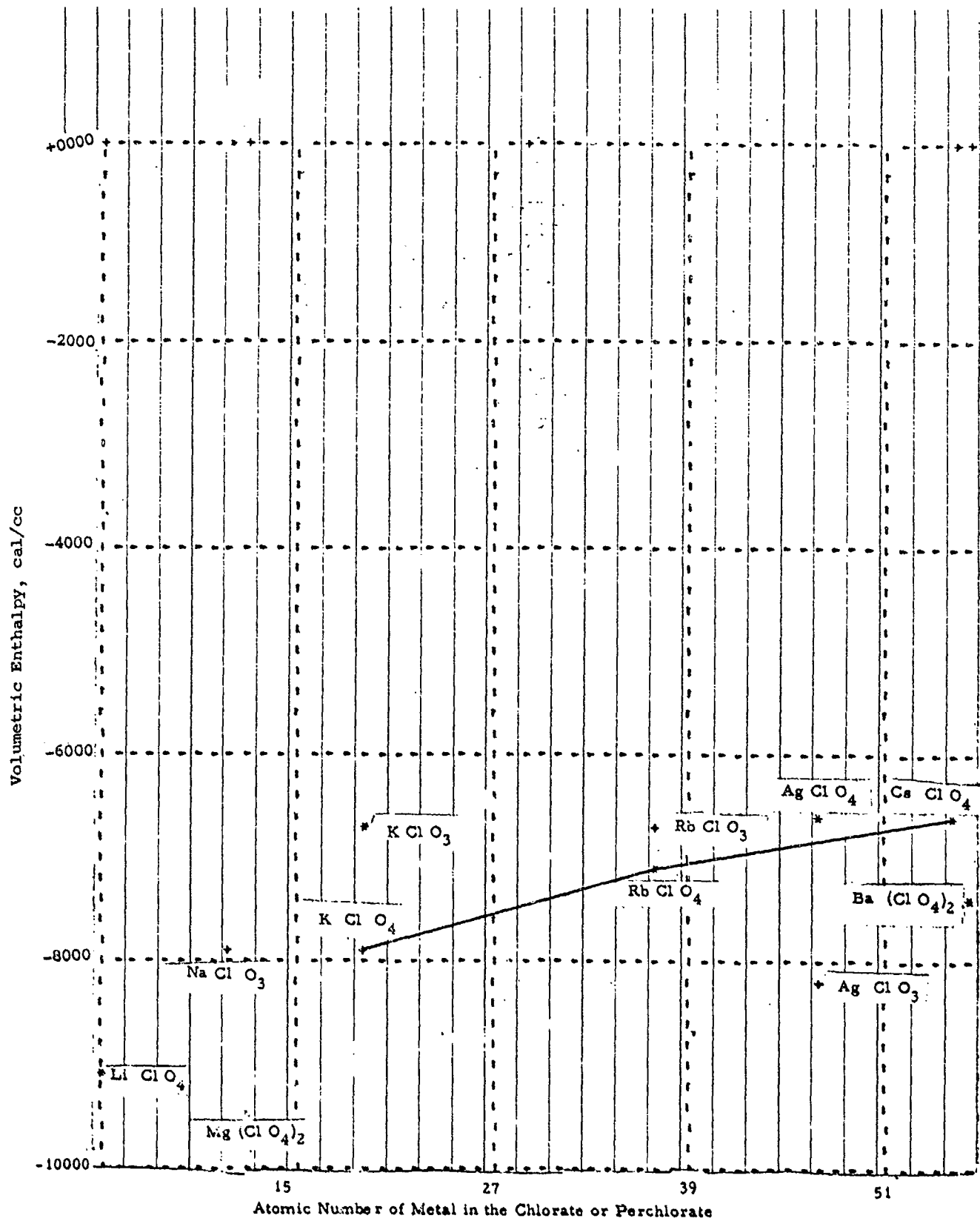


Figure 19

VOLUMETRIC ENTHALPIES OF REACTIONS
OF CHLORATES AND PERCHLORATES WITH Be

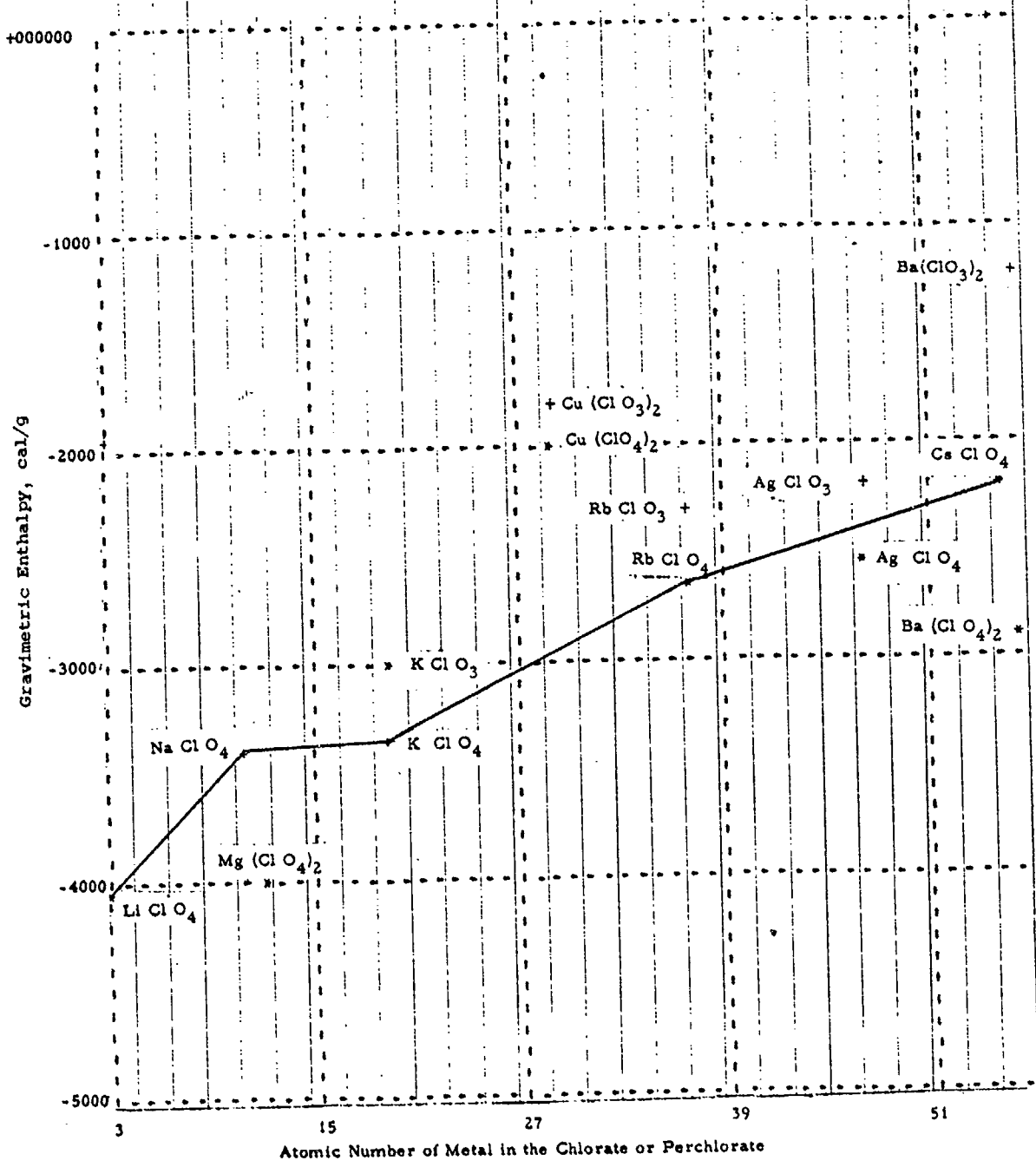


Figure 20

GRAVIMETRIC ENTHALPIES OF REACTIONS
OF CHLORATES AND PERCHLORATES WITH Be

Table 25

VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS WITH CHLORATES AND PERCHLORATES
(In descending order from top to bottom and left to right)

	Mg(ClO ₄) ₂	LiClO ₄	AgClO ₃	NaClO ₃	KClO ₄	Ba(ClO ₄) ₂	RbClO ₄	KClO ₃	RbClO ₃	AgClO ₄	CsClO ₄
BE	-9459	-9088	-8103	-7853	-7850	-7302	-7002	-6653	-6616	-6578	-6533
U	-7989	-7670	-6989	-6750	-6720	-6292	-6040	-5779	-5747	-5847	-5662
HF	-7874	-7562	-6905	-6675	-6643	-6228	-5981	-5728	-5696	-5688	-5612
AL	-7742	-7431	-6733	-6562	-6527	-6119	-5875	-5629	-5597	-5553	-5512
B	-7423	-7038	-6242	-6061	-6004	-5562	-5289	-5046	-5010	-4941	-4905
ZR	-7318	-7021	-6448	-6234	-6192	-5817	-5585	-5363	-5332	-5333	-5246
TH	-6998	-6750	-6289	-6102	-6063	-5743	-5542	-5348	-5320	-5320	-5245
TI	-6951	-6658	-6100	-5926	-5876	-5523	-5299	-5095	-5065	-5041	-4977
TA	-6730	-6388	-5767	-5596	-5530	-5155	-4912	-4713	-4679	-4626	-4577
SI	-6289	-5983	-5477	-5316	-5247	-4291	-4701	-4529	-4498	-4454	-4401
NB	-6249	-5914	-5380	-5205	-5128	-4786	-4554	-4381	-4348	-4307	-4243
SC	-6099	-5877	-5568	-5379	-5329	-5071	-4896	-4749	-4724	-4745	-4648
ND	-6036	-5832	-5583	-5374	-5327	-5086	-4922	-4783	-4759	-4802	-4689
LA	-5981	-5786	-5553	-5350	-5305	-5074	-4916	-4782	-4759	-4803	-4591
V	-5980	-5676	-5233	-5054	-4978	-4670	-4455	-4300	-4269	-4263	-4169
PR	-5946	-5747	-5514	-5307	-5259	-5026	-4866	-4732	-4709	-4754	-4639
CE	-5941	-5737	-5514	-5290	-5242	-5005	-4843	-4708	-4685	-4739	-4614
MG	-5886	-5683	-5411	-5243	-5193	-4960	-4799	-4666	-4643	-4661	-4572
CR	-5885	-5565	-5129	-4933	-4851	-4539	-4319	-4167	-4136	-4130	-4031
MN	-5132	-4839	-4626	-4395	-4310	-4074	-3892	-3786	-3758	-3804	-3662
W	-4928	-4587	-4276	-4080	-3965	-3701	-3489	-3392	-3359	-3353	-3239
GA	-4708	-4454	-4230	-4075	-3984	-3773	-3600	-3514	-3488	-3478	-3391
MO	-4449	-4115	-3896	-3697	-3569	-3339	-3138	-3072	-3043	-3048	-2928
FE	-4337	-4038	-3852	-3669	-3551	-3341	-3155	-3090	-3061	-3065	-2946
ZN	-4262	-4029	-3894	-3731	-3637	-3460	-3303	-3240	-3215	-3237	-3121
CA	-4195	-4068	-4031	-3891	-3839	-3725	-3628	-3576	-3560	-3606	-3504
LI	-4068	-3796	-3804	-3642	-3587	-3483	-3389	-3347	-3332	-3396	-3275
SN	-3759	-3521	-3441	-3283	-3175	-3021	-2870	-2832	-2807	-2818	-2706
GE	-3753	-3496	-3416	-3247	-3131	-2971	-2811	-2775	-2749	-2763	-2642
RE	-3654	-3329	-3264	-3058	-2910	-2736	-2553	-2531	-2500	-2526	-2371
C	-3628	-3295	-3236	-3025	-2873	-2699	-2513	-2494	-2463	-2491	-2331
IN	-3570	-3360	-3310	-3166	-3066	-2933	-2797	-2766	-2743	-2756	-2650
NI	-3462	-3206	-3172	-3001	-2878	-2734	-2580	-2559	-2533	-2555	-2423
CO	-3446	-3164	-3135	-2948	-2815	-2676	-2524	-2507	-2481	-2508	-2371
SR	-3211	-3112	-3159	-3029	-2976	-2909	-2837	-2819	-2806	-2862	-2755
SB	-2777	-2561	-2625	-2468	-2347	-2253	-2126	-2135	-2112	-2144	-2010
BA	-2701	-2615	-2701	-2571	-2520	-2473	-2412	-2408	-2397	-2462	-2350
CD	-2630	-2451	-2521	-2385	-2280	-2202	-2093	-2103	-2083	-2123	-1994
CU	-2182	-1935	-2105	-1930	-1784	-1722	-1597	-1644	-1619	-1670	-1505
OS	-2178	-1902	-2104	-1902	-1732	-1665	-1524	-1582	-1555	-1614	-1424
NA	-2078	-1823	-1957	-1698	-1627	-1663	-1565	-1583	-1574	-1690	-1531
BI	-1906	-1742	-1893	-1761	-1649	-1609	-1516	-1556	-1537	-1579	-1448
PB	-1862	-1720	-1855	-1739	-1641	-1606	-1524	-1559	-1543	-1580	-1464
K	-1299	-1080	-1245	-1068	-971	-1040	-931	-966	-957	-1072	-912
RB	-1105	-912	-1065	-910	-787	-878	-727	-799	-764	-920	-710
TL	-1092	-884	-1033	-945	-871	-872	-825	-872	-861	-906	-804
HG	-911	-759	-1023	-889	-764	-771	-697	-778	-761	-821	-669
CS	-911	-752	-882	-759	-655	-735	-606	-678	-651	-773	-584
AU	-107	629	-83	624	837	459	803	724	773	168	770
AG	-523	-190	-460	-329	-217	-248	-193	-284	-270	-332	-189

Table 26

GRAVIMETRIC ENTHALPIES OF REACTIONS OF METALS WITH CHLORATES AND PERCHLORATES
(In descending order from top to bottom and left to right)

	Mg(ClO ₄) ₂		NaClO ₃		KClO ₃		RbClO ₄		RbClO ₃		CsClO ₄		Cu(ClO ₃) ₂		NaClO ₄	
	LiClO ₄		KClO ₄		Ba(ClO ₄) ₂		AgClO ₄		AgClO ₃		Cu(ClO ₄) ₂		LiClO ₃		Ba(ClO ₃) ₂	
BE	-3998	-4037	-3374	-3348	-2999	-2891	-2638	-2533	-2281	-2167	-2174	-1078	-1771	-1935	-1729	-1225
LI	-3576	-3463	-2960	-2937	-2665	-2575	-2364	-2351	-2071	-2054	-1077	-1127	-3015	-3110	-3110	-2217
AL	-2933	-2934	-2565	-2570	-2321	-2242	-2067	-1999	-1831	-1747	-1747	-2234	-1097	-1077	-2015	-1398
B	-2912	-2912	-2455	-2408	-2168	-2076	-1878	-1860	-1632	-1533	-1540	-2083	-1692	-1758	-1793	-1116
MG	-2784	-2782	-2474	-2442	-2261	-2191	-2035	-2000	-1821	-1773	-1744	-1478	-1392	-1470	-1301	-1032
SI	-2486	-2473	-2157	-2112	-1935	-1859	-1699	-1644	-1502	-1425	-1422	-707	-640	-650	-470	-403
SC	-2364	-2383	-2154	-2122	-1984	-1924	-1794	-1770	-1622	-1594	-1654	-648	-909	-650	-787	-676
CA	-2257	-2245	-2065	-2034	-1920	-1869	-1757	-1754	-1607	-1594	-1646	-1260	-1214	-1274	-1125	-957
II	-2071	-2053	-1874	-1839	-1729	-1675	-1561	-1528	-1420	-1349	-1357	-865	-817	-835	-736	-634
ZR	-1777	-1758	-1643	-1610	-1534	-1491	-1403	-1379	-1296	-1257	-1244	-905	-892	-870	-781	-672
V	-1588	-1560	-1451	-1411	-1339	-1292	-1202	-1183	-1104	-1067	-1049	-829	-775	-789	-677	-574
CR	-1462	-1432	-1340	-1299	-1237	-1192	-1104	-1098	-1021	-992	-968	-752	-697	-706	-600	-511
NB	-1448	-1419	-1337	-1292	-1233	-1189	-1107	-1104	-1023	-999	-971	-721	-699	-662	-567	-471
NA	-1445	-1306	-1102	-1074	-1185	-1029	-1075	-981	-1001	-908	-954	-1443	-1381	-1446	-1317	-1112
C	-1433	-1376	-1233	-1140	-1079	-1012	-895	-8910	-803	-791	-732	-283	-197	-125	3	34
LA	-1280	-1262	-1224	-1200	-1170	-1145	-1097	-1102	-1045	-1039	-1012	-531	-531	-539	-453	-444
SP	-1235	-1216	-1179	-1155	-1125	-1100	-1052	-1072	-1001	-1013	-967	-722	-717	-733	-641	-605
PR	-1229	-1211	-1174	-1153	-1125	-1101	-1055	-1060	-1006	-1001	-973	-511	-513	-516	-434	-426
MN	-1221	-1190	-1063	-1028	-997	-965	-906	-8917	-834	-850	-813	-432	-605	-612	-514	-468
GE	-1208	-1190	-1157	-1133	-1106	-1082	-1036	-1044	-998	-996	-986	-986	-508	-510	-430	-424
ND	-1200	-1182	-1150	-1127	-1101	-1077	-1032	-1037	-986	-990	-954	-498	-500	-504	-422	-416
GA	-1177	-1147	-1100	-1061	-1025	-984	-924	-932	-886	-854	-821	-436	-705	-686	-703	-538
HF	-1172	-1153	-1121	-1096	-1070	-1046	-1000	-993	-953	-932	-920	-589	-563	-560	-510	-469
FE	-1030	-992	-958	-913	-884	-846	-781	-783	-732	-729	-696	-435	-412	-403	-317	-301
MO	-1030	-989	-957	-908	-871	-833	-765	-707	-652	-713	-611	-451	-393	-370	-300	-260
IH	-1025	-1008	-991	-970	-953	-933	-898	-895	-864	-850	-838	-734	-736	-733	-666	-616
GE	-1024	-986	-941	-906	-877	-839	-774	-792	-745	-723	-678	-17	22	62	82	72
TA	-1012	-988	-965	-935	-914	-887	-840	-850	-800	-794	-765	-467	-430	-417	-375	-358
K	-997	-954	-879	-802	-782	-801	-688	-799	-650	-665	-606	-224	-909	-635	-836	-765
U	-929	-912	-900	-879	-866	-848	-815	-806	-787	-765	-761	-365	-361	-357	-300	-301
ZN	-908	-881	-865	-842	-816	-789	-743	-752	-708	-703	-672	-503	-492	-479	-397	-371
BA	-816	-800	-795	-776	-768	-752	-723	-740	-704	-723	-682	-780	-748	-749	-722	-664
SN	-813	-782	-775	-759	-728	-700	-655	-675	-626	-630	-590	-417	-393	-373	-310	-290
W	-768	-737	-734	-699	-690	-663	-620	-641	-593	-600	-660	-420	-297	-257	-214	-197
CO	-750	-711	-711	-642	-608	-582	-541	-559	-522	-542	-487	-484	-364	-352	-260	-262
IN	-725	-698	-699	-660	-662	-635	-602	-621	-581	-597	-550	-406	-553	-538	-517	-449
NI	-692	-659	-664	-627	-622	-595	-554	-579	-534	-543	-499	-487	-366	-354	-272	-263
SR	-620	-587	-598	-541	-560	-535	-497	-524	-482	-495	-448	-210	-197	-181	-117	-132
RE	-620	-522	-506	-443	-448	-432	-374	-472	-370	-468	-337	-465	-445	-470	-417	-415
RE	-558	-525	-541	-504	-507	-482	-447	-476	-436	-451	-404	-380	-155	-127	-65	-82
CS	-452	-379	-374	-314	-335	-350	-280	-363	-261	-345	-248	-308	-312	-312	-275	-283
CU	-411	-388	-414	-379	-389	-366	-335	-370	-334	-355	-304	-271	-247	-245	-204	-201
CO	-445	-422	-439	-414	-420	-404	-382	-400	-378	-397	-356	-304	-259	-248	-193	-201
BI	-284	-264	-286	-245	-274	-264	-246	-270	-230	-256	-232	-187	-155	-135	-131	-112
CS	-265	-237	-269	-240	-254	-237	-217	-249	-224	-246	-201	-127	-111	-91	-50	-63
PE	-248	-215	-237	-217	-225	-216	-205	-224	-210	-223	-197	-139	-134	-129	-96	-108
IL	-115	-92	-103	-94	-101	-96	-91	-102	-96	-106	-39	-110	-109	-104	-87	-94
MG	-101	-86	-100	-92	-104	-95	-84	-108	-96	-113	-93	-67	-64	-53	-26	-40
AU	-12	64	69	95	84	53	93	21	49	-9	90	18	22	38	72	46
AG	-80	-25	-45	-99	-42	-34	-26	-48	-38	-46	-26	-35	-54	-43	-13	-30

I. Chloride Reactions

The computer was used to examine 10,545 reactions involving 102 chlorides, and 3061 of these reactions were printed. As a class, the chloride reactions are not especially energetic. The highest enthalpy recorded was only -3336 cal/cc, for the reaction of cerium with rhenium pentachloride. The chloride reactions are less energetic than the fluoride, oxide, chlorate, perchlorate, nitrate, nitrite, chromate, and silicide reactions.

The computer output for some of the more energetic reactions is shown in Table 27. Molybdenum and tungsten chlorides behave as some of the better oxidizers in the chloride systems. The reactions of molybdenum pentachloride, tungsten pentachloride, and tungsten hexachloride with various metals are included in the table.

The most energetic reactions are presented in Tables 28 and 29. On a volumetric basis the most effective metal reducing agents are the rare earths (cerium, lanthanum, praseodymium, neodymium, thorium, and uranium), the rare earth predecessors (yttrium and scandium), the alkali metals (lithium), the alkaline earth metals (beryllium, magnesium, and calcium), and hafnium and zirconium. Beryllium is not the most energetic reducing agent in the chloride systems, because the heat of formation of beryllium chloride is comparatively low. The heats of formation of the alkali earth chlorides increase monotonically, while the heats of formation of the alkalis with oxides exhibit a maximum at calcium. The chlorides increase from -122 to -205 kcal/mole from beryllium to barium; and the oxides increase from -146 to -151 kcal/mole from beryllium to calcium and then decrease to -133 kcal/mole at barium. The behavior of beryllium in the chloride systems may be considered normal and its behavior in the oxide systems anomalous. Its effectiveness in the oxide systems compared with the other alkaline earth metals is thus due to the relatively high heat of formation of the oxide. In addition, because of its low atomic volume and weight, it is still an effective reducing agent in the chloride systems, although it is exceeded in efficacy by several other metals including calcium and magnesium. The most effective oxidizers on a volumetric basis are rhenium pentachloride, hexachloroethane, tungsten tetrachloride, tungsten pentachloride, and tungsten hexachloride.

On a gravimetric basis the alkali metals (lithium, sodium, and potassium) are the most effective reducing agents, followed by the alkaline earth metals (calcium, magnesium, and beryllium), the rare earth predecessors (scandium and yttrium), and titanium. The alkali metals are relatively energetic on a gravimetric basis, and are much less energetic on a volumetric basis because of their extremely low densities. The most effective practical oxidizers on a gravimetric basis are the chlorides of carbon

Table 27

DATA ON VARIOUS REACTIONS OF METALS WITH CHLORIDES

	5 Ba	+ 2 MoCl ₅	=	2 Mo	+ 5 BaCl ₂
Heat of formation		-90.80			-205.56
Molecular weight	137.36	273.24		95.95	208.27
Density	3.50	2.93		10.20	
Melting point, °C	704.00	194.00		2610.00	962.00
Boiling point, °C	1638.00	268.00		4800.00	1189.00
Heat of reaction, kcal	-846.20				
Reactants' density	3.22				
Gravimetric enthalpy, cal/g	-686.14				
Volumetric enthalpy, cal/cc	-2210.16				
	5 Be	+ 2 MoCl ₅	=	2 Mo	+ 5 BeCl ₂
Heat of formation		-90.80			-122.30
Molecular weight	9.01	273.24		95.95	79.93
Density	1.85	2.93		10.20	1.90
Melting point, °C	1283.00	194.00		2610.00	405.00
Boiling point, °C	2970.00	268.00		4800.00	547.00
Heat of reaction, kcal	-429.90				
Reactants' density	2.80				
Gravimetric enthalpy, cal/g	-726.74				
Volumetric enthalpy, cal/cc	-2037.45				
	5 Bi	4 MoCl ₅	=	4 Mo	5 BiCl ₄
Heat of formation		-90.80			-120.00
Molecular weight	208.99	273.24		95.95	350.83
Density	9.80	2.93		10.20	
Melting point, °C	271.00	194.00		2610.00	225.00
Boiling point, °C	1420.00	268.00		4800.00	
Heat of reaction, kcal	-236.80				
Reactants' density	4.45				
Gravimetric enthalpy, cal/g	-110.76				
Volumetric enthalpy, cal/cc	-493.43				

Table 27 (cont.)

