Survey of Alternate Stored Chemical Energy Reactions

L. P. Cook
E. R. Plante

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Institute for Materials Science and Engineering
Ceramics Division
Gaithersburg, MD  20899

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L. P. Cook and E. R. Plante

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Survey of Alternate Stored Chemical Energy Reactions

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Abstract

A survey of eight alternative liquid metal stored chemical energy reactions has been made for purposes of comparison with the lithium-aluminum/water, lithium/sulfur hexafluoride, and other reaction schemes. The objective of the study was to survey the potential of these eight reactions as alternate stored chemical energy systems and to develop priorities for future study. Experimental data on the products of reaction and kinetics of reaction are presented for: Li/H\textsubscript{2}O; H\textsubscript{2}/O\textsubscript{2}), (Li/H\textsubscript{2}O; NaO\textsubscript{2}/H\textsubscript{2}O; H\textsubscript{2}/O\textsubscript{2}), (MgAl/H\textsubscript{2}O; H\textsubscript{2}/O\textsubscript{2}), and LiAl/C\textsubscript{10}O\textsubscript{3}F). These data have been collected using thermogravimetry and Knudsen effusion mass spectrometry, with x-ray diffraction analysis of experimental products. Among other results, the data show that the aluminum component of the fuels is relatively inert to oxidation up to 650 °C. Above this temperature, materials limitations have hampered the collection of experimental data.

Thermodynamic analysis has been used to extend the data on each of the eight reaction schemes, and to predict the chemical reaction which best represents the complete oxidation of each fuel by the indicated oxidant at 1100 K. Enthalpies have been calculated for each fuel/oxidant combination. Safety considerations are also discussed for each. Suggestions for future research are given, including suggestions for overcoming the materials problems encountered in this study.
I. Introduction

Recently there has been much interest in the use of light metals as fuel for stored chemical energy devices. A system currently in usage involves molten lithium metal and sulfur hexafluoride, according to the reaction,

$$8\text{Li} + \text{SF}_6 \rightarrow \text{Li}_2\text{S} + 6\text{LiF}$$  \[1\]

Under development (1) is a system using lithium aluminum alloy as the fuel and water as the oxidant, according to the reaction:

$$\text{LiAl} + 2\text{H}_2\text{O} \rightarrow \text{LiAlO}_2 + 2\text{H}_2$$  \[2a\]

The hydrogen liberated is combined with oxygen to yield water:

$$2\text{H}_2 + \text{O}_2 \rightarrow \text{H}_2\text{O}$$  \[2b\]

The water produced in this way is returned to \[2a\] to complete the cycle. In our laboratories investigation is continuing of reaction \[2a\], which is potentially much more complex than as written (2).

In addition to reaction [2], there are other possible alternate systems of interest and it is desirable to make a preliminary survey of these, to determine if certain ones might emerge as clear choices for further development, or at the least, if others might be eliminated from further consideration. The fuel/oxidant combinations that have been suggested are:
\[ \text{Li/H}_2\text{O; } \text{H}_2/\text{O}_2 \] [3]

\[ \text{Li/H}_2\text{O; NaO}_2/\text{H}_2\text{O; } \text{H}_2/\text{O}_2 \] [4]

\[ \text{MgAl/H}_2\text{O; } \text{H}_2/\text{O}_2 \] [5]

\[ \text{LiAl/C}_1\text{O}_3\text{F} \] [6]

\[ \text{LiAlMg/C}_1\text{O}_3\text{F} \] [7]

\[ \text{LiBe/C}_1\text{O}_3\text{F} \] [8]

\[ \text{Li/C}_{11}\text{F}_{20} \] [9]

\[ \text{LiB/NF}_3 \] [10]

Combinations [3], [4], and [5] utilize a final stage of combustion in which hydrogen is burned, in a reaction identical to reaction [2b] above. Combinations [6] through [10], however, are envisioned as largely single-stage energy release schemes. To fully evaluate all these candidates, it is desirable to have the following basic information:

(a) identity of the products of fuel/oxidant reaction

(b) an indication of the kinetics, especially the minimum temperature required for spontaneous combustion and self-sustaining reaction

(c) an estimate of the enthalpy of reaction

(d) knowledge of toxicity of reaction products

Information collected to date for each of the fuel/oxidant combinations is summarized in the paragraphs that follow. Most experiments were com-
pleted using a Mettler\textsuperscript{1} thermoanalysis system, except for reaction [6], which was also investigated mass spectrometrically. Following a presentation of data for each of the above reaction schemes, a general discussion and recommendations for follow-up research are given. Results of a literature search are given in an Appendix (Section XIII).

II. \textit{Li/H}_2O; H\textsubscript{2}/O\textsubscript{2}

A. \textbf{Starting Materials and Container Materials}

The starting material used for these experiments was finely powdered lithium metal (-140 mesh, 99.95\% pure on a metal basis). This material had some surface oxidation upon receipt from the vendor, causing it to have a slightly grayish cast; the contaminants were tentatively identified as lithium carbide (Li\textsubscript{2}C\textsubscript{2}), lithium hydride, and lithium hydroxide, on the basis of weak x-ray diffraction peaks. All materials handling operations involving the lithium metal were completed in a glove box.

Quantitative study of the oxidation of metallic lithium poses special materials problems. Any container must be capable of withstanding attack by both metallic lithium and the oxidant. Silica glass is not a suitable container in the presence of both the lithium fuel and the water oxidant. Graphite and molybdenum are mentioned in the literature (3, 4) as container materials for lithium alloys; however both are attacked by oxidants at relatively low temperatures. A nickel-based alloy would appear to offer promise; however, nickel could

\textsuperscript{1}Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.
be expected to undergo a certain degree of oxidation even at relatively low temperatures, affecting the results of sensitive thermogravimetric experiments, and possibly contaminating the sample. BN is a possible material, but experiments with LiAl (see below) suggest lithium absorption. Perhaps the strongest candidate crucible materials for future work are BeO (5) and MgO; however, as these were not available, all measurements to date were completed using readily available alumina crucibles at temperatures below the melting point of lithium metal.

B. Reaction Products

Lithium metal was reacted with water-saturated flowing argon (30,000 ppm H₂O) in the thermoanalyzer. At 25 °C, slow reaction of lithium metal with water produces LiOH.H₂O. However the reaction probably proceeds sequentially, starting with LiOH, as evidenced by x-ray analysis of samples from different zones within the reaction cell. Near the bottom of the cell, products were largely LiOH; near the top, the hydrate was dominant. At 100 °C, the reaction product is almost entirely LiOH; small amounts of the hydrate are believed to have formed as the experiment cooled.

C. Kinetics

The finely powdered lithium metal used in these experiments is highly reactive at room temperature in spite of the thin surface coating. This is evidenced by rapid reaction when deliberately exposed to the atmosphere. When placed in contact with water, violent reaction ensues, and explosion occurs due to spontaneous ignition of the evolved hydrogen.
In the thermoanalyzer experiments, the reaction was purposefully set up to proceed in controlled fashion. Reaction curves at 25 and 100 °C are shown in Fig. 1. The 25 °C curve shows a nearly linear segment from 0 to 1500 min. of reaction time, implying that reaction control in the early stages is not associated with build-up of a product layer, but rather may be linked to the rate of supply of the water vapor. The second half of the 25 °C curve is nonlinear. This could be due to the influence of the product layer of LiOH.H₂O, but is more likely to be due to the increased diffusion path required for vapor to reach the powders in the bottom of the cell. The reaction was stopped prior to completion. Theoretically completion would have occurred at a fractional weight gain of 5.1 (compared with 3.7 at the termination of the experiment). This number assumes complete conversion to Li(OH).H₂O.

By contrast, at 100 °C, the entire curve appears to be nonlinear. This suggests influence of the product layer (in this case LiOH). The reaction appears to have terminated in spite of the fact that the theoretical fractional weight gain of 2.5 was not reached. This probably indicates that the surface contamination of the Li powdered starting material is more severe than the x-ray analysis suggested. Future experiments will employ a much more nearly pure lithium powder.

D. Enthalpy

Thermodynamic data for calculation of the enthalpy of oxidation of molten lithium metal by H₂O are available in the JANAF tables (6). Enthalpy production in kcal per gram of fuel plus oxidant can be calculated, if the lithium oxidation reaction is combined with burning of the evolved hydrogen and recycling of water thus produced:
\[ Li + H_2O \rightarrow LiOH + (1/2)H_2 \]  

\[ (1/2)H_2 + (1/4)O_2 \rightarrow (1/2)H_2O \]  

\[ Li + (1/2)H_2O + (1/4)O_2 \rightarrow LiOH \text{ (combined reaction)} \]  

The calculated value\(^2\) at 1100 K (827 °C) is 3.5 kcal/g. If LiOH did not form, the combined reaction would be:

\[ 2Li + (1/2)O_2 \rightarrow Li_2O \]  

for which the enthalpy yield is 4.8 kcal/g. Clearly there is a heavy energy penalty paid by loss of hydrogen in the cycle to form LiOH.

E. Safety Considerations (7)

Lithium metal reacts exothermically with the moisture in human tissue, causing both thermal and chemical burns. An explosion hazard exists when the metal is exposed to moisture of any form, or to any other oxidizing material. When heated in air or burned it emits toxic fumes of Li_2O and LiOH. It reacts with nitrogen at high temperatures.

III. Li/H_2O; NaO_2/H_2O; H_2/O_2

A. Starting Materials

The Li/H_2O part of the reaction scheme has been discussed above. The role of NaO_2 is to provide oxygen for the second stage burning of hydrogen.

\(^2\)All energy yield calculations in this report are listed in terms of kcal per gram of fuel plus oxidant.
The NaO\textsubscript{2} used in these experiments was indicated by the vendor to be 95% NaO\textsubscript{2}. X-ray powder diffraction analysis of the starting material which consisted of pale yellow granules, yielded a very complex pattern containing peaks for NaOH, NaO\textsubscript{2}(I) and several unidentified peaks.

B. Reaction Products

NaO\textsubscript{2} was placed in a platinum cell in the thermoanalyzer. The sample was brought to temperature (25 or 100 °C) and then a stream of flowing water-saturated argon (30,000 ppm H\textsubscript{2}O) was introduced. At the conclusion of the 100 °C experiment the sample was x-rayed. This was not possible for the 25 °C experiment, which produced liquid; apparently the NaO\textsubscript{2} (or the NaOH produced from it) is deliquescent at 25 °C. The 100 °C experiment yielded predominantly NaOH; the lesser amount of NaOH.H\textsubscript{2}O present is thought to have formed as the experiment cooled.

C. Kinetics

Reaction curves for NaO\textsubscript{2}/H\textsubscript{2}O at 25 and 100 °C are shown in Fig. 2. The 25 °C curve consists of two linear weight gain portions. Interestingly the slope increases for the later segment. This is interpreted as follows. During the early 25 °C segment, the reaction involves loss of oxygen and gain of water:

\[ 2\text{NaO}_2 + 3\text{H}_2\text{O} \rightarrow 2(\text{NaOH}.\text{H}_2\text{O}) + (3/2)\text{O}_2 \]  

The theoretical fractional weight gain for this reaction is 0.06, which is near the change in slope for the 25 °C curve. During the later segment of the 25 °C reaction curve in Fig. 2, the product is thought to be the deliquescent liquid observed at the conclusion of the experiment, produced according to the reaction:
NaOH·H₂O + H₂O → (NaOH, H₂O) (L) [16]

Possibly formation of the liquid results in increased accessibility by the gas, explaining the increased slope.

At 100 °C, the reaction of NaO₂ with water vapor produces a nearly linear weight loss as would be expected from the reaction:

\[ 2\text{NaO}_2 + \text{H}_2\text{O} \rightarrow 2\text{NaOH} + (3/2)\text{O}_2 \] [17]

This reaction would yield a theoretical weight loss of 0.27. The 100 °C reaction apparently terminates at less than this value, reflecting the presence of the NaOH impurity noted in the x-ray analysis of the starting materials.

D. Enthalpy

If the sodium superoxide reaction is combined with the lithium/water oxidization reactions, we have the following:

\[ (1/3)\text{NaO}_2 + (1/6)\text{H}_2\text{O} \rightarrow (1/3)\text{NaOH} + (1/4)\text{O}_2 \] [18]

\[ \text{Li} + (1/2)\text{H}_2\text{O} + (1/4)\text{O}_2 \rightarrow \text{LiOH} \] [19]

\[ (1/3)\text{NaO}_2 + (2/3)\text{H}_2\text{O} + \text{Li} \rightarrow (1/3)\text{NaOH} + \text{LiOH} \] [20]

(combined reaction)

An enthalpy of formation for NaO₂ at 298 K can be estimated as -62.7 kcal.
Neglecting the heat required to bring the oxygen from the first stage up to 1100 K, the total energy release in reaction [20] is \(-2.2\) kcal/g. This is significantly less than the \(-3.5\) kcal/g calculated earlier for the \(\text{Li}/\text{H}_2\text{O}\); \(\text{H}_2\text{/O}_2\) combination. However it may be that there are advantages associated with use of a solid as the oxidant source rather than a compressed gas.

