23 Boron–Oxidizer Systems

23.1 OVERVIEW

This chapter concerns the adiabatic properties of the boron–oxygen system and another thirty boron–oxidizer combinations. Equation 23.1 is a general description of the chemical reactions in question, and Table 23.1 provides a broad overview of the most basic results. The thermochemical descriptions within this chapter were derived from the *FactPS* and *FToxid* databases of

TABLE 23.1
Boron–Oxidizer Systems

Section	Pages	Oxidizer	Maximum T_{ad} (K)
23.2	762	O_2	3687
23.3	764	TiO_2	1429
23.4	765	V_2O_5	2323
23.5	767	Nb_2O_5	2120
23.6	768	Ta_2O_5	1622
23.7	769	Cr_2O_3	1662
23.8	770	MoO_3	2323
23.9	772	WO_3	2323
23.10	773	MnO	1459
23.11	774	Mn_3O_4	1855
23.12	775	Mn_2O_3	2216
23.13	777	MnO_2	2316
23.14	779	FeO	2274
23.15	781	Fe_3O_4	2274
23.16	783	Fe_2O_3	2274
23.17	785	CoO	2322
23.18	787	Co_3O_4	2323
23.19	789	NiO	2323
23.20	790	Cu_2O	2314
23.21	791	CuO	2317
23.22	792	Ag_2O	2262
23.23	793	ZnO	1177
23.24	794	CdO	1094
23.25	795	HgO	2551
-	-	B_2O_3	-
-	-	SiO_2	-
23.26	796	SnO	2103
23.27	797	SnO_2	2303
23.28	798	PbO	2006
23.29	799	Pb_3O_4	2008
23.30	800	PbO_2	2189
23.31	801	Sb_2O_3	2018
23.32	802	Bi_2O_3	2039

FactSage 7.0.[*] Only pure substances were considered in the condensed phases. Gases were treated ideally, and ideal gas mixing was assumed. Charged species were not considered in any phase.

$$\begin{aligned}&\text{boron} + \text{oxidizer} \rightarrow \text{adiabatic equilibrium products}\\&(P = 1\text{ atm}, T_\text{i} = 298.15\text{ K}, T_\text{ad} = \text{adiabatic equilibrium temperature})\end{aligned} \tag{23.1}$$

Within each of the following sections, you will find one or two general figures as well as written descriptions of certain fuel-to-oxidizer ratios. Temperature points (T1, T2, and so on) describe features and points of interest along adiabatic temperature profiles. Similarly, gas points (G1, G2, and so on) refer to adiabatic gas production profiles. Some adiabatic temperature charts contain flat regions where the adiabatic temperature remains constant despite variations in the stoichiometry of the system. Some of these plateaus are described and explained (see Chapter 2 and Tables 2.10–2.15 for additional information).

23.2 BORON + O_2

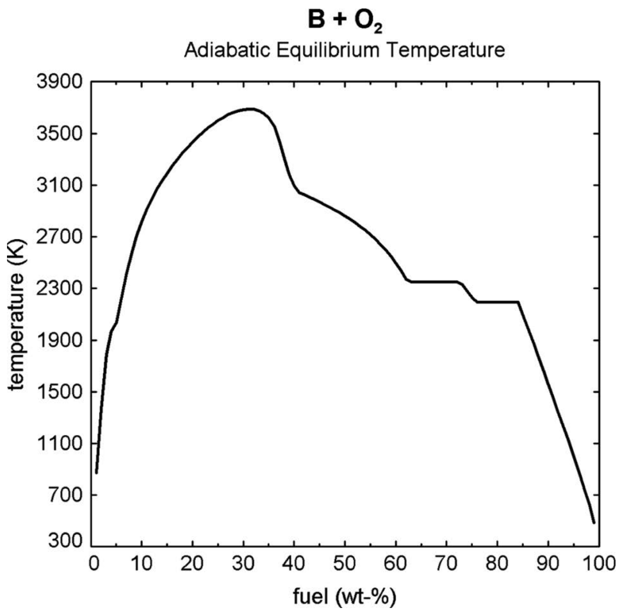

FIGURE 23.1 Adiabatic equilibrium temperature profile, B (fuel) + O_2 (oxidizer).

T1. 23% fuel, 3540.55 K
solids: none
liquids: none
gases: 34.48% BO_2, 29.52% B_2O_3, 13.87% O_2, 12.46% BO, 9.42% O, 0.25% $(BO)_2$
a combination of reactions with excess oxidizer remaining:
(25.3% fuel) $B + O_2 \rightarrow BO_2$
(31.1% fuel) $4B + 3O_2 \rightarrow 2B_2O_3$
(40.3% fuel) $2B + O_2 \rightarrow 2BO$

[*] Bale, C. W.; Pelton, A. D.; Thompson, W. T.; Eriksson, G.; Hack, K.; Chartrand, P.; Decterov, S.; Jung, I.-H.; Melançon, J.; Petersen, S. *FactSage,* version 7.0; CRCT ThermFact, Inc. and GTT-Technologies, 2015; www.factsage.com (accessed September, 2019).

T2. 31% fuel, 3686.99 K—*peak temperature*
solids: none
liquids: none
gases: 36.49% BO, 30.29% B_2O_3, 25.32% BO_2, 4.88% O, 1.82% O_2, 1.20% $(BO)_2$
a combination of reactions with excess oxidizer remaining:
(25.3% fuel) $B + O_2 \rightarrow BO_2$
(31.1% fuel) $4B + 3O_2 \rightarrow 2B_2O_3$
(40.3% fuel) $2B + O_2 \rightarrow 2BO$

T3. 38% fuel, 3304.37 K
solids: none
liquids: none
gases: 60.14% BO, 22.71% B_2O_3, 15.41% $(BO)_2$, 1.59% BO_2, 0.10% B_2O
a combination of reactions:
(31.1% fuel) $4B + 3O_2 \rightarrow 2B_2O_3$
(40.3% fuel) $2B + O_2 \rightarrow (BO)_2$
(40.3% fuel) $2B + O_2 \rightarrow 2BO$

T4. 41% fuel, 3040.51 K
solids: none
liquids: 0.68% B
gases: 50.00% BO, 42.46% $(BO)_2$, 3.65% B_2O_3, 2.97% B_2O, 0.18% B
a combination of reactions:
(31.1% fuel) $4B + 3O_2 \rightarrow 2B_2O_3$
(40.3% fuel) $2B + O_2 \rightarrow (BO)_2$
(40.3% fuel) $2B + O_2 \rightarrow 2BO$
(57.5% fuel) $4B + O_2 \rightarrow 2B_2O$

T5. 54% fuel, 2746.30 K
solids: none
liquids: 23.99% B
gases: 49.56% $(BO)_2$, 16.91% BO, 8.60% B_2O_3, 0.91% B_2O
a combination of reactions with excess fuel remaining:
(31.1% fuel) $4B + 3O_2 \rightarrow 2B_2O_3$
(40.3% fuel) $2B + O_2 \rightarrow (BO)_2$
(40.3% fuel) $2B + O_2 \rightarrow 2BO$

- Points 1–5 correspond to the maximum amounts of BO_2, B_2O_3, BO, B_2O, and $(BO)_2$, respectively.
- From 76% to 84% fuel, the temperature appears to be limited by the vaporization of boron oxides from B(s)/B_2O_3(l) mixtures, which occurs at 2192 K. Alone, B_2O_3(l) vaporizes with slight decomposition at about 2323 K.
- From 63% to 72% fuel, the temperature is limited to 2350 K by the B(s-l) transition.
- B(l) is present from 41% to 72% fuel with the maximum amount (38.76%) occurring at 62% fuel. B(g) is present from 40% to 45% fuel with the maximum amount (0.18%) occurring at 41% fuel. Pure B(l) vaporizes at 4141 K.

23.3 BORON + TiO_2

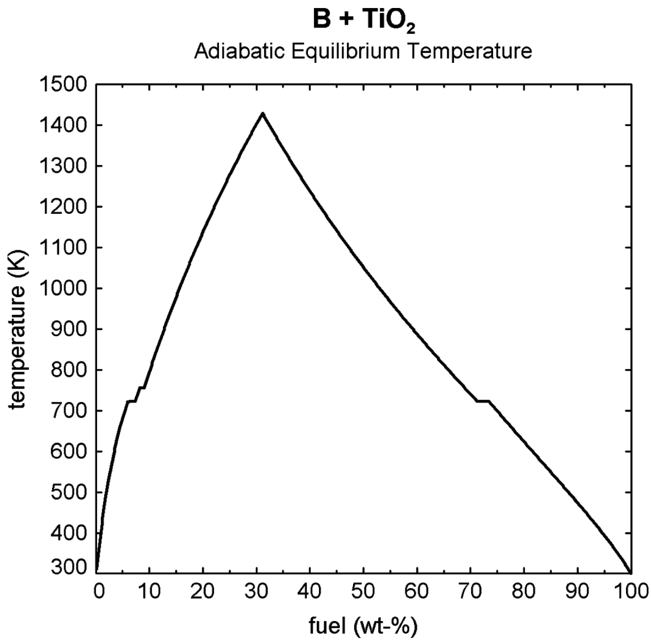

FIGURE 23.2 Adiabatic equilibrium temperature profile, B (fuel) + TiO_2 (oxidizer).

T1. 4.4% fuel, 656.18 K
solids: 85.83% Ti_2O_3, 13.98% B_2O_3, 0.19% TiB_2
liquids: none
gases: none

T2. 31.1% fuel, 1428.86 K—*peak temperature*
solids: 59.95% TiB_2
liquids: 40.04% B_2O_3
gases: none
simplified equation at 31.1% fuel: $10B + 3TiO_2 \rightarrow 2B_2O_3 + 3TiB_2$

- Elemental titanium is not predicted to occur at any point.

23.4 BORON + V_2O_5

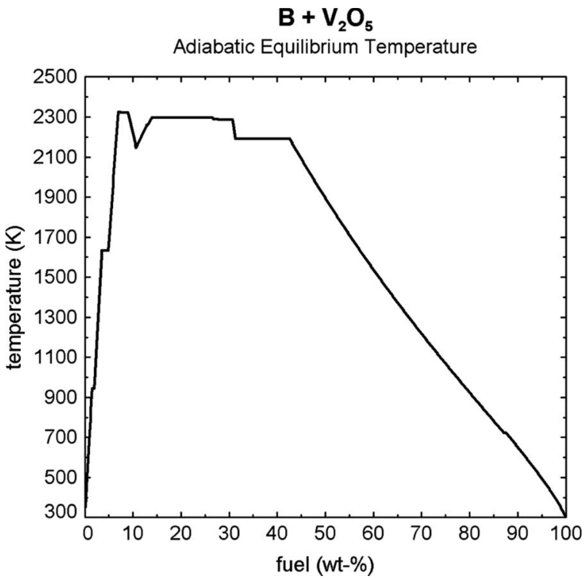

FIGURE 23.3 Adiabatic equilibrium temperature profile, B (fuel) + V_2O_5 (oxidizer).

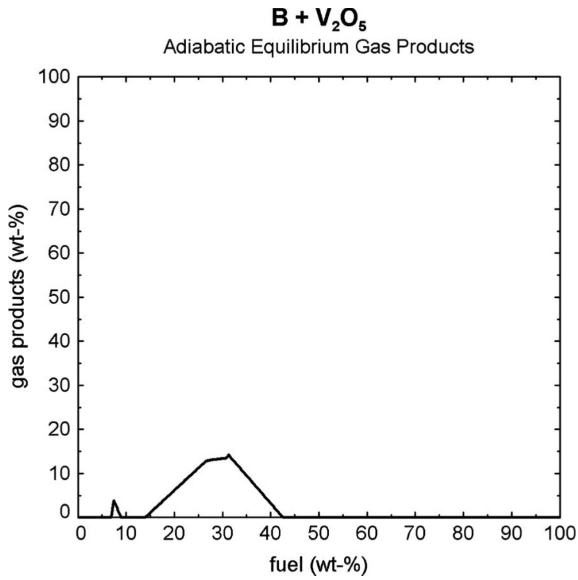

FIGURE 23.4 Adiabatic equilibrium gas production profile, B (fuel) + V_2O_5 (oxidizer).

T1. 3.8% fuel, 1633.00 K
solids: 63.94% VO_2
liquids: 23.52% VO_2, 12.24% B_2O_3, 0.31% V_2O_5
gases: none
simplified equation at 3.8% fuel: $2B + 3V_2O_5 \rightarrow B_2O_3 + 6VO_2$

T2. 7.3% fuel, 3.47% gas produced, 2323.01 K—*peak temperature*
solids: 75.43% V_2O_3
liquids: 20.06% B_2O_3, 1.04% VO_2
gases: 3.42% B_2O_3
simplified equation at 7.3% fuel: $4B + 3V_2O_5 \rightarrow 2B_2O_3 + 3V_2O_3$

T3. 10.6% fuel, 2146.71 K
solids: 0.58% V_2O_3
liquids: 65.29% VO, 34.13% B_2O_3
gases: none
simplified equation at 10.6% fuel: $2B + V_2O_5 \rightarrow B_2O_3 + 2VO$

T4. 26.5% fuel, 12.76% gas produced, 2294.55 K
solids: 52.82% V_3B_4
liquids: 34.42% B_2O_3
gases: 10.61% B_2O_3, 1.97% $(BO)_2$, 0.18% BO
simplified equation at 26.3% fuel: $18B + 3V_2O_5 \rightarrow 5B_2O_3 + 2V_3B_4$

T5. 27.6% fuel, 13.05% gas produced, 2288.93 K
solids: 53.33% V_2B_3, 0.14% V_3B_4
liquids: 33.49% B_2O_3
gases: 10.45% B_2O_3, 2.40% $(BO)_2$, 0.19% BO
simplified equation at 27.3% fuel: $19B + 3V_2O_5 \rightarrow 5B_2O_3 + 3V_2B_3$

T6. 30.6% fuel, 13.43% gas produced, 2286.03 K
solids: 54.84% VB_2, 0.50% V_2B_3
liquids: 31.23% B_2O_3
gases: 10.55% B_2O_3, 2.68% $(BO)_2$, 0.20% BO
simplified equation at 30.4% fuel: $22B + 3V_2O_5 \rightarrow 5B_2O_3 + 6VB_2$

- Elemental vanadium is not predicted to occur at any point.
- From 3.5% to 4.8% fuel, the temperature is limited to 1633 K by the VO_2(s-l) transition.
- From 31.2% to 42.4% fuel, the temperature appears to be limited by the vaporization of boron oxides from B(s)/B_2O_3(l) mixtures, which occurs at 2192 K.
- From 27.7% to 30.6% fuel, the temperature appears to be limited to 2286 K by the reaction of B_2O_3(l) and VB_2(s) which forms V_2B_3(s), $(BO)_2$(g), and BO(g). Some B_2O_3 is also vaporized.
- From 26.6% to 27.6% fuel, the temperature appears to be limited to 2289 K by the reaction of B_2O_3(l) and V_2B_3(s) which forms V_3B_4(s), $(BO)_2$(g), and BO(g). Some B_2O_3 is also vaporized.
- From 14.0% to 26.4% fuel, the temperature appears to be limited to 2297 K by the reaction of B_2O_3(l) and V_3B_4(s) which forms VO(l), $(BO)_2$(g), and BO(g). Some B_2O_3 is also vaporized.
- From 7.4% to 8.9% fuel, the temperature appears to be limited to 2321 K by the reaction of B_2O_3(l) and VO(l) which forms V_2O_3(s), $(BO)_2$(g), and BO(g). Some B_2O_3 is also vaporized.
- From 6.9% to 7.3% fuel, the temperature is limited to about 2323 K by the vaporization of B_2O_3(l).

G1. 31.2% fuel, 14.17% gas produced, 2191.63 K—*peak gas*
solids: 54.90% VB_2
liquids: 30.91% B_2O_3
gases: 8.51% $(BO)_2$, 5.41% B_2O_3, 0.24% BO
a combination of two reactions:
(30.4% fuel) $22B + 3V_2O_5 \rightarrow 5B_2O_3 + 6VB_2$
(34.9% fuel) $18B + 2V_2O_5 \rightarrow 5(BO)_2 + 4VB_2$

23.5 BORON + Nb_2O_5

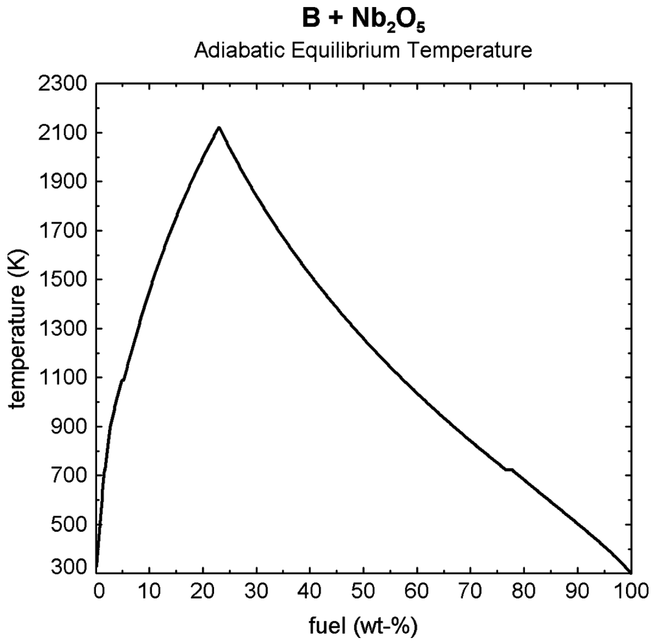

FIGURE 23.5 Adiabatic equilibrium temperature profile, B (fuel) + Nb_2O_5 (oxidizer).

T1. 2.7% fuel, 906.13 K
solids: 91.23% NbO_2, 0.20% NbB_2
liquids: 8.57% B_2O_3
gases: none

T2. 23.0% fuel, 2120.49 K—*peak temperature*
solids: 66.35% NbB_2
liquids: 33.61% B_2O_3
gases: none
simplified equation at 23.0% fuel: $22B + 3Nb_2O_5 \rightarrow 5B_2O_3 + 6NbB_2$

- Elemental niobium is not predicted to occur at any point.

23.6 BORON + Ta_2O_5

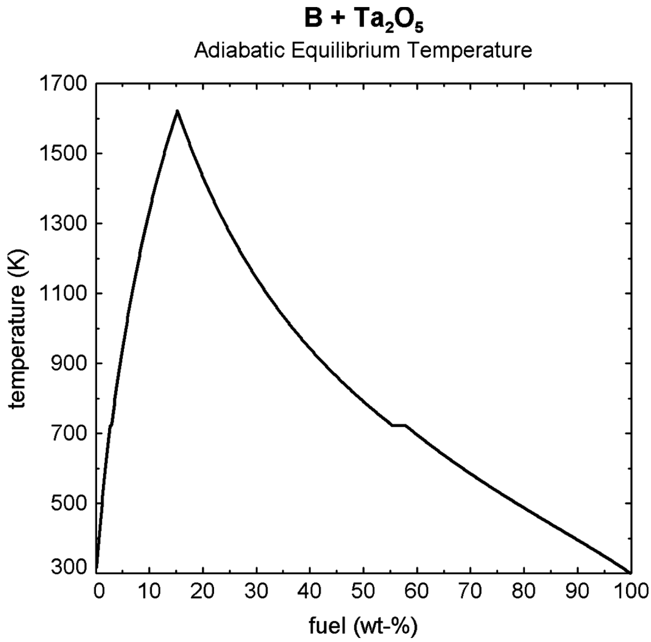

FIGURE 23.6 Adiabatic equilibrium temperature profile, B (fuel) + Ta_2O_5 (oxidizer).

T1. 15.2% fuel, 1622.00 K—*peak temperature*
solids: 77.68% TaB_2
liquids: 22.25% B_2O_3
gases: none
simplified equation at 15.2% fuel: $22B + 3Ta_2O_5 \rightarrow 5B_2O_3 + 6TaB_2$

- Elemental tantalum is not predicted to occur at any point.

23.7 BORON + Cr_2O_3

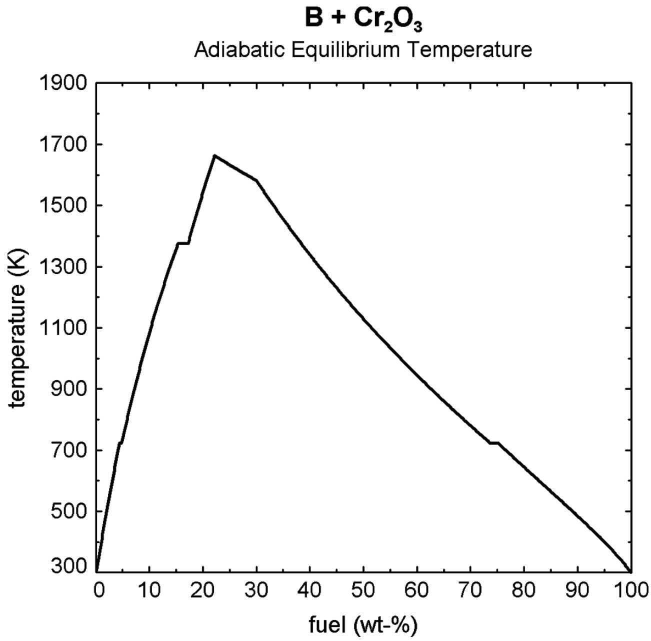

FIGURE 23.7 Adiabatic equilibrium temperature profile, B (fuel) + Cr_2O_3 (oxidizer).

T1. 17.2% fuel, 1375.76 K
solids: 31.78% CrB, 30.11% Cr, 0.34% Cr_2O_3
liquids: 37.77% B_2O_3
gases: none
a combination of two reactions:
(12.5% fuel) $2B + Cr_2O_3 \rightarrow B_2O_3 + 2Cr$
(22.1% fuel) $4B + Cr_2O_3 \rightarrow B_2O_3 + 2CrB$

T2. 22.2% fuel, 1661.90 K—*peak temperature*
solids: 63.92% CrB, 0.44% CrB_2
liquids: 35.64% B_2O_3
gases: none
simplified equation at 22.1% fuel: $4B + Cr_2O_3 \rightarrow B_2O_3 + 2CrB$

T3. 29.9% fuel, 1581.53 K
solids: 67.77% CrB_2, 0.12% CrB
liquids: 32.11% B_2O_3
gases: none
simplified equation at 29.9% fuel: $6B + Cr_2O_3 \rightarrow B_2O_3 + 2CrB_2$

- T1 corresponds to the maximum amount of Cr.
- From 15.4% to 17.2% fuel, the temperature appears to be limited by the $2CrB(s) + Cr_2O_3(s) \rightarrow 4Cr(s) + B_2O_3(l)$ reaction, which occurs at 1376 K.

23.8 BORON + MoO_3

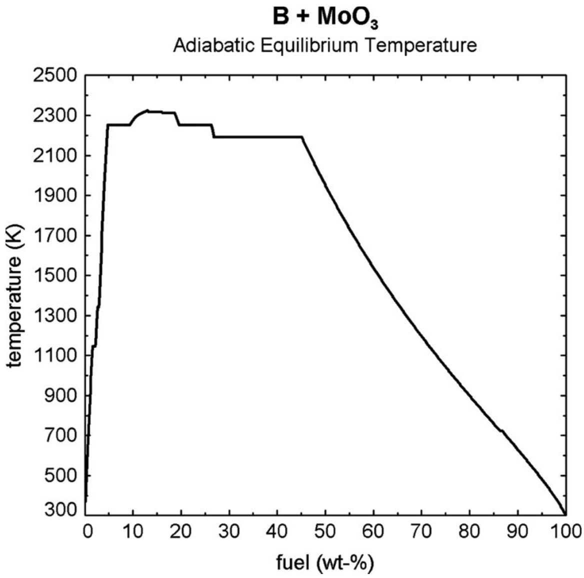

FIGURE 23.8 Adiabatic equilibrium temperature profile, B (fuel) + MoO_3 (oxidizer).

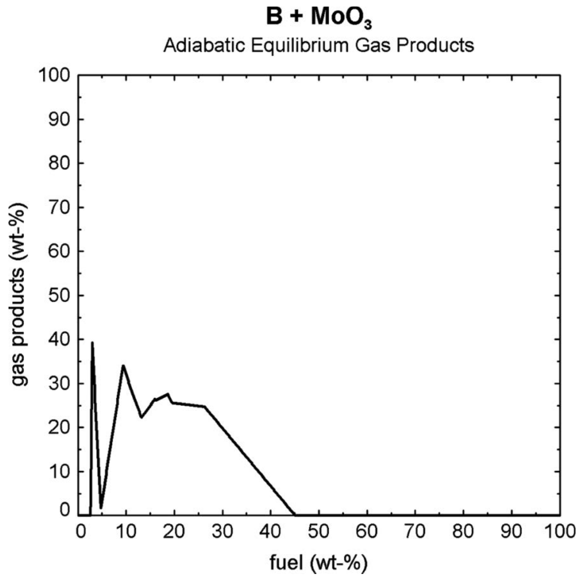

FIGURE 23.9 Adiabatic equilibrium gas production profile, B (fuel) + MoO_3 (oxidizer).

T1. 4.7% fuel, 1.70% gas produced, 2250.61 K
solids: 83.44% MoO_2
liquids: 14.86% B_2O_3
gases: 1.18% $(MoO_3)_3$, 0.28% B_2O_3, 0.14% $(MoO_3)_4$
simplified equation at 4.8% fuel: $2B + 3MoO_3 \rightarrow B_2O_3 + 3MoO_2$

T2. 13.0% fuel, 22.50% gas produced, 2322.95 K—*peak temperature*
solids: 57.68% Mo
liquids: 19.81% B_2O_3
gases: 21.90% B_2O_3, 0.18% $(MoO_3)_3$, 0.12% MoO_3, 0.11% $(MoO_3)_2$
simplified equation at 13.1% fuel: $2B + MoO_3 \rightarrow B_2O_3 + Mo$

T3. 15.8% fuel, 26.22% gas produced, 2316.69 K
solids: 56.33% Mo_2B, 2.79% Mo
liquids: 14.65% B_2O_3
gases: 25.05% B_2O_3, 0.96% $(BO)_2$, 0.19% BO
simplified equation at 15.8% fuel: $5B + 2MoO_3 \rightarrow 2B_2O_3 + Mo_2B$

T4. 18.6% fuel, 27.49% gas produced, 2310.90 K
solids: 59.93% MoB, 0.42% Mo_2B
liquids: 12.16% B_2O_3
gases: 25.36% B_2O_3, 1.85% $(BO)_2$, 0.27% BO
simplified equation at 18.4% fuel: $3B + MoO_3 \rightarrow B_2O_3 + MoB$

T5. 26.2% fuel, 24.69% gas produced, 2250.71 K
solids: 62.81% Mo_2B_5, 0.21% MoB
liquids: 12.30% B_2O_3
gases: 15.08% B_2O_3, 9.17% $(BO)_2$, 0.43% BO
a combination of two reactions:
(25.3% fuel) $9B + 2MoO_3 \rightarrow 2B_2O_3 + Mo_2B_5$
(29.2% fuel) $11B + 2MoO_3 \rightarrow 3(BO)_2 + Mo_2B_5$

- The maximum amount of molybdenum, 57.93% Mo(s), occurs at 13.1% fuel and 2321.52 K.
- From 26.8% to 45.0% fuel, the temperature appears to be limited by the vaporization of boron oxides from B(s)/B_2O_3(l) mixtures, which occurs at 2192 K.
- From 19.5% to 26.2% fuel, the temperature appears to be limited to 2251 K by the reaction of B_2O_3(l) and Mo_2B_5(s) which forms MoB(s), $(BO)_2$(g), and BO(g). Some B_2O_3 is also vaporized.
- The plateau from 4.8% to 9.3% fuel (2252 K) could not be attributed to a simple transition or reaction; species in this region include $(MoO_3)_n$(g), B_2O_3(g), B_2O_3(l), MoO_2(s), and Mo(s).
- From 16.1% to 18.6% fuel, the temperature appears to be limited to 2311 K by the reaction of B_2O_3(l) and MoB(s) which forms Mo_2B(s), $(BO)_2$(g), and BO(g). Some B_2O_3 is also vaporized.
- From 13.2% to 15.9% fuel, the temperature appears to be limited to 2317 K by the reaction of B_2O_3(l) and Mo_2B(s) which forms Mo(s), $(BO)_2$(g), and BO(g). Some B_2O_3 is also vaporized.

G1. 2.9% fuel, 39.18% gas produced, 1359.59 K—*peak gas*
solids: 51.49% MoO_2
liquids: 9.34% B_2O_3
gases: 22.05% $(MoO_3)_4$, 12.75% $(MoO_3)_3$, 4.36% $(MoO_3)_5$
one reaction with excess oxidizer remaining:
(4.8% fuel) $2B + 3MoO_3 \rightarrow B_2O_3 + 3MoO_2$

G2. 9.3% fuel, 33.96% gas produced, 2251.82 K
solids: 41.12% Mo, 0.62% MoO_2
liquids: 24.30% B_2O_3
gases: 23.43% $(MoO_3)_3$, 5.61% B_2O_3, 2.72% $(MoO_3)_4$, 1.81% $(MoO_3)_2$, 0.25% MoO_3
one reaction with excess oxidizer remaining:
(13.1% fuel) $2B + MoO_3 \rightarrow B_2O_3 + Mo$

G3. 18.6% fuel, 27.49% gas produced, 2310.90 K
see T4 for details

23.9 BORON + WO_3

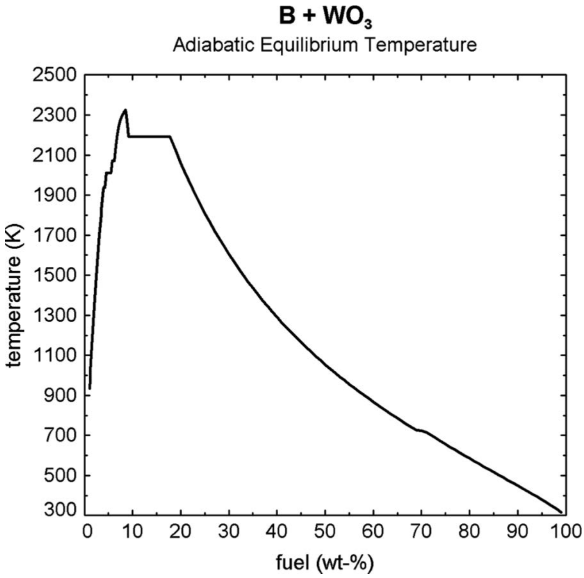

FIGURE 23.10 Adiabatic equilibrium temperature profile, B (fuel) + WO_3 (oxidizer).

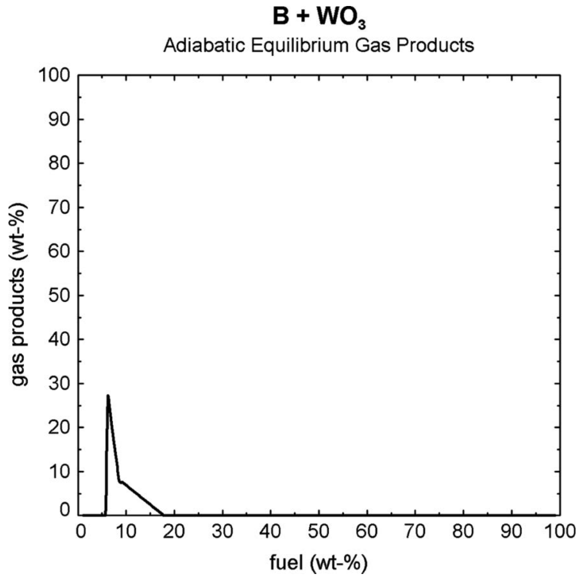

FIGURE 23.11 Adiabatic equilibrium gas production profile, B (fuel) + WO_3 (oxidizer).

T1. 3.0% fuel, 1699.34 K
solids: 89.66% WO_2, 0.68% $W_{18}O_{49}$
liquids: 9.66% B_2O_3
gases: none
simplified equation at 3.0% fuel: $2B + 3WO_3 \rightarrow B_2O_3 + 3WO_2$

T2. 8.5% fuel, 7.94% gas produced, 2322.83 K—*peak temperature*
solids: 72.25% W
liquids: 19.80% B_2O_3
gases: 7.51% B_2O_3, 0.29% $(WO_3)_2$
simplified equation at 8.5% fuel: $2B + WO_3 \rightarrow B_2O_3 + W$

- The maximum amount of tungsten, 72.48% W(s), occurs at 8.6% fuel and 2311.44 K.
- From 4.6% to 5.4% fuel, the temperature appears to be limited by the $3W_{18}O_{49}(s) \rightarrow 5W(s) + 49WO_3(l)$ decomposition, which occurs at 2011 K.
- The plateau from 5.7% to 6.2% fuel (2071 K) could not be attributed to a simple transition or reaction; species in this region include $(WO_3)_n$(g), W_3O_8(g), B_2O_3(g), WO_3(l), B_2O_3(l), and W(s). The vaporization of WO_3 and W_3O_8 from W(s)/WO_3(l) mixtures is expected to occur at 2087 K.
- From 9.2% to 17.7% fuel, the temperature appears to be limited by the vaporization of boron oxides from B(s)/B_2O_3(l) mixtures, which occurs at 2192 K.

G1. 6.2% fuel, 27.21% gas produced, 2071.06 K—*peak gas*
solids: 52.33% W
liquids: 19.67% B_2O_3, 0.79% WO_3
gases: 13.74% $(WO_3)_3$, 5.65% $(WO_3)_4$, 4.23% W_3O_8, 3.30% $(WO_3)_2$, 0.30% B_2O_3
a combination of two reactions with excess oxidizer remaining:
(1.0% fuel) $2B + 9WO_3 \rightarrow B_2O_3 + 3W_3O_8$
(8.5% fuel) $2B + WO_3 \rightarrow B_2O_3 + W$

23.10 BORON + MnO

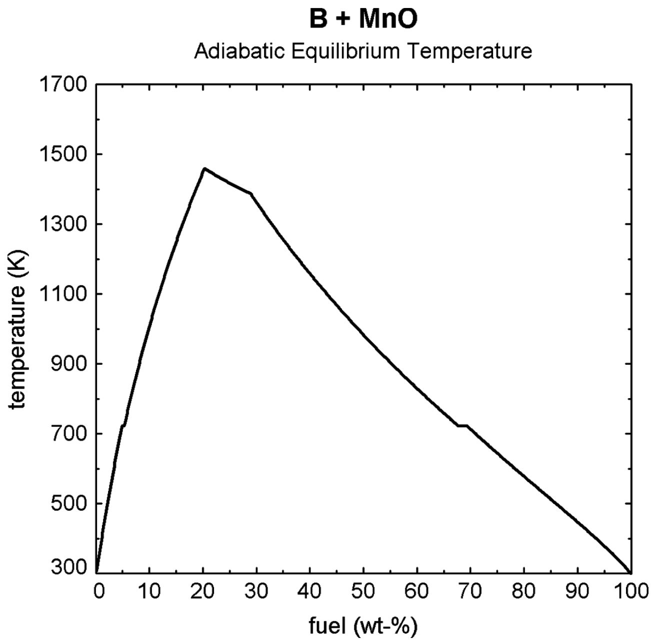

FIGURE 23.12 Adiabatic equilibrium temperature profile, B (fuel) + MnO (oxidizer).

T1. 20.3% fuel, 1458.92 K—*peak temperature*
solids: 73.53% MnB, 0.40% MnB_2
liquids: 26.07% B_2O_3
gases: none
simplified equation at 20.3% fuel: $5B + 3MnO \rightarrow B_2O_3 + 3MnB$

T2. 28.9% fuel, 1386.83 K
solids: 76.74% MnB_2
liquids: 23.26% B_2O_3
gases: none
simplified equation at 28.9% fuel: $8B + 3MnO \rightarrow B_2O_3 + 3MnB_2$

- Elemental manganese is not predicted to occur at any point.

23.11 BORON + Mn_3O_4

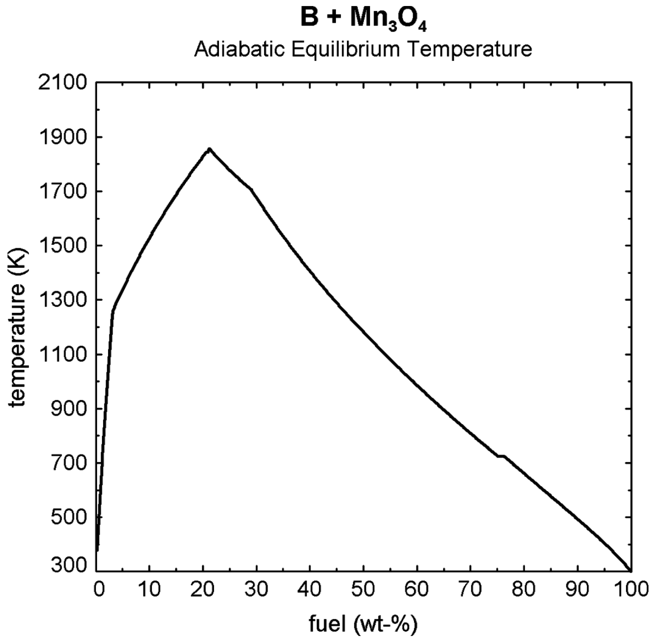

FIGURE 23.13 Adiabatic equilibrium temperature profile, B (fuel) + Mn_3O_4 (oxidizer).

T1. 3.1% fuel, 1257.51 K
solids: 89.94% MnO, 0.17% MnB
liquids: 9.89% B_2O_3
gases: none
simplified equation at 3.1% fuel: $2B + 3Mn_3O_4 \rightarrow B_2O_3 + 9MnO$

T2. 20.9% fuel, 1842.97 K
solids: 66.55% MnB
liquids: 32.06% B_2O_3, 1.30% Mn
gases: none
simplified equation at 21.1% fuel: $17B + 3Mn_3O_4 \rightarrow 4B_2O_3 + 9MnB$

T3. 21.1% fuel, 1855.08 K—*peak temperature*
solids: 67.87% MnB
liquids: 32.01% B_2O_3, 0.13% Mn
gases: none
simplified equation at 21.1% fuel: $17B + 3Mn_3O_4 \rightarrow 4B_2O_3 + 9MnB$

T4. 29.1% fuel, 1701.78 K
solids: 71.17% MnB_2
liquids: 28.77% B_2O_3
gases: none
simplified equation at 29.1% fuel: $26B + 3Mn_3O_4 \rightarrow 4B_2O_3 + 9MnB_2$

- T2 corresponds to the maximum amount of Mn.

23.12 BORON + Mn_2O_3

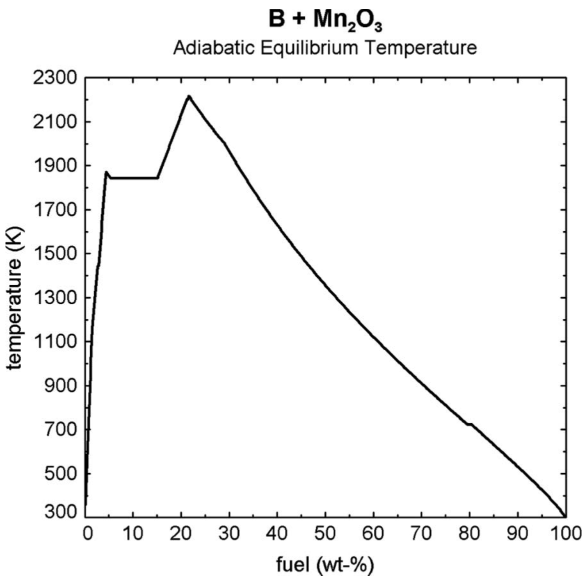

FIGURE 23.14 Adiabatic equilibrium temperature profile, B (fuel) + Mn_2O_3 (oxidizer).

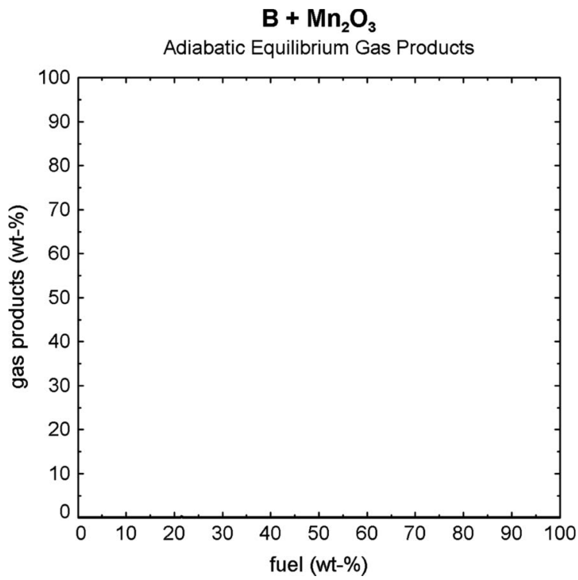

FIGURE 23.15 Adiabatic equilibrium gas production profile, B (fuel) + Mn_2O_3 (oxidizer).

T1. 1.5% fuel, 1157.89 K
solids: 95.14% Mn_3O_4
liquids: 4.83% B_2O_3
gases: none
simplified equation at 1.5% fuel: $2B + 9Mn_2O_3 \rightarrow B_2O_3 + 6Mn_3O_4$

T2. 4.4% fuel, 1870.66 K
solids: 85.56% MnO
liquids: 14.17% B_2O_3, 0.27% Mn
gases: none
simplified equation at 4.4% fuel: $2B + 3Mn_2O_3 \rightarrow B_2O_3 + 6MnO$

T3. 15.1% fuel, 1844.13 K
solids: 21.12% MnB
liquids: 41.44% Mn, 37.44% B_2O_3
gases: none
a combination of two reactions:
(12.0% fuel) $2B + Mn_2O_3 \rightarrow B_2O_3 + 2Mn$
(21.5% fuel) $4B + Mn_2O_3 \rightarrow B_2O_3 + 2MnB$

T4. 21.5% fuel, 2216.10 K—*peak temperature*
solids: 65.36% MnB
liquids: 34.58% B_2O_3
gases: none
simplified equation at 21.5% fuel: $4B + Mn_2O_3 \rightarrow B_2O_3 + 2MnB$

T5. 29.1% fuel, 1997.08 K
solids: 68.55% MnB_2, 0.19% MnB
liquids: 31.27% B_2O_3
gases: none
simplified equation at 29.1% fuel: $6B + Mn_2O_3 \rightarrow B_2O_3 + 2MnB_2$

- T3 corresponds to the maximum amount of Mn.
- From 5.3% to 15.0% fuel, the temperature appears to be limited by the $2MnB(s) + 3MnO(s) \rightarrow 5Mn(l) + B_2O_3(l)$ reaction, which occurs at 1843 K.

G1. 21.4% fuel, 0.28% gas produced, 2201.28 K—*peak gas*
solids: 64.65% MnB
liquids: 34.51% B_2O_3, 0.56% Mn
gases: 0.13% Mn, 0.11% B_2O_3
simplified equation at 21.5% fuel: $4B + Mn_2O_3 \rightarrow B_2O_3 + 2MnB$

23.13 BORON + MnO_2

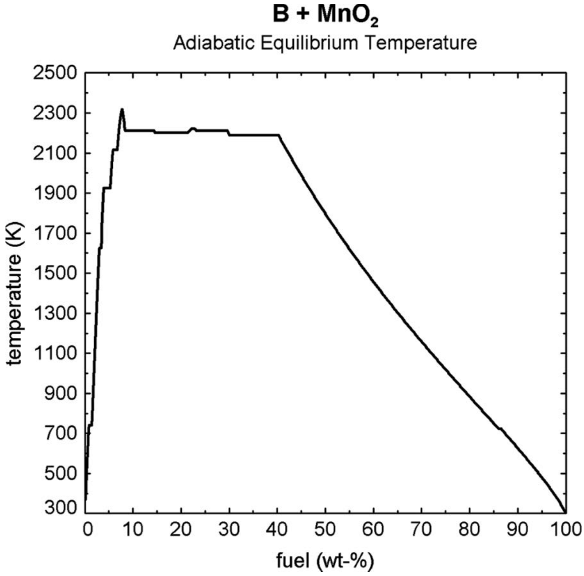

FIGURE 23.16 Adiabatic equilibrium temperature profile, B (fuel) + MnO_2 (oxidizer).

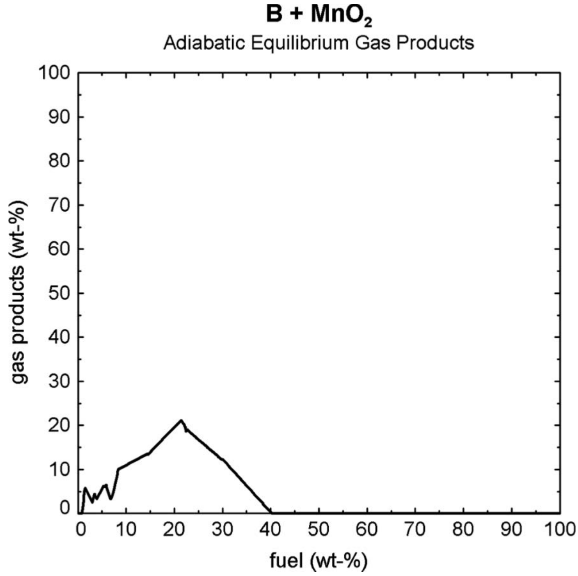

FIGURE 23.17 Adiabatic equilibrium gas production profile, B (fuel) + MnO_2 (oxidizer).

