SAND95-2448C CONF-960717--4
To be presented at the 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference,
Lake Buena Vista, FL, July 1-3, 1996

A SURVEY OF COMBUSTIBLE METALS, THERMITES, AND INTERMETALLICS FOR PYROTECHNIC APPLICATIONS*

S. H. Fischer and M. C. Grubelich
Sandia National Laboratories
Albuquerque, NM 87185-1453

ABSTRACT

Thermite mixtures, intermetallic reactants, and metal fuels have long been used in pyrotechnic applications. Advantage of these systems typically include high energy density, impact insensitivity, high combustion temperature, and a wide range of gas production. They generally exhibit high temperature stability, and possess insensitive ignition properties. In this paper, we review the applications, benefits, and characteristics of thermite mixtures, intermetallic reactants, and metal fuels.

INTRODUCTION

Exothermic reactions between a metal and a metal oxide (thermite), between metallic elements (intermetallic), and the combustion of metals (metal oxidation reactions) are extremely useful sources of energy production and material synthesis for numerous applications. For example, the thermite welding process was first demonstrated in 1898 and continues to be the most frequently used method for the field welding of railroad track.[1,2]

Other applications for thermite reactions include: thermite torches for underwater and atmospheric cutting and perforation; electronic hardware destruct devices; additives to propellants and explosives for increased performance; pyrotechnic switches; airbag gas generator materials; reactive fragments; high-temperature-stable igniters; free-standing insertable heat sources; devices to breech ordnance cases to relieve pressure during fuel fires; and methods of producing alumina liners *in situ* for pipes.

Applications for intermetallic reactions include: consumable port covers for ramjet engine inlets; tracer compositions for munitions; ramjet fuels; self-ejecting combustible plumes for large-area heating; ignition aids for thermites; thermal battery heat sources; incendiary projectiles; delay fuzes; additives to propellants to increase burn rate without significant decrease of specific impulse; and shaped-charge liners.

* This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

Metal fuels have been used as: additives to increase shock sensitivity of explosives; additives to increase explosive blast effects; fuel-air explosives; additives to both solid and liquid propellants to increase density impulse; methods of controlling combustion instability in solid propellant rockets; additives to solid and liquid fuels for ramjets to increase range; and fuels in numerous pyrotechnic devices.[2-22]

Thermite, intermetallic, and metal fuels (with an oxidizer) can be ignited via a thermal impulse from a hot-wire, exploding bridgewire (EBW), or semiconductor bridge (SCB) igniter as well as by laser impingement, mechanical methods, or shock initiation.[12,23-29] Many of these formulations are stable at high temperatures and are insensitive to the effects of moisture, corrosion, friction, spark, shock, contaminants, and variations in composition[15]. Clearly, these types of exothermic reaction mixtures provide the output for a wide variety of engineering applications with a large choice of ignition methods.

CALCULATIONS

The "traditional" thermite reaction is taken as the reaction of a stoichiometric mix of aluminum and magnetite (Fe_3O_4) reacting exothermically to completion to the products alumina (Al_2O_3) and iron. Many other thermite mixtures exist; many of these, as well as intermetallic and metal-oxidation reactions, are surveyed in this paper. Some of these reactions produce little or no gas. Others produce significant amounts of gaseous products. The reactant composition can be chosen to produce solid, liquid, and/or gaseous products as required for the particular application.[6,30,31]

Table 1 lists the theoretical maximum density (TMD) of the reactants, the adiabatic reaction temperature with and without taking into account the heats of phase changes, the state of the products, the amount of gas produced referenced to the total mass of the reactants (or products), and the heat of reaction based on the mass and volume of the reactants for a selection of exothermic thermite reactions. The same information for intermetallic reactions is listed in Table 2. In the field of intermetallic reactions, boron, carbon, and silicon are usually considered metallic.[15] In the present study, sulfur was also included. Analogous values (metal density and heat of reaction with respect to the mass and volume of the metal) for metal-oxidation reactions are listed in Table 3. Physical, thermochemical, and reaction data were taken from references 13, 14, 17, 18, 28, and 32-47.

The heat of reaction was calculated assuming complete adiabatic reaction of the reactants starting at 298K. The increase in temperature was calculated using the average specific heat over the temperature range from 298K to the adiabatic reaction temperature. If phase transitions (solid-solid, solid-liquid, or liquid-gas) occurred over that temperature range, the adiabatic reaction temperature was calculated taking into account the heats of those transitions and using the average specific heats for each temperature range between transitions. This calculated temperature is an upper limit for the ideal case of complete combustion and no energy losses.

In most of the calculations reported in the open literature, the adiabatic reaction temperature is calculated by the first method without taking into account the heats of the phase transitions. This does a inadequate job of dealing with the changes in heat capacity as phase changes occur and leads to erroneously high temperatures. For instance, for "traditional" thermite ($8Al + 3Fe_3O_4$) the adiabatic reaction temperature with no phase transitions taken into account was calculated as 4057K. In contrast, with the solid-solid, solid-liquid, and liquid-gas heats of transition included, the adiabatic reaction temperature was more accurately calculated as 3135K. Similarly, for Ti + 2B, the calculated adiabatic reaction temperature dropped from 3710K to 3498K. Measured reaction temperatures are in reasonable agreement with the calculated values. Temperatures ranging from 2800K to 3000K have been measured for $8Al + 3Fe_3O_4$, while that for Ti + 2B has been measured in the range of 3150K to 3300K.[15,47,50]

An accurate calculation of the adiabatic reaction temperature is important for determining whether the reaction is likely to be self-propagating. A strong indication that the reaction is self-propagating is if at least one of the product species is brought to its melt temperature.[43] Another indication that a reaction is self-propagating is an adiabatic reaction temperature greater than 2000K.[17] (Reactions which are not self-propagating under normal conditions may become so when initiated by a high-power stimulus, such as a high-energy shock. Self-propagation can also be promoted by preheating the reactants to a high temperature.[43]) It should be noted that, since the effect of phase changes on the product temperature takes a finite time, the initial temperature rise may control the diffusion and reaction rates before the temperature drops due to the phase changes.[28]

The reaction temperature is also a guide as to which materials are suitable for a given application. For some applications, such as cutting through metal, high temperatures are required. For others, such as air-bag inflation, low-temperature products are desirable.

DISCUSSION

For engineering applications, the "optimal" exothermic mixture is dependent on several factors which include: the energy per unit mass (or volume depending on the requirements of the application); the chemical stability of the reactants and products at normal operating temperatures; the chemical compatibility of the reactants and products with other materials present in the application; the toxicity of the reactants and products; the reaction rate; ease of processing; availability of the reactants; reaction temperature; state of the products; and cost.