E. Safety Considerations (7)

Hazards associated with lithium are noted in the discussion of \(\text{Li}/\text{H}_2\text{O}\) above. Sodium superoxide has much the same toxicity as NaOH, which it forms upon contact with moisture. Contact with skin could be expected to cause burns and ulceration; inhalation of the mist or powder could cause damage to the upper respiratory tract and lungs. Heating could cause violent decomposition. Contact with moisture or reducing agents could result in explosion.

IV. \(\text{MgAl}/\text{H}_2\text{O}; \text{H}_2/\text{O}_2\)

A. Starting Materials

Magnesium aluminum alloy of 50/50 atomic ratio was prepared in the NBS metals processing lab by melting high purity magnesium and aluminum together under a halide flux and casting the melt into a steel chill mold. The resulting ingot was very brittle and was easily crushed in a mortar and pestle in a glove box. A (-200, +400) sieve fraction was then prepared for the experiment and stored in the glove box until use. An x-ray diffraction pattern showed characteristic peaks for \(\text{Al}_2\text{Mg}_3\) with a few additional unidentified peaks of low intensity.
B. Reaction Products

The powdered alloy was placed in an alumina cell in a glove box and transferred to the thermoanalyzer system. Next the specimen was brought to 650 °C in an argon atmosphere. At this temperature the specimen was completely melted, according to the Mg-Al phase diagram (8). Next, argon saturated with water at 25 °C (30,000 ppm H₂O) was flowed continuously over the sample. At the conclusion of reaction the gray, porous sample was cooled, removed and x-rayed. The x-ray powder pattern showed strong peaks for aluminum metal and MgO (periclase). Apparently only the magnesium component of the molten alloy was oxidized, as there were no peaks for Al₂O₃, Mg₂Al₂O₄ or any other aluminous phases.

C. Kinetics

Rate data for the oxidation of molten MgAl by water vapor are shown in Fig. 3. The meaning of the step in the weight gain curve at about 100 minutes of reaction time is not clear. However the two segments of this curve on either side of the break have substantially linear portions, suggesting that diffusion through a product layer of increasing thickness is not a controlling factor during most of the reaction. The reaction appears to slow to a very low rate as the fraction reacted approaches 0.30. This is in agreement with the x-ray analysis, which indicates essentially all the Mg has been oxidized; complete oxidation of the Mg to periclase would correspond to a fractional weight gain of 0.31, very close to that observed; on the other hand, complete oxidation of both the magnesium and the aluminum would result in a fractional weight gain of 0.62.

D. Enthalpy

Referring to the system Mg-Al-O-H, at least three possible oxidation reactions involving the 1:1 alloy and water could occur. These are
summarized below:

\[
2\text{MgAl} + 5\text{H}_2\text{O} \rightarrow \text{MgO} + \text{MgAl}_2\text{O}_4 + 5\text{H}_2 \quad [21\text{a}]
\]

\[
5\text{H}_2 + (5/2)\text{O}_2 \rightarrow 5\text{H}_2\text{O} \quad [21\text{b}]
\]

\[
2\text{MgAl} + 5\text{H}_2\text{O} \rightarrow 2\text{MgO} + \text{Al}_2\text{O}_3 + 5\text{H}_2 \quad [22\text{a}]
\]

\[
5\text{H}_2 + (5/2)\text{O}_2 \rightarrow 5\text{H}_2\text{O} \quad [22\text{b}]
\]

\[
\text{MgAl} + \text{H}_2\text{O} \rightarrow \text{MgO} + \text{Al} + \text{H}_2 \quad [23\text{a}]
\]

\[
\text{H}_2\text{O} + (1/2)\text{O}_2 \rightarrow \text{H}_2\text{O} \quad [23\text{b}]
\]

To complete enthalpy calculations for these reactions an estimate for the enthalpy of formation of molten MgAl was made using the ideal solution approximation. Calculated enthalpy release values for the three reaction pairs are respectively, -3.8, -3.8, and -2.2 kcal/g. Clearly, formation of spinel (reaction [21a] vs. reaction [22a]) affects the energy yield very little. Reaction [23a] has been included because it is the one observed, and clearly its occurrence instead of [21a] or [22a] results in substantially lower energy yield. Presumably at some higher temperature the aluminum component will begin to react according to reaction [21a] or [22a].

E. Safety Considerations (7)

Hazards data are not available for MgAl alloy. Aluminum is not regarded as a poison, although inhalation of finely divided powders can damage the lungs. Magnesium on the other hand can cause chemical gas
gangrene if it enters the body, due to generation of hydrogen. Fine magnesium powder readily ignites by exposure to spark or flame.

V. LiAl/CIO$_3$F

A. Starting Materials

The starting material for these experiments was powdered LiAl. The material as received was packed under argon and visually showed no signs of surface contamination—all surfaces were bright and shiny. X-ray analysis showed only peaks of LiAl. All manipulations involving this material were done in a glove box through which a continuously purified argon atmosphere was recirculated. The material used in these experiments was a (-200, +400) sieve fraction. Transfer to the thermoanalyzer was accomplished in a glove bag, flushed repeatedly with purified argon.

The CIO$_3$F (perchloryl fluoride) was obtained from the vendor in cylinders containing either 100 g or 250 g. Principal impurities were N$_2$, O$_2$, CO$_2$, H$_2$O and HF (see section on mass spectrometry).

Gas was run through a corrosive gas regulator and then through a column containing NaOH pellets and molecular sieve, and finally through a flowmeter and then into the thermoanalyzer. The CIO$_3$F, a very dense gas, was piped directly into the crucibles in the thermoanalyzer experiments. Provision was made for mixing the CIO$_3$F with continuously variable amounts of argon. However, all thermoanalyzer experiments reported were carried out using a flow of pure CIO$_3$F since it was discovered that the reactions proceeded in controlled fashion so that no argon dilution was necessary. Although argon was used to flush the balance components
during the experiments, it is estimated that the effective partial pressure of ClO$_3$F over the specimens during these experiments was close to 1 atmosphere.

B. Reaction Products

Initially, experiments were conducted in alumina crucibles; however these were unsatisfactory above 700 °C, owing to the corrosiveness of the molten alloy. Crucibles of LiAlO$_2$ have been fabricated and these appear to offer promise for application in higher temperature experiments. Additionally MgO and BeO offer promise. Boron nitride crucibles were fabricated and tested in contact with LiAl at 800 °C. They seem to hold up to attack by the molten alloy well, except for a slight discoloration, which may be associated with diffusion of Li. Also a steady and extensive weight gain of the crucible occurred during preliminary tests under an atmosphere of purified argon. As we have no explanation for or solution to this problem, use of the BN crucibles was discontinued. Calcia-stabilized zirconia and silica glass crucibles were employed for the mass spectrometric studies, with mixed results. All other experiments reported employed alumina crucibles.

At the conclusion of the LiAl/ClO$_3$F experiments, crucibles were removed and placed in an inert atmosphere. X-ray mounts were prepared in the glove box and x-rayed under flowing N$_2$. Results of x-ray analysis are indicated in Table 1, below.

As can be seen from Table 1, experimental results vary greatly depending upon experimental conditions. The following generalizations can be made, however, for the range of conditions investigated (350-650 °C, P$_{\text{ClO}_3\text{F}} = 1$ atm; or, 900 °C, P$_{\text{ClO}_3\text{F}} = 10^{-5}$ atm).
(1) Fluorides (Li₃AlF₆, AlF₃, LiF) appear to be by far the dominant reaction products.

(2) Chlorides may form during initial stages of oxidation³ (see discussion of kinetics) but are relatively minor phases in the end products.

(3) The lithium in the alloy is preferentially oxidized leaving behind aluminum which behaves as though inert (see also discussion of MgAl oxidation).

(4) The occurrence of oxides as oxidation products is limited in these experiments to low partial pressures of ClO₃F and/or high temperatures.

C. Mass Spectrometry

i) Outline of Method

In this technique, the Li-Al alloy contained in a Knudsen cell is exposed to ClO₃F introduced into the cell through a gas inlet system. At appropriate temperatures, reaction products undergo vaporization into the source of the mass spectrometer where the gaseous products are ionized and mass analyzed. The major advantage of this method is that it can in principle detect gaseous reaction products. A second advantage is that the number of collisions of reactant vapor with the condensed phase may be controlled at a low value so that the kinetics of the process can be substantially solved.

In the present measurements, however, it was found that reaction rates are quite slow even up to temperatures as high as 1000 °C so that modifications in the experimental arrangement to enhance reaction rates will be advantageous.

³Oxidation is here used in the generic chemical sense.
ii) Vaporization Considerations

At low temperatures some of the reaction products may be relatively non-volatile so that they will not be detected by mass spectrometric analysis. On the basis of data in the literature, the metal chlorides are more volatile than the metal fluorides while the metal oxides are non-volatile up to temperatures of 1000 °C or so. Also, because the halides will form a salt solution, complexing to form interhalide compounds may influence the volatility of the solution. For example, formation of LiAlCl₄ would greatly reduce the pressure expected from formation of AlCl₃.

iii) Experimental set-up

These measurements were made using a fused silica effusion sampler. The Li-Al alloy was contained in a calcia-stabilized zirconia cup supported within the effusion sampler. The ClO₃F was delivered to the gas inlet tube through a small leak valve. The Li-Al alloy was loaded into the zirconia cell in a dry-box then transferred to the mass spectrometer under argon to reduce the reaction of the Li-Al alloy with ambient water vapor.

An effusion orifice of 1 mm diameter was used in the effusion sampler. This proved to be too large as the ClO₃F reacted much less rapidly with the Li-Al alloy than expected.

The control valve was attached to the ClO₃F cylinder in the dry box so the ClO₃F was diluted with Ar during the earlier parts of the experiment.

iv) Analysis of ClO₃F

Mass spectrometric sampling of the commercial ClO₃F gas showed predominant peaks at m/e values of 104, 102, 85, 83, 69, 67, 53, and 51 corresponding to the ³⁷Cl and ³⁵Cl isotopes of the species ClO₃F⁺,
CIO\textsuperscript{+}, CIO\textsubscript{2}\textsuperscript{+}, and CIO\textsuperscript{+}. Except for CIO\textsubscript{3}\textsuperscript{F\textsuperscript{+}}, these peaks are due to fragmentation of the CIO\textsubscript{3}\textsuperscript{F} during the ionization process using electrons at 30v. Besides the CIO\textsubscript{3}\textsuperscript{F}, Ar which was introduced from the dry box installation of the regulator was also observed. By comparing the mass spectrum with the CIO\textsubscript{3}\textsuperscript{F} gas flow on or off, it was determined that the CIO\textsubscript{3}\textsuperscript{F} also contained a small amount (perhaps a percent or so) of air (N\textsubscript{2}, O\textsubscript{2}, CO\textsubscript{2}, and H\textsubscript{2}O). The H\textsubscript{2}O had apparently partially reacted with the steel cylinder and produced slight traces of HF (mass 20), H\textsuperscript{35}Cl (36), and H\textsuperscript{37}Cl (38). However, it is not likely that the contamination had significant effect on the reaction of CIO\textsubscript{3}\textsuperscript{F} with the alloy.

v) Reaction of Li-Al Alloy with CIO\textsubscript{3}\textsuperscript{F}

The first mass peaks due to reaction of CIO\textsubscript{3}\textsuperscript{F} with the Li-Al alloy were observed at 420 °C. These peaks were Li\textsuperscript{+} from fragmentation of LiCl(g), LiCl\textsuperscript{+} from ionization of the LiCl(g) and Li\textsubscript{2}Cl\textsuperscript{+}, from ionization of the Li\textsubscript{2}Cl\textsubscript{2}(g) parent.

One might expect Al-Cl species in this temperature range but none were observed, in spite of the fact that loss of volatile substances is indicated by the analogous thermogravimetric experiment. It is clear from the presence of both LiCl(g) and Li\textsubscript{2}Cl\textsubscript{2}(g) that a condensed halide phase was formed on the sampler.

With time, the ratio of LiCl\textsuperscript{+}/Li\textsubscript{2}Cl\textsuperscript{+} gradually increased. This probably showed that LiF was also forming in the condensed phase and reducing the activity of LiCl. At 600 °C, Li\textsubscript{2}F\textsuperscript{+} from the fragmentation of Li\textsubscript{2}F\textsubscript{2} was observed in the mass spectrum. Over the temperature range from 600-900 °C ions corresponding to parent molecules LiCl, Li\textsubscript{2}Cl\textsubscript{2}, LiF, and Li\textsubscript{2}F\textsubscript{2} were observed. It did not appear that any Al bearing species were formed in the gas phase.
At the conclusion of the experiment, the Li-Al alloy still had a powdery appearance even through it had been heated several hundred degrees above the melting point.