T1. 3.8% fuel, 3.45% gas produced, 1878.85 K
solids: 84.40% Mn_3O_4
liquids: 12.15% B_2O_3
gases: 3.37% O_2
a combination of two reactions:
(5.2% fuel) $4B + 9MnO_2 \rightarrow 2B_2O_3 + 3Mn_3O_4$
(decomposition) $3MnO_2 \rightarrow Mn_3O_4 + O_2$

T2. 7.7% fuel, 6.98% gas produced, 2315.81 K—*peak temperature*
solids: none
liquids: 74.96% MnO, 18.06% B_2O_3
gases: 6.60% B_2O_3, 0.27% Mn
simplified equation at 7.7% fuel: $2B + 3MnO_2 \rightarrow B_2O_3 + 3MnO$

T3. 14.2% fuel, 13.37% gas produced, 2211.55 K
solids: none
liquids: 46.51% Mn, 38.35% B_2O_3, 1.77% MnO
gases: 6.34% Mn, 5.89% B_2O_3, 1.05% $(BO)_2$
simplified equation at 14.2% fuel: $4B + 3MnO_2 \rightarrow 2B_2O_3 + 3Mn$

T4. 23.0% fuel, 18.59% gas produced, 2214.88 K
solids: 55.74% MnB
liquids: 25.68% B_2O_3
gases: 8.56% B_2O_3, 7.65% $(BO)_2$, 2.09% Mn, 0.29% BO
a combination of two reactions:
(22.5% fuel) $7B + 3MnO_2 \rightarrow 2B_2O_3 + 3MnB$
(27.2% fuel) $3B + MnO_2 \rightarrow (BO)_2 + MnB$

T5. 29.9% fuel, 12.27% gas produced, 2193.99 K
solids: 61.29% MnB_2
liquids: 26.43% B_2O_3
gases: 6.97% $(BO)_2$, 4.78% B_2O_3, 0.32% Mn, 0.20% BO
a combination of two reactions:
(29.3% fuel) $10B + 3MnO_2 \rightarrow 2B_2O_3 + 3MnB_2$
(33.2% fuel) $4B + MnO_2 \rightarrow (BO)_2 + MnB_2$

- The maximum amount of manganese, 47.89% Mn(l) and 6.20% Mn(g), occurs at 14.4% fuel and 2206.25 K.
- The plateau from 3.9% to 5.2% fuel (1923 K) could not be attributed to a simple transition or reaction; species in this region include O_2(g), B_2O_3(g), B_2O_3(l), Mn_3O_4(s), and MnO(s). The $2Mn_3O_4(s) \rightarrow 6MnO(s) + O_2(g)$ decomposition is expected to occur at 1925 K.
- From 5.8% to 6.7% fuel, the temperature is limited to 2115 K by the MnO(s-l) transition.
- The plateau from 30.0% to 40.1% fuel (2189 K) could not be attributed to a simple transition or reaction; species in this region include $(BO)_2$(g), B_2O_3(g), BO(g), Mn(g), B_2O_3(l), MnB_2(s), and B(s).
- The plateau from 14.5% to 21.3% fuel (2201 K) could not be attributed to a simple transition or reaction; species in this region include Mn(g), B_2O_3(g), $(BO)_2$(g), BO(g), Mn(l), B_2O_3(l), and MnB(s).
- From 8.4% to 14.3% fuel, the temperature appears to be limited to 2212 K by the reaction of B_2O_3(l) and Mn(l) which forms MnO(l) and $(BO)_2$(g). Additionally, Mn and B_2O_3 are partly vaporized.
- From 23.1% to 29.5% fuel, the temperature appears to be limited to 2212 K by the reaction of B_2O_3(l) and MnB_2(s) which forms MnB(s), $(BO)_2$(g), and Mn(g). Some of the B_2O_3 is also vaporized.

G1. 21.3% fuel, 21.06% gas produced, 2201.28 K—*peak gas*
solids: 47.74% MnB
liquids: 30.88% B_2O_3, 0.33% Mn
gases: 9.52% Mn, 8.55% B_2O_3, 2.81% $(BO)_2$, 0.17% BO
a combination of two reactions:
(14.2% fuel) $4B + 3MnO_2 \rightarrow 2B_2O_3 + 3Mn$
(22.5% fuel) $7B + 3MnO_2 \rightarrow 2B_2O_3 + 3MnB$

23.14 BORON + FeO

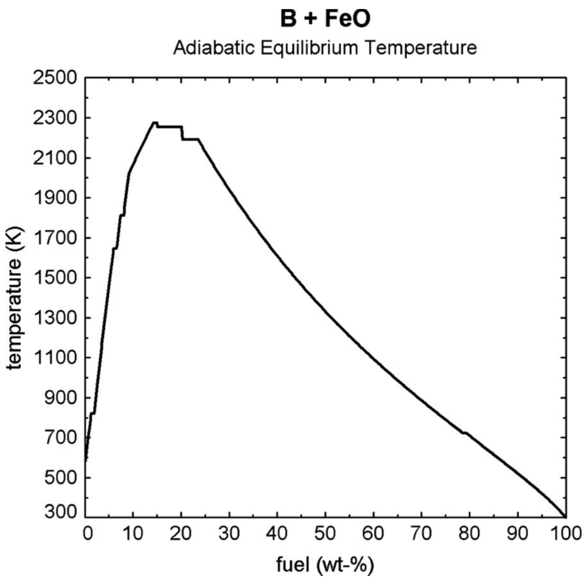

FIGURE 23.18 Adiabatic equilibrium temperature profile, B (fuel) + FeO (oxidizer).

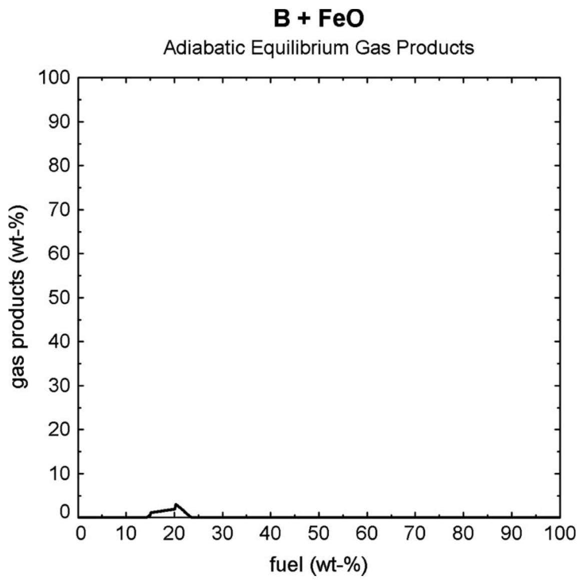

FIGURE 23.19 Adiabatic equilibrium gas production profile, B (fuel) + FeO (oxidizer).

T1. 9.1% fuel, 2017.85 K
solids: none
liquids: 70.51% Fe, 29.30% B_2O_3, 0.19% FeO
gases: none
simplified equation at 9.1% fuel: $2B + 3FeO \rightarrow B_2O_3 + 3Fe$

T2. 14.9% fuel, 0.62% gas produced, 2273.75 K—*peak temperature*
solids: 71.94% Fe_2B
liquids: 26.89% B_2O_3, 0.55% Fe
gases: 0.45% B_2O_3, 0.16% $(BO)_2$
simplified equation at 14.9% fuel: $7B + 6FeO \rightarrow 2B_2O_3 + 3Fe_2B$

T3. 20.1% fuel, 1.92% gas produced, 2252.47 K
solids: 73.69% FeB, 0.40% Fe_2B
liquids: 24.00% B_2O_3
gases: 1.19% B_2O_3, 0.69% $(BO)_2$
simplified equation at 20.1% fuel: $5B + 3FeO \rightarrow B_2O_3 + 3FeB$

- T1 corresponds to the maximum amount of Fe.
- From 6.0% to 6.5% fuel, the temperature is limited to 1644 K by the FeO(s-l) transition.
- From 7.4% to 8.0% fuel, the temperature is limited to 1811 K by the Fe(s-l) transition.
- From 20.3% to 23.4% fuel, the temperature appears to be limited by the vaporization of boron oxides from B(s)/B_2O_3(l) mixtures, which occurs at 2192 K.

- From 15.0% to 20.1% fuel, the temperature appears to be limited to 2252 K by the reaction of B_2O_3(l) and FeB(s) which forms Fe_2B(s) and $(BO)_2$(g). Some B_2O_3 is also vaporized.
- From 14.3% to 14.9% fuel, the temperature appears to be limited to 2274 K by the reaction of B_2O_3(l) and Fe_2B(s) which forms Fe(l) and $(BO)_2$(g). Some B_2O_3 is also vaporized.

G1. 20.3% fuel, 2.99% gas produced, 2191.59 K—*peak gas*
solids: 73.94% FeB
liquids: 23.01% B_2O_3
gases: 1.79% $(BO)_2$, 1.14% B_2O_3
simplified equation at 20.1% fuel: $5B + 3FeO \rightarrow B_2O_3 + 3FeB$

23.15 BORON + Fe_3O_4

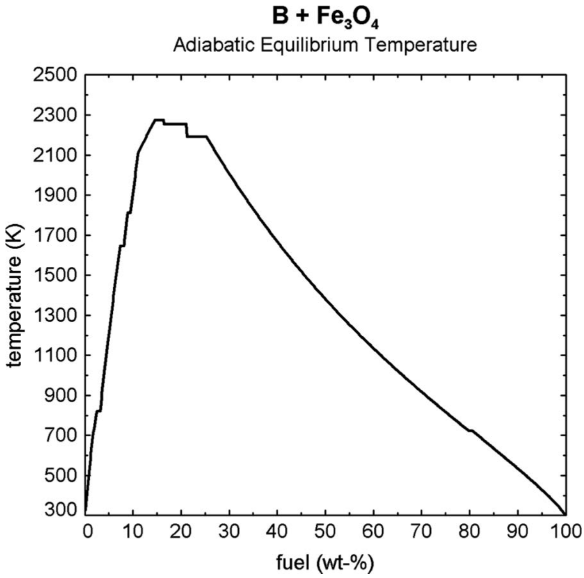

FIGURE 23.20 Adiabatic equilibrium temperature profile, B (fuel) + Fe_3O_4 (oxidizer).

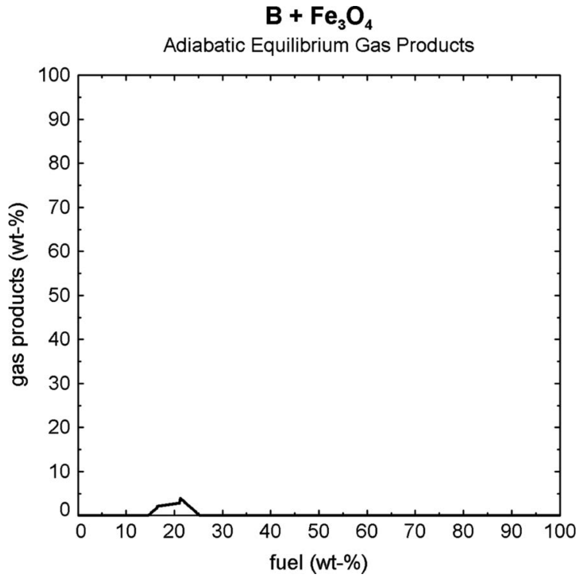

FIGURE 23.21 Adiabatic equilibrium gas production profile, B (fuel) + Fe_3O_4 (oxidizer).

T1. 11.1% fuel, 2113.36 K
solids: 0.35% Fe_2B
liquids: 64.01% Fe, 35.64% B_2O_3
gases: none
simplified equation at 11.1% fuel: $8B + 3Fe_3O_4 \rightarrow 4B_2O_3 + 9Fe$

T2. 16.3% fuel, 1.65% gas produced, 2273.75 K—*peak temperature*
solids: 66.01% Fe_2B
liquids: 31.98% B_2O_3, 0.37% Fe
gases: 1.19% B_2O_3, 0.42% $(BO)_2$
simplified equation at 16.3% fuel: $25B + 6Fe_3O_4 \rightarrow 8B_2O_3 + 9Fe_2B$

T3. 21.0% fuel, 2.79% gas produced, 2252.47 K
solids: 67.69% FeB, 0.49% Fe_2B
liquids: 29.03% B_2O_3
gases: 1.73% B_2O_3, 1.01% $(BO)_2$
simplified equation at 20.9% fuel: $17B + 3Fe_3O_4 \rightarrow 4B_2O_3 + 9FeB$

- T1 corresponds to the maximum amount of Fe.
- From 7.3% to 8.0% fuel, the temperature is limited to 1644 K by the FeO(s-l) transition.
- From 8.9% to 9.4% fuel, the temperature is limited to 1811 K by the Fe(s-l) transition.
- From 21.2% to 25.2% fuel, the temperature appears to be limited by the vaporization of boron oxides from B(s)/B_2O_3(l) mixtures, which occurs at 2192 K.
- From 16.4% to 21.0% fuel, the temperature appears to be limited to 2252 K by the reaction of B_2O_3(l) and FeB(s) which forms Fe_2B(s) and $(BO)_2$(g). Some B_2O_3 is also vaporized.
- From 14.6% to 16.3% fuel, the temperature appears to be limited to 2274 K by the reaction of B_2O_3(l) and Fe_2B(s) which forms Fe(l) and $(BO)_2$(g). Some B_2O_3 is also vaporized.

G1. 21.2% fuel, 3.87% gas produced, 2191.59 K—*peak gas*
solids: 68.06% FeB
liquids: 28.05% B_2O_3
gases: 2.32% $(BO)_2$, 1.48% B_2O_3
a combination of two reactions:
(20.9% fuel) $17B + 3Fe_3O_4 \rightarrow 4B_2O_3 + 9FeB$
(24.6% fuel) $7B + Fe_3O_4 \rightarrow 2(BO)_2 + 3FeB$

23.16 BORON + Fe_2O_3

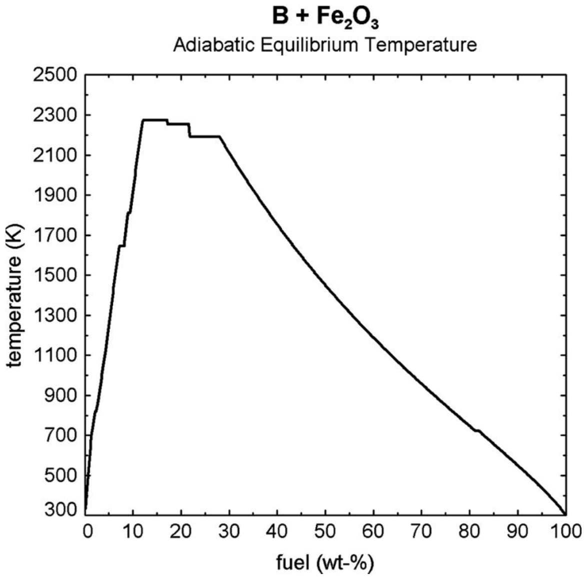

FIGURE 23.22 Adiabatic equilibrium temperature profile, B (fuel) + Fe_2O_3 (oxidizer).

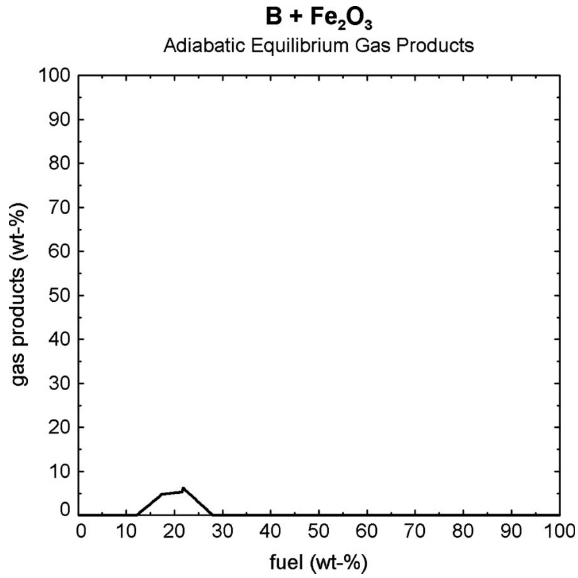

FIGURE 23.23 Adiabatic equilibrium gas production profile, B (fuel) + Fe_2O_3 (oxidizer).

T1. 4.3% fuel, 1125.79 K
solids: 85.53% FeO (wüstite), 0.62% Fe_3O_4 (magnetite)
liquids: 13.85% B_2O_3
gases: none
simplified equation at 4.3% fuel: $2B + 3Fe_2O_3 \rightarrow B_2O_3 + 6FeO$

T2. 11.9% fuel, 2261.69 K
solids: none
liquids: 61.40% Fe, 38.32% B_2O_3, 0.29% FeO
gases: none
simplified equation at 11.9% fuel: $2B + Fe_2O_3 \rightarrow B_2O_3 + 2Fe$

T3. 16.9% fuel, 4.31% gas produced, 2273.75 K—*peak temperature*
solids: 62.29% Fe_2B
liquids: 32.10% B_2O_3
gases: 3.11% B_2O_3, 1.11% $(BO)_2$
simplified equation at 16.9% fuel: $3B + Fe_2O_3 \rightarrow B_2O_3 + Fe_2B$

T4. 21.5% fuel, 5.27% gas produced, 2252.47 K
solids: 65.23% FeB, 0.27% Fe_2B
liquids: 29.23% B_2O_3
gases: 3.26% B_2O_3, 1.90% $(BO)_2$
simplified equation at 21.3% fuel: $4B + Fe_2O_3 \rightarrow B_2O_3 + 2FeB$

- T2 corresponds to the maximum amount of Fe.
- From 7.2% to 8.1% fuel, the temperature is limited to 1644 K by the FeO(s-l) transition.
- From 9.0% to 9.3% fuel, the temperature is limited to 1811 K by the Fe(s-l) transition.
- From 21.8% to 27.9% fuel, the temperature appears to be limited by the vaporization of boron oxides from B(s)/B_2O_3(l) mixtures, which occurs at 2192 K.
- From 17.1% to 21.5% fuel, the temperature appears to be limited to 2252 K by the reaction of B_2O_3(l) and FeB(s) which forms Fe_2B(s) and $(BO)_2$(g). Some B_2O_3 is also vaporized.
- From 12.1% to 17.0% fuel, the temperature appears to be limited to 2274 K by the reaction of B_2O_3(l) and Fe_2B(s) which forms Fe(l) and $(BO)_2$(g). Some B_2O_3 is also vaporized.

G1. 21.7% fuel, 6.14% gas produced, 2196.70 K—*peak gas*
solids: 65.36% FeB
liquids: 28.50% B_2O_3
gases: 3.58% $(BO)_2$, 2.45% B_2O_3, 0.10% BO
a combination of two reactions:
(21.3% fuel) $4B + Fe_2O_3 \rightarrow B_2O_3 + 2FeB$
(25.3% fuel) $10B + 2Fe_2O_3 \rightarrow 3(BO)_2 + 4FeB$

23.17 BORON + CoO

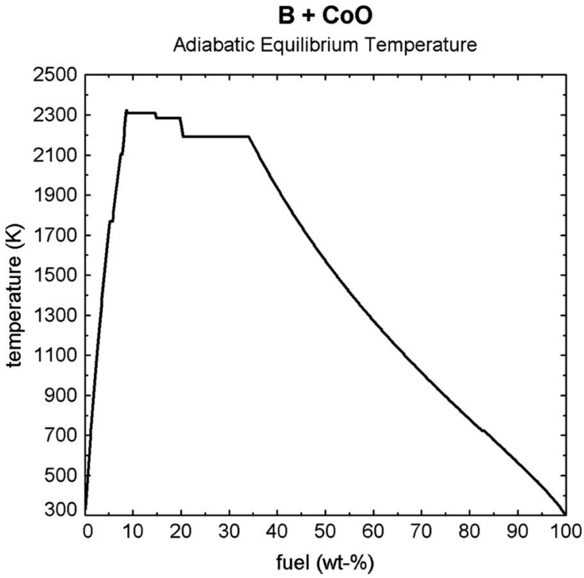

FIGURE 23.24 Adiabatic equilibrium temperature profile, B (fuel) + CoO (oxidizer).

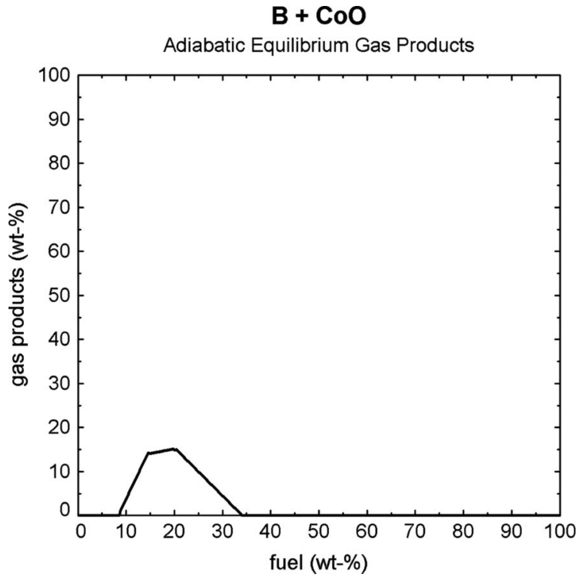

FIGURE 23.25 Adiabatic equilibrium gas production profile, B (fuel) + CoO (oxidizer).

T1. 8.7% fuel, 0.61% gas produced, 2322.23 K—*peak temperature*
solids: none
liquids: 71.14% Co, 27.41% B_2O_3, 0.84% CoO
gases: 0.60% B_2O_3
simplified equation at 8.8% fuel: $2B + 3CoO \rightarrow B_2O_3 + 3Co$

T2. 14.5% fuel, 14.23% gas produced, 2309.75 K
solids: 72.87% Co_2B
liquids: 12.45% B_2O_3, 0.45% Co
gases: 13.03% B_2O_3, 1.01% $(BO)_2$, 0.14% BO
simplified equation at 14.4% fuel: $7B + 6CoO \rightarrow 2B_2O_3 + 3Co_2B$

T3. 19.7% fuel, 15.08% gas produced, 2283.40 K
solids: 73.86% CoB, 0.80% Co_2B
liquids: 10.27% B_2O_3
gases: 11.63% B_2O_3, 3.20% $(BO)_2$, 0.23% BO
a combination of two reactions:
(19.4% fuel) $5B + 3CoO \rightarrow B_2O_3 + 3CoB$
(22.4% fuel) $4B + 2CoO \rightarrow (BO)_2 + 2CoB$

- The maximum amount of cobalt, 71.56% Co(l), occurs at 8.8% fuel and 2309.75 K.
- From 5.2% to 5.6% fuel, the temperature is limited to 1768 K by the Co(s-l) transition.
- From 7.4% to 7.7% fuel, the temperature is limited to 2103 K by the CoO(s-l) transition.
- From 20.4% to 34.0% fuel, the temperature appears to be limited by the vaporization of boron oxides from $B(s)/B_2O_3(l)$ mixtures, which occurs at 2192 K.

- From 14.8% to 19.7% fuel, the temperature appears to be limited to 2283 K by the reaction of B_2O_3(l) and CoB(s) which forms Co_2B(s), $(BO)_2$(g), and BO(g). Some B_2O_3 is also vaporized.
- From 8.8% to 14.5% fuel, the temperature appears to be limited to 2310 K by the reaction of B_2O_3(l) and Co_2B(s) which forms Co(l), $(BO)_2$(g), and BO(g). Some B_2O_3 is also vaporized.

G1. 14.5% fuel, 14.23% gas produced, 2309.75 K
see T2 for details

G2. 19.7% fuel, 15.08% gas produced, 2283.40 K—*peak gas*
see T3 for details

23.18 BORON + Co_3O_4

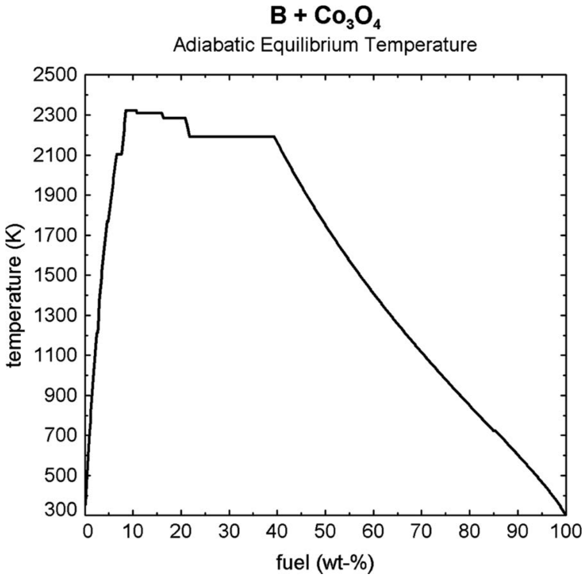

FIGURE 23.26 Adiabatic equilibrium temperature profile, B (fuel) + Co_3O_4 (oxidizer).

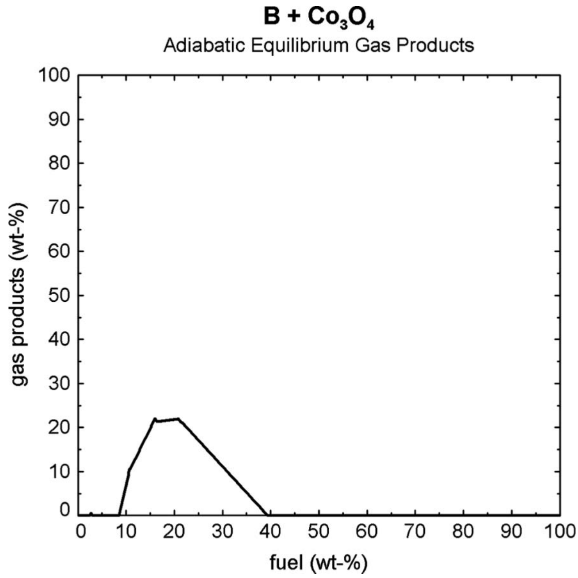

FIGURE 23.27 Adiabatic equilibrium gas production profile, B (fuel) + Co_3O_4 (oxidizer).

T1. 2.9% fuel, 1365.09 K
solids: 90.65% CoO
liquids: 9.34% B_2O_3
gases: none
simplified equation at 2.9% fuel: $2B + 3Co_3O_4 \rightarrow B_2O_3 + 9CoO$

T2. 10.7% fuel, 10.55% gas produced, 2322.61 K—*peak temperature*
solids: none
liquids: 65.53% Co, 23.92% B_2O_3
gases: 10.42% B_2O_3
simplified equation at 10.7% fuel: $8B + 3Co_3O_4 \rightarrow 4B_2O_3 + 9Co$

T3. 15.9% fuel, 21.90% gas produced, 2309.74 K
solids: 66.59% Co_2B
liquids: 10.83% B_2O_3, 0.68% Co
gases: 20.05% B_2O_3, 1.55% $(BO)_2$, 0.22% BO
simplified equation at 15.8% fuel: $25B + 6Co_3O_4 \rightarrow 8B_2O_3 + 9Co_2B$

T4. 20.8% fuel, 21.90% gas produced, 2283.40 K
solids: 68.60% CoB, 0.18% Co_2B
liquids: 9.32% B_2O_3
gases: 16.89% B_2O_3, 4.64% $(BO)_2$, 0.34% BO
a combination of two reactions:
(20.3% fuel) $17B + 3Co_3O_4 \rightarrow 4B_2O_3 + 9CoB$
(23.9% fuel) $7B + Co_3O_4 \rightarrow 2(BO)_2 + 3CoB$

- T2 corresponds to the maximum amount of Co.
- From 6.6% to 7.5% fuel, the temperature is limited to 2103 K by the CoO(s-l) transition.
- From 21.7% to 39.2% fuel, the temperature appears to be limited by the vaporization of boron oxides from B(s)/B_2O_3(l) mixtures, which occurs at 2192 K.
- From 16.4% to 20.8% fuel, the temperature appears to be limited to 2283 K by the reaction of B_2O_3(l) and CoB(s) which forms Co_2B(s), $(BO)_2$(g), and BO(g). Some B_2O_3 is also vaporized.
- From 10.8% to 15.9% fuel, the temperature appears to be limited to 2310 K by the reaction of B_2O_3(l) and Co_2B(s) which forms Co(l), $(BO)_2$(g), and BO(g). Some B_2O_3 is also vaporized.
- From 8.5% to 10.7% fuel, the temperature is limited to about 2323 K by the vaporization of B_2O_3(l).

G1. 15.9% fuel, 21.90% gas produced, 2309.74 K—*peak gas*
see T3 for details

G2. 20.8% fuel, 21.90% gas produced, 2283.40 K—*peak gas*
see T4 for details

23.19 BORON + NiO

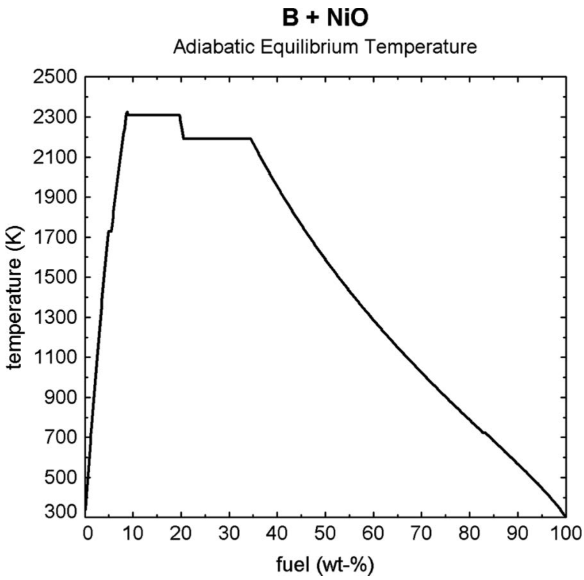

FIGURE 23.28 Adiabatic equilibrium temperature profile, B (fuel) + NiO (oxidizer).

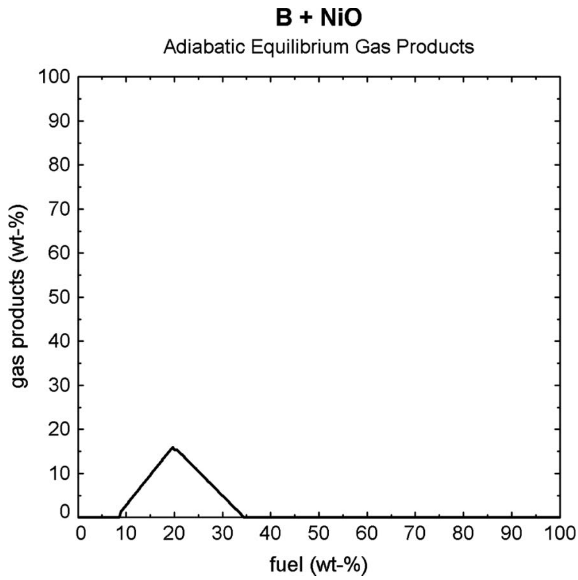

FIGURE 23.29 Adiabatic equilibrium gas production profile, B (fuel) + NiO (oxidizer).

T1. 8.8% fuel, 0.92% gas produced, 2323.08 K—*peak temperature*
solids: none
liquids: 71.66% Ni, 27.42% B_2O_3
gases: 0.91% B_2O_3
simplified equation at 8.8% fuel: $2B + 3NiO \rightarrow B_2O_3 + 3Ni$

T2. 19.6% fuel, 15.85% gas produced, 2306.47 K
solids: 74.77% NiB
liquids: 9.38% B_2O_3
gases: 14.22% B_2O_3, 1.41% $(BO)_2$, 0.17% BO
simplified equation at 19.4% fuel: $5B + 3NiO \rightarrow B_2O_3 + 3NiB$

- T1 corresponds to the maximum amount of Ni.
- From 4.9% to 5.4% fuel, the temperature is limited to 1728 K by the Ni(s-l) transition.
- From 20.5% to 34.4% fuel, the temperature appears to be limited by the vaporization of boron oxides from B(s)/B_2O_3(l) mixtures, which occurs at 2192 K.
- From 8.9% to 19.5% fuel, the temperature appears to be limited to 2310 K by the reaction of B_2O_3(l) and NiB(s) which forms Ni(l), $(BO)_2$(g), and BO(g). Some B_2O_3 is also vaporized.

G1. 19.6% fuel, 15.85% gas produced, 2306.47 K—*peak gas*
see T2 for details

23.20 BORON + Cu_2O

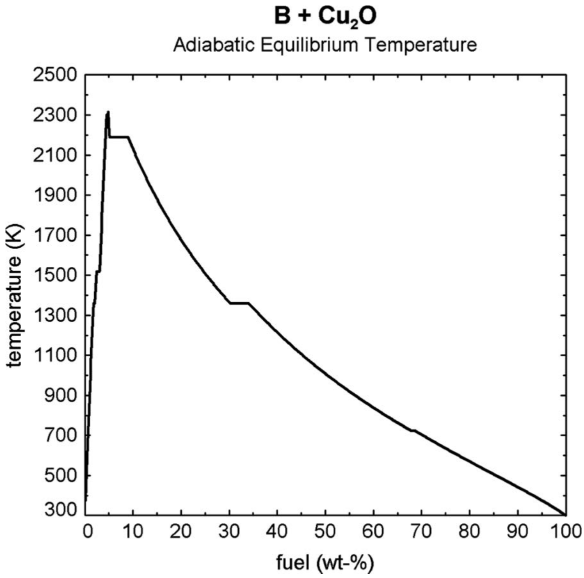

FIGURE 23.30 Adiabatic equilibrium temperature profile, B (fuel) + Cu_2O (oxidizer).

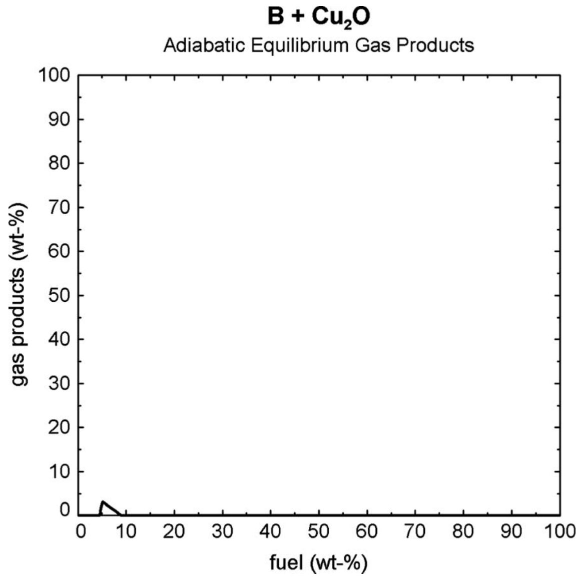

FIGURE 23.31 Adiabatic equilibrium gas production profile, B (fuel) + Cu_2O (oxidizer).

T1. 4.8% fuel, 2.06% gas produced, 2314.36 K—*peak temperature*
solids: none
liquids: 84.45% Cu, 13.49% B_2O_3
gases: 1.92% B_2O_3, 0.10% Cu
simplified equation at 4.8% fuel: $2B + 3Cu_2O \rightarrow B_2O_3 + 6Cu$

- T1 corresponds to the maximum amount of Cu.
- From 30.3% to 34.0% fuel, the temperature is limited to 1358 K by the Cu(s-l) transition.
- From 2.4% to 2.9% fuel, the temperature is limited to 1517 K by the Cu_2O(s-l) transition.
- The plateau from 5.1% to 8.9% fuel (2189 K) could not be attributed to a simple transition or reaction; species in this region include $(BO)_2$(g), B_2O_3(g), Cu(l), B_2O_3(l), and B(s). The vaporization of boron oxides from B(s)/B_2O_3(l) mixtures is expected to occur at 2192 K.

G1. 5.1% fuel, 3.04% gas produced, 2189.18 K—*peak gas*
solids: none
liquids: 84.22% Cu, 12.67% B_2O_3
gases: 1.79% $(BO)_2$, 1.13% B_2O_3
simplified equation at 4.8% fuel: $2B + 3Cu_2O \rightarrow B_2O_3 + 6Cu$

23.21 BORON + CuO

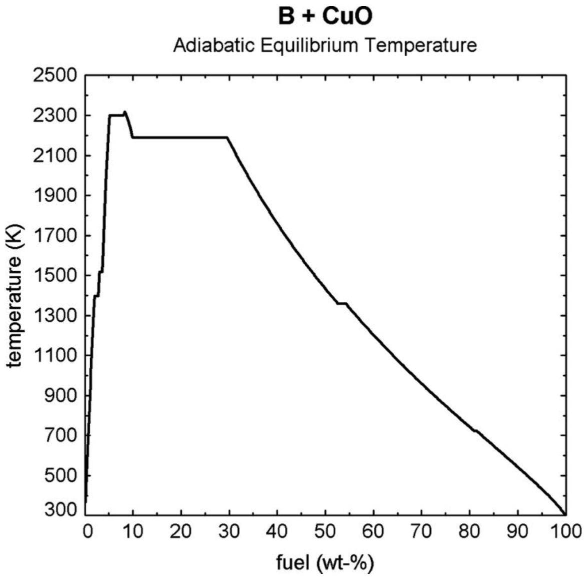

FIGURE 23.32 Adiabatic equilibrium temperature profile, B (fuel) + CuO (oxidizer).

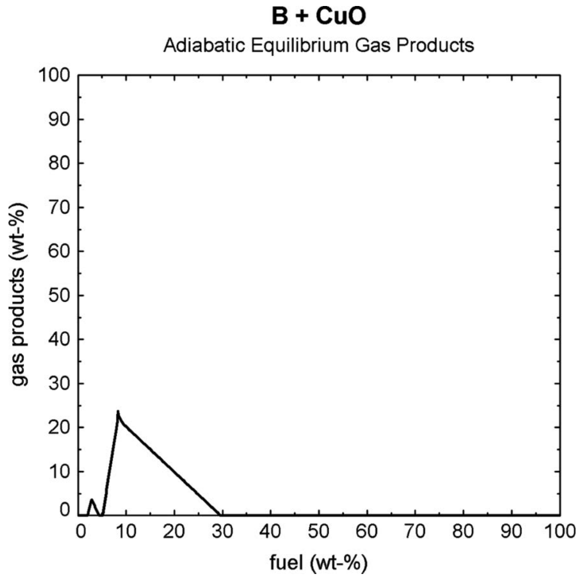

FIGURE 23.33 Adiabatic equilibrium gas production profile, B (fuel) + CuO (oxidizer).

T1. 4.3% fuel, 1956.58 K
solids: none
liquids: 86.08% Cu_2O, 13.84% B_2O_3
gases: none
simplified equation at 4.3% fuel: $2B + 6CuO \rightarrow B_2O_3 + 3Cu_2O$

T2. 8.3% fuel, 23.66% gas produced, 2316.70 K—*peak temperature*
solids: none
liquids: 72.07% Cu, 4.27% B_2O_3
gases: 22.31% B_2O_3, 1.17% Cu, 0.14% BO_2
simplified equation at 8.3% fuel: $2B + 3CuO \rightarrow B_2O_3 + 3Cu$

- The maximum amount of copper, 72.61% Cu(l) and 0.93% Cu(g), occurs at 7.9% fuel and 2299.82 K.
- From 52.6% to 54.1% fuel, the temperature is limited to 1358 K by the Cu(s-l) transition.
- From 2.0% to 2.7% fuel, the temperature appears to be limited by the $4CuO(s) \rightarrow 2Cu_2O(s) + O_2(g)$ decomposition, which occurs at 1397 K.
- From 3.0% to 3.6% fuel, the temperature is limited to 1517 K by the Cu_2O(s-l) transition.
- The plateau from 9.9% to 29.5% fuel (2189 K) could not be attributed to a simple transition or reaction; species in this region include $(BO)_2$(g), B_2O_3(g), Cu(g), BO(g), Cu(l), B_2O_3(l), and B(s). The vaporization of boron oxides from B(s)/B_2O_3(l) mixtures is expected to occur at 2192 K.
- The plateau from 5.1% to 7.8% fuel (2300 K) could not be attributed to a simple transition or reaction; species include B_2O_3(g), O_2(g), Cu(g), BO_2(g), Cu(l), Cu_2O(l), and B_2O_3(l).

G1. 8.3% fuel, 23.66% gas produced, 2316.70 K—*peak gas*
see T2 for details

23.22 BORON + Ag_2O

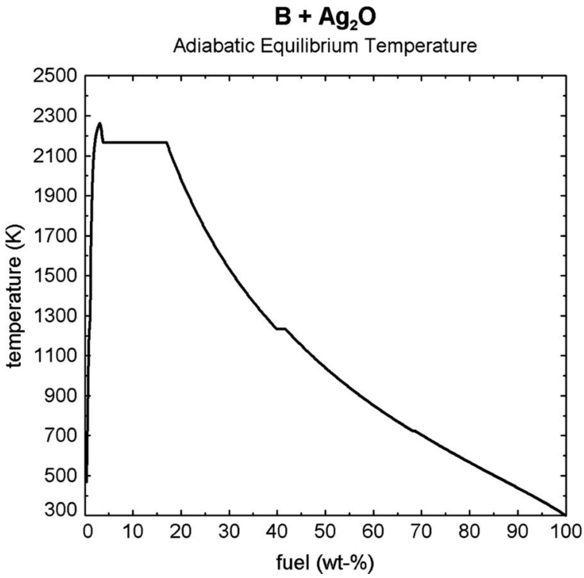

FIGURE 23.34 Adiabatic equilibrium temperature profile, B (fuel) + Ag_2O (oxidizer).

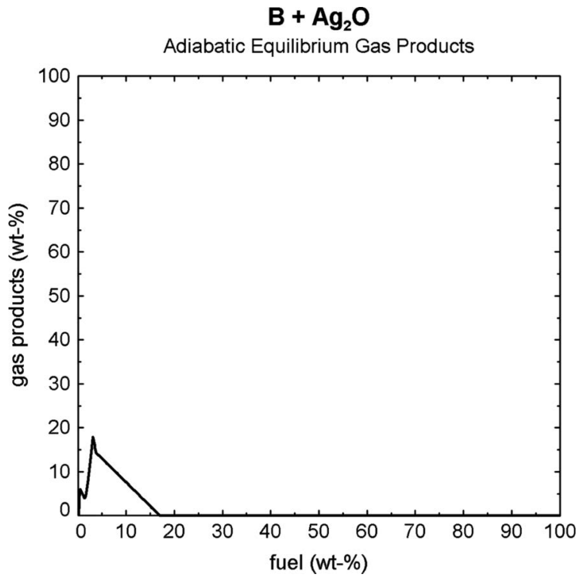

FIGURE 23.35 Adiabatic equilibrium gas production profile, B (fuel) + Ag_2O (oxidizer).

T1. 3.0% fuel, 17.78% gas produced, 2261.91 K—*peak temperature*
solids: none
liquids: 81.27% Ag, 0.95% B_2O_3
gases: 8.67% Ag, 8.60% B_2O_3, 0.37% Ag_2, 0.13% BO_2
simplified equation at 3.0% fuel: $2B + 3Ag_2O \rightarrow B_2O_3 + 6Ag$

- Ag_2O(s) is unstable above 468 K. The maximum amount of silver, 92.72% Ag(s), occurs at just 0.4% fuel and 639.07 K.
- From 39.8% to 41.5% fuel, the temperature is limited to 1234 K by the Ag(s-l) transition.
- The plateau from 3.8% to 16.9% fuel (2165 K) could not be attributed to a simple transition or reaction; species in this region include $(BO)_2$(g), B_2O_3(g), Ag(g), Ag_2(g), BO(g), Ag(l), B_2O_3(l), and B(s). The vaporization of boron oxides from B(s)/B_2O_3(l) mixtures is expected to occur at 2192 K.

G1. 3.0% fuel, 17.78% gas produced, 2261.91 K—*peak gas*
see T1 for details

23.23 BORON + ZnO

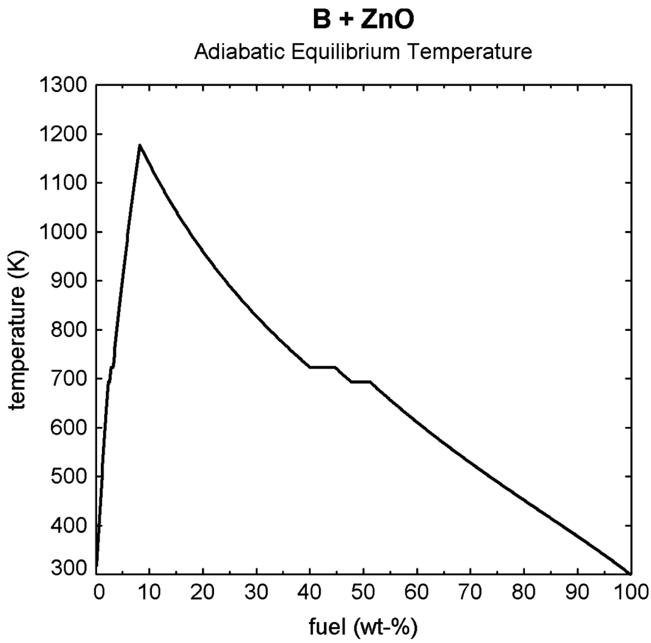

FIGURE 23.36 Adiabatic equilibrium temperature profile, B (fuel) + ZnO (oxidizer).

T1. 8.2% fuel, 1176.98 K—*peak temperature*
solids: none
liquids: 73.75% Zn, 26.18% B_2O_3
gases: none
simplified equation at 8.1% fuel: $2B + 3ZnO \rightarrow B_2O_3 + 3Zn$

- T1 corresponds to the maximum amount of Zn.
- From 47.7% to 51.1% fuel, the temperature is limited to 693 K by the Zn(s-l) transition.
- From 40.0% to 44.6% fuel, the temperature is limited to 723 K by the B_2O_3(s-l) transition.

23.24 BORON + CdO

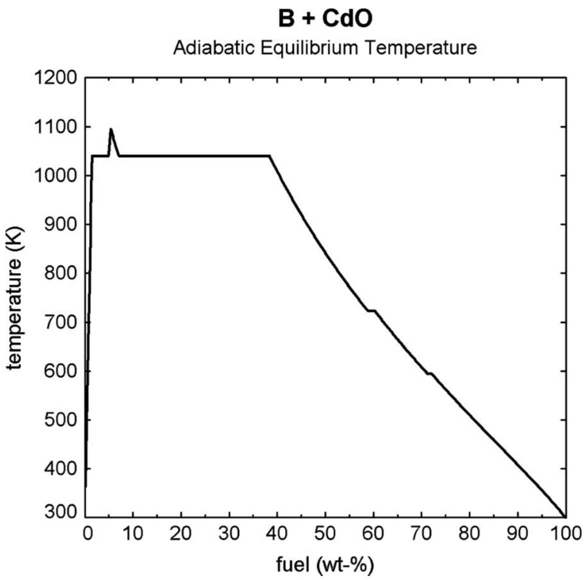

FIGURE 23.37 Adiabatic equilibrium temperature profile, B (fuel) + CdO (oxidizer).