	5 Mg	+ 2 MoCl ₅	= 2 Mo	+ 5 MgCl ₂
Heat of formation		-90.80		-153.40
Molecular weight	24.32	273.24	95.95	95.23
Density	1.74T	2.93	10.20	2.32
Melting point, °C	650.00P	194.00	2610.00	714.00
Boiling point, °C	1120.00	268.00	4800.00	1418.00
Heat of reaction, kcal	-585.40			
Reactants' density	2.6C			
Gravimetric enthalpy, cal/g	-876.24			
Volumetric enthalpy, cal/cc	-2282.04			

	5 Mn	+ 2 MoCl ₅	= 2 Mo	+ 5 MnCl ₂
Heat of formation		-90.80		-115.30
Molecular weight	54.94	273.24	95.95	125.84
Density	7.20	2.93	10.20	2.98
Melting point, °C	1244.00	194.00	2610.00	650.00
Boiling point, °C	2087.00	268.00	4800.00	1190.00
Heat of reaction, kcal	-394.90			
Reactants' density	3.65			
Gravimetric enthalpy, cal/g	-480.39			
Volumetric enthalpy, cal/cc	-1756.73			

	5 Na	+ MoCl ₅	= Mo	+ 5 NaCl
Heat of formation		-90.80		-98.23
Molecular weight	22.99	273.24	95.95	58.45
Density	.97	2.93	10.20	2.16
Melting point, °C	98.00	194.00	2610.00	808.00
Boiling point, °C	889.00	268.00	4800.00	1465.00
Heat of reaction, kcal	-400.36			
Reactants' density	1.83			
Gravimetric enthalpy, cal/g	-1031.34			
Volumetric enthalpy, cal/cc	-1890.01			

Table 27 (cont.)

	5 Ba	+	2 WCl ₅	=	2 W	+	5 BaCl ₂
Heat of formation			-84.00		183.86		-205.56
Molecular weight	137.36		361.21		19.30		208.27
Density	3.50		3.88		380.00		962.00
Melting point, °C	704.00		248.00		5900.00		1189.00
Boiling point, °C	1638.00		276.00				
Heat of reaction, kcal	-859.80						
Reactants' density	3.68						
Gravimetric enthalpy, cal/g	-610.12						
Volumetric enthalpy, cal/cc	-2246.91						
	5 Be	+	2 WCl ₅	=	2 W	+	5 BeCl ₂
Heat of formation			-84.00		183.86		-122.30
Molecular weight	9.01		361.21		19.30		79.93
Density	1.85		3.88		380.00		1.90
Melting point, °C	1283.00		248.00		5900.00		405.00
Boiling point, °C	2970.00		276.00				547.00
Heat of reaction, kcal	-443.50						
Reactants' density	3.64						
Gravimetric enthalpy, cal/g	-577.86						
Volumetric enthalpy, cal/cc	-2103.99						
	5 Bi	+	4 WCl ₅	=	4 W	+	5 BiCl ₄
Heat of formation			-84.00		183.86		-120.00
Molecular weight	208.99		361.21		19.30		350.83
Density	9.80		3.88		380.00		225.00
Melting point, °C	271.00		248.00		5900.00		
Boiling point, °C	1420.00		276.00				
Heat of reaction, kcal	-254.00						
Reactants' density	5.19						
Gravimetric enthalpy, cal/g	-106.03						
Volumetric enthalpy, cal/cc	-550.59						

Table 27 (cont.)

	5 Mg	+ 2 WCl ₃	=	2 W	+ 5 MgCl ₂
Heat of formation		-84.00			-153.40
Molecular weight	24.32	361.21		183.86	95.23
Density	1.74	3.88		19.30	2.32
Melting point, °C	650.00	248.00		380.00	714.00
Boiling point, °C	1120.00	276.00		5900.00	1418.00
Heat of reaction, kcal	-599.00				
Reactants' density	3.29				
Gravimetric enthalpy, cal/g	-709.70				
Volumetric enthalpy, cal/cc	-2336.96				

	5 Mn	+ 2 WCl ₅	=	2 W	+ 5 MnCl ₂
Heat of formation		-84.00			-115.30
Molecular weight	54.94	361.21		183.86	125.84
Density	7.20	3.88		19.30	2.98T
Melting point, °C	1244.00	248.00		380.00	650.00
Boiling point, °C	2087.00	276.00		5900.00	1190.00
Heat of reaction, kcal	-408.50				
Reactants' density	4.44				
Gravimetric enthalpy, cal/g	-409.68				
Volumetric enthalpy, cal/cc	-1818.92				

	5 Na	+ WCl ₅	=	W	+ 5 NaCl
Heat of formation		-84.00			-98.23
Molecular weight	22.99	361.21		183.86	58.45
Density	9.97	3.88		19.30	2.16
Melting point, °C	98.00	248.00		380.00	808.00
Boiling point, °C	889.00	276.00		5900.00	1465.00
Heat of reaction, kcal	-407.16				
Reactants' density	2.25				
Gravimetric enthalpy, cal/g	-855.08				
Volumetric enthalpy, cal/cc	-1923.05				

Table 27 (cont.)

	2 La	+	WCl ₆	=	W	+	2 LaCl ₃
Heat of formation			-98.70				-263.60
Molecular weight			396.66		183.86		245.29
Density			3.52		19.30		3.84
Melting point, °C	138.92				380.00		870.00
Boiling point, °C	6.15				5900.00		
Heat of reaction, kcal	880.00		284.00				
Reactants' density	1800.00		336.50				
Gravimetric enthalpy, cal/g	-428.50						
Volumetric enthalpy, cal/cc	4.27						
	-635.29						
	-2714.35						
	6 Li	+	WCl ₆	=	W	+	6 LiCl
Heat of formation			-98.70				-97.70
Molecular weight			396.66		183.86		42.40
Density			3.52		19.30		2.07T
Melting point, °C	6.94				380.00		610.00
Boiling point, °C	.53				5900.00		1382.00
Heat of reaction, kcal	180.00		284.00F				
Reactants' density	1326.00		336.50				
Gravimetric enthalpy, cal/g	-487.50						
Volumetric enthalpy, cal/cc	2.30						
	-1112.25						
	-2556.84						
	3 Mg	+	WCl ₆	=	W	+	3 MgCl ₂
Heat of formation			-98.70				-153.40
Molecular weight			396.66		163.86		95.23
Density			3.52		19.30		2.32
Melting point, °C	24.32				380.00		714.00
Boiling point, °C	1.74				5900.00		1418.00
Heat of reaction, kcal	650.00		284.00				
Reactants' density	1120.00		336.50				
Gravimetric enthalpy, cal/g	-361.50						
Volumetric enthalpy, cal/cc	3.04						
	-769.77						
	-2338.01						

Table 28

MOST ENERGETIC CHLORIDE REACTIONS WITH METALS,
IN TERMS OF VOLUMETRIC ENTHALPY

Reaction						Enthalpy, cal/cc
5	Ce	+	3 ReCl ₅	=	3 Re + 5 CeCl ₃	-3336
5	La	+	3 ReCl ₅	=	3 Re + 5 LaCl ₃	-3301
5	Pr	+	3 ReCl ₅	=	3 Re + 5 PrCl ₃	-3259
5	Nd	+	3 ReCl ₅	=	3 Re + 5 NdCl ₃	-3244
5	Y	+	3 ReCl ₅	=	3 Re + 5 YCl ₃	-3178
2	Ce	+	C ₂ Cl ₆	=	2 C + 2 CeCl ₃	-3047
2	La	+	C ₂ Cl ₆	=	2 C + 2 LaCl ₃	-3025
5	Li	+	ReCl ₅	=	Re + 5 LiCl	-3006
5	U	+	3 ReCl ₅	=	3 Re + 5 UCl ₃	-2986
2	Pr	+	C ₂ Cl ₆	=	2 C + 2 PrCl ₃	-2986
2	Nd	+	C ₂ Cl ₆	=	2 C + 2 NdCl ₃	-2970
5	Ca	+	2 ReCl ₅	=	2 Re + 5 CaCl ₂	-2916
5	Hf	+	3 ReCl ₅	=	3 Re + 5 HfCl ₃	-2899
2	Y	+	C ₂ Cl ₆	=	2 C + 2 YCl ₃	-2897
5	Mg	+	2 ReCl ₅	=	2 Re + 5 MgCl ₂	-2872
5	Sc	+	3 ReCl ₅	=	3 Re + 5 ScCl ₃	-2860
5	Th	+	4 ReCl ₅	=	4 Re + 5 ThCl ₄	-2859
5	Zr	+	3 ReCl ₅	=	3 Re + 5 ZrCl ₃	-2824
6	Li	+	C ₂ Cl ₆	=	2 C + 6 LiCl	-2814
4	Ce	+	3 WCl ₄	=	3 W + 4 CeCl ₃	-2807
4	La	+	3 WCl ₄	=	3 W + 4 LaCl ₃	-2788
4	Pr	+	3 WCl ₄	=	3 W + 4 PrCl ₃	-2745
3	Ca	+	C ₂ Cl ₆	=	2 C + 3 CaCl ₂	-2735
5	Ce	+	3 WCl ₅	=	3 W + 5 CeCl ₃	-2731
2	Ce	+	WCl ₆	=	W + 2 CeCl ₃	-2730
5	Be	+	2 ReCl ₅	=	2 Re + 5 BeCl ₂	-2729
4	Nd	+	3 WCl ₄	=	3 W + 4 NdCl ₃	-2726
2	U	+	C ₂ Cl ₆	=	2 C + 2 UCl ₃	-2725
5	La	+	3 WCl ₅	=	3 W + 5 LaCl ₃	-2715

Table 28 (cont.)

Reaction						Enthalpy, cal/cc				
2	La	+	WCl ₆	=	W	+	2	LaCl ₃	-2714	
5	Sr	+	2 ReCl ₅	=	2	Re	+	5	SrCl ₂	-2682
5	Ce	+	3 MoCl ₅	=	3	Mo	+	5	CeCl ₃	-2676
5	Pr	+	3 WCl ₅	=	3	W	+	5	PrCl ₃	-2672
2	Pr	+	WCl ₆	=	W	+	2	PrCl ₃	-2671	
5	La	+	3 MoCl ₅	=	3	Mo	+	5	LaCl ₃	-2661
3	Mg	+	C ₂ Cl ₆	=	2	C	+	3	MgCl ₂	-2656
4	Ce	+	3 C ₂ Cl ₄	=	6	C	+	4	CeCl ₃	-2655
2	Hf	+	C ₂ Cl ₆	=	2	C	+	2	HfCl ₃	-2655
5	Nd	+	3 WCl ₅	=	3	W	+	5	NdCl ₃	-2653
2	Nd	+	WCl ₆	=	W	+	2	NdCl ₃	-2652	
4	La	+	3 C ₂ Cl ₄	=	6	C	+	4	LaCl ₃	-2643
2	Sc	+	C ₂ Cl ₆	=	2	C	+	2	ScCl ₃	-2638
4	Y	+	3 WCl ₄	=	3	W	+	4	YCl ₃	-2632
3	Th	+	2 C ₂ Cl ₆	=	4	C	+	3	ThCl ₄	-2629
5	Pr	+	3 MoCl ₅	=	3	Mo	+	5	PrCl ₃	-2617
4	Li	+	WCl ₄	=	W	+	4	LiCl	-2612	
4	Pr	+	3 C ₂ Cl ₄	=	6	C	+	4	PrCl ₃	-2609
5	Nd	+	3 MoCl ₅	=	3	Mo	+	5	NdCl ₃	-2598
2	Zr	+	C ₂ Cl ₆	=	2	C	+	2	ZrCl ₃	-2596
4	Nd	+	3 C ₂ Cl ₄	=	6	C	+	4	NdCl ₃	-2593
5	Ba	+	2 ReCl ₅	=	2	Re	+	5	BaCl ₂	-2576
5	Y	+	3 WCl ₅	=	3	W	+	5	YCl ₃	-2558
2	Y	+	WCl ₆	=	W	+	2	YCl ₃	-2558	
5	Li	+	WCl ₅	=	W	+	5	LiCl	-2556	
6	Li	+	WCl ₆	=	W	+	6	LiCl	-2556	
3	Sr	+	C ₂ Cl ₆	=	2	C	+	3	SrCl ₂	-2547
2	Ca	+	WCl ₄	=	W	+	2	CaCl ₂	-2529	
4	Li	+	C ₂ Cl ₄	=	2	C	+	4	LiCl	-2523
4	Ce	+	3 CCl ₄	=	3	C	+	4	CeCl ₃	-2523
	Ce	+	MoCl ₃	=	Mo	+	1	CeCl ₃	-2521	

Table 28 (cont.)

Reaction						Enthalpy, cal/cc
4 Y	+	3 C ₂ Cl ₄	=	6 C	+ 4 YCl ₃	-2516
4 La	+	3 CCl ₄	=	3 C	+ 4 LaCl ₃	-2513
5 Li	+	MoCl ₅	=	Mo	+ 5 LiCl	-2512
La	+	MoCl ₃	=	Mo	+ LaCl ₃	-2509
5 Y	+	3 MoCl ₅	=	3 Mo	+ 5 YCl ₃	-2500
3 Be	+	C ₂ Cl ₆	=	2 C	+ 3 BeCl ₂	-2494
3 Ca	+	WCl ₆	=	W	+ 3 CaCl ₂	-2477
5 Ca	+	2 WCl ₅	=	2 W	+ 5 CaCl ₂	-2476
4 Pr	+	3 CCl ₄	=	3 C	+ 4 PrCl ₃	-2476
Pr	+	MoCl ₃	=	Mo	+ PrCl ₃	-2464
3 Ba	+	C ₂ Cl ₆	=	2 C	+ 3 BaCl ₂	-2462
4 Nd	+	3 CCl ₄	=	3 C	+ 4 NdCl ₃	-2459
2 Ca	+	C ₂ Cl ₄	=	2 C	+ 2 CaCl ₂	-2457
Nd	+	MoCl ₃	=	Mo	+ NdCl ₃	-2444
4 U	+	3 WCl ₄	=	3 W	+ 4 UCl ₃	-2436
5 Ca	+	2 MoCl ₅	=	2 Mo	+ 5 CaCl ₂	-2432
4 Li	+	CCl ₄	=	C	+ 4 LiCl	-2408
2 Mg	+	WCl ₄	=	W	+ 2 MgCl ₂	-2396
5 Ce	+	3 NbCl ₅	=	3 Nb	+ 5 CeCl ₃	-2395
3 Li	+	MoCl ₃	=	Mo	+ 3 LiCl	-2387
5 La	+	3 NbCl ₅	=	3 Nb	+ 5 LaCl ₃	-2386
5 Ce	+	3 TaCl ₅	=	3 Ta	+ 5 CeCl ₃	-2374
4 Y	+	3 CCl ₄	=	3 C	+ 4 YCl ₃	-2371
2 U	+	WCl ₆	=	W	+ 2 UCl ₃	-2369
5 U	+	3 WCl ₅	=	3 W	+ 5 UCl ₃	-2368
4 U	+	3 C ₂ Cl ₄	=	6 C	+ 4 UCl ₃	-2368
4 Hf	+	3 WCl ₄	=	3 W	+ 4 HfCl ₃	-2365
4 Sc	+	3 WCl ₄	=	3 W	+ 4 ScCl ₃	-2365
5 La	+	3 TaCl ₅	=	3 Ta	+ 5 LaCl ₃	-2365
2 Sr	+	WCl ₄	=	W	+ 2 SrCl ₂	-2357
Ce	+	AuCl ₃	=	Au	+ CeCl ₃	-2349

Table 28 (cont.)

Reaction						Enthalpy, cal/cc	
Th	+	WCl ₄	=	W	+	ThCl ₄	-2347
2 Mg	+	C ₂ Cl ₄	=	2 C	+	2 MgCl ₂	-2343
La	+	AuCl ₃	=	Au	+	LaCl ₃	-2342
5 Pr	+	3 NbCl ₅	=	3 Nb	+	5 PrCl ₃	-2341
5 Mn	+	2 ReCl ₅	=	2 Re	+	5 MnCl ₂	-2339
2 Ca	+	CCl ₄	=	C	+	2 CaCl ₂	-2339
3 Mg	+	WCl ₆	=	W	+	3 MgCl ₂	-2338
Y	+	MoCl ₃	=	Mo	+	YCl ₃	-2336
5 Mg	+	2 WCl ₅	=	2 W	+	5 MgCl ₂	-2336
2 Sr	+	C ₂ Cl ₄	=	2 C	+	2 SrCl ₂	-2324
5 Nd	+	3 NbCl ₅	=	3 Nb	+	5 NdCl ₃	-2320
5 Pr	+	3 TaCl ₅	=	3 Ta	+	5 PrCl ₃	-2320
4 Sc	+	3 C ₂ Cl ₄	=	6 C	+	4 ScCl ₃	-2318
3 Sr	+	WCl ₆	=	W	+	3 SrCl ₂	-2316
4 Hf	+	3 C ₂ Cl ₄	=	6 C	+	4 HfCl ₃	-2316
5 Sr	+	2 WCl ₅	=	2 W	+	5 SrCl ₂	-2315
3 Ca	+	2 MoCl ₃	=	2 Mo	+	3 CaCl ₂	-2307
5 U	+	3 MoCl ₅	=	3 Mo	+	5 UCl ₃	-2306
4 Zr	+	3 WCl ₄	=	3 W	+	4 ZrCl ₃	-2306
2 Sc	+	WCl ₆	=	W	+	2 ScCl ₃	-2306
Pr	+	AuCl ₃	=	Au	+	PrCl ₃	-2306
5 Sc	+	3 WCl ₅	=	3 W	+	5 ScCl ₃	-2305
Th	+	C ₂ Cl ₄	=	2 C	+	ThCl ₄	-2304
2 Hf	+	WCl ₆	=	W	+	2 HfCl ₃	-2302
5 Hf	+	3 WCl ₅	=	3 W	+	5 HfCl ₃	-2301
5 Nd	+	3 TaCl ₅	=	3 Ta	+	5 NdCl ₃	-2298
5 Li	+	NbCl ₅	=	Nb	+	5 LiCl	-2288
Nd	+	AuCl ₃	=	Au	+	NdCl ₃	-2288
3 Th	+	2 WCl ₆	=	2 W	+	3 ThCl ₄	-2287
5 Th	+	4 WCl ₅	=	4 W	+	5 ThCl ₄	-2285
2 Ba	+	WCl ₄	=	W	+	2 BaCl ₂	-2283

Table 28 (cont.)

Reaction						Enthalpy, cal/cc	
5 Mg	+	2 MoCl ₅	=	2 Mo	+	5 MgCl ₂	-2282
5 Al	+	3 ReCl ₅	=	3 Re	+	5 AlCl ₃	-2278
5 Sr	+	2 MoCl ₅	=	2 Mo	+	5 SrCl ₂	-2276
4 Zr	+	3 C ₂ Cl ₄	=	6 C	+	4 ZrCl ₃	-2273
5 Li	+	TaCl ₅	=	Ta	+	5 LiCl	-2270
3 Li	+	AuCl ₃	=	Au	+	3 LiCl	-2266
2 Ba	+	C ₂ Cl ₄	=	2 C	+	2 BaCl ₂	-2265
5 Sc	+	3 MoCl ₅	=	3 Mo	+	5 ScCl ₃	-2248
3 Ba	+	WCl ₆	=	W	+	3 BaCl ₂	-2247
2 Zr	+	WCl ₆	=	W	+	2 ZrCl ₃	-2247
5 Ba	+	2 WCl ₅	=	2 W	+	5 BaCl ₂	-2246
5 Zr	+	3 WCl ₅	=	3 W	+	5 ZrCl ₃	-2245
5 Hf	+	3 MoCl ₅	=	3 Mo	+	5 HfCl ₃	-2240
5 Ti	+	3 ReCl ₅	=	3 Re	+	5 TiCl ₃	-2229
2 Ce	+	3 WCl ₂	=	3 W	+	2 CeCl ₃	-2228
5 Th	+	4 MoCl ₅	=	4 Mo	+	5 ThCl ₄	-2226
2 La	+	3 WCl ₂	=	3 W	+	2 LaCl ₃	-2223
2 Sr	+	CCl ₄	=	C	+	2 SrCl ₂	-2213
5 Ba	+	2 MoCl ₅	=	2 Mo	+	5 BaCl ₂	-2210
4 U	+	3 CCl ₄	=	3 C	+	4 UCl ₃	-2210
5 Ca	+	2 NbCl ₅	=	2 Nb	+	5 CaCl ₂	-2209
5 Y	+	3 NbCl ₅	=	3 Nb	+	5 YCl ₃	-2208
3 Ca	+	2 AuCl ₃	=	2 Au	+	3 CaCl ₂	-2201
2 Ce	+	3 MoCl ₂	=	3 Mo	+	2 CeCl ₃	-2200
2 Mg	+	CCl ₄	=	C	+	2 MgCl ₂	-2198
Y	+	AuCl ₃	=	Au	+	YCl ₃	-2197
2 La	+	3 MoCl ₂	=	3 Mo	+	2 LaCl ₃	-2196
5 Ca	+	2 TaCl ₅	=	2 Ta	+	5 CaCl ₂	-2191
3 Mn	+	C ₂ Cl ₆	=	2 C	+	3 MnCl ₂	-2188
5 Na	+	ReCl ₅	=	Re	+	5 NaCl	-2185
5 Zr	+	3 MoCl ₅	=	3 Mo	+	5 ZrCl ₃	-2185

Table 28 (cont.)

Reaction						Enthalpy, cal/cc	
5 Y	+	3 TaCl ₅	=	3 Ta	+	5 YCl ₃	-2184
2 Pr	+	3 WCl ₂	=	3 W	+	2 PrCl ₃	-2182
2 Be	+	C ₂ Cl ₄	=	2 C	+	2 BeCl ₂	-2168
4 Sc	+	3 CCl ₄	=	3 C	+	4 ScCl ₃	-2168
3 Sr	+	2 MoCl ₃	=	2 Mo	+	3 SrCl ₂	-2166
2 Be	+	WCl ₄	=	W	+	2 BeCl ₂	-2164
2 Nd	+	3 WCl ₂	=	3 W	+	2 NdCl ₃	-2162
2 Li	+	WCl ₂	=	W	+	2 LiCl	-2159
2 Ba	+	CCl ₄	=	C	+	2 BaCl ₂	-2159
4 Hf	+	3 CCl ₄	=	3 C	+	4 HfCl ₃	-2157
2 Pr	+	3 MoCl ₂	=	3 Mo	+	2 PrCl ₃	-2153
Th	+	CCl ₄	=	C	+	ThCl ₄	-2148
2 Ce	+	3 CuCl ₂	=	3 Cu	+	2 CeCl ₃	-2144
2 La	+	3 CuCl ₂	=	3 Cu	+	2 LaCl ₃	-2141
U	+	MoCl ₃	=	Mo	+	UCl ₃	-2136
2 Al	+	C ₂ Cl ₆	=	2 C	+	2 AlCl ₃	-2135
2 Li	+	MoCl ₂	=	Mo	+	2 LiCl	-2134
2 Nd	+	3 MoCl ₂	=	3 Mo	+	2 NdCl ₃	-2132
3 Mg	+	7 MoCl ₃	=	2 Mo	+	3 MgCl ₂	-2130
6 Na	+	C ₂ Cl ₆	=	2 C	+	6 NaCl	-2119
4 Zr	+	3 CCl ₄	=	3 C	+	4 ZrCl ₃	-2113
3 Ba	+	2 MoCl ₃	=	2 Mo	+	3 BaCl ₂	-2108
3 Be	+	WCl ₆	=	W	+	3 BeCl ₂	-2106
5 Be	+	2 WCl ₅	=	2 W	+	5 BeCl ₂	-2103
2 Pr	+	3 CuCl ₂	=	3 Cu	+	2 PrCl ₃	-2097
2 Ti	+	C ₂ Cl ₆	=	2 C	+	2 TiCl ₃	-2096
5 V	+	2 ReCl ₅	=	2 Re	+	5 VCl ₂	-2092
3 Sr	+	2 AuCl ₃	=	2 Au	+	3 SrCl ₂	-2092
Sc	+	MoCl ₃	=	Mo	+	ScCl ₃	-2090
Ca	+	WCl ₂	=	W	+	CaCl ₂	-2089
2 Li	+	CuCl ₂	=	Cu	+	2 LiCl	-2088

Table 28 (cont.)