An x-ray diffraction pattern of the residue revealed the presence of LiAlO$_2$ with perhaps an equal amount of unreacted Al (see Table 1).

vi) Al-ClO$_3$F Interaction

Because Al bearing species were not observed from the Li-Al alloy, a mass spectrometric experiment was carried out using only powdered Al in the effusion cell. The purpose of this experiment was to see if it was possible to form Al bearing species by reactions with ClO$_3$F. Near 500 °C species corresponding to the halide ions AlF$^+$, AlCl$^+$, AlF$_2^+$, AlClF$^+$, Al$_3^+$, AlF$_2$Cl$^+$, AlCl$_2$F$^+$, and AlCl$_3^+$ were observed. Because of the number of complex species in the vapor phase, the existence of a condensed phase at this temperature consisting of mainly AlF$_3$ seems likely. The duration of the experiment during which Al-halide species was generated was quite short. All of the Al bearing species decreased with time and increasing the ClO$_3$F flow rate and the temperature had no effect on increasing their intensity. This seems to indicate that the chlorination and fluoridation processes took place at only selected sites in the Al powder which were gradually depleted or lost, perhaps because of oxidation.

At 760 °C, most of the Al halide peaks had vanished except for AlF$_2^+$ which is a major fragmentation product of AlF$_3$(g). The experiment was terminated after a brief heating period at 800 °C. Visual examination of the residue at the conclusion of the experiment revealed that most of the sample still had a powdery texture but a few small spheres resulting from melting the sample were also present. Since the sample
was heated to about 150 °C above the melting point of Al, the powdery
texture of the sample must result from an oxide skeleton on the outside
surface of each grain in the powder. The sample initially weighed
118 mg and gained 2.2 mg during the experiment, despite loss of the
halides, indicating that a small amount of oxidation took place.

D. Kinetics

Thermogravimetric rate data for the reaction of LiAl with ClO$_3$F are
shown in Fig. 4 at temperatures of 350, 450, 550 and 650 °C. It is
presumed on the basis of the Li-Al phase diagram (9) that the LiAl was
solid during these experiments. With the exception of the 350 °C ex-
periment, rate curves all initially show a rapid weight gain at a nearly
steady rate. This continues until a weight fraction gain of between 0.5
and 0.7 has been reached. At this point the rate of weight gain decreases
for a short time and then increases again. This behavior is especially
pronounced in the 650 °C experiment, where a small weight loss with time
is apparent, followed by an increase in the rate of weight gain. This
weight loss (and possibly, as well, the temporary decrease in rate of
gain at all four temperatures) is best interpreted as due to formation
of a volatile reaction product, most probably AlCl$_3$. Continued reaction
leads to a similar ultimate weight gain of between 0.9 and 1.1 for
experiments at all four temperatures, 350, 450, 550 and 560 °C (see
Table 1). This is true in spite of the fact that the products are
somewhat different in each case. Table 2 lists hypothetical reactions
of LiAl with Cl, O and F and combinations thereof, together with theo-
retical weight gains. These reactions have been derived with the aid of
thermodynamically calculated equilibrium phase compatibilities shown in
Fig. 7. Calculated weight gains are highly variable, but the partial
fluorination reactions [26] and [27] of Table 2 best approximate the
experimental products observed (Table 1). The fractional weight gains calculated for these reactions are 0.56 and 1.12, respectively, encompassing the range observed.

It seems likely from the curves in Fig. 4 that more than one reaction has occurred during the oxidation of LiAl by ClO$_3$F. It also seems likely that early stage condensed phase products undergo subsequent reaction with time to yield a new generation of products. In future experiments, reaction of LiAl with ClO$_3$F will be completed at higher temperatures, where hopefully a rapid approach to equilibrium will eliminate many of these complications. It is hoped that mass spectrometer measurements will be carried out at higher pressures of ClO$_3$F using a transpiration system.

E. **Enthalpy**

From Table 1 it can be seen that the reaction products at temperatures of 650 °C and below differ greatly, depending upon temperature. Further, oxidation of the alloy is far from complete, and the majority of the aluminum component of the alloy appears to have remained in the metallic state. The reaction products suggest disequilibrium among themselves; for example, Li$_3$AlF$_6$, AlF$_3$ and LiF are not in stable equilibrium together. The principal difficulty then is in extrapolating these limited results to a higher temperature such as 1100 K, at which oxidation could be expected to be much more complete, so that a meaningful enthalpy yield calculation can be done.

The LiAl/ClO$_3$F reaction can be described by the five component chemical system Li-Al-Cl-O-F. Fortunately thermodynamic data are available for many of the end-member compounds in this system and so a preliminary thermodynamic analysis can be completed. This results in an
estimated equilibrium reaction for complete oxidation which can be used
to calculate enthalpy yield. The thermodynamic analysis was completed
as follows. Fig. 5 depicts graphically the compositional regions of
interest in the three principal quaternary subsystems contained within
the five component system. Fig. 6 shows calculated phase compatibilities
for important ternary reciprocal systems in Fig. 5. These compatibilities
are schematic and indicate major features of phase equilibria which are
consistent with known thermodynamic data, according to the reactions in
Table 3. On the basis of Fig. 6, Fig. 7 has been constructed. This
shows calculated equilibrium relations at 1100 K for the phase regions
shown in Fig. 5. Based on Fig. 6 and 7, Fig. 8 has been constructed,
showing calculated equilibrium relations at 1100 K among phases most
likely to form as products of complete reaction of LiAl and ClO_3F. The
reaction suggested by Fig. 8 is:

\[ 2\text{LiAl} + \text{ClO}_3\text{F} \rightarrow \text{Al}_2\text{O}_3 + \text{LiF} + \text{LiCl} \quad [74x] \]

It should be emphasized that there is no direct experimental evidence
yet in support of this reaction: however on purely thermodynamic grounds
it is the favored reaction. To complete the enthalpy calculation, data
for LiAl were estimated using the ideal solution approximation. The
resulting value of enthalpy yield for this reaction is 3.8 kcal/g.

F. Safety Considerations (7)

Safety hazards associated with LiAl are similar to those associated
with Li as noted above, although reaction with moisture is considerably
less vigorous at room temperature. Perchloryl fluoride is a highly
toxic gas which causes symptoms of asphyxiation and poisoning similar to
CO, although recovery is said to be rapid provided exposure has not been prolonged. The gas has a sweet odor, but this cannot be relied upon to indicate toxic concentrations. Perchloryl fluoride is readily absorbed through the skin. Although nonflammable, it does support combustion, as it is a powerful oxidizer. When heated to decomposition, it emits highly toxic fumes of chlorides and fluorides.

VI. LiAlMg/ClO$_3$F

A. Enthalpy

At the time of writing, experiments have not yet been completed in this system, owing to lack of available starting material. Therefore enthalpy yield estimates must be made solely on the basis of preliminary thermodynamic analysis. The fuel/oxidant reaction is represented by the 6-component system Li-Al-Mg-Cl-O-F. The phase equilibrium topology is of course impossible to represent in three dimensions; nonetheless, progress can be made by consideration of the six quaternary reciprocal systems shown in Fig. 9. By calculation of the reactions in Table 4, the schematic ternary phase compatibilities shown in Fig. 10 have been derived. From additional reactions in Table 4 and compatibilities in Fig. 10, construction of Figs. 11 and 12 was made possible. Fig. 11 pertains to progressive chlorination, fluorination or oxygenation of fuel. Fig. 12 relates to the equilibrium products of complete reaction. Table 5 gives some postulated equilibrium reactions involving progressive reaction of LiAlMg fuel with Cl, F, O and combinations thereof.

Based on the above considerations, the following is thought to represent complete reaction of LiAlMg alloy (1:1:1 atomic) with ClO$_3$F:
The calculated enthalpy yield for this reaction at 1100 K is 3.6 kcal/g.

B. Safety Considerations (7)

Safety hazards are similar to those noted for LiAlMg/ClO₃F above.

VII. LiBe/ClO₃F

A. Enthalpy

Because of the toxicity of beryllium and beryllium compounds, experiments have not been conducted on the oxidation of lithium-beryllium alloy by ClO₃F. Hence any estimate of enthalpy release must rely solely upon thermodynamic estimates of the actual reaction. A thermodynamic analysis of the five component system Li-Be-Cl-O-F was completed as follows. Fig. 13 shows the three quaternary subsystems of interest. Based on reactions in Table 6, the ternary phase compatibilities in Fig. 14 have been constructed. Based on these compatibilities and additional reactions in Table 6, the schematic quaternary phase compatibilities in Fig. 15 have been derived; these show the results of progressive chlorination, fluorination, or oxygenation of LiBe fuel (Table 7 lists equilibrium reactions involving LiBe fuel with various combinations of Cl, 0 and F). Fig. 16 indicates calculated compatibilities among likely reaction products. The reaction postulated on the basis of thermodynamic data for complete oxidation of LiBe by PCF is:

\[ 8\text{LiBe} + 3\text{ClO}_3\text{F} \rightarrow 8\text{BeO} + \text{Li}_2\text{O} + 3\text{LiF} + 3\text{LiCl} \] [169]

The enthalpy released by this reaction at 1100 K would be 4.6 kcal/g.
B. Safety Considerations (7)

Lithium and beryllium do not form stable intermetallic compounds together (10) and would be expected to be present together in fuel as the chemically uncombined metals. For a discussion of Li safety hazards, see Li/H₂O above. Beryllium is highly toxic both in metallic form and in compound form. Many of the beryllium salts have high vapor pressures, especially when heated. Symptoms of exposure usually involve respiratory distress of varying severity; symptoms may be delayed for several years after exposure. Chronic berylliosis can lead to death from respiratory and cardiac failure. In addition to harm incurred by inhalation, beryllium and its compounds also act on the skin, causing lesions and tumors. Beryllium by itself does not present an explosion hazard, however the admixed lithium in the fuel obviously does. For a discussion of perchloryl fluoride safety refer to LiAl/ClO₃F above.

VIII. Li/C₁₁F₂₀

A. Starting Materials

The fluorocarbon compound C₁₁F₂₀ was not obtainable from commercial suppliers; the closest molecular weight compound available was the structurally similar double ring compound C₁₁F₁₉, an apparently stable, clear liquid. Experiments have not yet been completed due to the necessity of installing a special furnace with a boiling chamber for the liquid oxidant on the thermoanalyzer. It is hoped that loan from another facility of a water vapor furnace (which would also provide 1 atm of P₄H₂O for the Li/H₂O and MgAl/H₂O experiments) will provide a solution to this experimental problem.
B. Enthalpy

In the absence of experimental data, it is again necessary to utilize thermodynamic estimates in arriving at an oxidation reaction for the enthalpy calculation. The system Li-F-C provides a compositional representation of the Li/C\textsubscript{11}F\textsubscript{20} reaction. By using calculated reactions in Table 8, Fig. 17 can be constructed, showing schematic phase compatibilities at 1100 K. On this basis, the thermodynamically estimated oxidation reaction is:

\[ C\textsubscript{11}F\textsubscript{20} + 20\text{Li} \rightarrow 11\text{C} + 20\text{LiF} \]  \[ 176 \]

As no enthalpy data have been located for C\textsubscript{11}F\textsubscript{20}, it is necessary to make an estimate. This can be done by extending the procedures used for estimating properties of hydrocarbon molecules. A very approximate value of 900 kcal/mole is obtained in this way for 298 K. The calculated enthalpy yield at 298 K is 3.1 kcal/g. Presumably the value at 1100 K would be somewhat higher.

C. Safety Considerations (7)

For a discussion of Li safety hazards, see Li/H\textsubscript{2}O above. Data are not available for the C\textsubscript{11}F\textsubscript{19} obtained, but the related compound C\textsubscript{11}F\textsubscript{20} is a highly stable molecule which has been used to develop a synthetic blood substitute.

IX. LiB/NF\textsubscript{3}

A. Starting Materials

NF\textsubscript{3} has been obtained from a commercial source in small cylinders.
Principal impurities are stated by the vendor as N\textsubscript{2}, HF, NO and H\textsubscript{2}O. A source of LiB has been located but the material has not yet been procured, and so there are not experimental data on the reaction at this point in time.