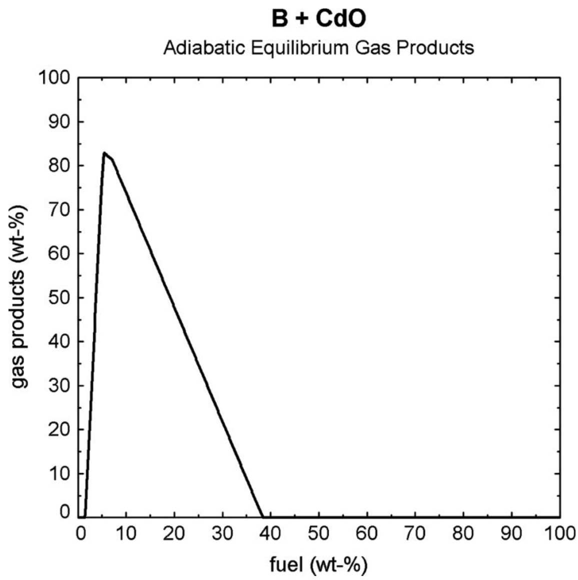

FIGURE 23.38 Adiabatic equilibrium gas production profile, B (fuel) + CdO (oxidizer).

T1. 5.3% fuel, 82.66% gas produced, 1094.04 K—*peak temperature*
solids: 0.27% CdO
liquids: 17.07% B_2O_3
gases: 82.66% Cd
simplified equation at 5.3% fuel: $2B + 3CdO \rightarrow B_2O_3 + 3Cd$

- G1 corresponds to the maximum amount of Cd.
- From 1.5% to 4.8% and 7.1% to 38.3% fuel, the temperature is limited to 1040 K by the Cd(l-g) transition.

G1. 5.4% fuel, 82.81% gas produced, 1092.86 K—*peak gas*
solids: none
liquids: 17.10% B_2O_3
gases: 82.81% Cd
simplified equation at 5.3% fuel: $2B + 3CdO \rightarrow B_2O_3 + 3Cd$

23.25 BORON + HgO

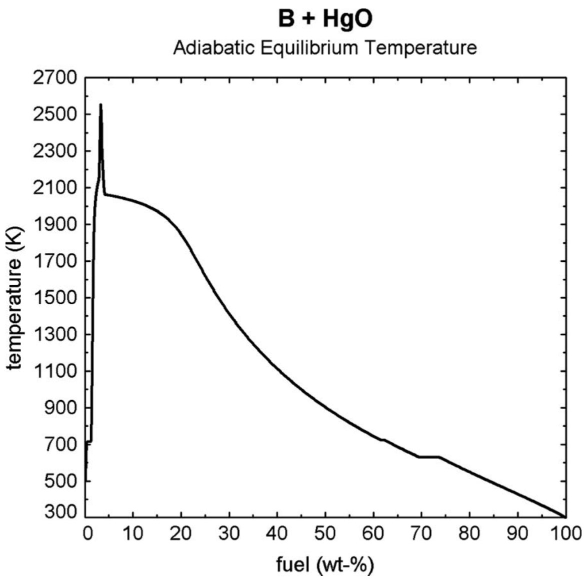

FIGURE 23.39 Adiabatic equilibrium temperature profile, B (fuel) + HgO (oxidizer).

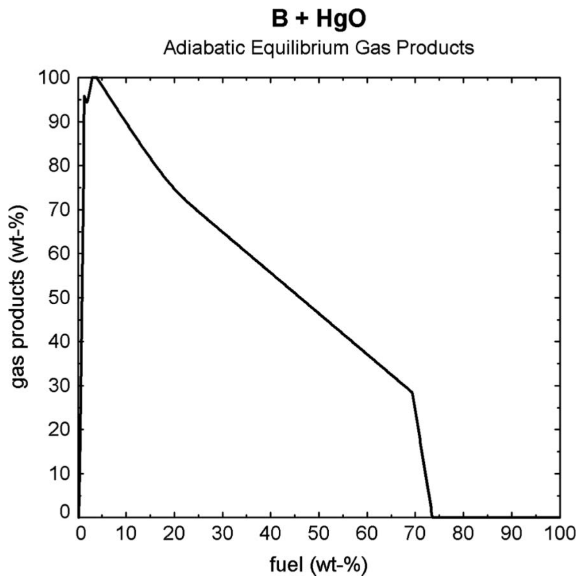

FIGURE 23.40 Adiabatic equilibrium gas production profile, B (fuel) + HgO (oxidizer).

T1. 1.9% fuel, 94.54% gas produced, 1911.26 K
solids: none
liquids: 5.46% B_2O_3
gases: 89.66% Hg, 2.93% O_2, 1.16% HgO, 0.62% B_2O_3, 0.12% Hg_2
a combination of two reactions with excess oxidizer remaining:
(3.2% fuel) $2B + 3HgO \rightarrow B_2O_3 + 3Hg$
(decomposition) $2HgO \rightarrow 2Hg + O_2$

T2. 3.2% fuel, 100% gas produced, 2550.78 K—*peak temperature*
solids: none
liquids: none
gases: 89.54% Hg, 9.92% B_2O_3, 0.33% BO_2
simplified equation at 3.2% fuel: $2B + 3HgO \rightarrow B_2O_3 + 3Hg$

- HgO(s) is unstable above 716 K.
- T1 and T2 correspond to the maximum amounts of Hg.
- The system produces 100% gas from 2.9% to 3.9% fuel.

G1. 3.2% fuel, 100% gas produced, 2550.78 K—*peak gas*
see T2 for details

23.26 BORON + SnO

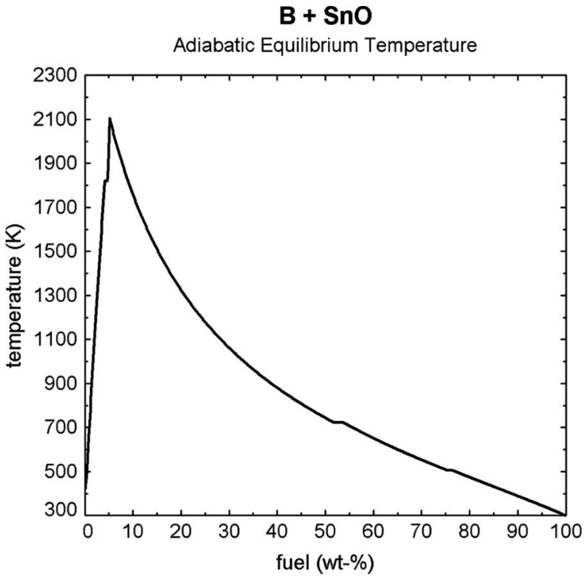

FIGURE 23.41 Adiabatic equilibrium temperature profile, B (fuel) + SnO (oxidizer).

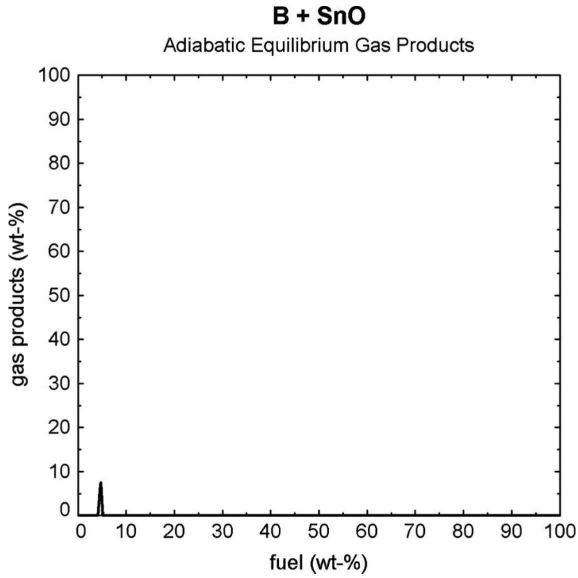

FIGURE 23.42 Adiabatic equilibrium gas production profile, B (fuel) + SnO (oxidizer).

T1. 5.1% fuel, 2103.30 K—*peak temperature*
solids: none
liquids: 83.63% Sn, 16.35% B_2O_3
gases: none
simplified equation at 5.1% fuel: $2B + 3SnO \rightarrow B_2O_3 + 3Sn$

- T1 corresponds to the maximum amount of Sn.
- From 4.2% to 4.6% fuel, the temperature appears to be limited by the vaporization of SnO from Sn(l)/SnO_2(s) mixtures, which occurs at about 1820 K.

G1. 4.7% fuel, 7.47% gas produced, 1835.18 K—*peak gas*
solids: none
liquids: 77.41% Sn, 15.12% B_2O_3
gases: 3.40% $(SnO)_2$, 1.54% SnO, 1.31% $(SnO)_4$, 1.20% $(SnO)_3$
one reaction with excess oxidizer remaining:
(5.1% fuel) $2B + 3SnO \rightarrow B_2O_3 + 3Sn$

23.27 BORON + SnO_2

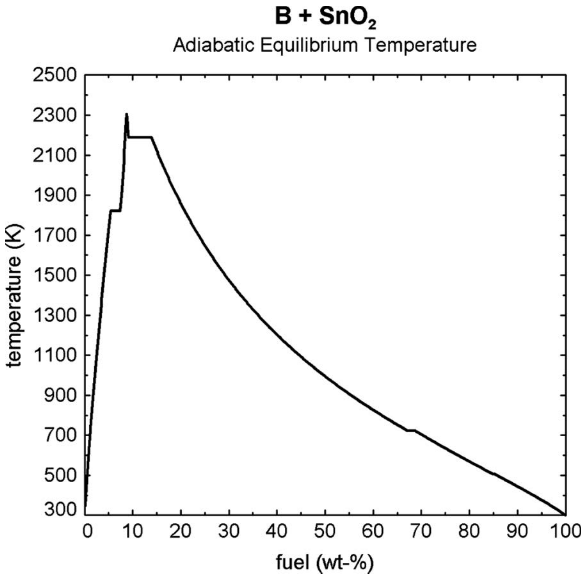

FIGURE 23.43 Adiabatic equilibrium temperature profile, B (fuel) + SnO_2 (oxidizer).

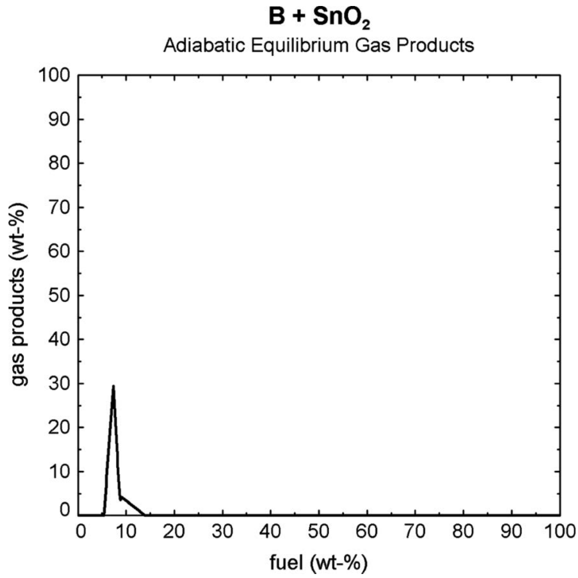

FIGURE 23.44 Adiabatic equilibrium gas production profile, B (fuel) + SnO_2 (oxidizer).

T1. 8.7% fuel, 3.94% gas produced, 2302.71 K—*peak temperature*
solids: none
liquids: 71.02% Sn, 25.04% B_2O_3
gases: 2.92% B_2O_3, 0.68% SnO, 0.27% Sn
simplified equation at 8.7% fuel: $4B + 3SnO_2 \rightarrow 2B_2O_3 + 3Sn$

- The maximum amount of tin, 71.54% Sn(l) and 0.26% Sn(g), occurs at 8.8% fuel and 2287.07 K.
- From 5.4% to 7.2% fuel, the temperature appears to be limited by the vaporization of SnO from Sn(l)/SnO_2(s) mixtures, which occurs at about 1820 K.
- The plateau from 9.1% to 13.8% fuel (2189 K) could not be attributed to a simple transition or reaction; species in this region include $(BO)_2$(g), B_2O_3(g), Sn(g), Sn(l), B_2O_3(l), and B(s). The vaporization of boron oxides from B(s)/B_2O_3(l) mixtures is expected to occur at 2192 K.

G1. 7.3% fuel, 29.33% gas produced, 1821.06 K—*peak gas*
solids: none
liquids: 47.21% Sn, 23.47% B_2O_3
gases: 12.97% $(SnO)_2$, 5.88% $(SnO)_4$, 5.44% SnO, 4.98% $(SnO)_3$
a combination of two reactions:
(4.6% fuel) $2B + 3SnO_2 \rightarrow B_2O_3 + 3SnO$
(8.7% fuel) $4B + 3SnO_2 \rightarrow 2B_2O_3 + 3Sn$

23.28 BORON + PbO

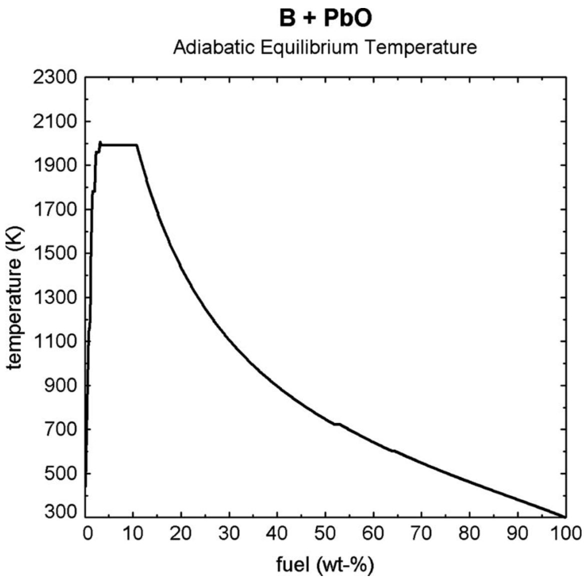

FIGURE 23.45 Adiabatic equilibrium temperature profile, B (fuel) + PbO (oxidizer).

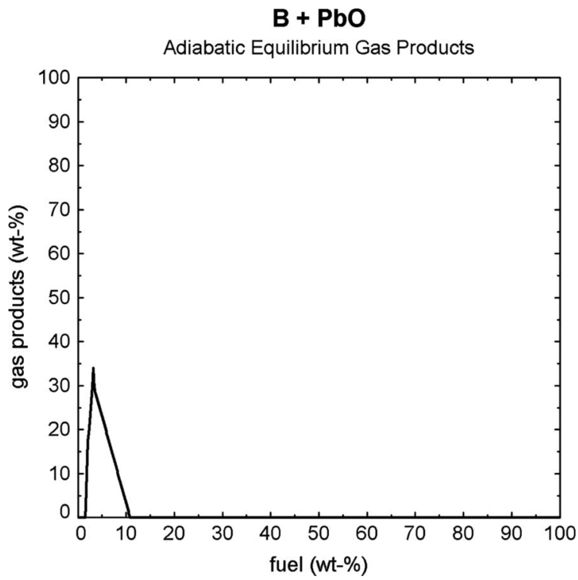

FIGURE 23.46 Adiabatic equilibrium gas production profile, B (fuel) + PbO (oxidizer).

T1. 2.2% fuel, 19.08% gas produced, 1935.98 K
solids: 29.47% PbB_2O_4
liquids: 51.46% Pb
gases: 11.71% Pb, 7.20% PbO
one reaction with excess oxidizer remaining:
(2.4% fuel) $2B + 4PbO \rightarrow PbB_2O_4 + 3Pb$

T2. 3.1% fuel, 33.93% gas produced, 2006.15 K—*peak temperature*
solids: none
liquids: 56.66% Pb, 9.41% B_2O_3
gases: 32.17% Pb, 0.90% PbO, 0.57% B_2O_3, 0.29% Pb_2
simplified equation at 3.1% fuel: $2B + 3PbO \rightarrow B_2O_3 + 3Pb$

- The maximum amount of lead, 59.50% Pb(l), 30.10% Pb(g), and 0.26% Pb_2(g), occurs at 3.2% fuel and 1998.62 K.
- From 1.6% to 2.0% fuel, the temperature appears to be limited by the vaporization of Pb and PbO from Pb(l)/PbO(l) mixtures, which occurs at 1780 K.
- From 2.3% to 2.8% fuel, the temperature appears to be limited by the vaporization of Pb, PbO, and B_2O_3 from Pb(l)/PbB_2O_4(s) mixtures, which occurs at 1960 K.
- The plateau from 3.3% to 10.7% fuel (1991 K) could not be attributed to a simple transition or reaction; species in this region include Pb(g), Pb_2(g), $(BO)_2$(g), B_2O_3(g), Pb(l), B_2O_3(l), and B(s). Alone, Pb(l) is expected to vaporize at 2020 K.

G1 3.1% fuel, 33.93% gas produced, 2006.15 K—*peak gas*
see T2 for details

23.29 BORON + Pb_3O_4

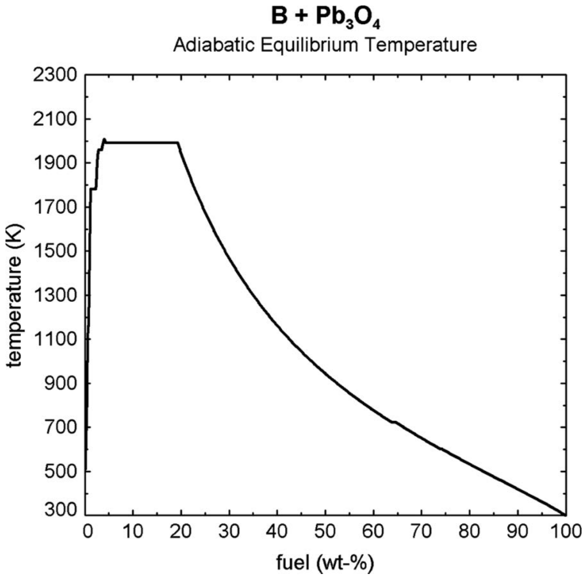

FIGURE 23.47 Adiabatic equilibrium temperature profile, B (fuel) + Pb_3O_4 (oxidizer).

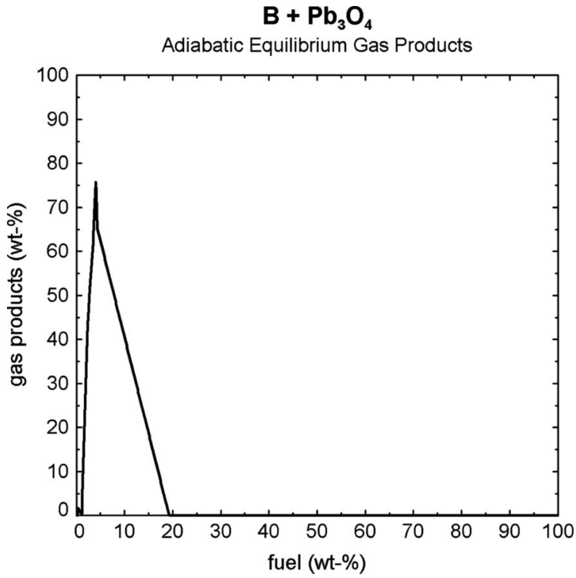

FIGURE 23.48 Adiabatic equilibrium gas production profile, B (fuel) + Pb_3O_4 (oxidizer).

T1. 1.0% fuel, 0.34% gas produced, 1663.01 K
solids: 13.54% PbB_2O_4
liquids: 86.12% PbO
gases: 0.25% PbO
simplified equation at 1.0% fuel: $2B + 3Pb_3O_4 \rightarrow PbB_2O_4 + 8PbO$

T2. 4.0% fuel, 75.61% gas produced, 2008.01 K—*peak temperature*
solids: none
liquids: 12.82% Pb, 11.58% B_2O_3
gases: 72.50% Pb, 1.30% B_2O_3, 1.14% PbO, 0.65% Pb_2
simplified equation at 4.0% fuel: $8B + 3Pb_3O_4 \rightarrow 4B_2O_3 + 9Pb$

- The maximum amount of lead, 15.31% Pb(l), 71.00% Pb(g), and 0.64% Pb_2(g), occurs at 4.1% fuel and 2005.75 K.
- From 1.1% to 2.2% fuel, the temperature appears to be limited by the vaporization of Pb and PbO from Pb(l)/PbO(l) mixtures, which occurs at 1780 K.
- From 2.8% to 3.5% fuel, the temperature appears to be limited by the vaporization of Pb, PbO, and B_2O_3 from Pb(l)/PbB_2O_4(s) mixtures, which occurs at 1960 K.
- The plateau from 4.3% to 19.2% fuel (1991 K) could not be attributed to a simple transition or reaction; species in this region include Pb(g), Pb_2(g), $(BO)_2$(g), B_2O_3(g), Pb(l), B_2O_3(l), and B(s). Alone, Pb(l) is expected to vaporize at 2020 K.

G1. 4.0% fuel, 75.61% gas produced, 2008.01 K—*peak gas*
see T2 for details

23.30 BORON + PbO_2

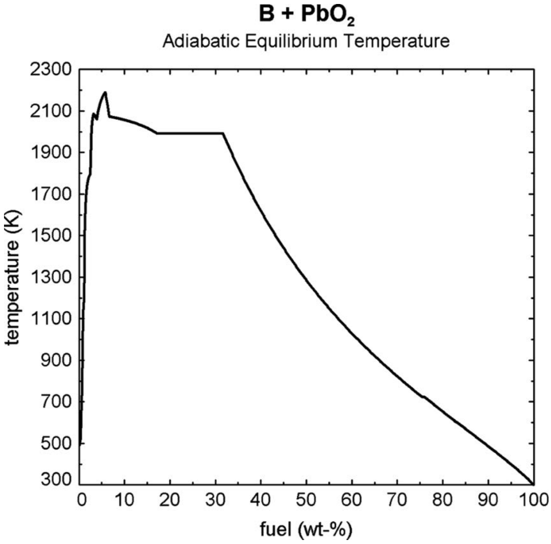

FIGURE 23.49 Adiabatic equilibrium temperature profile, B (fuel) + PbO_2 (oxidizer).

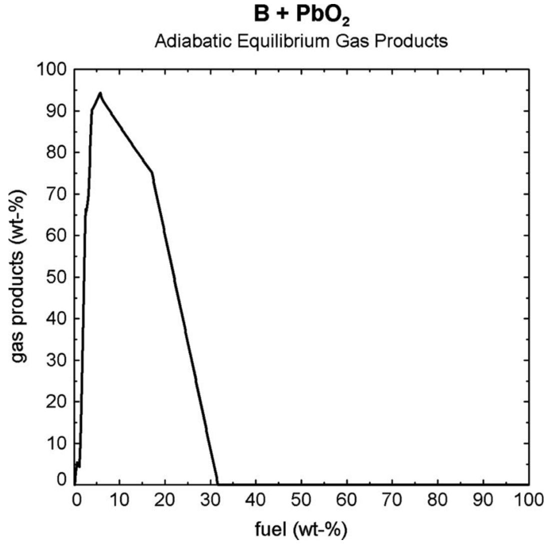

FIGURE 23.50 Adiabatic equilibrium gas production profile, B (fuel) + PbO_2 (oxidizer).

T1. 2.4% fuel, 63.30% gas produced, 1795.56 K
solids: 32.48% PbB_2O_4
liquids: 4.23% PbO
gases: 61.08% PbO, 1.27% O_2, 0.94% Pb
a combination of two reactions:
(2.9% fuel) $2B + 3PbO_2 \rightarrow PbB_2O_4 + 2PbO$
(decomposition) $2PbO_2 \rightarrow 2PbO + O_2$

T2. 3.1% fuel, 69.82% gas produced, 2084.98 K
solids: 30.18% PbB_2O_4
liquids: none
gases: 58.11% PbO, 8.63% Pb, 2.73% B_2O_3, 0.25% O_2
a combination of two reactions:
(2.9% fuel) $2B + 3PbO_2 \rightarrow PbB_2O_4 + 2PbO$
(5.7% fuel) $4B + 3PbO_2 \rightarrow 2B_2O_3 + 3Pb$

T3. 5.7% fuel, 94.28% gas produced, 2188.92 K—*peak temperature*
solids: none
liquids: 5.72% B_2O_3
gases: 81.07% Pb, 12.38% B_2O_3, 0.39% Pb_2, 0.24% PbO, 0.15% $(BO)_2$
simplified equation at 5.7% fuel: $4B + 3PbO_2 \rightarrow 2B_2O_3 + 3Pb$

- The maximum amount of lead, 81.17% Pb(g) and 0.39% Pb_2(g), occurs at 5.8% fuel and 2180.12 K.
- The plateau from 17.1% to 31.6% fuel (1991 K) could not be attributed to a simple transition or reaction; species in this region include Pb(g), Pb_2(g), $(BO)_2$(g), B_2O_3(g), Pb(l), B_2O_3(l), and B(s). Alone, Pb(l) is expected to vaporize at 2020 K.

G1. 5.7% fuel, 94.28% gas produced, 2188.92 K—*peak gas*
see T3 for details

23.31 BORON + Sb_2O_3

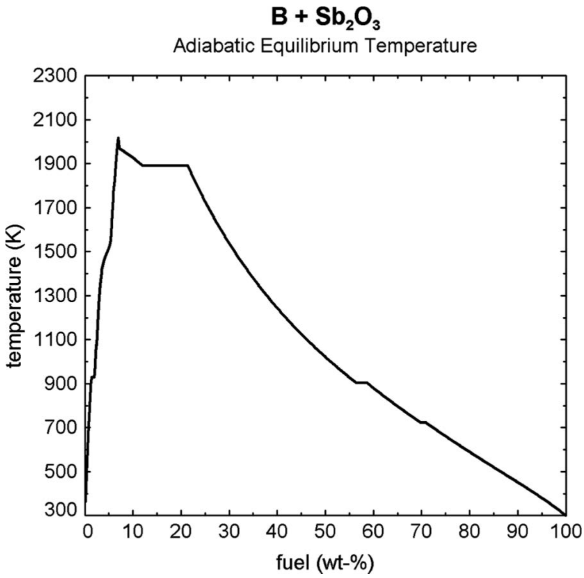

FIGURE 23.51 Adiabatic equilibrium temperature profile, B (fuel) + Sb_2O_3 (oxidizer).

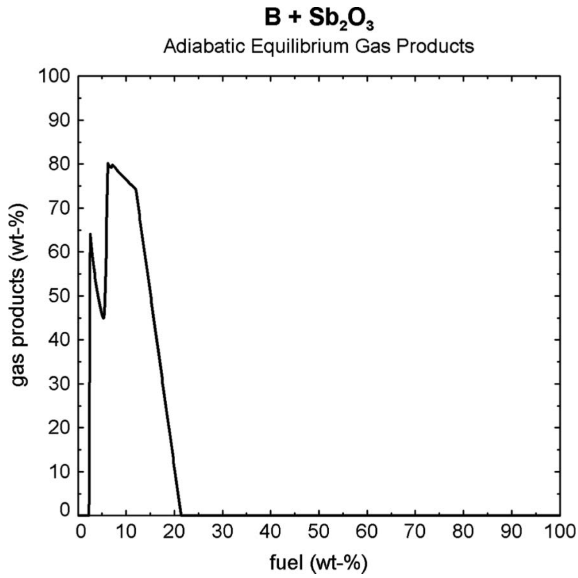

FIGURE 23.52 Adiabatic equilibrium gas production profile, B (fuel) + Sb_2O_3 (oxidizer).

T1. 6.9% fuel, 79.22% gas produced, 2017.54 K—*peak temperature*
solids: none
liquids: 20.79% B_2O_3
gases: 61.16% Sb_2, 11.95% Sb_4, 4.32% Sb, 1.29% B_2O_3, 0.39% SbO, 0.10% $(BO)_2$
simplified equation at 6.9% fuel: $2B + Sb_2O_3 \rightarrow B_2O_3 + 2Sb$

- The maximum amount of antimony, 3.88% Sb(g), 60.17% Sb_2(g), and 13.60% Sb_4(g), occurs at 7.0% fuel and 1995.05 K.
- The plateau from 12.0% to 21.3% fuel (1890 K) could not be attributed to a simple transition or reaction; species in this region include Sb_n(g), $(BO)_2$(g), B_2O_3(g), Sb(l), B_2O_3(l), and B(s). Alone, Sb(l) is expected to vaporize at 1899 K.

G1. 2.5% fuel, 64.02% gas produced, 1117.38 K
solids: none
liquids: 27.93% Sb, 8.05% B_2O_3
gases: 63.74% Sb_4O_6, 0.19% Sb_4
one reaction with excess oxidizer remaining:
(6.9% fuel) $2B + Sb_2O_3 \rightarrow B_2O_3 + 2Sb$

G2. 6.2% fuel, 80.16% gas produced, 1825.29 K—*peak gas*
solids: none
liquids: 19.84% B_2O_3
gases: 39.75% Sb_2, 24.46% Sb_4, 14.47% SbO, 1.35% Sb, 0.12% B_2O_3
a combination of two reactions:
(2.4% fuel) $2B + 3Sb_2O_3 \rightarrow B_2O_3 + 6SbO$
(6.9% fuel) $2B + Sb_2O_3 \rightarrow B_2O_3 + 2Sb$

23.32 BORON + Bi_2O_3

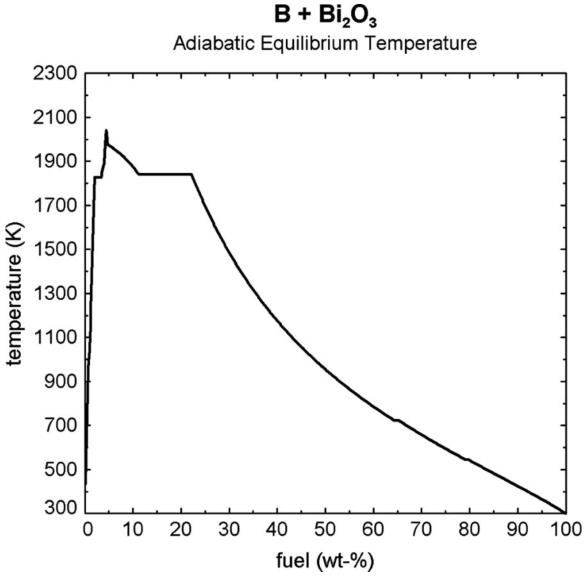

FIGURE 23.53 Adiabatic equilibrium temperature profile, B (fuel) + Bi_2O_3 (oxidizer).

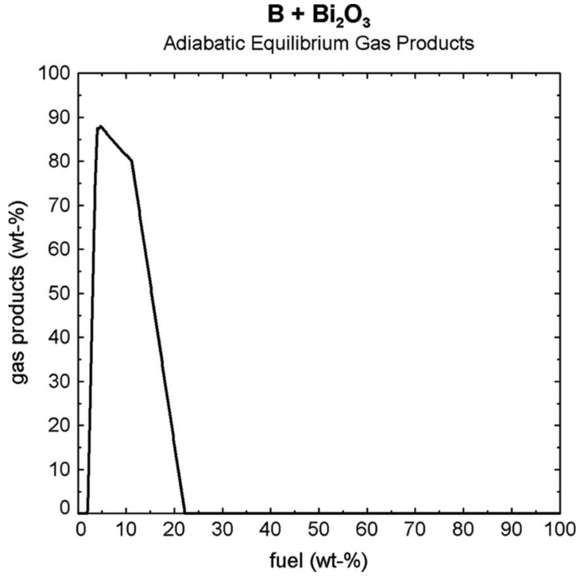

FIGURE 23.54 Adiabatic equilibrium gas production profile, B (fuel) + Bi_2O_3 (oxidizer).

T1. 4.4% fuel, 87.57% gas produced, 2039.42 K—*peak temperature*
solids: none
liquids: 12.43% B_2O_3
gases: 50.71% Bi, 34.07% Bi_2, 1.73% B_2O_3, 1.05% BiO
simplified equation at 4.4% fuel: $2B + Bi_2O_3 \rightarrow B_2O_3 + 2Bi$

- The maximum amount of bismuth, 50.13% Bi(g) and 35.53% Bi_2(g), occurs at 4.5% fuel and 2027.49 K.
- From 2.0% to 3.3% fuel, the temperature appears to be limited by the vaporization of BiO and Bi from Bi(l)/Bi_2O_3(l) mixtures, which occurs at 1827 K.
- The plateau from 11.1% to 22.1% fuel (1842 K) could not be attributed to a simple transition or reaction; species in this region include Bi(g), Bi_2(g), $(BO)_2$(g), B_2O_3(g), Bi(l), B_2O_3(l), and B(s). Alone, Bi(l) is expected to vaporize at 1846 K.

G1. 4.7% fuel, 87.92% gas produced, 1974.96 K—*peak gas*
solids: none
liquids: 12.01% B_2O_3
gases: 45.17% Bi, 40.31% Bi_2, 1.56% $(BO)_2$, 0.85% B_2O_3
simplified equation at 4.4% fuel: $2B + Bi_2O_3 \rightarrow B_2O_3 + 2Bi$

24 Aluminum–Oxidizer Systems

24.1 OVERVIEW

This chapter concerns the adiabatic properties of the aluminum–oxygen system and another thirty-two aluminum–oxidizer combinations. Equation 24.1 is a general description of the chemical reactions in question, and Table 24.1 provides a broad overview of the most basic results. The thermochemical descriptions within this chapter were derived from the *FactPS* and *FToxid* databases of

TABLE 24.1
Aluminum–Oxidizer Systems

Section	Pages	Oxidizer	Maximum T_{ad} (K)
24.2	804	O_2	4006
24.3	806	TiO_2	2022
24.4	807	V_2O_5	3117
24.5	809	Nb_2O_5	2705
24.6	811	Ta_2O_5	2348
24.7	812	Cr_2O_3	2327
24.8	813	MoO_3	3791
24.9	815	WO_3	3874
24.10	817	MnO	2213
24.11	818	Mn_3O_4	2336
24.12	820	Mn_2O_3	2336
24.13	822	MnO_2	3380
24.14	824	FeO	2981
24.15	826	Fe_3O_4	3124
24.16	828	Fe_2O_3	3126
24.17	830	CoO	3189
24.18	832	Co_3O_4	3198
24.19	834	NiO	3182
24.20	836	Cu_2O	2837
24.21	837	CuO	2839
24.22	839	Ag_2O	2427
24.23	840	ZnO	1580
24.24	841	CdO	2576
24.25	843	HgO	3650
24.26	845	B_2O_3	2327
24.27	847	SiO_2	1759
24.28	848	SnO	2839
24.29	850	SnO_2	2835
24.30	851	PbO	2327
24.31	853	Pb_3O_4	3103
24.32	855	PbO_2	3647
24.33	857	Sb_2O_3	2703
24.34	859	Bi_2O_3	3202

FactSage 7.0.* Only pure substances were considered in the condensed phases. Gases were treated ideally, and ideal gas mixing was assumed. Charged species were not considered in any phase.

$$\text{aluminum} + \text{oxidizer} \rightarrow \text{adiabatic equilibrium products}$$
$$(P = 1 \text{ atm}, T_i = 298.15 \text{ K}, T_{ad} = \text{adiabatic equilibrium temperature}) \tag{24.1}$$

Within each of the following sections, you will find one or two general figures as well as written descriptions of certain fuel-to-oxidizer ratios. Temperature points (T1, T2, and so on) describe features and points of interest along adiabatic temperature profiles. Similarly, gas points (G1, G2, and so on) refer to adiabatic gas production profiles. Some adiabatic temperature charts contain flat regions where the adiabatic temperature remains constant despite variations in the stoichiometry of the system. Some of these plateaus are described and explained (see Chapter 2 and Tables 2.10–2.15 for more information). The first part of Chapter 5 is also about aluminum.

24.2 ALUMINUM + O_2

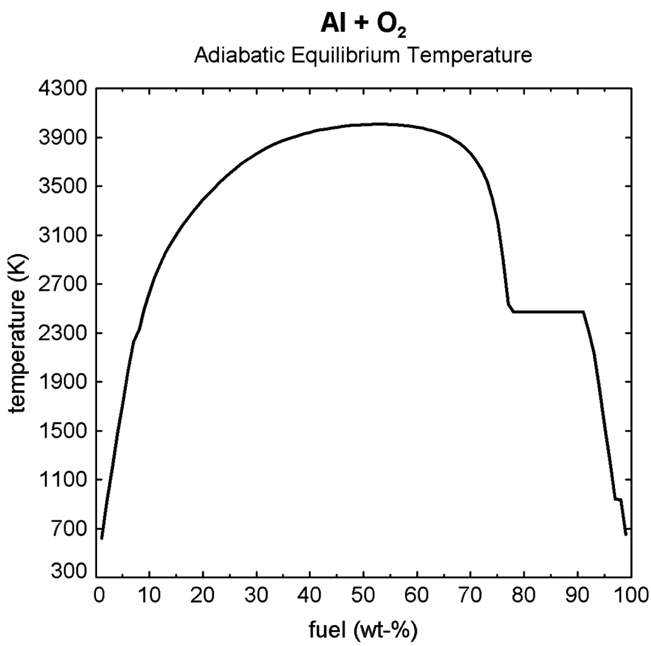

FIGURE 24.1 Adiabatic equilibrium temperature profile, Al (fuel) + O_2 (oxidizer).

T1. 36% fuel, 3889.65 K
solids: none
liquids: 52.30% Al_2O_3
major gases: 18.98% O, 16.19% O_2, 8.12% AlO
other gases: 1.44% Al_2O_2, 1.19% Al, 0.99% Al_2O, 0.77% AlO_2
a combination of two reactions with excess oxidizer remaining:
(52.9% fuel) $4Al + 3O_2 \rightarrow 2Al_2O_3$
(62.8% fuel) $2Al + O_2 \rightarrow 2AlO$

* Bale, C. W.; Pelton, A. D.; Thompson, W. T.; Eriksson, G.; Hack, K.; Chartrand, P.; Decterov, S.; Jung, I.-H.; Melançon, J.; Petersen, S. *FactSage,* version 7.0; CRCT ThermFact, Inc. and GTT-Technologies, 2015; www.factsage.com (accessed September, 2019).

T2. 53% fuel, 4006.19 K—*peak temperature*
solids: none
liquids: 34.93% Al_2O_3
major gases: 22.11% AlO, 12.47% O, 10.69% Al_2O, 7.78% Al, 6.55% Al_2O_2
other gases: 4.40% O_2, 0.99% AlO_2
a combination of reactions with unreacted fuel and oxidizer remaining:
(52.9% fuel) $4Al + 3O_2 \rightarrow 2Al_2O_3$
(62.8% fuel) $2Al + O_2 \rightarrow 2AlO$
(62.8% fuel) $2Al + O_2 \rightarrow Al_2O_2$
(77.1% fuel) $4Al + O_2 \rightarrow 2Al_2O$

T3. 63% fuel, 3951.74 K
solids: none
liquids: 38.06% Al_2O_3
major gases: 20.56% Al_2O, 17.66% AlO, 11.40% Al, 6.84% Al_2O_2
other gases: 4.21% O, 0.81% O_2, 0.41% AlO_2
a combination of reactions with unreacted fuel and oxidizer remaining:
(52.9% fuel) $4Al + 3O_2 \rightarrow 2Al_2O_3$
(62.8% fuel) $2Al + O_2 \rightarrow 2AlO$
(62.8% fuel) $2Al + O_2 \rightarrow Al_2O_2$
(77.1% fuel) $4Al + O_2 \rightarrow 2Al_2O$

T4. 77% fuel, 2534.93 K
solids: none
liquids: 8.35% Al_2O_3
gases: 83.34% Al_2O, 8.15% Al, 0.13% Al_2
a combination of two reactions with excess fuel remaining:
(52.9% fuel) $4Al + 3O_2 \rightarrow 2Al_2O_3$
(77.1% fuel) $4Al + O_2 \rightarrow 2Al_2O$

- The first, third, and fourth points correspond to the maximum amounts of Al_2O_3, Al_2O_2, and Al_2O, respectively. The second point corresponds to the maximum amounts of AlO and AlO_2.
- From 78% to 91% fuel, the temperature appears to be limited by the vaporization of Al_2O and Al from Al(l)/Al_2O_3(l) mixtures, which occurs at 2470 K. Pure Al(l) vaporizes at 2790 K.
- Al_2O_3(l) decomposes into a gaseous mixture of AlO, O, Al_2O, Al, Al_2O_2, O_2, and AlO_2 at 4006 K. This appears to limit any further increase in temperature.
- Al(g) is present from 26% to 91% fuel. The maximum amount, 15.69%, occurs at 72% fuel.

24.3 ALUMINUM + TiO_2

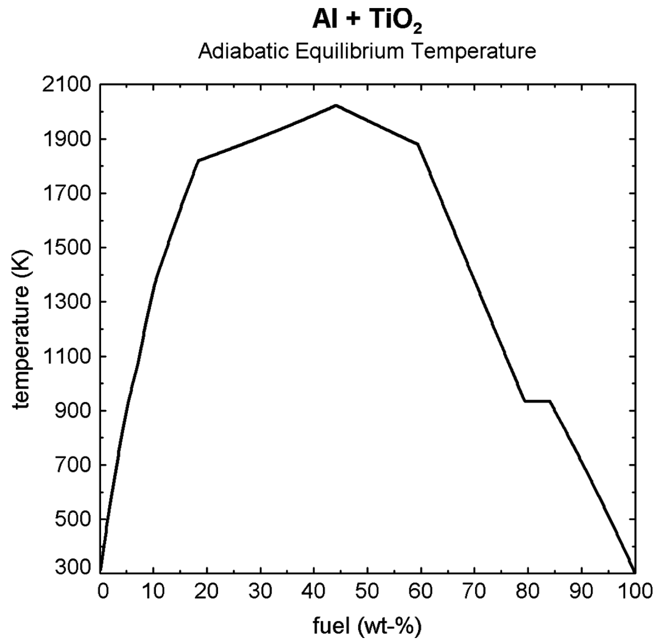

FIGURE 24.2 Adiabatic equilibrium temperature profile, Al (fuel) + TiO_2 (oxidizer).

T1. 10.1% fuel, 1358.95 K
solids: 80.32% Ti_2O_3, 19.08% Al_2O_3 (corundum), 0.59% Ti_3O_5
liquids: none
gases: none
simplified equation at 10.1% fuel: $2Al + 6TiO_2 \rightarrow Al_2O_3 + 3Ti_2O_3$

T2. 18.4% fuel, 1819.31 K
solids: 65.22% TiO, 34.74% Al_2O_3 (corundum)
liquids: none
gases: none
simplified equation at 18.4% fuel: $2Al + 3TiO_2 \rightarrow Al_2O_3 + 3TiO$

T3. 44.1% fuel, 2022.42 K—*peak temperature*
solids: 52.34% TiAl, 47.58% Al_2O_3 (corundum)
liquids: none
gases: none
simplified equation at 44.1% fuel: $7Al + 3TiO_2 \rightarrow 2Al_2O_3 + 3TiAl$

T4. 59.4% fuel, 1878.51 K
solids: 65.39% $TiAl_3$, 34.56% Al_2O_3 (corundum)
liquids: none
gases: none
simplified equation at 59.4% fuel: $13Al + 3TiO_2 \rightarrow 2Al_2O_3 + 3TiAl_3$

- Elemental titanium is not predicted to occur at any point.

24.4 ALUMINUM + V_2O_5

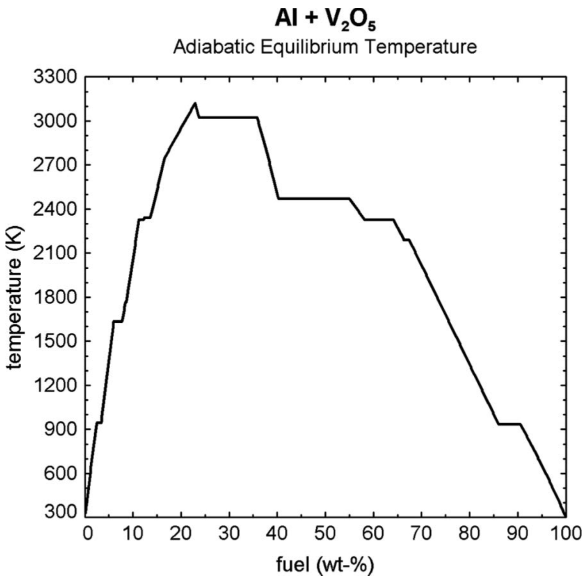

FIGURE 24.3 Adiabatic equilibrium temperature profile, Al (fuel) + V_2O_5 (oxidizer).

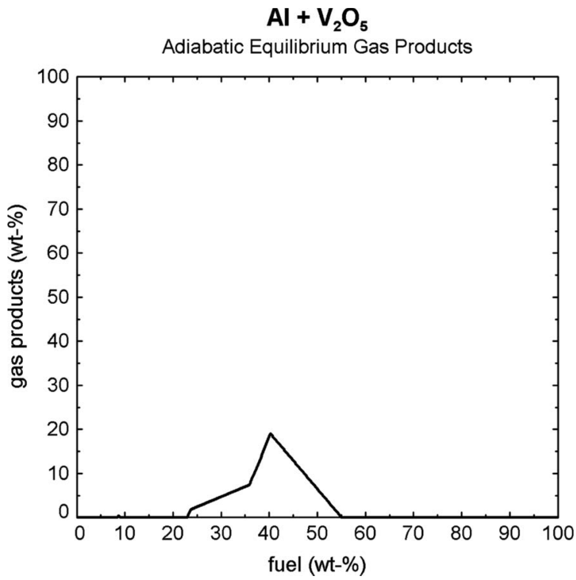

FIGURE 24.4 Adiabatic equilibrium gas production profile, Al (fuel) + V_2O_5 (oxidizer).