Reaction						Enthalpy, cal/cc	
5 Sr	+	2 NbCl ₅	=	2 Nb	+	5 SrCl ₂	-2082
2 Nd	+	3 CuCl ₂	=	3 Cu	+	2 NdCl ₃	-2076
Ce	+	FeCl ₃	=	Fe	+	CeCl ₃	-2075
La	+	FeCl ₃	=	Fe	+	LaCl ₃	-2073
Hf	+	MoCl ₃	=	Mo	+	HfCl ₃	-2072
5 Sr	+	2 TaCl ₅	=	2 Ta	+	5 SrCl ₂	-2065
3 Th	+	4 MoCl ₃	=	4 Mo	+	3 ThCl ₄	-2063
Ca	+	MoCl ₂	=	Mo	+	CaCl ₂	-2062
2 Y	+	3 WCl ₂	=	3 W	+	2 YCl ₃	-2056
3 Ba	+	2 AuCl ₃	=	2 Au	+	3 BaCl ₂	-2048
3 Mg	+	2 AuCl ₃	=	2 Au	+	3 MgCl ₂	-2042
Ce	+	3 AuCl	=	3 Au	+	CeCl ₃	-2040
La	+	3 AuCl	=	3 Au	+	LaCl ₃	-2039
U	+	AuCl ₃	=	Au	+	UCl ₃	-2039
5 Be	+	2 MoCl ₅	=	2 Mo	+	5 BeCl ₂	-2037
5 Ba	+	2 NbCl ₅	=	2 Nb	+	5 BaCl ₂	-2031

Table 29

MOST ENERGETIC CHLORIDE REACTIONS WITH METALS,
IN TERMS OF GRAVIMETRIC ENTHALPY

Reaction						Enthalpy, cal/g	
Li	+	BCl	=	B	+	LiCl	-2316
4 Li	+	C ₂ Cl ₄	=	2 C	+	4 LiCl	-2002
4 Li	+	CCl ₄	=	C	+	4 LiCl	-1968
6 Li	+	C ₂ Cl ₆	=	2 C	+	6 LiCl	-1933
Ca	+	2 BCl	=	2 B	+	CaCl ₂	-1818
Na	+	BCl	=	B	+	NaCl	-1787
Mg	+	2 BCl	=	2 B	+	MgCl ₂	-1750
Be	+	2 BCl	=	2 B	+	BeCl ₂	-1708
Sc	+	3 BCl	=	3 B	+	ScCl ₃	-1619
2 Ca	+	C ₂ Cl ₄	=	2 C	+	2 CaCl ₂	-1532
K	+	BCl	=	B	+	KCl	-1519
4 Na	+	C ₂ Cl ₄	=	2 C	+	4 NaCl	-1512
2 Ca	+	CCl ₄	=	C	+	2 CaCl ₂	-1481
Al	+	3 BCl	=	3 B	+	AlCl ₃	-1465
4 Na	+	CCl ₄	=	C	+	4 NaCl	-1463
3 Ca	+	C ₂ Cl ₆	=	2 C	+	3 CaCl ₂	-1462
6 Na	+	C ₂ Cl ₆	=	2 C	+	6 NaCl	-1444
6 Li	+	MoCl ₆	=	Mo	+	6 LiCl	-1416
2 Mg	+	C ₂ Cl ₄	=	2 C	+	2 MgCl ₂	-1416
3 Li	+	BCl ₃	=	B	+	3 LiCl	-1399
Sr	+	2 BCl	=	2 B	+	SrCl ₂	-1382
Y	+	3 BCl	=	3 B	+	YCl ₃	-1368
2 Mg	+	CCl ₄	=	C	+	2 MgCl ₂	-1350
Li	+	AlCl	=	Al	+	LiCl	-1337
3 Mg	+	C ₂ Cl ₆	=	2 C	+	3 MgCl ₂	-1330
2 Be	+	C ₂ Cl ₄	=	2 C	+	2 BeCl ₂	-1313
4 Li	+	CrCl ₄	=	Cr	+	4 LiCl	-1294
Ti	+	3 BCl	=	3 B	+	TiCl ₃	-1294
5 Li	+	MoCl ₅	=	Mo	+	5 LiCl	-1291

Table 29 (cont.)

Reaction						Enthalpy, cal/g
4	Sc	+	3 C ₂ Cl ₄	=	6 C + 4 ScCl ₃	-1290
4	K	+	C ₂ Cl ₄	=	2 C + 4 KCl	-1283
4	Li	+	MnCl ₄	=	Mn + 4 LiCl	-1250
	Zr	+	3 BCl	=	3 B + ZrCl ₃	-1237
4	K	+	CCl ₄	=	C + 4 KCl	-1235
2	Be	+	CCl ₄	=	C + 2 BeCl ₂	-1229
	La	+	3 BCl	=	3 B + LaCl ₃	-1225
5	Li	+	NbCl ₅	=	Nb + 5 LiCl	-1224
6	K	+	C ₂ Cl ₆	=	2 C + 6 KCl	-1224
4	Sc	+	3 CCl ₄	=	3 C + 4 ScCl ₃	-1221
3	Be	+	C ₂ Cl ₆	=	2 C + 3 BeCl ₂	-1208
	Ce	+	3 BCl	=	3 B + CeCl ₃	-1208
2	Sc	+	C ₂ Cl ₆	=	2 C + 2 ScCl ₃	-1204
4	Li	+	SiCl ₄	=	Si + 4 LiCl	-1203
	Si	+	4 BCl	=	4 B + SiCl ₄	-1197
	Pr	+	3 BCl	=	3 B + PrCl ₃	-1196
4	Li	+	MoCl ₄	=	Mo + 4 LiCl	-1174
	Nd	+	3 BCl	=	3 B + NdCl ₃	-1169
2	Sr	+	C ₂ Cl ₄	=	2 C + 2 SrCl ₂	-1152
5	Li	+	SbCl ₅	=	Sb + 5 LiCl	-1149
4	Li	+	VCl ₄	=	V + 4 LiCl	-1146
	Li	+	GeCl	=	Ge + LiCl	-1131
	Mn	+	2 BCl	=	2 B + MnCl ₂	-1128
	V	+	3 BCl	=	3 B + VCl ₃	-1126
3	Ca	+	MoCl ₆	=	Mo + 3 CaCl ₂	-1119
6	Na	+	MoCl ₆	=	Mo + 6 NaCl	-1118
	Ba	+	2 BCl	=	2 B + BaCl ₂	-1116
6	Li	+	WCl ₆	=	W + 6 LiCl	-1112
	Cr	+	3 BCl	=	3 B + CrCl ₃	-1107
2	Sr	+	CCl ₄	=	C + 2 SrCl ₂	-1102
3	Sr	+	C ₂ Cl ₆	=	2 C + 3 SrCl ₂	-1092

Table 29 (cont.)

Reaction						Enthalpy, cal/g	
Ca	+	2 AlCl	=	2 Al	+	CaCl ₂	-1092
Na	+	AlCl	=	Al	+	NaCl	-1092
4 Y	+	3 C ₂ Cl ₄	=	6 C	+	4 YCl ₃	-1090
4 Al	+	3 C ₂ Cl ₄	=	6 C	+	4 AlCl ₃	-1083
4 Li	+	GeCl ₄	=	Ge	+	4 LiCl	-1076
3 Li	+	FeCl ₃	=	Fe	+	3 LiCl	-1072
5 Li	+	ReCl ₅	=	Re	+	5 LiCl	-1050
3 Na	+	BCl ₃	=	B	+	3 NaCl	-1045
3 Ca	+	2 BCl ₃	=	2 B	+	3 CaCl ₂	-1043
5 Na	+	MoCl ₅	=	Mo	+	5 NaCl	-1031
5 Ca	+	2 MoCl ₅	=	2 Mo	+	5 CaCl ₂	-1028
4 Y	+	3 CCl ₄	=	3 C	+	4 YCl ₃	-1027
3 Li	+	MoCl ₃	=	Mo	+	3 LiCl	-1022
5 Li	+	WCl ₅	=	W	+	5 LiCl	-1021
2 Y	+	C ₂ Cl ₆	=	2 C	+	2 YCl ₃	-1016
4 Na	+	CrCl ₄	=	Cr	+	4 NaCl	-1010
2 Ca	+	CrCl ₄	=	Cr	+	2 CaCl ₂	-1007
3 Li	+	MnCl ₃	=	Mn	+	3 LiCl	-1005
Na	+	GeCl	=	Ge	+	NaCl	- 997
Ca	+	2 GeCl	=	2 Ge	+	CaCl ₂	- 994
4 La	+	3 C ₂ Cl ₄	=	6 C	+	4 LaCl ₃	- 992
4 Al	+	3 CCl ₄	=	3 C	+	4 AlCl ₃	- 992
2 Li	+	CuCl ₂	=	Cu	+	2 LiCl	- 985
6 K	+	MoCl ₆	=	Mo	+	6 KCl	- 984
Hf	+	4 BCl	=	4 B	+	HfCl ₄	- 982
4 Na	+	MnCl ₄	=	Mn	+	4 NaCl	- 979
2 Al	+	C ₂ Cl ₆	=	2 C	+	2 AlCl ₃	- 978
K	+	AlCl	=	Al	+	KCl	- 977
5 Na	+	NbCl ₅	=	Nb	+	5 NaCl	- 976
4 Ce	+	3 C ₂ Cl ₄	=	6 C	+	4 CeCl ₃	- 975
Rb	+	BCl	+	B	+	RbCl	- 975

Table 29 (cont.)

Reaction						Enthalpy, cal/g
2 Ca	+	MnCl ₄	=	Mn	+ 2 CaCl ₂	- 974
4 Li	+	TiCl ₄	=	Ti	+ 4 LiCl	- 972
5 Ca	+	2 NbCl ₅	=	2 Nb	+ 5 CaCl ₂	- 971
3 Mg	+	MoCl ₆	=	Mo	+ 3 MgCl ₂	- 969
	Ga	+ 3 BCl	=	3 B	+ GaCl ₃	- 969
4 Pr	+	3 C ₂ Cl ₄	=	6 C	+ 4 PrCl ₃	- 963
	Mg	+ 2 AlCl	=	2 Al	+ MgCl ₂	- 962
4 Zr	+	3 C ₂ Cl ₄	=	6 C	+ 4 ZrCl ₃	- 954
	Zn	+ 2 BCl	=	2 B	+ ZnCl ₂	- 953
4 Na	+	MoCl ₄	=	Mo	+ 4 NaCl	- 952
	Li	+ GaCl	=	Ga	+ LiCl	- 951
2 Ca	+	MoCl ₄	=	Mo	+ 2 CaCl ₂	- 946
4 Ti	+	3 C ₂ Cl ₄	=	6 C	+ 4 TiCl ₃	- 944
4 La	+	3 CCl ₄	=	3 C	+ 4 LaCl ₃	- 938
4 Nd	+	3 C ₂ Cl ₄	=	6 C	+ 4 NdCl ₃	- 938
5 Li	+	TaCl ₅	=	Ta	+ 5 LiCl	- 937
5 Na	+	SbCl ₅	=	Sb	+ 5 NaCl	- 933
2 La	+	C ₂ Cl ₆	=	2 C	+ 2 LaCl ₃	- 931
4 Li	+	ReCl ₄	=	Re	+ 4 LiCl	- 929
	Th	+ 4 BCl	=	4 B	+ ThCl ₄	- 928
	K	+ GeCl	=	Ge	+ KCl	- 928
5 Ca	+	2 SbCl ₅	=	2 Sb	+ 5 CaCl ₂	- 927
2 Ba	+	C ₂ Cl ₄	=	2 C	+ 2 BaCl ₂	- 926
4 Ce	+	3 CCl ₄	=	3 C	+ 4 CeCl ₃	- 921
6 Na	+	WCl ₆	=	W	+ 6 NaCl	- 917
5 K	+	MoCl ₅	=	Mo	+ 5 KCl	- 917
6 Li	+	Al ₂ Cl ₆	=	2 Al	+ 6 LiCl	- 916
4 Na	+	SiCl ₄	=	Si	+ 4 NaCl	- 916
2 Ce	+	C ₂ Cl ₆	=	2 C	+ 2 CeCl ₃	- 914
3 Ca	+	WCl ₆	=	W	+ 3 CaCl ₂	- 911

Table 29 (cont.)

Reaction						Enthalpy, cal/g
4 Pr	+	3 CCl ₄	=	3 C	+ 4 PrCl ₃	- 908
4 Li	+	OsCl ₄	=	Os	+ 4 LiCl	- 908
Mg	+	2 GeCl	=	2 Ge	+ MgCl ₂	- 907
2 Ca	+	SiCl ₄	=	Si	+ 2 CaCl ₂	- 907
3 K	+	BCl ₃	=	B	+ 3 KCl	- 906
4 Li	+	WCl ₄	=	W	+ 4 LiCl	- 904
4 Li	+	SnCl ₄	=	Sn	+ 4 LiCl	- 903
Ge	+	4 BCl	=	4 B	+ GeCl ₄	- 901
2 Pr	+	C ₂ Cl ₆	=	2 C	+ 2 PrCl ₃	- 901
4 Na	+	VCl ₄	=	V	+ 4 NaCl	- 895
Fe	+	2 BCl	=	2 B	+ FeCl ₂	- 894
4 K	+	CrCl ₄	=	Cr	+ 4 KCl	- 892
Sc	+	3 AlCl	=	3 Al	+ ScCl ₃	- 887
2 Ca	+	VCl ₄	=	V	+ 2 CaCl ₂	- 886
4 Zr	+	3 CCl ₄	=	3 C	+ 4 ZrCl ₃	- 885
Sr	+	2 AlCl	=	2 Al	+ SrCl ₂	- 885
3 Li	+	CrCl ₃	=	Cr	+ 3 LiCl	- 884
4 Nd	+	3 CCl ₄	=	3 C	+ 4 NdCl ₃	- 883
2 Sc	+	MoCl ₆	=	Mo	+ 2 ScCl ₃	- 882
3 Sr	+	MoCl ₆	=	Mo	+ 3 SrCl ₂	- 881
2 Ba	+	CCl ₄	=	C	+ 2 BaCl ₂	- 881
5 Na	+	ReCl ₅	=	Re	+ 5 NaCl	- 880
2 Zr	+	C ₂ Cl ₆	=	2 C	+ 2 ZrCl ₃	- 877
2 Nd	+	C ₂ Cl ₆	=	2 C	+ 2 NdCl ₃	- 876
3 Ba	+	C ₂ Cl ₆	=	2 C	+ 3 BaCl ₂	- 876
5 Mg	+	2 MoCl ₅	=	2 Mo	+ 5 MgCl ₂	- 876
3 Li	+	VCl ₃	=	V	+ 3 LiCl	- 876
5 Ca	+	2 ReCl ₅	=	2 Re	+ 5 CaCl ₂	- 873
5 K	+	NbCl ₅	=	Nb	+ 5 KCl	- 871
4 K	+	MnCl ₄	=	Mn	+ 4 KCl	- 868

Table 29 (cont.)

Reaction						Enthalpy, cal/g	
Sr	+	2 GeCl	=	2 Ge	+	SrCl ₂	- 865
Sc	+	3 GeCl	=	3 Ge	+	ScCl ₃	- 861
4 Na	+	GeCl ₄	=	Ge	+	4 NaCl	- 858
4 Ti	+	3 CCl ₄	=	3 C	+	4 TiCl ₃	- 857
4 K	+	MoCl ₄	=	Mo	+	4 KCl	- 856
3 Na	+	FeCl ₃	=	Fe	+	3 NaCl	- 855
5 Na	+	WCl ₅	=	W	+	5 NaCl	- 855
3 Li	+	GaCl ₃	=	Ga	+	3 LiCl	- 851
Co	+	2 BCl	=	2 B	+	CoCl ₂	- 851
2 Ca	+	GeCl ₄	=	Ge	+	2 CaCl ₂	- 848
2 Ti	+	C ₂ Cl ₆	=	2 C	+	2 TiCl ₃	- 847
5 Ca	+	2 WCl ₅	=	2 W	+	3 CaCl ₂	- 847
3 Na	+	MoCl ₃	=	Mo	+	3 NaCl	- 846
3 Mg	+	2 BCl ₃	=	2 B	+	3 MgCl ₂	- 846
3 Ca	+	2 FeCl ₃	=	2 Fe	+	3 CaCl ₂	- 846
5 K	+	SbCl ₅	=	Sb	+	5 KCl	- 841
Be	+	2 AlCl	=	2 Al	+	BeCl ₂	- 840
3 Ca	+	2 MoCl ₃	=	2 Mo	+	3 CaCl ₂	- 838
2 Li	+	MoCl ₂	=	Mo	+	2 LiCl	- 837
Ni	+	2 BCl	=	2 B	+	NiCl ₂	- 837
Na	+	GaCl	=	Ga	+	NaCl	- 836
2 Mg	+	CrCl ₄	=	Cr	+	2 MgCl ₂	- 836
2 Li	+	NiCl ₂	=	Ni	+	2 LiCl	- 835
U	+	4 BCl	=	4 B	+	UCl ₄	- 835
6 K	+	WCl ₆	=	W	+	6 KCl	- 833
Be	+	2 GeCl	=	2 Ge	+	BeCl ₂	- 831
Ca	+	2 GaCl	=	2 Ga	+	CaCl ₂	- 830
2 Mn	+	C ₂ Cl ₄	=	2 C	+	2 MnCl ₂	- 825
3 Be	+	MoCl ₆	=	Mo	+	3 BeCl ₂	- 824
3 Li	+	AlCl ₃	=	Al	+	3 LiCl	- 823

Table 29 (cont.)

Reaction						Enthalpy, cal/g	
5 Sr	+	2 MoCl ₅	=	2 Mo	+	5 SrCl ₂	- 821
2 Li	+	CoCl ₂	=	Co	+	2 LiCl	- 818
3 Li	+	AuCl ₃	=	Au	+	3 LiCl	- 816
2 Na	+	CuCl ₂	=	Cu	+	2 NaCl	- 816
5 Mg	+	2 NbCl ₅	=	2 Nb	+	5 MgCl ₂	- 811
3 Li	+	SbCl ₃	=	Sb	+	3 LiCl	- 810
2 Li	+	FeCl ₂	=	Fe	+	2 LiCl	- 809
In	+	3 BCl	=	3 B	+	InCl ₃	- 808
4 K	+	SiCl ₄	=	Si	+	4 KCl	- 808
Ca	+	CuCl ₂	=	Cu	+	CaCl ₂	- 806
5 K	+	ReCl ₅	=	Re	+	5 KCl	- 806
4 Rb	+	C ₂ Cl ₄	=	2 C	+	4 RbCl	- 804
Y	+	3 GeCl	=	3 Ge	+	YCl ₃	- 804
3 Na	+	MnCl ₃	=	Mn	+	3 NaCl	- 802
2 Mg	+	MnCl ₄	=	Mn	+	2 MgCl ₂	- 801

(tetrachloroethylene, carbon tetrachloride, and hexachloroethane), chromium tetrachloride, molybdenum hexachloride, and molybdenum pentachloride.

The periodic relationships of the chloride reactions are shown in Figures 21, 22, and 23. It is interesting to compare the general periodic trends, shown by the solid connecting lines, in the chloride, oxide, and fluoride systems. Lithium, which is one of the best reducing agents in the chloride systems, is of moderate efficacy in the oxide and fluoride systems. It occurs at one of the most energetic peaks in the chloride systems. Unlike the oxide systems, magnesium is more energetic than aluminum in the fluoride and chloride systems. Titanium is relatively less energetic in the chloride systems than in the fluoride and oxide systems. The areas including strontium, yttrium, zirconium, the rare earths, hafnium, and tantalum are similar in all three systems.

It is also of interest to compare the trends within the different periodic groups. The trends within each group are similar in all three systems except for the alkaline earths. Thus, most of the groups exhibit less energetic reactions as the atomic number increases. The primary exception to this is the titanium-zirconium-hafnium group, which exhibits an increase in the volumetric energy with increasing atomic number because the lanthanide contraction minimizes the effect of the volume. The behavior of the alkaline earths is therefore striking. Instead of decreasing in energy with increasing atomic number, maximum energy is reached at calcium. This occurs because the heat of formation of the chlorides increases monotonically at a rate which is compensated by the increase in atomic volume and weight when calcium is reached. After calcium, the increase in heat of formation is not enough to overcome the effect of the increase in atomic volume and weight.

The reactions of the chlorides with lithium metal are depicted in Figures 22 and 23. These curves are approximately the inverse of the curves in Figure 21 because the metals that are effective reducing agents form chlorides that are poor oxidizing agents. The chlorides of carbon (hexachloroethane, tetrachloroethylene, and carbon tetrachloride), the transition metal chlorides (vanadium trichloride, chromium trichloride, iron trichloride, cobalt dichloride, nickel dichloride, copper dichloride, molybdenum pentachloride, molybdenum trichloride, tantalum pentachloride, tungsten tetrachloride, tungsten pentachloride and tungsten hexachloride), gold trichloride, mercury dichloride, lead tetrachloride, and bismuth trichloride are effective oxidizers on a volumetric basis. In general, the higher the oxidation state of the metal in the chloride, the more energetic are its reactions. For instance, note the volumetric outputs of molybdenum di-, tri-, and pentachloride. There are many exceptions however, such as vanadium tetra- and trichloride and tungsten tetra- and pentachloride.

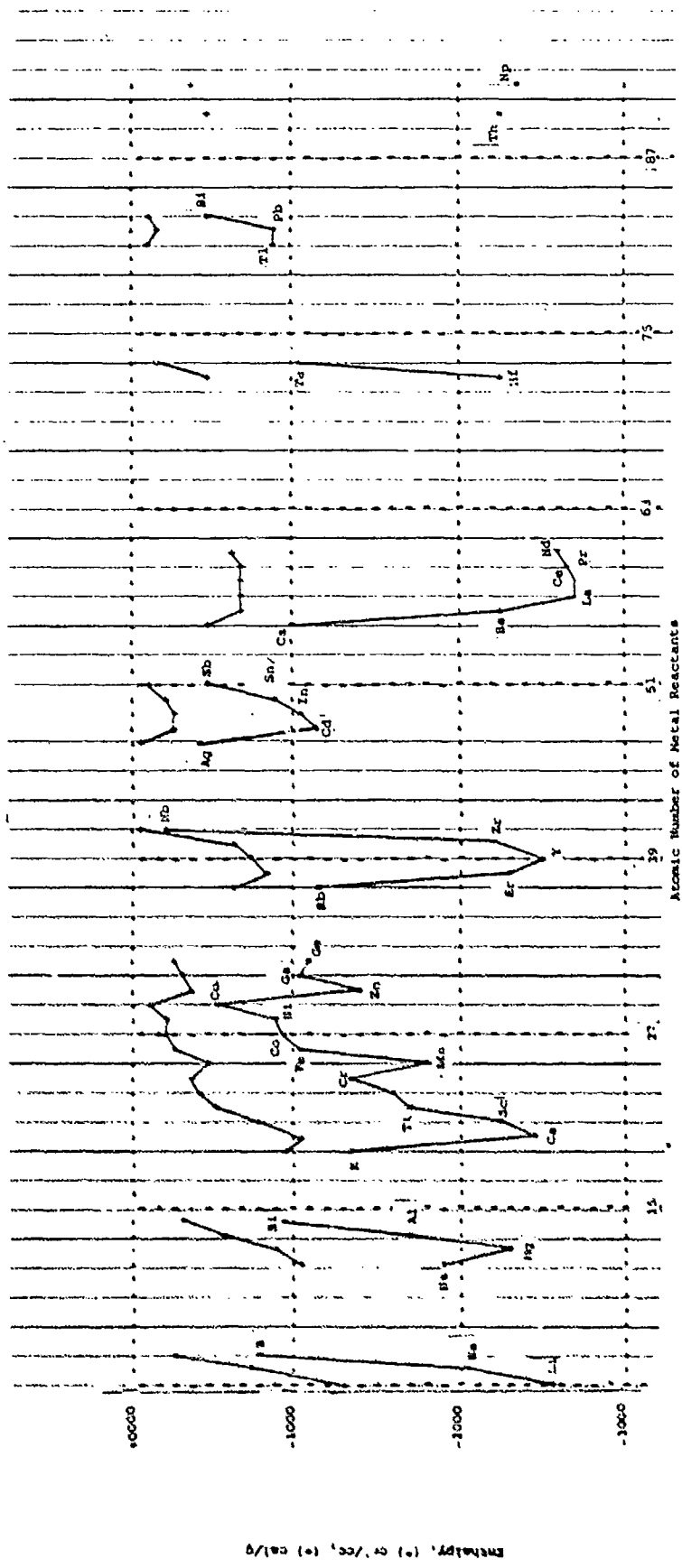
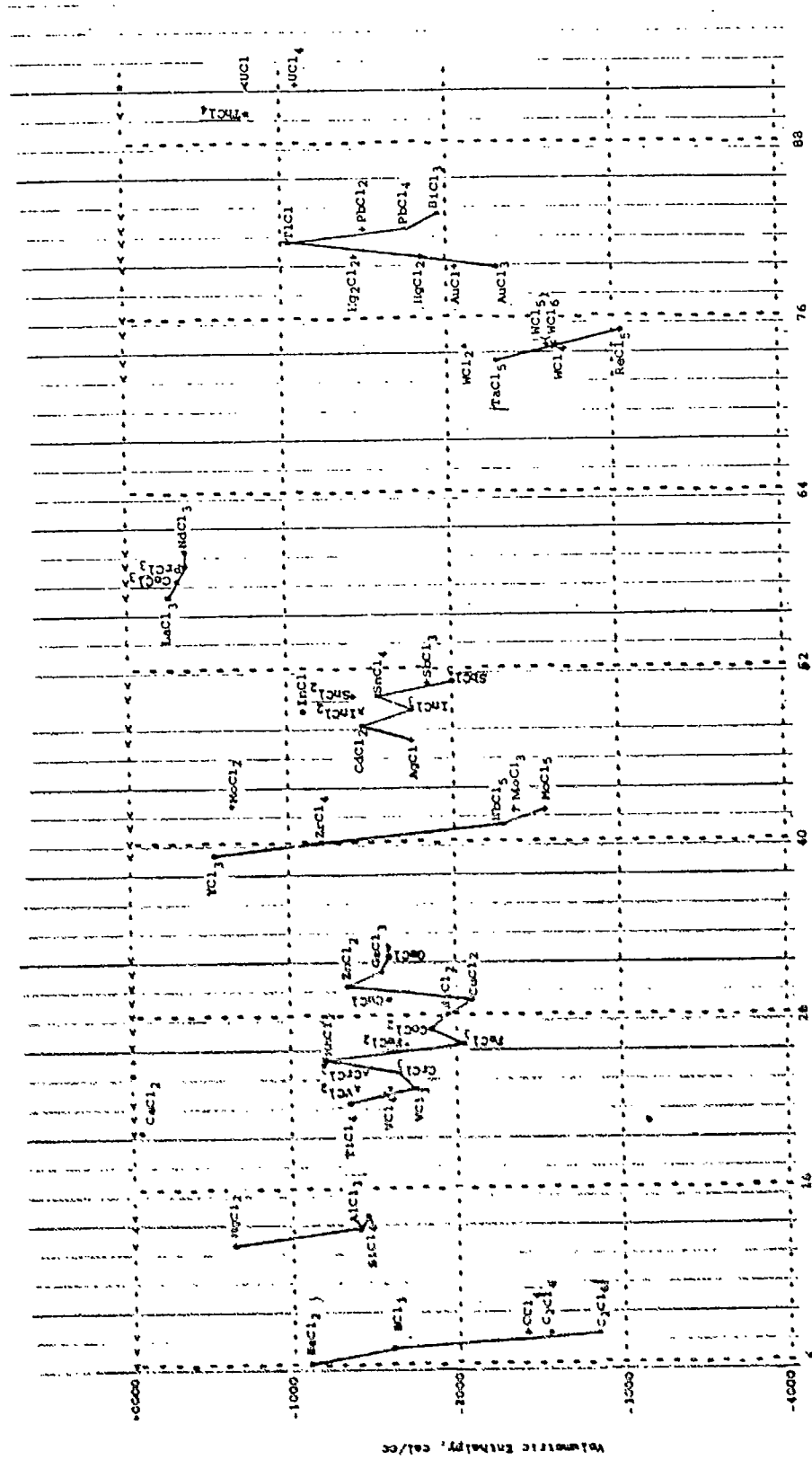