B. Enthalpy

In the absence of experimental data on the LiB/NF\textsubscript{3} reaction, thermo-dynamic analysis of the system Li-B-N-F (Fig. 18) is essential. Using the reactions in Table 9, the schematic 1100 K ternary phase relations in Fig. 19 have been calculated. Fig. 20 gives calculated compatibilities among product phases at 1100 K. Table 10 gives reactions for progressive degrees of oxidation of LiB fuel by NF\textsubscript{3}. The suggested reaction for complete oxidation of LiB by NF\textsubscript{3} is:

\[ 3\text{LiB} + 2\text{NF}_3 \rightarrow 3\text{LiF} + \text{BN} \quad [185] \]

Boron trifluoride (BF\textsubscript{3}) is a gas even at relatively low temperatures, and so this would not be a desirable reaction. However by simply adding excess lithium to the fuel, in principle the following reaction could be obtained:

\[ 2\text{Li} + \text{LiB} + \text{NF}_3 \rightarrow 3\text{LiF} + \text{BN} \quad [186] \]

Depending upon the kinetics, BF\textsubscript{3} might still form as an intermediate product, but the equilibrium final partial pressure would be very low. Although LiB is known as a stable compound, thermochemical data were not available. It has been assumed that at 1100 K it would be molten, and the ideal solution approximation has been applied to give an enthalpy of formation of 0.0 kcal. The enthalpy yield of reaction [180] can then be calculated as 4.6 kcal/g.

C. Safety Considerations (7)

Handling properties and toxicity of the compound LiB apparently
have not found their way into appropriate compendiums, but it is reasonable to assume that the comments made above under discussion of safety for Li and LiAl fuels would also apply here. The compound is used in pyrotechnical devices, and so there may be a potential explosion hazard. With regard to NF₃, it is a colorless gas with a moldy odor and a high toxicity similar to HF. It could therefore be expected to be extremely corrosive to the respiratory tract and skin. Prolonged exposure may cause skeletal changes.

X. Summary and Discussion

In terms of energy release/unit mass, ranking of various stored energy reactions is as in Table 11, which includes for reference, two schemes not otherwise discussed in this report:

\[
\text{Mg} + \text{H}_2\text{O} \rightarrow \text{MgO} + \text{H}_2 \tag{187a}
\]
\[
\text{H}_2 + (1/2)\text{O}_2 \rightarrow \text{H}_2\text{O} \tag{187b}
\]
\[
2\text{Al} + 3\text{H}_2\text{O} \rightarrow \text{Al}_2\text{O}_3 + 3\text{H}_2 \tag{188a}
\]
\[
3\text{H}_2 + (3/2)\text{O}_2 \rightarrow 3\text{H}_2\text{O} \tag{188b}
\]

Several points should be made regarding the ranking in Table 11. First, direct experimental evidence for several of these reactions has not yet been obtained, due in part to materials limitations. Although we are optimistic that these will soon be overcome, in the meantime the ranking
in Table 11 may have only limited practical significance. An example is
the reaction Li/H₂O [14]. Theoretically it should be high on the list
at 4.8 kcal/g. However in practice this yield may not be achieved due
to formation of LiOH, which irreversibly ties up hydrogen in the water
cycle, and reaction [13], with an enthalpy yield of 3.5 could prevail
instead. Also there are presumably other factors such as safety to be
considered. The high toxicity of beryllium makes the practicality of
utilizing reaction [169] questionable. On the other hand, it could
probably be said that since fuel or oxidant or both are inherently
chemically unstable, all of the reaction schemes involve some degree of
toxicity to human tissue or other safety hazards, and suitable safeguards
must be employed with any reaction scheme to eliminate the possibility
of containment failure or runaway reaction. For example, lithium metal
exposed to moist air at room temperature rapidly generates hydrogen.
Perchloryl fluoride has a toxic effect similar to CO. NF₃ is not only
toxic but extremely hazardous under pressure. When all such factors are
considered, undoubtedly the Mg/H₂O, MgAl/H₂O and Al/H₂O schemes pose the
least safety hazard; however the latter two fuels may require very high
temperature operation to overcome the kinetic barriers to oxidation of
the aluminum. In terms of safety the LiAl/H₂O scheme is also high on
the list, as LiAl is much less reactive than lithium upon exposure to
air. Furthermore from a practical viewpoint, there may be other factors
to consider besides enthalpy yield. For example, although the Li/C₁₁F₂₀
and Li/H₂O; NaO₂/H₂O schemes rank low in Table 11, there may be certain
advantages associated with not having to store gaseous oxidizers.

Additional experimental work is necessary at higher temperatures
than attained to date in order to verify the reactions presented in
Table 11. Evidence to date suggests several of the reactions are kinetically hindered at temperatures below 650 °C. We are optimistic that the materials limitations encountered in this preliminary study will be overcome, so that relevant experimental data on high temperature kinetics and phase equilibria can be systematically gathered in the near future.

XI. Future Work

The highest priority involves finding suitable container materials so that thermogravimetric experiments can be extended to higher temperatures. Rod stock of high density MgO has been obtained and is being fabricated into crucibles. Also beryllia crucibles will be machined to order by a vendor equipped to do this safely. Crucibles of LiAlO₂ have already been fabricated. We are optimistic that use of one or more of these materials will allow us to extend the temperature range of experimentation into the 650-1000 °C region.

After the container problem is solved the first priority will be to determine if the oxidation reactions can be made to go to completion, and if so what the minimum temperature is at which this will occur. Once optimum conditions for reaction are determined, an attempt will be made to measure enthalpy of reaction directly using DTA.

Simultaneously with these experiments phase equilibrium measurements will commence. The first experiments will involve heating the predicted end products of the reactions together in sealed capsules, quenching and examining to see if they really are in equilibrium as suggested by the thermodynamically calculated reaction. This will give important information on solubilities (both liquid and solid) as well.
It is hoped that mass spectrometric measurement of species vapor pressures during these reactions can be completed using the NBS transpiration mass spectrometry system. This apparatus allows measurements of species at pressures up to 10 atm, which would more closely simulate actual reactor conditions. Top priority would be given to the investigation of the LiAl/ClO$_3$F and LiAlMg/ClO$_3$F systems. Also, the (Li + LiB)/NF$_3$ and Li/C$_{11}$F$_{20}$ systems might be amenable to investigation by this approach.
XII. References Cited


XIII. Appendix: Results of Literature Survey

Following are bibliographic listings which have been selected from a computerized literature search of the Chemical Abstracts Data Base (1967-1984). References are not annotated, and low temperature as well as high temperature studies have been included. References are loosely grouped according to search categories that roughly correspond to the various alternate stored chemical energy reaction fuels and oxidants.
A. Oxidation of Lithium metal, including kinetics and oxidation by water


B. Oxidation of aluminum metal, including kinetics and oxidation by water


Section B, continued


Section B, continued


Section B, continued


Section B, continued


Section B, continued


Section B, continued


Wiedmer, E. and Grauer, R., 1974, Behavior of aluminum electrodes in fluoride solutions: Aluminum (Duesseldorf), V. 50, No. 4, p. 268-70.


C. Reaction of LiAl alloy with water


D. Oxidation of LiAl alloy


E. Oxidation of Magnesium metal, including kinetics and oxidation by water


Section E, continued


Section E, continued


F. Oxidation of aluminum-magnesium alloy, including kinetics and oxidation by water


Section F, continued


Section F, continued


G. Lithium-beryllium alloys


H. Lithium-boron alloys

Bischof, J.; Dlouhy, Z.; Kvitek, V. and Vobecky, M., 1972, Determination of boron and lithium in materials by an (n, alpha) nuclear reaction: Jad. Energ., V. 18, No. 9, p. 269-8.

Born, E. and Loewedey, R., 1975, Diffusion of the products of the nuclear reaction 10B(n, alpha)7Li and hydrogen in single crystals of beta-rhombohedral boron: Atomkernenergie, V. 26, No. 4, p. 283-4.


Section H, continued


Section H, continued


I. Perchloryl fluoride and nitrogen trifluoride


Section I, continued


Section I, continued


Section I, continued


J. Fluorocarbon (C_{11}F_{20})


Section J, continued


XIV. Tables
Table 1. X-ray Diffraction Analysis of LiAl/ClO$_3$F Experimental Products

<table>
<thead>
<tr>
<th>Expt.</th>
<th>Max Temp.</th>
<th>%Wt. Gain</th>
<th>Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>TGA</td>
<td>650 °C</td>
<td>109.86</td>
<td>α-Li$_3$AlF$_6$, LiF*, AlF$_3$, Al</td>
</tr>
<tr>
<td>(isothermal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGA</td>
<td>550 °C</td>
<td>97.58</td>
<td>Al, β-Li$_3$AlF$_6$, AlF$_3$, LiF</td>
</tr>
<tr>
<td>(isothermal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGA</td>
<td>450 °C</td>
<td>98.52</td>
<td>Al, β-Li$_3$AlF$_6$, AlF$_3$, LiF, (LiCl)</td>
</tr>
<tr>
<td>(isothermal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGA</td>
<td>350 °C</td>
<td>109.26</td>
<td>Al, AlF$_3$, Li$_3$AlF$_6$</td>
</tr>
<tr>
<td>(isothermal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass Spec.</td>
<td>900 °C</td>
<td>---</td>
<td>γLiAlO$_2$, Al</td>
</tr>
<tr>
<td>(non-isothermal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGA</td>
<td>650 °C</td>
<td>91.69</td>
<td>αLi$_3$AlF$_6$, AlF$_3$, Al, LiF</td>
</tr>
<tr>
<td>(non-isothermal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGA</td>
<td>650 °C</td>
<td>50.43</td>
<td>LiCl, Al, LiAl, γLiAlO$_2$, LiF</td>
</tr>
<tr>
<td>Partial React.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(isothermal)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*LiF apparently contains a small amount LiCl in solid solution, as judged by x-ray line shifts
<table>
<thead>
<tr>
<th>Reaction #</th>
<th>Type of Reaction</th>
<th>Reaction</th>
<th>Final Wt. Gain at Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>[24]</td>
<td>chlorination</td>
<td>LiAl + ClO$_3$F $\rightarrow$ LiCl + Al + (3/2)O$_2$ + (1/2)F$_2$</td>
<td>+0.51</td>
</tr>
<tr>
<td>[25]</td>
<td>chlorination</td>
<td>LiAl + 4ClO$_3$F $\rightarrow$ LiCl + AlCl$_3$(g) + 6O$_2$ + 2F$_2$</td>
<td>+0.25</td>
</tr>
<tr>
<td>[26]</td>
<td>fluorination</td>
<td>LiAl + ClO$_3$F $\rightarrow$ LiF + Al + (3/2)O$_2$ + (1/2)Cl$_2$</td>
<td>+0.56</td>
</tr>
<tr>
<td>[27]</td>
<td>fluorination</td>
<td>3LiAl + 6ClO$_3$F $\rightarrow$ Li$_3$AlF$_6$ + 2Al + 9O$_2$ + 3Cl$_2$</td>
<td>+1.12</td>
</tr>
<tr>
<td>[28]</td>
<td>fluorination</td>
<td>3LiAl + 12ClO$_3$F $\rightarrow$ Li$_3$AlF$_6$ + 2AlF$_3$ + 18O$_2$ + 6F$_2$</td>
<td>+2.24</td>
</tr>
<tr>
<td>[29]</td>
<td>oxygenation</td>
<td>3LiAl + 2ClO$_3$F $\rightarrow$ 3LiAlO$_2$ + Cl$_2$ + F$_2$</td>
<td>+0.94</td>
</tr>
<tr>
<td>[30]</td>
<td>chlorination &amp; oxygenation</td>
<td>5LiAl + 2ClO$_3$F $\rightarrow$ 3LiAlO$_2$ + 2LiCl + 2Al + F$_2$</td>
<td>+0.98</td>
</tr>
<tr>
<td>[31]</td>
<td>chlorination &amp; oxygenation</td>
<td>7LiAl + 4ClO$_3$F $\rightarrow$ 3LiAlO$_2$ + 4LiCl + 2AlO$_3$ + 2F$_2$</td>
<td>+1.41</td>
</tr>
<tr>
<td>[32]</td>
<td>fluorination &amp; oxygenation</td>
<td>5LiAl + 2ClO$_3$F $\rightarrow$ 3LiAlO$_2$ + 2LiF + 2Al + Cl$_2$</td>
<td>+0.79</td>
</tr>
<tr>
<td>[33]</td>
<td>fluorination &amp; oxygenation</td>
<td>7LiAl + 4ClO$_3$F $\rightarrow$ 3LiAlO$_2$ + 4LiF + 2AlO$_3$ + Cl$_2$</td>
<td>+1.12</td>
</tr>
<tr>
<td>[34]</td>
<td>chlorination &amp; fluorination</td>
<td>2LiAl + ClO$_3$F $\rightarrow$ LiCl + LiF + 2Al + (3/2)O$_2$</td>
<td>+0.80</td>
</tr>
<tr>
<td>[35]</td>
<td>chlorination &amp; fluorination</td>
<td>9LiAl + 6ClO$_3$F $\rightarrow$ 6LiCl + Li$_3$AlF$_6$ + 8Al + 9O$_2$</td>
<td>+1.07</td>
</tr>
<tr>
<td>[36]</td>
<td>chlorination &amp; fluorination</td>
<td>3LiAl + 6ClO$_3$F $\rightarrow$ 3LiCl + 2AlF$_3$ + AlCl$_3$(g) + 9O$_2$</td>
<td>+1.90</td>
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<tr>
<td>[37]</td>
<td>chlorination &amp; fluorination &amp; oxygenation</td>
<td>7LiAl + 2ClO$_3$F $\rightarrow$ 2LiCl + 3LiAlO$_2$ + 2LiF + 4Al</td>
<td>+0.86</td>
</tr>
<tr>
<td>[38]</td>
<td>chlorination &amp; fluorination &amp; oxygenation</td>
<td>2LiAl + ClO$_3$F $\rightarrow$ Al$_2$O$_3$ + LiF + LiCl</td>
<td>+1.51</td>
</tr>
</tbody>
</table>
### Table 3. Calculated Phase Compatibilities in System Li-Al-O-Cl-F at 1100 K