From Tables 1 and 2, thermite and intermetallic compositions can be selected to produce solid, liquid, or gaseous reaction products as required for a particular application. In situations where gas production is undesirable, such as obturated systems, applications for which it is desirable to control the reaction rate by conduction rather than convection, or systems which may be adversely affected by pressure variations, solid and liquid products are more suitable. However, in order to perform mechanical work, rapidly convey the product (as in a torch-type output), or inflate items such as airbags, the production of gases is required.

For the selection of metal fuels similar compromises apply. Desirable properties for metal fuels are a high heat of combustion per unit mass of metal (or of the metal and the oxidizer for some applications), a high density, and low melt and vaporization temperatures. Table 3 contains several properties of importance. Ideally one would select boron or beryllium based on their high energy content. Unfortunately, low combustion efficiency and toxicity, respectively, limit the application of these metals. In general, the wide use of aluminum in propellant, pyrotechnic, and explosive formulations is because of its many desirable properties. Most other metals have applications in systems requiring very specific properties. For example, zirconium is used where ignition sensitivity and high reaction rates are required, while copper is used when a good heat conductor is necessary.

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

SUMMARY

Numerous thermite and intermetallic energetic compositions exist that can be used for a wide variety of engineering applications. Metal combustion reactions are also of great utility. A comprehensive list of these materials and their energetic properties, including a computation of adiabatic reaction temperatures with and without phase changes, was presented here. Comparison to experimentally measured reaction temperatures shows reasonable agreement with the calculated adiabatic reaction temperatures. The heats of reaction and temperatures provide a useful guide for choosing exothermic formulations for engineering applications.

REFERENCES

1. E. Moin, The Current Status of Field Welding of Rail, *Railway Track Struct.*, October 1988.
2. A. A. Shidlovskiy, *Principles of Pyrotechnics*, Mashinostroyeniye Press, 1964.
3. J. H. Mohler, D. L. Halcomb, and D. R. Begeal, *An Effective Low-Profile Thermite Torch*, MLM--3650(OP), 1990.
4. S. J. Marziano and R. E. Donnard, *Thermite Penetrator Device*, U. S. Patent 4,216,721, 1980.
5. S. Calsson and H. Schmid, *Rocket and Ramjet Propellants*, European Patent Application 0 487 473 A1, 1991.
6. J. C. Hinshaw and R. J. Blau, *Thermite Compositions for Use as Gas Generators*, International Application WO 95/04672, 1995.
7. A. Gibson, L. D. Haws, and J. H. Mohler, *Integral Low-Energy Thermite Igniter*, PATENTS-US--A6494487, 1983.
8. J. H. Westbrook, Miscellaneous Applications, Chapter 31 in *Intermetallic Compounds, Vol. 2, Practice*, ed. J. H. Westbrook and R. L. Fleisher, pp. 645-656, 1994.
9. A. C. Munger, J. H. Mohler, and M. D. Kelly, Feasibility of a Free-Standing Insertable Heat Source, *Proc. Int. Pyrotechnics Seminar, 8th*, 496-511, 1982.
10. M. A. Riley, P. D. Zavitsanos, C. Files, D. Walz, and A. C. Ratzel, *Particulate Plume Radiation via Intermetallic Reactions*, SAND91-2696A, abstract for presentation to Int. Pyro. Soc. Ann. Meeting, July 1992, Breckenridge, CO.
11. J. H. McLain, *Pyrotechnics from the Viewpoint of Solid State Chemistry*, Franklin Institute Press, 1980.
12. A. P. Hardt, *Study of Tracer Munitions Using Intermetallic Reactions*, FA-TR-74043, 1974.
13. R. J. Hancox, *The Development of Plastic Thermite*, MRL-R-868, 1983.
14. R. J. Hancox, The Development of Plastic Thermite, *Proc. Int. Pyrotechnics Seminar, 9th*, 257-274, 1984.
15. A. P. Hardt, *Incendiary Potential of Exothermic Intermetallic Reactions*, AFATL-TR-71-87, 1971.
16. J. L. Prentice, *Heat Sources for Thermal Batteries: Exothermic Intermetallic Reactions*, US Patent 4,158,084, 1979.
17. L. L. Wang, Z. A. Munir, and Y. M. Maximov, "Thermite Reactions: Their Utilization in the Synthesis and Processing of Materials, *J. Matls. Sci* 28 (1993) 3693-3708, 1993.
18. C. S. Cross, *Improvements in or relating to Explosive Compositions*, Patent Specification 1,165,027, 1969.
19. J. Covino, *Bonding Agents for Thermite Compositions*, US Patent 5,035,756, 1989.
20. H. E. Montgomery, Jr., *Reactive Fragment*, U. S. Patent 3,961,576, 1976.
21. J. A. Trimble and T. D. Meyers, *Nonejectable Port Cover for Ramjet Engines*, CPIA-PUB-455-VOL-III, JANNAF Propulsion Meeting, 1986.
22. R. F. Vetter, *Rocket Motor Thermal Case Penetrator - An Approach to Fast Cookoff Hazard Reduction*, CPIA-PUB-425-VOL-III, JANNAF Propulsion Meeting, 1985.
23. N. Le Poidevin, A Fuse for Thermite Reaction, letter to *Sch Science Review* 48 164 (243-4), 1966.
24. A. C. Munger and M. D. Kelly, Parameters Affecting Hot Wire Ignition of Thermite Mixtures, *Proc. Int. Pyrotechnics Seminar, 9th*, 405-414, 1984.
25. R. W. Bickes, Jr., M. C. Grubelich, S. M. Harris, J. A. Merson, J. H. Weinlein, *An Overview of Semiconductor Bridge, SCB, Applications at Sandia National Laboratories*," 31st AIAA Joint Propulsion Conference and Exhibit, San Diego, July 10-12, 1995, SAND95-0968C.
26. A. P. Hardt, Shock Initiation of Thermite, *Proc. Int. Pyrotechnic Seminar, 13th*, 425-438, 1988.
27. L. L. Wang, Z. A. Munir, and J. B. Holt, *J. Matls. Synthesis and Processing*, vol. 2, No. 4, 1994.
28. P. V. Phung and A. P. Hardt, "Ignition Characteristics of Gasless Reactions," *Comb. and Flame* 22 323-335 (1974).
29. R. W. Bickes, Jr., M. C. Grubelich, J. A. Romero, D. J. Staley, R. J. Buss, P. P. Ward, and K. L. Erickson, *A New Concept for Very Low Energy Detonators and Torches*, SAND96-0703, March 1996.
30. D. L. Halcomb and J. H. Mohler, *High- and Low-Temperature-Stable Thermite Composition for Producing High-Pressure, High-Velocity Gases*, U. S. Patent 4,963,203, 1990.