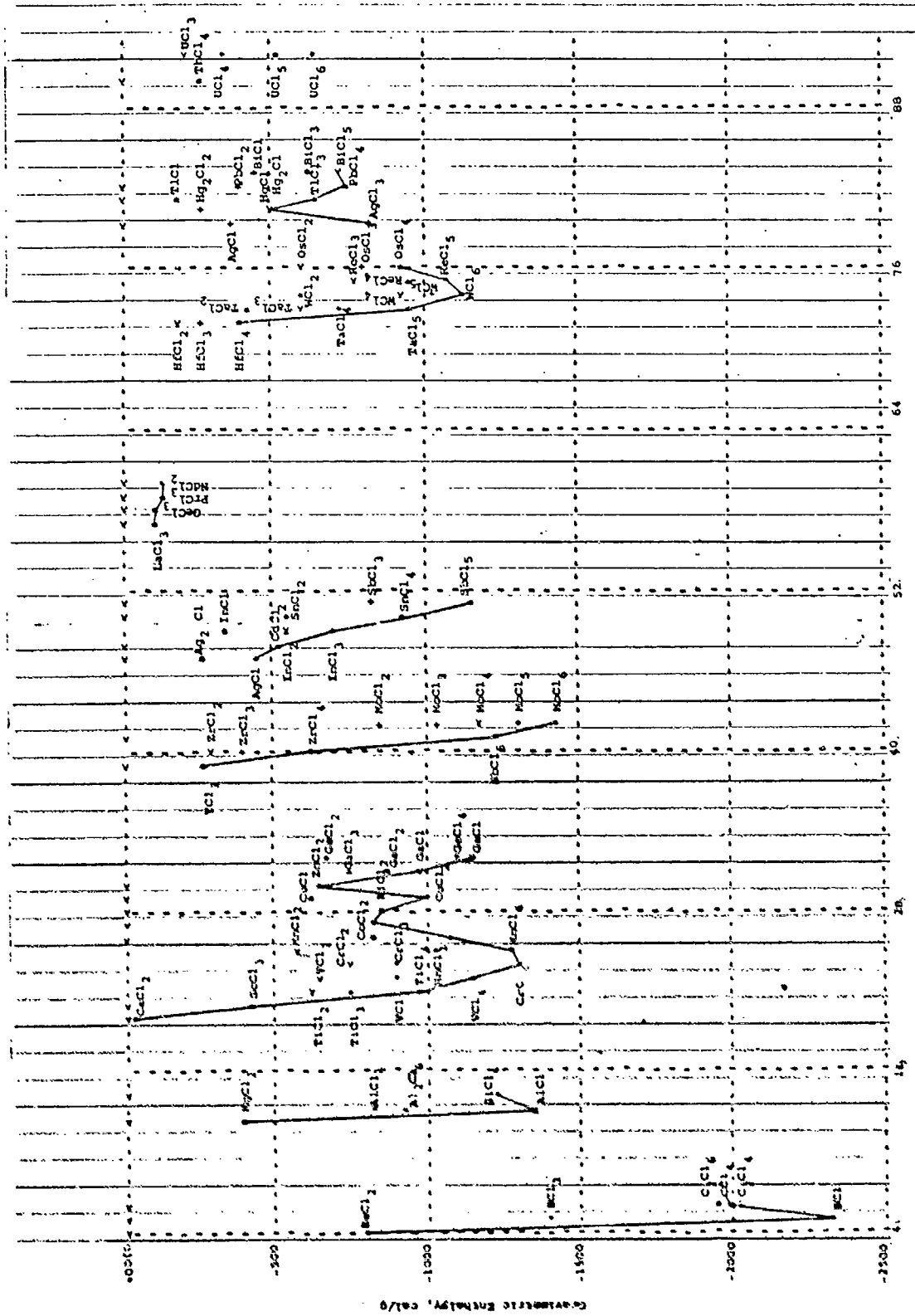
Figure 21
CALYMETRIC AND VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS WITH MoCl₅



Atomic Number of Metal in the Chloride

Figure 22

VOLUMETRIC ENTHALPIES OF REACTIONS OF CHLORIDES WITH LI



Atomic Number of Metal in the Chloride

Figure 23

GRAVIMETRIC ENTHALPIES OF REACTIONS OF CHLORIDES WITH LI

The behavior of the chlorides on a gravimetric basis is similar to the volumetric behavior. The chlorides of carbon and the chlorides of many of the transition metals are effective oxidizers. Again, the higher the oxidation state of the metal in the chloride, the more energetic are its reactions. This is illustrated dramatically in Figure 23 by the chlorides of titanium, chromium, manganese, zirconium, molybdenum, indium, tin, antimony, hafnium, tantalum, tungsten, rhenium, osmium, lead, bismuth, and uranium. There are a few exceptions, such as the chlorides of boron, aluminum, gallium, germanium, and mercury. It is interesting that the first three are the first elements in Group IIIA. Evidently, in this group the addition of chloride atoms does not increase the heat of formation of the chloride enough to compensate for the increase in weight of the additional chlorine atoms. Similar charts for the other chlorides and metals indicate similar trends, except for displacement of the vertical scale.

Summaries of the volumetric and gravimetric enthalpies of all the chloride reactions are presented in Tables 30 and 31, respectively. The most energetic reactions are in the upper left-hand corner of the chart. The same trends noted previously are apparent.

Table 30

VOLUOMETRIC ENTHALPIES OF REACTIONS OF METALS WITH CHLORIDES
(In descending order from top to bottom and left to right)

	BaCl ₂	C ₂ G16	WCl ₄	WCl ₃	WCl ₂	MoCl ₅	CoCl ₄	MoCl ₃	NbCl ₅	TaCl ₅	AuCl ₃	WCl ₂	MoCl ₂	CuCl ₂	FeCl ₃	AuCl	SbCl ₅	BiCl ₃	NiCl ₂	HgCl ₂	CoCl ₂
CC	-3336	-3047	-2807	-2731	-2730	-2676	-2523	-2521	-2395	-2374	-2449	-2224	-2200	-2184	-2075	-2040	-2020	-1943	-1943	-1856	-1814
LA	-3201	-3025	-2788	-2715	-2714	-2661	-2507	-2505	-2396	-2342	-2425	-2224	-2196	-2181	-2073	-2039	-2019	-1942	-1942	-1858	-1821
PR	-3249	-3046	-2788	-2715	-2714	-2661	-2507	-2505	-2396	-2342	-2425	-2224	-2196	-2181	-2073	-2039	-2019	-1942	-1942	-1858	-1821
NO	-3248	-3070	-2774	-2701	-2699	-2646	-2492	-2490	-2381	-2327	-2410	-2209	-2181	-2166	-2058	-2024	-2004	-1927	-1927	-1843	-1806
LI	-3176	-2897	-2632	-2558	-2553	-2500	-2346	-2344	-2235	-2181	-2264	-2063	-2035	-2020	-1912	-1878	-1858	-1781	-1781	-1697	-1660
V	-2906	-2725	-2474	-2400	-2399	-2346	-2192	-2190	-2081	-2027	-2110	-1909	-1881	-1866	-1758	-1724	-1704	-1627	-1627	-1543	-1506
CA	-2695	-2655	-2364	-2290	-2289	-2236	-2082	-2080	-1971	-1917	-2000	-1800	-1772	-1757	-1649	-1615	-1595	-1518	-1518	-1434	-1397
PG	-2672	-2656	-2364	-2290	-2289	-2236	-2082	-2080	-1971	-1917	-2000	-1800	-1772	-1757	-1649	-1615	-1595	-1518	-1518	-1434	-1397
SC	-2672	-2656	-2364	-2290	-2289	-2236	-2082	-2080	-1971	-1917	-2000	-1800	-1772	-1757	-1649	-1615	-1595	-1518	-1518	-1434	-1397
FM	-2626	-2598	-2304	-2230	-2229	-2176	-2022	-2020	-1911	-1857	-1940	-1740	-1712	-1697	-1589	-1555	-1535	-1458	-1458	-1374	-1337
ZE	-2729	-2699	-2367	-2293	-2292	-2239	-2085	-2083	-1974	-1920	-2003	-1803	-1775	-1760	-1652	-1618	-1598	-1521	-1521	-1437	-1400
SE	-2692	-2676	-2384	-2310	-2309	-2256	-2102	-2100	-1991	-1937	-2020	-1820	-1792	-1777	-1669	-1635	-1615	-1538	-1538	-1454	-1417
DA	-2576	-2542	-2250	-2176	-2175	-2123	-1969	-1967	-1858	-1804	-1887	-1687	-1659	-1644	-1536	-1502	-1482	-1405	-1405	-1321	-1284
PA	-2339	-2188	-1847	-1773	-1772	-1720	-1566	-1564	-1455	-1401	-1484	-1284	-1256	-1241	-1133	-1099	-1079	-1002	-1002	-918	-881
AL	-2272	-2135	-1794	-1720	-1719	-1667	-1513	-1511	-1402	-1348	-1431	-1231	-1203	-1188	-1080	-1046	-1026	-949	-949	-865	-828
TI	-2226	-2096	-1760	-1711	-1710	-1658	-1504	-1502	-1393	-1339	-1422	-1222	-1194	-1179	-1071	-1037	-1017	-940	-940	-856	-819
AA	-2155	-2119	-1808	-1823	-1822	-1770	-1616	-1614	-1505	-1451	-1534	-1334	-1306	-1291	-1183	-1149	-1129	-1052	-1052	-968	-931
VA	-2092	-1997	-1654	-1633	-1632	-1580	-1426	-1424	-1315	-1261	-1344	-1144	-1116	-1101	-993	-959	-939	-862	-862	-778	-741
VA	-2136	-1978	-1630	-1616	-1615	-1563	-1409	-1407	-1298	-1244	-1327	-1127	-1099	-1084	-976	-942	-922	-845	-845	-761	-724
CA	-1803	-1797	-1501	-1490	-1489	-1437	-1283	-1281	-1172	-1118	-1201	-1001	-973	-958	-850	-816	-796	-719	-719	-635	-598
CO	-1592	-1517	-1192	-1180	-1179	-1127	-973	-971	-862	-808	-891	-691	-663	-648	-540	-506	-486	-409	-409	-325	-288
K	-1465	-1457	-1144	-1139	-1138	-1086	-932	-930	-821	-767	-850	-650	-622	-607	-500	-466	-446	-369	-369	-285	-248
LA	-1504	-1418	-1073	-1066	-1065	-1013	-859	-857	-748	-694	-777	-577	-549	-534	-426	-392	-372	-295	-295	-211	-174
LA	-1371	-1392	-1010	-1004	-1003	-951	-797	-795	-688	-634	-717	-517	-489	-474	-366	-332	-312	-235	-235	-151	-114
B	-1304	-1307	-984	-978	-977	-925	-771	-769	-662	-608	-691	-491	-463	-448	-340	-306	-286	-209	-209	-125	-88
GE	-1433	-1442	-1114	-1109	-1108	-1056	-902	-900	-793	-739	-822	-622	-594	-579	-471	-437	-417	-340	-340	-256	-219
HI	-1433	-1443	-1094	-1088	-1087	-1035	-881	-879	-772	-718	-801	-601	-573	-558	-450	-416	-396	-319	-319	-235	-198
HI	-1306	-1381	-1054	-1048	-1047	-995	-841	-839	-732	-678	-761	-561	-533	-518	-410	-376	-356	-279	-279	-195	-158
NI	-1260	-1271	-1160	-1156	-1155	-1103	-949	-947	-840	-786	-869	-669	-641	-626	-518	-484	-464	-387	-387	-303	-266
NI	-1141	-1242	-814	-810	-809	-757	-603	-601	-494	-440	-523	-323	-295	-280	-172	-138	-118	-41	-41	43	6
B	-1209	-1250	-933	-932	-931	-879	-725	-723	-616	-562	-645	-445	-417	-402	-294	-260	-240	-163	-163	-80	-43
FB	-1200	-1287	-941	-940	-939	-887	-733	-731	-626	-572	-655	-455	-427	-412	-304	-270	-250	-173	-173	-90	-53
TD	-1090	-1134	-896	-896	-895	-843	-689	-687	-580	-526	-609	-409	-381	-366	-258	-224	-204	-127	-127	-44	3
CU	-1043	-1063	-864	-864	-863	-811	-657	-655	-550	-496	-579	-379	-351	-336	-228	-194	-174	-100	-100	-16	21
SE	-786	-899	-554	-554	-553	-501	-347	-345	-240	-186	-269	-69	-41	-26	12	28	44	69	69	125	182
CU	-828	-930	-528	-528	-527	-475	-321	-319	-214	-160	-243	-43	-15	10	26	42	58	83	83	139	206
PI	-793	-908	-533	-533	-532	-480	-326	-324	-221	-167	-250	-40	-12	13	29	45	60	85	85	141	208
AC	-651	-747	-492	-492	-491	-439	-285	-283	-180	-126	-209	-29	-1	14	30	46	61	86	86	142	209
PC	-576	-621	-415	-415	-414	-362	-208	-206	-105	-51	-138	-18	10	26	42	58	73	98	98	154	221
E	-255	-405	-426	-426	-425	-373	-219	-217	-116	-62	-149	-19	9	25	41	57	72	97	97	153	220
GE	-117	-381	-272	-272	-271	-219	-65	-63	-62	-61	-60	-59	-58	-57	-56	-55	-54	-53	-52	-51	-50
GS																					
SU																					
MG																					
AN	-528	-712	-445	-297	-312	-234	-606	458	-83	-482	156	-40									

Table 30 (cont.)

	SnCl ₄	FeCl ₃	AgCl	PbCl ₂	VCl ₄	FeCl ₂	CsCl ₂	BCl ₃	VCl ₃	CuCl	GeCl ₄	SnCl ₄	GaCl ₃	PbCl ₂	CdCl ₂	Hg ₂ Cl ₂	SiCl ₄	CrCl ₂	InCl ₂	VCl ₂	SnCl ₂	AlCl ₃
CE	-1605	-1731	-1722	-1693	-1591	-1655	-1605	-1561	-1559	-1558	-1528	-1498	-1463	-1426	-1359	-1376	-1362	-1346	-1359	-1288	-1287	-1245
LA	-1604	-1746	-1723	-1693	-1591	-1655	-1605	-1561	-1559	-1558	-1528	-1498	-1463	-1426	-1359	-1376	-1362	-1346	-1359	-1288	-1287	-1245
PR	-1740	-1441	-1643	-1656	-1615	-1558	-1528	-1498	-1463	-1426	-1359	-1376	-1362	-1346	-1359	-1288	-1287	-1245	-1350	-1283	-1298	-1261
AD	-1741	-1639	-1661	-1635	-1590	-1528	-1503	-1472	-1463	-1453	-1426	-1399	-1361	-1361	-1301	-1328	-1304	-1278	-1277	-1190	-1230	-1166
LI	-1807	-1737	-1736	-1711	-1707	-1662	-1599	-1598	-1495	-1426	-1322	-1251	-1174	-1117	-1132	-1100	-1094	-1049	-1131	-1100	-1094	-949
F	-1615	-1490	-1537	-1516	-1426	-1367	-1362	-1377	-1371	-1378	-1348	-1322	-1251	-1174	-1132	-1100	-1094	-1049	-1131	-1100	-1094	-949
U	-1428	-1263	-1353	-1341	-1185	-1116	-1196	-1185	-1201	-1178	-1174	-1149	-1042	-1002	-1352	-1346	-1368	-1322	-1346	-1289	-1301	-1271
CA	-1378	-1444	-1669	-1647	-1622	-1586	-1503	-1515	-1512	-1532	-1507	-1482	-1449	-1413	-1353	-1328	-1368	-1322	-1346	-1289	-1301	-1271
PG	-1378	-1444	-1669	-1647	-1622	-1586	-1503	-1515	-1512	-1532	-1507	-1482	-1449	-1413	-1353	-1328	-1368	-1322	-1346	-1289	-1301	-1271
PC	-1482	-1373	-1414	-1348	-1284	-1272	-1216	-1266	-1258	-1270	-1244	-1214	-1134	-1058	-1014	-1025	-1070	-1028	-1028	-906	-723	-884
IM	-1368	-1245	-1320	-1310	-1124	-1095	-1121	-1121	-1128	-1175	-1149	-1125	-1017	-957	-890	-1036	-974	-870	-861	-788	-937	-751
ZH	-1368	-1245	-1320	-1310	-1124	-1095	-1121	-1121	-1128	-1175	-1149	-1125	-1017	-957	-890	-1036	-974	-870	-861	-788	-937	-751
BE	-1151	-1435	-1601	-1592	-1577	-1500	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495
DE	-1151	-1435	-1601	-1592	-1577	-1500	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495	-1495
SA	-1643	-1476	-1544	-1576	-1530	-1516	-1494	-1481	-1479	-1480	-1459	-1426	-1405	-1379	-1331	-1351	-1337	-1322	-1318	-1267	-1282	-1252
PH	-904	-579	-860	-874	-867	-845	-804	-721	-699	-739	-718	-704	-501	-480	-342	-653	-534	-316	-417	-417	-434	-434
LI	-694	-697	-856	-864	-826	-766	-743	-723	-707	-723	-707	-522	-483	-483	-483	-483	-552	-483	-483	-483	-456	-456
NA	-1616	-1315	-1371	-1363	-1274	-1276	-1245	-1273	-1265	-1276	-1255	-1241	-1184	-1105	-1116	-1173	-1145	-1106	-1116	-1039	-1092	-1021
V	-824	-749	-766	-804	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625
ZI	-824	-749	-766	-804	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625	-625
CR	-222	-148	-694	-530	-38	-207	-83	-320	-343	-413	-399	-350	-155	-118	-375	-234	-234	-234	-234	-234	-234	-234
CO	-403	-384	-423	-423	-423	-423	-423	-423	-423	-423	-423	-423	-423	-423	-423	-423	-423	-423	-423	-423	-423	-423
GA	-1034	-876	-1012	-1015	-905	-827	-845	-852	-846	-857	-847	-938	-850	-804	-826	-905	-870	-819	-838	-760	-831	-746
K	-571	-354	-395	-395	-182	-146	-243	-314	-448	-536	-513	-507	-477	-238	-117	-479	-344	-89	-210	-210	-242	-242
FE	-222	-148	-694	-530	-38	-207	-83	-320	-343	-413	-399	-350	-155	-118	-375	-234	-234	-234	-234	-234	-234	-234
IA	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207
CO	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207
SI	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207	-207
GF	-490	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410
AI	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410	-410
MI	-809	-809	-809	-809	-809	-809	-809	-809	-809	-809	-809	-809	-809	-809	-809	-809	-809	-809	-809	-809	-809	-809
HO	-112	-112	-112	-112	-112	-112	-112	-112	-112	-112	-112	-112	-112	-112	-112	-112	-112	-112	-112	-112	-112	-112
U	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232	-232
PR	-767	-679	-756	-764	-653	-680	-650	-714	-707	-720	-713	-708	-651	-639	-608	-690	-655	-602	-623	-551	-623	-519
SE																						
CU																						
BL																						
AG																						
PO																						
A																						
RE																						
US																						
MG																						
AP																						

Table 30 (cont.)