<table>
<thead>
<tr>
<th>Reaction #</th>
<th>Subsystem</th>
<th>Reaction</th>
<th>$\Delta G_R$ (1100 K), kcal</th>
</tr>
</thead>
<tbody>
<tr>
<td>[39]</td>
<td>Li$_2$O-Al$_2$O$_3$-Li-Al</td>
<td>2Li$_2$O(c) + LiAl(l) → LiAlO$_2$(c) + 4Li(l)</td>
<td>- 9.6</td>
</tr>
<tr>
<td>[40]</td>
<td>Li$_2$O-Al$_2$O$_3$-Li-Al</td>
<td>2Li$_2$O(c) + Al(l) → LiAlO$_2$(c) + 3Li(l)</td>
<td>- 11.1</td>
</tr>
<tr>
<td>[41]</td>
<td>Li$_2$O-Al$_2$O$_3$-Li-Al</td>
<td>3Li(l) + 2Al$_2$O$_3$(c) → 3LiAlO$_2$(c) + Al(l)</td>
<td>- 47.6</td>
</tr>
<tr>
<td>[42]</td>
<td>Li$_2$O-Al$_2$O$_3$-Li-Al</td>
<td>3LiAlO$_2$(c) + 2Al(l) → 2Al$_2$O$_3$(c) + 3LiAl(l)</td>
<td>+ 43.1</td>
</tr>
<tr>
<td>[43]</td>
<td>Li$_2$O-Al$_2$O$_3$-Li-Al</td>
<td>3Li$_2$O(c) + 2LiAl(l) → 8Li(l) + Al$_2$O$_3$(c)</td>
<td>+ 10.1</td>
</tr>
<tr>
<td>[44]</td>
<td>Li$_2$O-Al$_2$O$_3$-Li-Al</td>
<td>Al$_2$O$_3$(c) + 6LiAl(l) → 3Li$_2$O(c) + 8Al(l)</td>
<td>+ 2.0</td>
</tr>
<tr>
<td>[45]</td>
<td>Li$_2$O-Al$_2$O$_3$-Li-Al</td>
<td>LiAlO$_2$(c) + 3LiAl(l) → 2Li$_2$O(c) + 4Al(l)</td>
<td>+ 15.7</td>
</tr>
<tr>
<td>[46]</td>
<td>Li$_2$O-Al$_2$O$_3$-Li-Al</td>
<td>3LiAlO$_2$(c) + LiAl(l) → 2Al$_2$O$_3$(c) + 4Li(l)</td>
<td>+ 49.2</td>
</tr>
<tr>
<td>[47]</td>
<td>Li$_2$O-Al$_2$O$_3$-Li-Al</td>
<td>3Li$_2$O(c) + 2Al(l) → Al$_2$O$_3$(c) + 6Li(l)</td>
<td>+ 7.1</td>
</tr>
<tr>
<td>[48]</td>
<td>Li$_2$O-Al$_2$O$_3$-LiCl-AlCl$_3$</td>
<td>2Li$_2$O(c) + AlCl$_3$(g) → LiAlO$_2$(c) + 3LiCl(l)</td>
<td>- 117.5</td>
</tr>
<tr>
<td>[49]</td>
<td>Li$_2$O-Al$_2$O$_3$-LiCl-AlCl$_3$</td>
<td>6LiCl(l) + Al$_2$O$_3$(c) → 3Li$_2$(o) + 2AlCl$_3$(g)</td>
<td>+ 205.6</td>
</tr>
<tr>
<td>[50]</td>
<td>Li$_2$O-Al$_2$O$_3$-LiCl-AlCl$_3$</td>
<td>3LiCl(l) + 2Al$_2$O$_3$(c) → 3LiAlO$_2$(c) + AlCl$_3$(g)</td>
<td>+ 58.7</td>
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<tr>
<td>[51]</td>
<td>LiCl-AlCl$_3$-LiF-AlF$_3$</td>
<td>3LiCl(l) + AlF$_3$(c) → 3LiF(c) + AlCl$_3$(g)</td>
<td>+ 32.7</td>
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<td>[52]</td>
<td>LiCl-AlCl$_3$-LiF-AlF$_3$</td>
<td>3LiCl(l) + Li$_3$AlF$_6$(l) → 6LiF(c) + AlCl$_3$(g)</td>
<td>+ 44.1</td>
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<td>[53]</td>
<td>LiCl-AlCl$_3$-LiF-AlF$_3$</td>
<td>Li$_3$AlF$_6$(l) + AlCl$_3$(g) → 3LiCl(l) + 2AlF$_3$(c)</td>
<td>- 21.4</td>
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<tr>
<td>[54]</td>
<td>LiCl-AlCl$_3$-Li-Al</td>
<td>3LiAl(l) + AlCl$_3$(g) → 3LiCl(l) + 4Al(l)</td>
<td>- 101.8</td>
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<tr>
<td>[55]</td>
<td>LiCl-AlCl$_3$-Li-Al</td>
<td>4Li(l) + AlCl$_3$(g) → 3LiCl(l) + LiAl(l)</td>
<td>- 107.9</td>
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<td>[56]</td>
<td>LiCl-AlCl$_3$-Li-Al</td>
<td>3LiCl(l) + Al(l) → 3Li(l) + AlCl$_3$(g)</td>
<td>+ 106.4</td>
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<tr>
<td>[57]</td>
<td>Li$_2$O-Al$_2$O$_3$-LiF-AlF$_3$</td>
<td>6LiF(c) + Al$_2$O$_3$(c) $\rightarrow$ 3Li$_2$O(c) + 2AlF$_3$(c)</td>
<td>+140.2</td>
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<td>[58]</td>
<td>Li$_2$O-Al$_2$O$_3$-LiF-AlF$_3$</td>
<td>LiAlO$_2$(c) + Li$_3$AlF$_6$(l) $\rightarrow$ 2Li$_2$O(c) + 2AlF$_3$(c)</td>
<td>+96.1</td>
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<tr>
<td>[59]</td>
<td>Li$_2$O-Al$_2$O$_3$-LiF-AlF$_3$</td>
<td>3LiAlO$_2$(c) + Li$_3$AlF$_6$(l) $\rightarrow$ 6LiF(c) + 2Al$_2$O$_3$(c)</td>
<td>-14.7</td>
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<tr>
<td>[60]</td>
<td>Li$_2$O-Al$_2$O$_3$-LiF-AlF$_3$</td>
<td>3LiAlO$_2$(c) + AlF$_3$(c) $\rightarrow$ 3LiF(c) + 2Al$_2$O$_3$(c)</td>
<td>-26.0</td>
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<tr>
<td>[61]</td>
<td>Li$_2$O-Al$_2$O$_3$-LiF-AlF$_3$</td>
<td>LiAlO$_2$(c) + 3LiF(c) $\rightarrow$ 2Li$_2$O(c) + AlF$_3$(c)</td>
<td>+84.8</td>
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<tr>
<td>[62]</td>
<td>Li$_2$O-Al$_2$O$_3$-LiF-AlF$_3$</td>
<td>2Li$_3$AlF$_6$(l) + 3Li$_2$O(c) $\rightarrow$ 12LiF(c) + Al$_2$O$_3$(c)</td>
<td>-117.5</td>
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<td>[63]</td>
<td>Li$_2$O-Al$_2$O$_3$-LiF-AlF$_3$</td>
<td>Li$_3$AlF$_6$(l) + 2Li$_2$O(c) $\rightarrow$ 6LiF(c) + LiAlO$_2$(c)</td>
<td>-73.4</td>
</tr>
<tr>
<td>[64]</td>
<td>Li$_2$O-Al$_2$O$_3$-LiF-AlF$_3$</td>
<td>2Li$_3$AlF$_6$(l) + Al$_2$O$_3$(c) $\rightarrow$ 3Li$_2$O(c) + 4AlF$_3$(c)</td>
<td>+162.8</td>
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<td>[65]</td>
<td>Li$_2$O-Al$_2$O$_3$-LiF-AlF$_3$</td>
<td>Li$_3$AlF$_6$(l) + 2Al$_2$O$_3$(c) $\rightarrow$ 3LiAlO$_2$(c) + 2AlF$_3$(c)</td>
<td>+37.3</td>
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<td>[66]</td>
<td>LiF-AlF$_3$-Li-Al</td>
<td>3Li(l) + AlF$_3$(c) $\rightarrow$ 3LiF(c) + Al(l)</td>
<td>-73.6</td>
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<td>[67]</td>
<td>LiF-AlF$_3$-Li-Al</td>
<td>Li$_3$AlF$_6$(l) + 3LiAl(l) $\rightarrow$ 6LiF(c) + 4Al(l)</td>
<td>-57.8</td>
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<tr>
<td>[68]</td>
<td>LiF-AlF$_3$-Li-Al</td>
<td>4Li(l) + 2AlF$_3$(c) $\rightarrow$ Li$_3$AlF$_6$(l) + LiAl(l)</td>
<td>-86.5</td>
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<td>[69]</td>
<td>LiF-AlF$_3$-Li-Al</td>
<td>3LiAl(l) + AlF$_3$(c) $\rightarrow$ 3LiF(c) + 4Al(l)</td>
<td>-69.1</td>
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<td>[70]</td>
<td>LiF-AlF$_3$-Li-Al</td>
<td>Li$_3$AlF$_6$(l) + Al(l) $\rightarrow$ 3Li(l) + 2AlF$_3$(c)</td>
<td>+85.0</td>
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<td>[71]</td>
<td>LiF-AlF$_3$-LiAl</td>
<td>Li$_3$AlF$_6$(l) + 4Al(l) $\rightarrow$ 2AlF$_3$(c) + 3LiAl(l)</td>
<td>+80.4</td>
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<td>[72]</td>
<td>LiFAlF$_3$-LiAl</td>
<td>Li$_3$AlF$_6$(l) + 3Li(l) $\rightarrow$ 6LiF(c) + Al(l)</td>
<td>-62.3</td>
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<td>[73]</td>
<td>LiF-AlF$_3$-Li-Al</td>
<td>LiAl(l) + 3LiF(c) $\rightarrow$ 4Li(l) + AlF$_3$(c)</td>
<td>+75.1</td>
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<td>[74]</td>
<td>LiF-AlF$_3$-Li-Al</td>
<td>LiAl(l) + 6LiF(c) $\rightarrow$ 4Li(l) + Li$_3$AlF$_6$(l)</td>
<td>+63.8</td>
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<tr>
<td>Reaction #</td>
<td>Subsystem</td>
<td>Reaction</td>
<td>$\Delta G_R(1100\text{ K})$, kcal</td>
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<td>[75]</td>
<td>MgO-Li$_2$O-MgF$_2$-LiF</td>
<td>MgO(c) + 2LiF((l)) $\rightarrow$ Li$_2$O(c) + MgF$_2$(c)</td>
<td>+ 28.1</td>
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<tr>
<td>[76]</td>
<td>MgO-Li$_2$O-MgCl$_2$-LiCl</td>
<td>MgO(c) + 2(MgCl$_2$·LiCl)((l)) $\rightarrow$ 3MgCl$_2$((l)) + Li$_2$O(c)</td>
<td>+ 52.2</td>
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<tr>
<td>[77]</td>
<td>MgO-Li$_2$O-MgCl$_2$-LiCl</td>
<td>MgO(c) + 2LiCl((l)) $\rightarrow$ MgCl$_2$((l)) + Li$_2$O(c)</td>
<td>+ 49.1</td>
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<tr>
<td>[78]</td>
<td>MgO-Li$_2$O-MgCl$_2$-LiCl</td>
<td>MgO(c) + 3LiCl((l)) $\rightarrow$ (MgCl$_2$·LiCl)((l)) + Li$_2$O(c)</td>
<td>+ 47.6</td>
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<tr>
<td>[79]</td>
<td>Mg-Li-MgO-Li$_2$O</td>
<td>2Mg((l)) + Li$_2$O(c) $\rightarrow$ 2MgLi((l)) + MgO(c)</td>
<td>- 9.8</td>
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<td>[80]</td>
<td>Mg-Li-MgO-Li$_2$O</td>
<td>Mg((l)) + LiO$_2$(c) $\rightarrow$ MgO(c) + 2Li((l))</td>
<td>- 6.8</td>
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<td>[81]</td>
<td>Mg-Li-MgO-Li$_2$O</td>
<td>MgO(c) + 3Li((l)) $\rightarrow$ MgLi((l)) + Li$_2$O(c)</td>
<td>+ 5.3</td>
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<td>[82]</td>
<td>MgF$_2$-LiF-MgCl$_2$-LiCl</td>
<td>3MgCl$_2$((l)) + 2LiF((l)) $\rightarrow$ 2(MgCl$_2$·LiCl)((l)) + MgF$_2$(c)</td>
<td>- 24.1</td>
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<tr>
<td>[83]</td>
<td>MgF$_2$-LiF-MgCl$_2$-LiCl</td>
<td>3LiCl((l)) + MgF$_2$(c) $\rightarrow$ (MgCl$_2$·LiCl)((l)) + 2LiF(c)</td>
<td>+ 19.6</td>
</tr>
<tr>
<td>[84]</td>
<td>MgF$_2$-LiF-MgCl$_2$-LiCl</td>
<td>MgCl$_2$((l)) + 2LiF(c) $\rightarrow$ 2LiCl((l)) + MgF$_2$(c)</td>
<td>- 21.1</td>
</tr>
<tr>
<td>[85]</td>
<td>Mg-Al-MgO-Al$_2$O$_3$</td>
<td>3MgO(c) + 2MgAl(l) $\rightarrow$ 5Mg(l) + Al$_2$O$_3$(c)</td>
<td>+ 30.6</td>
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<tr>
<td>[86]</td>
<td>Mg-Al-MgO-Al$_2$O$_3$</td>
<td>4MgO(c) + 2MgAl(l) $\rightarrow$ 5Mg(l) + MgAl$_2$O$_4$(c)</td>
<td>+ 22.6</td>
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<tr>
<td>[87]</td>
<td>Mg-Al-MgO-Al$_2$O$_3$</td>
<td>4MgO(c) + 2Al(l) $\rightarrow$ MgAl$_2$O$_4$(c) + 3Mg(l)</td>
<td>+ 19.5</td>
</tr>
<tr>
<td>[88]</td>
<td>Mg-Al-MgO-Al$_2$O$_3$</td>
<td>3MgAl$_2$O$_4$(c) + 2Al(l) $\rightarrow$ 3Mg(l) + 4Al$_2$O$_3$(c)</td>
<td>+ 51.6</td>
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<tr>
<td>[89]</td>
<td>Mg-Al-MgO-Al$_2$O$_3$</td>
<td>3MgAl$_2$O$_4$(c) + 5Al(l) $\rightarrow$ 4Al$_2$O$_3$(c) + 3MgAl(l)</td>
<td>+ 47.0</td>
</tr>
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<td>[90]</td>
<td>Mg-Al-MgO-Al$_2$O$_3$</td>
<td>3MgO(c) + 3Al(l) $\rightarrow$ Al$_2$O$_3$(c) + 3MgAl(l)</td>
<td>+ 23.0</td>
</tr>
<tr>
<td>Reaction #</td>
<td>Subsystem</td>
<td>Reaction</td>
<td>$\Delta G_R$ (1100 K), kcal</td>
</tr>
<tr>
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<tr>
<td>[91]</td>
<td>Mg-Al-MgO-Al$_2$O$_3$</td>
<td>MgAl$_2$O$_4$ (c) + 3MgAl(\text{l}) $\rightarrow$ 4MgO(c) + 5Al(\text{l})</td>
<td>- 15.0</td>
</tr>
<tr>
<td>[92]</td>
<td>Mg-Al-MgO-Al$_2$O$_3$</td>
<td>3MgAl$_2$O$_4$ (c) + 2MgAl(\text{l}) $\rightarrow$ 5Mg(\text{l}) + 4Al$_2$O$_3$ (c)</td>
<td>+ 54.6</td>
</tr>
<tr>
<td>[93]</td>
<td>Mg-Al-MgO-Al$_2$O$_3$</td>
<td>3MgO(c) + 2Al(\text{l}) $\rightarrow$ 3Mg(\text{l}) + Al$_2$O$_3$ (c)</td>
<td>+ 27.5</td>
</tr>
<tr>
<td>[94]</td>
<td>Mg-Al-MgF$_2$-AlF$_3$</td>
<td>3MgF$_2$(c) + 2Al(\text{l}) $\rightarrow$ 2AlF$_3$(c) + 3Mg(\text{l})</td>
<td>+ 83.5</td>
</tr>
<tr>
<td>[95]</td>
<td>Mg-Al-MgF$_2$-AlF$_3$</td>
<td>3MgF$_2$(c) + 5Al(\text{l}) $\rightarrow$ 2AlF$_3$(c) + 3MgAl(\text{l})</td>
<td>+ 79.0</td>
</tr>
<tr>
<td>[96]</td>
<td>Mg-Al-MgF$_2$-AlF$_3$</td>
<td>5Mg(\text{l}) + 2AlF$_3$(c) $\rightarrow$ 3MgF$_2$(c) + 2MgAl(\text{l})</td>
<td>- 86.5</td>
</tr>
<tr>
<td>[97]</td>
<td>Mg-Al-MgCl$_2$-AlCl$_3$</td>
<td>5Mg(\text{l}) + 2AlCl$_3$(g) $\rightarrow$ 3MgCl$_2$(\text{g}) + 2MgAl(\text{l})</td>
<td>- 88.8</td>
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<tr>
<td>[98]</td>
<td>Mg-Al-MgCl$_2$-AlCl$_3$</td>
<td>3MgCl$_2$(\text{g}) + 2Al(\text{l}) $\rightarrow$ 3Mg(\text{l}) + 2AlCl$_3$(g)</td>
<td>+ 85.8</td>
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<tr>
<td>[99]</td>
<td>Mg-Al-MgCl$_2$-AlCl$_3$</td>
<td>3MgCl$_2$(\text{g}) + 5Al(\text{l}) $\rightarrow$ 3MgAl(\text{l}) + 2AlCl$_3$(g)</td>
<td>+ 81.2</td>
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<tr>
<td>[100]</td>
<td>MgF$_2$-AlF$_3$-MgCl$_2$-AlCl$_3$</td>
<td>MgCl$_2$(\text{g}) + AlF$_3$(c) $\rightarrow$ MgF$_2$(c) + AlCl$_3$(g)</td>
<td>+ 56.3</td>
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<tr>
<td>[101]</td>
<td>Mg-Li-MgF$_2$-LiF</td>
<td>3Mg(\text{l}) + 2LiF(c) $\rightarrow$ MgF$_2$(c) + 2MgLi(\text{l})</td>
<td>+ 18.2</td>
</tr>
<tr>
<td>[102]</td>
<td>Mg-Li-MgF$_2$-LiF</td>
<td>MgLi(\text{l}) + 2LiF(c) $\rightarrow$ MgF$_2$(c) + 3Li(\text{l})</td>
<td>+ 22.8</td>
</tr>
<tr>
<td>[103]</td>
<td>Mg-Li-MgF$_2$-LiF</td>
<td>MgF$_2$(c) + 2Li(\text{l}) $\rightarrow$ 2LiF(c) + Mg(\text{l})</td>
<td>- 21.2</td>
</tr>
<tr>
<td>[104]</td>
<td>MgO-Al$_2$O$_3$-MgCl$_2$-AlCl$_3$</td>
<td>4MgO(c) + AlCl$_3$(g) $\rightarrow$ MgCl$_2$(\text{g}) + MgAl$_2$O$_4$(c)</td>
<td>+ 33.0</td>
</tr>
<tr>
<td>[105]</td>
<td>MgO-Al$_2$O$_3$-MgCl$_2$-AlCl$_3$</td>
<td>3MgCl$_2$(\text{g}) + Al$_2$O$_3$(c) $\rightarrow$ 3MgO(c) + 2AlCl$_3$(g)</td>
<td>+ 58.2</td>
</tr>
<tr>
<td>[106]</td>
<td>MgO-Al$_2$O$_3$-MgCl$_2$-AlCl$_3$</td>
<td>3MgAl$_2$O$_4$(c) + 2AlCl$_3$(g) $\rightarrow$ 3MgCl$_2$(\text{g}) + 4Al$_2$O$_3$(c)</td>
<td>- 34.2</td>
</tr>
<tr>
<td>Reaction #</td>
<td>Subsystem</td>
<td>Reaction</td>
<td>( \Delta G_R ) (1100 K), kcal</td>
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<tr>
<td>[107]</td>
<td>MgO-Al₂O₃-MgF₂-AlF₃</td>
<td>3MgF₂(c) + MgAl₂O₄(c) \rightarrow 4MgO(c) + 2AlF₃(c)</td>
<td>+ 64.0</td>
</tr>
<tr>
<td>[108]</td>
<td>MgO-Al₂O₃-MgF₂-AlF₃</td>
<td>3MgO(c) + 2AlF₃(c) \rightarrow 3MgF₂(c) + Al₂O₃(c)</td>
<td>- 56.0</td>
</tr>
<tr>
<td>[109]</td>
<td>MgO-Al₂O₃-MgF₂-AlF₃</td>
<td>2AlF₃(c) + 3MgAl₂O₄(c) \rightarrow 3MgF₂(c) + 4Al₂O₃(c)</td>
<td>- 31.9</td>
</tr>
<tr>
<td>[110]</td>
<td>Mg-Li-MgCl₂-LiCl</td>
<td>3MgCl₂(ℓ) + 2Li(ℓ) \rightarrow 2(MgCl₂·LiCl)(ℓ) + Mg(ℓ)</td>
<td>- 45.4</td>
</tr>
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<td>[111]</td>
<td>Mg-Li-MgCl₂-LiCl</td>
<td>MgCl₂(ℓ) + 2Li(ℓ) \rightarrow Mg(ℓ) + 2LiCl(ℓ)</td>
<td>- 42.3</td>
</tr>
<tr>
<td>[112]</td>
<td>Mg-Li-MgCl₂-LiCl</td>
<td>(MgCl₂·LiCl)(ℓ) + 2Li(ℓ) \rightarrow 3LiCl(ℓ) + Mg(ℓ)</td>
<td>- 40.8</td>
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<tr>
<td>[113]</td>
<td>MgO-Al₂O₃-Li₂O-MgCl₂-AlCl₃-LiCl</td>
<td>MgCl₂(ℓ) + 2LiAlO₂(c) \rightarrow MgAl₂O₄(c) + 2LiCl(ℓ)</td>
<td>- 27.8</td>
</tr>
<tr>
<td>[114]</td>
<td>MgO-Al₂O₃-Li₂O-MgF₂-AlF₃-LiF</td>
<td>MgF₂(c) + 2LiAlO₂(c) \rightarrow MgAl₂O₄(c) + 2LiF(c)</td>
<td>- 6.7</td>
</tr>
<tr>
<td>[115]</td>
<td>MgO-Al₂O₃-Li₂O-MgF₂-AlF₃-LiF</td>
<td>Li₃AlF₆(ℓ) + 3MgAl₂O₄(c) \rightarrow 3LiAlO₂(c) + 3MgF₂(c) + 2Al₂O₃(c)</td>
<td>+ 5.4</td>
</tr>
<tr>
<td>[116]</td>
<td>MgO-Al₂O₃-Li₂O-MgF₂-AlF₃-LiF</td>
<td>2Li₃AlF₆(ℓ) + 6MgAl₂O₄(c) \rightarrow 6MgF₂(c) + 6LiAlO₂(c) + 4Al₂O₃(c)</td>
<td>+ 10.8</td>
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<tr>
<td>[117]</td>
<td>MgO-Al₂O₃-Li₂O-MgF₂-AlF₃-LiF</td>
<td>Li₃AlF₆(ℓ) + 2MgO + 2LiF(c) + 2MgF₂(c) + LiAlO₂(c)</td>
<td>- 17.3</td>
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<tr>
<td>Reaction #</td>
<td>Subsystem</td>
<td>Reaction</td>
<td>$\Delta G_R (1100 \text{ K})$, kcal</td>
</tr>
<tr>
<td>------------</td>
<td>-----------</td>
<td>----------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>[118]</td>
<td>MgF$_2$-AlF$_3$-LiF-MgCl$_2$-AlCl$_3$-LiCl</td>
<td>$3\text{MgCl}_2(\ell) + 2\text{Li}_3\text{AlF}_6(\ell) \rightarrow 6\text{LiCl}(\ell) + 3\text{MgF}_2(\ell) + 2\text{AlF}_3(\ell)$</td>
<td>- 40.6</td>
</tr>
<tr>
<td>[119]</td>
<td>Mg-Al-Li-MgF$_2$-AlF$_3$-LiF</td>
<td>$2\text{Li}_3\text{AlF}_6(\ell) + 3\text{Mg}(\ell) \rightarrow 6\text{LiF}(\ell) + 3\text{MgF}_2(\ell) + 2\text{Al}(\ell)$</td>
<td>- 60.9</td>
</tr>
<tr>
<td>[120]</td>
<td>Mg-Al-Li-MgO-Al$_2$O$_3$-Li$_2$O</td>
<td>$\text{LiAlO}_2(\ell) + 2\text{Mg}(\ell) \rightarrow 2\text{MgO}(\ell) + \text{LiAl}(\ell)$</td>
<td>- 4.0</td>
</tr>
<tr>
<td>[121]</td>
<td>Mg-Al-Li-MgO-Al$_2$O$_3$-Li$_2$O</td>
<td>$\text{MgAl}_2\text{O}_4(\ell) + 2\text{Li}(\ell) \rightarrow 2\text{LiAlO}_2(\ell) + \text{Mg}(\ell)$</td>
<td>- 14.6</td>
</tr>
<tr>
<td>[122]</td>
<td>Mg-Al-Li-MgO-Al$_2$O$_3$-Li$_2$O</td>
<td>$2\text{MgAl}_2\text{O}_4(\ell) + 3\text{Li}(\ell) \rightarrow 2\text{MgO}(\ell) + 3\text{LiAlO}_2(\ell) + \text{Al}(\ell)$</td>
<td>- 31.6</td>
</tr>
<tr>
<td>Reaction #</td>
<td>Type of Reaction</td>
<td>Reaction</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>[123]</td>
<td>chlorination</td>
<td>LiAlMg + ClO$_3$F $\rightarrow$ Mg + Al + LiCl + (1/2)F$_2$ + (3/2)O$_2$</td>
<td></td>
</tr>
<tr>
<td>[124]</td>
<td>chlorination</td>
<td>LiAlMg + 3ClO$_3$F $\rightarrow$ MgCl$_2$ + LiCl + Al + (3/2)F$_2$ + (9/2)O$_2$</td>
<td></td>
</tr>
<tr>
<td>[125]</td>
<td>chlorination</td>
<td>LiAlMg + 6ClO$_3$F $\rightarrow$ LiCl + MgCl$_2$ + AlCl$_3$(g) + 3F$_2$ + 9O$_2$</td>
<td></td>
</tr>
<tr>
<td>[126]</td>
<td>fluorination</td>
<td>LiAlMg + ClO$_3$F $\rightarrow$ Mg + Al + LiF + (1/2)F$_2$ + (3/2)O$_2$</td>
<td></td>
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<tr>
<td>[127]</td>
<td>fluorination</td>
<td>3LiAlMg + 12ClO$_3$F $\rightarrow$ 3MgF$_2$ + Li$_3$AlF$_6$ + 2Al + 6Cl$_2$ + 18O$_2$</td>
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<td>[128]</td>
<td>fluorination</td>
<td>3LiAlMg + 18ClO$_3$F $\rightarrow$ 3MgF$_2$ + 2AlF$_3$ + Li$_3$AlF$_6$ + 9Cl$_2$ + 27O$_2$</td>
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<tr>
<td>[129]</td>
<td>oxygenation</td>
<td>LiAlMg + (2/3)ClO$_3$F $\rightarrow$ Mg + LiAlO$_2$ + (2/3)Cl$_2$ + (1/3)F$_2$</td>
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</tr>
<tr>
<td>[130]</td>
<td>oxygenation</td>
<td>LiAlMg + ClO$_3$F $\rightarrow$ MgO + LiAlO$_2$ + (1/2)Cl$_2$ + (1/2)F$_2$</td>
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<tr>
<td>[131]</td>
<td>chlorination &amp; oxygenation</td>
<td>7LiAlMg + 6ClO$_3$F $\rightarrow$ 6LiCl + 3MgAl$_2$O$_4$ + LiAlO$_2$ + 4MgO + 3F$_2$</td>
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<tr>
<td>[132]</td>
<td>fluorination &amp; oxygenation</td>
<td>7LiAlMg + 6ClO$_3$F $\rightarrow$ 6LiF + 3MgAl$_2$O$_4$ + LiAlO$_2$ + 4MgO + 3Cl$_2$</td>
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<tr>
<td>[133]</td>
<td>chlorination &amp; fluorination</td>
<td>LiAlMg + 3ClO$_3$F $\rightarrow$ LiCl + AlF$_3$ + MgCl$_2$ + (9/2)O$_2$</td>
<td></td>
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<tr>
<td>[134]</td>
<td>chlorination &amp; fluorination &amp; oxygenation</td>
<td>4LiAlMg + 3ClO$_3$F $\rightarrow$ MgF$_2$ + LiF + 3LiCl + 2MgAl$_2$O$_4$ + MgO</td>
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</table>
Table 6. Calculated Phase Compatibilities in System Li-Be-O-Cl-F at 1100 K