31. R. J. Hancox, *Compositions and Devices for High Temperature Combustion*, Patent Application WO 85/00364, EP0148252, 1985.
32. *TAPP Thermochemical and Physical Properties*, Version 2.2, E. S. Microware, 1994.
33. G. V. Samsanov, *The Oxide Handbook*, Inst. of Problems in Materials Science, Academy of Sciences of the Ukrainian SSR, Kiev, USSR.
34. I. Barin, *Thermochemical Data of Pure Substances*, 1989, VCH.
35. I. Barin, O Knacke, and O. Kubaschewski, *Thermochemical Properties of Inorganic Substances*, 1977, Springer-Verlag.
36. N. A. Lange, *Handbook of Chemistry*, Tenth Edition, 1961.
37. R. H. Perry and C. H. Chilton, *Chemical Engineer's Handbook, 5th Edition*, 1973.
38. R. C. Weast and M. J. Astle, *CRC Handbook of Chemistry and Physics, 59th Edition*, CRC Press, 1978.
39. C. E. Wicks and F. E. Block, *Thermodynamic Properties of 65 Elements--Their Oxides. Halides, Carbides, and Nitrides*, Bureau of Mines, U. S. Dept. of Interior, 1963.
40. W. H. Gitzen, *Alumina As a Ceramic Material*, ACS, 1970.
41. Bismuth and Bismuth Alloys, in *Kirk-Othmer Encyclopedia of Chemical Technology, Volume 4*, John Wiley & Sons, 1992
42. A. A. Shidlovskii and V. V. Gorbunov, "Combustion of Nickel-Aluminum Thermite," *Fizika Goreniya I Vzryva*, vol. 18, no. 4, 420-422, 1983.
43. A. P. Hardt and P. V. Phung, "Propagation of Gasless Reactions in Solids – I. Analytical Study of Exothermic Intermetallic Reactions Rates." *Comb. And Flame* 21 77-89, 1973.
44. J. Mohler, personal communications, 1996.
45. Y. S. Touloukian, *Thermophysical Properties of High Temperature Solid Materials*, 1967.
46. J. V. Goodfellow, *Improvements in or relating to Explosive Compositions*, Patent Spec. 1,165,027, 1969.
47. A. G. Merzhanov, *Pyrotechnical Aspects of Self-Propagating High-Temperature Synthesis (SHS)*, NSWCCR/RDTN-94/004, 1994.
48. V. A. Begolyubov, *Temperature of an Aluminothermic Process as a Function of Heat Evolved per Kilogram*, Stal' 17, 531-535, 1957 (translation SAND80-6013).
49. D. A. Powers and F. E. Arellano, *Direct Observation of Melt Behavior During High Temperature Melt/Concrete Interaction*, SAND81-1754, 1982.
50. W. W. Tarbell, R. E. Blose, and F. E. Arellano, *Molten Thermite Teeming Into an Iron Oxide Particle Bed*, SAND82-2475, 1984.

Table 1 - Thermite Reactions

reactants		adiabatic reaction temperature (K)		state of products		gas production		heat of reaction	
constituents	ρ_{TMD}, g/cm^3	w/o phase changes	w/ phase changes	state of oxide	state of metal	moles gas per 100 g	g of gas per g	-Q, cal/g	-Q, cal/cm^3
$2Al + 3AgO$	6.085	7503	3253	l-g	gas	0.7519	0.8083	896.7	5457
$2Al + 3Ag_2O$	6.386	4941	2436	liquid	l-g	0.4298	0.4636	504.8	3224
$2Al + B_2O_3$	2.524	2621	2327	s-l	solid	0.0000	0.0000	780.7	1971
$2Al + Bi_2O_3$	7.188	3995	3253	l-g	gas	0.4731	0.8941	506.1	3638
$2Al + 3CoO$	5.077	3392	3201	liquid	l-g	0.0430	0.0254	824.7	4187
$8Al + 3Co_3O_4$	4.716	3938	3201	liquid	l-g	0.2196	0.1294	1012	4772
$2Al + Cr_2O_3$	4.190	2789	2327	s-l	liquid	0.0000	0.0000	622.0	2606
$2Al + 3CuO$	5.109	5718	2843	liquid	l-g	0.5400	0.3431	974.1	4976
$2Al + 3Cu_2O$	5.280	4132	2843	liquid	l-g	0.1221	0.0776	575.5	3039
$2Al + Fe_2O_3$	4.175	4382	3135	liquid	l-g	0.1404	0.0784	945.4	3947
$8Al + 3Fe_3O_4$	4.264	4057	3135	liquid	l-g	0.0549	0.0307	878.8	3747
$2Al + 3HgO$	8.986	7169	3253	l-g	gas	0.5598	0.9913	476.6	4282
$10Al + 3I_2O_5$	4.119	8680	>3253*	gas	gas	0.6293	1.0000	1486	6122
$4Al + 3MnO_2$	4.014	4829	2918	liquid	gas	0.8136	0.4470	1159	4651
$2Al + MoO_3$	3.808	5574	3253	l-g	liquid	0.2425	0.2473	1124	4279
$10Al + 3Nb_2O_5$	4.089	3240	2705	liquid	solid	0.0000	0.0000	600.2	2454
$2Al + 3NiO$	5.214	3968	3187	liquid	l-g	0.0108	0.0063	822.3	4288
$2Al + Ni_2O_3$	4.045	5031	3187	liquid	l-g	0.4650	0.2729	1292	5229
$2Al + 3PbO$	8.018	3968	2327	s-l	gas	0.4146	0.8591	337.4	2705
$4Al + 3PbO_2$	7.085	6937	3253	l-g	gas	0.5366	0.9296	731.9	5185
$8Al + 3Pb_3O_4$	7.428	5427	3253	l-g	gas	0.4215	0.8466	478.1	3551
$2Al + 3PdO$	7.281	5022	3237	liquid	l-g	0.6577	0.6998	754.3	5493
$4Al + 3SiO_2$	2.668	2010	1889	solid	liquid	0.0000	0.0000	513.3	1370
$2Al + 3SnO$	5.540	3558	2876	liquid	l-g	0.1070	0.1270	427.0	2366
$4Al + 3SnO_2$	5.356	5019	2876	liquid	l-g	0.2928	0.3476	686.8	3678
$10Al + 3Ta_2O_5$	6.339	3055	2452	liquid	solid	0.0000	0.0000	335.6	2128
$4Al + 3TiO_2$	3.590	1955	1752	solid	liquid	0.0000	0.0000	365.1	1311
$16Al + 3U_3O_8$	4.957	1406	1406	solid	solid	0.0000	0.0000	487.6	2417
$10Al + 3V_2O_5$	3.107	3953	3273	l-g	liquid	0.0699	0.0356	1092	3394
$4Al + 3WO_2$	8.085	4176	3253	l-g	solid	0.0662	0.0675	500.6	4047
$2Al + WO_3$	5.458	5544	3253	l-g	liquid	0.1434	0.1463	696.4	3801
$2B + Cr_2O_3$	4.590	977	917	liquid	solid	0.0000	0.0000	182.0	835.3
$2B + 3CuO$	5.665	4748	2843	gas	l-g	0.4463	0.2430	738.1	4182
$2B + Fe_2O_3$	4.661	2646	2065	liquid	liquid	0.0000	0.0000	590.1	2751
$8B + 3Fe_3O_4$	4.644	2338	1903	liquid	liquid	0.0000	0.0000	530.1	2462
$4B + 3MnO_2$	4.394	3000	2133	l-g	liquid	0.3198	0.1715	773.1	3397
$8B + 3Pb_3O_4$	8.223	4217	2019	liquid	l-g	0.4126	0.8550	326.9	2688
$3Be + B_2O_3$	1.850	3278	2573	liquid	s-l	0.0000	0.0000	1639	3033
$3Be + Cr_2O_3$	4.089	3107	2820	s-l	liquid	0.0000	0.0000	915.0	3741