	ZnCl ₂	TiCl ₄	ZrCl ₄	MnCl ₂	IrCl ₃	BeCl ₂	UCl ₄	TiCl ₃	TaCl ₅	UCl ₃	MgCl ₂	YCl ₃	NaCl ₃	CeCl ₃	LaCl ₃	PrCl ₃	GaCl ₂	LiCl	NaCl	SeCl ₂	RbCl	CsCl		
CE	-1219	-1417	-1093	-1035	-980	-914	-825	-916	-547	-561	-365	-281	-73			-30								
LA	-1233	-1729	-1071	-1024	-994	-934	-907	-930	-505	-589	-397	-311	-111	-38		-68								
PR	-1162	-1184	-1014	-997	-961	-874	-846	-890	-532	-527	-332	-251	-42											
RD	-1153	-1159	-981	-964	-940	-843	-811	-867	-494	-490	-293	-215												
LI	-1318	-1300	-1180	-1173	-1084	-1073	-1034	-1030	-702	-782	-625	-536	-389	-321	-286	-351	-76							
Y	-922	-1017	-793	-777	-686	-647	-607	-738	-272	-274	-60													
U																								
CA	-1266	-1281	-1111	-1096	-1035	-996	-974	-974	-713	-705	-586	-402	-308	-282	-208	-271								
HF	-756	-804	-545	-523	-657	-608	-573																	
IG	-877	-924	-690	-677	-731	-594	-513	-171	-199	-202														
SC	-612	-654	-600	-587	-695	-650	-613	-411	-89	-95														
TH	-753	-804	-520	-516	-631	-545	-374	-504																
ZR	-768	-794			-631		-508																	
BE	-942	-945	-137	-148	-434		-331																	
SR	-1224	-1221	-1101	-1088	-1034	-948	-979	-978	-783	-737	-596	-517	-384	-323	-291	-349	-102	-34	-17					
BA	-1233	-1230	-1119	-1107	-1030	-1023	-1006	-998	-744	-780	-689	-573	-452	-402	-385	-419	-260	-222	-192	-193				
IN																								
AL	-212	-242			-278		-309																	
TI																								
HA	-1024	-1043	-913	-903	-642	-828	-808	-845	-612	-607	-486	-425	-306	-256	-230	-274	-70		-12					
V																								
ZN																								
CR																								
CD																								
CA																								
K	-772	-795	-687	-681	-714	-631	-613	-678	-487	-480	-406	-308	-288	-255	-238	-269	-132	-95	-80	-70	-13			
FZ																								
TA																								
CO																								
SI																								
GR																								
IN																								
NI																								
KB	-697	-697	-582	-582	-637	-583	-528	-498	-415	-414	-383	-311	-238	-210	-195	-222	-101	-68	-56	-47				
B																								
SN																								
PB																								
PL																								
TL																								
CS																								
SB																								
CU																								
BI																								
AG																								
PD																								
W																								
RE																								
C5																								
AU																								
HG																								
RA																								

Table 31

GRAVIMETRIC ENTHALPIES OF REACTIONS OF METALS WITH CHLORIDES
(in descending order from top to bottom and left to right)

	BCL ₂	C ₂ Cl ₄	CCl ₄	C ₂ Cl ₆	MoCl ₆	AlCl ₃	BCL ₃	MoCl ₅	CrCl ₃	HfCl ₄	MnCl ₄	MoCl ₄	SbCl ₅	GeCl ₄	SiCl ₄	BCL ₄	ReCl ₅	WCl ₆	GeCl ₄	FeCl ₃	WCl ₅
Li	-2316	-2002	-1969	-1816	-1337	-1399	-1791	-1294	-1224	-1250	-1174	-1189	-1131	-1203	-1196	-1050	-1112	-1074	-1072	-1021	
Na	-1787	-1512	-1468	-1316	-1092	-1054	-1031	-1010	-976	-979	-952	-933	-927	-928	-916	-892	-892	-857	-854	-855	
Ca	-1816	-1532	-1481	-1314	-1092	-1054	-1031	-1010	-976	-979	-952	-933	-927	-928	-916	-892	-892	-857	-854	-855	
K	-1519	-1243	-1234	-1094	-977	-952	-921	-917	-872	-871	-856	-856	-851	-851	-851	-851	-851	-851	-851	-851	
SA	-1382	-1157	-1103	-1047	-882	-882	-876	-836	-811	-831	-795	-773	-773	-761	-761	-761	-761	-761	-761	-761	
Fe	-1750	-1415	-1350	-1293	-1132	-1132	-1132	-1094	-1069	-1069	-1069	-1069	-1069	-1069	-1069	-1069	-1069	-1069	-1069	-1069	
Zn	-1356	-1200	-1200	-1132	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	
Y	-1366	-1200	-1200	-1132	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	
DE	-1706	-1313	-1220	-1132	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	-982	
BA	-1116	-926	-934	-846	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	
LA	-1232	-992	-934	-846	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	
CE	-1268	-975	-921	-846	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	
PR	-1106	-903	-850	-771	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	
PA	-1167	-938	-884	-807	-757	-757	-757	-757	-757	-757	-757	-757	-757	-757	-757	-757	-757	-757	-757	-757	
ND	-1217	-954	-900	-823	-773	-773	-773	-773	-773	-773	-773	-773	-773	-773	-773	-773	-773	-773	-773	-773	
Zr	-1254	-988	-934	-857	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	
TI	-1254	-988	-934	-857	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	
TI	-1254	-988	-934	-857	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	-807	
RB	-973	-808	-784	-766	-682	-682	-682	-682	-682	-682	-682	-682	-682	-682	-682	-682	-682	-682	-682	-682	
AL	-1463	-1033	-992	-932	-823	-823	-823	-823	-823	-823	-823	-823	-823	-823	-823	-823	-823	-823	-823	-823	
IN	-1126	-925	-871	-791	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	
IN	-1126	-925	-871	-791	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	
TH	-1126	-925	-871	-791	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	
V	-1126	-925	-871	-791	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	-741	
CS	-730	-579	-554	-524	-484	-484	-484	-484	-484	-484	-484	-484	-484	-484	-484	-484	-484	-484	-484	-484	
CR	-1173	-830	-804	-774	-734	-734	-734	-734	-734	-734	-734	-734	-734	-734	-734	-734	-734	-734	-734	-734	
HF	-982	-835	-820	-776	-736	-736	-736	-736	-736	-736	-736	-736	-736	-736	-736	-736	-736	-736	-736	-736	
HF	-982	-835	-820	-776	-736	-736	-736	-736	-736	-736	-736	-736	-736	-736	-736	-736	-736	-736	-736	-736	
SI	-1107	-773	-757	-727	-687	-687	-687	-687	-687	-687	-687	-687	-687	-687	-687	-687	-687	-687	-687	-687	
CO	-851	-697	-681	-641	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	
U	-803	-651	-635	-595	-555	-555	-555	-555	-555	-555	-555	-555	-555	-555	-555	-555	-555	-555	-555	-555	
GA	-901	-749	-733	-693	-653	-653	-653	-653	-653	-653	-653	-653	-653	-653	-653	-653	-653	-653	-653	-653	
GE	-901	-749	-733	-693	-653	-653	-653	-653	-653	-653	-653	-653	-653	-653	-653	-653	-653	-653	-653	-653	
FZ	-894	-742	-726	-686	-646	-646	-646	-646	-646	-646	-646	-646	-646	-646	-646	-646	-646	-646	-646	-646	
IN	-868	-716	-700	-660	-620	-620	-620	-620	-620	-620	-620	-620	-620	-620	-620	-620	-620	-620	-620	-620	
IN	-868	-716	-700	-660	-620	-620	-620	-620	-620	-620	-620	-620	-620	-620	-620	-620	-620	-620	-620	-620	
CO	-851	-697	-681	-641	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	
NI	-851	-697	-681	-641	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	-601	
SM	-763	-607	-591	-551	-511	-511	-511	-511	-511	-511	-511	-511	-511	-511	-511	-511	-511	-511	-511	-511	
B	-703	-547	-531	-491	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	
ED	-703	-547	-531	-491	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	
ED	-703	-547	-531	-491	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	
HB	-703	-547	-531	-491	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	
HB	-703	-547	-531	-491	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	-451	
SB	-651	-495	-479	-439	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	
TA	-651	-495	-479	-439	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	
TA	-651	-495	-479	-439	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	-399	
BI	-545	-389	-373	-333	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	
FB	-545	-389	-373	-333	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	
FB	-545	-389	-373	-333	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	-293	
CU	-632	-476	-460	-420	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	
CU	-632	-476	-460	-420	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	
MO	-632	-476	-460	-420	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	
C	-632	-476	-460	-420	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	
TL	-632	-476	-460	-420	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	
TL	-632	-476	-460	-420	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	
W	-546	-390	-374	-334	-294	-294	-294	-294	-294	-294	-294	-294	-294	-294	-294	-294	-294	-294	-294	-294	
RE	-443	-287	-271	-231	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	
OS	-443	-287	-271	-231	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	
OS	-443	-287	-271	-231	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	-191	
A3	-333	-177	-161	-121	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	
A3	-333	-177	-161	-121	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	
H3	-333	-177	-161	-121	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	
AU	-333	-177	-161	-121	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	-81	

Table 31 (cont.)

	MnCl ₂	MnCl ₃	MnCl ₄	TiCl ₃	TiCl ₄	WCl ₄	SrCl ₄	AuCl ₃	MoCl ₂	MnCl ₂	GaCl ₃	VCl ₃	Al ₂ Cl ₆	CoCl ₂	AlCl ₃	SbCl ₃	OsCl ₃
Li	1022	81005	-985	-914	-908	-904	-903	-916	-837	-825	-884	-876	-916	-818	-823	-810	-781
Na	-816	-820	-794	-759	-758	-770	-755	-715	-716	-688	-704	-696	-766	-674	-635	-684	-683
Ca	-760	-762	-763	-743	-746	-741	-732	-705	-705	-674	-644	-630	-648	-660	-614	-671	-672
K	-778	-734	-748	-685	-682	-716	-696	-675	-670	-645	-645	-634	-641	-627	-583	-640	-645
Rb	-695	-636	-670	-648	-648	-648	-609	-617	-605	-560	-557	-534	-548	-552	-443	-571	-558
Br	-691	-607	-650	-629	-629	-629	-570	-593	-572	-508	-490	-470	-471	-490	-476	-524	-555
Cl	-537	-407	-446	-434	-434	-434	-412	-426	-407	-349	-329	-314	-316	-338	-306	-474	-514
SC	-498	-354	-387	-352	-352	-352	-326	-348	-327	-284	-284	-271	-215	-320	-117	-341	-486
Y	-393	-299	-319	-292	-292	-292	-254	-274	-252	-210	-210	-200	-158	-223	-105	-365	-420
BE	-368	-270	-282	-267	-267	-267	-228	-248	-227	-183	-183	-170	-128	-223	-105	-448	-476
BA	-359	-260	-272	-257	-257	-257	-218	-238	-217	-173	-173	-158	-116	-223	-105	-448	-476
LA	-361	-262	-274	-259	-259	-259	-220	-240	-219	-175	-175	-160	-118	-223	-105	-448	-476
CR	-370	-269	-281	-264	-264	-264	-225	-245	-224	-180	-180	-165	-123	-223	-105	-448	-476
PR	-361	-260	-272	-257	-257	-257	-218	-238	-217	-173	-173	-160	-118	-223	-105	-448	-476
HD	-346	-246	-258	-243	-243	-243	-204	-224	-203	-159	-159	-144	-102	-223	-105	-448	-476
ZR	-497	-348	-380	-267	-267	-267	-228	-248	-227	-183	-183	-170	-128	-223	-105	-448	-476
TI	-339	-242	-254	-239	-239	-239	-199	-219	-198	-154	-154	-140	-98	-223	-105	-448	-476
RI	-331	-234	-246	-231	-231	-231	-191	-211	-190	-146	-146	-132	-90	-223	-105	-448	-476
AL	-331	-234	-246	-231	-231	-231	-191	-211	-190	-146	-146	-132	-90	-223	-105	-448	-476
LI	-374	-294	-306	-289	-289	-289	-250	-270	-249	-205	-205	-190	-148	-223	-105	-448	-476
TH	-345	-265	-277	-262	-262	-262	-223	-243	-222	-178	-178	-163	-121	-223	-105	-448	-476
V	-347	-267	-279	-264	-264	-264	-225	-245	-224	-180	-180	-165	-123	-223	-105	-448	-476
CS	-408	-318	-330	-313	-313	-313	-274	-294	-273	-229	-229	-214	-172	-223	-105	-448	-476
CR	-374	-294	-306	-289	-289	-289	-250	-270	-249	-205	-205	-190	-148	-223	-105	-448	-476
HZ	-340	-260	-272	-257	-257	-257	-218	-238	-217	-173	-173	-160	-118	-223	-105	-448	-476
HT	-340	-260	-272	-257	-257	-257	-218	-238	-217	-173	-173	-160	-118	-223	-105	-448	-476
ZN	-378	-298	-310	-293	-293	-293	-254	-274	-253	-209	-209	-194	-152	-223	-105	-448	-476
SI	-322	-242	-254	-239	-239	-239	-199	-219	-198	-154	-154	-140	-98	-223	-105	-448	-476
U	-336	-257	-269	-252	-252	-252	-213	-233	-212	-168	-168	-153	-111	-223	-105	-448	-476
GA	-322	-242	-254	-239	-239	-239	-199	-219	-198	-154	-154	-140	-98	-223	-105	-448	-476
GY	-324	-244	-256	-241	-241	-241	-201	-221	-200	-156	-156	-141	-99	-223	-105	-448	-476
FE	-300	-220	-232	-217	-217	-217	-177	-197	-176	-132	-132	-117	-75	-223	-105	-448	-476
IN	-198	-84	-172	-157	-157	-157	-117	-137	-116	-72	-72	-57	-15	-223	-105	-448	-476
CO	-177	-84	-172	-157	-157	-157	-117	-137	-116	-72	-72	-57	-15	-223	-105	-448	-476
CD	-177	-84	-172	-157	-157	-157	-117	-137	-116	-72	-72	-57	-15	-223	-105	-448	-476
NI	-166	-81	-174	-159	-159	-159	-119	-139	-118	-74	-74	-59	-17	-223	-105	-448	-476
SH	-158	-81	-175	-160	-160	-160	-120	-140	-119	-75	-75	-60	-18	-223	-105	-448	-476
B	-168	-81	-175	-160	-160	-160	-120	-140	-119	-75	-75	-60	-18	-223	-105	-448	-476
CD	-300	-220	-232	-217	-217	-217	-177	-197	-176	-132	-132	-117	-75	-223	-105	-448	-476
RB	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15	-15
SB	-131	-40	-129	-114	-114	-114	-74	-94	-73	-29	-29	-14	-62	-121	-108	-202	-186
TA	-131	-40	-129	-114	-114	-114	-74	-94	-73	-29	-29	-14	-62	-121	-108	-202	-186
BI	-49	-85	-111	-86	-86	-86	-46	-66	-45	-1	-1	-8	-36	-85	-89	-177	-169
PI	-124	-39	-107	-82	-82	-82	-42	-62	-41	-1	-1	-8	-36	-85	-89	-177	-169
CU	-352	-107	-244	-150	-150	-150	-110	-130	-109	-65	-65	-50	-8	-108	-108	-202	-186
CU	-352	-107	-244	-150	-150	-150	-110	-130	-109	-65	-65	-50	-8	-108	-108	-202	-186
IO	-100	-47	-129	-94	-94	-94	-54	-74	-53	-9	-9	-4	-62	-121	-108	-202	-186
TL	-100	-47	-129	-94	-94	-94	-54	-74	-53	-9	-9	-4	-62	-121	-108	-202	-186
M	-100	-47	-129	-94	-94	-94	-54	-74	-53	-9	-9	-4	-62	-121	-108	-202	-186
RE	-100	-47	-129	-94	-94	-94	-54	-74	-53	-9	-9	-4	-62	-121	-108	-202	-186
OS	-100	-47	-129	-94	-94	-94	-54	-74	-53	-9	-9	-4	-62	-121	-108	-202	-186
AG	-100	-47	-129	-94	-94	-94	-54	-74	-53	-9	-9	-4	-62	-121	-108	-202	-186
HG	-100	-47	-129	-94	-94	-94	-54	-74	-53	-9	-9	-4	-62	-121	-108	-202	-186
AU	-100	-47	-129	-94	-94	-94	-54	-74	-53	-9	-9	-4	-62	-121	-108	-202	-186

Table 31 (cont.)

	FeCl ₃	FeCl ₂	FeCl ₁	CaCl ₂	CaCl ₁	TaCl ₄	CrCl ₂	BeCl ₂	TiCl ₃	IMCl ₃	TiCl ₃	OsCl ₂	WCl ₂	CuCl	BiCl ₃	GeCl ₂	UCl ₆	VCl ₂ ZnCl ₂	TiCl ₂ ZrCl ₄	
LI	-769	-790	-730	-740	-715	715	-737	-779	-731	-690	-630	-594	-585	-618	-602	-669	-637	-643	-639	-616
HA	-671	-644	-632	-620	-616	600	-603	-599	-590	-575	-555	-535	-526	-541	-530	-527	-534	-527	-532	-501
CA	-600	-540	-519	-506	-497	495	-488	-468	-459	-444	-424	-414	-415	-427	-417	-404	-421	-406	-415	-478
R	-577	-518	-493	-480	-471	468	-461	-441	-432	-417	-397	-387	-388	-401	-391	-378	-395	-380	-388	-479
SR	-501	-475	-443	-430	-421	416	-404	-384	-375	-360	-340	-330	-331	-344	-334	-321	-338	-323	-330	-404
ICZ	-461	-419	-387	-374	-365	360	-353	-333	-324	-309	-289	-279	-280	-293	-283	-270	-287	-272	-279	-272
SC	-409	-367	-335	-322	-313	308	-301	-281	-272	-257	-237	-227	-228	-241	-231	-218	-235	-220	-227	-210
Y	-349	-307	-275	-262	-253	250	-243	-223	-214	-199	-179	-169	-170	-183	-173	-160	-177	-162	-169	-236
BE	-299	-257	-225	-212	-203	200	-193	-173	-164	-149	-129	-119	-120	-133	-123	-110	-127	-112	-119	-58
RA	-259	-217	-185	-172	-163	160	-153	-133	-124	-109	-89	-79	-80	-93	-83	-70	-87	-72	-79	-354
LA	-219	-177	-145	-132	-123	120	-113	-93	-84	-69	-49	-39	-40	-53	-43	-30	-47	-32	-39	-290
CE	-179	-137	-105	-92	-83	80	-73	-53	-44	-29	-9	1	2	-13	-3	10	-3	4	11	-278
PA	-139	-97	-65	-52	-43	40	-33	-13	-4	11	21	22	23	-7	3	18	11	25	34	-270
HD	-99	-57	-25	-12	-3	0	1	1	1	1	1	1	1	1	1	1	1	1	1	-254
ZR	-69	-27	5	12	21	20	21	22	23	24	25	26	27	28	29	30	31	32	33	-147
TI	-39	1	29	36	45	44	45	46	47	48	49	50	51	52	53	54	55	56	57	-315
RD	-1	39	67	74	83	82	83	84	85	86	87	88	89	90	91	92	93	94	95	-73
AL	39	77	105	112	121	120	121	122	123	124	125	126	127	128	129	130	131	132	133	-7
EN	79	117	145	152	161	160	161	162	163	164	165	166	167	168	169	170	171	172	173	-118
TH	119	157	185	192	201	200	201	202	203	204	205	206	207	208	209	210	211	212	213	-240
Y	159	197	225	232	241	240	241	242	243	244	245	246	247	248	249	250	251	252	253	-267
CR	199	237	265	272	281	280	281	282	283	284	285	286	287	288	289	290	291	292	293	-101
CK	239	277	305	312	321	320	321	322	323	324	325	326	327	328	329	330	331	332	333	-144
EP	279	317	345	352	361	360	361	362	363	364	365	366	367	368	369	370	371	372	373	-170
ZN	319	357	385	392	401	400	401	402	403	404	405	406	407	408	409	410	411	412	413	-212
SI	359	397	425	432	441	440	441	442	443	444	445	446	447	448	449	450	451	452	453	-240
U	399	437	465	472	481	480	481	482	483	484	485	486	487	488	489	490	491	492	493	-267
GA	439	477	505	512	521	520	521	522	523	524	525	526	527	528	529	530	531	532	533	-300
CE	479	517	545	552	561	560	561	562	563	564	565	566	567	568	569	570	571	572	573	-333
FS	519	557	585	592	601	600	601	602	603	604	605	606	607	608	609	610	611	612	613	-366
PH	559	597	625	632	641	640	641	642	643	644	645	646	647	648	649	650	651	652	653	-399
CO	599	637	665	672	681	680	681	682	683	684	685	686	687	688	689	690	691	692	693	-432
NI	639	677	705	712	721	720	721	722	723	724	725	726	727	728	729	730	731	732	733	-465
SH	679	717	745	752	761	760	761	762	763	764	765	766	767	768	769	770	771	772	773	-498
B	719	757	785	792	801	800	801	802	803	804	805	806	807	808	809	810	811	812	813	-531
CD	759	797	825	832	841	840	841	842	843	844	845	846	847	848	849	850	851	852	853	-564
H5	799	837	865	872	881	880	881	882	883	884	885	886	887	888	889	890	891	892	893	-597
SO	839	877	905	912	921	920	921	922	923	924	925	926	927	928	929	930	931	932	933	-630
TA	879	917	945	952	961	960	961	962	963	964	965	966	967	968	969	970	971	972	973	-663
BI	919	957	985	992	1001	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	-696
PI	959	997	1025	1032	1041	1040	1041	1042	1043	1044	1045	1046	1047	1048	1049	1050	1051	1052	1053	-729
CB	999	1037	1065	1072	1081	1080	1081	1082	1083	1084	1085	1086	1087	1088	1089	1090	1091	1092	1093	-762
CU	1039	1077	1105	1112	1121	1120	1121	1122	1123	1124	1125	1126	1127	1128	1129	1130	1131	1132	1133	-795
PL	1079	1117	1145	1152	1161	1160	1161	1162	1163	1164	1165	1166	1167	1168	1169	1170	1171	1172	1173	-828
C	1119	1157	1185	1192	1201	1200	1201	1202	1203	1204	1205	1206	1207	1208	1209	1210	1211	1212	1213	-861
TL	1159	1197	1225	1232	1241	1240	1241	1242	1243	1244	1245	1246	1247	1248	1249	1250	1251	1252	1253	-894
M	1199	1237	1265	1272	1281	1280	1281	1282	1283	1284	1285	1286	1287	1288	1289	1290	1291	1292	1293	-927
RE	1239	1277	1305	1312	1321	1320	1321	1322	1323	1324	1325	1326	1327	1328	1329	1330	1331	1332	1333	-960
OS	1279	1317	1345	1352	1361	1360	1361	1362	1363	1364	1365	1366	1367	1368	1369	1370	1371	1372	1373	-993
AG	1319	1357	1385	1392	1401	1400	1401	1402	1403	1404	1405	1406	1407	1408	1409	1410	1411	1412	1413	-1026
AS	1359	1397	1425	1432	1441	1440	1441	1442	1443	1444	1445	1446	1447	1448	1449	1450	1451	1452	1453	-1059
BS	1399	1437	1465	1472	1481	1480	1481	1482	1483	1484	1485	1486	1487	1488	1489	1490	1491	1492	1493	-1092
AU	1439	1477	1505	1512	1521	1520	1521	1522	1523	1524	1525	1526	1527	1528	1529	1530	1531	1532	1533	-1125

Table 31 (cont.)

	TaCl ₅	SrCl ₂	InCl ₂	MnCl ₂	MgCl ₂	CaCl ₂	UCl ₂	BaCl ₂	AsCl ₃	TaCl ₂	AuCl	PbCl ₂	SnCl ₃	HfCl ₄	ZrCl ₃	MgCl ₂	InCl	UCl ₄	Hg ₂ Cl ₂
Li	-577	-249	-588	-573	5880	-491	-519	-423	-448	-415	-572	-375	-419	-390	-384	-384	-310	-342	-271
Na	-508	-879	-873	-877	4845	-445	-481	-431	-403	-374	-351	-341	-335	-324	-325	-304	-316	-302	-256
Ca	-440	-643	-657	-656	4855	-435	-484	-412	-409	-359	-342	-327	-303	-298	-298	-270	-296	-274	-247
K	-288	-463	-460	-454	4447	-436	-441	-423	-405	-375	-352	-343	-341	-326	-331	-316	-315	-304	-243
Sr	-344	-612	-460	-387	4421	-348	-347	-367	-366	-332	-327	-306	-269	-284	-270	-243	-280	-260	-240
Rb	-345	-225	-317	-253	3785	-324	-340	-254	-297	-247	-278	-223	-49	-140	-94	-129	-198	-151	-147
Sc	-918	-209	-280	-268	3268	-305	-324	-215	-273	-220	-263	-199	-56	-103	-52	-176	-187	-124	-175
Y	-316	-203	-284	-222	3266	-300	-351	-229	-274	-224	-266	-209	-56	-132	-93	-20	-107	-122	-122
Be	-337	-104	-134	-51	3133	-237	-152	-99	-268	-204	-242	-126	244	-269	-246	-224	-266	-244	-233
La	-291	-373	-367	-343	3199	-306	-351	-331	-362	-304	-313	-268	244	-269	-246	-224	-266	-244	-233
Ba	-326	-320	-314	-274	3178	-331	-328	-333	-333	-263	-284	-242	147	-150	-165	-118	-220	-177	-149
Ce	-330	-317	-310	-265	3174	-324	-324	-268	-266	-250	-280	-235	135	-151	-154	-106	-214	-169	-194
Pr	-333	-317	-304	-265	3170	-314	-324	-261	-261	-251	-277	-231	126	-174	-147	-97	-210	-162	-191
Nd	-332	-310	-293	-244	3165	-311	-323	-246	-246	-242	-272	-223	113	-163	-135	-84	-203	-153	-146
Zr	-295	-218	-210	-210	3231	-251	-154	-156	-223	-174	-231	-150	142	-66	-66	-71	-71	-142	-97
Ti	-155	-127	-110	-308	3293	-184	-318	-32	-222	-159	-187	-36	215	-236	-221	-196	-247	-223	-221
Al	-162	-338	-333	-308	3279	-142	-298	-32	-260	-164	-297	-267	144	-68	-68	-68	-68	-68	-96
Mg	-154	-331	-117	-308	3303	-142	-298	-32	-260	-164	-297	-267	144	-68	-68	-68	-68	-68	-96
Th	-192	-184	-112	-112	3290	-184	-104	-47	-221	-203	-150	-143	24	-24	-15	-124	-55	-134	-85
V	-199	-279	-260	-230	3266	-164	-104	-18	-239	-180	-176	-260	163	-166	-171	-148	-208	-174	-194
Cr	-73	-160	-154	-97	3252	-217	-143	-123	-265	-195	-148	-139	210	-116	-20	-116	-52	-125	-67
Mn	-86	-61	-50	-50	3255	-131	-23	-23	-217	-109	-45	-39	154	-28	-28	-28	-28	-28	-27
Fe	-180	-167	-160	-230	3265	-202	-202	-236	-252	-202	-200	-128	115	-115	-11	-115	-115	-124	-39
Co	-224	-167	-160	-230	3234	-89	-194	-64	-194	-64	-136	-136	144	-45	-45	-45	-45	-45	-48
Ni	-224	-167	-160	-230	3226	-101	-188	-60	-188	-60	-126	-126	144	-45	-45	-45	-45	-45	-48
Cu	-224	-167	-160	-230	3226	-87	-189	-45	-189	-45	-116	-116	144	-45	-45	-45	-45	-45	-48
Zn	-224	-167	-160	-230	3218	-86	-181	-49	-181	-49	-112	-112	144	-45	-45	-45	-45	-45	-48
As	-224	-167	-160	-230	3205	-73	-172	-55	-172	-55	-105	-105	144	-45	-45	-45	-45	-45	-48
Se	-224	-167	-160	-230	3218	-41	-177	-20	-177	-20	-105	-105	144	-45	-45	-45	-45	-45	-48
Br	-224	-167	-160	-230	3228	-46	-170	-20	-170	-20	-105	-105	144	-45	-45	-45	-45	-45	-48
Kr	-224	-167	-160	-230	3164	-60	-128	-21	-128	-21	-80	-80	144	-45	-45	-45	-45	-45	-48
Rb	-224	-167	-160	-230	3178	-60	-128	-21	-128	-21	-80	-80	144	-45	-45	-45	-45	-45	-48
Sr	-224	-167	-160	-230	3193	-60	-128	-21	-128	-21	-80	-80	144	-45	-45	-45	-45	-45	-48
Ta	-224	-167	-160	-230	3169	-60	-128	-21	-128	-21	-80	-80	144	-45	-45	-45	-45	-45	-48
Bi	-224	-167	-160	-230	3182	-60	-128	-21	-128	-21	-80	-80	144	-45	-45	-45	-45	-45	-48
Pb	-224	-167	-160	-230	3170	-60	-128	-21	-128	-21	-80	-80	144	-45	-45	-45	-45	-45	-48
Cu	-224	-167	-160	-230	3151	-60	-128	-21	-128	-21	-80	-80	144	-45	-45	-45	-45	-45	-48
Nd	-224	-167	-160	-230	3114	-60	-128	-21	-128	-21	-80	-80	144	-45	-45	-45	-45	-45	-48
C	-224	-167	-160	-230	3154	-60	-128	-21	-128	-21	-80	-80	144	-45	-45	-45	-45	-45	-48
W	-224	-167	-160	-230	3132	-60	-128	-21	-128	-21	-80	-80	144	-45	-45	-45	-45	-45	-48
Re	-224	-167	-160	-230	3121	-60	-128	-21	-128	-21	-80	-80	144	-45	-45	-45	-45	-45	-48
Os	-224	-167	-160	-230	3123	-60	-128	-21	-128	-21	-80	-80	144	-45	-45	-45	-45	-45	-48
As	-224	-167	-160	-230	3143	-60	-128	-21	-128	-21	-80	-80	144	-45	-45	-45	-45	-45	-48
Hg	-224	-167	-160	-230	3143	-60	-128	-21	-128	-21	-80	-80	144	-45	-45	-45	-45	-45	-48
Au	-224	-167	-160	-230	3143	-60	-128	-21	-128	-21	-80	-80	144	-45	-45	-45	-45	-45	-48

Table 31 (cont.)