T1. 9.0% fuel, 1859.52 K
solids: 17.01% Al_2O_3 (corundum)
liquids: 82.99% VO_2
gases: none
simplified equation at 9.0% fuel: $2Al + 3V_2O_5 \rightarrow Al_2O_3 + 6VO_2$

T2. 16.5% fuel, 2744.20 K
solids: none
liquids: 68.68% V_2O_3, 31.18% Al_2O_3, 0.15% VO_2
gases: none
simplified equation at 16.5% fuel: $4Al + 3V_2O_5 \rightarrow 2Al_2O_3 + 3V_2O_3$

T3. 22.9% fuel, 3117.01 K—*peak temperature*
solids: none
liquids: 56.75% VO, 43.21% Al_2O_3
gases: none
simplified equation at 22.9% fuel: $2Al + V_2O_5 \rightarrow Al_2O_3 + 2VO$

T4. 35.8% fuel, 7.45% gas produced, 3016.82 K
solids: none
liquids: 56.98% Al_2O_3, 35.58% V
gases: 5.89% Al_2O, 1.06% Al, 0.25% V, 0.16% VO
a combination of two reactions with excess fuel remaining:
(33.1% fuel) $10Al + 3V_2O_5 \rightarrow 5Al_2O_3 + 6V$
(59.7% fuel) $10Al + V_2O_5 \rightarrow 5Al_2O + 2V$

- T4 corresponds to the maximum amount of V.
- From 6.0% to 7.6% fuel, the temperature is limited to 1633 K by the VO_2(s-l) transition.
- From 66.3% to 67.3% fuel, the temperature is limited to 2190 K by the V(s-l) transition.
- From 11.3% to 12.1% and 58.1% to 64.1% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- From 12.3% to 13.5% fuel, the temperature is limited to 2340 K by the V_2O_3(s-l) transition.
- From 40.2% to 54.9% fuel, the temperature appears to be limited by the vaporization of Al_2O and Al from Al(l)/Al_2O_3(l) mixtures, which occurs at 2470 K.
- From 23.7% to 35.7% fuel, the temperature appears to be limited to 3022 K by the reaction of V(l) and Al_2O_3(l) which forms VO(l-g), Al_2O(g), and Al(g). Some of the V is vaporized as well.

G1. 40.2% fuel, 18.98% gas produced, 2469.55 K—*peak gas*
solids: none
liquids: 47.42% Al_2O_3, 33.49% V, 0.10% Al
gases: 17.39% Al_2O, 1.56% Al
a combination of two reactions with excess fuel remaining:
(33.1% fuel) $10Al + 3V_2O_5 \rightarrow 5Al_2O_3 + 6V$
(59.7% fuel) $10Al + V_2O_5 \rightarrow 5Al_2O + 2V$

24.5 ALUMINUM + Nb_2O_5

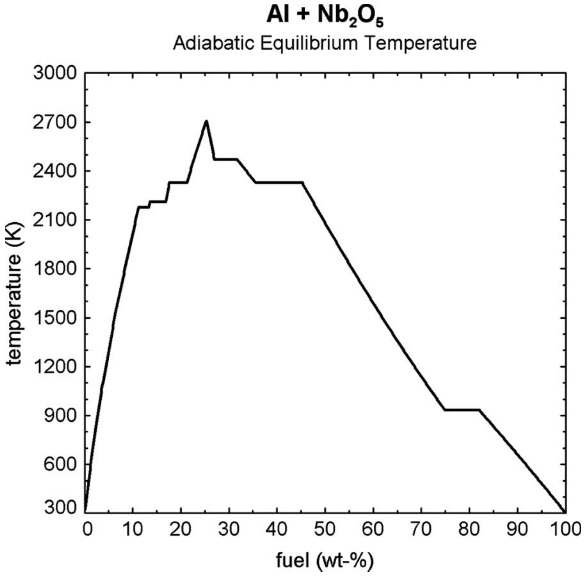

FIGURE 24.5 Adiabatic equilibrium temperature profile, Al (fuel) + Nb_2O_5 (oxidizer).

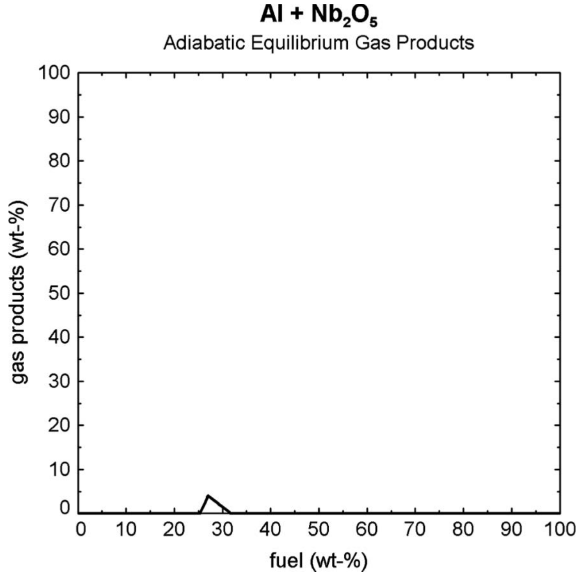

FIGURE 24.6 Adiabatic equilibrium gas production profile, Al (fuel) + Nb_2O_5 (oxidizer).

T1. 6.3% fuel, 1518.23 K
solids: 87.49% NbO_2, 11.90% Al_2O_3 (corundum), 0.60% Nb_2O_5
liquids: none
gases: none
simplified equation at 6.3% fuel: $2Al + 3Nb_2O_5 \rightarrow Al_2O_3 + 6NbO_2$

T2. 16.9% fuel, 2221.56 K
solids: 31.93% Al_2O_3 (corundum), 0.15% Nb
liquids: 67.92% NbO
gases: none
simplified equation at 16.9% fuel: $2Al + Nb_2O_5 \rightarrow Al_2O_3 + 2NbO$

T3. 25.3% fuel, 2704.64 K—*peak temperature*
solids: 52.22% Nb
liquids: 47.74% Al_2O_3
gases: none
simplified equation at 25.3% fuel: $10Al + 3Nb_2O_5 \rightarrow 5Al_2O_3 + 6Nb$

- T3 corresponds to the maximum amount of Nb.
- From 11.2% to 13.3% fuel, the temperature is limited to 2175 K by the NbO_2(s-l) transition.
- From 13.6% to 16.8% fuel, the temperature is limited to 2210 K by the NbO(s-l) transition.
- From 17.6% to 21.2% and 35.5% to 45.1% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- From 27.0% to 31.6% fuel, the temperature appears to be limited by the vaporization of Al_2O and Al from Al(l)/Al_2O_3(l) mixtures, which occurs at 2470 K.

G1. 27.0% fuel, 3.95% gas produced, 2469.66 K—*peak gas*
solids: 51.03% Nb
liquids: 44.91% Al_2O_3, 0.11% Al
gases: 3.62% Al_2O, 0.32% Al
a combination of two reactions:
(25.3% fuel) $10Al + 3Nb_2O_5 \rightarrow 5Al_2O_3 + 6Nb$
(50.4% fuel) $10Al + Nb_2O_5 \rightarrow 5Al_2O + 2Nb$

24.6 ALUMINUM + Ta_2O_5

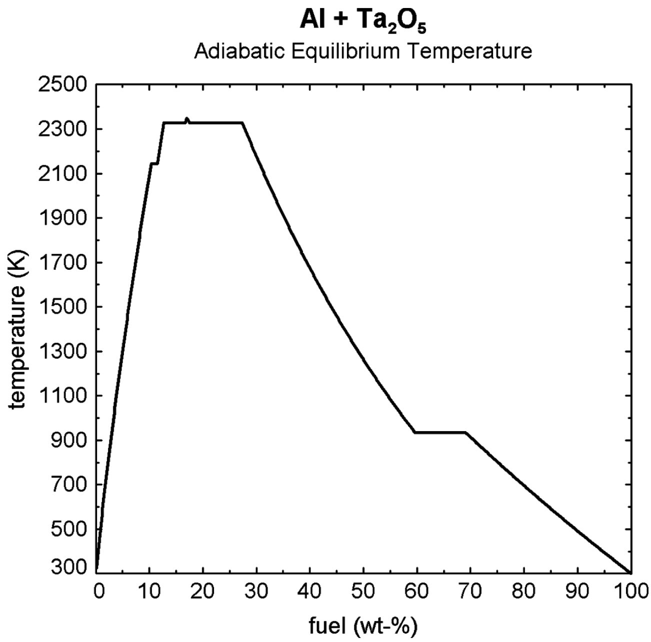

FIGURE 24.7 Adiabatic equilibrium temperature profile, Al (fuel) + Ta_2O_5 (oxidizer).

T1. 16.9% fuel, 2347.88 K—*peak temperature*
solids: 68.00% Ta
liquids: 31.93% Al_2O_3
gases: none
simplified equation at 16.9% fuel: $10Al + 3Ta_2O_5 \rightarrow 5Al_2O_3 + 6Ta$

- T1 corresponds to the maximum amount of Ta.
- From 10.3% to 11.4% fuel, the temperature is limited to 2143 K by the Ta_2O_5(s-l) transition.
- From 12.7% to 16.6% and 17.4% to 27.3% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.

24.7 ALUMINUM + Cr_2O_3

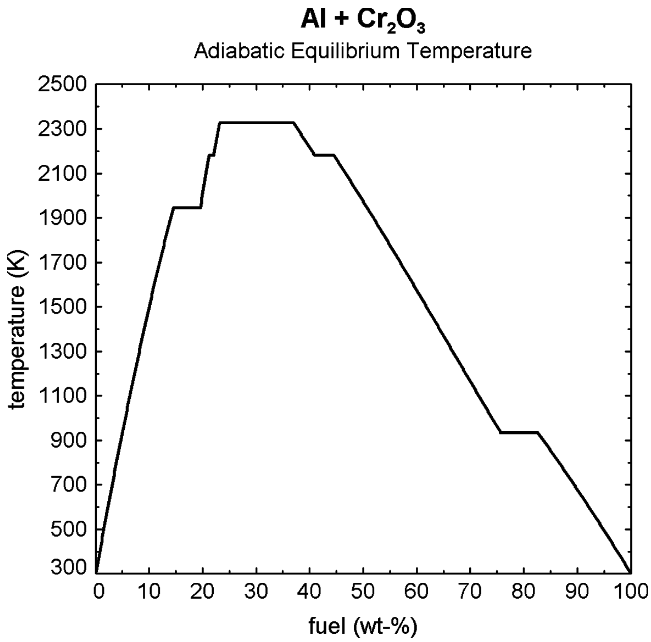

FIGURE 24.8 Adiabatic equilibrium temperature profile, Al (fuel) + Cr_2O_3 (oxidizer).

T1. 19.5% fuel, 1944.22 K
solids: 36.85% Al_2O_3 (corundum), 28.95% Cr, 0.34% Cr_2O_3
liquids: 33.86% CrO
gases: none
a combination of two reactions:
(10.6% fuel) $2Al + 3Cr_2O_3 \rightarrow Al_2O_3 + 6CrO$
(26.2% fuel) $2Al + Cr_2O_3 \rightarrow Al_2O_3 + 2Cr$

T2. 26.2% fuel, 2327.02 K—*peak temperature*
solids: 9.96% Al_2O_3 (corundum)
liquids: 50.49% Cr, 39.54% Al_2O_3
gases: none
simplified equation at 26.2% fuel: $2Al + Cr_2O_3 \rightarrow Al_2O_3 + 2Cr$

- T2 corresponds to the maximum amount of Cr.
- From 14.5% to 19.5% fuel, the temperature appears to be limited by the formation of CrO(l) from Cr(s)/Cr_2O_3(s) mixtures, which occurs at 1944 K.
- From 21.2% to 22.0% and 40.9% to 44.4% fuel, the temperature is limited to 2180 K by the Cr(s-l) transition.
- From 23.2% to 36.9% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.

24.8 ALUMINUM + MoO_3

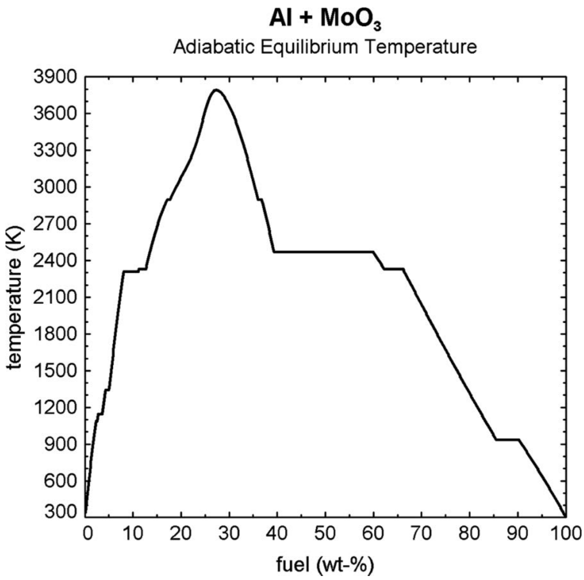

FIGURE 24.9 Adiabatic equilibrium temperature profile, Al (fuel) + MoO_3 (oxidizer).

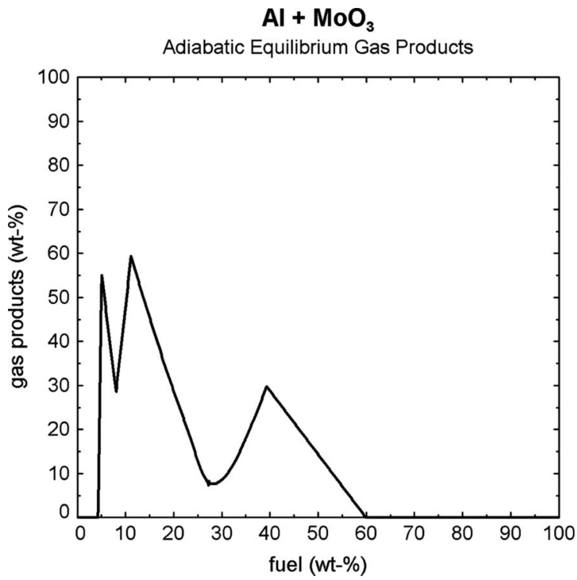

FIGURE 24.10 Adiabatic equilibrium gas production profile, Al (fuel) + MoO_3 (oxidizer).

T1. 7.9% fuel, 28.90% gas produced, 2288.93 K
solids: 56.17% MoO_2, 14.93% Al_2O_3 (corundum)
liquids: none
gases: 23.68% $(MoO_3)_3$, 3.37% $(MoO_3)_4$, 1.54% $(MoO_3)_2$, 0.18% MoO_3, 0.11% $(MoO_3)_5$
one reaction with excess oxidizer remaining:
(11.1% fuel) $2Al + 3MoO_3 \rightarrow Al_2O_3 + 3MoO_2$

T2. 27.3% fuel, 8.28% gas produced, 3790.99 K—*peak temperature*
solids: none
liquids: 47.79% Al_2O_3, 43.93% Mo
major gases: 3.38% MoO, 1.85% MoO_2, 1.08% Al_2O, 0.67% AlO
other gases: 0.58% Al, 0.27% Al_2O_2, 0.17% MoO_3, 0.14% Mo, 0.12% O
simplified equation at 27.3% fuel: $2Al + MoO_3 \rightarrow Al_2O_3 + Mo$

T3. 30.1% fuel, 8.70% gas produced, 3651.05 K
solids: none
liquids: 45.89% Al_2O_3, 45.41% Mo
gases: 4.48% Al_2O, 1.64% Al, 1.06% MoO, 0.72% AlO, 0.41% Al_2O_2, 0.24% MoO_2
a combination of two reactions with excess fuel remaining:
(27.3% fuel) $2Al + MoO_3 \rightarrow Al_2O_3 + Mo$
(52.9% fuel) $6Al + MoO_3 \rightarrow 3Al_2O + Mo$

- T3 corresponds to the maximum amount of Mo.
- From 8.0% to 11.1% fuel, the temperature appears to be limited by the vaporization of MoO_3 from Mo(s)/MoO_2(s) mixtures, which occurs at 2308 K.

- From 11.2% to 12.6% and 62.3% to 66.1% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- From 39.3% to 59.8% fuel, the temperature appears to be limited by the vaporization of Al_2O and Al from Al(l)/Al_2O_3(l) mixtures, which occurs at 2470 K.
- From 17.1% to 17.6% and 35.9% to 36.7% fuel, the temperature is limited to 2896 K by the Mo(s-l) transition.

G1. 5.0% fuel, 54.98% gas produced, 1356.41 K
solids: 35.57% MoO_2, 9.45% Al_2O_3 (corundum)
liquids: none
gases: 31.05% $(MoO_3)_4$, 17.71% $(MoO_3)_3$, 6.20% $(MoO_3)_5$
one reaction with excess oxidizer remaining:
(11.1% fuel) $2Al + 3MoO_3 \rightarrow Al_2O_3 + 3MoO_2$

G2. 11.1% fuel, 59.29% gas produced, 2308.16 K—*peak gas*
solids: 20.97% Al_2O_3 (corundum), 19.71% Mo
liquids: none
gases: 48.59% $(MoO_3)_3$, 6.69% $(MoO_3)_4$, 3.31% $(MoO_3)_2$, 0.42% MoO_3, 0.20% $(MoO_3)_5$
one reaction with excess oxidizer remaining:
(27.3% fuel) $2Al + MoO_3 \rightarrow Al_2O_3 + Mo$

G3. 39.3% fuel, 29.67% gas produced, 2469.66 K
solids: 40.46% Mo
liquids: 29.78% Al_2O_3
gases: 27.19% Al_2O, 2.43% Al
a combination of two reactions with excess fuel remaining:
(27.3% fuel) $2Al + MoO_3 \rightarrow Al_2O_3 + Mo$
(52.9% fuel) $6Al + MoO_3 \rightarrow 3Al_2O + Mo$

24.9 ALUMINUM + WO_3

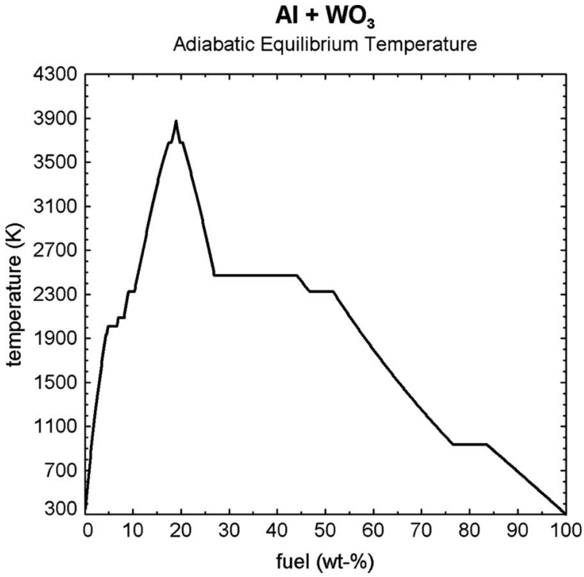

FIGURE 24.11 Adiabatic equilibrium temperature profile, Al (fuel) + WO_3 (oxidizer).

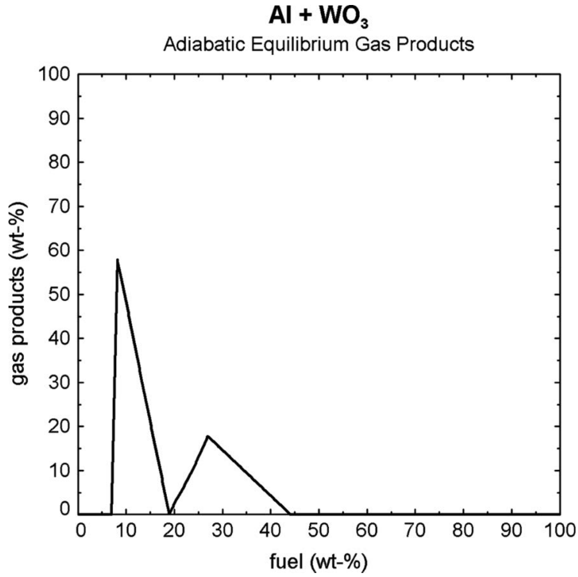

FIGURE 24.12 Adiabatic equilibrium gas production profile, Al (fuel) + WO_3 (oxidizer).

T1. 4.3% fuel, 1920.99 K
solids: 54.70% $W_{18}O_{49}$, 37.17% WO_2, 8.12% Al_2O_3 (corundum)
liquids: none
gases: none
a combination of two reactions:
(2.1% fuel) $10Al + 54WO_3 \rightarrow 5Al_2O_3 + 3W_{18}O_{49}$
(7.2% fuel) $2Al + 3WO_3 \rightarrow Al_2O_3 + 3WO_2$

T2. 18.9% fuel, 3873.71 K—*peak temperature*
solids: none
liquids: 64.30% W, 35.63% Al_2O_3
gases: none
simplified equation at 18.9% fuel: $2Al + WO_3 \rightarrow Al_2O_3 + W$

- T2 corresponds to the maximum amount of W.
- From 4.8% to 6.6% fuel, the temperature appears to be limited by the $3W_{18}O_{49}(s) \rightarrow 5W(s) + 49WO_3(l)$ decomposition, which occurs at 2011 K.
- From 7.0% to 8.1% fuel, the temperature appears to be limited by the vaporization of WO_3 and W_3O_8 from W(s)/WO_3(l) mixtures, which occurs at 2087 K.
- From 9.1% to 10.2% and 46.7% to 51.5% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- From 26.9% to 44.0% fuel, the temperature appears to be limited by the vaporization of Al_2O and Al from Al(l)/Al_2O_3(l) mixtures, which occurs at 2470 K.
- From 17.4% to 17.9% and 19.7% to 20.2% fuel, the temperature is limited to 3680 K by the W(s-l) transition.

G1. 8.1% fuel, 57.78% gas produced, 2087.07 K—*peak gas*
solids: 26.76% W, 15.31% Al_2O_3 (corundum)
liquids: 0.15% WO_3
gases: 29.26% $(WO_3)_3$, 11.90% $(WO_3)_4$, 9.25% W_3O_8, 7.37% $(WO_3)_2$
a combination of two reactions with excess oxidizer remaining:
(2.5% fuel) $2Al + 9WO_3 \rightarrow Al_2O_3 + 3W_3O_8$
(18.9% fuel) $2Al + WO_3 \rightarrow Al_2O_3 + W$

G2. 26.9% fuel, 17.76% gas produced, 2469.66 K
solids: 57.97% W
liquids: 24.24% Al_2O_3
gases: 16.27% Al_2O, 1.46% Al
a combination of two reactions with excess fuel remaining:
(18.9% fuel) $2Al + WO_3 \rightarrow Al_2O_3 + W$
(41.1% fuel) $6Al + WO_3 \rightarrow 3Al_2O + W$

24.10 ALUMINUM + MnO

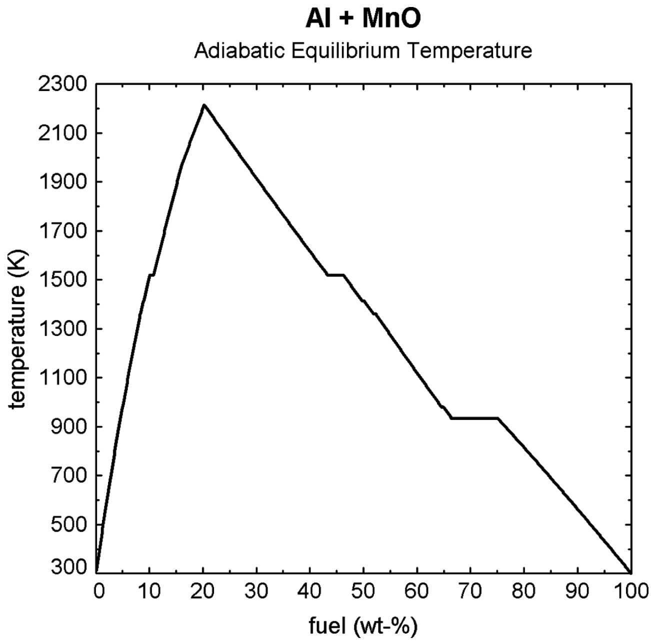

FIGURE 24.13 Adiabatic equilibrium temperature profile, Al (fuel) + MnO (oxidizer).

T1. 16.0% fuel, 1966.89 K
solids: 50.94% $MnAl_2O_4$ (galaxite), 0.19% Al_2O_3 (corundum)
liquids: 48.87% Mn
gases: none
simplified equation at 16.0% fuel: $2Al + 4MnO \rightarrow MnAl_2O_4 + 3Mn$

T2. 20.2% fuel, 2212.56 K—*peak temperature*
solids: 37.97% Al_2O_3 (corundum), 0.34% $MnAl_2O_4$ (galaxite)
liquids: 61.70% Mn
gases: none
simplified equation at 20.2% fuel: $2Al + 3MnO \rightarrow Al_2O_3 + 3Mn$

- The maximum amount of manganese, 61.72% Mn(l), occurs at 20.3% fuel and 2211.89 K.
- From 10.0% to 10.7% and 43.3% to 46.2% fuel, the temperature is limited to 1519 K by the Mn(s-l) transition.

24.11 ALUMINUM + Mn_3O_4

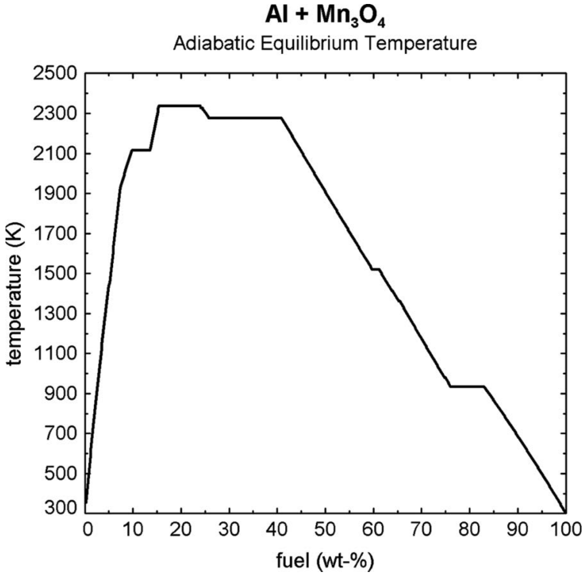

FIGURE 24.14 Adiabatic equilibrium temperature profile, Al (fuel) + Mn_3O_4 (oxidizer).

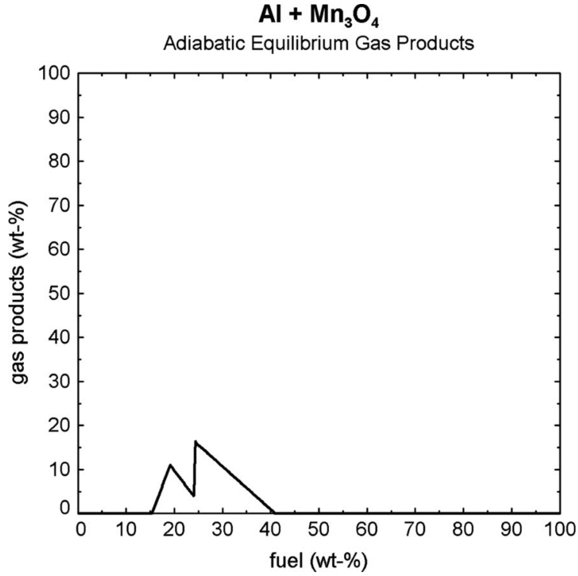

FIGURE 24.15 Adiabatic equilibrium gas production profile, Al (fuel) + Mn_3O_4 (oxidizer).

T1. 7.3% fuel, 1927.71 K
solids: 76.57% MnO, 23.39% $MnAl_2O_4$ (galaxite)
liquids: none
gases: none
simplified equation at 7.3% fuel: $2Al + 3Mn_3O_4 \rightarrow MnAl_2O_4 + 8MnO$

T2. 19.1% fuel, 10.94% gas produced, 2335.90 K—*peak temperature*
solids: 60.95% $MnAl_2O_4$ (galaxite)
liquids: 27.97% Mn, 0.14% Al_2O_3
gases: 10.94% Mn
simplified equation at 19.1% fuel: $2Al + Mn_3O_4 \rightarrow MnAl_2O_4 + 2Mn$

T3. 23.9% fuel, 4.04% gas produced, 2335.90 K—*peak temperature*
solids: 0.29% $MnAl_2O_4$ (galaxite)
liquids: 50.68% Mn, 44.98% Al_2O_3
gases: 4.04% Mn
simplified equation at 23.9% fuel: $8Al + 3Mn_3O_4 \rightarrow 4Al_2O_3 + 9Mn$

- The maximum amount of manganese, 50.78% Mn(l) and 3.97% Mn(g), occurs at 24.0% fuel and 2327.68 K.
- From 59.8% to 61.1% fuel, the temperature is limited to 1519 K by the Mn(s-l) transition.
- From 9.8% to 13.5% fuel, the temperature is limited to 2115 K by the MnO(s-l) transition.
- The plateau from 25.8% to 40.8% fuel (2276 K) could not be attributed to a simple transition or reaction; species in this region include Mn(g), Al_2O(g), Al(g), Mn(l), Al(l), and Al_2O_3(s).
- From 15.4% to 23.9% fuel, the temperature is limited to 2336 K by the Mn(l-g) transition.

G1. 19.1% fuel, 10.94% gas produced, 2335.90 K
see T2 for details

G2. 24.3% fuel, 16.29% gas produced, 2325.66 K—*peak gas*
solids: 44.62% Al_2O_3 (corundum)
liquids: 39.09% Mn
gases: 15.44% Mn, 0.73% Al_2O, 0.12% Al
simplified equation at 23.9% fuel: $8Al + 3Mn_3O_4 \rightarrow 4Al_2O_3 + 9Mn$

24.12 ALUMINUM + Mn_2O_3

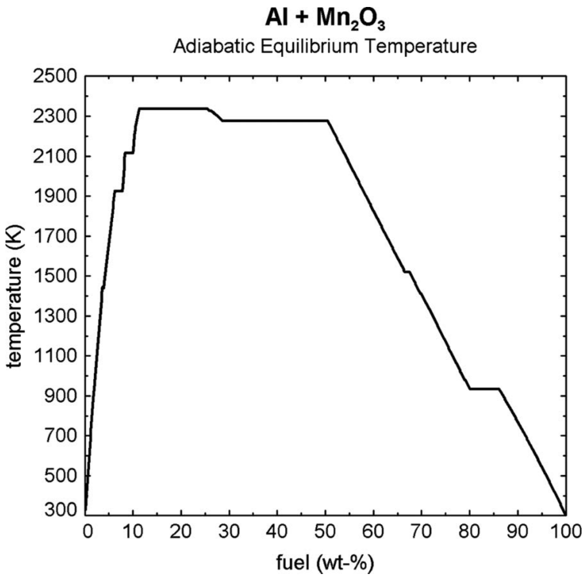

FIGURE 24.16 Adiabatic equilibrium temperature profile, Al (fuel) + Mn_2O_3 (oxidizer).

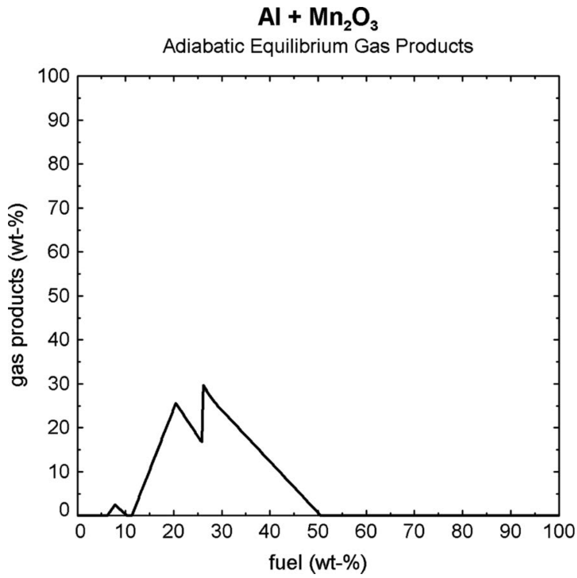

FIGURE 24.17 Adiabatic equilibrium gas production profile, Al (fuel) + Mn_2O_3 (oxidizer).

T1. 4.1% fuel, 1488.91 K
solids: 86.84% Mn_3O_4, 13.14% $MnAl_2O_4$ (galaxite)
liquids: none
gases: none
simplified equation at 4.1% fuel: $2Al + 8Mn_2O_3 \rightarrow MnAl_2O_4 + 5Mn_3O_4$

T2. 10.2% fuel, 2200.29 K
solids: 32.68% $MnAl_2O_4$ (galaxite)
liquids: 67.29% MnO
gases: none
simplified equation at 10.2% fuel: $2Al + 3Mn_2O_3 \rightarrow MnAl_2O_4 + 5MnO$

T3. 20.4% fuel, 25.51% gas produced, 2335.96 K—*peak temperature*
solids: 65.36% $MnAl_2O_4$ (galaxite)
liquids: 9.09% Mn
gases: 25.51% Mn
simplified equation at 20.4% fuel: $6Al + 4Mn_2O_3 \rightarrow 3MnAl_2O_4 + 5Mn$

T4. 25.5% fuel, 17.04% gas produced, 2335.25 K—*peak temperature*
solids: none
liquids: 48.10% Al_2O_3, 34.86% Mn
gases: 16.99% Mn
simplified equation at 25.5% fuel: $2Al + Mn_2O_3 \rightarrow Al_2O_3 + 2Mn$

- T4 corresponds to the maximum amount of Mn.
- From 66.5% to 67.4% fuel, the temperature is limited to 1519 K by the Mn(s-l) transition.

- From 6.2% to 7.7% fuel, the temperature appears to be limited by the $2Mn_3O_4(s) \rightarrow 6MnO(s) + O_2(g)$ decomposition, which occurs at 1925 K.
- From 8.4% to 9.9% fuel, the temperature is limited to 2115 K by the MnO(s-l) transition.
- The plateau from 28.6% to 50.4% fuel (2276 K) could not be attributed to a simple transition or reaction; species in this region include Mn(g), $Al_2O(g)$, Al(g), Mn(l), Al(l), and $Al_2O_3(s)$.
- From 11.3% to 25.4% fuel, the temperature is limited to 2336 K by the Mn(l-g) transition.

G1. 20.4% fuel, 25.51% gas produced, 2335.96 K
see T3 for details

G2. 26.1% fuel, 29.62% gas produced, 2326.37 K—*peak gas*
solids: 47.13% Al_2O_3 (corundum)
liquids: 23.26% Mn
gases: 28.18% Mn, 1.24% Al_2O, 0.20% Al
simplified equation at 25.5% fuel: $2Al + Mn_2O_3 \rightarrow Al_2O_3 + 2Mn$

24.13 ALUMINUM + MnO_2

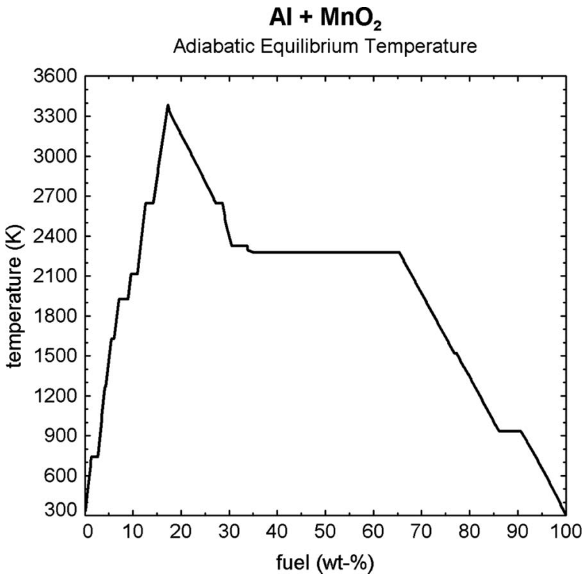

FIGURE 24.18 Adiabatic equilibrium temperature profile, Al (fuel) + MnO_2 (oxidizer).

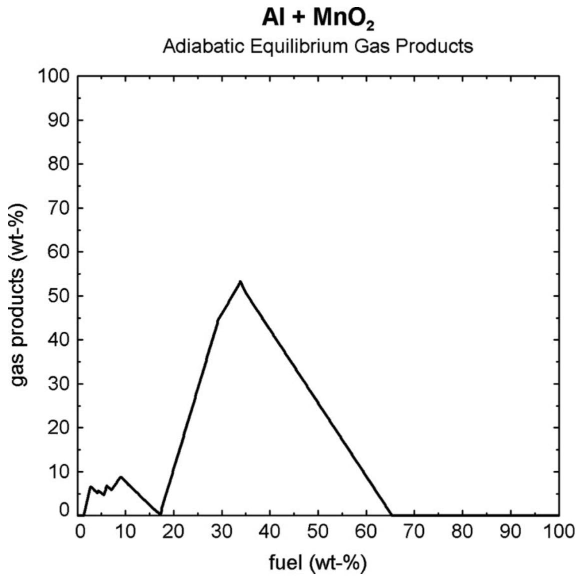

FIGURE 24.19 Adiabatic equilibrium gas production profile, Al (fuel) + MnO_2 (oxidizer).

T1. 5.4% fuel, 4.70% gas produced, 1620.31 K
solids: 78.00% Mn_2O_3 (bixbyite), 17.30% $MnAl_2O_4$ (galaxite)
liquids: none
gases: 4.70% O_2
a combination of two reactions:
(11.0% fuel) $2Al + 5MnO_2 \rightarrow MnAl_2O_4 + 2Mn_2O_3$
(decomposition) $4MnO_2 \rightarrow 2Mn_2O_3 + O_2$

T2. 7.0% fuel, 5.88% gas produced, 1915.37 K
solids: 71.70% Mn_3O_4, 22.43% $MnAl_2O_4$ (galaxite)
liquids: none
gases: 5.87% O_2
a combination of two reactions:
(13.4% fuel) $2Al + 4MnO_2 \rightarrow MnAl_2O_4 + Mn_3O_4$
(decomposition) $3MnO_2 \rightarrow Mn_3O_4 + O_2$

T3. 12.5% fuel, 4.99% gas produced, 2637.95 K
solids: 40.05% $MnAl_2O_4$ (galaxite)
liquids: 54.96% MnO
gases: 4.92% O_2
a combination of two reactions:
(17.1% fuel) $2Al + 3MnO_2 \rightarrow MnAl_2O_4 + 2MnO$
(decomposition) $2MnO_2 \rightarrow 2MnO + O_2$

T4. 17.2% fuel, 0.28% gas produced, 3379.96 K—*peak temperature*
solids: none
liquids: 67.23% MnO, 32.50% Al_2O_3
gases: 0.26% Mn
simplified equation at 17.1% fuel: $2Al + 3MnO_2 \rightarrow Al_2O_3 + 3MnO$

T5. 29.3% fuel, 44.74% gas produced, 2490.38 K
solids: none
liquids: 55.26% Al_2O_3
gases: 44.68% Mn
simplified equation at 29.3% fuel: $4Al + 3MnO_2 \rightarrow 2Al_2O_3 + 3Mn$

- T5 corresponds to the maximum amount of Mn.
- From 7.1% to 8.9% fuel, the temperature appears to be limited by the $2Mn_3O_4(s) \rightarrow 6MnO(s) + O_2(g)$ decomposition, which occurs at 1925 K.
- From 9.6% to 10.9% fuel, the temperature is limited to 2115 K by the MnO(s-l) transition.
- The plateau from 35.1% to 65.2% fuel (2276 K) could not be attributed to a simple transition or reaction; species in this region include Mn(g), $Al_2O(g)$, Al(g), Mn(l), Al(l), and $Al_2O_3(s)$. Alone, Mn(l) is expected to boil at 2336 K.
- From 30.5% to 33.6% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- From 12.6% to 14.1% and 27.2% to 28.5% fuel, the temperature appears to be limited by the $MnAl_2O_4(s) \rightarrow MnO(l) + Al_2O_3(l)$ decomposition, which occurs at 2647 K.

G1. 33.8% fuel, 53.23% gas produced, 2298.64 K—*peak gas*
solids: 46.78% Al_2O_3 (corundum)
liquids: none
gases: 41.83% Mn, 10.26% Al_2O, 1.12% Al
a combination of two reactions with excess fuel remaining:
(29.3% fuel) $4Al + 3MnO_2 \rightarrow 2Al_2O_3 + 3Mn$
(55.4% fuel) $4Al + MnO_2 \rightarrow 2Al_2O + Mn$

24.14 ALUMINUM + FeO

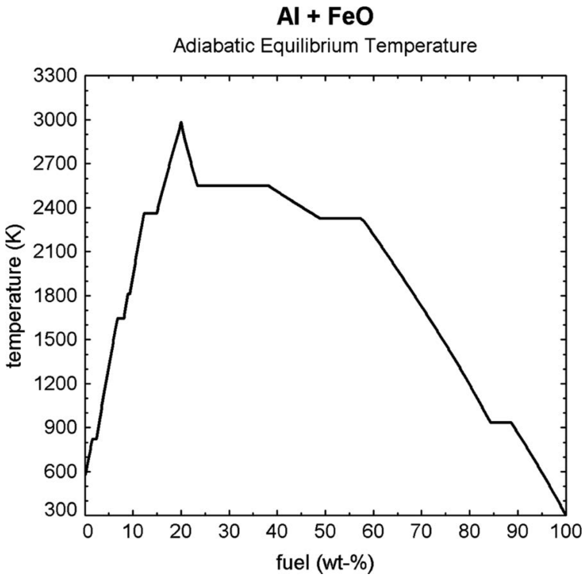

FIGURE 24.20 Adiabatic equilibrium temperature profile, Al (fuel) + FeO (oxidizer).

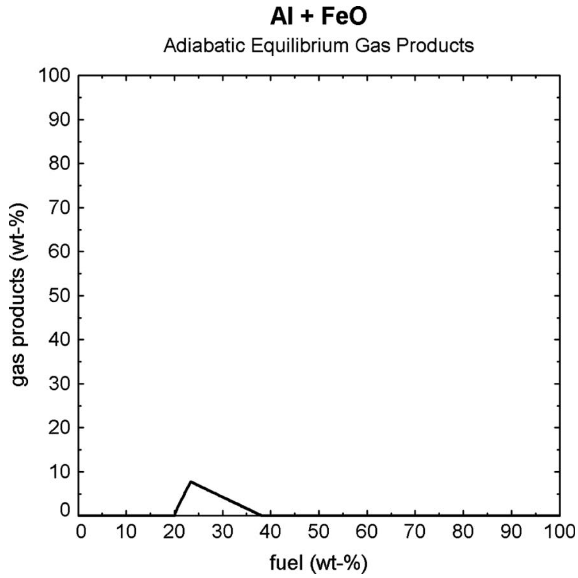

FIGURE 24.21 Adiabatic equilibrium gas production profile, Al (fuel) + FeO (oxidizer).

T1. 12.2% fuel, 2355.59 K
solids: 39.29% $FeAl_2O_4$ (hercynite)
liquids: 37.88% Fe, 22.83% FeO
gases: none
one reaction with excess oxidizer remaining:
(15.8% fuel) $2Al + 4FeO \rightarrow FeAl_2O_4 + 3Fe$

T2. 20.0% fuel, 2981.01 K—*peak temperature*
solids: none
liquids: 62.09% Fe, 37.79% Al_2O_3, 0.12% FeO
gases: none
simplified equation at 20.0% fuel: $2Al + 3FeO \rightarrow Al_2O_3 + 3Fe$

T3. 57.9% fuel, 2310.07 K
solids: 80.03% $FeAl_3$, 19.92% Al_2O_3 (corundum)
liquids: none
gases: none
simplified equation at 57.9% fuel: $11Al + 3FeO \rightarrow Al_2O_3 + 3FeAl_3$

- The maximum amount of iron, 61.97% Fe(l) and 0.14% Fe(g), occurs at 20.1% fuel and 2966.79 K.
- From 6.8% to 8.0% fuel, the temperature is limited to 1644 K by the FeO(s-l) transition.
- From 48.9% to 57.2% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- From 12.3% to 14.8% fuel, the temperature appears to be limited by the $FeAl_2O_4$(s) $\rightarrow$ FeO(l) + Al_2O_3(l) decomposition, which occurs at 2360 K.
- From 23.4% to 38.0% fuel, the temperature appears to be limited to 2551 K by the reaction of $FeAl_3$(s) and Al_2O_3(l) which forms Al_2O(g), Al(g), and Fe(l-g).

G1. 23.4% fuel, 7.65% gas produced, 2550.80 K—*peak gas*
solids: 0.20% $FeAl_3$
liquids: 59.15% Fe, 33.00% Al_2O_3
gases: 6.65% Al_2O, 0.67% Al, 0.31% Fe
a combination of two reactions:
(20.0% fuel) $2Al + 3FeO \rightarrow Al_2O_3 + 3Fe$
(42.9% fuel) $2Al + FeO \rightarrow Al_2O + Fe$

24.15 ALUMINUM + Fe_3O_4

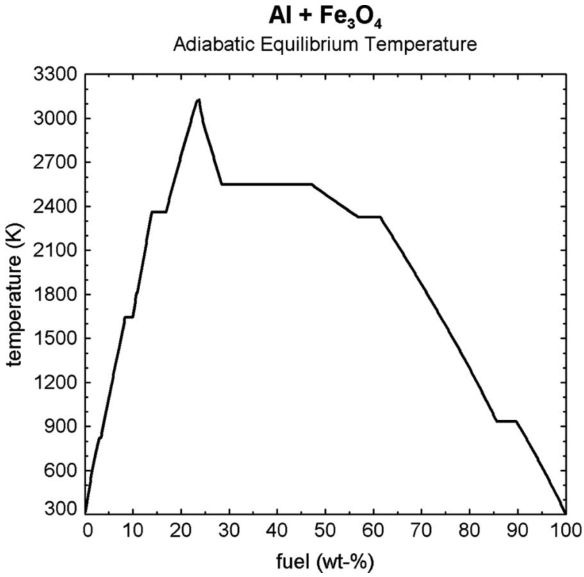

FIGURE 24.22 Adiabatic equilibrium temperature profile, Al (fuel) + Fe_3O_4 (oxidizer).