<table>
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<tr>
<th>Reaction #</th>
<th>Subsystem</th>
<th>Reaction</th>
<th>$\Delta G_R \ (1100 \text{ K}), \text{ kcal} $</th>
</tr>
</thead>
<tbody>
<tr>
<td>[135]</td>
<td>Li-Be-LiF-BeF$_2$</td>
<td>$2\text{Li}(\ell) + \text{Li}_2\text{BeF}_4(\ell) \rightarrow 4\text{LiF}(c) + \text{Be}(c)$</td>
<td>- 28.3</td>
</tr>
<tr>
<td>[136]</td>
<td>Li-Be-LiF-BeF$_2$</td>
<td>$2\text{Li}(\ell) + 4\text{LiBeF}_3(\ell) \rightarrow 3\text{Li}_2\text{BeF}_4(\ell) + \text{Be}(c)$</td>
<td>- 42.1</td>
</tr>
<tr>
<td>[137]</td>
<td>Li-Be-LiF-BeF$_2$</td>
<td>$2\text{Li}(\ell) + \text{LiBeF}_3(\ell) \rightarrow 3\text{LiF}(c) + \text{Be}(c)$</td>
<td>- 31.7</td>
</tr>
<tr>
<td>[138]</td>
<td>Li-Be-LiF-BeF$_2$</td>
<td>$2\text{Li}(\ell) + \text{BeF}_2(\ell) \rightarrow 2\text{LiF}(c) + \text{Be}(c)$</td>
<td>- 38.6</td>
</tr>
<tr>
<td>[139]</td>
<td>Li-Be-LiF-BeF$_2$</td>
<td>$2\text{Li}(\ell) + 2\text{BeF}_2(\ell) \rightarrow \text{Li}_2\text{BeF}_4(\ell) + \text{Be}(c)$</td>
<td>- 48.9</td>
</tr>
<tr>
<td>[140]</td>
<td>Li-Be-LiF-BeF$_2$</td>
<td>$2\text{Li}(\ell) + 3\text{BeF}_2(\ell) \rightarrow 2\text{LiBeF}_3(\ell) + \text{Be}(c)$</td>
<td>- 52.2</td>
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<tr>
<td>[141]</td>
<td>Li$_2$O-BeO-LiF-BeF$_2$</td>
<td>$\text{Li}_2\text{O}(c) + \text{Li}_2\text{BeF}_4(\ell) \rightarrow 4\text{LiF}(c) + \text{BeO}(c)$</td>
<td>- 39.7</td>
</tr>
<tr>
<td>[142]</td>
<td>Li$_2$O-BeO-LiF-BeF$_4$</td>
<td>$\text{Li}_2\text{O}(c) + 4\text{LiBeF}_3(\ell) \rightarrow 3\text{Li}_2\text{BeF}_4(\ell) + \text{BeO}(c)$</td>
<td>- 53.5</td>
</tr>
<tr>
<td>[143]</td>
<td>Li$_2$O-BeO-LiF-BeF$_4$</td>
<td>$\text{Li}_2\text{O}(c) + \text{LiBeF}_3(\ell) \rightarrow 3\text{LiF}(c) + \text{BeO}(c)$</td>
<td>- 43.1</td>
</tr>
<tr>
<td>[144]</td>
<td>Li$_2$O-BeO-LiF-BeF$_4$</td>
<td>$\text{Li}_2\text{O}(c) + \text{BeF}_2(\ell) \rightarrow 2\text{LiF}(c) + \text{BeO}(c)$</td>
<td>- 50.0</td>
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<tr>
<td>[145]</td>
<td>Li$_2$O-BeO-LiF-BeF$_4$</td>
<td>$\text{Li}_2\text{O}(c) + 2\text{BeF}_2(\ell) \rightarrow \text{BeO}(c) + \text{Li}_2\text{BeF}_4(\ell)$</td>
<td>- 60.3</td>
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<tr>
<td>[146]</td>
<td>Li$_2$O-BeO-LiF-BeF$_4$</td>
<td>$\text{Li}_2\text{O}(c) + 3\text{BeF}_2(\ell) \rightarrow \text{BeO}(c) + 2\text{LiBeF}_3(\ell)$</td>
<td>- 63.6</td>
</tr>
<tr>
<td>[147]</td>
<td>Li-Be-LiCl-BeCl$_2$</td>
<td>$2\text{LiCl}(\ell) + \text{Be}(c) \rightarrow \text{BeCl}_2(g) + 2\text{Li}(\ell)$</td>
<td>+ 63.9</td>
</tr>
<tr>
<td>[148]</td>
<td>Li-Be-Li$_2$O-BeO</td>
<td>$2\text{Li}(\ell) + \text{BeO}(c) \rightarrow \text{Li}_2\text{O}(c) + \text{Be}(c)$</td>
<td>+ 11.4</td>
</tr>
<tr>
<td>[149]</td>
<td>Li$_2$O-BeO-LiCl-BeCl$_2$</td>
<td>$\text{Li}_2\text{O}(c) + \text{BeCl}_2(g) \rightarrow 2\text{LiCl}(\ell) + \text{BeO}(c)$</td>
<td>- 75.3</td>
</tr>
<tr>
<td>[150]</td>
<td>LiCl-BeCl$_2$-LiF-BeF$_2$</td>
<td>$2\text{LiCl}(\ell) + \text{Li}_2\text{BeF}_4(\ell) \rightarrow 4\text{LiF}(c) + \text{BeCl}_2(g)$</td>
<td>+ 35.6</td>
</tr>
<tr>
<td>Reaction #</td>
<td>Subsystem</td>
<td>Reaction</td>
<td>( \Delta G_R ) (1100 K), kcal</td>
</tr>
<tr>
<td>------------</td>
<td>-----------</td>
<td>----------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>[151]</td>
<td>LiCl-BeCl(_2)-LiF-BeF(_2)</td>
<td>2LiCl((l)) + LiBeF(_3)((l)) (\rightarrow) 3LiF((c)) + BeCl(_2)(g)</td>
<td>+ 32.1</td>
</tr>
<tr>
<td>[152]</td>
<td>LiCl-BeCl(_2)-LiF-BeF(_2)</td>
<td>2LiCl((l)) + BeF(_2)((l)) (\rightarrow) 2LiF((c)) + BeCl(_2)(g)</td>
<td>+ 25.3</td>
</tr>
<tr>
<td>[153]</td>
<td>LiCl-BeCl(_2)-LiF-BeF(_2)</td>
<td>Li(_2)BeF(_4)((l)) + BeCl(_2)(g) (\rightarrow) 2LiCl((l)) + 2BeF(_2)((l))</td>
<td>- 15.0</td>
</tr>
<tr>
<td>[154]</td>
<td>LiCl-BeCl(_2)-LiF-BeF(_2)</td>
<td>2LiCl((l)) + 4LiBeF(_3)((l)) (\rightarrow) 3Li(_2)BeF(_4)((l)) + BeCl(_2)(g)</td>
<td>+ 21.8</td>
</tr>
<tr>
<td>[155]</td>
<td>LiCl-BeCl(_2)-LiF-BeF(_2)</td>
<td>2LiBeF(_3)((l)) + BeCl(_2)(g) (\rightarrow) 2LiCl((l)) + 3BeF(_2)((l))</td>
<td>- 11.6</td>
</tr>
<tr>
<td>Reaction #</td>
<td>Type of Reaction</td>
<td>Reaction</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
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<td>--------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>[156]</td>
<td>fluorination</td>
<td>Li + Be + ClO₃F → LiF + Be + (1/2)Cl₂ + (3/2)O₂</td>
<td></td>
</tr>
<tr>
<td>[157]</td>
<td>fluorination</td>
<td>Li + Be + 2ClO₃F → LiF + BeF₂ + Cl₂ + 3O₂</td>
<td></td>
</tr>
<tr>
<td>[158]</td>
<td>chlorination</td>
<td>Li + Be + ClO₃F → LiCl + Be + (1/2)F₂ + (3/2)O₂</td>
<td></td>
</tr>
<tr>
<td>[159]</td>
<td>chlorination</td>
<td>Li + Be + 3ClO₃F → LiCl + BeCl₂(g) + (3/2)F₂ + (9/2)O₂</td>
<td></td>
</tr>
<tr>
<td>[160]</td>
<td>oxygenation</td>
<td>3Li + 3Be + ClO₃F → 3Li + 3BeO + (1/2)Cl₂ + (1/2)F₂</td>
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</tr>
<tr>
<td>[161]</td>
<td>oxygenation</td>
<td>3Li + 3Be + ClO₃F → (3/2)Li₂O + 3BeO + (1/2)Cl₂ + (1/2)F₂</td>
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<tr>
<td>[162]</td>
<td>fluorination &amp; oxygenation</td>
<td>3Li + 3Be + ClO₃F → LiF + 2Li + 3BeO + (1/2)Cl₂</td>
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<tr>
<td>[163]</td>
<td>fluorination &amp; oxygenation</td>
<td>3Li + 3Be + ClO₃F → 2Li₂O + 3BeO + (1/2)Cl₂ + (1/2)F₂</td>
<td></td>
</tr>
<tr>
<td>[164]</td>
<td>chlorination &amp; oxygenation</td>
<td>3Li + 3Be + ClO₃F → 2Li + 3BeO + LiCl + (1/2)F₂</td>
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<tr>
<td>[165]</td>
<td>chlorination &amp; oxygenation</td>
<td>7Li + 7Be + 3ClO₃F → 2Li₂O + 3LiCl + 7BeO + (3/2)F₂</td>
<td></td>
</tr>
<tr>
<td>[166]</td>
<td>chlorination &amp; fluorination</td>
<td>2Li + 2Be + ClO₃F → LiF + LiCl + 2Be + (3/2)O₂</td>
<td></td>
</tr>
<tr>
<td>[167]</td>
<td>chlorination &amp; fluorination</td>
<td>2Li + 2Be + 2ClO₃F → Be + BeF₂ + 2LiCl + 3O₂</td>
<td></td>
</tr>
<tr>
<td>[168]</td>
<td>chlorination &amp; fluorination</td>
<td>4Li + 4Be + 6ClO₃F → 3BeF₂ + 4LiCl + BeCl₂(g) + 9O₂</td>
<td></td>
</tr>
<tr>
<td>[169]</td>
<td>chlorination &amp; fluorination &amp; oxygenation</td>
<td>8Li + 8Be + 3ClO₃F → 8BeO + Li₂O + 3LiF + 3LiCl</td>
<td></td>
</tr>
</tbody>
</table>
Table 8. Calculated Phase Compatibility in System Li-C-F at 1100 K