* More data needed for this calculation.

Table 1 - Thermite Reactions (cont.)

reactants		adiabatic reaction temperature (K)		state of products		gas production		heat of reaction	
constituents	ρ_{TMD}, g/cm^3	w/o phase changes	w/ phase changes	state of oxide	state of metal	moles gas per 100 g	g of gas per g	-Q, cal/g	-Q, cal/cm^3
$Be + CuO$	5.119	3761	2820	s-l	liquid	0.0000	0.0000	1221	6249
$3Be + Fe_2O_3$	4.163	4244	3135	liquid	l-g	0.1029	0.0568	1281	5332
$4Be + Fe_3O_4$	4.180	4482	3135	liquid	l-g	0.0336	0.0188	1175	4910
$2Be + MnO_2$	3.882	6078	2969	liquid	gas	0.9527	0.5234	1586	6158
$2Be + PbO_2$	7.296	8622	4123	l-g	gas	0.4665	0.8250	875.5	6387
$4Be + Pb_3O_4$	7.610	5673	3559	liquid	gas	0.4157	0.8614	567.8	4322
$2Be + SiO_2$	2.410	2580	2482	solid	liquid	0.0000	0.0000	936.0	2256
$3Hf + 2B_2O_3$	6.125	2656	2575	solid	liquid	0.0000	0.0000	296.5	1816
$3Hf + 2Cr_2O_3$	7.971	2721	2572	solid	liquid	0.0000	0.0000	302.3	2410
$Hf + 2CuO$	8.332	5974	2843	solid	l-g	0.3881	0.2466	567.6	4730
$3Hf + 2Fe_2O_3$	7.955	5031	2843	solid	l-g	0.2117	0.1183	473.3	3765
$2Hf + Fe_3O_4$	7.760	4802	2843	solid	l-g	0.1835	0.1025	450.4	3496
$Hf + MnO_2$	8.054	5644	3083	s-l	gas	0.3263	0.3131	534.6	4305
$2Hf + Pb_3O_4$	9.775	9382	4410	liquid	gas	0.2877	0.5962	345.9	3381
$Hf + SiO_2$	6.224	2117	1828	solid	liquid	0.0000	0.0000	203.3	1265
$2La + 3AgO$	6.827	8177	4173	liquid	gas	0.4619	0.4983	646.7	4416
$2La + 3CuO$	6.263	6007	2843	liquid	l-g	0.3737	0.2374	606.4	3798
$2La + Fe_2O_3$	5.729	4590	3135	liquid	l-g	0.1234	0.0689	529.6	3034
$2La + 3HgO$	8.962	7140	≥4473*	l-g	gas	.32 - .43	0.65 - 1	392.0	3513
$10La + 3I_2O_5$	5.501	9107	≥4473*	gas	gas	0.3347	1.0000	849.2	4672
$4La + 3MnO_2$	5.740	5270	3120	liquid	gas	0.3674	0.2019	593.4	3406
$2La + 3PbO$	8.207	4598	2609	liquid	gas	0.3166	0.6561	287.4	2359
$4La + 3PbO_2$	7.629	7065	≥4473*	gas	gas	0.3927	1.0000	518.8	3958
$8La + 3Pb_3O_4$	7.789	5628	4049	liquid	gas	0.2841	0.5886	378.6	2949
$2La + 3PdO$	7.769	5635	3237	liquid	l-g	0.2450	0.2606	536.2	4166
$4La + 3WO_2$	8.366	3826	3218	liquid	solid	0.0000	0.0000	361.2	3022
$2La + WO_3$	6.572	5808	4367	liquid	liquid	0.0000	0.0000	445.8	2930
$6Li + B_2O_3$	0.891	2254	1843	s-l	solid	0.0000	0.0000	1293	1152
$6Li + Cr_2O_3$	1.807	2151	1843	s-l	solid	0.0000	0.0000	799.5	1445
$2Li + CuO$	2.432	4152	2843	liquid	l-g	0.2248	0.1428	1125	2736
$6Li + Fe_2O_3$	1.863	3193	2510	liquid	liquid	0.0000	0.0000	1143	2130
$8Li + Fe_3O_4$	0.517	3076	2412	liquid	liquid	0.0000	0.0000	1053	2036
$4Li + MnO_2$	1.656	3336	2334	liquid	l-g	0.4098	0.2251	1399	2317
$6Li + MoO_3$	1.688	4035	2873	l-g	solid	0.2155	0.0644	1342	2265
$8Li + Pb_3O_4$	4.133	4186	2873	l-g	liquid	0.1655	0.0496	536.7	2218
$4Li + SiO_2$	1.177	1712	1687	solid	s-l	0.0000	0.0000	763.9	898.7
$6Li + WO_3$	2.478	3700	2873	l-g	solid	0.0113	0.0034	825.4	2046
$3Mg + B_2O_3$	1.785	6389	3873	l-g	liquid	0.4981	0.2007	2134	1195
$3Mg + Cr_2O_3$	3.164	3788	2945	solid	l-g	0.1023	0.0532	813.1	2573

* More data needed for this calculation.