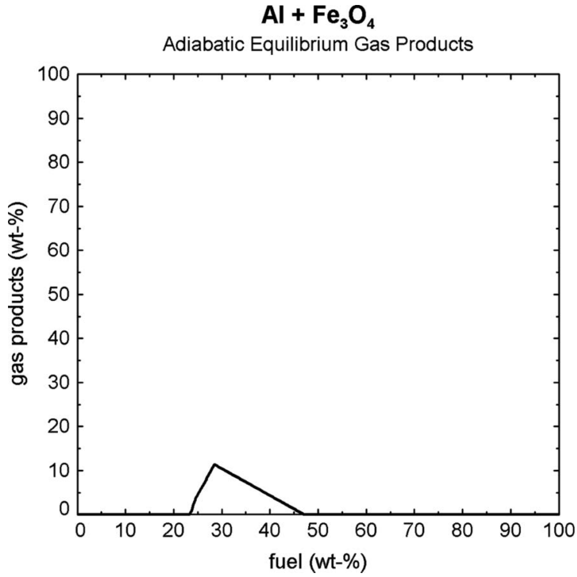

FIGURE 24.23 Adiabatic equilibrium gas production profile, Al (fuel) + Fe_3O_4 (oxidizer).

T1. 7.2% fuel, 1453.88 K
solids: 76.69% FeO (wüstite), 23.19% $FeAl_2O_4$ (hercynite), 0.12% Fe_3O_4 (magnetite)
liquids: none
gases: none
simplified equation at 7.2% fuel: $2Al + 3Fe_3O_4 \rightarrow FeAl_2O_4 + 8FeO$

T2. 13.8% fuel, 2348.11 K
solids: 44.45% $FeAl_2O_4$ (hercynite)
liquids: 33.50% FeO, 22.05% Fe
gases: none
a combination of two reactions:
(7.2% fuel) $2Al + 3Fe_3O_4 \rightarrow FeAl_2O_4 + 8FeO$
(18.9% fuel) $2Al + Fe_3O_4 \rightarrow FeAl_2O_4 + 2Fe$

T3. 16.8% fuel, 2359.74 K
solids: none
liquids: 36.17% FeO, 32.09% Fe, 31.74% Al_2O_3
gases: none
a combination of two reactions:
(7.2% fuel) $2Al + 3Fe_3O_4 \rightarrow Al_2O_3 + 9FeO$
(23.7% fuel) $8Al + 3Fe_3O_4 \rightarrow 4Al_2O_3 + 9Fe$

T4. 23.7% fuel, 0.86% gas produced, 3124.47 K—*peak temperature*
solids: none
liquids: 54.36% Fe, 44.78% Al_2O_3
gases: 0.82% Fe
simplified equation at 23.7% fuel: $8Al + 3Fe_3O_4 \rightarrow 4Al_2O_3 + 9Fe$

T5. 57.6% fuel, 2327.02 K
solids: 75.07% $FeAl_3$, 2.52% Al_2O_3 (corundum)
liquids: 22.37% Al_2O_3
gases: none
simplified equation at 57.6% fuel: $35Al + 3Fe_3O_4 \rightarrow 4Al_2O_3 + 9FeAl_3$

- T4 corresponds to the maximum amount of Fe.
- From 8.4% to 9.8% fuel, the temperature is limited to 1644 K by the FeO(s-l) transition.
- From 56.8% to 61.3% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- From 13.9% to 16.7% fuel, the temperature appears to be limited by the $FeAl_2O_4(s) \rightarrow FeO(l) + Al_2O_3(l)$ decomposition, which occurs at 2360 K.
- From 28.4% to 46.9% fuel, the temperature appears to be limited to 2551 K by the reaction of $FeAl_3$(s) and Al_2O_3(l) which forms Al_2O(g), Al(g), and Fe(l-g).

G1. 28.4% fuel, 11.34% gas produced, 2550.80 K—*peak gas*
solids: 0.11% $FeAl_3$
liquids: 51.31% Fe, 37.24% Al_2O_3
gases: 9.87% Al_2O, 1.00% Al, 0.46% Fe
a combination of two reactions with excess fuel remaining:
(23.7% fuel) $8Al + 3Fe_3O_4 \rightarrow 4Al_2O_3 + 9Fe$
(48.2% fuel) $8Al + Fe_3O_4 \rightarrow 4Al_2O + 3Fe$

24.16 ALUMINUM + Fe_2O_3

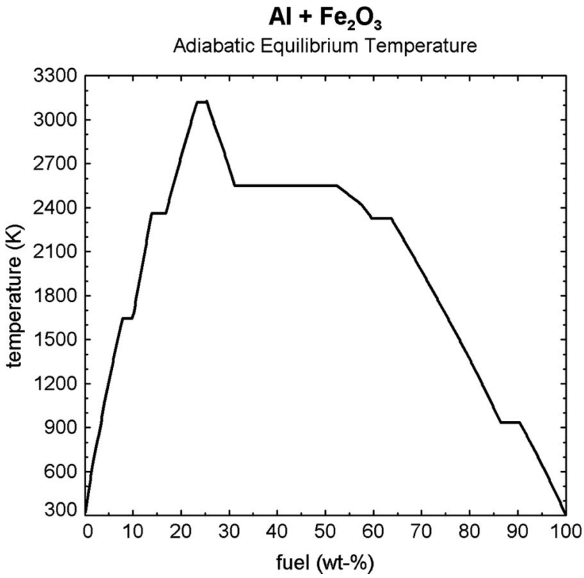

FIGURE 24.24 Adiabatic equilibrium temperature profile, Al (fuel) + Fe_2O_3 (oxidizer).

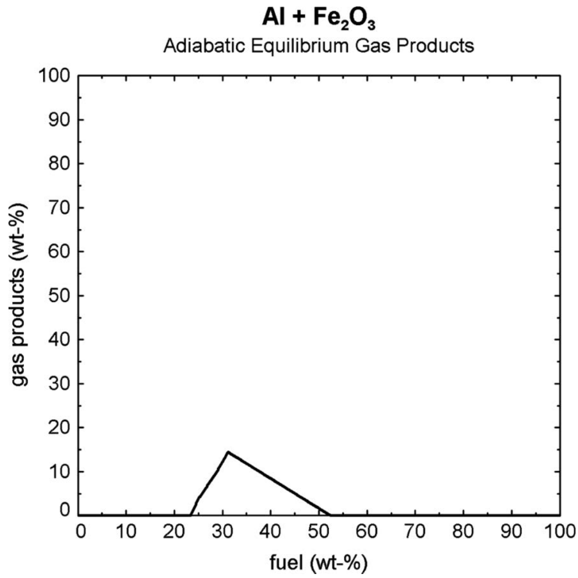

FIGURE 24.25 Adiabatic equilibrium gas production profile, Al (fuel) + Fe_2O_3 (oxidizer).

T1. 10.1% fuel, 1679.89 K
solids: 32.53% $FeAl_2O_4$ (hercynite), 0.34% Fe_3O_4 (magnetite)
liquids: 67.13% FeO
gases: none
simplified equation at 10.1% fuel: $2Al + 3Fe_2O_3 \rightarrow FeAl_2O_4 + 5FeO$

T2. 13.8% fuel, 2353.85 K
solids: 44.45% $FeAl_2O_4$ (hercynite)
liquids: 42.85% FeO, 12.70% Fe
gases: none
a combination of two reactions:
(10.1% fuel) $2Al + 3Fe_2O_3 \rightarrow FeAl_2O_4 + 5FeO$
(20.2% fuel) $6Al + 4Fe_2O_3 \rightarrow 3FeAl_2O_4 + 5Fe$

T3. 16.8% fuel, 2364.24 K
solids: none
liquids: 45.20% FeO, 31.74% Al_2O_3, 23.06% Fe
gases: none
a combination of two reactions:
(10.1% fuel) $2Al + 3Fe_2O_3 \rightarrow Al_2O_3 + 6FeO$
(25.3% fuel) $2Al + Fe_2O_3 \rightarrow Al_2O_3 + 2Fe$

T4. 25.3% fuel, 4.23% gas produced, 3126.19 K—*peak temperature*
solids: none
liquids: 48.13% Fe, 47.64% Al_2O_3
gases: 4.10% Fe
simplified equation at 25.3% fuel: $2Al + Fe_2O_3 \rightarrow Al_2O_3 + 2Fe$

T5. 57.5% fuel, 2419.30 K
solids: 72.81% $FeAl_3$
liquids: 27.14% Al_2O_3
gases: none
simplified equation at 57.5% fuel: $8Al + Fe_2O_3 \rightarrow Al_2O_3 + 2FeAl_3$

- T4 corresponds to the maximum amount of Fe.
- From 7.8% to 9.7% fuel, the temperature is limited to 1644 K by the FeO(s-l) transition.
- From 59.6% to 63.6% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- From 13.9% to 16.7% fuel, the temperature appears to be limited by the $FeAl_2O_4(s) \rightarrow FeO(l) + Al_2O_3(l)$ decomposition, which occurs at 2360 K.
- From 31.1% to 52.3% fuel, the temperature appears to be limited to 2551 K by the reaction of $FeAl_3$(s) and Al_2O_3(l) which forms Al_2O(g), Al(g), and Fe(l-g).
- From 23.3% to 25.1% fuel, the temperature appears to be limited by the vaporization of Fe and FeO from Fe(l)/FeO(l) mixtures, which occurs at 3120 K.

G1. 31.1% fuel, 14.40% gas produced, 2550.80 K—*peak gas*
solids: 0.15% $FeAl_3$
liquids: 47.55% Fe, 37.90% Al_2O_3
gases: 12.53% Al_2O, 1.27% Al, 0.58% Fe
a combination of two reactions with excess fuel remaining:
(25.3% fuel) $2Al + Fe_2O_3 \rightarrow Al_2O_3 + 2Fe$
(50.3% fuel) $6Al + Fe_2O_3 \rightarrow 3Al_2O + 2Fe$

24.17 ALUMINUM + CoO

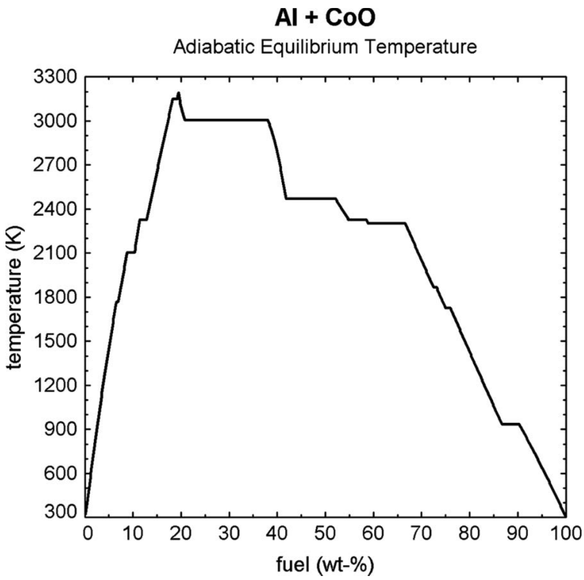

FIGURE 24.26 Adiabatic equilibrium temperature profile, Al (fuel) + CoO (oxidizer).

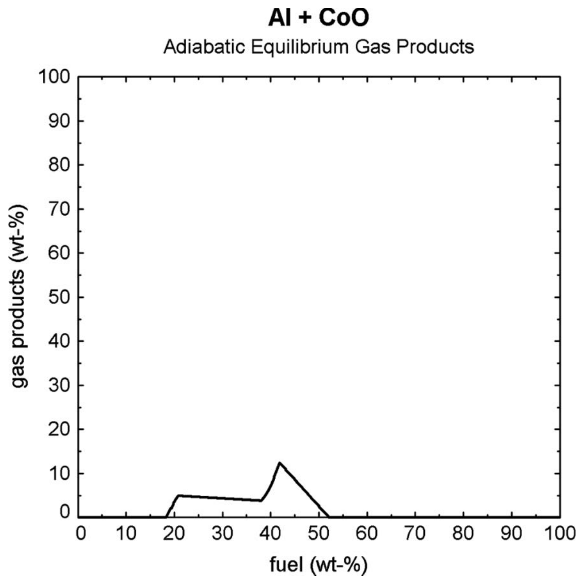

FIGURE 24.27 Adiabatic equilibrium gas production profile, Al (fuel) + CoO (oxidizer).

T1. 19.4% fuel, 2.15% gas produced, 3189.12 K—*peak temperature*
solids: none
liquids: 61.33% Co, 36.52% Al_2O_3
gases: 2.06% Co
simplified equation at 19.4% fuel: $2Al + 3CoO \rightarrow Al_2O_3 + 3Co$

T2. 37.5% fuel, 3.83% gas produced, 3004.73 K
solids: none
liquids: 67.38% CoAl, 27.43% Al_2O_3, 1.36% Co
gases: 1.86% Al_2O, 1.57% Co, 0.37% Al
simplified equation at 37.5% fuel: $5Al + 3CoO \rightarrow Al_2O_3 + 3CoAl$

T3. 66.6% fuel, 2300.19 K
solids: 56.34% Co_2Al_5, 15.15% Al_2O_3 (corundum)
liquids: 28.52% Al
gases: none
one reaction with excess fuel remaining:
(53.3% fuel) $19Al + 6CoO \rightarrow 2Al_2O_3 + 3Co_2Al_5$

T4. 73.1% fuel, 1862.98 K
solids: 50.22% $CoAl_3$, 12.20% Al_2O_3 (corundum)
liquids: 37.58% Al
gases: none
one reaction with excess fuel remaining:
(56.9% fuel) $11Al + 3CoO \rightarrow Al_2O_3 + 3CoAl_3$

T5. 76.0% fuel, 1721.95 K
solids: 57.76% Co_2Al_9, 10.89% Al_2O_3 (corundum)
liquids: 31.35% Al
gases: none
one reaction with excess fuel remaining:
(65.0% fuel) $31Al + 6CoO \rightarrow 2Al_2O_3 + 3Co_2Al_9$

- The maximum amount of cobalt, 61.66% Co(l) and 1.89% Co(g), occurs at 19.2% fuel and 3158.75 K.
- From 74.9% to 75.9% fuel, the temperature appears to be limited by the $Co_2Al_9(s) \rightarrow 2CoAl_3(s) + 3Al(l)$ decomposition, which occurs at 1728 K.
- From 72.5% to 73.0% fuel, the temperature appears to be limited by the $2CoAl_3(s) \rightarrow Co_2Al_5(s) + Al(l)$ decomposition, which occurs at 1865 K.
- From 8.8% to 10.2% fuel, the temperature is limited to 2103 K by the CoO(s-l) transition.
- From 58.9% to 66.5% fuel, the temperature appears to be limited by the $Co_2Al_5(s) \rightarrow 2CoAl(l) + 3Al(l)$ decomposition, which occurs at 2302 K.
- From 11.4% to 12.8% and 54.8% to 58.4% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- From 41.8% to 52.0% fuel, the temperature appears to be limited by the vaporization of Al_2O and Al from Al(l)/Al_2O_3(l) mixtures, which occurs at 2470 K.
- From 20.8% to 37.8% fuel, the temperature appears to be limited to 3005 K by the reaction of CoAl(l) and Al_2O_3(l) which forms Co(l-g), Al_2O(g), and Al(g).
- From 18.3% to 19.1% fuel, the temperature appears to be limited by the formation of Co(g) and O_2(g) from Co(l)/CoO(l) mixtures, which occurs at 3150 K.

G1. 41.8% fuel, 12.37% gas produced, 2469.57 K—*peak gas*
solids: none
liquids: 66.72% CoAl, 20.89% Al_2O_3
gases: 11.33% Al_2O, 1.01% Al
a combination of two reactions with excess fuel remaining:
(37.5% fuel) $5Al + 3CoO \rightarrow Al_2O_3 + 3CoAl$
(51.9% fuel) $3Al + CoO \rightarrow Al_2O + CoAl$

24.18 ALUMINUM + Co_3O_4

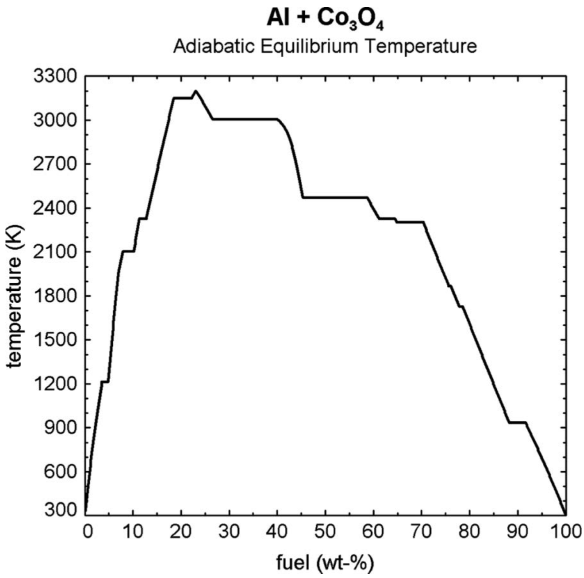

FIGURE 24.28 Adiabatic equilibrium temperature profile, Al (fuel) + Co_3O_4 (oxidizer).

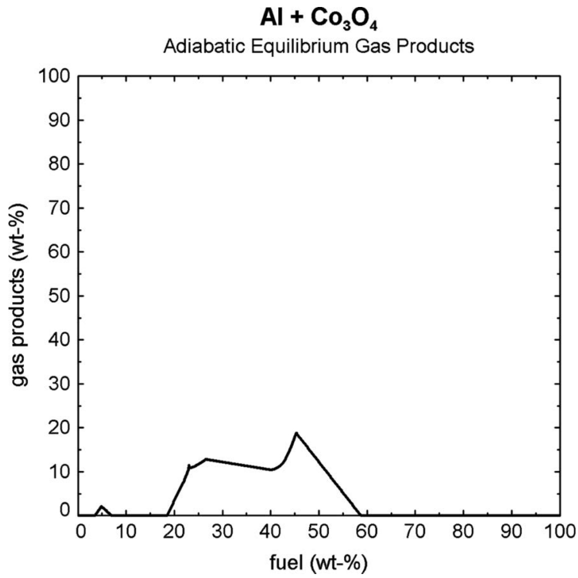

FIGURE 24.29 Adiabatic equilibrium gas production profile, Al (fuel) + Co_3O_4 (oxidizer).

T1. 7.0% fuel, 1969.26 K
solids: 86.60% CoO, 13.23% Al_2O_3 (corundum)
liquids: 0.17% Co
gases: none
simplified equation at 7.0% fuel: $2Al + 3Co_3O_4 \rightarrow Al_2O_3 + 9CoO$

T2. 23.0% fuel, 11.42% gas produced, 3198.33 K—*peak temperature*
solids: none
liquids: 45.18% Co, 43.40% Al_2O_3
gases: 11.36% Co
simplified equation at 23.0% fuel: $8Al + 3Co_3O_4 \rightarrow 4Al_2O_3 + 9Co$

T3. 38.8% fuel, 10.61% gas produced, 3004.73 K
solids: none
liquids: 53.54% CoAl, 32.00% Al_2O_3, 3.85% Co
gases: 5.15% Al_2O, 4.36% Co, 1.03% Al
a combination of reactions with excess fuel remaining:
(23.0% fuel) $8Al + 3Co_3O_4 \rightarrow 4Al_2O_3 + 9Co$
(38.8% fuel) $17Al + 3Co_3O_4 \rightarrow 4Al_2O_3 + 9CoAl$
(55.2% fuel) $11Al + Co_3O_4 \rightarrow 4Al_2O + 3CoAl$

T4. 70.3% fuel, 2301.45 K
solids: 46.77% Co_2Al_5, 16.77% Al_2O_3 (corundum)
liquids: 36.47% Al
gases: none
one reaction with excess fuel remaining:
(53.3% fuel) $61Al + 6Co_3O_4 \rightarrow 8Al_2O_3 + 9Co_2Al_5$

T5. 76.1% fuel, 1863.60 K
solids: 41.65% $CoAl_3$, 13.49% Al_2O_3 (corundum)
liquids: 44.86% Al
gases: none
one reaction with excess fuel remaining:
(56.7% fuel) $35Al + 3Co_3O_4 \rightarrow 4Al_2O_3 + 9CoAl_3$

T6. 78.5% fuel, 1727.57 K
solids: 48.30% Co_2Al_9, 12.14% Al_2O_3 (corundum)
liquids: 39.56% Al
gases: none
one reaction with excess fuel remaining:
(64.4% fuel) $97Al + 6Co_3O_4 \rightarrow 8Al_2O_3 + 9Co_2Al_9$

- The maximum amount of cobalt, 49.13% Co(l) and 7.92% Co(g), occurs at 22.3% fuel and 3154.78 K.
- From 3.6% to 4.7% fuel, the temperature appears to be limited by the $2Co_3O_4(s) \rightarrow 6CoO(s) + O_2(g)$ decomposition, which occurs at 1213 K.
- From 77.8% to 78.5% fuel, the temperature appears to be limited by the $Co_2Al_9(s) \rightarrow 2CoAl_3(s) + 3Al(l)$ decomposition, which occurs at 1728 K.
- From 7.9% to 10.1% fuel, the temperature is limited to 2103 K by the CoO(s-l) transition.
- From 64.8% to 70.2% fuel, the temperature appears to be limited by the $Co_2Al_5(s) \rightarrow 2CoAl(l) + 3Al(l)$ decomposition, which occurs at 2302 K.
- From 11.3% to 12.7% and 61.1% to 64.4% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- From 45.3% to 58.6% fuel, the temperature appears to be limited by the vaporization of Al_2O and Al from Al(l)/Al_2O_3(l) mixtures, which occurs at 2470 K.
- From 26.5% to 39.8% fuel, the temperature appears to be limited to 3005 K by the reaction of CoAl(l) and Al_2O_3(l) which forms Co(l-g), Al_2O(g), and Al(g).
- From 18.5% to 22.2% fuel, the temperature appears to be limited by the formation of Co(g) and O_2(g) from Co(l)/CoO(l) mixtures, which occurs at 3150 K.

G1. 45.2% fuel, 18.77% gas produced, 2472.21 K—*peak gas*
solids: none
liquids: 58.64% CoAl, 22.59% Al_2O_3
gases: 17.19% Al_2O, 1.54% Al
a combination of two reactions with excess fuel remaining:
(38.8% fuel) $17Al + 3Co_3O_4 \rightarrow 4Al_2O_3 + 9CoAl$
(55.2% fuel) $11Al + Co_3O_4 \rightarrow 4Al_2O + 3CoAl$

24.19 ALUMINUM + NiO

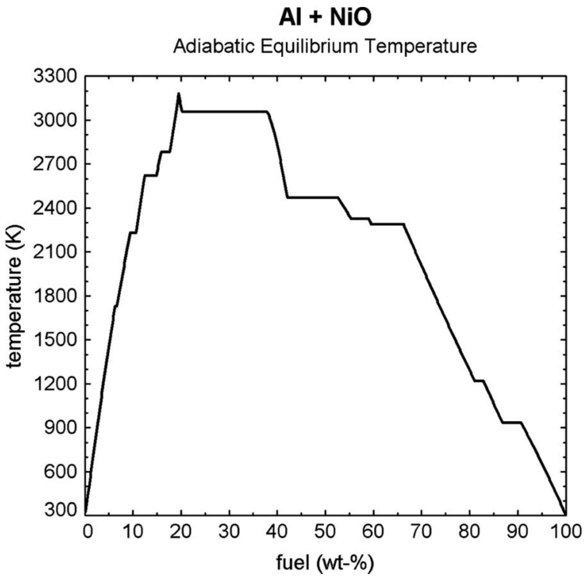

FIGURE 24.30 Adiabatic equilibrium temperature profile, Al (fuel) + NiO (oxidizer).

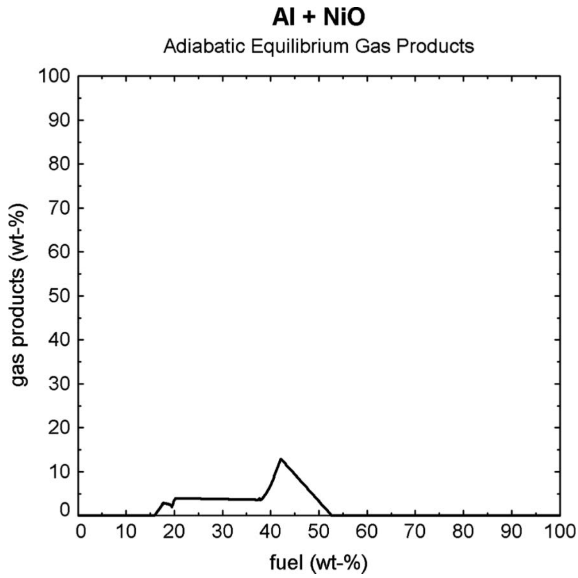

FIGURE 24.31 Adiabatic equilibrium gas production profile, Al (fuel) + NiO (oxidizer).

T1. 19.4% fuel, 1.97% gas produced, 3181.54 K—*peak temperature*
solids: none
liquids: 61.39% Ni, 36.65% Al_2O_3
gases: 1.93% Ni
simplified equation at 19.4% fuel: $2Al + 3NiO \rightarrow Al_2O_3 + 3Ni$

T2. 37.6% fuel, 3.93% gas produced, 3055.87 K
solids: none
liquids: 68.37% NiAl, 27.70% Al_2O_3
gases: 2.19% Ni, 1.39% Al_2O, 0.32% Al
simplified equation at 37.6% fuel: $5Al + 3NiO \rightarrow Al_2O_3 + 3NiAl$

T3. 66.3% fuel, 2281.12 K
solids: 44.74% Ni_2Al_3, 15.33% Al_2O_3 (corundum)
liquids: 39.92% Al
gases: none
one reaction with excess fuel remaining:
(43.9% fuel) $13Al + 6NiO \rightarrow 2Al_2O_3 + 3Ni_2Al_3$

T4. 82.9% fuel, 1213.79 K
solids: 31.97% $NiAl_3$, 7.78% Al_2O_3 (corundum)
liquids: 60.25% Al
gases: none
one reaction with excess fuel remaining:
(57.0% fuel) $11Al + 3NiO \rightarrow Al_2O_3 + 3NiAl_3$

- The maximum amount of nickel, 63.69% Ni(l) and 0.58% Ni(g), occurs at 17.7% fuel and 2789.24 K.
- From 81.0% to 82.8% fuel, the temperature appears to be limited by the $2NiAl_3(s) \rightarrow Ni_2Al_3(s) + 3Al(l)$ decomposition, which occurs at 1219 K.
- From 9.4% to 10.6% fuel, the temperature is limited to 2230 K by the NiO(s-l) transition.
- From 59.6% to 66.2% fuel, the temperature appears to be limited by the $Ni_2Al_3(s) \rightarrow 2NiAl(l) + Al(l)$ decomposition, which occurs at 2287 K.
- From 55.3% to 58.8% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- From 42.1% to 52.5% fuel, the temperature appears to be limited by the vaporization of Al_2O and Al from Al(l)/Al_2O_3(l) mixtures, which occurs at 2470 K.
- From 12.4% to 14.8% fuel, the temperature appears to be limited by the $(NiO)(Al_2O_3)(s) \rightarrow NiO(l) + Al_2O_3(l)$ decomposition, which occurs at 2621 K.
- From 15.9% to 17.6% fuel, the temperature appears to be limited by the $2NiO(l) \rightarrow 2Ni(l\text{-}g) + O_2(g)$ decomposition, which occurs at 2783 K. Some of the NiO is vaporized as well.
- From 20.3% to 37.5% fuel, the temperature appears to be limited to 3056 K by the reaction of NiAl(l) and Al_2O_3(l) which forms Ni(l-g), Al_2O(g), and Al(g).

G1. 42.1% fuel, 12.83% gas produced, 2469.60 K—*peak gas*
solids: none
liquids: 66.41% NiAl, 20.64% Al_2O_3, 0.13% Al
gases: 11.75% Al_2O, 1.05% Al
a combination of two reactions with excess fuel remaining:
(37.6% fuel) $5Al + 3NiO \rightarrow Al_2O_3 + 3NiAl$
(52.0% fuel) $3Al + NiO \rightarrow Al_2O + NiAl$

24.20 ALUMINUM + Cu_2O

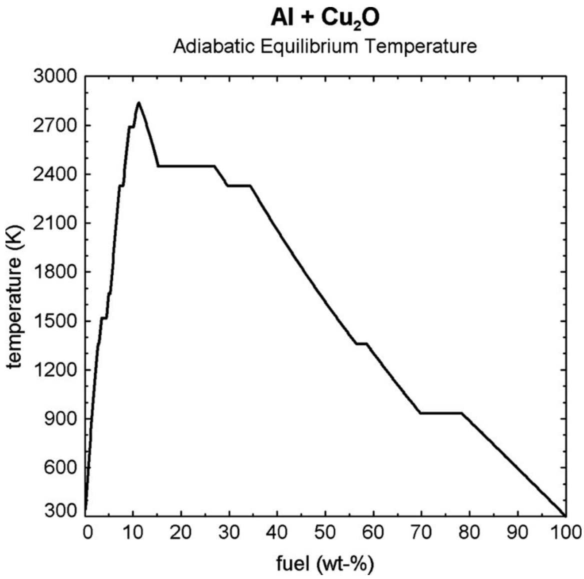

FIGURE 24.32 Adiabatic equilibrium temperature profile, Al (fuel) + Cu_2O (oxidizer).

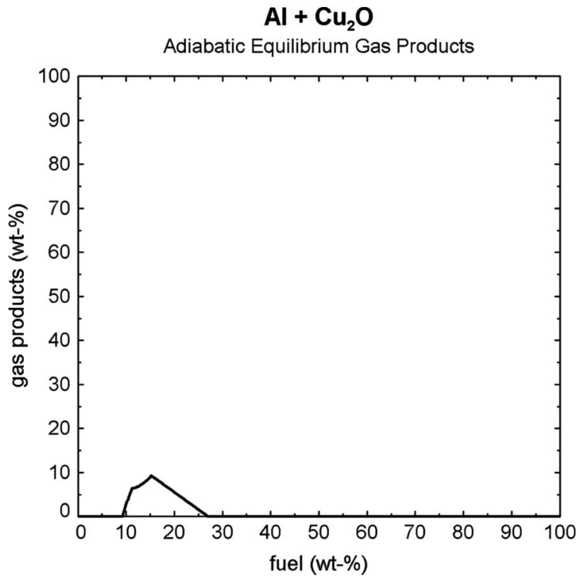

FIGURE 24.33 Adiabatic equilibrium gas production profile, Al (fuel) + Cu_2O (oxidizer).

T1. 11.2% fuel, 6.38% gas produced, 2837.23 K—*peak temperature*
solids: none
liquids: 72.55% Cu, 21.07% Al_2O_3
gases: 5.99% Cu, 0.33% Cu_2
simplified equation at 11.2% fuel: $2Al + 3Cu_2O \rightarrow Al_2O_3 + 6Cu$

- The maximum amount of copper, 77.47% Cu(l), 2.19% Cu(g), and 0.10% Cu_2(g), occurs at 10.1% fuel and 2695.50 K.
- From 56.4% to 58.5% fuel, the temperature is limited to 1358 K by the Cu(s-l) transition.
- From 3.4% to 4.4% fuel, the temperature is limited to 1517 K by the Cu_2O(s-l) transition.
- From 7.2% to 7.8% and 29.7% to 34.3% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- The plateau from 15.2% to 26.9% fuel (2448 K) could not be attributed to a simple transition or reaction; species in this region include Al_2O(g), Cu(g), Al(g), Cu(l), Al_2O_3(l), and Al(l). The vaporization of Al_2O and Al from Al(l)/Al_2O_3(l) mixtures is expected to occur at 2470 K.
- From 9.2% to 10.0% fuel, the temperature appears to be limited by the $2Cu_2O(l) \rightarrow 4Cu(l\text{-}g) + O_2(g)$ decomposition, which occurs at 2688 K.

G1. 15.2% fuel, 9.23% gas produced, 2447.53 K—*peak gas*
solids: none
liquids: 74.11% Cu, 16.57% Al_2O_3
gases: 7.35% Al_2O, 1.18% Cu, 0.66% Al
a combination of two reactions:
(11.2% fuel) $2Al + 3Cu_2O \rightarrow Al_2O_3 + 6Cu$
(27.4% fuel) $2Al + Cu_2O \rightarrow Al_2O + 2Cu$

24.21 ALUMINUM + CuO

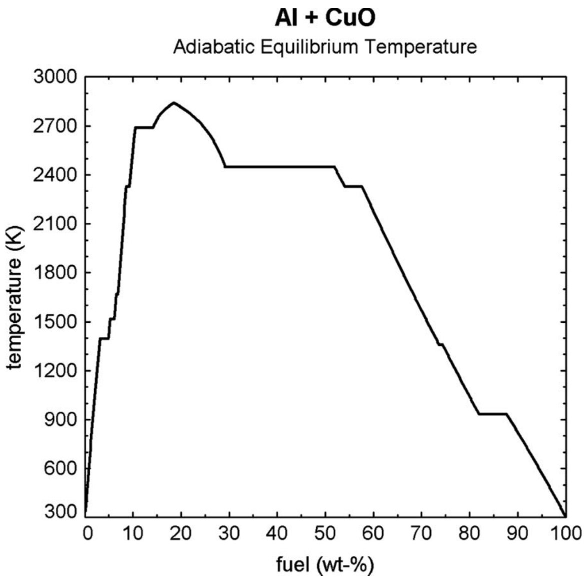

FIGURE 24.34 Adiabatic equilibrium temperature profile, Al (fuel) + CuO (oxidizer).

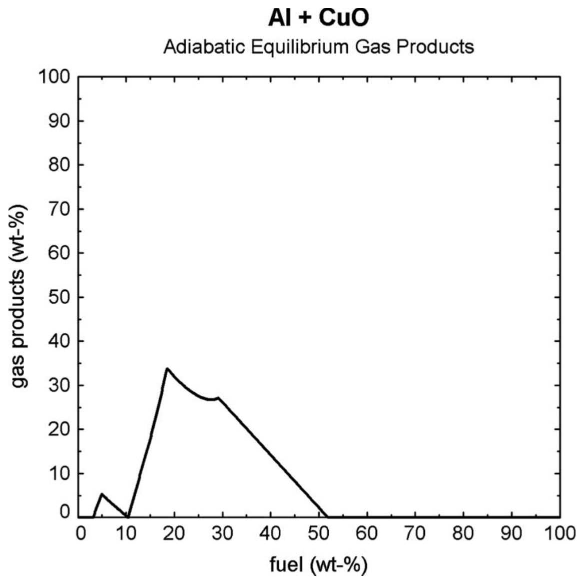

FIGURE 24.35 Adiabatic equilibrium gas production profile, Al (fuel) + CuO (oxidizer).

T1. 6.4% fuel, 3.72% gas produced, 1626.70 K
solids: 29.06% $Cu_2Al_2O_4$
liquids: 67.22% Cu_2O
gases: 3.72% O_2
a combination of two reactions:
(10.2% fuel) $2Al + 6CuO \rightarrow Cu_2Al_2O_4 + 2Cu_2O$
(decomposition) $4CuO \rightarrow 2Cu_2O + O_2$

T2. 10.2% fuel, 2640.41 K
solids: none
liquids: 80.40% Cu_2O, 19.27% Al_2O_3, 0.33% Cu
gases: none
simplified equation at 10.2% fuel: $2Al + 6CuO \rightarrow Al_2O_3 + 3Cu_2O$

T3. 14.1% fuel, 14.57% gas produced, 2688.56 K
solids: none
liquids: 58.79% Cu, 26.64% Al_2O_3
gases: 9.04% Cu, 4.52% O_2, 0.50% CuO, 0.39% Cu_2, 0.11% O
a combination of two reactions:
(18.4% fuel) $2Al + 3CuO \rightarrow Al_2O_3 + 3Cu$
(decomposition) $2CuO \rightarrow 2Cu + O_2$

T4. 18.4% fuel, 33.57% gas produced, 2838.99 K—*peak temperature*
solids: none
liquids: 34.76% Al_2O_3, 31.66% Cu
gases: 31.71% Cu, 1.76% Cu_2
simplified equation at 18.4% fuel: $2Al + 3CuO \rightarrow Al_2O_3 + 3Cu$

- T3 corresponds to the maximum amount of Cu.
- From 73.6% to 74.3% fuel, the temperature is limited to 1358 K by the Cu(s-l) transition.
- From 3.1% to 4.8% fuel, the temperature appears to be limited by the $4CuO(s) \rightarrow 2Cu_2O(s) + O_2(g)$ decomposition, which occurs at 1397 K.
- From 5.2% to 6.1% fuel, the temperature is limited to 1517 K by the Cu_2O(s-l) transition.
- From 8.6% to 9.1% and 54.0% to 57.5% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- The plateau from 29.2% to 51.8% fuel (2448 K) could not be attributed to a simple transition or reaction; species in this region include Al_2O(g), Cu(g), Al(g), Cu(l), Al_2O_3(l), and Al(l). The vaporization of Al_2O and Al from Al(l)/Al_2O_3(l) mixtures is expected to occur at 2470 K.
- From 10.5% to 14.0% fuel, the temperature appears to be limited by the $2Cu_2O(l) \rightarrow 4Cu(l\text{-}g) + O_2(g)$ decomposition, which occurs at 2688 K.

G1. 18.5% fuel, 33.71% gas produced, 2838.96 K—*peak gas*
solids: none
liquids: 34.78% Al_2O_3, 31.51% Cu
gases: 31.84% Cu, 1.76% Cu_2
simplified equation at 18.4% fuel: $2Al + 3CuO \rightarrow Al_2O_3 + 3Cu$

G2. 29.1% fuel, 27.11% gas produced, 2447.93 K
solids: none
liquids: 53.08% Cu, 19.81% Al_2O_3
gases: 21.57% Al_2O, 3.46% Cu, 1.94% Al
a combination of two reactions with excess fuel remaining:
(18.4% fuel) $2Al + 3CuO \rightarrow Al_2O_3 + 3Cu$
(40.4% fuel) $2Al + CuO \rightarrow Al_2O + Cu$

24.22 ALUMINUM + Ag_2O

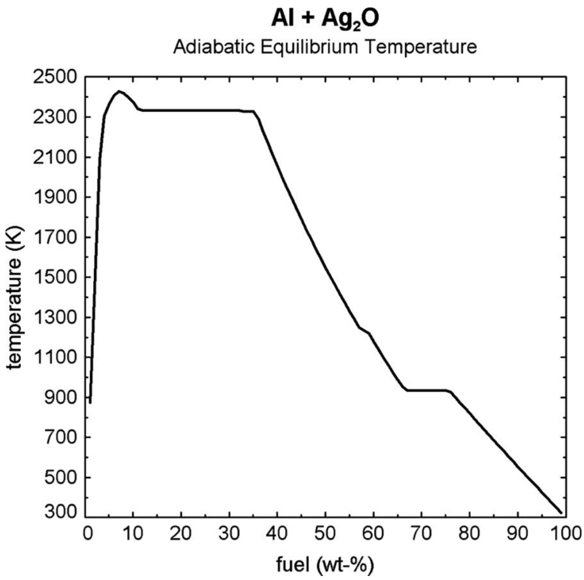

FIGURE 24.36 Adiabatic equilibrium temperature profile, Al (fuel) + Ag_2O (oxidizer).

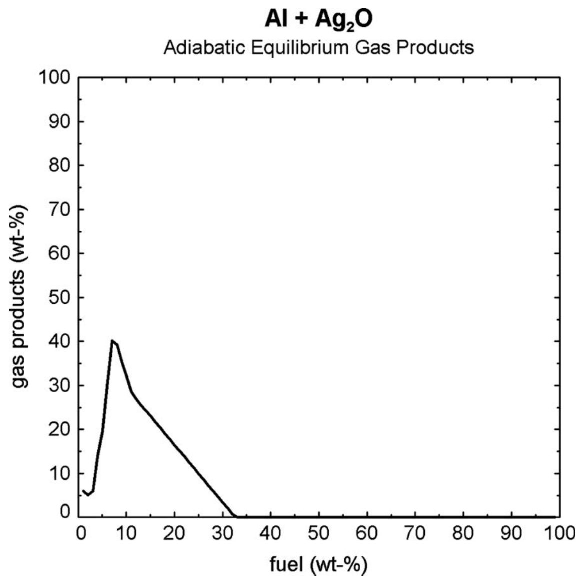

FIGURE 24.37 Adiabatic equilibrium gas production profile, Al (fuel) + Ag_2O (oxidizer).

T1. 7% fuel, 40.13% gas produced, 2427.04 K—*peak temperature*
solids: none
liquids: 46.64% Ag, 13.23% Al_2O_3
gases: 37.77% Ag, 2.17% Ag_2, 0.19% O_2
simplified equation at 7.2% fuel: $2Al + 3Ag_2O \rightarrow Al_2O_3 + 6Ag$

- $Ag_2O(s)$ is unstable above 468 K. The maximum amount of silver, 92.17% Ag(s), occurs at just 1% fuel and 873.20 K.
- From 33% to 35% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- The plateau from 12% to 32% fuel (2332 K) could not be attributed to a simple transition or reaction; species in this region include Ag(g), Al_2O(g), Ag_2(g), Al(g), Ag(l), Al_2O_3(l), and Al(l). Alone, Ag(l) is expected to vaporize at 2430 K. The vaporization of Al_2O and Al from Al(l)/Al_2O_3(l) mixtures is expected to occur at 2470 K.

G1. 7% fuel, 40.13% gas produced, 2427.04 K—*peak gas*
see T1 for details

24.23 ALUMINUM + ZnO

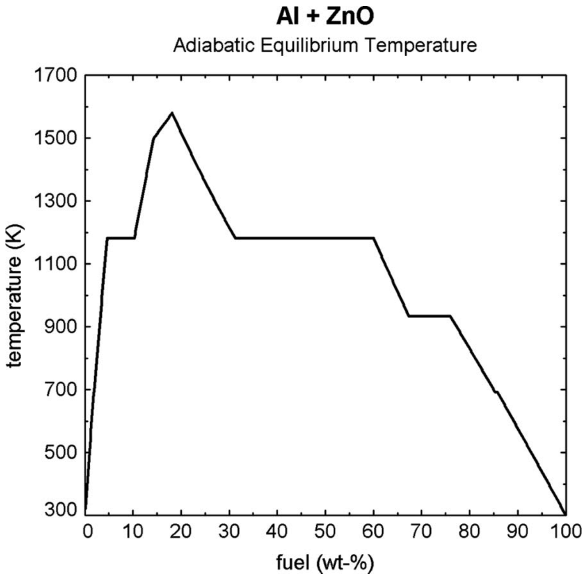

FIGURE 24.38 Adiabatic equilibrium temperature profile, Al (fuel) + ZnO (oxidizer).

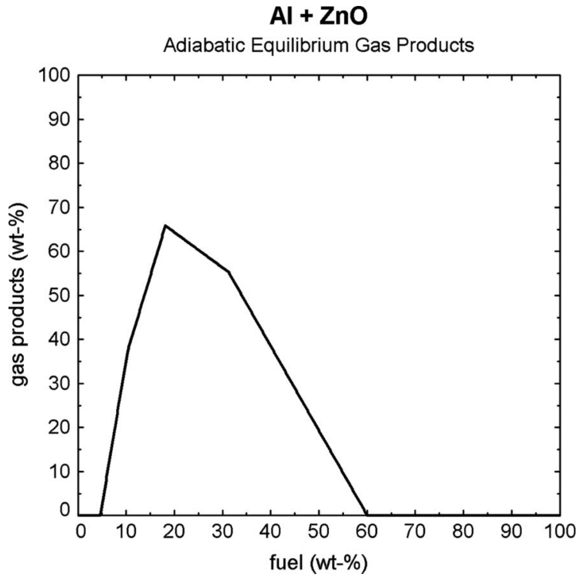

FIGURE 24.39 Adiabatic equilibrium gas production profile, Al (fuel) + ZnO (oxidizer).

T1. 14.2% fuel, 51.61% gas produced, 1497.11 K
solids: 48.25% $ZnAl_2O_4$, 0.14% ZnO (zincite)
liquids: none
gases: 51.61% Zn
simplified equation at 14.2% fuel: $2Al + 4ZnO \rightarrow ZnAl_2O_4 + 3Zn$

T2. 18.1% fuel, 65.79% gas produced, 1579.70 K—*peak temperature*
solids: 34.18% Al_2O_3 (corundum)
liquids: none
gases: 65.79% Zn
simplified equation at 18.1% fuel: $2Al + 3ZnO \rightarrow Al_2O_3 + 3Zn$

- T2 corresponds to the maximum amount of Zn.
- From 67.4% to 75.9% fuel, the temperature is limited to 933 K by the Al(s-l) transition.
- From 4.6% to 10.2% and 31.2% to 59.9% fuel, the temperature is limited to 1181 K by the Zn(l-g) transition.

G1. 18.1% fuel, 65.79% gas produced, 1579.70 K—*peak gas*
see T2 for details

24.24 ALUMINUM + CdO

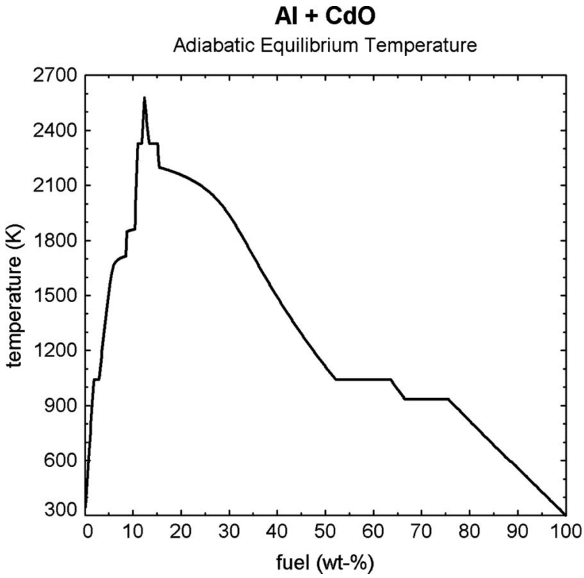

FIGURE 24.40 Adiabatic equilibrium temperature profile, Al (fuel) + CdO (oxidizer).