<table>
<thead>
<tr>
<th>Reaction #</th>
<th>Subsystem</th>
<th>Reaction</th>
<th>$\Delta G_R(1100 \text{ K}), \text{ kcal}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[170]</td>
<td>Li-C-F</td>
<td>$10\text{Li}(\ell) + 2\text{CF}_4(g) \rightarrow \text{Li}_2\text{C}_2(c) + 8\text{LiF}(c)$</td>
<td>-620.7</td>
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<tr>
<td>[171]</td>
<td>Li-C-F</td>
<td>$4\text{LiF}(c) + 5\text{C}(c) + 2\text{Li}_2\text{C}_2(c) + \text{CF}_4(g)$</td>
<td>+284.5</td>
</tr>
<tr>
<td>[172]</td>
<td>Li-C-F</td>
<td>$\text{Li}_2\text{C}_2(c) + 5\text{F}_2(g) \rightarrow 2\text{CF}_4(g) + 2\text{LiF}(c)$</td>
<td>-600.0</td>
</tr>
<tr>
<td>[173]</td>
<td>Li-C-F</td>
<td>$2\text{C}(c) + 2\text{LiF}(c) + \text{Li}_2\text{C}_2(c) + 2\text{F}(g)$</td>
<td>+233.8</td>
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<td>[174]</td>
<td>Li-C-F</td>
<td>$\text{Li}_2\text{C}_2(c) + 8\text{F}(g) \rightarrow 2\text{Li}(\ell) + 2\text{CF}_4(g)$</td>
<td>-355.9</td>
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<tr>
<td>[175]</td>
<td>Li-C-F</td>
<td>$4\text{LiF}(c) + \text{C}(g) \rightarrow 4\text{Li}(\ell) + \text{CF}_4(g)$</td>
<td>+305.2</td>
</tr>
<tr>
<td>Reaction #</td>
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<td>Reaction</td>
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<tr>
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<tr>
<td>[177]</td>
<td>Li-B-LiF-BF$_3$</td>
<td>$4\text{Li}(\ell) + \text{BF}_3(g) \rightarrow 3\text{LiF}(c) + \text{LiB}(c)$</td>
<td></td>
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<tr>
<td>[178]</td>
<td>Li-B-LiF-BF$_3$</td>
<td>$3\text{LiF}(c) + \text{B}(c) \rightarrow 3\text{Li}(\ell) + \text{BF}_3(g)$</td>
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</tr>
<tr>
<td>[179]</td>
<td>Li-B-LiF-BF$_3$</td>
<td>$3\text{LiF}(c) + 3\text{B}(c) \rightarrow 3\text{LiB}(c) + \text{BF}_3(g)$</td>
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<td>[180]</td>
<td>Li-B-Li$_3$N-BN</td>
<td>$\text{Li}_3\text{N}(c) + \text{LiB}(c) + 4\text{Li}(\ell) + \text{BN}(c)$</td>
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<td>[181]</td>
<td>Li-B-Li$_3$N-BN</td>
<td>$\text{Li}_3\text{N}(c) + \text{B}(c) \rightarrow 3\text{Li}(\ell) + \text{BN}(c)$</td>
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<td>[182]</td>
<td>Li-B-Li$_3$N-BN</td>
<td>$3\text{LiB}(c) + \text{BN}(c) \rightarrow \text{Li}_3\text{N}(c) + 4\text{B}(c)$</td>
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<tr>
<td>[183]</td>
<td>Li$_3$N-BN-LiF-BF$_3$</td>
<td>$3\text{LiF}(c) + \text{BN}(c) \rightarrow \text{Li}_3\text{N}(c) + \text{BF}_3(g)$</td>
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</tbody>
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$\Delta G_R (1100 \text{ K}), \text{ kcal}$