Table 1 - Thermite Reactions (cont.)

reactants		adiabatic reaction temperature (K)		state of products		gas production		heat of reaction	
constituents	ρ_{TMD}, g/cm^3	w/o phase changes	w/ phase changes	state of oxide	state of metal	moles gas per 100 g	g of gas per g	-Q, cal/g	-Q, cal/cm^3
$Mg + CuO$	3.934	6502	2843	solid	l-g	0.8186	0.5201	1102	4336
$3Mg + Fe_2O_3$	3.224	4703	3135	liquid	l-g	0.2021	0.1129	1110	3579
$4Mg + Fe_3O_4$	3.274	4446	3135	liquid	l-g	0.1369	0.0764	1033	3383
$2Mg + MnO_2$	2.996	5209	3271	liquid	gas	0.7378	0.4053	1322	3961
$4Mg + Pb_3O_4$	5.965	5883	3873	l-g	gas	0.4216	0.8095	556.0	3316
$2Mg + SiO_2$	2.148	3401	2628	solid	l-g	0.9200	0 - .26	789.6	1695
$2Nd + 3AgO$	7.244	7628	3602	liquid	gas	0.4544	0.4902	625.9	4534
$2Nd + 3CuO$	6.719	5921	2843	liquid	l-g	0.3699	0.2350	603.4	4054
$2Nd + 3HgO$	9.430	7020	<5374*	gas	gas	0.4263	1.0000	392.7	3703
$10Nd + 3I_2O_5$	5.896	10067	<7580*	gas	gas	0.3273	1.0000	840.6	4956
$4Nd + 3MnO_2$	6.241	5194	3287	liquid	gas	0.3580	0.1967	589.9	3682
$4Nd + 3PbO_2$	8.148	6938	<5284*	gas	gas	0.3862	1.0000	517.8	4219
$8Nd + 3Pb_3O_4$	8.218	5553	3958	liquid	gas	0.2803	0.5808	379.6	3120
$2Nd + 3PdO$	8.297	6197	3237	liquid	l-g	0.2394	0.2547	532.7	4420
$4Nd + 3WO_2$	9.016	4792	3778	liquid	liquid	0.0000	0.0000	362.9	3272
$2Nd + WO_3$	7.074	5438	4245	liquid	liquid	0.0000	0.0000	446.1	3156
$2Ta + 5AgO$	9.341	6110	2436	liquid	l-g	0.4229	0.4562	466.2	4355
$2Ta + 5CuO$	9.049	4044	2843	liquid	l-g	0.0776	0.0493	390.3	3532
$6Ta + 5Fe_2O_3$	9.185	2383	2138	solid	liquid	0.0000	0.0000	235.0	2558
$2Ta + 5HgO$	12.140	5285	≤4199*	liquid	gas	0.3460	0.6942	263.3	3120
$2Ta + I_2O_5$	7.615	8462	7240	gas	gas	0.2875	1.0000	648.6	4939
$2Ta + 5PbO$	10.640	2752	2019	solid	l-g	0.1475	0.3056	154.5	1644
$4Ta + 5PbO_2$	11.215	4935	3472	liquid	gas	0.2604	0.5397	338.6	3797
$8Ta + 5Pb_3O_4$	10.510	3601	2019	solid	l-g	0.2990	0.6196	225.0	2365
$2Ta + 5PdO$	11.472	4344	3237	liquid	l-g	0.0575	0.0612	360.4	4135
$4Ta + 5WO_2$	13.515	2556	2196	liquid	solid	0.0000	0.0000	145.1	1962
$6Ta + 5WO_3$	9.876	2883	2633	liquid	solid	0.0000	0.0000	206.2	2036
$3Th + 2B_2O_3$	6.688	3959	3135	solid	liquid	0.0000	0.0000	337.8	2259
$3Th + 2Cr_2O_3$	8.300	4051	2945	solid	l-g	0.0590	0.0307	334.5	2776
$Th + 2CuO$	8.582	7743	2843	solid	l-g	0.4301	0.3421	558.7	4795
$3Th + 2Fe_2O_3$	8.280	6287	3135	solid	l-g	0.2619	0.1463	477.9	3957
$2Th + Fe_3O_4$	8.092	5912	3135	solid	l-g	0.2257	0.1261	458.5	3710
$Th + MnO_2$	8.391	7151	3910	liquid	gas	0.3135	0.1722	529.2	4440
$Th + PbO_2$	10.19	10612	4673	l-g	gas	0.2817	0.6231	482.8	4922
$2Th + Pb_3O_4$	9.845	8532	4673	l-g	gas	0.2695	0.5633	360.5	3549
$Th + SiO_2$	6.732	3813	2628	solid	l-g	0 - .34	0 -.10	258.2	1738
$3Ti + 2B_2O_3$	2.791	1498	1498	solid	solid	0.0000	0.0000	276.6	772.0
$3Ti + 2Cr_2O_3$	4.959	1814	1814	solid	solid	0.0000	0.0000	296.2	1469
$Ti + 2CuO$	5.830	5569	2843	liquid	l-g	0.3242	0.2060	730.5	4259

* More data needed for this calculation.

Table 1 - Thermite Reactions (cont.)