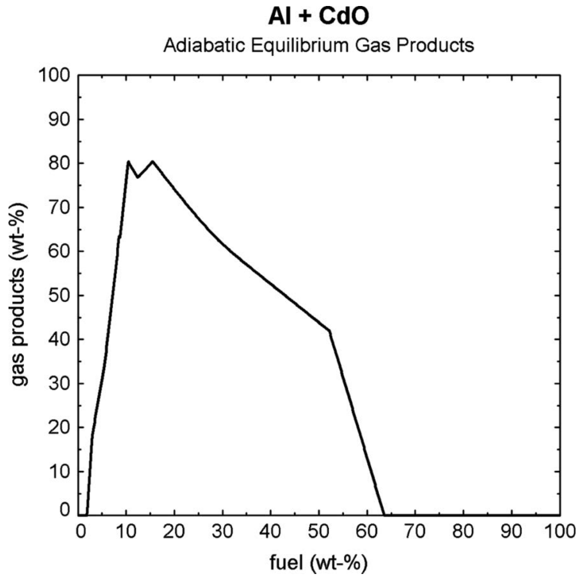

FIGURE 24.41 Adiabatic equilibrium gas production profile, Al (fuel) + CdO (oxidizer).

T1. 8.6% fuel, 63.29% gas produced, 1775.33 K
solids: 36.71% $(CdO)(Al_2O_3)$
liquids: none
gases: 60.80% Cd, 1.48% CdO, 1.00% O_2
a combination of two reactions with excess oxidizer remaining:
(9.5% fuel) $2Al + 4CdO \rightarrow (CdO)(Al_2O_3) + 3Cd$
(decomposition) $2CdO \rightarrow 2Cd + O_2$

T2. 12.3% fuel, 76.79% gas produced, 2575.55 K—*peak temperature*
solids: none
liquids: 23.21% Al_2O_3
gases: 76.77% Cd
simplified equation at 12.3% fuel: $2Al + 3CdO \rightarrow Al_2O_3 + 3Cd$

- The maximum amount of cadmium, 76.96% Cd(g), occurs at 10.9% fuel and 2271.09 K.
- From 1.9% to 2.8% and 52.2% to 63.5% fuel, the temperature is limited to 1040 K by the Cd(l-g) transition.
- From 11.0% to 11.7% and 13.4% to 15.0% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.

G1. 10.4% fuel, 80.35% gas produced, 1907.66 K—*peak gas*
solids: 19.65% Al_2O_3 (corundum)
liquids: none
gases: 76.82% Cd, 1.85% CdO, 1.68% O_2
a combination of two reactions with excess oxidizer remaining:
(12.3% fuel) $2Al + 3CdO \rightarrow Al_2O_3 + 3Cd$
(decomposition) $2CdO \rightarrow 2Cd + O_2$

G2. 15.4% fuel, 80.35% gas produced, 2213.28 K—*peak gas*
solids: 19.64% Al_2O_3 (corundum)
liquids: none
gases: 74.06% Cd, 5.66% Al_2O, 0.63% Al
a combination of two reactions:
(12.3% fuel) $2Al + 3CdO \rightarrow Al_2O_3 + 3Cd$
(29.6% fuel) $2Al + CdO \rightarrow Al_2O + Cd$

G3. 29.6% fuel, 62.03% gas produced, 1950.41 K
solids: 18.47% Al_2O_3 (corundum)
liquids: 19.50% Al
gases: 61.63% Cd, 0.35% Al_2O
one reaction with excess fuel remaining:
(12.3% fuel) $2Al + 3CdO \rightarrow Al_2O_3 + 3Cd$

24.25 ALUMINUM + HgO

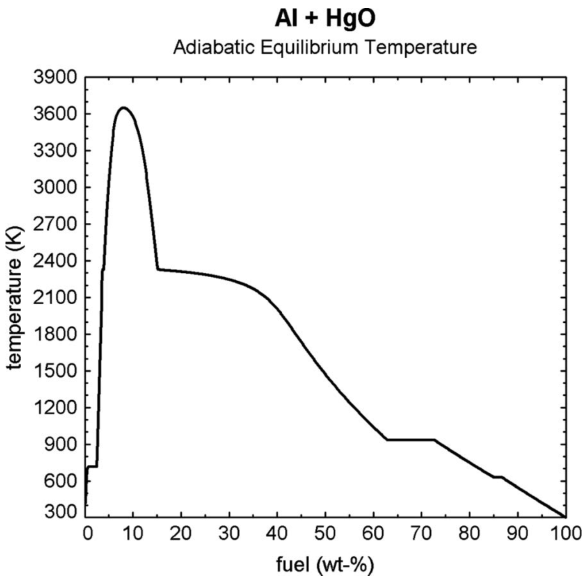

FIGURE 24.42 Adiabatic equilibrium temperature profile, Al (fuel) + HgO (oxidizer).

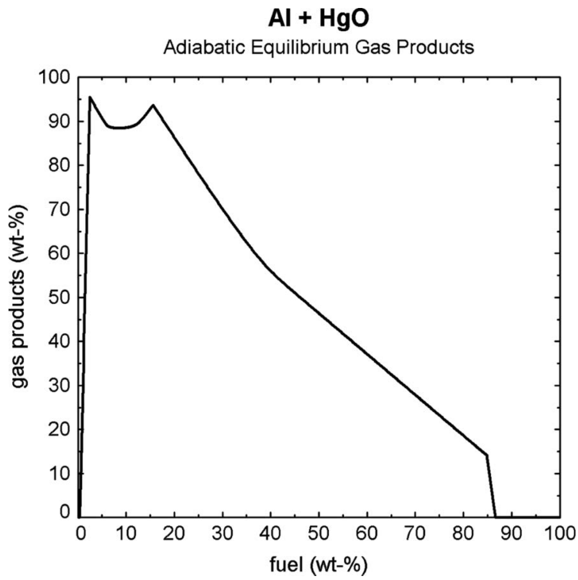

FIGURE 24.43 Adiabatic equilibrium gas production profile, Al (fuel) + HgO (oxidizer).

T1. 3.4% fuel, 93.58% gas produced, 2052.23 K
solids: 6.42% Al_2O_3 (corundum)
liquids: none
gases: 88.25% Hg, 4.02% O_2, 1.20% HgO, 0.11% Hg_2
a combination of two reactions with excess oxidizer remaining:
(7.7% fuel) $2Al + 3HgO \rightarrow Al_2O_3 + 3Hg$
(decomposition) $2HgO \rightarrow 2Hg + O_2$

T2. 8.0% fuel, 88.45% gas produced, 3649.85 K—*peak temperature*
solids: none
liquids: 11.55% Al_2O_3
major gases: 85.03% Hg, 1.07% AlO, 0.66% Al_2O
other gases: 0.54% O, 0.52% Al, 0.28% Al_2O_2, 0.14% O_2, 0.13% HgO
simplified equation at 7.7% fuel: $2Al + 3HgO \rightarrow Al_2O_3 + 3Hg$

- HgO(s) is unstable above 716 K.
- T1 corresponds to the maximum amount of Hg.

G1. 2.4% fuel, 95.46% gas produced, 715.47 K—*peak gas*
solids: 4.53% Al_2O_3 (corundum)
liquids: none
gases: 80.10% Hg, 10.47% HgO, 4.30% O_2, 0.59% Hg_2

G2. 15.6% fuel, 93.55% gas produced, 2324.76 K
solids: 6.42% Al_2O_3 (corundum)
liquids: none
gases: 78.10% Hg, 14.05% Al_2O, 1.31% Al
a combination of two reactions with excess fuel remaining:
(7.7% fuel) $2Al + 3HgO \rightarrow Al_2O_3 + 3Hg$
(19.9% fuel) $2Al + HgO \rightarrow Al_2O + Hg$

G3. 19.9% fuel, 86.39% gas produced, 2310.26 K
solids: 7.16% Al_2O_3 (corundum)
liquids: 6.45% Al
gases: 74.12% Hg, 11.14% Al_2O, 1.06% Al
a combination of two reactions with excess fuel remaining:
(7.7% fuel) $2Al + 3HgO \rightarrow Al_2O_3 + 3Hg$
(19.9% fuel) $2Al + HgO \rightarrow Al_2O + Hg$

24.26 ALUMINUM + B_2O_3

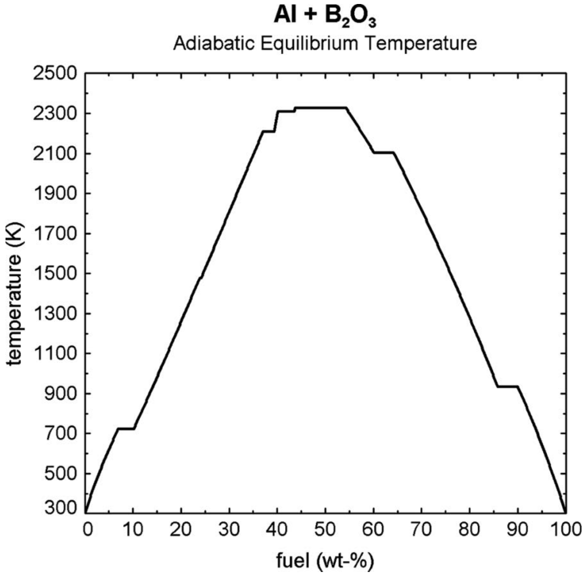

FIGURE 24.44 Adiabatic equilibrium temperature profile, Al (fuel) + B_2O_3 (oxidizer).

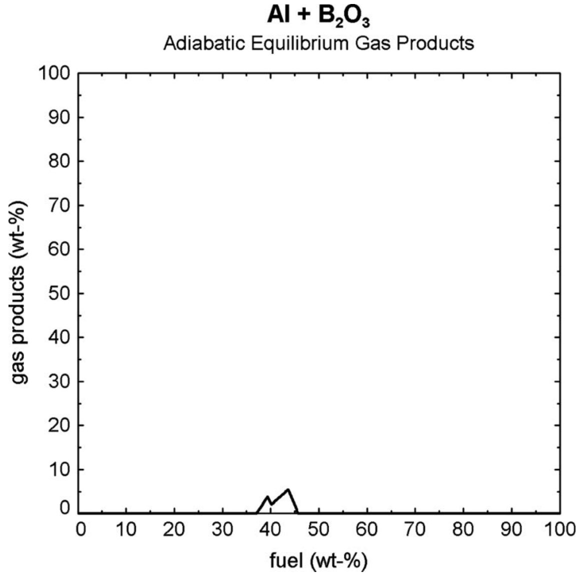

FIGURE 24.45 Adiabatic equilibrium gas production profile, Al (fuel) + B_2O_3 (oxidizer).

T1. 40.0% fuel, 2.12% gas produced, 2302.21 K
solids: 80.21% $(Al_2O_3)_9(B_2O_3)_2$, 17.67% AlB_{12}
liquids: none
gases: 1.09% $(BO)_2$, 0.72% B_2O_3, 0.25% $AlBO_2$
simplified equation at 40.7% fuel: $39Al + 22B_2O_3 \rightarrow 2(Al_2O_3)_9(B_2O_3)_2 + 3AlB_{12}$

T2. 45.7% fuel, 2327.02 K—*peak temperature*
solids: 36.31% Al_2O_3 (corundum), 20.37% AlB_{12}
liquids: 43.22% Al_2O_3, 0.10% Al
gases: none
simplified equation at 45.6% fuel: $13Al + 6B_2O_3 \rightarrow 6Al_2O_3 + AlB_{12}$

T3. 64.2% fuel, 2101.22 K
solids: 52.43% Al_2O_3 (corundum), 24.99% AlB_2
liquids: 22.58% Al
gases: none
one reaction with excess fuel remaining:
(53.8% fuel) $3Al + B_2O_3 \rightarrow Al_2O_3 + AlB_2$

- Elemental boron is not predicted to occur at any point.
- From 60.1% to 64.1% fuel, the temperature appears to be limited by the $6AlB_2(s) \rightarrow AlB_{12}(s) + 5Al(l)$ decomposition, which occurs at 2104 K.
- From 37.0% to 39.3% fuel, the temperature appears to be limited to 2208 K by the reaction of $B_2O_3(l)$ and $AlB_{12}(s)$ which forms $(BO)_2(g)$ and $AlBO_2(g)$. Some of the B_2O_3 is also vaporized.

- From 40.1% to 43.5% fuel, the temperature appears to be limited to 2310 K by the reaction of AlB_{12}(s) and $(Al_2O_3)_9(B_2O_3)_2$(s) which forms Al_2O_3(s), $(BO)_2$(g), B_2O_3(g), $AlBO_2$(g), and BO(g).
- From 43.8% to 54.2% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.

G1. 39.3% fuel, 3.75% gas produced, 2207.85 K
solids: 78.92% $(Al_2O_3)_9(B_2O_3)_2$, 17.25% AlB_{12}
liquids: none
gases: 1.90% $(BO)_2$, 1.62% B_2O_3, 0.17% $AlBO_2$
one reaction with excess oxidizer remaining:
(40.7% fuel) $39Al + 22B_2O_3 \rightarrow 2(Al_2O_3)_9(B_2O_3)_2 + 3AlB_{12}$

G2. 43.5% fuel, 5.37% gas produced, 2309.51 K—*peak gas*
solids: 74.34% Al_2O_3 (corundum), 18.92% AlB_{12}, 1.37% $(Al_2O_3)_9(B_2O_3)_2$
liquids: none
gases: 2.75% $(BO)_2$, 1.77% B_2O_3, 0.69% $AlBO_2$, 0.15% BO
one reaction with excess oxidizer remaining:
(45.6% fuel) $13Al + 6B_2O_3 \rightarrow 6Al_2O_3 + AlB_{12}$

24.27 ALUMINUM + SiO_2

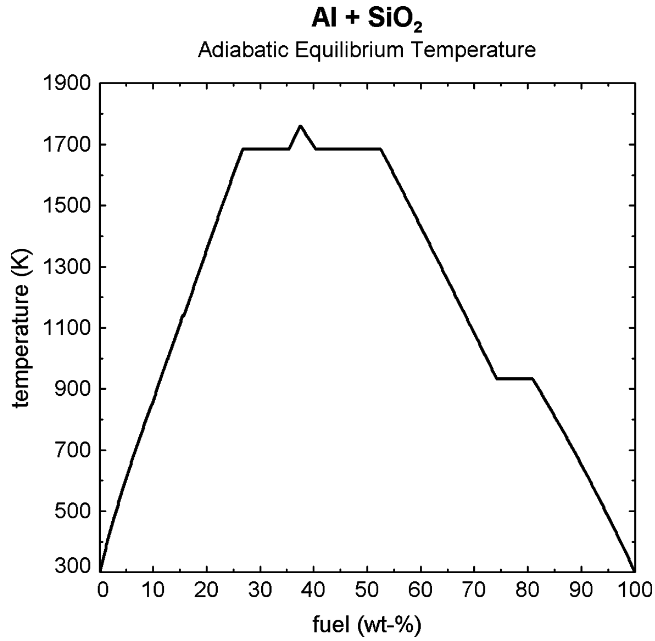

FIGURE 24.46 Adiabatic equilibrium temperature profile, Al (fuel) + SiO_2 (oxidizer).

T1. 26.4% fuel, 1671.55 K
solids: 79.28% Al_2SiO_5 (sillimanite), 20.61% Si, 0.11% SiO_2 (tridymite)
liquids: none
gases: none
simplified equation at 26.4% fuel: $4Al + 5SiO_2 \rightarrow 2Al_2SiO_5 + 3Si$

T2. 37.5% fuel, 1759.40 K—*peak temperature*
solids: 70.71% Al_2O_3 (corundum)
liquids: 29.22% Si
gases: none
simplified equation at 37.5% fuel: $4Al + 3SiO_2 \rightarrow 2Al_2O_3 + 3Si$

- T2 corresponds to the maximum amount of Si.
- From 26.7% to 35.3% and 40.3% to 52.4% fuel, the temperature is limited to 1685 K by the Si(s-l) transition.

24.28 ALUMINUM + SnO

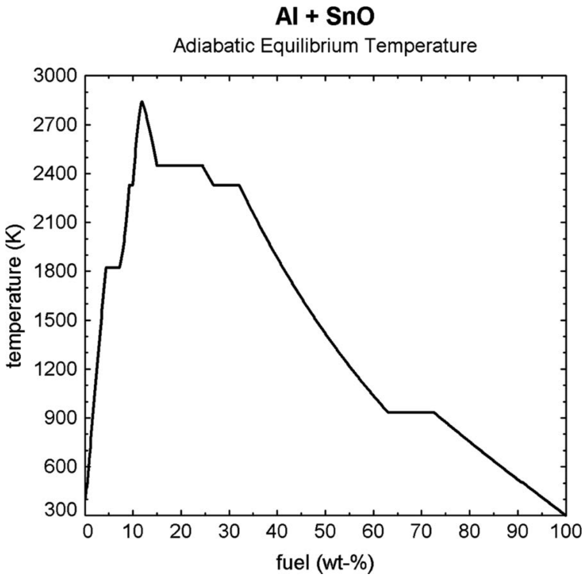

FIGURE 24.47 Adiabatic equilibrium temperature profile, Al (fuel) + SnO (oxidizer).

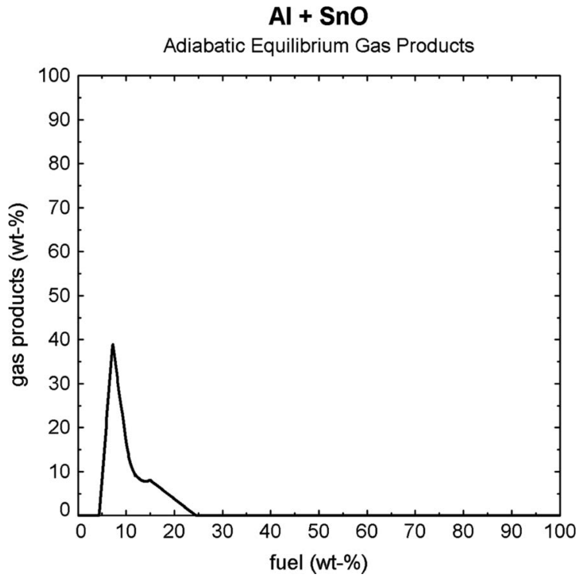

FIGURE 24.48 Adiabatic equilibrium gas production profile, Al (fuel) + SnO (oxidizer).

T1. 11.8% fuel, 8.98% gas produced, 2839.43 K—*peak temperature*
solids: none
liquids: 68.95% Sn, 22.07% Al_2O_3
gases: 7.38% Sn, 0.93% Sn_2, 0.52% SnO, 0.11% Al_2O
simplified equation at 11.8% fuel: $2Al + 3SnO \rightarrow Al_2O_3 + 3Sn$

- The maximum amount of tin, 68.77% Sn(l), 7.59% Sn(g), and 0.96% Sn_2(g), occurs at 11.9% fuel and 2834.99 K.
- From 4.4% to 7.1% fuel, the temperature appears to be limited by the vaporization of SnO from Sn(l)/SnO_2(s) mixtures, which occurs at about 1820 K.
- From 9.2% to 9.8% and 26.7% to 32.0% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- The plateau from 14.9% to 24.3% fuel (2449 K) could not be attributed to a simple transition or reaction; species in this region include Al_2O(g), Al(g), Sn(g), Sn_2(g), Sn(l), Al_2O_3(l), and Al(l). The vaporization of Al_2O and Al from Al(l)/Al_2O_3(l) mixtures is expected to occur at 2470 K.

G1. 7.2% fuel, 38.89% gas produced, 1828.56 K—*peak gas*
solids: 13.60% Al_2O_3 (corundum)
liquids: 47.50% Sn
gases: 17.49% $(SnO)_2$, 7.62% SnO, 7.31% $(SnO)_4$, 6.45% $(SnO)_3$
one reaction with excess oxidizer remaining:
(11.8% fuel) $2Al + 3SnO \rightarrow Al_2O_3 + 3Sn$

G2. 14.9% fuel, 8.05% gas produced, 2448.81 K
solids: none
liquids: 73.29% Sn, 18.65% Al_2O_3
gases: 5.81% Al_2O, 1.59% Sn, 0.52% Al, 0.11% Sn_2
a combination of two reactions:
(11.8% fuel) $2Al + 3SnO \rightarrow Al_2O_3 + 3Sn$
(28.6% fuel) $2Al + SnO \rightarrow Al_2O + Sn$

24.29 ALUMINUM + SnO_2

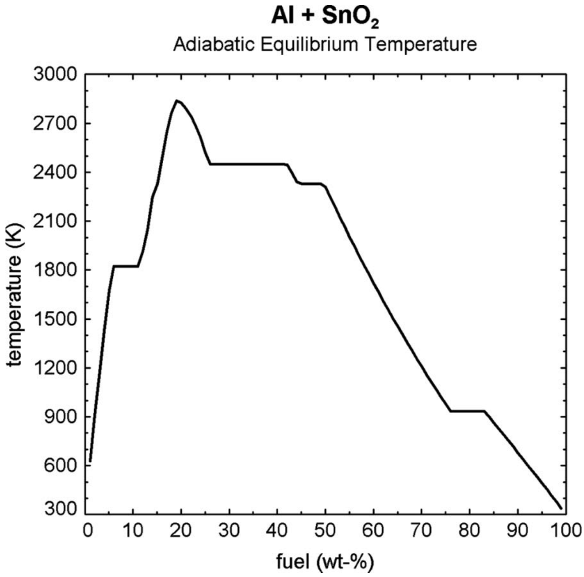

FIGURE 24.49 Adiabatic equilibrium temperature profile, Al (fuel) + SnO_2 (oxidizer).

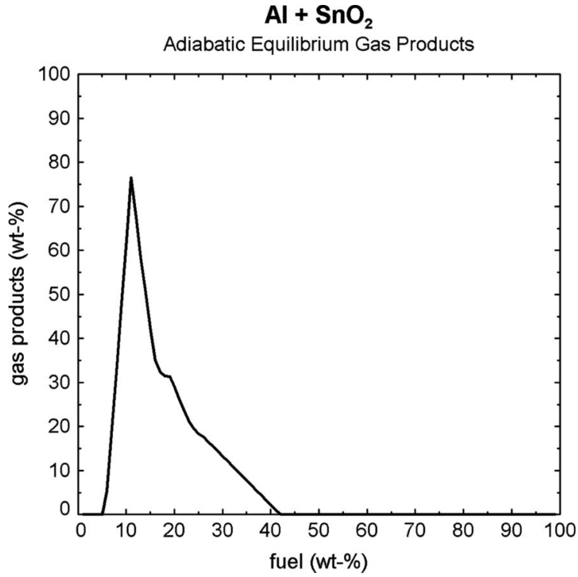

FIGURE 24.50 Adiabatic equilibrium gas production profile, Al (fuel) + SnO_2 (oxidizer).

T1. 19% fuel, 31.36% gas produced, 2835.21 K—*peak temperature*
solids: none
liquids: 35.66% Al_2O_3, 32.98% Sn
gases: 24.82% Sn, 3.26% SnO, 3.13% Sn_2
a combination of two reactions:
(10.7% fuel) $2Al + 3SnO_2 \rightarrow Al_2O_3 + 3SnO$
(19.3% fuel) $4Al + 3SnO_2 \rightarrow 2Al_2O_3 + 3Sn$

- The maximum amount of tin, 35.80% Sn(l), 23.57% Sn(g), and 2.93% Sn_2(g), occurs at 20% fuel and 2825.04 K.
- From 6% to 11% fuel, the temperature appears to be limited by the vaporization of SnO from Sn(l)/SnO_2(s) mixtures, which occurs at about 1820 K.
- From 45% to 49% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- The plateau from 26% to 41% fuel (2449 K) could not be attributed to a simple transition or reaction; species in this region include Al_2O(g), Al(g), Sn(g), Sn_2(g), Sn(l), Al_2O_3(l), and Al(l). The vaporization of Al_2O and Al from Al(l)/Al_2O_3(l) mixtures is expected to occur at 2470 K.

G1. 11% fuel, 76.49% gas produced, 1821.42 K—*peak gas*
solids: 20.78% Al_2O_3 (corundum), 0.15% SnO_2 (cassiterite)
liquids: 2.58% Sn
gases: 33.88% $(SnO)_2$, 15.38% $(SnO)_4$, 14.20% SnO, 13.01% $(SnO)_3$
a combination of two reactions:
(10.7% fuel) $2Al + 3SnO_2 \rightarrow Al_2O_3 + 3SnO$
(19.3% fuel) $4Al + 3SnO_2 \rightarrow 2Al_2O_3 + 3Sn$

G2. 19% fuel, 31.36% gas produced, 2835.21 K
see T1 for details

24.30 ALUMINUM + PbO

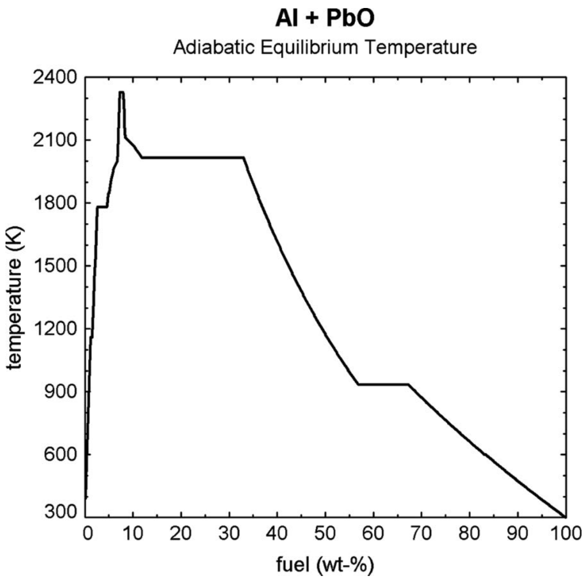

FIGURE 24.51 Adiabatic equilibrium temperature profile, Al (fuel) + PbO (oxidizer).

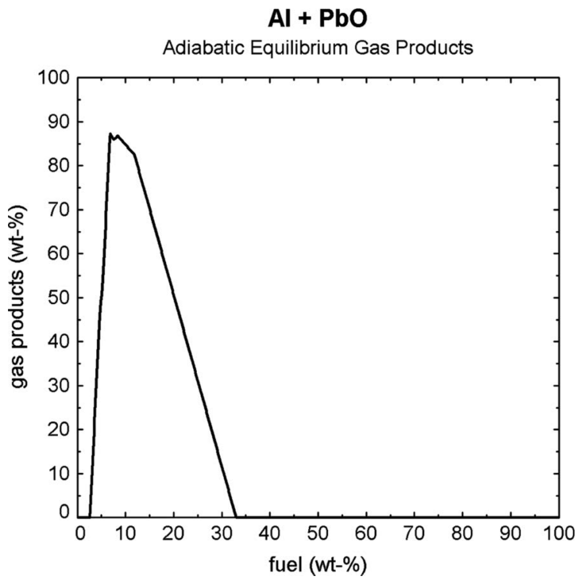

FIGURE 24.52 Adiabatic equilibrium gas production profile, Al (fuel) + PbO (oxidizer).

T1. 7.5% fuel, 85.94% gas produced, 2327.01 K—*peak temperature*
solids: 9.49% Al_2O_3 (corundum)
liquids: 4.57% Al_2O_3
gases: 85.39% Pb, 0.48% Pb_2
simplified equation at 7.5% fuel: $2Al + 3PbO \rightarrow Al_2O_3 + 3Pb$

- T1 corresponds to the maximum amount of Pb.
- From 1.2% to 1.5% fuel, the temperature is limited to 1159 K by the PbO(s-l) transition.
- From 2.6% to 4.5% fuel, the temperature appears to be limited by the vaporization of Pb and PbO from Pb(l)/PbO(l) mixtures, which occurs at 1780 K.
- The plateau from 11.8% to 32.9% fuel (2016 K) could not be attributed to a simple transition or reaction; species in this region include Pb(g), Pb_2(g), Al_2O(g), Al(l), Pb(l), and Al_2O_3(s). Alone, Pb(l) is expected to vaporize at 2020 K.
- From 7.2% to 7.8% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.

G1. 6.8% fuel, 87.15% gas produced, 2043.14 K—*peak gas*
solids: 12.85% Al_2O_3 (corundum)
liquids: none
gases: 77.70% Pb, 8.82% PbO, 0.63% Pb_2
one reaction with excess oxidizer remaining:
(7.5% fuel) $2Al + 3PbO \rightarrow Al_2O_3 + 3Pb$

G2. 8.3% fuel, 86.72% gas produced, 2135.65 K
solids: 13.28% Al_2O_3 (corundum)
liquids: none
gases: 84.52% Pb, 1.41% Al_2O, 0.61% Pb_2, 0.18% Al
a combination of two reactions:
(7.5% fuel) $2Al + 3PbO \rightarrow Al_2O_3 + 3Pb$
(19.5% fuel) $2Al + PbO \rightarrow Al_2O + Pb$

24.31 ALUMINUM + Pb_3O_4

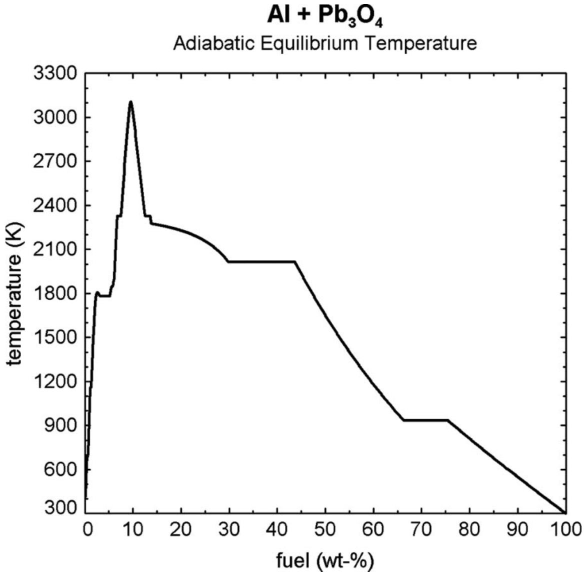

FIGURE 24.53 Adiabatic equilibrium temperature profile, Al (fuel) + Pb_3O_4 (oxidizer).

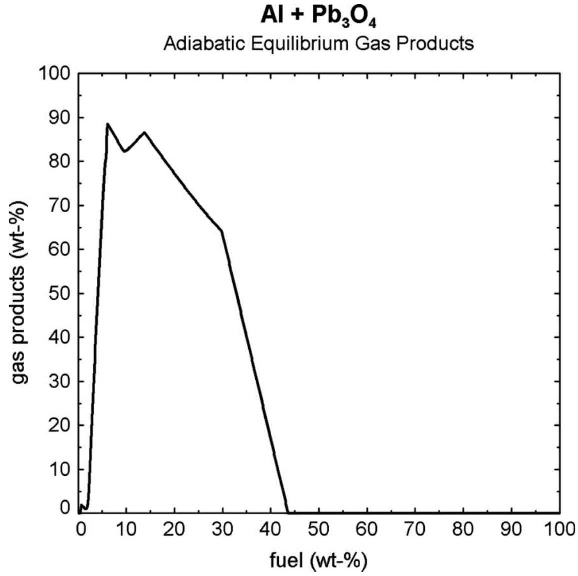

FIGURE 24.54 Adiabatic equilibrium gas production profile, Al (fuel) + Pb_3O_4 (oxidizer).

T1. 2.6% fuel, 16.09% gas produced, 1806.15 K
solids: 6.70% $(PbO)(Al_2O_3)_6$
liquids: 77.21% PbO
gases: 15.22% PbO, 0.84% Pb
simplified equation at 2.6% fuel: $12Al + 18Pb_3O_4 \rightarrow (PbO)(Al_2O_3)_6 + 53PbO$

T2. 9.5% fuel, 82.32% gas produced, 3102.99 K—*peak temperature*
solids: none
liquids: 17.68% Al_2O_3
gases: 80.78% Pb, 1.19% PbO, 0.17% Pb_2
simplified equation at 9.5% fuel: $8Al + 3Pb_3O_4 \rightarrow 4Al_2O_3 + 9Pb$

T3. 9.9% fuel, 82.46% gas produced, 3031.17 K
solids: none
liquids: 17.54% Al_2O_3
gases: 81.22% Pb, 0.47% Al_2O, 0.31% PbO, 0.22% Al, 0.18% Pb_2
simplified equation at 9.5% fuel: $8Al + 3Pb_3O_4 \rightarrow 4Al_2O_3 + 9Pb$

- T3 corresponds to the maximum amount of Pb.
- From 3.1% to 5.1% fuel, the temperature appears to be limited by the vaporization of Pb and PbO from Pb(l)/PbO(l) mixtures, which occurs at 1780 K.
- The plateau from 29.8% to 43.5% fuel (2016 K) could not be attributed to a simple transition or reaction; species in this region include Pb(g), Pb_2(g), Al_2O(g), Al(l), Pb(l), and Al_2O_3(s). Alone, Pb(l) is expected to vaporize at 2020 K.
- From 6.7% to 7.4% and 12.5% to 13.5% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.

G1. 6.1% fuel, 88.47% gas produced, 1906.21 K—*peak gas*
solids: 11.53% Al_2O_3 (corundum)
liquids: none
gases: 46.57% PbO, 41.67% Pb, 0.24% Pb_2
a combination of two reactions:
(2.6% fuel) $2Al + 3Pb_3O_4 \rightarrow Al_2O_3 + 9PbO$
(9.5% fuel) $8Al + 3Pb_3O_4 \rightarrow 4Al_2O_3 + 9Pb$

G2. 13.7% fuel, 86.56% gas produced, 2277.61 K
solids: 13.44% Al_2O_3 (corundum)
liquids: none
gases: 77.90% Pb, 7.55% Al_2O, 0.75% Al, 0.35% Pb_2
a combination of two reactions:
(9.5% fuel) $8Al + 3Pb_3O_4 \rightarrow 4Al_2O_3 + 9Pb$
(23.9% fuel) $8Al + Pb_3O_4 \rightarrow 4Al_2O + 3Pb$

24.32 ALUMINUM + PbO_2

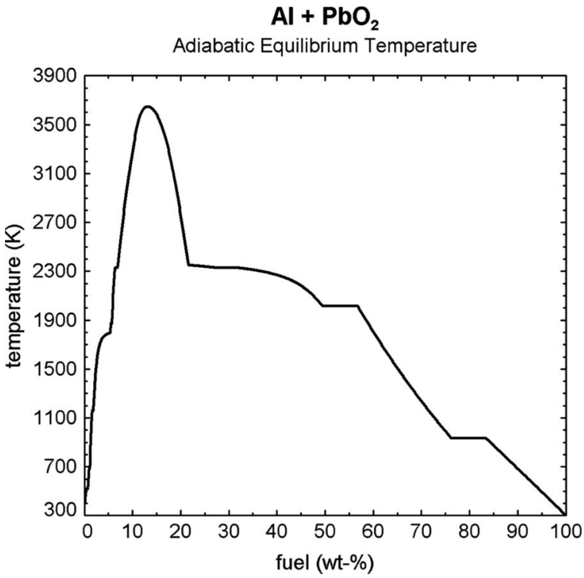

FIGURE 24.55 Adiabatic equilibrium temperature profile, Al (fuel) + PbO_2 (oxidizer).

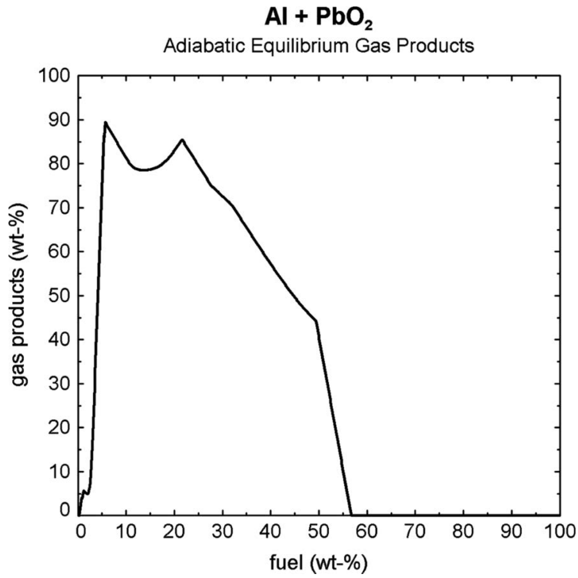

FIGURE 24.56 Adiabatic equilibrium gas production profile, Al (fuel) + PbO_2 (oxidizer).

T1. 7.0% fuel, 86.77% gas produced, 2388.59 K
solids: none
liquids: 13.23% Al_2O_3
gases: 69.68% PbO, 15.86% Pb, 1.20% O_2
a combination of reactions:
(7.0% fuel) $2Al + 3PbO_2 \rightarrow Al_2O_3 + 3PbO$
(13.1% fuel) $4Al + 3PbO_2 \rightarrow 2Al_2O_3 + 3Pb$
(decomposition) $PbO_2 \rightarrow Pb + O_2$

T2. 13.1% fuel, 78.53% gas produced, 3646.89 K—*peak temperature*
solids: none
liquids: 21.47% Al_2O_3
major gases: 70.15% Pb, 5.45% PbO, 0.94% AlO, 0.64% Al_2O
other gases: 0.49% Al, 0.42% O, 0.26% Al_2O_2, 0.10% O_2
simplified equation at 13.1% fuel: $4Al + 3PbO_2 \rightarrow 2Al_2O_3 + 3Pb$

T3. 15.8% fuel, 78.92% gas produced, 3508.84 K
solids: none
liquids: 21.08% Al_2O_3
major gases: 71.52% Pb, 3.16% Al_2O, 1.46% Al, 1.45% PbO
other gases: 0.81% AlO, 0.36% Al_2O_2
a combination of two reactions with excess fuel remaining:
(13.1% fuel) $4Al + 3PbO_2 \rightarrow 2Al_2O_3 + 3Pb$
(31.1% fuel) $4Al + PbO_2 \rightarrow 2Al_2O + Pb$

- T3 corresponds to the maximum amount of Pb.
- The plateau from 49.4% to 56.6% fuel (2016 K) could not be attributed to a simple transition or reaction; species in this region include Pb(g), Pb_2(g), Al_2O(g), Al(l), Pb(l), and Al_2O_3(s). Alone, Pb(l) is expected to vaporize at 2020 K.
- From 6.4% to 6.8% and 27.6% to 31.9% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.

G1. 5.6% fuel, 89.42% gas produced, 1873.26 K—*peak gas*
solids: 10.58% Al_2O_3 (corundum)
liquids: none
gases: 85.74% PbO, 2.17% Pb, 1.50% O_2
a combination of reactions:
(7.0% fuel) $2Al + 3PbO_2 \rightarrow Al_2O_3 + 3PbO$
(decomposition) $2PbO_2 \rightarrow 2PbO + O_2$
(decomposition) $PbO_2 \rightarrow Pb + O_2$

G2. 21.5% fuel, 85.42% gas produced, 2360.54 K
solids: none
liquids: 14.58% Al_2O_3
gases: 67.80% Pb, 15.91% Al_2O, 1.49% Al, 0.19% Pb_2
a combination of two reactions with excess fuel remaining:
(13.1% fuel) $4Al + 3PbO_2 \rightarrow 2Al_2O_3 + 3Pb$
(31.1% fuel) $4Al + PbO_2 \rightarrow 2Al_2O + Pb$

24.33 ALUMINUM + Sb_2O_3

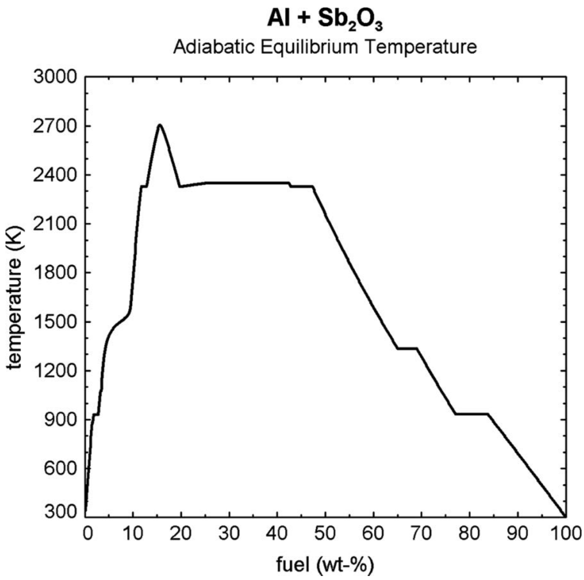

FIGURE 24.57 Adiabatic equilibrium temperature profile, Al (fuel) + Sb_2O_3 (oxidizer).

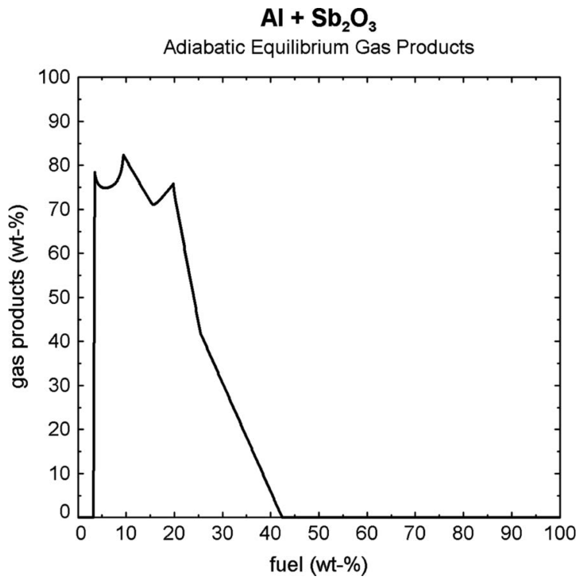

FIGURE 24.58 Adiabatic equilibrium gas production profile, Al (fuel) + Sb_2O_3 (oxidizer).

T1. 15.5% fuel, 71.13% gas produced, 2703.45 K—*peak temperature*
solids: none
liquids: 28.87% Al_2O_3
gases: 36.21% Sb, 32.21% Sb_2, 2.39% SbO, 0.18% Al_2O
simplified equation at 15.6% fuel: $2Al + Sb_2O_3 \rightarrow Al_2O_3 + 2Sb$

T2. 27.0% fuel, 37.83% gas produced, 2348.74 K
solids: none
liquids: 38.32% AlSb, 21.88% Al_2O_3, 1.97% Al
gases: 21.01% Sb_2, 8.39% Sb, 7.51% Al_2O, 0.69% Al, 0.20% Sb_4
a combination of reactions with excess fuel remaining:
(15.6% fuel) $2Al + Sb_2O_3 \rightarrow Al_2O_3 + 2Sb$
(27.0% fuel) $4Al + Sb_2O_3 \rightarrow Al_2O_3 + 2AlSb$
(35.7% fuel) $6Al + Sb_2O_3 \rightarrow 3Al_2O + 2Sb$

T3. 42.4% fuel, 2344.37 K
solids: none
liquids: 58.78% AlSb, 21.08% Al, 20.15% Al_2O_3
gases: none
one reaction with excess fuel remaining:
(27.0% fuel) $4Al + Sb_2O_3 \rightarrow Al_2O_3 + 2AlSb$

- The maximum amount of antimony, 34.26% Sb(g) and 34.98% Sb_2(g), occurs at 16.3% fuel and 2663.40 K.
- From 65.1% to 68.9% fuel, the temperature is limited to 1333 K by the AlSb(s-l) transition.

- From 11.7% to 12.8%, 19.6% to 20.0%, and 42.8% to 47.2% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.
- From 25.5% to 42.3% fuel, the temperature appears to be limited by the vaporization of Sb, Al_2O, and Al from AlSb(l)/Al_2O_3(l) mixtures, which occurs at 2349 K.

G1. 3.4% fuel, 78.44% gas produced, 1092.86 K
solids: 6.42% Al_2O_3 (corundum)
liquids: 15.14% Sb
gases: 78.19% Sb_4O_6, 0.18% Sb_4
one reaction with excess oxidizer remaining:
(15.6% fuel) $2Al + Sb_2O_3 \rightarrow Al_2O_3 + 2Sb$

G2. 9.4% fuel, 82.24% gas produced, 1581.32 K—*peak gas*
solids: 17.76% Al_2O_3 (corundum)
liquids: none
gases: 55.64% SbO, 15.30% Sb_4, 10.55% Sb_2, 0.57% Sb_4O_6, 0.18% Sb
a combination of two reactions:
(5.8% fuel) $2Al + 3Sb_2O_3 \rightarrow Al_2O_3 + 6SbO$
(15.6% fuel) $2Al + Sb_2O_3 \rightarrow Al_2O_3 + 2Sb$

G3. 19.7% fuel, 75.73% gas produced, 2327.02 K
solids: 1.32% Al_2O_3 (corundum)
liquids: 22.95% Al_2O_3
gases: 50.65% Sb_2, 15.62% Sb, 7.85% Al_2O, 0.80% Sb_4, 0.79% Al
a combination of two reactions:
(15.6% fuel) $2Al + Sb_2O_3 \rightarrow Al_2O_3 + 2Sb$
(35.7% fuel) $6Al + Sb_2O_3 \rightarrow 3Al_2O + 2Sb$

24.34 ALUMINUM + Bi_2O_3

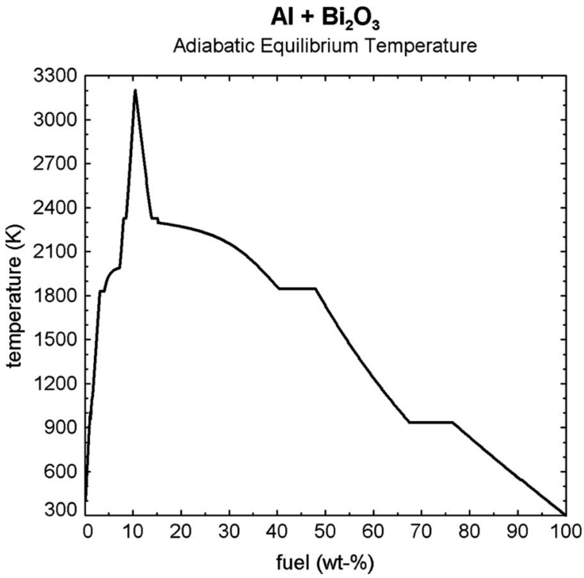

FIGURE 24.59 Adiabatic equilibrium temperature profile, Al (fuel) + Bi_2O_3 (oxidizer).