	Ag ₂ Cl	ZrCl ₂	HfCl ₃	YCl ₃	TbCl ₄	DCl ₃	TiCl ₄	HfCl ₂	MgCl ₃	PrCl ₃	CeCl ₃	LaCl ₃	CaCl ₂	LaCl	NaCl	SrCl ₂	BaCl ₂	RbCl	CsCl
LI	-258	-286	271	-281	-263	-217	-197	-191	-142	-131	-122	-110	-43	-8					
NA	-245	-247	239	-226	-231	-197	-187	-174	-126	-116	-109	-98	-41						
A	-236	-222	217	-196	-209	-177	-177	-153	-98	-88	-80	-70							
K	-230	-233	254	-248	-248	-215	-197	-193	-158	-150	-143	-134	-96	-79	-60	-43	-9	-7	-3
SR	-230	-212	208	-190	-202	-176	-176	-157	-111	-103	-97	-88	-40	-15	-7				
HG	-173	-85	62	-51	-51	34	-109	-30											
SC	-160	-11	-32	-21	-21	-20	-96	-7											
Y	-168	-52	66	-56	-56	-50	-108	-37											
BE	-118	-202	200	-183	-194	-173	-174	-156	-118	-111	-110	-105	-82	-73	-65	-55			
BA	-224	-120	126	-88	-178	-104	-155	-83	-23	-15	-8								
LA	-191	-111	118	-76	-110	-97	-131	-93	-15	-6									
CE	-184	-104	112	-68	-104	-92	-128	-73	-8										
PR	-179	-94	113	-57	-95	-84	-123	-70											
ND	-140	-94	117			-82													
ZR	-94	-182	182	-103	-176	-159	-165	-144	-107	-101	-96		-56	-40	-32	-23	+		
TI	-94																		
RE	-215																		
AL	-94																		
IN	-95																		
LN	-130																		
TH	-63																		
V	-159	-144	147	-147	-142	-131	-146	-120	-86	-81	-77	-72	-45	-33	-27	-21	33	32	
CS	-59																		
CR	-125																		
HP	-66																		
ZN	-28																		
SI	-121																		
U																			
GA	-37																		
GE	-49																		
FE	-41																		
IN	-29																		
CO	-20																		
NI	-25																		
SR	-9																		
B	-50																		
CD																			
NB																			
SB																			
TA																			
BI																			
PB																			
CU																			
MO																			
C																			
TL																			
W																			
RE																			
OS																			
AG																			
HG																			
AU																			

J. Chromate Reactions

The reactions between 49 metals and 5 chromates were programmed on the computer. A total of 2920 possible reactions was examined, and 114 of these were printed. As mentioned previously, when two reactants undergo more than one reaction, only the most energetic one is printed. The reactions with positive enthalpies are also discarded. The chromates are the least energetic of the oxide systems examined. The most energetic reaction exhibits an enthalpy of only -3845 cal/cc.

Representative computer data for a few of the chromate reactions are illustrated in Table 32. The relatively low energies of these reactions are due primarily to the high heat of formation of the chromates. The high heats of formation of the product oxides partially compensate for this.

The periodic variation of the enthalpies of the reactions of the metals with lead chromate is shown in Figure 24. The trends are the same as those observed in the other oxide systems. The Group II metals (beryllium, magnesium, and calcium), the Group IVB metals (titanium, zirconium, and hafnium) and the rare earths (lanthanum, cerium, praseodymium, neodymium, samarium, gadolinium, terbium, holmium, erbium, thorium, uranium, and neptunium) are effective reducing agents. With the exception of Group IVB, which is anomalous because of the lanthanide contraction, the energies within a group tend to decrease with increasing atomic number. This is apparent in Group IA (lithium, rubidium, and cesium), Group IIA (beryllium, magnesium, strontium, and barium), Group VB (vanadium, niobium, and tantalum), and Group VIB (chromium, molybdenum, and tungsten). Except for displacement of the vertical scale, the other chromates exhibit similar trends.

The most energetic chromate reactions are listed in Tables 33 and 34. A summary of the enthalpies of all the chromate reactions is presented in Tables 35 and 36. The trends described previously are evident in Tables 35 and 36. Lead and silver chromate are the most effective oxidizers on a volumetric basis, and sodium and lead chromate are the most effective on a gravimetric basis.

Table 32

DATA ON REACTIONS OF VARIOUS METALS WITH CHROMATES

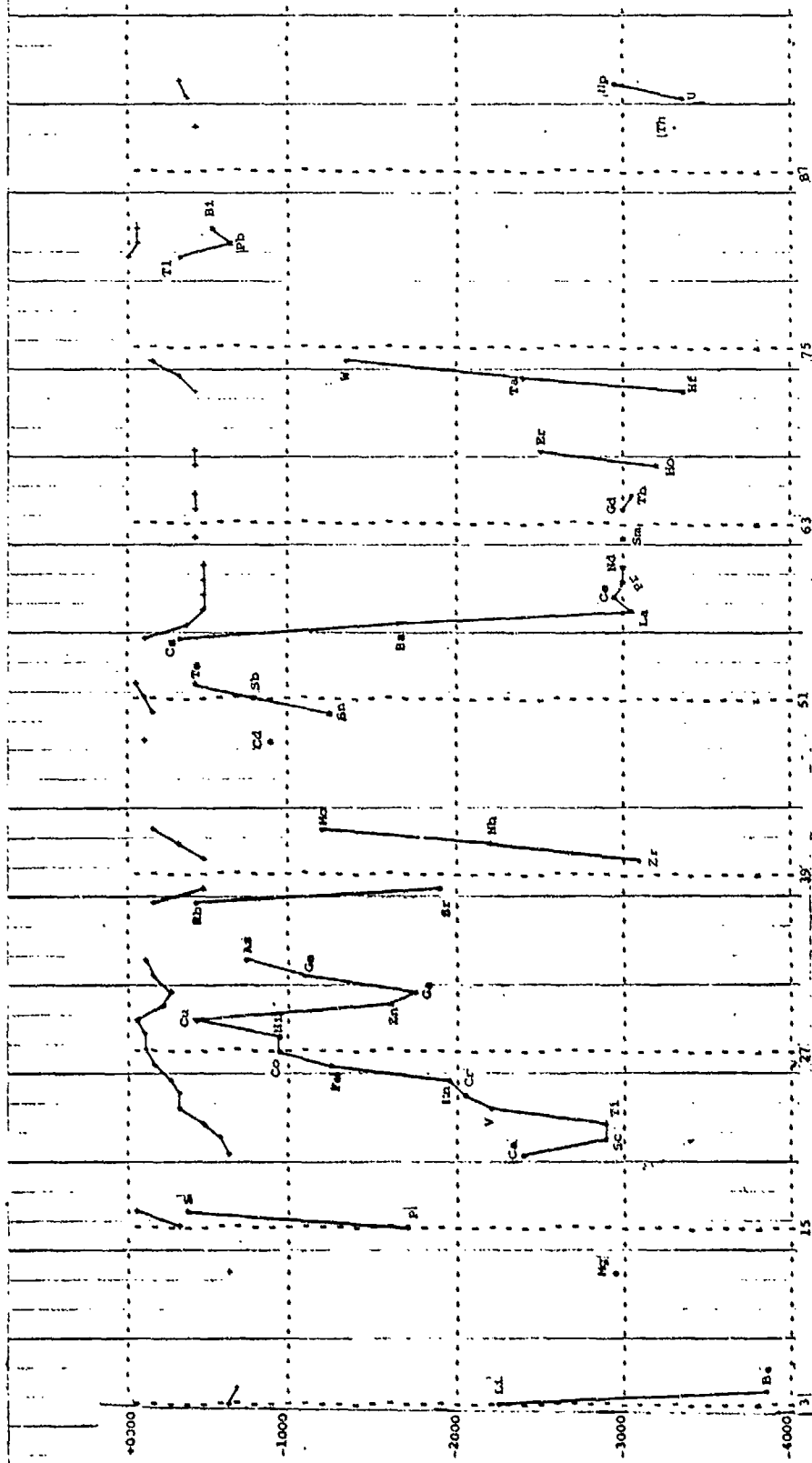
	3 Ge	+ 4 Ag ₂ CrO ₄	= 4 Ag ₂ O	+ 3 GeO ₂	+ 2 Cr ₂ O ₃
Heat of formation		-170.15	-7.31	-128.30	-269.70
Molecular weight	72.60	331.70	231.76	104.60	152.02
Density	5.35	5.63	7.14	4.70	5.21
Melting point, °C	960.00		300.00	1000.00	2265.00
Boiling point, °C	2700.00				
Heat of reaction, kcal	-272.92				
Reactants' density	5.58				
Gravimetric enthalpy, cal/g	-176.66				
Volumetric enthalpy, cal/cc	-986.58				
	3 Hf	+ 4 Ag ₂ CrO ₄	= 4 Ag ₂ O	+ 3 HfO ₂	+ 2 Cr ₂ O ₃
Heat of formation		-170.15	-7.31	-271.50	-269.70
Molecular weight	178.50	331.77	231.76	210.60	152.02
Density	13.30	5.63	7.14	9.68	5.21
Melting point, °C	2227.00		300.00	2810.00	2265.00
Boiling point, °C	3200.00				
Heat of reaction, kcal	-702.52				
Reactants' density	6.74				
Gravimetric enthalpy, cal/g	-377.18				
Volumetric enthalpy, cal/cc	-2543.64				
	2 Ho	+ 2 Ag ₂ CrO ₄	= 2 Ag ₂ O	+ Ho ₂ O ₃	+ Cr ₂ O ₃
Heat of formation		-170.15	-7.31	-449.60	-269.70
Molecular weight	164.94	331.77	231.76	377.88	152.02
Density	8.76	5.63	7.14		5.21
Melting point, °C			300.00		2265.00
Boiling point, °C					
Heat of reaction, kcal	-393.61				
Reactants' density	6.38				
Gravimetric enthalpy, cal/g	-396.22				
Volumetric enthalpy, cal/cc	-2529.31				

Table 32 (cont.)

	2 La	+ 2 Ag ₂ CrO ₄	= 2 Ag ₂ O	+ La ₂ O ₃	+ Cr ₂ O ₃
Heat of formation		-170.15	-7.31	-458.00	-269.70
Molecular weight		331.77	231.76	325.84	152.02
Density		5.63	7.14	5.51	5.21
Melting point, °C	138.92		300.00	2315.00	2265.00
Boiling point, °C	6.15			4200.00	
Heat of reaction, kcal	880.00				
Reactants' density	1800.00				
Gravimetric enthalpy, cal/g	-402.01				
Volumetric enthalpy, cal/cc	5.77				
	-427.95				
	-2464.22				
	6 Li	+ 2 Ag ₂ CrO ₄	= 2 Ag ₂ O	+ 3 Li ₂ O	+ Cr ₂ O ₃
Heat of formation		-170.15	-7.31	-142.40	-269.70
Molecular weight		331.77	231.76	29.88	152.02
Density		5.63	7.14	2.01	5.21
Melting point, °C	6.94		300.00	1700.00	2265.00
Boiling point, °C	.53				
Heat of reaction, kcal	180.00				
Reactants' density	1326.00				
Gravimetric enthalpy, cal/g	-371.21				
Volumetric enthalpy, cal/cc	3.60				
	-526.41				
	-1894.52				
	3 Mg	+ 2 Ag ₂ CrO ₄	= 2 Ag ₂ O	+ 3 MgO	+ Cr ₂ O ₃
Heat of formation		-170.15	-7.31	-143.84	-269.70
Molecular weight		331.77	231.76	40.32	152.02
Density		5.63	7.14	3.58	5.21
Melting point, °C	24.32		300.00	2800.00	2265.00
Boiling point, °C	1.74				
Heat of reaction, kcal	650.00				
Reactants' density	1120.00				
Gravimetric enthalpy, cal/g	-375.53				
Volumetric enthalpy, cal/cc	4.61				
	-509.89				
	-2348.64				

Table 32 (cont.)

	8 La	+ 6 PbCrO ₄	= 3 Pb ₂ O	+ 4 La ₂ O ₃	+ 3 Cr ₂ O ₃
Heat of formation		-217.70	-51.20	-458.00	-269.70
Molecular weight	138.92	323.22	430.42	325.84	152.02
Density	6.15	6.30	8.34	6.51	5.21
Melting point, °C	880.00	844.00		2315.00	2265.00
Boiling point, °C	1800.00			4200.00	
Heat of reaction, kcal	-1488.50				
Reactants' density	6.24				
Gravimetric enthalpy, cal/g	-487.92				
Volumetric enthalpy, cal/cc	-3046.85				
	8 Li	+ 2 PbCrO ₄	= Pb ₂ O	+ 4 Li ₂ O	+ Cr ₂ O ₃
Heat of formation		-217.70	-51.20	-142.40	-269.70
Molecular weight	6.94	323.22	430.42	29.88	152.02
Density	.53	6.30	8.34	2.01	5.21
Melting point, °C	180.00	844.00		1700.00	2265.00
Boiling point, °C	1326.00				
Heat of reaction, kcal	-455.10				
Reactants' density	3.40				
Gravimetric enthalpy, cal/g	-648.33				
Volumetric enthalpy, cal/cc	-2203.03				
	4 Mg	+ 2 PbCrO ₄	= Pb ₂ O	+ 4 MgO	+ Cr ₂ O ₃
Heat of formation		-217.70	-51.20	-143.84	-269.70
Molecular weight	24.32	323.22	430.42	40.32	152.02
Density	1.74	6.30	8.34	3.58	5.21
Melting point, °C	650.00	844.00		2800.00	2265.00
Boiling point, °C	1120.00				
Heat of reaction, kcal	-460.86				
Reactants' density	4.69				
Gravimetric enthalpy, cal/g	-619.67				
Volumetric enthalpy, cal/cc	-2907.31				



Enthalpy, (+ve) kcal/cc, (+ve) kcal/g

Atomic Number of Metal Reactants

Figure 24

GRAVIMETRIC AND VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS WITH PbCrO_3

Table 33

MOST ENERGETIC CHROMATE AND DICHROMATE REACTIONS WITH METALS,
IN TERMS OF VOLUMETRIC ENTHALPY

Reaction					Enthalpy, cal/cc
4 Be +	2 Pb(CrO ₄)	=	Pb ₂ O + 4 BeO +	Cr ₂ O ₃	-3845
2 U +	2 Pb(CrO ₄)	=	Pb ₂ O + 2 UO ₂ +	Cr ₂ O ₃	-3322
2 Hf +	2 Pb(CrO ₄)	=	Pb ₂ O + 2 HfO ₂ +	Cr ₂ O ₃	-3310
2 Th +	2 Pb(CrO ₄)	=	Pb ₂ O + 2 ThO ₂ +	Cr ₂ O ₃	-3259
8 Ho +	6 Pb(CrO ₄)	=	3 Pb ₂ O + 4 Ho ₂ O ₃ +	4 Ho ₂ O ₃	-3173
2 Zr +	2 Pb(CrO ₄)	=	Pb ₂ O + 2 ZrO ₂ +	Cr ₂ O ₃	-3065
8 Tb +	6 Pb(CrO ₄)	=	3 Pb ₂ O + 4 Tb ₂ O ₃ +	3 Cr ₂ O ₃	-3048
8 La +	6 Pb(CrO ₄)	=	3 Pb ₂ O + 4 La ₂ O ₃ +	3 Cr ₂ O ₃	-3046
8 Sm +	6 Pb(CrO ₄)	=	3 Pb ₂ O + 4 Sm ₂ O ₃ +	3 Cr ₂ O ₃	-2999
8 Nd +	6 Pb(CrO ₄)	=	3 Pb ₂ O + 4 Nd ₂ O ₃ +	3 Cr ₂ O ₃	-2998
8 Gd +	6 Pb(CrO ₄)	=	3 Pb ₂ O + 4 Gd ₂ O ₃ +	3 Cr ₂ O ₃	-2986
8 Pr +	6 Pb(CrO ₄)	=	3 Pb ₂ O + 4 Pr ₂ O ₃ +	3 Cr ₂ O ₃	-2980
8 Ce +	6 Pb(CrO ₄)	=	3 Pb ₂ O + 4 Ce ₂ O ₃ +	3 Cr ₂ O ₃	-2939
2 Np +	2 Pb(CrO ₄)	=	Pb ₂ O + 2 NpO ₂ +	Cr ₂ O ₃	-2914
4 Mg +	2 Pb(CrO ₄)	=	Pb ₂ O + 4 MgO +	Cr ₂ O ₃	-2907
3 Be +	2 Ag ₂ (CrO ₄)	=	2 Ag ₂ O + 3 BeO +	Cr ₂ O ₃	-2881
8 Sc +	6 Pb(CrO ₄)	=	3 Pb ₂ O + 4 Sc ₂ O ₃ +	3 Cr ₂ O ₃	-2879
8 Ti +	6 Pb(CrO ₄)	=	3 Pb ₂ O + 4 Ti ₂ O ₃ +	3 Cr ₂ O ₃	-2861
3 Th +	4 Ag ₂ (CrO ₄)	=	4 Ag ₂ O + 3 ThO ₂ +	2 Cr ₂ O ₃	-2563
3 U +	4 Ag ₂ (CrO ₄)	=	4 Ag ₂ O + 3 UO ₂ +	2 Cr ₂ O ₃	-2546
3 Hf +	4 Ag ₂ (CrO ₄)	=	4 Ag ₂ O + 3 HfO ₂ +	2 Cr ₂ O ₃	-2543
2 Ho +	2 Ag ₂ (CrO ₄)	=	2 Ag ₂ O + Ho ₂ O ₃ +	Cr ₂ O ₃	-2529
8 Er +	6 Pb(CrO ₄)	=	3 Pb ₂ O + 4 Er ₂ O ₃ +	3 Cr ₂ O ₃	-2499
2 La +	2 Ag ₂ (CrO ₄)	=	2 Ag ₂ O + La ₂ O ₃ +	Cr ₂ O ₃	-2464
2 Tb +	2 Ag ₂ (CrO ₄)	=	2 Ag ₂ O + Tb ₂ O ₃ +	Cr ₂ O ₃	-2439
2 Nd +	2 Ag ₂ (CrO ₄)	=	2 Ag ₂ O + Nd ₂ O ₃ +	Cr ₂ O ₃	-2415
2 Pr +	2 Ag ₂ (CrO ₄)	=	2 Ag ₂ O + Pr ₂ O ₃ +	Cr ₂ O ₃	-2408
2 Sm +	2 Ag ₂ (CrO ₄)	=	2 Ag ₂ O + Sm ₂ O ₃ +	Cr ₂ O ₃	-2406
2 Gd +	2 Ag ₂ (CrO ₄)	=	2 Ag ₂ O + Gd ₂ O ₃ +	Cr ₂ O ₃	-2398

Table 33 (cont.)

Reaction		Enthalpy, cal/cc
4 Ca + 2 Pb(CrO ₄)	= Pb ₂ O + 4 CaO + Cr ₂ O ₃	-2393
3 Zr + 4 Ag ₂ (CrO ₄)	= 4 Ag ₂ O + 3 ZrO ₂ + 2 Cr ₂ O ₃	-2377
8 Ta + 10 Pb(CrO ₄)	= 5 Pb ₂ O + 4 Ta ₂ O ₅ + 5 Cr ₂ O ₃	-2377
2 Ce + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + Ce ₂ O ₃ + Cr ₂ O ₃	-2371
3 Mg + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 MgO + Cr ₂ O ₃	-2348
2 Sc + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + Sc ₂ O ₃ + Cr ₂ O ₃	-2306
3 Be + 2 Ba(CrO ₄)	= 2 BaO + 3 BeO + Cr ₂ O ₃	-2293
3 Np + 4 Ag ₂ (CrO ₄)	= 4 Ag ₂ O + 3 NpO ₂ + 2 Cr ₂ O ₃	-2265
2 Ti + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + Ti ₂ O ₃ + Cr ₂ O ₃	-2233
8 Li + 2 Pb(CrO ₄)	= Pb ₂ O + 4 Li ₂ O + Cr ₂ O ₃	-2203
2 Nb + 2 Pb(CrO ₄)	= Pb ₂ O + Nb ₂ O ₄ + Cr ₂ O ₃	-2197
8 V + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 V ₂ O ₃ + 3 Cr ₂ O ₃	-2170
2 Er + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + Er ₂ O ₃ + Cr ₂ O ₃	-2113
3 Ca + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 CaO + Cr ₂ O ₃	-2044
3 Th + 4 Ba(CrO ₄)	= 4 BaO + 3 ThO ₂ + 2 Cr ₂ O ₃	-2030
3 Be + 2 Na ₂ (CrO ₄)	= 2 Na ₂ O + 3 BeO + Cr ₂ O ₃	-2022
8 Cr + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 Cr ₂ O ₃ + 3 Cr ₂ O ₃	-2011
2 La + 2 Ba(CrO ₄)	= 2 BaO + La ₂ O ₃ + Cr ₂ O ₃	-1976
3 Hf + 4 Ba(CrO ₄)	= 4 BaO + 3 HfO ₂ + 2 Cr ₂ O ₃	-1966
2 Tb + 2 Ba(CrO ₄)	= 2 BaO + Tb ₂ O ₃ + Cr ₂ O ₃	-1927
2 Nd + 2 Ba(CrO ₄)	= 2 BaO + Nd ₂ O ₃ + Cr ₂ O ₃	-1915
2 Pr + 2 Ba(CrO ₄)	= 2 BaO + Pr ₂ O ₃ + Cr ₂ O ₃	-1912
4 Mn + 2 Pb(CrO ₄)	= Pb ₂ O + 4 MnO + Cr ₂ O ₃	-1904
2 Sm + 2 Ba(CrO ₄)	= 2 BaO + Sm ₂ O ₃ + Cr ₂ O ₃	-1897
6 Li + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 Li ₂ O + Cr ₂ O ₃	-1894
4 Sr + 2 Pb(CrO ₄)	= Pb ₂ O + 4 SrO + Cr ₂ O ₃	-1894
2 Gd + 2 Ba(CrO ₄)	= 2 BaO + Gd ₂ O ₃ + Cr ₂ O ₃	-1890
2 Ce + 2 Ba(CrO ₄)	= 2 BaO + Ce ₂ O ₃ + Cr ₂ O ₃	-1870
6 Ta + 10 Ag ₂ (CrO ₄)	= 10 Ag ₂ O + 3 Ta ₂ O ₅ + 5 Cr ₂ O ₃	-1861
3 Zr + 4 Ba(CrO ₄)	= 4 BaO + 3 ZrO ₂ + 2 Cr ₂ O ₃	-1799
2 Sc + 2 Ba(CrO ₄)	= 2 BaO + Sc ₂ O ₃ + Cr ₂ O ₃	-1782

Table 33 (cont.)