reactants		adiabatic reaction temperature (K)		state of products		gas production		heat of reaction	
constituents	ρ_{TMD}, g/cm^3	w/o phase changes	w/ phase changes	state of oxide	state of metal	moles gas per 100 g	g of gas per g	-Q, cal/g	-Q, cal/cm^3
$3Ti + 2Fe_2O_3$	5.010	3358	2614	liquid	liquid	0.0000	0.0000	612.0	3066
$Ti + Fe_3O_4$	4.974	3113	2334	liquid	liquid	0.0000	0.0000	563.0	2800
$Ti + MnO_2$	4.826	3993	2334	liquid	l-g	0.3783	0.2078	752.7	3633
$2Ti + Pb_3O_4$	8.087	5508	2498	liquid	gas	0.3839	0.7955	358.1	2896
$Ti + SiO_2$	3.241	715	715	solid	solid	0.0000	0.0000	75.0	243.1
$2Y + 3CuO$	5.404	7668	3124	liquid	l-g	0.7204	0.4577	926.7	5008
$8Y + 3Fe_3O_4$	4.803	5791	3135	liquid	l-g	0.3812	0.2129	856.3	4113
$10Y + 3I_2O_5$	4.638	12416	>4573*	gas	gas	0.4231	1.0000	1144	5308
$4Y + 3MnO_2$	4.690	7405	<5731*	gas	gas	0.8110	1.0000	1022	4792
$2Y + MoO_3$	4.567	8778	≥4573*	gas	liquid	0.6215	1.0000	1005	4589
$2Y + Ni_2O_3$	4.636	7614	3955	liquid	gas	0.5827	0.3420	1120	5194
$4Y + 3PbO_2$	6.875	9166	≥4573*	gas	gas	0.4659	1.0000	751.0	5163
$2Y + 3PdO$	7.020	8097	3237	liquid	l-g	0.4183	0.4451	768.1	5371
$4Y + 3SnO_2$	5.604	7022	4573	l-g	gas	.37 - .62	0.44 - 1	726.1	4068
$10Y + 3Ta_2O_5$	6.316	5564	≥4573*	l-g	liquid	0 - 0.23	0 - 0.51	469.7	2966
$10Y + 3V_2O_5$	3.970	7243	≥3653*	l-g	gas	0.2130	0.4181	972.5	3861
$2Y + WO_3$	5.677	8296	≥4573*	gas	liquid	0.2441	0.5512	732.2	4157
$3Zr + 2B_2O_3$	3.782	2730	2573	solid	s-l	0.2930	0.0317	437.4	1654
$3Zr + 2Cr_2O_3$	5.713	2915	2650	solid	liquid	0.0000	0.0000	423.0	2417
$Zr + 2CuO$	6.400	6103	2843	solid	l-g	0.5553	0.3529	752.9	4818
$3Zr + 2Fe_2O_3$	5.744	4626	3135	liquid	l-g	0.0820	0.0458	666.2	3827
$2Zr + Fe_3O_4$	5.668	4103	3135	liquid	l-g	0.0277	0.0155	625.1	3543
$Zr + MnO_2$	5.647	5385	2983	s-l	gas	0.5613	0.3084	778.7	4398
$2Zr + Pb_3O_4$	8.359	6595	3300	l-g	gas	0.3683	0.7440	408.1	3412
$Zr + SiO_2$	4.098	2233	1687	solid	s-l	0.0000	0.0000	299.7	1228

* More data needed for this calculation.

Table 2 - Intermetallic Reactions

reactants		adiabatic reaction temperature (K)		state of intermetallic product	gas production		heat of reaction	
constituents	ρ_{TMD}, g/cm^3	w/o phase changes	w/ phase changes		moles gas per 100 g	g gas per g	-Q, cal/g	-Q, cal/cm^3
Al + 2B	2.607	2251	≥1253*	l-g	0 - 2.1	0 - 1	742	1940
4Al + 3C	2.574	1673	1673	solid	0.0	0.0	371	965
2Al + Ca	2.051	2836	1738	liquid	0.0	0.0	558	1140
4Al + Ca	2.248	1880	≥973*	s-l	0.0	0.0	348	782
4Al + Ce	4.095	1173	1173	solid	0.0	0.0	126	458
Al + Co	5.171	2195	≥1913*	s-l	0.0	0.0	307	1590
4Al + Co	3.581	*	*	*	*	*	231	637
5Al + 2Co	3.999	1755	≥1453*	s-l	0.0	0.0	277	1110
3Al + Cr	3.568	793	793	solid	0.0	0.0	120	430
Al + Cu	5.294	935	935	solid	0.0	0.0	108	573
Al + Fe	4.844	1423	1423	solid	0.0	0.0	211	1020
3Al + Fe	3.688	1407	1407	solid	0.0	0.0	278	1020
4Al + La	3.946	1495	*	s-l	0.0	0.0	166	780
Al + Li	1.476	1160	≥973*	s-l	0.0	0.0	345	509
Al + Mn	4.676	803	803	solid	0.0	0.0	124	586
Al + Ni	5.165	2362	≥1911*	s-l	0.0	0.0	330	1710
Al + 3Ni	6.820	1524	1524	solid	0.0	0.0	180	1230
Al + Pd	7.072	2725	2653	liquid	0.0	0.0	327	2890
4Al + Pr	4.094	1703	*	s-l	0.0	0.0	216	800
Al + Pt	11.63	3379	3073	liquid	0.0	0.0	216	2510
4Al + Pu	6.708	1403	1403	solid	0.0	0.0	123	820
2Al + 3S	2.102	*	*	*	0.0	0.0	800	1680
Al + Ta	9.952	1011	1011	solid	0.0	0.0	56.7	564
3Al + Ta	6.407	665	665	solid	0.0	0.0	35.9	230
Al + Ti	3.628	1597	1597	solid	0.0	0.0	240	872
Al + 3Ti	4.071	*	*	*	*	*	138	560
2Al + Ti	3.326	1643	*	l-s	*	*	314	1100
3Al + Ti	3.172	1591	1591	solid	0.0	0.0	272	862
3Al + 2Ti	3.448	*	*	*	*	*	158	544
4Al + U	6.582	1205	*	liquid	0.0	0.0	89.8	591
3Al + V	3.412	1023	1023	solid	0.0	0.0	198	792
2Al + Zr	4.240	1923	*	l-s	*	*	267	1130
4B + C	2.444	1202	1202	solid	0.0	0.0	308	751
6B + Ce	4.374	2388	2388	solid	0.0	0.0	395	1730
2B + Cr	4.622	1571	1571	solid	0.0	0.0	306	1410
2B + Hf	8.232	3945	3653	liquid	0.0	0.0	401	3300
6B + La	4.198	2503	*	l-s	0.0	0.0	560	2350
2B + Mg	2.031	1706	1706	dec	0.0	0.0	479	972
6B + Mg	2.234	918	918	solid	0.0	0.0	251	600

* More data needed for this calculation.

Table 2 - Intermetallic Reactions (cont.)