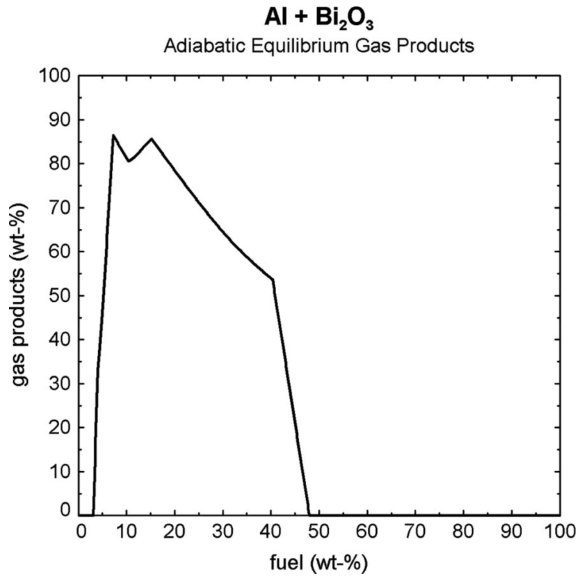

FIGURE 24.60 Adiabatic equilibrium gas production profile, Al (fuel) + Bi_2O_3 (oxidizer).

T1. 10.4% fuel, 80.56% gas produced, 3201.96 K—*peak temperature*
solids: none
liquids: 19.44% Al_2O_3
gases: 79.32% Bi, 0.82% Bi_2, 0.25% BiO
simplified equation at 10.4% fuel: $2Al + Bi_2O_3 \rightarrow Al_2O_3 + 2Bi$

- The maximum amount of bismuth, 79.31% Bi(g) and 0.85% Bi_2(g), occurs at 10.5% fuel and 3189.63 K.
- From 3.1% to 4.0% fuel, the temperature appears to be limited by the vaporization of BiO and Bi from Bi(l)/Bi_2O_3(l) mixtures, which occurs at 1827 K.
- From 40.3% to 47.9% fuel, the temperature appears to be limited to 1845 K by the vaporization of Bi(l). Alone, Bi(l) is expected to vaporize at 1846 K.
- From 8.0% to 8.5% and 13.9% to 15.0% fuel, the temperature is limited to 2327 K by the Al_2O_3(s-l) transition.

G1. 7.2% fuel, 86.40% gas produced, 1992.12 K—*peak gas*
solids: 13.60% Al_2O_3 (corundum)
liquids: none
gases: 37.74% Bi, 23.28% Bi_2, 22.93% BiO, 1.42% O_2, 1.03% Bi_2O_3
a combination of reactions with excess oxidizer remaining:
(3.7% fuel) $2Al + 3Bi_2O_3 \rightarrow Al_2O_3 + 6BiO$
(10.4% fuel) $2Al + Bi_2O_3 \rightarrow Al_2O_3 + 2Bi$
(decomposition) $2Bi_2O_3 \rightarrow 4Bi + 3O_2$

G2. 15.1% fuel, 85.60% gas produced, 2307.77 K
solids: 14.40% Al_2O_3 (corundum)
liquids: none
gases: 66.27% Bi, 9.88% Bi_2, 8.59% Al_2O, 0.84% Al
a combination of two reactions:
(10.4% fuel) $2Al + Bi_2O_3 \rightarrow Al_2O_3 + 2Bi$
(25.8% fuel) $6Al + Bi_2O_3 \rightarrow 3Al_2O + 2Bi$

25 Silicon–Oxidizer Systems

25.1 OVERVIEW

This chapter concerns the adiabatic properties of the silicon–oxygen system and another thirty-one silicon–oxidizer combinations. Equation 25.1 is a general description of the chemical reactions in question, and Table 25.1 provides a broad overview of the most basic results. The thermochemical descriptions within this chapter were derived from the *FactPS* and *FToxid* databases of

TABLE 25.1
Silicon–Oxidizer Systems

Section	Pages	Oxidizer	Maximum T_{ad} (K)
25.2	862	O_2	3147
25.3	864	TiO_2	1272
25.4	865	V_2O_5	2633
25.5	867	Nb_2O_5	2334
25.6	869	Ta_2O_5	1705
25.7	870	Cr_2O_3	1941
25.8	871	MoO_3	2905
25.9	873	WO_3	2875
25.10	875	MnO	1770
25.11	877	Mn_3O_4	2168
25.12	879	Mn_2O_3	2304
25.13	881	MnO_2	3045
25.14	884	FeO	2481
25.15	886	Fe_3O_4	2644
25.16	888	Fe_2O_3	2812
25.17	890	CoO	2862
25.18	892	Co_3O_4	3039
25.19	894	NiO	2843
25.20	896	Cu_2O	2791
25.21	897	CuO	2814
25.22	899	Ag_2O	2430
25.23	900	ZnO	1181
25.24	901	CdO	1781
25.25	902	HgO	2923
25.26	904	B_2O_3	1090
-	-	SiO_2	-
25.27	905	SnO	2573
25.28	906	SnO_2	2574
25.29	908	PbO	2019
25.30	909	Pb_3O_4	2411
25.31	911	PbO_2	2876
25.32	913	Sb_2O_3	2262
25.33	915	Bi_2O_3	2559

*FactSage 7.0.** Only pure substances were considered in the condensed phases. Gases were treated ideally, and ideal gas mixing was assumed. Charged species were not considered in any phase.

$$\text{silicon} + \text{oxidizer} \rightarrow \text{adiabatic equilibrium products}$$
$$(P = 1\ \text{atm},\ T_\text{i} = 298.15\ \text{K},\ T_\text{ad} = \text{adiabatic equilibrium temperature}) \quad (25.1)$$

Within each of the following sections, you will find one or two general figures as well as written descriptions of certain fuel-to-oxidizer ratios. Temperature points (T1, T2, and so on) describe features and points of interest along adiabatic temperature profiles. Similarly, gas points (G1, G2, and so on) refer to adiabatic gas production profiles. Some adiabatic temperature charts contain flat regions where the adiabatic temperature remains constant despite variations in the stoichiometry of the system. Some of these plateaus are described and explained (see Chapter 2 and Tables 2.10–2.15 for additional information).

25.2 SILICON + O_2

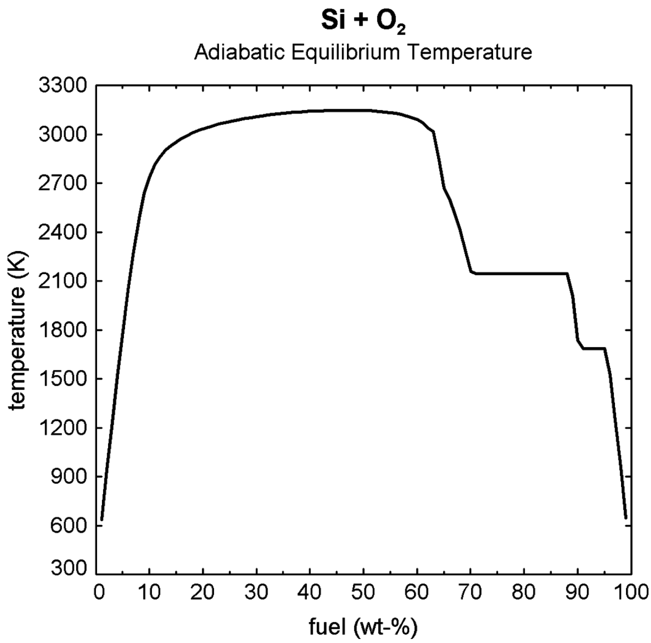

FIGURE 25.1 Adiabatic equilibrium temperature profile, Si (fuel) + O_2 (oxidizer).

T1. 21% fuel, 3043.55 K
solids: none
liquids: 21.51% SiO_2
gases: 55.99% O_2, 14.31% SiO, 4.28% O, 3.92% SiO_2
a combination of two reactions with excess oxidizer remaining:
(46.7% fuel) $Si + O_2 \rightarrow SiO_2$
(63.7% fuel) $2Si + O_2 \rightarrow 2SiO$

* Bale, C. W.; Pelton, A. D.; Thompson, W. T.; Eriksson, G.; Hack, K.; Chartrand, P.; Decterov, S.; Jung, I.-H.; Melançon, J.; Petersen, S. *FactSage,* version 7.0; CRCT ThermFact, Inc. and GTT-Technologies, 2015; www.factsage.com (accessed September, 2019).

T2. 47% fuel, 3147.42 K—*peak temperature*
solids: none
liquids: 0.85% SiO_2
gases: 67.02% SiO, 20.11% O_2, 8.36% SiO_2, 3.67% O
a combination of two reactions with excess oxidizer remaining:
(46.7% fuel) $Si + O_2 \rightarrow SiO_2$
(63.7% fuel) $2Si + O_2 \rightarrow 2SiO$

T3. 64% fuel, 2859.63 K
solids: none
liquids: none
gases: 99.19% SiO, 0.76% Si
simplified equation at 63.7% fuel: $2Si + O_2 \rightarrow 2SiO$

- The first and third points correspond to the maximum amounts of SiO_2 and SiO, respectively.
- From 91% to 95% fuel, the temperature is limited to 1685 K by the Si(s-l) transition.
- From 71% to 88% fuel, the temperature appears to be limited by the vaporization of SiO from Si(l)/SiO_2(l) mixtures, which occurs at 2145 K.
- SiO_2(l) vaporizes and partially decomposes into gaseous SiO, O_2, and O at 3147 K. This appears to limit any further increase in temperature. SiO(g) is stable at much higher temperatures, with only minor decomposition expected at 4500 K.
- Si(l) is present from 65% to 95% fuel with the maximum amount (81.22%) occurring at 90% fuel. Si(g) is present from 64% to 68% fuel with the maximum amount (0.98%) occurring at 65% fuel. Pure Si(l) vaporizes at 3462 K.

25.3 SILICON + TiO_2

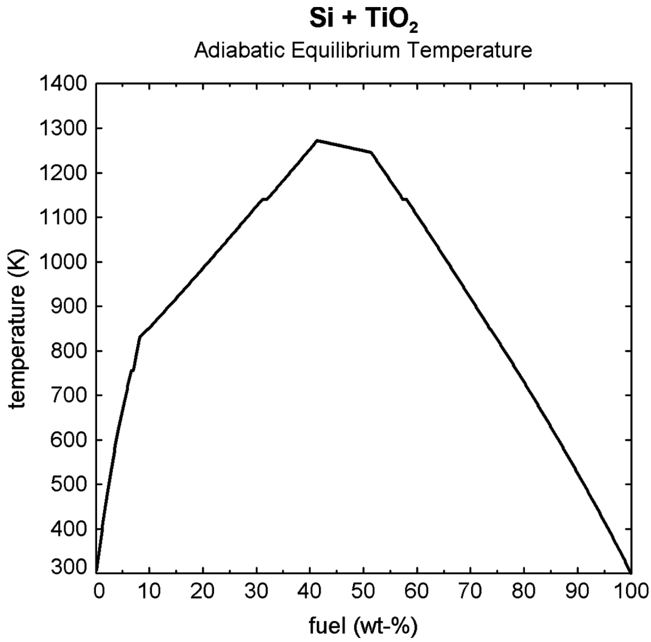

FIGURE 25.2 Adiabatic equilibrium temperature profile, Si (fuel) + TiO_2 (oxidizer).

T1. 41.3% fuel, 1271.61 K—*peak temperature*
solids: 55.78% TiSi, 44.16% SiO_2 (tridymite)
liquids: none
gases: none
simplified equation at 41.3% fuel: $2Si + TiO_2 \rightarrow SiO_2 + TiSi$

T2. 51.3% fuel, 1245.38 K
solids: 63.15% $TiSi_2$, 36.64% SiO_2 (tridymite), 0.21% TiSi
liquids: none
gases: none
simplified equation at 51.3% fuel: $3Si + TiO_2 \rightarrow SiO_2 + TiSi_2$

- Elemental titanium is not predicted to occur at any point.
- From 31.1% to 31.9% and 57.4% to 57.9% fuel, the temperature is limited to 1140 K by the quartz → tridymite transition of SiO_2(s).

25.4 SILICON + V_2O_5

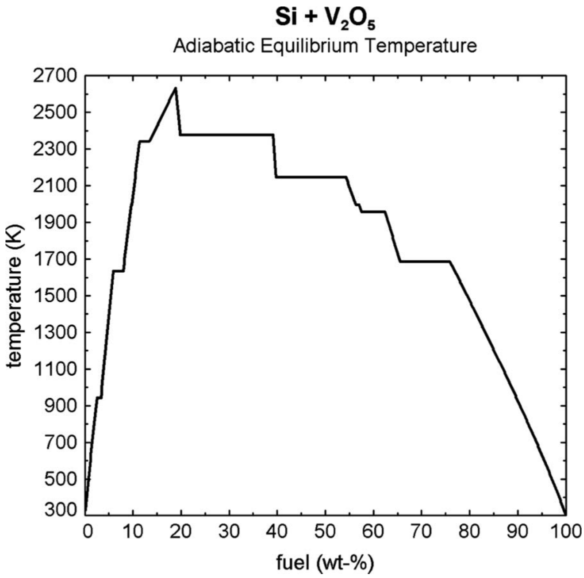

FIGURE 25.3 Adiabatic equilibrium temperature profile, Si (fuel) + V_2O_5 (oxidizer).

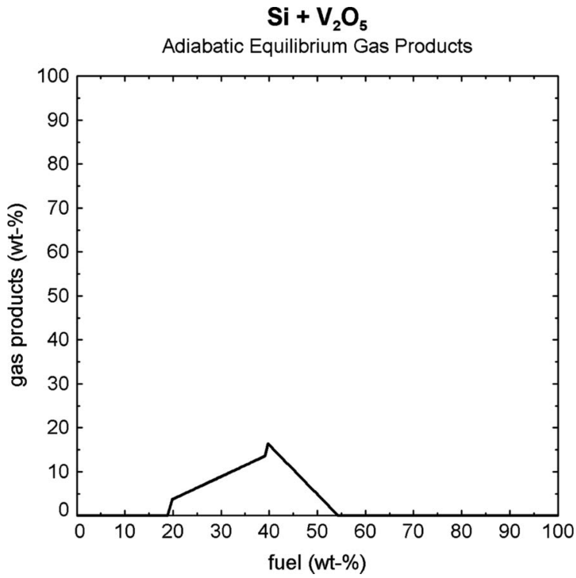

FIGURE 25.4 Adiabatic equilibrium gas production profile, Si (fuel) + V_2O_5 (oxidizer).

T1. 7.2% fuel, 1633.00 K
solids: 26.98% VO_2, 15.40% SiO_2 (tridymite), 0.37% V_2O_3
liquids: 57.25% VO_2
gases: none
simplified equation at 7.2% fuel: $Si + 2V_2O_5 \rightarrow SiO_2 + 4VO_2$

T2. 13.4% fuel, 2342.25 K
solids: none
liquids: 71.07% V_2O_3, 28.67% SiO_2, 0.26% VO
gases: none
simplified equation at 13.4% fuel: $Si + V_2O_5 \rightarrow SiO_2 + V_2O_3$

T3. 18.8% fuel, 2632.68 K—*peak temperature*
solids: none
liquids: 59.69% VO, 40.22% SiO_2
gases: none
simplified equation at 18.8% fuel: $3Si + 2V_2O_5 \rightarrow 3SiO_2 + 4VO$

T4. 36.4% fuel, 12.17% gas produced, 2375.23 K
solids: 39.05% V_5Si_3
liquids: 40.53% SiO_2, 8.25% VO
gases: 12.16% SiO
a combination of reactions:
(18.8% fuel) $3Si + 2V_2O_5 \rightarrow 3SiO_2 + 4VO$
(36.4% fuel) $37Si + 10V_2O_5 \rightarrow 25SiO_2 + 4V_5Si_3$
(48.9% fuel) $31Si + 5V_2O_5 \rightarrow 25SiO + 2V_5Si_3$

T5. 62.4% fuel, 1954.01 K
solids: 44.29% VSi_2, 31.05% SiO_2 (cristobalite)
liquids: 24.66% Si
gases: none
one reaction with excess fuel remaining:
(50.1% fuel) $13Si + 2V_2O_5 \rightarrow 5SiO_2 + 4VSi_2$

- Elemental vanadium is not predicted to occur at any point.
- From 5.9% to 7.9% fuel, the temperature is limited to 1633 K by the VO_2(s-l) transition.
- From 65.5% to 75.8% fuel, the temperature is limited to 1685 K by the Si(s-l) transition.
- From 57.5% to 62.3% fuel, the temperature appears to be limited by the $5VSi_2(s) \rightarrow V_5Si_3(s) + 7Si(l)$ decomposition, which occurs at 1958 K.
- From 56.3% to 57.0% fuel, the temperature is limited to 1996 K by the SiO_2(s-l) transition.
- From 39.7% to 54.2% fuel, the temperature appears to be limited by the vaporization of SiO from Si(l)/SiO_2(l) mixtures, which occurs at 2145 K.
- From 11.4% to 13.3% fuel, the temperature is limited to 2340 K by the V_2O_3(s-l) transition.
- From 19.8% to 39.1% fuel, the temperature appears to be limited by the $V_5Si_3(s) + 8SiO_2(l) \rightarrow 5VO(l) + 11SiO(g)$ reaction, which occurs at 2375 K.

G1. 39.7% fuel, 16.32% gas produced, 2144.86 K—*peak gas*
solids: 44.95% V_5Si_3
liquids: 38.68% SiO_2
gases: 16.32% SiO
a combination of two reactions:
(36.4% fuel) $37Si + 10V_2O_5 \rightarrow 25SiO_2 + 4V_5Si_3$
(48.9% fuel) $31Si + 5V_2O_5 \rightarrow 25SiO + 2V_5Si_3$

25.5 SILICON + Nb_2O_5

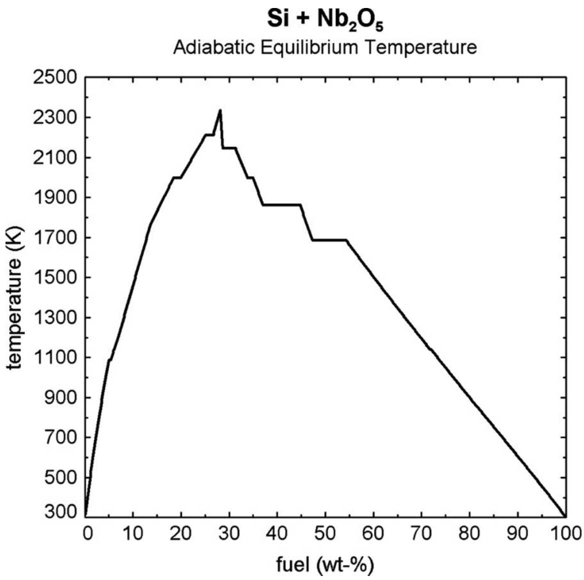

FIGURE 25.5 Adiabatic equilibrium temperature profile, Si (fuel) + Nb_2O_5 (oxidizer).

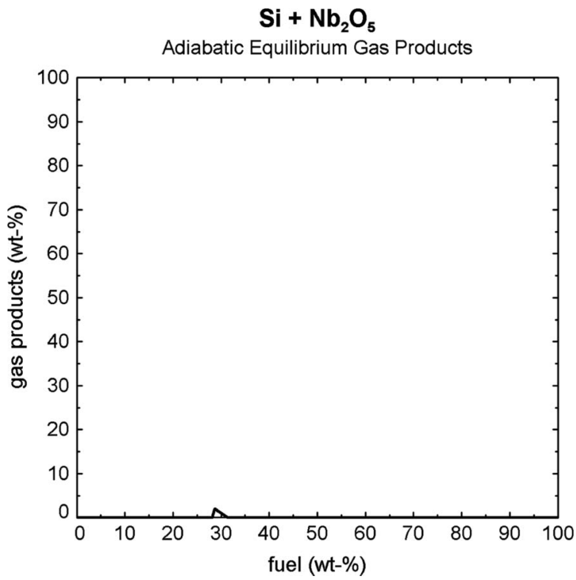

FIGURE 25.6 Adiabatic equilibrium gas production profile, Si (fuel) + Nb_2O_5 (oxidizer).

T1. 5.0% fuel, 1087.81 K
solids: 88.95% NbO_2, 10.70% SiO_2 (quartz), 0.36% Nb_2O_5
liquids: none
gases: none
simplified equation at 5.0% fuel: $Si + 2Nb_2O_5 \rightarrow SiO_2 + 4NbO_2$

T2. 13.7% fuel, 1768.76 K
solids: 70.64% NbO, 29.28% SiO_2 (cristobalite)
liquids: none
gases: none
simplified equation at 13.7% fuel: $3Si + 2Nb_2O_5 \rightarrow 3SiO_2 + 4NbO$

T3. 28.1% fuel, 2333.82 K—*peak temperature*
solids: 59.35% Nb_5Si_3
liquids: 40.62% SiO_2
gases: none
simplified equation at 28.1% fuel: $37Si + 10Nb_2O_5 \rightarrow 25SiO_2 + 4Nb_5Si_3$

T4. 40.7% fuel, 1860.13 K
solids: 33.51% SiO_2 (cristobalite), 29.62% $NbSi_2$, 27.17% Nb_5Si_3
liquids: 9.71% Si
gases: none
a combination of two reactions with excess fuel remaining:
(28.1% fuel) $37Si + 10Nb_2O_5 \rightarrow 25SiO_2 + 4Nb_5Si_3$
(40.7% fuel) $13Si + 2Nb_2O_5 \rightarrow 5SiO_2 + 4NbSi_2$

T5. 44.8% fuel, 1855.78 K
solids: 61.92% $NbSi_2$, 31.19% SiO_2 (cristobalite)
liquids: 6.89% Si
gases: none
one reaction with excess fuel remaining:
(40.7% fuel) $13Si + 2Nb_2O_5 \rightarrow 5SiO_2 + 4NbSi_2$

- Elemental niobium is not predicted to occur at any point.
- From 47.3% to 54.2% fuel, the temperature is limited to 1685 K by the Si(s-l) transition.
- From 37.1% to 44.7% fuel, the temperature appears to be limited by the $5NbSi_2(s) \rightarrow Nb_5Si_3(s) + 7Si(l)$ decomposition, which occurs at 1860 K.
- From 18.4% to 19.8% and 33.8% to 34.9% fuel, the temperature is limited to 1996 K by the SiO_2(s-l) transition.
- From 28.6% to 31.2% fuel, the temperature appears to be limited by the vaporization of SiO from Si(l)/SiO_2(l) mixtures, which occurs at 2145 K.
- From 25.1% to 26.6% fuel, the temperature is limited to 2210 K by the NbO(s-l) transition.

G1. 28.6% fuel, 1.99% gas produced, 2144.86 K—*peak gas*
solids: 58.97% Nb_5Si_3
liquids: 38.99% SiO_2
gases: 1.99% SiO
a combination of two reactions:
(28.1% fuel) $37Si + 10Nb_2O_5 \rightarrow 25SiO_2 + 4Nb_5Si_3$
(39.6% fuel) $31Si + 5Nb_2O_5 \rightarrow 25SiO + 2Nb_5Si_3$

25.6 SILICON + Ta_2O_5

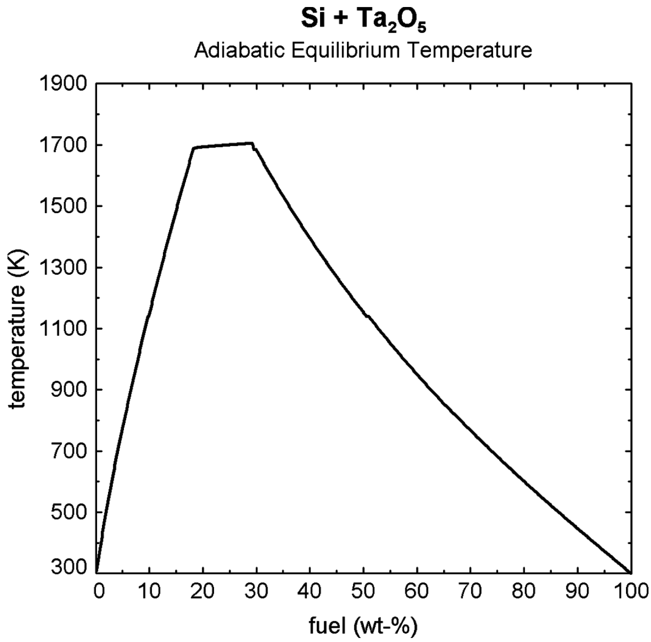

FIGURE 25.7 Adiabatic equilibrium temperature profile, Si (fuel) + Ta_2O_5 (oxidizer).

T1. 18.2% fuel, 1687.43 K
solids: 71.94% Ta_2Si, 27.81% SiO_2 (tridymite), 0.26% Ta_5Si_3
liquids: none
gases: none
simplified equation at 18.2% fuel: $7Si + 2Ta_2O_5 \rightarrow 5SiO_2 + 2Ta_2Si$

T2. 19.1% fuel, 1691.64 K
solids: 72.05% Ta_5Si_3, 27.50% SiO_2 (tridymite), 0.45% $TaSi_2$
liquids: none
gases: none
simplified equation at 19.0% fuel: $37Si + 10Ta_2O_5 \rightarrow 25SiO_2 + 4Ta_5Si_3$

T3. 29.2% fuel, 1705.10 K—*peak temperature*
solids: 75.69% $TaSi_2$, 24.07% SiO_2 (tridymite), 0.25% Ta_5Si_3
liquids: none
gases: none
simplified equation at 29.2% fuel: $13Si + 2Ta_2O_5 \rightarrow 5SiO_2 + 4TaSi_2$

- Elemental tantalum is not predicted to occur at any point.
- From 29.5% to 29.8% fuel, the temperature is limited to 1685 K by the Si(s-l) transition.

25.7 SILICON + Cr_2O_3

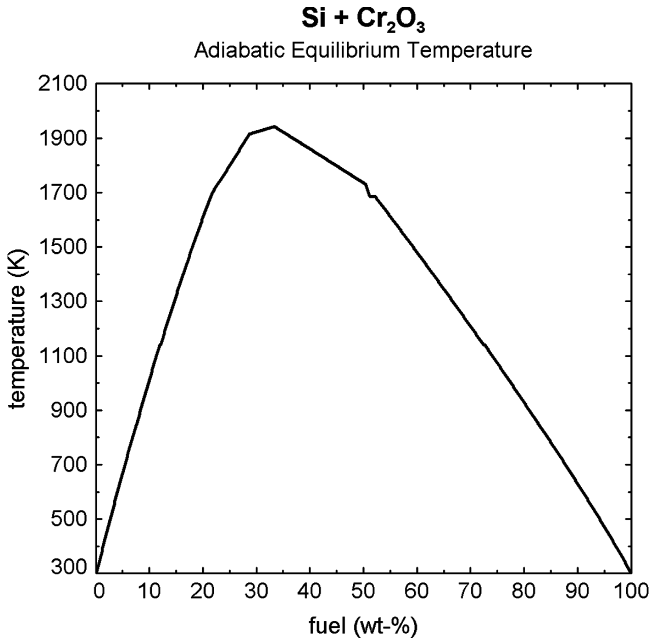

FIGURE 25.8 Adiabatic equilibrium temperature profile, Si (fuel) + Cr_2O_3 (oxidizer).

T1. 21.7% fuel, 1698.18 K
solids: 53.57% Cr, 46.42% SiO_2 (tridymite)
liquids: none
gases: none
simplified equation at 21.7% fuel: $3Si + 2Cr_2O_3 \rightarrow 3SiO_2 + 4Cr$

T2. 28.6% fuel, 1913.83 K
solids: 57.54% Cr_3Si, 42.34% SiO_2 (cristobalite), 0.13% Cr_5Si_3
liquids: none
gases: none
simplified equation at 28.6% fuel: $13Si + 6Cr_2O_3 \rightarrow 9SiO_2 + 4Cr_3Si$

T3. 33.3% fuel, 1941.33 K—*peak temperature*
solids: 60.39% Cr_5Si_3, 39.55% SiO_2 (cristobalite)
liquids: none
gases: none
simplified equation at 33.3% fuel: $27Si + 10Cr_2O_3 \rightarrow 15SiO_2 + 4Cr_5Si_3$

T4. 50.4% fuel, 1729.34 K
solids: 70.57% $CrSi_2$, 29.41% SiO_2 (tridymite)
liquids: none
gases: none
simplified equation at 50.4% fuel: $11Si + 2Cr_2O_3 \rightarrow 3SiO_2 + 4CrSi_2$

- T1 corresponds to the maximum amount of Cr.
- From 51.2% to 52.1% fuel, the temperature is limited to 1685 K by the Si(s-l) transition.

25.8 SILICON + MoO_3

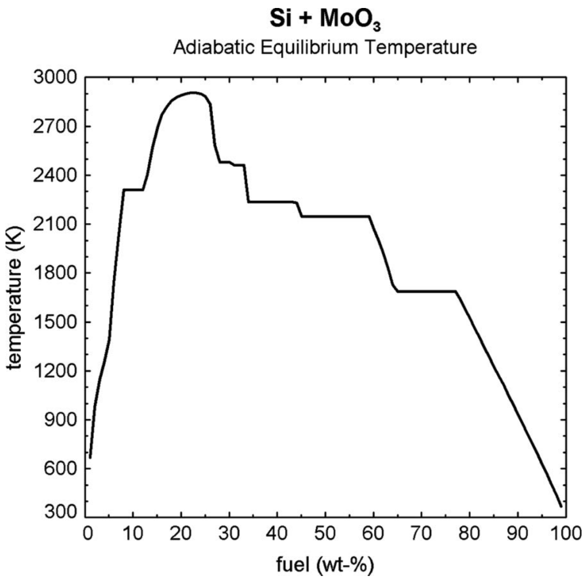

FIGURE 25.9 Adiabatic equilibrium temperature profile, Si (fuel) + MoO_3 (oxidizer).

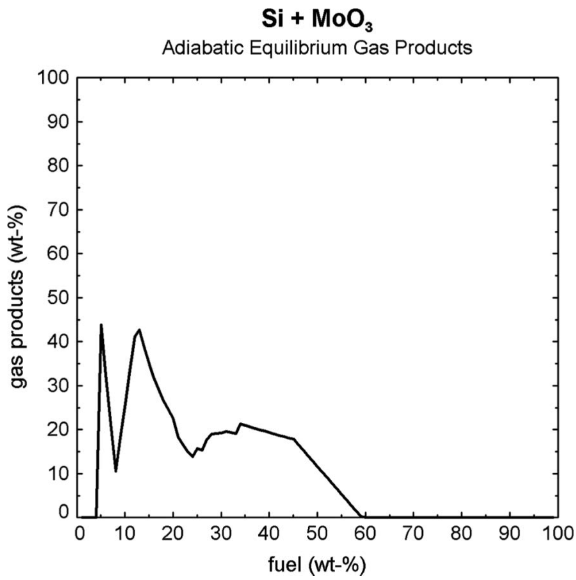

FIGURE 25.10 Adiabatic equilibrium gas production profile, Si (fuel) + MoO_3 (oxidizer).

T1. 9% fuel, 18.18% gas produced, 2308.05 K
solids: 56.10% MoO_2, 6.47% Mo
liquids: 19.25% SiO_2
gases: 14.90% $(MoO_3)_3$, 2.05% $(MoO_3)_4$, 1.02% $(MoO_3)_2$, 0.13% MoO_3
a combination of two reactions with excess oxidizer remaining:
(8.9% fuel) $Si + 2MoO_3 \rightarrow SiO_2 + 2MoO_2$
(22.6% fuel) $3Si + 2MoO_3 \rightarrow 3SiO_2 + 2Mo$

T2. 23% fuel, 14.92% gas produced, 2904.58 K—*peak temperature*
solids: none
liquids: 46.21% Mo, 38.87% SiO_2
major gases: 7.49% SiO, 2.38% MoO_3, 2.25% MoO_2, 1.23% $(MoO_3)_3$, 1.03% $(MoO_3)_2$
other gases: 0.37% MoO, 0.13% SiO_2
a combination of two reactions with excess oxidizer remaining:
(22.6% fuel) $3Si + 2MoO_3 \rightarrow 3SiO_2 + 2Mo$
(36.9% fuel) $3Si + MoO_3 \rightarrow 3SiO + Mo$

T3. 27% fuel, 17.72% gas produced, 2584.49 K
solids: 48.66% Mo
liquids: 33.63% SiO_2
gases: 17.70% SiO
a combination of two reactions:
(22.6% fuel) $3Si + 2MoO_3 \rightarrow 3SiO_2 + 2Mo$
(36.9% fuel) $3Si + MoO_3 \rightarrow 3SiO + Mo$

T4. 31% fuel, 19.52% gas produced, 2458.84 K
solids: 49.01% Mo_3Si, 1.57% Mo_5Si_3

liquids: 29.90% SiO_2
gases: 19.51% SiO
a combination of two reactions:
(26.3% fuel) $11Si + 6MoO_3 \rightarrow 9SiO_2 + 2Mo_3Si$
(39.4% fuel) $10Si + 3MoO_3 \rightarrow 9SiO + Mo_3Si$

T5. 34% fuel, 21.21% gas produced, 2233.73 K
solids: 51.14% Mo_5Si_3, 0.79% $MoSi_2$
liquids: 26.87% SiO_2
gases: 21.20% SiO
a combination of two reactions:
(29.1% fuel) $21Si + 10MoO_3 \rightarrow 15SiO_2 + 2Mo_5Si_3$
(41.3% fuel) $18Si + 5MoO_3 \rightarrow 15SiO + Mo_5Si_3$

T6. 44% fuel, 18.08% gas produced, 2230.10 K
solids: 59.18% $MoSi_2$
liquids: 22.74% SiO_2
gases: 18.08% SiO
a combination of two reactions:
(40.6% fuel) $7Si + 2MoO_3 \rightarrow 3SiO_2 + 2MoSi_2$
(49.4% fuel) $5Si + MoO_3 \rightarrow 3SiO + MoSi_2$

- T3 corresponds to the maximum amount of Mo.
- From 65% to 77% fuel, the temperature is limited to 1685 K by the Si(s-l) transition.
- From 45% to 59% fuel, the temperature appears to be limited by the vaporization of SiO from Si(l)/SiO_2(l) mixtures, which occurs at 2145 K.
- From 34% to 43% fuel, the temperature appears to be limited by the $5MoSi_2(s) + 7SiO_2(l) \rightarrow Mo_5Si_3(s) + 14SiO(g)$ reaction, which occurs at 2234 K.
- From 8% to 12% fuel, the temperature appears to be limited by the vaporization of MoO_3 from Mo(s)/MoO_2(s) mixtures, which occurs at 2308 K.
- From 31% to 33% fuel, the temperature appears to be limited by the $3Mo_5Si_3(s) + 4SiO_2(l) \rightarrow 5Mo_3Si(s) + 8SiO(g)$ reaction, which occurs at 2459 K.
- From 28% to 30% fuel, the temperature appears to be limited by the $Mo_3Si(s) + SiO_2(l) \rightarrow 3Mo(s) + 2SiO(g)$ reaction, which occurs at 2477 K.

G1. 5% fuel, 43.74% gas produced, 1388.70 K—*peak gas*
solids: 45.56% MoO_2, 10.70% SiO_2 (tridymite)
liquids: none
gases: 23.85% $(MoO_3)_4$, 15.54% $(MoO_3)_3$, 4.33% $(MoO_3)_5$
one reaction with excess oxidizer remaining:
(8.9% fuel) $Si + 2MoO_3 \rightarrow SiO_2 + 2MoO_2$

G2. 13% fuel, 42.65% gas produced, 2403.78 K
solids: 29.57% Mo
liquids: 27.78% SiO_2
major gases: 34.81% $(MoO_3)_3$, 4.07% $(MoO_3)_4$, 3.00% $(MoO_3)_2$
other gases: 0.52% MoO_3, 0.11% $(MoO_3)_5$, 0.11% MoO_2
one reaction with excess oxidizer remaining:
(22.6% fuel) $3Si + 2MoO_3 \rightarrow 3SiO_2 + 2Mo$

G3. 34% fuel, 21.21% gas produced, 2233.73 K
See T5 for details

25.9 SILICON + WO_3

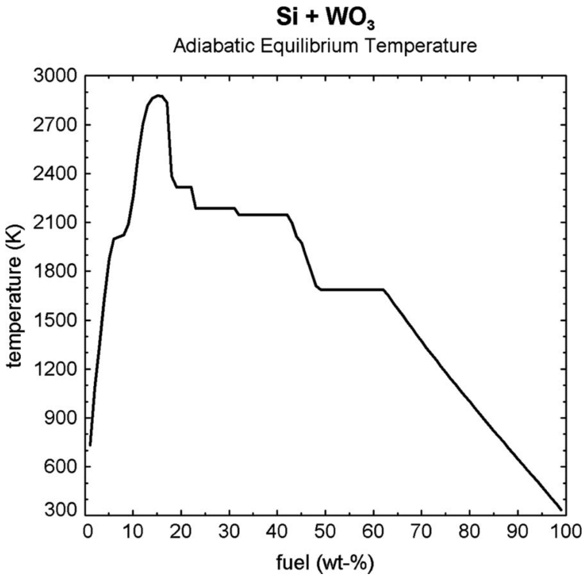

FIGURE 25.11 Adiabatic equilibrium temperature profile, Si (fuel) + WO_3 (oxidizer).

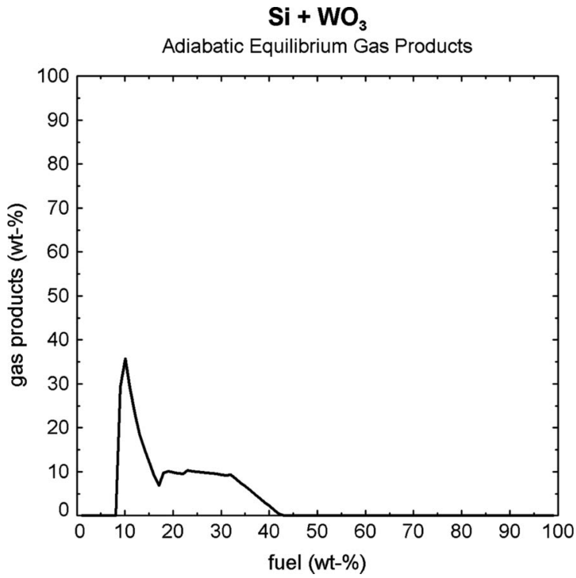

FIGURE 25.12 Adiabatic equilibrium gas production profile, Si (fuel) + WO_3 (oxidizer).

T1. 15% fuel, 11.97% gas produced, 2875.17 K—*peak temperature*
solids: 60.65% W
liquids: 27.39% SiO_2
gases: 7.22% $(WO_3)_2$, 3.42% SiO, 0.74% W_3O_8, 0.40% $(WO_3)_3$
a combination of two reactions with excess oxidizer remaining:
(15.4% fuel) $3Si + 2WO_3 \rightarrow 3SiO_2 + 2W$
(26.7% fuel) $3Si + WO_3 \rightarrow 3SiO + W$

T2. 17% fuel, 6.83% gas produced, 2834.00 K
solids: 65.43% W
liquids: 27.74% SiO_2
gases: 6.30% SiO, 0.42% $(WO_3)_2$
a combination of two reactions:
(15.4% fuel) $3Si + 2WO_3 \rightarrow 3SiO_2 + 2W$
(26.7% fuel) $3Si + WO_3 \rightarrow 3SiO + W$

T3. 23% fuel, 10.25% gas produced, 2185.53 K
solids: 65.91% W_5Si_3, 0.89% WSi_2
liquids: 22.95% SiO_2
gases: 10.25% SiO
a combination of two reactions:
(20.3% fuel) $21Si + 10WO_3 \rightarrow 15SiO_2 + 2W_5Si_3$
(30.4% fuel) $18Si + 5WO_3 \rightarrow 15SiO + W_5Si_3$

T4. 32% fuel, 9.25% gas produced, 2144.86 K
solids: 70.40% WSi_2
liquids: 20.13% SiO_2, 0.22% Si
gases: 9.25% SiO
a combination of two reactions:
(29.8% fuel) $7Si + 2WO_3 \rightarrow 3SiO_2 + 2WSi_2$
(37.7% fuel) $5Si + WO_3 \rightarrow 3SiO + WSi_2$

- T2 corresponds to the maximum amount of W.
- From 49% to 62% fuel, the temperature is limited to 1685 K by the Si(s-l) transition.
- From 32% to 42% fuel, the temperature appears to be limited by the vaporization of SiO from Si(l)/SiO_2(l) mixtures, which occurs at 2145 K.
- From 23% to 31% fuel, the temperature appears to be limited by the $5WSi_2(s) + 7SiO_2(l) \rightarrow W_5Si_3(s) + 14SiO(g)$ reaction, which occurs at 2186 K.
- From 19% to 22% fuel, the temperature appears to be limited by the $W_5Si_3(s) + 3SiO_2(l) \rightarrow 5W(s) + 6SiO(g)$ reaction, which occurs at 2316 K.

G1. 10% fuel, 35.63% gas produced, 2261.46 K—*peak gas*
solids: 42.99% W
liquids: 21.39% SiO_2
gases: 15.33% $(WO_3)_3$, 9.30% $(WO_3)_2$, 7.20% W_3O_8, 3.78% $(WO_3)_4$
a combination of two reactions with excess oxidizer remaining:
(2.0% fuel) $Si + 6WO_3 \rightarrow SiO_2 + 2W_3O_8$
(15.4% fuel) $3Si + 2WO_3 \rightarrow 3SiO_2 + 2W$

25.10 SILICON + MnO

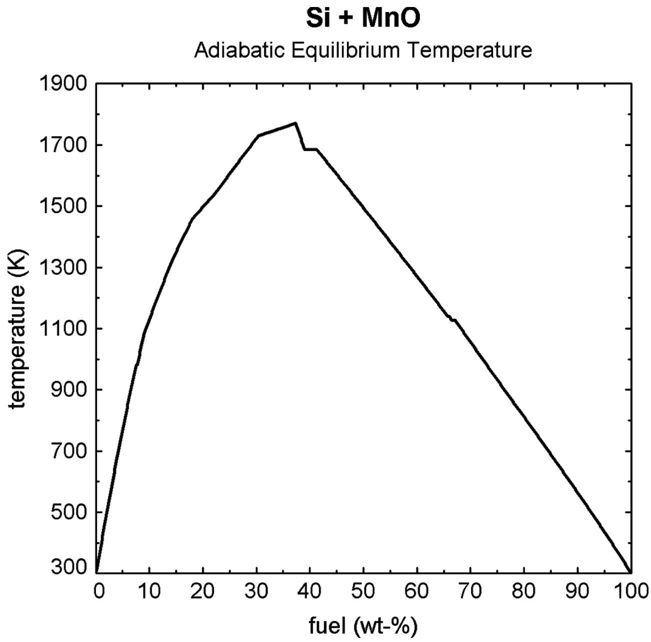

FIGURE 25.13 Adiabatic equilibrium temperature profile, Si (fuel) + MnO (oxidizer).

T1. 9.0% fuel, 1083.88 K
solids: 64.72% Mn_2SiO_4 (tephroite), 35.21% Mn
liquids: none
gases: none
simplified equation at 9.0% fuel: $Si + 4MnO \rightarrow Mn_2SiO_4 + 2Mn$

T2. 14.2% fuel, 1321.23 K
solids: 60.47% Mn_2SiO_4 (tephroite), 39.01% Mn_3Si, 0.51% $MnSiO_3$ (rhodonite)
liquids: none
gases: none
simplified equation at 14.2% fuel: $5Si + 12MnO \rightarrow 3Mn_2SiO_4 + 2Mn_3Si$

T3. 18.0% fuel, 1457.50 K
solids: 50.08% $MnSiO_3$ (rhodonite), 49.45% Mn_3Si, 0.47% Mn_2SiO_4 (tephroite)
liquids: none
gases: none
simplified equation at 18.0% fuel: $5Si + 9MnO \rightarrow 3MnSiO_3 + 2Mn_3Si$

T4. 22.5% fuel, 1546.19 K
solids: 52.27% Mn_5Si_3, 47.71% $MnSiO_3$ (rhodonite)
liquids: none
gases: none
simplified equation at 22.5% fuel: $11Si + 15MnO \rightarrow 5MnSiO_3 + 2Mn_5Si_3$

T5. 30.3% fuel, 1728.04 K
solids: 70.41% Mn_5Si_3, 29.36% SiO_2 (tridymite), 0.23% $MnSiO_3$ (rhodonite)
liquids: none
gases: none
simplified equation at 30.3% fuel: $11Si + 10MnO \rightarrow 5SiO_2 + 2Mn_5Si_3$

T6. 37.2% fuel, 1769.62 K—*peak temperature*
solids: 72.79% MnSi, 26.60% SiO_2 (cristobalite), 0.61% Mn_5Si_3
liquids: none
gases: none
simplified equation at 37.3% fuel: $3Si + 2MnO \rightarrow SiO_2 + 2MnSi$

- T1 corresponds to the maximum amount of Mn.
- From 39.0% to 41.1% fuel, the temperature is limited to 1685 K by the Si(s-l) transition.