-112.0
+110.5
+106.0
-31.0
-32.5
+37.1
+143.0
Table 10. Progressive Oxidation of LiB by NF$_3$

<table>
<thead>
<tr>
<th>Reaction #</th>
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<tr>
<td>[184]</td>
<td>3LiB + NF$_3$ → 2B + 3LiF + BN</td>
</tr>
<tr>
<td>[185]</td>
<td>3LiB + 2NF$_3$ → 3LiF + BF$_3$ + 2BN</td>
</tr>
<tr>
<td>Reaction #</td>
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</tr>
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<td>[14]</td>
<td>Li</td>
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<tr>
<td>[169]</td>
<td>Li + Be</td>
</tr>
<tr>
<td>[186]</td>
<td>2Li + LiB</td>
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<td>[2]</td>
<td>LiAl</td>
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<td>[188]</td>
<td>Al</td>
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<td>MgAl</td>
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<td>LiAl</td>
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<td>[187]</td>
<td>Mg</td>
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<td>[134]</td>
<td>LiAlMg</td>
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<td>[13]</td>
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* Calculation ignores weight of recycled water in dual stage reactions

** Calculated at 298 K

*** From ref. (11)
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Figure 10, continued.
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Office of Naval Research
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Technical Information Division
Naval Research Laboratory
4555 Overlook Avenue SW
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Dr. Jerry A. Smith
Chemistry Division
Office of Naval Research
800 N. Quincy Street
Arlington, VA. 22217

Dr. Albert D. Wood
Technology Programs
Office of Naval Research
800 N. Quincy St.
Arlington, VA. 22217

Dr. H.W. Carhart
Combustion & Fuels
Naval Research Laboratory
Washington, DC 20375

Professor Allen Fuhs
Department of Aeronautics
Naval Post Graduate School
Monterey, California 93943

Division Director
Engineering and Weapons
US Naval Academy
Annapolis, Maryland 21402

Mr. Francis J. Romano
Code 63R3
Naval Sea Systems Command
Washington, DC 20363
Mr. Robert Tompkins  
Code 36621, Bldg 126T  
Naval Underwater Systems Center  
Newport, Rhode Island 02841

Mr. Maurice F. Murphy  
Code R33, Room 4-1711  
Naval Surface Weapons, White Oak  
Silver Spring, Maryland 20910

Dr. Kurt Mueller  
Code R10  
Energetic Materials Division  
Naval Surface Weapons Center, White Oak  
Silver Spring, Maryland 20910

Dr. Lynn A. Parnell  
Code 6341  
Naval Ocean Systems Center  
San Diego, California 92152

Dr. Earl Quandt, Jr.  
Code 2704  
David Taylor Naval Ship Research and Development Center  
Annapolis, MD 21402

Mr. Richard Bloomquist  
Code 2752  
David Taylor Naval Ship R&D Center  
Annapolis, Maryland 21402

Dr. Lawrence P. Cook  
High Temperature Processes Group  
National Bureau of Standards  
Washington, DC 20234
Professor A. Murty Kanury  
Department of Mechanical Engineering  
Oregon State University  
Corvallis, Oregon 97331

Professor Irvin Glassman  
Department of Mechanical & Aerospace Engineering  
Engineering Quadrangle  
Princeton University  
Princeton, New York 08544

Professor Norman Chigier  
Department of Mechanical Engineering  
Carnegie-Mellon University  
Pittsburgh, Pennsylvania 15213

Professor George Janz  
Cogswell Laboratory, R306  
Department of Chemistry  
Rensselaer Polytechnic Institute  
Troy, New York  12181

Dr. Leonard Leibowitz  
Chemical Technology Division  
Argonne National Laboratory  
9700 South Case Avenue  
Argonne, Illinois  60439

Professor John Tarbell  
104 Fenske Laboratory  
Pennsylvania State University  
University Park, Pennsylvania 16801

Professor Thomas E. Daubert  
104 Fenske Laboratory  
Pennsylvania State University  
University State Park, Pennsylvania 16801

Dr. J. Braunstein  
Research Division  
Oak Ridge Operations  
Department E  
Oak Ridge, Tennessee  37831
Mr. Norman D. Hubele  
Fluidic Systems, MS 1301-RR  
Garrett Pneumatic Systems Division  
2801 East Washington St.  
Phoenix, Arizona 85034

Dr. Hugh H. Darsie  
Advanced Technology Group  
Sunstrand Energy Systems  
4747 Harrison Avenue  
Rockford, Illinois 61101

Professor Gerard M. Faeth  
Department of Aerospace Engineering  
University of Michigan  
Ann Arbor, Michigan 48109

Dr. Dan H. Kiely  
Power & Energy Group  
The Pennsylvania State University  
Applied Research Laboratory  
P.O. Box 30  
State College, Pennsylvania 16801

Professor Darryl E. Metzger  
Department of Mechanical & Aerospace Engineering  
Arizona State University  
Tempe, Arizona 85281

Dr. Dae H. Cho  
Reactor Analysis & Safety Division  
Argonne National Laboratory  
Argonne, Illinois 60439

Professor S.H. Chan  
Department of Mechanical Engineering  
The University of Wisconsin-Milwaukee  
P.O. Box 784  
Milwaukee, Wisconsin 53201

Professor George A. Brown  
Department of Mechanical Engineering and Applied Mechanics  
University of Rhode Island  
Kingston, Rhode Island 02881
A survey of eight alternative liquid metal stored chemical energy reactions has been made for purposes of comparison with the lithium-aluminum/water, lithium/sulfur hexafluoride, and other reaction schemes. The objective of the study was to survey the potential of these eight reactions as alternate stored chemical energy systems and to develop priorities for future study. Experimental data on the products of reaction and kinetics of reaction are presented for: (Li/H_2O; H_2/O_2), (Li/H_2O; Na_2O/H_2O; H_2/O_2), (MgAl/H_2O; H_2/O_2), and (LiAl/C10F). These data have been collected using thermogravimetry and Knudsen effusion mass spectrometry, with x-ray diffraction analysis of experimental products. Among other results, the data show that the aluminum component of the fuels is relatively inert to oxidation up to 650°C. Above this temperature, materials limitations have hampered the collection of experimental data.

Thermodynamic analysis has been used to extend the data on each of the eight reaction schemes, and to predict the chemical reaction with best represents the complete oxidation of each fuel by the indicated oxidant at 1100 K. Enthalpies have been calculated for each fuel/oxidant combination. Safety considerations are also discussed for each. Suggestions for future research are given, including suggestions for overcoming the materials problems encountered in this study.

**12. KEY WORDS** (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)
- enthalpy yield, kinetics, liquid metal combustion, lithium, lithium-aluminum
- lithium-boron, lithium-beryllium, magnesium-aluminum, nitrogen trifluoride, water