Reaction				Enthalpy, cal/cc
2 La + 2 Na ₂ (CrO ₄)	=	2 Na ₂ O + La ₂ O ₃ + Cr ₂ O ₃		-1768
6 Nb + 8 Ag ₂ (CrO ₄)	=	8 Ag ₂ O + 3 Nb ₂ O ₄ + 4 Cr ₂ O ₃		-1749
2 V + 2 Ag ₂ (CrO ₄)	=	2 Ag ₂ O + V ₂ O ₃ + Cr ₂ O ₃		-1732
3 Hf + 4 Na ₂ (CrO ₄)	=	4 Na ₂ O + 3 HfO ₂ + 2 Cr ₂ O ₃		-1722
8 Ga + 6 Pb(CrO ₄)	=	3 Pb ₂ O + 4 Ga ₂ O ₃ + 3 Cr ₂ O ₃		-1711
2 Nd + 2 Na ₂ (CrO ₄)	=	2 Na ₂ O + Nd ₂ O ₃ + Cr ₂ O ₃		-1705
2 Sm + 2 Na ₂ (CrO ₄)	=	2 Na ₂ O + Sm ₂ O ₃ + Cr ₂ O ₃		-1684
2 Gd + 2 Na ₂ (CrO ₄)	=	2 Na ₂ O + Gd ₂ O ₃ + Cr ₂ O ₃		-1679
3 Np + 4 Ba(CrO ₄)	=	4 BaO + 3 NpO ₂ + 2 Cr ₂ O ₃		-1677
3 Sr + 2 Ag ₂ (CrO ₄)	=	2 Ag ₂ O + 3 SrO + Cr ₂ O ₃		-1676
2 Al + 2 Na ₂ (CrO ₄)	=	2 Na ₂ O + Al ₂ O ₃ + Cr ₂ O ₃		-1665
8 P + 6 Pb(CrO ₄)	=	3 Pb ₂ O + 4 P ₂ O ₃ + 3 Cr ₂ O ₃		-1658
2 Ti + 2 Ba(CrO ₄)	=	2 BaO + Ti ₂ O ₃ + Cr ₂ O ₃		-1649
4 Ba + 2 Pb(CrO ₄)	=	Pb ₂ O + 4 BaO + Cr ₂ O ₃		-1614
2 Sc + 2 Na ₂ (CrO ₄)	=	2 Na ₂ O + Sc ₂ O ₃ + Cr ₂ O ₃		-1570
4 Zn + 2 Pb(CrO ₄)	=	Pb ₂ O + 4 ZnO + Cr ₂ O ₃		-1566
3 Zr + 4 Na ₂ (CrO ₄)	=	4 Na ₂ O + 3 ZrO ₂ + 2 Cr ₂ O ₃		-1565
3 Mn + 2 Ag ₂ (CrO ₄)	=	2 Ag ₂ O + 3 MnO + Cr ₂ O ₃		-1561
3 Ba + 2 Ag ₂ (CrO ₄)	=	2 Ag ₂ O + 3 BaO + Cr ₂ O ₃		-1460
2 Ga + 2 Ag ₂ (CrO ₄)	=	2 Ag ₂ O + Ga ₂ O ₃ + Cr ₂ O ₃		-1426
2 P + 2 Ag ₂ (CrO ₄)	=	2 Ag ₂ O + P ₂ O ₃ + Cr ₂ O ₃		-1407
3 Zn + 2 Ag ₂ (CrO ₄)	=	2 Ag ₂ O + 3 ZnO + Cr ₂ O ₃		-1330
4 W + 6 Pb(CrO ₄)	=	3 Pb ₂ O + 4 WO ₃ + 3 Cr ₂ O ₃		-1329
3 Sr + 2 Ba(CrO ₄)	=	2 BaO + 3 SrO + Cr ₂ O ₃		-1296
3 Fe + 2 Pb(CrO ₄)	=	Pb ₂ O + Fe ₃ O ₄ + Cr ₂ O ₃		-1230
2 Sn + 2 Pb(CrO ₄)	=	Pb ₂ O + 2 SnO ₂ + Cr ₂ O ₃		-1206
2 Mo + 2 Pb(CrO ₄)	=	Pb ₂ O + 2 MoO ₂ + Cr ₂ O ₃		-1198
3 Sr + 2 Na ₂ (CrO ₄)	=	2 Na ₂ O + 3 SrO + Cr ₂ O ₃		-1162
W + 2 Ag ₂ (CrO ₄)	=	2 Ag ₂ O + WO ₃ + Cr ₂ O ₃		-1136
2 Al + 2 K ₂ (CrO ₄)	=	2 K ₂ O + Al ₂ O ₃ + Cr ₂ O ₃		-1113

Table 33 (cont.)

Reaction		Enthalpy, cal/cc
2 Ge + 2 Pb(CrO ₄)	= Pb ₂ O + 2 GeO ₂ + Cr ₂ O ₃	-1095
9 Fe + 8 Ag ₂ (CrO ₄)	= 8 Ag ₂ O + 3 Fe ₃ O ₄ + 4 Cr ₂ O ₃	-1076
3 Sn + 4 Ag ₂ (CrO ₄)	= 4 Ag ₂ O + 3 SnO ₂ + 2 Cr ₂ O ₃	-1068
3 Ge + 4 Ag ₂ (CrO ₄)	= 4 Ag ₂ O + 3 GeO ₂ + 2 Cr ₂ O ₃	-986
3 Ni + 2 Pb(CrO ₄)	= 2 PbO + 3 NiO + Cr ₂ O ₃	-933
3 Co + 2 Pb(CrO ₄)	= 2 PbO + 3 CoO + Cr ₂ O ₃	-903
3 Ni + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 NiO + Cr ₂ O ₃	-865
3 Cd + 2 Pb(CrO ₄)	= 2 PbO + 3 CdO + Cr ₂ O ₃	-859
3 Cd + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 CdO + Cr ₂ O ₃	-806
4 Sb + 4 Pb(CrO ₄)	= 4 PbO + Sb ₄ O ₆ + 2 Cr ₂ O ₃	-773
2 As + 2 Pb(CrO ₄)	= 2 PbO + As ₂ O ₃ + Cr ₂ O ₃	-739
3 Pb + 2 Pb(CrO ₄)	= 2 PbO + 3 PbO + Cr ₂ O ₃	-611
3 Bi + 2 Pb(CrO ₄)	= 2 PbO + 3 BiO + Cr ₂ O ₃	-533
3 Te + 4 Pb(CrO ₄)	= 4 PbO + 3 TeO ₂ + 2 Cr ₂ O ₃	-417
3 Te + 4 Ag ₂ (CrO ₄)	= 4 Ag ₂ O + 3 TeO ₂ + 2 Cr ₂ O ₃	-407
3 Cu + 2 Pb(CrO ₄)	= 2 PbO + 3 CuO + Cr ₂ O ₃	-406
6 Rb + 2 Pb(CrO ₄)	= 2 PbO + 3 Rb ₂ O + Cr ₂ O ₃	-401
6 Rb + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 Rb ₂ O + Cr ₂ O ₃	-399
S + 2 Pb(CrO ₄)	= 2 PbO + SO ₃ + Cr ₂ O ₃	-370
6 Cs + 2 Pb(CrO ₄)	= 2 PbO + 3 Cs ₂ O + Cr ₂ O ₃	-315
6 Tl + 2 Pb(CrO ₄)	= 2 PbO + 3 Tl ₂ O + Cr ₂ O ₃	-314
6 Rb + 2 Ba(CrO ₄)	= 2 BaO + 3 Rb ₂ O + Cr ₂ O ₃	-202
6 Rb + 2 Na ₂ (CrO ₄)	= 2 Na ₂ O + 3 Rb ₂ O + Cr ₂ O ₃	-154
6 Rb + 2 K ₂ (CrO ₄)	= 2 K ₂ O + 3 Rb ₂ O + Cr ₂ O ₃	-38

Table 34

MOST ENERGETIC CHROMATE AND DICHROMATE REACTIONS WITH METALS,
IN TERMS OF GRAVIMETRIC ENTHALPY

Reaction		Enthalpy, cal/g
3 Be + 2 Na ₂ (CrO ₄)	= 2 Na ₂ O + 3 BeO + Cr ₂ O ₃	-772
4 Be + 2 Pb(CrO ₄)	= Pb ₂ O + 4 BeO + Cr ₂ O ₃	-687
8 Li + 2 Pb(CrO ₄)	= Pb ₂ O + 4 Li ₂ O + Cr ₂ O ₃	-648
4 Mg + 2 Pb(CrO ₄)	= Pb ₂ O + 4 MgO + Cr ₂ O ₃	-619
2 Al + 2 Na ₂ (CrO ₄)	= 2 Na ₂ O + Al ₂ O ₃ + Cr ₂ O ₃	-614
4 Ca + 2 Pb(CrO ₄)	= Pb ₂ O + 4 CaO + Cr ₂ O ₃	-611
2 Sc + 2 Na ₂ (CrO ₄)	= 2 Na ₂ O + Sc ₂ O ₃ + Cr ₂ O ₃	-590
8 Sc + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 Sc ₂ O ₃ + 3 Cr ₂ O ₃	-565
3 Be + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 BeO + Cr ₂ O ₃	-553
3 Be + 2 Ba(CrO ₄)	= 2 BaO + 3 BeO + Cr ₂ O ₃	-546
6 Li + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 Li ₂ O + Cr ₂ O ₃	-526
3 Ca + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 CaO + Cr ₂ O ₃	-509
3 Mg + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 MgO + Cr ₂ O ₃	-509
8 La + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 La ₂ O ₃ + 3 Cr ₂ O ₃	-487
2 Zr + 2 Pb(CrO ₄)	= Pb ₂ O + 2 ZrO ₂ + Cr ₂ O ₃	-484
8 Ti + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 Ti ₂ O ₃ + 3 Cr ₂ O ₃	-484
2 La + 2 Na ₂ (CrO ₄)	= 2 Na ₂ O + La ₂ O ₃ + Cr ₂ O ₃	-484
3 Zr + 4 Na ₂ (CrO ₄)	= 4 Na ₂ O + 3 ZrO ₂ + 2 Cr ₂ O ₃	-478
2 Sc + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + Sc ₂ O ₃ + Cr ₂ O ₃	-471
8 Pr + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 Pr ₂ O ₃ + 3 Cr ₂ O ₃	-467
8 Nd + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 Nd ₂ O ₃ + 3 Cr ₂ O ₃	-460
8 Ce + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 Ce ₂ O ₃ + 3 Cr ₂ O ₃	-456
4 Sr + 2 Pb(CrO ₄)	= Pb ₂ O + 4 SrO + Cr ₂ O ₃	-451
2 Nd + 2 Na ₂ (CrO ₄)	= 2 Na ₂ O + Nd ₂ O ₃ + Cr ₂ O ₃	-449
8 Er + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 Er ₂ O ₃ + 3 Cr ₂ O ₃	-448
8 Ho + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 Ho ₂ O ₃ + 3 Cr ₂ O ₃	-446
2 Sc + 2 Ba(CrO ₄)	= 2 BaO + Sc ₂ O ₃ + Cr ₂ O ₃	-443
8 Sm + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 Sm ₂ O ₃ + 3 Cr ₂ O ₃	-443
3 Sr + 2 Na ₂ (CrO ₄)	= 2 Na ₂ O + 3 SrO + Cr ₂ O ₃	-437

Table 34 (cont.)

Reaction		Enthalpy, cal/g
8 Tb + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 Tb ₂ O ₃ + 3 Cr ₂ O ₃	-437
8 Gd + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 Gd ₂ O ₃ + 3 Cr ₂ O ₃	-435
2 Sm + 2 Na ₂ (CrO ₄)	= 2 Na ₂ O + Sm ₂ O ₃ + Cr ₂ O ₃	-427
2 La + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + La ₂ O ₃ + Cr ₂ O ₃	-427
2 Hf + 2 Pb(CrO ₄)	= Pb ₂ O + 2 HfO ₂ + Cr ₂ O ₃	-427
2 Th + 2 Pb(CrO ₄)	= Pb ₂ O + 2 ThO ₂ + Cr ₂ O ₃	-422
2 Gd + 2 Na ₂ (CrO ₄)	= 2 Na ₂ O + Gd ₂ O ₃ + Cr ₂ O ₃	-418
3 Zr + 4 Ag ₂ (CrO ₄)	= 4 Ag ₂ O + 3 ZrO ₂ + 2 Cr ₂ O ₃	-413
2 Pr + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + Pr ₂ O ₃ + Cr ₂ O ₃	-410
2 Ti + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + Ti ₂ O ₃ + Cr ₂ O ₃	-409
2 Al + 2 K ₂ (CrO ₄)	= 2 K ₂ O + Al ₂ O ₃ + Cr ₂ O ₃	-408
3 Hf + 4 Na ₂ (CrO ₄)	= 4 Na ₂ O + 3 HfO ₂ + 2 Cr ₂ O ₃	-406
2 Nd + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + Nd ₂ O ₃ + Cr ₂ O ₃	-405
2 Ce + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + Ce ₂ O ₃ + Cr ₂ O ₃	-401
2 Er + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + Er ₂ O ₃ + Cr ₂ O ₃	-398
2 La + 2 Ba(CrO ₄)	= 2 BaO + La ₂ O ₃ + Cr ₂ O ₃	-397
3 Sr + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 SrO + Cr ₂ O ₃	-396
2 Ho + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + Ho ₂ O ₃ + Cr ₂ O ₃	-396
2 Sm + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + Sm ₂ O ₃ + Cr ₂ O ₃	-391
2 Tb + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + Tb ₂ O ₃ + Cr ₂ O ₃	-388
2 Gd + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + Gd ₂ O ₃ + Cr ₂ O ₃	-386
2 U + 2 Pb(CrO ₄)	= Pb ₂ O + 2 UO ₂ + Cr ₂ O ₃	-379
2 Pr + 2 Ba(CrO ₄)	= 2 BaO + Pr ₂ O ₃ + Cr ₂ O ₃	-378
3 Th + 4 Ag ₂ (CrO ₄)	= 4 Ag ₂ O + 3 ThO ₂ + 2 Cr ₂ O ₃	-377
3 Hf + 4 Ag ₂ (CrO ₄)	= 4 Ag ₂ O + 3 HfO ₂ + 2 Cr ₂ O ₃	-377
3 Zr + 4 Ba(CrO ₄)	= 4 BaO + 3 ZrO ₂ + 2 Cr ₂ O ₃	-374
2 Nd + 2 Ba(CrO ₄)	= 2 BaO + Nd ₂ O ₃ + Cr ₂ O ₃	-372
2 Ce + 2 Ba(CrO ₄)	= 2 BaO + Ce ₂ O ₃ + Cr ₂ O ₃	-367
2 Ti + 2 Ba(CrO ₄)	= 2 BaO + Ti ₂ O ₃ + Cr ₂ O ₃	-366
3 Sr + 2 Ba(CrO ₄)	= 2 BaO + 3 SrO + Cr ₂ O ₃	-360
2 Sm + 2 Ba(CrO ₄)	= 2 BaO + Sm ₂ O ₃ + Cr ₂ O ₃	-356

Table 34 (cont.)

Reaction		Enthalpy, cal/g
2 Tb + 2 Ba(CrO ₄)	= 2 BaO + Tb ₂ O ₃ + Cr ₂ O ₃	-352
2 Gd + 2 Ba(CrO ₄)	= 2 BaO + Gd ₂ O ₃ + Cr ₂ O ₃	-350
4 Ba + 2 Pb(CrO ₄)	= Pb ₂ O + 4 BaO + Cr ₂ O ₃	-350
8 V + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 V ₂ O ₃ + 3 Cr ₂ O ₃	-347
3 U + 4 Ag ₂ (CrO ₄)	= 4 Ag ₂ O + 3 UO ₂ + 2 Cr ₂ O ₃	-341
3 Th + 4 Ba(CrO ₄)	= 4 BaO + 3 ThO ₂ + 2 Cr ₂ O ₃	-341
3 Hf + 4 Ba(CrO ₄)	= 4 BaO + 3 HfO ₂ + 2 Cr ₂ O ₃	-337
2 Np + 2 Pb(CrO ₄)	= Pb ₂ O + 2 NpO ₂ + Cr ₂ O ₃	-336
8 P + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 P ₂ O ₃ + 3 Cr ₂ O ₃	-336
2 Nb + 2 Pb(CrO ₄)	= Pb ₂ O + Nb ₂ O ₄ + Cr ₂ O ₃	-328
3 Ba + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 BaO + Cr ₂ O ₃	-320
8 Cr + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 Cr ₂ O ₃ + 3 Cr ₂ O ₃	-312
3 Np + 4 Ag ₂ (CrO ₄)	= 4 Ag ₂ O + 3 NpO ₂ + 2 Cr ₂ O ₃	-307
2 V + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + V ₂ O ₃ + Cr ₂ O ₃	-305
8 Ta + 10 Pb(CrO ₄)	= 5 Pb ₂ O + 4 Ta ₂ O ₅ + 5 Cr ₂ O ₃	-304
2 P + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + P ₂ O ₃ + Cr ₂ O ₃	-294
4 Mn + 2 Pb(CrO ₄)	= Pb ₂ O + 4 MnO + Cr ₂ O ₃	-292
6 Nb + 8 Ag ₂ (CrO ₄)	= 8 Ag ₂ O + 3 Nb ₂ O ₄ + 4 Cr ₂ O ₃	-292
6 Ta + 10 Ag ₂ (CrO ₄)	= 10 Ag ₂ O + 3 Ta ₂ O ₅ + 5 Cr ₂ O ₃	-277
8 Ga + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 Ga ₂ O ₃ + 3 Cr ₂ O ₃	-275
3 Mn + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 MnO + Cr ₂ O ₃	-265
3 Np + 4 Ba(CrO ₄)	= 4 BaO + 3 NpO ₂ + 2 Cr ₂ O ₃	-258
2 Ga + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + Ga ₂ O ₃ + Cr ₂ O ₃	-251
4 Zn + 2 Pb(CrO ₄)	= Pb ₂ O + 4 ZnO + Cr ₂ O ₃	-240
3 Zn + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 ZnO + Cr ₂ O ₃	-225
3 Fe + 2 Pb(CrO ₄)	= Pb ₂ O + Fe ₃ O ₄ + Cr ₂ O ₃	-187
2 Sn + 2 Pb(CrO ₄)	= Pb ₂ O + 2 SnO ₂ + Cr ₂ O ₃	-184
9 Fe + 8 Ag ₂ (CrO ₄)	= 8 Ag ₂ O + 3 Fe ₃ O ₄ + 4 Cr ₂ O ₃	-182
3 Sn + 4 Ag ₂ (CrO ₄)	= 4 Ag ₂ O + 3 SnO ₂ + 2 Cr ₂ O ₃	-180
2 Ge + 2 Pb(CrO ₄)	= Pb ₂ O + 2 GeO ₂ + Cr ₂ O ₃	-179
3 Ge + 4 Ag ₂ (CrO ₄)	= 4 Ag ₂ O + 3 GeO ₂ + 2 Cr ₂ O ₃	-176
2 Mo + 2 Pb(CrO ₄)	= Pb ₂ O + 2 MoO ₂ + Cr ₂ O ₃	-173

Table 34 (cont.)

Reaction		Enthalpy, cal/g
4 W + 6 Pb(CrO ₄)	= 3 Pb ₂ O + 4 WO ₃ + 3 Cr ₂ O ₃	-171
1 W + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + WO ₃ + Cr ₂ O ₃	-170
6 Rb + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 Rb ₂ O + Cr ₂ O ₃	-153
6 Rb + 2 Pb(CrO ₄)	= 2 PbO + 3 Rb ₂ O + Cr ₂ O ₃	-151
3 Ni + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 NiO + Cr ₂ O ₃	-141
3 Ni + 2 Pb(CrO ₄)	= 2 PbO + 3 NiO + Cr ₂ O ₃	-138
3 Co + 2 Pb(CrO ₄)	= 2 PbO + 3 CoO + Cr ₂ O ₃	-134
3 Cd + 2 Ag ₂ (CrO ₄)	= 2 Ag ₂ O + 3 CdO + Cr ₂ O ₃	-126
3 Cd + 2 Pb(CrO ₄)	= 2 PbO + 3 CdO + Cr ₂ O ₃	-123
4 Sb + 4 Pb(CrO ₄)	= 4 PbO + Sb ₄ O ₆ + 2 Cr ₂ O ₃	-120
2 As + 2 Pb(CrO ₄)	= 2 PbO + As ₂ O ₃ + Cr ₂ O ₃	-119
6 Cs + 2 Pb(CrO ₄)	= 2 PbO + 3 Cs ₂ O + Cr ₂ O ₃	-115
6 Rb + 2 Ba(CrO ₄)	= 2 BaO + 3 Rb ₂ O + Cr ₂ O ₃	-88
6 Rb + 2 Na ₂ (CrO ₄)	= 2 Na ₂ O + 3 Rb ₂ O + Cr ₂ O ₃	-83
3 Pb + 2 Pb(CrO ₄)	= 2 PbO + 3 PbO + Cr ₂ O ₃	-75
3 Te + 4 Ag ₂ (CrO ₄)	= 4 Ag ₂ O + 3 TeO ₂ + 2 Cr ₂ O ₃	-70
3 Bi + 2 Pb(CrO ₄)	= 2 PbO + 3 BiO + Cr ₂ O ₃	-69
3 Te + 4 Pb(CrO ₄)	= 4 PbO + 3 TeO ₂ + 2 Cr ₂ O ₃	-66
S + 2 Pb(CrO ₄)	= 2 PbO + SO ₃ + Cr ₂ O ₃	-64
3 Cu + 2 Pb(CrO ₄)	= 2 PbO + 3 CuO + Cr ₂ O ₃	-60
6 Ti + 2 Pb(CrO ₄)	= 2 PbO + 3 Ti ₂ O + Cr ₂ O ₃	-34
6 Rb + 2 K ₂ (CrO ₄)	= 2 K ₂ O + 5 Rb ₂ O + Cr ₂ O ₃	-20

Table 35

VOLUMETRIC ENTHALPIES (cal/cc) OF REACTIONS OF METALS
WITH CHROMATES AND DICHROMATES
(In descending order from top to bottom and left to right)

<u>Metal</u>	<u>PbCrO₄</u>	<u>Ag₂CrO₄</u>	<u>BaCrO₄</u>	<u>Na₂CrO₄</u>	<u>K₂CrO₄</u>
Be	-3845	-2881	-2293	-2022	
U	-3322	-2546			
Hf	-3310	-2543	-1966	-1722	
Th	-3259	-2563	-2030		
Ho	-3173	-2529			
Zr	-3065	-2377	-1799	-1565	
Tb	-3048	-2439	-1927		
La	-3046	-2464	-1976	-1768	
Sm	-2999	-2406	-1897	-1684	
Nd	-2998	-2415	-1915	-1705	
Gd	-2986	-2398	-1890	-1679	
Pr	-2980	-2408	-1912		
Ce	-2939	-2371	-1870		
Np	-2914	-2265	-1677		
Mg	-2907	-2348			
Sc	-2879	-2303	-1782	-1570	
Ti	-2861	-2233	-1649		
Er	-2499	-2113			
Ca	-2393	-2044			
Ta	-2377	-1861			
Li	-2203	-1894			
Nb	-2197	-1749			
V	-2170	-1732			
Cr	-2011				
Mn	-1904	-1551			
Sr	-1894	-1676	-1296	-116?	
Al				-1665	-1113
P	-1658	-1407			
Bc	-1614	-1460			
Zn	-1566	-1330			
Ga	-1711	-1426			
W	-1329	-1136			
Fe	-1230	-1076			
Sn	-1206	-1068			
Mo	-1198				
Ge	-1095	-986			
Ni	-933	-865			
Co	-903				
Cd	-859	-806			
Sb	-773				
As	-739				
Pb	-611				
Bi	-533				
Te	-417	-407			
Cu	-406				
Rb	-401	-399	-202	-154	-38
S	-370				
Cs	-315				
Tl	-314				

Table 36

GRAVIMETRIC ENTHALPIES (cal/g) OF REACTIONS OF METALS
WITH CHROMATES AND DICHROMATES
(In descending order from top to bottom and left to right)

Metal	Na_2CrO_4	PbCrO_4	Ag_2CrO_4	BaCrO_4	K_2CrO_4
Be	-772	-687	-553	-546	
Li		-648	-526		
Mg		-619	-509		
Al	-614				-408
Ca		-611	-509		
Sc	-590	-565	-471	-443	
La	-484	-487	-427	-397	
Zr	-478	-484	-413	-374	
Ti		-484	-409	-366	
Pr		-467	-410	-378	
Nd	-449	-460	-405	-372	
Ce		-456	-401	-367	
Sr	-437	-451	-396	-360	
Er		-448	-398		
Ho		-446	-396		
Sm	-427	-443	-391	-356	
Tb		-437	-388	-352	
Gd	-418	-435	-386	-350	
Hf	-406	-427	-377	-337	
Th		-422	-377	-341	
U		-379	-341		
Ba		-350	-320		
V		-347	-305		
Np		-336	-307	-258	
P		-336	-294		
Nb		-328	-292		
Cr		-312			
Ta		-304	-277		
Mn		-292	-265		
Ga		-275	-251		
Zn		-240	-225		
Fe		-187	-182		
Sn		-184	-180		
Ge		-179	-176		
Mo		-173			
W		-171	-170		
Rb	-83	-151	-153	-88	-20
Ni		-138	-141		
Co		-134			
Cd		-123	-126		
Sb		-120			
As		-119			
Cs		-115			
Pb		-75			
Te		-66	-70		
Bi		-69			
S		-64			
Cu		-60			
Tl		-34			

K. Boride Reactions

The reactions of 3 metals with 8 borides resulted in 14 reactions. Although the properties for only a few reactions were calculated, they are of interest because of the refractory nature of the products and reactants. Some representative reactions are shown in Table 37, and the volumetric and gravimetric enthalpies of all the boride reactions are listed in Tables 38 and 39. Except for boron carbide, the enthalpies are low. However, the reactions of titanium and zirconium with boron carbide are energetic. It would be interesting to examine these reactions experimentally to determine the effect of the refractoriness of the reactants and products on the behavior of the reactions.