25.11 SILICON + Mn_3O_4

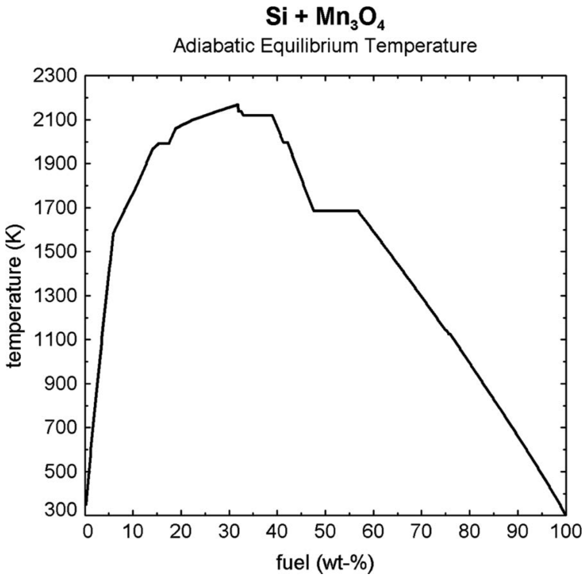

FIGURE 25.14 Adiabatic equilibrium temperature profile, Si (fuel) + Mn_3O_4 (oxidizer).

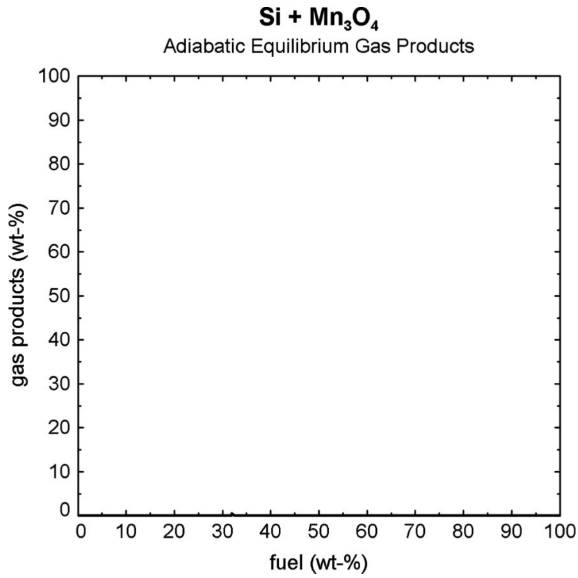

FIGURE 25.15 Adiabatic equilibrium gas production profile, Si (fuel) + Mn_3O_4 (oxidizer).

T1. 5.8% fuel, 1578.16 K
solids: 58.22% MnO, 41.71% Mn_2SiO_4 (tephroite)
liquids: none
gases: none
simplified equation at 5.8% fuel: $Si + 2Mn_3O_4 \rightarrow Mn_2SiO_4 + 4MnO$

T2. 10.9% fuel, 1805.90 K
solids: 78.38% Mn_2SiO_4 (tephroite), 0.37% MnO
liquids: 21.25% Mn
gases: none
simplified equation at 10.9% fuel: $Si + Mn_3O_4 \rightarrow Mn_2SiO_4 + Mn$

T3. 14.1% fuel, 1967.61 K
solids: 75.28% Mn_2SiO_4 (tephroite), 24.25% Mn_3Si, 0.47% $MnSiO_3$ (rhodonite)
liquids: none
gases: none
simplified equation at 14.1% fuel: $4Si + 3Mn_3O_4 \rightarrow 3Mn_2SiO_4 + Mn_3Si$

T4. 18.8% fuel, 2058.87 K
solids: 62.00% $MnSiO_3$ (rhodonite), 37.85% Mn_3Si
liquids: 0.15% Mn
gases: none
simplified equation at 18.8% fuel: $17Si + 9Mn_3O_4 \rightarrow 12MnSiO_3 + 5Mn_3Si$

T5. 22.3% fuel, 2098.06 K
solids: 59.13% $MnSiO_3$ (rhodonite), 40.74% Mn_5Si_3
liquids: 0.14% SiO_2
gases: none
simplified equation at 22.3% fuel: $7Si + 3Mn_3O_4 \rightarrow 4MnSiO_3 + Mn_5Si_3$

T6. 31.8% fuel, 2168.18 K—*peak temperature*
solids: 64.17% Mn_5Si_3
liquids: 35.79% SiO_2
gases: none
simplified equation at 31.8% fuel: $19Si + 5Mn_3O_4 \rightarrow 10SiO_2 + 3Mn_5Si_3$

T7. 39.0% fuel, 2115.38 K
solids: 66.40% MnSi
liquids: 32.04% SiO_2, 1.56% Si
gases: none
one reaction with excess fuel remaining:
(38.0% fuel) $5Si + Mn_3O_4 \rightarrow 2SiO_2 + 3MnSi$

- T2 corresponds to the maximum amount of Mn.
- From 47.5% to 56.7% fuel, the temperature is limited to 1685 K by the Si(s-l) transition.
- From 15.4% to 17.4% fuel, the temperature appears to be limited by the $Mn_3Si(s) + 3Mn_2SiO_4(s) \rightarrow 5Mn(l) + 4MnSiO_3(s)$ reaction, which occurs at 1992 K.
- From 41.3% to 42.0% fuel, the temperature is limited to 1996 K by the SiO_2(s-l) transition.
- From 32.9% to 38.9% fuel, the temperature appears to be limited by the $5MnSi(s) \rightarrow Mn_5Si_3(s) + 2Si(l)$ decomposition, which occurs at 2119 K.

G1. 31.9% fuel, 0.40% gas produced, 2138.46 K—*peak gas*
solids: 64.07% Mn_5Si_3
liquids: 35.51% SiO_2
gases: 0.38% SiO
simplified equation at 31.8% fuel: $19Si + 5Mn_3O_4 \rightarrow 10SiO_2 + 3Mn_5Si_3$

25.12 SILICON + Mn_2O_3

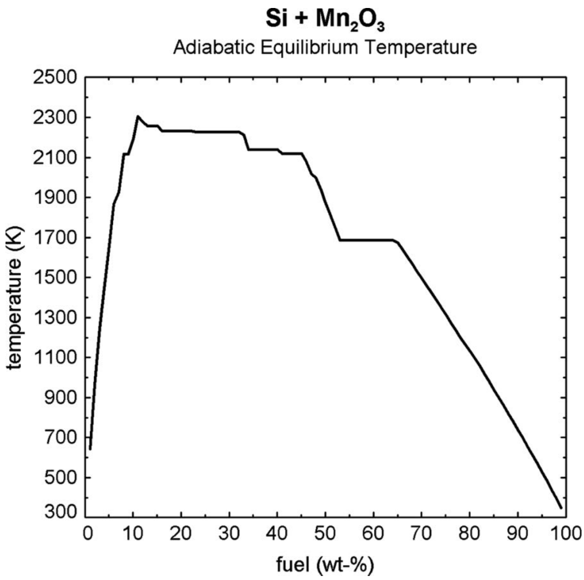

FIGURE 25.16 Adiabatic equilibrium temperature profile, Si (fuel) + Mn_2O_3 (oxidizer).

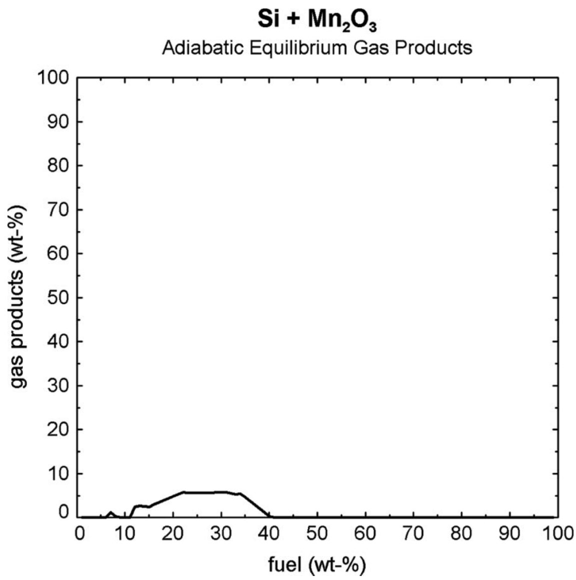

FIGURE 25.17 Adiabatic equilibrium gas production profile, Si (fuel) + Mn_2O_3 (oxidizer).

T1. 8% fuel, 0.21% gas produced, 2115.15 K
solids: 57.53% Mn_2SiO_4 (tephroite), 26.51% MnO
liquids: 15.75% MnO
gases: 0.21% O_2
simplified equation at 8.2% fuel: $Si + 2Mn_2O_3 \rightarrow Mn_2SiO_4 + 2MnO$

T2. 11% fuel, 2304.34 K—*peak temperature*
solids: 79.10% Mn_2SiO_4 (tephroite)
liquids: 12.06% Mn, 8.84% MnO
gases: none
a combination of two reactions:
(8.2% fuel) $Si + 2Mn_2O_3 \rightarrow Mn_2SiO_4 + 2MnO$
(11.8% fuel) $3Si + 4Mn_2O_3 \rightarrow 3Mn_2SiO_4 + 2Mn$

T3. 12% fuel, 2.38% gas produced, 2275.12 K
solids: 83.81% Mn_2SiO_4 (tephroite)
liquids: 13.81% Mn
gases: 1.84% Mn, 0.54% SiO
simplified equation at 11.8% fuel: $3Si + 4Mn_2O_3 \rightarrow 3Mn_2SiO_4 + 2Mn$

T4. 15% fuel, 2.43% gas produced, 2255.15 K
solids: 61.90% $MnSiO_3$ (rhodonite), 9.18% Mn_2SiO_4 (tephroite)
liquids: 26.50% Mn
gases: 1.71% Mn, 0.72% SiO
a combination of two reactions:
(11.8% fuel) $3Si + 4Mn_2O_3 \rightarrow 3Mn_2SiO_4 + 2Mn$
(15.1% fuel) $Si + Mn_2O_3 \rightarrow MnSiO_3 + Mn$

T5. 22% fuel, 5.70% gas produced, 2230.54 K
solids: 62.63% $MnSiO_3$ (rhodonite), 30.77% Mn_5Si_3
liquids: 0.90% Mn
gases: 3.58% Mn, 2.12% SiO
simplified equation at 22.2% fuel: $8Si + 5Mn_2O_3 \rightarrow 5MnSiO_3 + Mn_5Si_3$

T6. 46% fuel, 2077.55 K
solids: 56.80% MnSi
liquids: 30.83% SiO_2, 12.38% Si
gases: none
one reaction with excess fuel remaining:
(38.4% fuel) $7Si + 2Mn_2O_3 \rightarrow 3SiO_2 + 4MnSi$

- T4 corresponds to the maximum amount of Mn.
- From 53% to 64% fuel, the temperature is limited to 1685 K by the Si(s-l) transition.
- From 8% to 9% fuel, the temperature is limited to 2115 K by the MnO(s-l) transition.
- From 41% to 45% fuel, the temperature appears to be limited by the $5MnSi(s) \rightarrow Mn_5Si_3(s) + 2Si(l)$ decomposition, which occurs at 2119 K.
- The plateau from 34% to 40% fuel (2138 K) could not be attributed to a simple transition or reaction; species in this region include SiO(g), Mn(g), SiO_2(l), Si(l), and Mn_5Si_3(s). The vaporization of SiO from Si(l)/SiO_2(l) mixtures is expected to occur at 2145 K.
- From 23% to 32% fuel, the temperature appears to be limited by the $Mn_5Si_3(s) + 3SiO_2(l) \rightarrow 5Mn(g) + 6SiO(g)$ reaction, which occurs at 2227 K.
- From 16% to 22% fuel, the temperature appears to be limited by the $2Mn_5Si_3(s) + 3MnSiO_3(s) \rightarrow 13Mn(l\text{-}g) + 9SiO(g)$ reaction, which occurs at 2231 K.
- From 13% to 15% fuel, the temperature appears to be limited by the $Mn(l) + 3MnSiO_3(s) \rightarrow 2Mn_2SiO_4(s) + SiO(g)$ reaction, which occurs at 2255 K.

G1. 22% fuel, 5.70% gas produced, 2230.54 K—*peak gas*
See T5 for details

G2. 31% fuel, 5.70% gas produced, 2226.96 K—*peak gas*
solids: 54.00% Mn_5Si_3, 8.77% $MnSiO_3$ (rhodonite)
liquids: 31.54% SiO_2
gases: 3.02% Mn, 2.67% SiO
a combination of two reactions:
(22.2% fuel) $8Si + 5Mn_2O_3 \rightarrow 5MnSiO_3 + Mn_5Si_3$
(32.4% fuel) $27Si + 10Mn_2O_3 \rightarrow 15SiO_2 + 4Mn_5Si_3$

25.13 SILICON + MnO_2

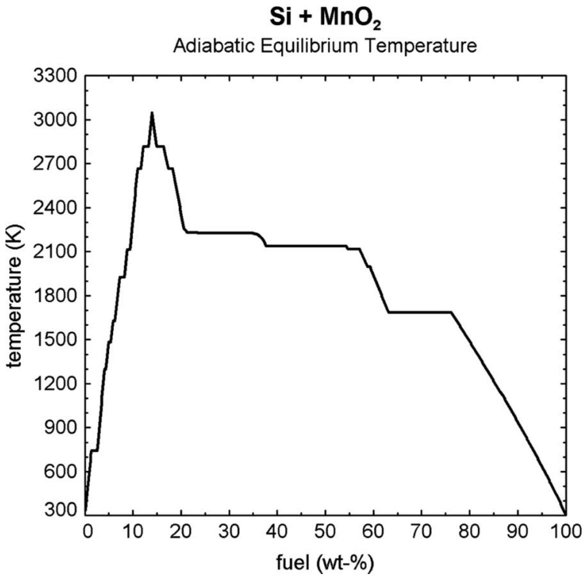

FIGURE 25.18 Adiabatic equilibrium temperature profile, Si (fuel) + MnO_2 (oxidizer).

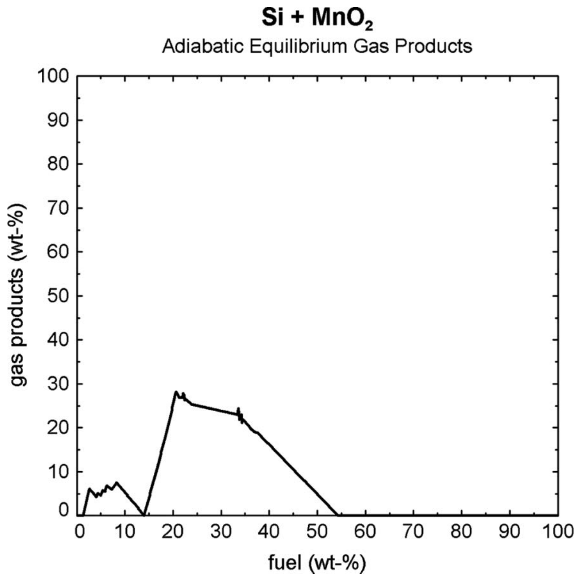

FIGURE 25.19 Adiabatic equilibrium gas production profile, Si (fuel) + MnO_2 (oxidizer).

T1. 5.7% fuel, 5.43% gas produced, 1606.24 K
solids: 53.58% Mn_2O_3 (bixbyite), 40.99% Mn_2SiO_4 (tephroite)
liquids: none
gases: 5.43% O_2
a combination of two reactions:
(13.9% fuel) $Si + 2MnO_2 \rightarrow Mn_2SiO_4$
(decomposition) $4MnO_2 \rightarrow 2Mn_2O_3 + O_2$

T2. 7.1% fuel, 6.01% gas produced, 1898.53 K
solids: 51.06% Mn_2SiO_4 (tephroite), 42.94% Mn_3O_4
liquids: none
gases: 6.00% O_2
a combination of two reactions:
(13.9% fuel) $Si + 2MnO_2 \rightarrow Mn_2SiO_4$
(decomposition) $3MnO_2 \rightarrow Mn_3O_4 + O_2$

T3. 10.9% fuel, 4.00% gas produced, 2646.04 K
solids: 78.33% Mn_2SiO_4 (tephroite)
liquids: 17.67% MnO
gases: 3.93% O_2
a combination of two reactions:
(13.9% fuel) $Si + 2MnO_2 \rightarrow Mn_2SiO_4$
(decomposition) $2MnO_2 \rightarrow 2MnO + O_2$

T4. 12.0% fuel, 2.60% gas produced, 2792.14 K
solids: 55.85% $MnSiO_3$ (rhodonite)
liquids: 41.55% MnO
gases: 2.47% O_2
a combination of two reactions:
(13.9% fuel) $Si + 2MnO_2 \rightarrow MnSiO_3 + MnO$
(decomposition) $2MnO_2 \rightarrow 2MnO + O_2$

T5. 13.9% fuel, 3044.64 K—*peak temperature*
solids: none
liquids: 70.25% MnO, 29.73% SiO_2
gases: none
simplified equation at 13.9% fuel: $Si + 2MnO_2 \rightarrow SiO_2 + 2MnO$

T6. 21.2% fuel, 26.85% gas produced, 2230.98 K
solids: 69.31% $MnSiO_3$ (rhodonite)
liquids: 3.84% Mn
gases: 16.89% Mn, 9.96% SiO
a combination of two reactions:
(17.7% fuel) $2Si + 3MnO_2 \rightarrow 2MnSiO_3 + Mn$
(39.3% fuel) $2Si + MnO_2 \rightarrow 2SiO + Mn$

T7. 37.5% fuel, 18.81% gas produced, 2144.16 K
solids: 49.94% Mn_5Si_3
liquids: 31.25% SiO_2
gases: 17.53% SiO, 1.28% Mn
a combination of two reactions:
(34.1% fuel) $8Si + 5MnO_2 \rightarrow 5SiO_2 + Mn_5Si_3$
(45.6% fuel) $13Si + 5MnO_2 \rightarrow 10SiO + Mn_5Si_3$

T8. 57.1% fuel, 2116.31 K
solids: 40.97% MnSi
liquids: 29.65% SiO_2, 29.38% Si
gases: none
one reaction with excess fuel remaining:
(39.3% fuel) $2Si + MnO_2 \rightarrow SiO_2 + MnSi$

- T6 corresponds to the maximum amount of Mn.
- From 63.1% to 76.1% fuel, the temperature is limited to 1685 K by the Si(s-l) transition.
- From 7.2% to 8.2% fuel, the temperature appears to be limited by the $2Mn_3O_4(s) \rightarrow 6MnO(s) + O_2(g)$ decomposition, which occurs at 1925 K.
- From 58.7% to 59.2% fuel, the temperature is limited to 1996 K by the SiO_2(s-l) transition.
- From 8.8% to 9.3% fuel, the temperature is limited to 2115 K by the MnO(s-l) transition.
- From 54.6% to 57.0% fuel, the temperature appears to be limited by the $5MnSi(s) \rightarrow Mn_5Si_3(s) + 2Si(l)$ decomposition, which occurs at 2119 K.
- The plateau from 37.6% to 54.2% fuel (2138 K) could not be attributed to a simple transition or reaction; species in this region include SiO(g), Mn(g), SiO_2(l), Si(l), and Mn_5Si_3(s). The vaporization of SiO from Si(l)/SiO_2(l) mixtures is expected to occur at 2145 K.

- From 23.8% to 33.9% fuel, the temperature appears to be limited by the $Mn_5Si_3(s)$ + $3SiO_2(l) \rightarrow 5Mn(g) + 6SiO(g)$ reaction, which occurs at 2227 K.
- From 21.3% to 22.1% fuel, the temperature appears to be limited by the $2Mn_5Si_3(s)$ + $3MnSiO_3(s) \rightarrow 13Mn(l\text{-}g) + 9SiO(g)$ reaction, which occurs at 2231 K.
- From 11.0% to 11.6% and 17.3% to 18.1% fuel, the temperature appears to be limited by the $Mn_2SiO_4(s) \rightarrow MnSiO_3(s) + MnO(l)$ decomposition, which occurs at 2665 K.
- From 12.1% to 13.2% and 14.9% to 16.3% fuel, the temperature appears to be limited by the $MnSiO_3(s) \rightarrow MnO(l) + SiO_2(l)$ decomposition, which occurs at 2818 K.

G1. 20.6% fuel, 28.17% gas produced, 2255.15 K—*peak gas*
solids: 71.10% $MnSiO_3$ (rhodonite), 0.53% Mn_2SiO_4 (tephroite)
liquids: 0.20% Mn
gases: 19.87% Mn, 8.30% SiO
a combination of two reactions:
(17.7% fuel) $2Si + 3MnO_2 \rightarrow 2MnSiO_3 + Mn$
(39.3% fuel) $2Si + MnO_2 \rightarrow 2SiO + Mn$

25.14 SILICON + FeO

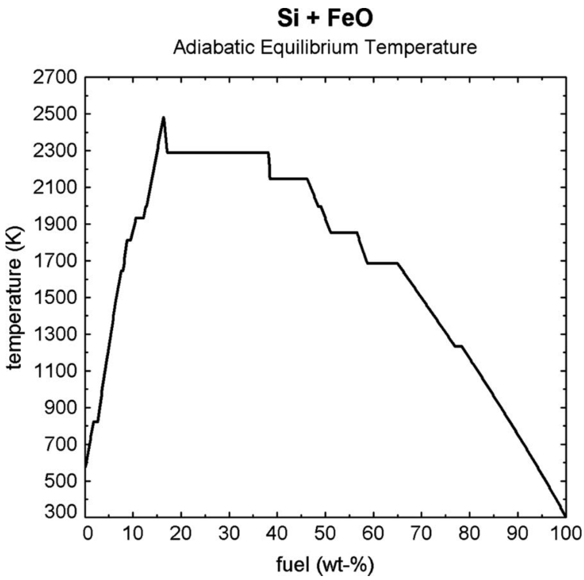

FIGURE 25.20 Adiabatic equilibrium temperature profile, Si (fuel) + FeO (oxidizer).

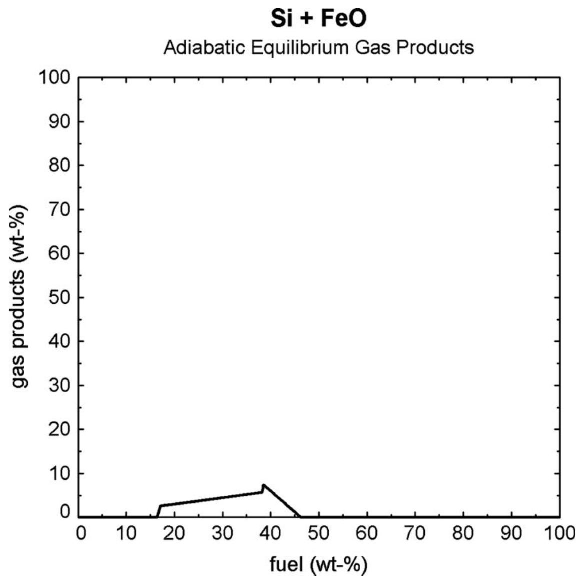

FIGURE 25.21 Adiabatic equilibrium gas production profile, Si (fuel) + FeO (oxidizer).

T1. 8.9% fuel, 1810.95 K
solids: 64.57% Fe_2SiO_4 (fayalite), 23.15% Fe
liquids: 12.25% Fe
gases: none
simplified equation at 8.9% fuel: $Si + 4FeO \rightarrow Fe_2SiO_4 + 2Fe$

T2. 16.3% fuel, 2480.66 K—*peak temperature*
solids: none
liquids: 64.82% Fe, 34.87% SiO_2, 0.31% FeO
gases: none
simplified equation at 16.4% fuel: $Si + 2FeO \rightarrow SiO_2 + 2Fe$

T3. 38.1% fuel, 5.75% gas produced, 2280.81 K
solids: 72.26% FeSi
liquids: 21.99% SiO_2
gases: 5.72% SiO
a combination of two reactions:
(37.0% fuel) $3Si + 2FeO \rightarrow SiO_2 + 2FeSi$
(43.9% fuel) $2Si + FeO \rightarrow SiO + FeSi$

T4. 43.9% fuel, 2.19% gas produced, 2144.85 K
solids: 65.54% FeSi
liquids: 21.97% SiO_2, 10.31% Si
gases: 2.19% SiO
a combination of two reactions with excess fuel remaining:
(37.0% fuel) $3Si + 2FeO \rightarrow SiO_2 + 2FeSi$
(43.9% fuel) $2Si + FeO \rightarrow SiO + FeSi$

T5. 52.6% fuel, 1852.10 K
solids: 41.07% FeSi, 20.69% Fe_3Si_7, 19.82% SiO_2 (cristobalite)
liquids: 18.42% Si
gases: none
a combination of two reactions with excess fuel remaining:
(37.0% fuel) $3Si + 2FeO \rightarrow SiO_2 + 2FeSi$
(52.6% fuel) $17Si + 6FeO \rightarrow 3SiO_2 + 2Fe_3Si_7$

T6. 56.6% fuel, 1845.17 K
solids: 73.32% Fe_3Si_7, 18.15% SiO_2 (cristobalite)
liquids: 8.53% Si
gases: none
one reaction with excess fuel remaining:
(52.6% fuel) $17Si + 6FeO \rightarrow 3SiO_2 + 2Fe_3Si_7$

T7. 78.3% fuel, 1232.64 K
solids: 57.09% Si, 33.83% $FeSi_2$, 9.07% SiO_2 (tridymite)
liquids: none
gases: none
one reaction with excess fuel remaining:
(49.4% fuel) $5Si + 2FeO \rightarrow SiO_2 + 2FeSi_2$

- The maximum amount of iron, 64.98% Fe(l), occurs at 16.4% fuel and 2472.88 K.
- From 76.9% to 78.2% fuel, the temperature appears to be limited by the $3FeSi_2(s) + Si(s) \rightarrow Fe_3Si_7(s)$ reaction, which occurs at 1233 K.
- From 58.7% to 64.9% fuel, the temperature is limited to 1685 K by the Si(s-l) transition.
- From 8.8% to 9.4% fuel, the temperature is limited to 1811 K by the Fe(s-l) transition.
- From 51.1% to 56.5% fuel, the temperature appears to be limited by the $Fe_3Si_7(s) \rightarrow 3FeSi(s) + 4Si(l)$ decomposition, which occurs at 1852 K.
- From 10.7% to 12.1% fuel, the temperature appears to be limited by the $Fe_2SiO_4(s) \rightarrow 2FeO(l) + SiO_2(s)$ decomposition, which occurs at 1933 K.
- From 38.5% to 46.1% fuel, the temperature appears to be limited by the vaporization of SiO from $Si(l)/SiO_2(l)$ mixtures, which occurs at 2145 K.
- From 17.1% to 38.0% fuel, the temperature appears to be limited by the $FeSi(s) + SiO_2(l) \rightarrow Fe(l) + 2SiO(g)$ reaction, which occurs at 2290 K.

G1. 38.5% fuel, 7.34% gas produced, 2144.85 K—*peak gas*
solids: 71.84% FeSi
liquids: 20.71% SiO_2
gases: 7.34% SiO
a combination of two reactions:
(37.0% fuel) $3Si + 2FeO \rightarrow SiO_2 + 2FeSi$
(43.9% fuel) $2Si + FeO \rightarrow SiO + FeSi$

25.15 SILICON + Fe_3O_4

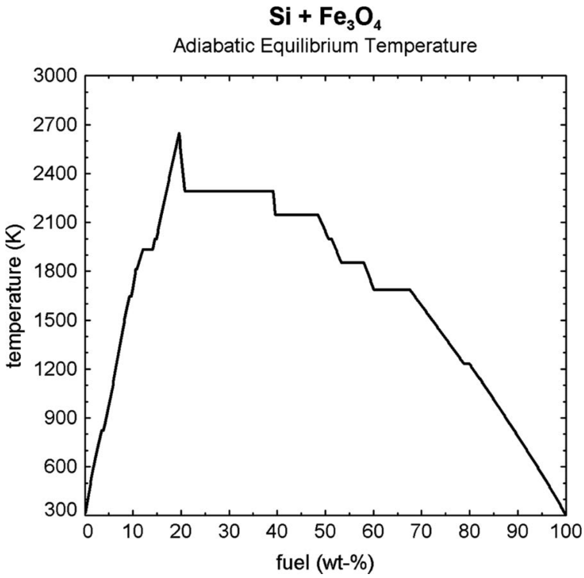

FIGURE 25.22 Adiabatic equilibrium temperature profile, Si (fuel) + Fe_3O_4 (oxidizer).

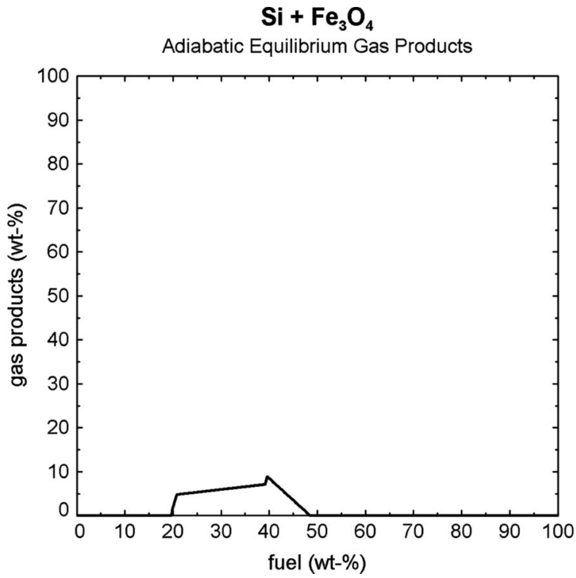

FIGURE 25.23 Adiabatic equilibrium gas production profile, Si (fuel) + Fe_3O_4 (oxidizer).

T1. 5.7% fuel, 1087.52 K
solids: 58.32% FeO (wüstite), 41.36% Fe_2SiO_4 (fayalite), 0.32% Fe_3O_4 (magnetite)
liquids: none
gases: none
simplified equation at 5.7% fuel: $Si + 2Fe_3O_4 \rightarrow Fe_2SiO_4 + 4FeO$

T2. 10.8% fuel, 1810.95 K
solids: 78.36% Fe_2SiO_4 (fayalite), 0.57% Fe
liquids: 20.87% Fe, 0.21% FeO
gases: none
simplified equation at 10.8% fuel: $Si + Fe_3O_4 \rightarrow Fe_2SiO_4 + Fe$

T3. 19.5% fuel, 2644.32 K—*peak temperature*
solids: none
liquids: 58.13% Fe, 41.72% SiO_2, 0.15% FeO
gases: none
simplified equation at 19.5% fuel: $2Si + Fe_3O_4 \rightarrow 2SiO_2 + 3Fe$

T4. 39.2% fuel, 7.38% gas produced, 2266.17 K
solids: 66.07% FeSi
liquids: 26.55% SiO_2
gases: 7.34% SiO
a combination of two reactions:
(37.8% fuel) $5Si + Fe_3O_4 \rightarrow 2SiO_2 + 3FeSi$
(45.9% fuel) $7Si + Fe_3O_4 \rightarrow 4SiO + 3FeSi$

T5. 45.9% fuel, 2.51% gas produced, 2144.85 K
solids: 58.83% FeSi
liquids: 26.37% SiO_2, 12.29% Si
gases: 2.51% SiO
a combination of two reactions with excess fuel remaining:
(37.8% fuel) $5Si + Fe_3O_4 \rightarrow 2SiO_2 + 3FeSi$
(45.9% fuel) $7Si + Fe_3O_4 \rightarrow 4SiO + 3FeSi$

T6. 58.0% fuel, 1848.31 K
solids: 66.05% Fe_3Si_7, 21.80% SiO_2 (cristobalite)
liquids: 12.15% Si
gases: none
one reaction with excess fuel remaining:
(52.2% fuel) $9Si + Fe_3O_4 \rightarrow 2SiO_2 + Fe_3Si_7$

T7. 79.9% fuel, 1230.12 K
solids: 60.40% Si, 29.17% $FeSi_2$, 10.43% SiO_2 (tridymite)
liquids: none
gases: none
one reaction with excess fuel remaining:
(49.2% fuel) $8Si + Fe_3O_4 \rightarrow 2SiO_2 + 3FeSi_2$

- The maximum amount of iron, 58.15% Fe(l), occurs at 19.6% fuel and 2623.95 K.
- From 78.8% to 79.8% fuel, the temperature appears to be limited by the $3FeSi_2(s) + Si(s) \rightarrow Fe_3Si_7(s)$ reaction, which occurs at 1233 K.
- From 60.1% to 67.5% fuel, the temperature is limited to 1685 K by the Si(s-l) transition.
- From 53.3% to 57.9% fuel, the temperature appears to be limited by the $Fe_3Si_7(s) \rightarrow 3FeSi(s) + 4Si(l)$ decomposition, which occurs at 1852 K.
- From 12.1% to 14.0% fuel, the temperature appears to be limited by the $Fe_2SiO_4(s) \rightarrow 2FeO(l) + SiO_2(s)$ decomposition, which occurs at 1933 K.
- From 14.5% to 14.8% and 50.7% to 51.2% fuel, the temperature is limited to 1996 K by the SiO_2(s-l) transition.
- From 39.6% to 48.4% fuel, the temperature appears to be limited by the vaporization of SiO from Si(l)/SiO_2(l) mixtures, which occurs at 2145 K.
- From 20.8% to 39.1% fuel, the temperature appears to be limited by the $FeSi(s) + SiO_2(l) \rightarrow Fe(l) + 2SiO(g)$ reaction, which occurs at 2290 K.

G1. 39.5% fuel, 8.81% gas produced, 2149.83 K—*peak gas*
solids: 65.79% FeSi
liquids: 25.40% SiO_2
gases: 8.81% SiO
a combination of two reactions:
(37.8% fuel) $5Si + Fe_3O_4 \rightarrow 2SiO_2 + 3FeSi$
(45.9% fuel) $7Si + Fe_3O_4 \rightarrow 4SiO + 3FeSi$

25.16 SILICON + Fe_2O_3

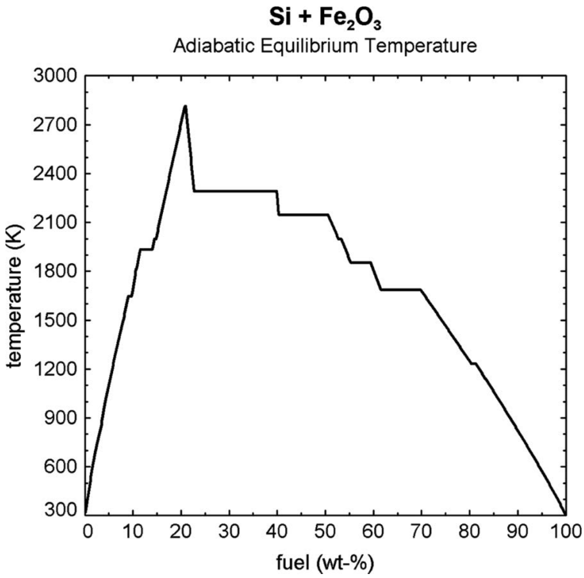

FIGURE 25.24 Adiabatic equilibrium temperature profile, Si (fuel) + Fe_2O_3 (oxidizer).

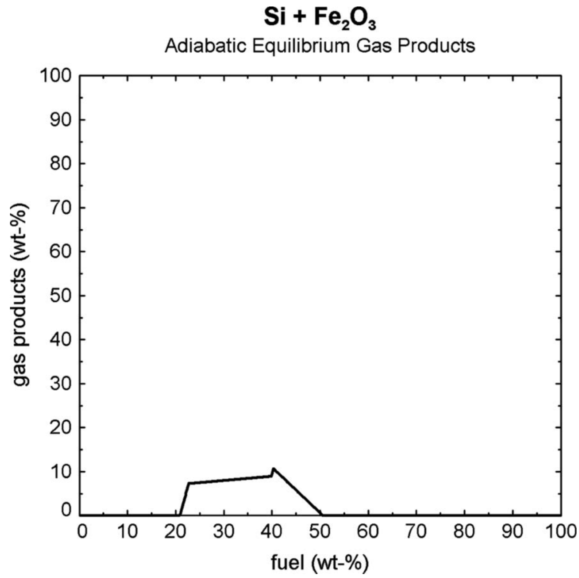

FIGURE 25.25 Adiabatic equilibrium gas production profile, Si (fuel) + Fe_2O_3 (oxidizer).

T1. 8.1% fuel, 1521.76 K
solids: 58.77% Fe_2SiO_4 (fayalite), 41.16% FeO (wüstite)
liquids: none
gases: none
simplified equation at 8.1% fuel: $Si + 2Fe_2O_3 \rightarrow Fe_2SiO_4 + 2FeO$

T2. 11.4% fuel, 1920.47 K
solids: 82.71% Fe_2SiO_4 (fayalite)
liquids: 14.35% Fe, 2.94% FeO
gases: none
a combination of two reactions:
(8.1% fuel) $Si + 2Fe_2O_3 \rightarrow Fe_2SiO_4 + 2FeO$
(11.7% fuel) $3Si + 4Fe_2O_3 \rightarrow 3Fe_2SiO_4 + 2Fe$

T3. 20.9% fuel, 0.22% gas produced, 2812.05 K—*peak temperature*
solids: none
liquids: 55.20% Fe, 44.50% SiO_2
gases: 0.16% SiO
simplified equation at 20.9% fuel: $3Si + 2Fe_2O_3 \rightarrow 3SiO_2 + 4Fe$

T4. 39.9% fuel, 9.22% gas produced, 2265.12 K
solids: 63.12% FeSi
liquids: 27.67% SiO_2
gases: 9.18% SiO
a combination of two reactions:
(38.1% fuel) $7Si + 2Fe_2O_3 \rightarrow 3SiO_2 + 4FeSi$
(46.8% fuel) $5Si + Fe_2O_3 \rightarrow 3SiO + 2FeSi$

T5. 46.8% fuel, 3.86% gas produced, 2144.85 K
solids: 55.92% FeSi
liquids: 27.40% SiO_2, 12.82% Si
gases: 3.86% SiO
a combination of two reactions with excess fuel remaining:
(38.1% fuel) $7Si + 2Fe_2O_3 \rightarrow 3SiO_2 + 4FeSi$
(46.8% fuel) $5Si + Fe_2O_3 \rightarrow 3SiO + 2FeSi$

T6. 59.5% fuel, 1844.79 K
solids: 61.57% Fe_3Si_7, 22.86% SiO_2 (cristobalite)
liquids: 15.58% Si
gases: none
one reaction with excess fuel remaining:
(52.0% fuel) $37Si + 6Fe_2O_3 \rightarrow 9SiO_2 + 4Fe_3Si_7$

T7. 81.2% fuel, 1231.95 K
solids: 63.01% Si, 26.38% $FeSi_2$, 10.61% SiO_2 (tridymite)
liquids: none
gases: none
one reaction with excess fuel remaining:
(49.2% fuel) $11Si + 2Fe_2O_3 \rightarrow 3SiO_2 + 4FeSi_2$

- T3 corresponds to the maximum amount of Fe.
- From 80.3% to 81.1% fuel, the temperature appears to be limited by the $3FeSi_2(s) + Si(s) \rightarrow Fe_3Si_7(s)$ reaction, which occurs at 1233 K.
- From 9.0% to 9.6% fuel, the temperature is limited to 1644 K by the FeO(s-l) transition.
- From 61.5% to 69.7% fuel, the temperature is limited to 1685 K by the Si(s-l) transition.
- From 55.3% to 59.4% fuel, the temperature appears to be limited by the $Fe_3Si_7(s) \rightarrow 3FeSi(s) + 4Si(l)$ decomposition, which occurs at 1852 K.
- From 11.5% to 13.9% fuel, the temperature appears to be limited by the $Fe_2SiO_4(s) \rightarrow 2FeO(l) + SiO_2(s)$ decomposition, which occurs at 1933 K.
- From 52.7% to 53.2% fuel, the temperature is limited to 1996 K by the SiO_2(s-l) transition.
- From 40.3% to 50.5% fuel, the temperature appears to be limited by the vaporization of SiO from Si(l)/SiO_2(l) mixtures, which occurs at 2145 K.
- From 22.7% to 39.8% fuel, the temperature appears to be limited by the $FeSi(s) + SiO_2(l) \rightarrow Fe(l) + 2SiO(g)$ reaction, which occurs at 2290 K.

G1. 40.2% fuel, 10.64% gas produced, 2149.33 K—*peak gas*
solids: 62.86% FeSi
liquids: 26.50% SiO_2
gases: 10.64% SiO
a combination of two reactions:
(38.1% fuel) $7Si + 2Fe_2O_3 \rightarrow 3SiO_2 + 4FeSi$
(46.8% fuel) $5Si + Fe_2O_3 \rightarrow 3SiO + 2FeSi$

25.17 SILICON + CoO

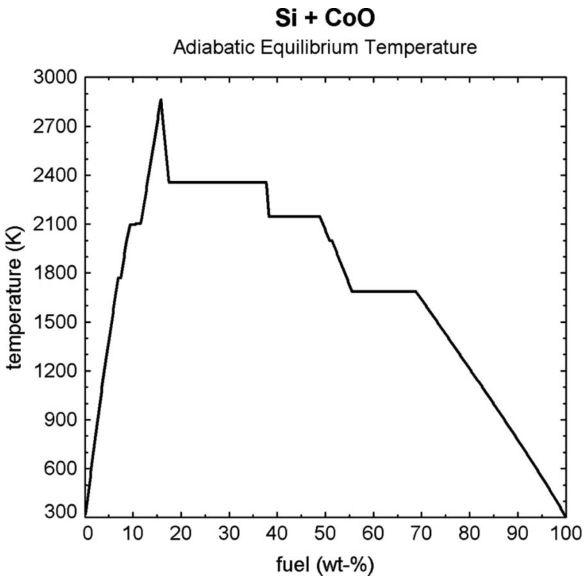

FIGURE 25.26 Adiabatic equilibrium temperature profile, Si (fuel) + CoO (oxidizer).

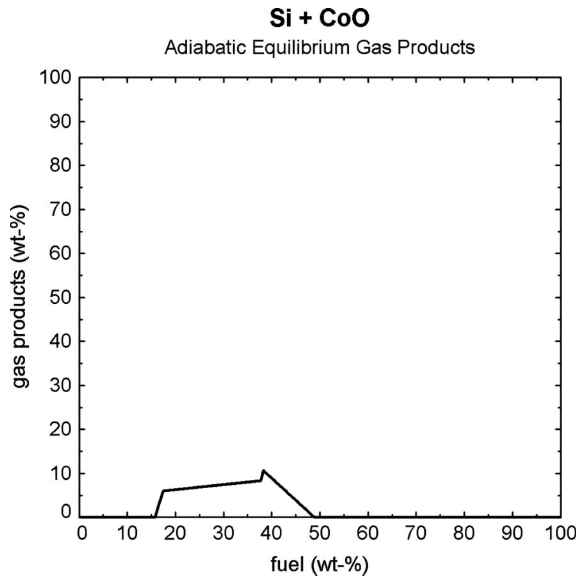

FIGURE 25.27 Adiabatic equilibrium gas production profile, Si (fuel) + CoO (oxidizer).

T1. 8.6% fuel, 1991.29 K
solids: 63.76% Co_2SiO_4, 0.15% SiO_2 (cristobalite)
liquids: 36.09% Co
gases: none
simplified equation at 8.6% fuel: $Si + 4CoO \rightarrow Co_2SiO_4 + 2Co$

T2. 15.8% fuel, 2861.89 K—*peak temperature*
solids: none
liquids: 66.20% Co, 33.71% SiO_2
gases: none
simplified equation at 15.8% fuel: $Si + 2CoO \rightarrow SiO_2 + 2Co$

T3. 37.7% fuel, 8.50% gas produced, 2336.94 K
solids: 72.29% CoSi
liquids: 19.22% SiO_2
gases: 8.46% SiO
a combination of two reactions:
(36.0% fuel) $3Si + 2CoO \rightarrow SiO_2 + 2CoSi$
(42.8% fuel) $2Si + CoO \rightarrow SiO + CoSi$

T4. 42.8% fuel, 6.00% gas produced, 2144.86 K
solids: 66.43% CoSi
liquids: 18.84% SiO_2, 8.73% Si
gases: 6.00% SiO
a combination of two reactions with excess fuel remaining:
(36.0% fuel) $3Si + 2CoO \rightarrow SiO_2 + 2CoSi$
(42.8% fuel) $2Si + CoO \rightarrow SiO + CoSi$

- T2 corresponds to the maximum amount of cobalt.
- From 55.6% to 68.7% fuel, the temperature is limited to 1685 K by the Si(s-l) transition.
- From 6.9% to 7.3% fuel, the temperature is limited to 1768 K by the Co(s-l) transition.
- From 50.9% to 51.3% fuel, the temperature is limited to 1996 K by the SiO_2(s-l) transition.
- From 9.4% to 10.4% fuel, the temperature appears to be limited by the $Co_2SiO_4(s) \rightarrow 2CoO(s) + SiO_2(l)$ decomposition, which occurs at 2096 K.
- From 10.6% to 11.5% fuel, the temperature is limited to 2103 K by the CoO(s-l) transition.
- From 38.2% to 48.7% fuel, the temperature appears to be limited by the vaporization of SiO from Si(l)/SiO_2(l) mixtures, which occurs at 2145 K.
- From 17.4% to 37.6% fuel, the temperature appears to be limited by the $CoSi(s) + SiO_2(l) \rightarrow Co(l) + 2SiO(g)$ reaction, which occurs at 2354 K.

G1. 38.2% fuel, 10.62% gas produced, 2144.86 K—*peak gas*
solids: 71.77% CoSi
liquids: 17.55% SiO_2
gases: 10.61% SiO
a combination of two reactions:
(36.0% fuel) $3Si + 2CoO \rightarrow SiO_2 + 2CoSi$
(42.8% fuel) $2Si + CoO \rightarrow SiO + CoSi$