reactants		adiabatic reaction temperature (K)		state of intermetallic product	gas production		heat of reaction	
constituents	ρ_{TMD}, g/cm^3	w/o phase changes	w/ phase changes		moles gas per 100 g	g gas per g	-Q, cal/g	-Q, cal/cm^3
2B + Mn	4.732	1386	1386	solid	0.0	0.0	294	1390
2B + Mo	6.091	1533	1533	solid	0.0	0.0	196	1280
2B + Nb	5.875	2793	2793	solid	0.0	0.0	524	3080
6B + Sm	4.684	1233	1233	solid	0.0	0.0	232	1050
6B + Si	2.497	503	503	solid	0.0	0.0	76.4	177
2B + Ta	10.36	2766	2766	solid	0.0	0.0	247	2560
4B + Th	7.240	1823	1823	solid	0.0	0.0	189	1360
B + Ti	3.922	3559	≥2453*	l or g	0 - 1.7	0 - 1	652	2560
2B + Ti	3.603	3710	3498	liquid	0.0	0.0	1320	5170
2B + U	12.220	1335	1335	solid	0.0	0.0	149	1820
4B + U	9.407	2124	2124	solid	0.0	0.0	209	1960
B + V	4.749	2574	2574	solid	0.0	0.0	536	2540
2B + V	4.187	2960	2960	s-l	0.0	0.0	671	2810
5B + 2W	10.37	1233	1233	solid	0.0	0.0	83	1350
6B + Y	3.354	973	973	solid	0.0	0.0	156	503
2B + Zr	4.926	3783	3673	liquid	0.0	0.0	683	3360
3Ba + 2Bi	5.185	1673	*	liquid	0.0	0.0	87.3	169
Ba + 2C	3.236	1466	1466	solid	0.0	0.0	111	359
2Ba + Pb	4.025	1913	≥1201*	l-g	0 - .21	0 - 1	143	576
3Ba + 2Sb	4.252	1833	*	liquid	*	*	133	563
2Ba + Sn	4.153	2398	*	l-g	0 - .25	0 - 1	240	1000
Be + 2C	2.131	3043	*	l-g	0 - .33	0 - 1	1750	3720
2Be + C	1.995	1932	1932	solid	0.0	0.0	931	1860
5Be + Nb	3.920	1663	1663	solid	0.0	0.0	336	1300
13Be + Pu	4.756	723	723	solid	0.0	0.0	100	476
13Be + U	4.679	773	773	solid	0.0	0.0	110	513
Bi + K	3.723	1253	*	liquid	0.0	0.0	55	204
Bi + 3K	2.071	1791	*	liquid?	*	*	127	263
Bi + Li	6.319	1273	≥688*	liquid	0.0	0.0	85.5	535
2C + Ca	1.757	1113	1113	solid	0.0	0.0	223	392
2C + Ce	5.201	1779	1779	solid	0.0	0.0	170	884
3C + 7Cr	5.978	1175	1175	solid	0.0	0.0	136	813
C +Hf	9.084	4441	≥4223*	s-l	0.0	0.0	315	2860
2C + La	4.905	1973	1973	solid	0.0	0.0	178	870
3C + 7Mn	6.130	742	742	solid	0.0	0.0	62.1	380
C + 2Mo	7.662	1077	1077	solid	0.0	0.0	62.3	477
2C + 2Na	1.206	733	733	solid	0.0	0.0	137	165
0.98C + Nb	6.522	3182	3182	solid	0.0	0.0	317	2070
C + Nb	9.678	3003	3003	solid	0.0	0.0	321	2060
C + 2Nb	7.328	2634	2634	solid	0.0	0.0	230	1680

* More data needed for this calculation.

Table 2 - Intermetallic Reactions (cont.)

reactants		adiabatic reaction temperature (K)		state of intermetallic product	gas production		heat of reaction	
constituents	ρ_{TMD}, g/cm^3	w/o phase changes	w/ phase changes		moles gas per 100 g	g gas per g	-Q, cal/g	-Q, cal/cm^3
C + Si	2.416	1914	1914	solid	0.0	0.0	436	1050
2C + Sr	2.518	1242	1242	solid	0.0	0.0	160	404
C + Ta	11.90	2678	2678	solid	0.0	0.0	179	2120
1.94C + Th	8.230	2211	2211	solid	0.0	0.0	138	1140
2C + Th	8.169	3073	3073	solid	0.0	0.0	179	1280
C + Ti	3.754	3644	3523	liquid	0.0	0.0	736	2760
C + U	13.96	1871	1871	solid	0.0	0.0	93.6	1310
2C + U	11.29	1573	1573	solid	0.0	0.0	95.5	1080
C + V	4.499	2121	2121	solid	0.0	0.0	383	1720
C + W	13.20	1259	1259	solid	0.0	0.0	49.0	647
C + Zr	5.276	3800	3800	solid	0.0	0.0	455	2400
Ca + 2Mg	1.649	801	801	solid	0.0	0.0	108	178
2Ca + Pb	4.105	1713	≥1476*	liquid	0.0	0.0	172	705
Ca + Si	2.490	2504	2504	liquid	0.0	0.0	529	1320
Ca + Sn	3.772	3622	≥1273*	l or g	0 - 1.5	0 - 1	239	903
2Ca + Sn	2.927	2994	≥1408*	l or g	0 - .50	0 - 1	377	1100
11Cd + Pu	1.056	843	843	solid	0.0	0.0	31	293
Ce + Mg	4.713	1552	*	s-l	0.0	0.0	111	523
2Ce + Pb	8.194	1653	≥1653*	s-l	0.0	0.0	81.5	665
Ce + 2Si	4.547	2083	*	liquid	0.0	0.0	255	1100
Ce + Zn	6.904	1413	>1098*	liquid	0.0	0.0	78	535
Co + Si	4.862	1733	≥1733*	s-l	0.0	0.0	299	1450
Cr + Si	4.316	1231	1231	solid	0.0	0.0	159	684
Cr + 2Si	3.625	1530	1530	solid	0.0	0.0	222	804
3Cr + Si	5.558	1493	1493	solid	0.0	0.0	179	996
5Cr + 3Si	4.900	1671	1671	solid	0.0	0.0	226	1110
Cu + 2Mg	3.199	665	665	solid	0.0	0.0	61.0	195
2Cu + Mg	5.368	721	721	solid	0.0	0.0	52.9	284
Cu + Pd	10.64	873	873	solid	0.0	0.0	44.5	472
Fe + Si	4.564	1659	1659	solid	0.0	0.0	225	1020
Ge + 2Mg	4.123	1678	1391	s-l	0.0	0.0	207	853
2Ge + Nb	6.269	1443	1443	solid	0.0	0.0	84.4	524
Li + Pb	6.848	1258	≥755*	liquid	0.0	0.0	67.2	460
Li + Sb	4.123	1333	*	liquid	0.0	0.0	170	700
Li + Sn	4.298	1516	*	s-l	0.0	0.0	134	576
Mg + S	2.037	7039	*	*	*	*	1500	3060
3Mg + 2Sb	4.039	1433	1433	solid	0.0	0.0	121	484
Mg + Se	3.398	4817	*	*	*	*	678	2300
2Mg + Si	1.956	1286	1286	solid	0.0	0.0	247	483
2Mg + Sn	3.787	1163	1163	solid	0.0	0.0	113	450

* More data needed for this calculation.