Table 37

DATA ON REACTIONS OF VARIOUS METALS WITH BORIDES

	4 N	+	CB ₄	=	C	+	4 NB
Heat of formation			12.20		12.01		60.30
Molecular weight	14.01		55.29		2.25		24.83
Density	.81		2.50				2.20
Melting point, °C			2450.00				3000.00
Boiling point, °C			3500.00		4347.00		
Heat of reaction, kcal	-229.00						
Reactants' density	1.22						
Gravimetric enthalpy, cal/g	-2057.10						
Volumetric enthalpy, cal/cc	-2503.76						
	2 Ti	+	CB ₄	=	C	+	2 TiB ₂
Heat of formation			12.20		12.01		70.00
Molecular weight	47.90		55.29		2.25		69.54
Density	4.50		2.50				4.5
Melting point, °C	1812.00		2450.00				
Boiling point, °C	3000.00		3500.00		4347.00		
Heat of reaction, kcal	-127.80						
Reactants' density	3.48						
Gravimetric enthalpy, cal/g	-845.85						
Volumetric enthalpy, cal/cc	-2944.37						
	2 Zr	+	CB ₄	=	C	+	2 ZrB ₂
Heat of formation			12.20		12.01		76.40
Molecular weight	91.22		55.29		2.25		112.86
Density	6.40		2.50				6.08
Melting point, °C	1852.00		2450.00				
Boiling point, °C	2900.00		3500.00		4347.00		
Heat of reaction, kcal	-140.60						
Reactants' density	4.70						
Gravimetric enthalpy, cal/g	-591.43						
Volumetric enthalpy, cal/cc	-2777.43						

Table 37 (cont.)

	2 N	+	TiB ₂	=	Ti	+	2 NB
Heat of formation			70.00				-60.30
Molecular weight	14.01		69.54		47.90		24.83
Density	.81		4.5		4.50		2.20
Melting point, °C					1812.00		3000.00
Boiling point, °C					3000.00		
Heat of reaction, kcal	-50.60						
Reactants' density	1.95						
Gravimetric enthalpy, cal/g	-518.68						
Volumetric enthalpy, cal/cc	-1010.97						
	5 N	+ <td>Ti₂B₅ <td>= <td>2 Ti <td>+ <td>5 NB</td> </td></td></td></td>	Ti ₂ B ₅ <td>= <td>2 Ti <td>+ <td>5 NB</td> </td></td></td>	= <td>2 Ti <td>+ <td>5 NB</td> </td></td>	2 Ti <td>+ <td>5 NB</td> </td>	+ <td>5 NB</td>	5 NB
Heat of formation			-105.00				-60.30
Molecular weight	14.01		149.90		47.90		24.83
Density	.81		4.63		4.50		2.20
Melting point, °C					1812.00		3000.00
Boiling point, °C					3000.00		
Heat of reaction, kcal	-196.50						
Reactants' density	1.85						
Gravimetric enthalpy, cal/g	-893.43						
Volumetric enthalpy, cal/cc	-1650.44						
	5 Zr	+ <td>2 Ti₂B₅ <td>= <td>4 Ti <td>+ <td>5 ZrB₂ </td></td></td></td></td>	2 Ti ₂ B ₅ <td>= <td>4 Ti <td>+ <td>5 ZrB₂ </td></td></td></td>	= <td>4 Ti <td>+ <td>5 ZrB₂ </td></td></td>	4 Ti <td>+ <td>5 ZrB₂ </td></td>	+ <td>5 ZrB₂ </td>	5 ZrB ₂
Heat of formation			-105.00				-76.40
Molecular weight	91.22		149.90		47.90		112.86
Density	6.40		4.63		4.50		6.08
Melting point, °C	1852.00				1812.00		
Boiling point, °C	2900.00				3000.00		
Heat of reaction, kcal	-172.00						
Reactants' density	5.56						
Gravimetric enthalpy, cal/g	-227.54						
Volumetric enthalpy, cal/cc	-1264.55						

Table 38

VOLUMETRIC ENTHALPIES (cal/cc) OF REACTIONS OF METALS WITH BORIDES
(In descending order from top to bottom and left to right)

<u>Metal</u>	<u>CB₄</u>	<u>Ti₂B₅</u>	<u>TiB₂</u>	<u>ZrB₂</u>	<u>TiB</u>
Ti	-2944				
N	-2503	-1650	-1037	- 830	- 804
Zr	-2777	-1264	- 221		- 110

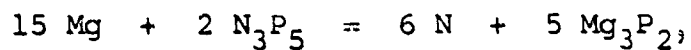
Table 39

GRAVIMETRIC ENTHALPIES (cal/g) OF REACTIONS OF METALS WITH BORIDES
(In descending order from top to bottom and left to right)

<u>Metal</u>	<u>CB₄</u>	<u>ZrB₂</u>	<u>Ti₂B₅</u>	<u>TiB₂</u>	<u>TiB</u>	<u>ZrB₂</u>	<u>Ti₂B</u>	<u>ZrB</u>
N	-2057	-1551	- 893	- 518	- 334	- 313	- 201	- 183
Ti	- 845	- 277			- 20			
Zr	- 591		- 227	- 39				

L. Phosphide Reactions

A total of 25 phosphides and 500 reactions was surveyed. The phosphides do not form an energetic class of reactions. The most energetic revealed in these studies,



yields only -1439 cal/cc. A few representative reactions are shown in Table 40.

Table 40

DATA ON REACTIONS OF VARIOUS METALS WITH PHOSPHIDES

	9 Mg	+ 2 Au ₂ P ₃	= 4 Au	+ 3 Mg ₃ P ₂
Heat of formation		-24.10		-128.00
Molecular weight	24.32	487.34	197.00	134.91
Density	1.74	6.67	19.30	
Melting point, °C	650.00		1063.00	
Boiling point, °C	1120.00		2660.00	
Heat of reaction, kcal	-335.00			
Reactants' density	4.39			
Gravimetric enthalpy, cal/g	-281.34			
Volumetric enthalpy, cal/cc	-1254.91			
	3 Mg	+ Ba ₃ P ₂	= 3 Ba	+ Mg ₃ P ₂
Heat of formation		-118.00		-128.00
Molecular weight	24.32	474.03	137.36	134.91
Density	1.74		3.50	
Melting point, °C	650.00		704.00	
Boiling point, °C	1120.00		1638.00	
Heat of reaction, kcal	-10.00			
Reactants' density				
Gravimetric enthalpy, cal/g	-18.28			
Volumetric enthalpy, cal/cc				
	3 Mg	+ Ca ₃ P ₂	= 3 Ca	+ Mg ₃ P ₂
Heat of formation		-120.50		-128.00
Molecular weight	24.32	182.20	40.08	134.91
Density	1.74	2.24	1.55	
Melting point, °C	650.00	1600.00	850.00	
Boiling point, °C	1120.00		1240.00	
Heat of reaction, kcal	-7.50			
Reactants' density	2.07			
Gravimetric enthalpy, cal/g	-29.39			
Volumetric enthalpy, cal/cc	-60.81			

Table 40 (cont.)

	3 Mg	+ 2 Cu ₃ P	=	6 Cu	+ Mg ₃ P ₂
Heat of formation		-36.40			-128.00
Molecular weight		221.60		63.54	134.91
Density	24.32	6.40		8.92	
Melting point, °C	1.74			1083.00	
Boiling point, °C	650.00			2582.00	
Heat of reaction, kcal	1120.00				
Reactants' density	-55.20				
Gravimetric enthalpy, cal/g	4.64				
Volumetric enthalpy, cal/cc	-106.94				
	-496.49				

	3 Mg	+ CuP ₂	=	Cu	+ Mg ₃ P ₂
Heat of formation		-28.90			-128.00
Molecular weight		125.49		63.54	134.91
Density	24.32			8.92	
Melting point, °C	1.74			1083.00	
Boiling point, °C	650.00			2582.00	
Heat of reaction, kcal	1120.00				
Reactants' density	-99.10				
Gravimetric enthalpy, cal/g					
Volumetric enthalpy, cal/cc	-499.37				

	3 Mg	+ 2 FeP	=	2 Fe	+ Mg ₃ P ₂
Heat of formation		-28.00			-128.00
Molecular weight		86.83		55.85	134.91
Density	24.32	5.20		7.86	
Melting point, °C	1.74			1535.00	
Boiling point, °C	650.00			2800.00	
Heat of reaction, kcal	1120.00				
Reactants' density	-72.00				
Gravimetric enthalpy, cal/g	3.27				
Volumetric enthalpy, cal/cc	-291.95				
	-955.83				

M. Organic Fluoride Reactions

A limited survey was made of the reactions of organic fluorides with metals. The properties were tabulated for 76 organic fluorides for which data on heat of formation were available. These included perfluorinated compounds, partially fluorinated hydrocarbons, mixed halogenated organics, and organics containing various combinations of hydrogen, oxygen, nitrogen and fluorine. The enthalpies of reactions of 89 metals* with carbon tetrafluoride and hexafluoroethane were calculated. Both of these compounds are effective oxidizers.

The volumetric enthalpies for the 30 most energetic reactions of each fluoride are listed in Tables 41 and 42. Each reaction is represented by the metal reactant and the product fluoride. The Group IIA metals (beryllium, magnesium, calcium, strontium, and barium), the Group IVB metals (titanium, zirconium, and hafnium), and the rare earth metals (yttrium, lanthanum, neodymium, praseodymium, uranium, and thorium) are very energetic with these fluorides.

* In this instance each valence state of a metal is considered as a separate unit.

Table 41

VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS
WITH ORGANIC FLUORIDES C_2F_6

<u>Reaction</u>	<u>Product</u>	<u>Enthalpy, cal/cc</u>
Be	BeF_2	-5.75
Y	YF_3	-5.14
La	LaF_3	-5.02
Nd	NdF_3	-4.98
Pr	PrF_3	-4.97
U	UF_3	-4.74
Mg	MgF_2	-4.73
Hf	HfF_3	-4.54
U	UF_4	-4.53
Th	ThF_4	-4.50
Sc	ScF_3	-4.47
Zr	ZrF_3	-4.46
Zr	ZrF_4	-4.45
Hf	HfF_4	-4.36
Li	LiF	-4.18
Ca	CaF_2	-4.14
Ti	TiF_3	-4.07
Th	ThF_3	-4.05
Ce	CeF_3	-4.05
Al	AlF_3	-4.04
Hf	HfF_2	-3.92
U	UF_5	-3.85
Zr	ZrF_2	-3.84
V	VF_2	-3.59
Ti	TiF_4	-3.48
B	BF_3	-3.47

Table 41 (cont.)

<u>Reaction</u>	<u>Product</u>	<u>Enthalpy,</u> <u>cal/cc</u>
Si	SiF ₄	-3.42
Mn	MnF ₂	-3.36
Ti	TiF ₂	-3.32
Ce	CeF ₄	-3.30
V	VF ₃	-3.29
Cr	CrF ₃	-3.26
Ba	BaF ₂	-3.23
U	UF ₆	-3.16
Cr	CrF ₂	-3.15
Ta	TaF ₃	-2.90
V	VF ₄	-2.83
Zn	ZnF ₂	-2.82
Ta	TaF ₂	-2.80
Ga	GaF ₃	-2.75
Na	NaF	-2.67
Mn	MnF ₃	-2.63
Fe	FeF ₃	-2.59
Ni	NiF ₂	-2.53
Co	CoF ₂	-2.51
In	InF ₃	-2.45
Ge	GeF ₂	-2.34
Cd	CdF ₂	-2.25
Cr	CrF ₄	-2.22
Ta	TaF ₅	-2.19
Ga	GaF ₂	-2.18
Cr	CrF ₅	-2.16

Table 41 (cont.)

<u>Reaction</u>	<u>Product</u>	<u>Enthalpy,</u> <u>cal/cc</u>
W	WF ₆	-2.09
In	InF ₂	-1.97
Mo	MoF ₆	-1.96
Nb	NbF ₅	-1.94
V	VF ₅	-1.91
Ge	GeF ₄	-1.91
Sn	SnF ₂	-1.89
Mo	MoF ₅	-1.89
Pb	PbF ₂	-1.83
Bi	BiF ₄	-1.76
Sb	SbF ₃	-1.75
N	NF ₃	-1.70
Bi	BiF ₃	-1.64
K	KF	-1.63
Mo	MoF ₄	-1.62
Co	CoF ₃	-1.53
W	WF ₄	-1.52
Fe	FeF ₂	-1.50
Sn	SnF ₄	-1.50
Cu	CuF ₂	-1.47
Rb	RbF	-1.34
Sb	SbF ₅	-1.31
Bi	BiF ₂	-1.30
Mn	MnF ₄	-1.22
W	WF ₅	-1.16

Table 42

VOLUMETRIC ENTHALPIES OF REACTIONS OF METALS
WITH ORGANIC FLUORIDES CF_4

<u>Reaction</u>	<u>Product</u>	<u>Enthalpy, cal/cc</u>
Be	BeF_2	-5.14
Y	YF_3	-4.69
La	LaF_3	-4.57
Nd	NdF_3	-4.57
Pr	PrF_3	-4.51
Mg	MgF_2	-4.24
U	UF_3	-4.167
Th	ThF_4	-3.94
Sc	ScF_3	-3.93
U	UF_4	-3.90
Zr	ZrF_4	-3.83
Li	LiF	-3.82
Ca	CaF_2	-3.75
Hf	HfF_4	-3.72
Ce	CeF_3	-3.64
Th	ThF_3	-3.52
Al	AlF_3	-3.37
Sr	SrF_2	-3.23
U	UF_5	-3.14
V	VF_2	-2.93
Ba	BaF_2	-2.88
Ce	CeF_4	-2.76
Ti	TiF_4	-2.73
Si	SiF_4	-2.68
B	BF_3	-2.66
Mn	MnF_2	-2.65
V	VF_3	-2.54

Table 42 (cont.)

<u>Reaction</u>	<u>Product</u>	<u>Enthalpy, cal/cc</u>
Cr	CrF ₃	-2.48
Cr	CrF ₂	-2.42
U	UF ₆	-2.36
Na	NaF	-2.33
Ta	TaF ₃	-2.16
Ta	TaF ₂	-2.12
Zn	ZnF ₂	-2.12
Ga	GaF ₃	-2.00
V	VF ₄	-1.99
Mn	MnF ₃	-1.80
Fe	FeF ₃	-1.75
In	InF ₃	-1.75
Ni	NiF ₂	-1.73
Co	CoF ₂	-1.71
Au	AuF	-1.71
Cd	CdF ₂	-1.58
Au	AuF ₃	-1.45
K	KF ³	-1.41
Os	OsF ₈	-1.39
Os	OsF ₆	-1.35
In	InF ₂	-1.33
Cr	CrF ₄	-1.31
Ta	TaF ₅	-1.30
Sn	SnF ₂	-1.26
Pb	PbF ₂	-1.22
Cr	CrF ₅	-1.22
Ge	GeF ₄	-1.56
Rb	RbF	-1.14

Table 42 (cont.)

<u>Reaction</u>	<u>Product</u>	<u>Enthalpy, cal/cc</u>
Nb	NbF ₅	-1.03
Sb	SbF ₃	-1.03
Mo	MoF ₆	-1.01
Bi	BiF ₄	-1.01
V	VF ₅	-1.01
Bi	BiF ₃	- .95
Mo	MoF ₅	- .95
Cs	CsF	- .88
Mo	MoF ₄	- .69
Sn	SnF ₄	- .66
Fe	FeF ₂	- .64
Cu	CuF ₂	- .60
W	Wf ₄	- .58
Co	CoF ₃	- .58
In	InF	- .57
Sb	SbF ₅	- .43
Tl	TlF	- .37
Cu	CuF	- .30
Ag	AgF	- .28

IV. ENTHALPY BEHAVIOR PATTERNS

The groups examined in the present study are compared in Table 43 according to the energy of their reactions. The most meaningful comparison would involve reactions between one metal and the compounds of another metal, e.g., the reactions of magnesium with the carbide, nitride, oxide, fluoride, silicide, phosphide, and sulfide of lithium. Because of the limited data available, however, the values in Table 43 apply to reactions of the metals with different compounds in each system. These compounds are listed at the top of each column.

Table 43

COMPARISON OF THE REACTION ENERGIES OF THE GROUPS STUDIED

Family	Volumetric Enthalpy, kcal/cc				
	Group IV	Group V		Group VI	Group VII
2	Li_2C_2	Fe_2N	$\text{Ba}(\text{N}_3)_2$	LiNO_3	CoF_3
Be	-	-2.4	-3.3	-7.8	-5.1
Mg	0	-1.3	-1.3	-5.0	-4.1
Al	-0.1	-1.9	-2.5	-6.4	-3.0
Ta	-2.5	-1.8	-2.5	-5.1	-1.8
Ba	-	-0	-	-2.2	-2.8
Th	-0.6	-2.2	-2.6	-5.9	-3.8
3	CoSi_2	N_3P_5	FeS_2	CoCl_2	WCl_4
Be	-	-	-2.1	-1.2	-2.2
Mg	-0.1	-1.4	-2.4	-1.5	-2.4
Al	-	-	-1.2	-1.0	-1.8
Ta	-	-	-	-	-1.1
Ba	-5.1	-	-1.4	-1.7	-2.3
Th	-	-	-3.2	-1.4	-2.4

The oxide and fluoride reactions tend to be the most energetic. The nitrates and nitrites are included in the oxide system since the reaction products are invariably oxides. The nitrides, including the more energetic azides, the chlorides, the sulfides, and the carbides, are the next most energetic, in that order. The phosphides are the least energetic. Among the metals this order is followed by the reactions of beryllium,

magnesium, aluminum, tantalum, and thorium, with minor irregularities associated with each metal. Except for the highly energetic barium silicide system, barium follows a similar order.

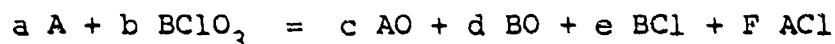
The silicide and chloride systems are unusual in that the heats of formation, in Group II at least, increase greatly with increasing atomic number. In the other systems the heats of formation tend to remain relatively constant or to decrease with increasing atomic number.

Although the data are limited, it appears that compounds of the elements of the second period, i.e., the carbides, nitrides, oxides, and fluorides, are more energetic than those of the third period, i.e., the phosphides and sulfides. Again, the silicides are an exception, being more energetic than the carbides.

V. RELATION OF THE DATA TO REALITY

In using or interpreting the calculated data, the stoichiometry, free energy, and kinetics associated with experimental conditions must be considered.

In almost all cases, the calculated values represent the stoichiometric reaction that has the highest calculated enthalpy. However, many of the reactant combinations can undergo, theoretically at least, several different stoichiometric reactions which produce different combinations of products. The reactions of a metal with a chlorate, for instance, may produce different combinations of oxides and chlorides; i.e., the coefficients c, d, e, and f in the following equation can have values of zero or higher in any combination that will yield a balanced equation.



There is no way of predicting the stoichiometry of a reaction in an experimental situation. Thus, experimentally, a reaction may not yield the maximum energy outputs that were calculated. Also, the reaction mixtures that function most satisfactorily in practical applications usually deviate appreciably from the stoichiometric ratio.

Only enthalpies were considered in the present program. The enthalpy (ΔH) is of most interest for present purposes because it is a measure of the amount of heat energy liberated by a reaction at a particular temperature. Conceptually, a reaction such as



can be considered to occur at an infinitesimal rate at 298°K and to liberate 380.2 kcal of thermal energy. This energy will be dissipated by conduction, convection, and radiation. Since radiative transfer is an inefficient process at such a low temperature, most of the energy will be lost by conduction and convection. Conversely, the reaction may be carried out under adiabatic conditions, in which case the energy liberated will be used to heat the products of the reaction to a temperature determined by the heat content of the products and by the manner in which the enthalpy, entropy, and free energy of the reaction vary with temperature.

In reality, however, these types of reactions proceed rapidly under partially adiabatic conditions after they are initiated, and the products of the reaction are heated to very high temperatures by the energy liberated. As the products cool from a high temperature to 298°K, they effectively convert a sizeable portion of the thermal energy to radiative energy. And since radiation is our primary concern, the

the enthalpy is the most significant thermodynamic quantity. Fortunately, it also is the function which is most frequently available in the literature.

The free energy (ΔF) defines the equilibrium state of a reaction and thus indicates the extent to which a reaction can occur. The free energy can be considered the enthalpy minus a correction term consisting of $T\Delta S$, where T is the temperature and ΔS is the entropy change. In most instances and especially in the present case, where large negative enthalpies are involved, the correction term is small compared with the enthalpy, and $\Delta H_{298} \sim \Delta F_{298}$. The change of the enthalpy with temperature is small because it depends on the change in heat capacity between the products and the reactants, and this change is usually small if no phase changes occur. The amount of energy liberated per mole of reaction will therefore be relatively independent of temperature. On the other hand, the free energy is strongly dependent on temperature. In fact, there is usually a temperature at which the free energy of a reaction passes through zero, indicating that the direction of the reaction has reversed. This means that although the energy output for a mole of reaction may be the same at different temperatures, the reaction will only occur to a small extent when the free energy is near zero.

Thus, although a theoretical reaction may be very energetic, it may, in fact, proceed to such a small extent that the thermal output will be greatly reduced. In a future program it may be interesting to examine the behavior of the free-energy function of some of the more interesting reactions for which free-energy data of the constituents are available.

A factor not considered but very important for practical applications is the kinetics of the reactions. There is no way of predicting the kinetics of these types of reactions. Although a reaction may be highly energetic, its kinetics may be such that the output of thermal energy is too slow to be utilized practically. In addition, these reactions must be heated to a temperature at which they can propagate at a finite rate. This temperature cannot be predicted, but is very important for practical applications and even for theoretical studies.

Because of all these unknown factors in the experimental and practical realizations of these reactions, an extensive experimental program involving several areas of study is necessary. Calorimetric studies can be used to determine the validity of the present calculations. The thermal output can be studied as a function of the stoichiometry of the reaction and the physical variations of the reactants. To further substantiate the calculations, the products of the reactions can be chemically analyzed. For theoretical and practical applications the kinetics and mechanisms of the reactions can

be studied by burning rate, radiation, and spectroscopic studies, and differential thermal analysis and thermogravimetric analysis at different stoichiometries, different ambient conditions, and different variations of the physical properties of the reactants.

In summary, the thermal data presented in this report provide a rational method for choosing reactions to be studied experimentally for theoretical and practical applications. The ancillary data included on the physical properties of the reactants and the products of each reaction aid in the selection, since these properties may be important for the theoretical and practical applications.

VI. SUMMARY

The heats of reactions of metals with oxides, nitrites, chlorates, perchlorates, chromates, chlorides, fluorides, sulfides, nitrides, azides, carbides, phosphides, and silicides were tabulated on a Univac 1105 computer. The reactions involving chlorates, oxides, nitrates, nitrites, and fluorides tend to be the most energetic. The metals associated with the highest energies released are beryllium, magnesium, aluminum, lithium, calcium, titanium, zirconium, hafnium, lanthanum, cesium, neodymium, praseodymium, thorium, and uranium. The highest energy, -9459 cal/cc, is realized by the reaction of beryllium with magnesium perchlorate.

In all, about 20,000 reactions were tabulated. Each reaction was recorded in the primary tabulation in the form of a balanced equation. This was followed by a tabulation of input data, consisting of heats of formation, molecular weight, melting and boiling points, and also output data, consisting of reaction density and heat of reaction on molar, gravimetric, and volumetric bases.

In consequence of this large amount of detail, a page of data consists of only three equations and the data are voluminous. Therefore, only the most significant results are presented in this report and the remainder summarized. The full utility of the compilation is best realized by the establishment of secondary computer programs, designed to present the data in forms to meet specific requirements. Thus, computer programs were prepared to summarize the data in each class of reactions in descending orders of volumetric and gravimetric heats of reaction. Other programs were used to present graphically the heats of the reactions of a metal with all the oxidants of a particular class or an oxidant with all the metals, on molar, volumetric, and gravimetric bases. Still other programmed tabulations show in grid form the data for all metals with oxidizers (oxides, fluorides, chlorates, etc.), arranged in order of the energy of reaction.

The tabulations of the data presented in this report were prepared to meet the requirements of a specific problem. However, the special merit of the system lies in its versatility, since the possible treatments of the data can be varied to cope with innumerable applications involving other uses of these data.

VII. FUTURE WORK

The studies presented here have been essentially completed as far as the enthalpies are concerned. Almost all systems of potential interest for which data are available are included. It would be of interest, however, to calculate the free energy and equilibria of certain reactions as a function of temperature. These calculations would predict the maximum temperature and the extent of the reactions. They would be limited to reactions for which free energy and specific heat data are available.