Table 2 - Intermetallic Reactions (cont.)

reactants		adiabatic reaction temperature (K)		state of intermetallic product	gas production		heat of reaction	
constituents	ρ_{TMD}, g/cm^3	w/o phase changes	w/ phase changes		moles gas per 100 g	g gas per g	-Q, cal/g	-Q, cal/cm^3
Mg + Te	4.311	4676	*	*	*	*	329	1420
2Mg + Th	5.767	1067	1067	solid	0.0	0.0	54	311
Mg + U	9.874	2213	*	liquid	0.0	0.0	157	1570
Mg+ Y	3.343	1943	*	liquid	0.0	0.0	274	912
Mn + S	2.370	1394	1394	solid	0.0	0.0	164	390
Mn + Si	4.415	1615	≥1543*	s-l	0.0	0.0	224	989
Mn + 1.7Si	3.846	1433	*	s-l	0.0	0.0	226	847
Mo + 2Si	4.581	1854	1854	solid	0.0	0.0	187	855
Mo + 7Si	3.265	1823	1823	solid	0.0	0.0	206	940
3Mo + Si	7.308	1278	1278	solid	0.0	0.0	76.9	562
5Mo + 3Si	6.476	788	788	solid	0.0	0.0	43.1	279
Na + Sb	3.453	1090	*	liquid	0.0	0.0	110	380
Na + Sn	3.548	1073	1073	solid	0.0	0.0	71.4	254
Nb + Ni	8.695	1083	1083	solid	0.0	0.0	71	610
Nb + 2Si	4.463	1897	1897	solid	0.0	0.0	201	898
5Nb + 3Si	6.233	2518	2518	solid	0.0	0.0	222	1390
Ni + Si	4.855	1838	>1265*	s-l	0.0	0.0	235	1140
Pd + Sn	8.966	1599	*	s-l	0.0	0.0	112	1000
Pu + 12Zn	8.409	973	973	solid	0.0	0.0	71.3	600
S + Zn	2.419	4144	*	l-g*	0.0	0.0	500	1210
Si + 2Ta	11.788	1836	1836	solid	0.0	0.0	76.9	907
2Si + Ta	7.086	1781	1781	solid	0.0	0.0	120	8510
3Si + 5Ta	11.195	920	920	solid	0.0	0.0	80.9	906
2Si + Th	6.659	2323	2323	solid	0.0	0.0	144	961
2Si + Ti	3.134	1913	≥1773*	s-l	0.0	0.0	308	967
3Si + 5Ti	3.719	2548	≥2403*	s-l	0.0	0.0	428	1590
2Si + U	8.369	1663	1663	solid	0.0	0.0	106	940
2Si + V	3.429	3341	2023	s-l	0.0	0.0	700	2400
2Si + W	7.480	1549	1549	solid	0.0	0.0	92.6	693
Si + Y	3.754	2108	*	s-l	0.0	0.0	275	1000
Si + 2Zr	5.291	2787	≥2198*	liquid	0.0	0.0	236	1250
2Si + Zr	4.004	1988	1893	liquid	0.0	0.0	258	1040
3Si + 5Zr	5.141	1132	1132	solid	0.0	0.0	255	1310
2U + 17Zn	8.778	973	973	solid	0.0	0.0	60	530
2Zn + Zr	6.816	1723	*	l-s	0.0	0.0	170	1160

* More data needed for this calculation.

Table 3 - Metal Combustion Reactions

metal	oxide	MW, g/mol (metal)	ρ_{TMD}, g/cm^3 (metal)	ΔH_f°, kcal/mol	Q, cal/g of metal	Q, cal/ cm^3 of metal	T_{fus}, K, of metal	T_{vap}, K, of metal
Ag	Ag_2O	107.88	10.5	7.42	34.39	361.1	1234	2436
Al	Al_2O_3	26.98	2.70	400.5	7422	20040	933	2740
B	B_2O_3	10.82	2.5	304.0	14050	35120	2573	4139
Be	BeO	9.01	1.85	143.2	15890	29400	1553	3243
Bi	Bi_2O_3	209.0	9.87	137.2	328.2	3240	544	1837
Ce	Ce_2O_3	140.13	6.8	435.2	1553	10560	1048	3699
Co	CoO	58.93	8.90	56.87	965.0	8589	1701	3201
Cr	Cr_2O_3	52.01	7.14	272.4	2619	18700	2180	2945
Cs	Cs_2O	132.91	1.90	75.95	571.4	1086	301	951
Cs	Cs_2O_3	132.91	1.90	111.3	837.3	1591	301	951
Cs	CsO_2	131.91	1.90	62.04	466.8	886.9	301	951
Cu	CuO	63.54	8.93	37.30	587.0	5244	1356	2843
Cu	Cu_2O	63.54	8.93	40.80	321.1	2868	1356	2843
Fe	Fe_2O_3	55.85	7.86	197.0	1764	13860	1811	3135
Fe	Fe_3O_4	55.85	7.86	267.3	1595	12540	1811	3135
Hf	HfO_2	178.50	11.40	266.2	1491	17000	2495	4964
La	La_2O_3	138.92	6.15	428.7	1543	9489	1193	3730
Li	Li_2O	6.94	0.534	152.1	10960	5852	454	1620
Mg	MgO	24.32	1.74	151.8	6241	10860	923	1363
Mn	Mn_3O_4	54.94	7.30	331.7	2012	14690	1519	2334
Mo	MoO_3	95.95	9.01	178.1	1856	16720	2896	4952
Nb	Nb_2O_5	92.91	8.57	454.0	2443	20940	2750	5015
Nd	Nd_2O_3	144.27	7.01	433.6	1503	10530	1292	3341
Ni	NiO	58.69	8.90	57.29	976.1	8688	1728	3187
Pb	Pb_3O_4	207.20	11.3	171.8	276.4	3133	601	2019
Pd	PdO	106.40	12.0	27.60	259.4	3113	1828	3237
Pt	Pt_3O_4	195.09	21.4	64.05	109.4	2347	2042	4100
Si	SiO_2	28.09	2.49	217.7	7750	19298	1687	2628
Sn	SnO_2	118.70	7.31	138.8	1169	8548	505	2876
Sr	SrO_2	87.62	2.6	153.3	1750	4549	1042	1657
Ta	Ta_2O_5	180.95	16.6	489.0	1351	22430	3290	5698
Th	ThO_2	232.04	11.2	293.5	1265	14170	2023	5063
Ti	TiO_2	47.90	4.50	225.8	4714	21210	1693	3560
U	U_3O_8	238.07	18.9	854.4	1196	22610	1408	4091
V	V_2O_5	50.95	5.87	370.6	3634	21350	2183	3653
W	WO_2	183.86	19.3	140.9	766.6	14790	3695	5936
W	WO_3	183.86	19.3	201.5	1096	21150	3695	5936
Y	Y_2O_3	88.92	4.47	501.4	2819	12600	1799	3611
Zn	ZnO	65.38	7.14	83.76	1281	9147	692	1180
Zr	ZrO_2	123.22	5.68	263.0	2135	12130	2125	4650