Table 2-59 Chemical Reactions and Heats of Combustion of Pure Combustible Materials
[perfect combustion (except No. 1)]

			Heat of combustion,[a] Btu per						
				lb of vapor (except C & S)		cu ft			
No.	Combustible material	Reaction	lb-mole gross	gross	net[b]	gross	net[b]	gal liquid gross	Cu ft gas per gal liquid[c]
1	Carbon (graphite)	$C + 0.5\,O_2 = CO$	47,460	3,950	3,950	...	...		
2	Carbon (coke)	$C + O_2 = CO_2$	174,000	14,500	14,500	...	...		
3	Graphite	$C + O_2 = CO_2$	169,860	14,093	14,093	...	...		
4	Carbon monoxide	$CO + 0.5\,O_2 = CO_2$	122,400	4,347	4,347	321.37[d]	321.37[d]		
5	Hydrogen	$H_2 + 0.5\,O_2 = H_2O$	123,100	61,095	51,623	325.02[d]	274.58[d]		
Paraffin hydrocarbons									
6	Methane	$CH_4 + 2\,O_2 = CO_2 + 2\,H_2O$	382,980	23,875	21,495	1012.32[d]	911.45[d]	59,755	59.0
7	Ethane	$C_2H_6 + 3.5\,O_2 = 2\,CO_2 + 3\,H_2O$	671,190	22,323	20,418	1773.42[d]	1622.10[d]	74,010	41.3
8	Propane	$C_3H_8 + 5\,O_2 = 3\,CO_2 + 4\,H_2O$	955,430	21,669	19,937	2523.82[d]	2322.01[d]	91,740	35.91
9	*n*-Butane	$C_4H_{10} + 6.5\,O_2 = 4\,CO_2 + 5\,H_2O$	1,239,130	21,321	19,678	3270.69[d]	3018.48[d]	103,787	30.77
10	*iso*-Butane	$C_4H_{10} + 6.5\,O_2 = 4\,CO_2 + 5\,H_2O$	1,236,230	21,271	19,628	3261.17[d]	3008.96[d]	100,176	29.77
11	*n*-Pentane	$C_5H_{12} + 8\,O_2 = 5\,CO_2 + 6\,H_2O$	1,521,880	21,095	19,507	4019.65[d]	3717.15[d]	105,822	26.35
12	*iso*-Pentane	$C_5H_{12} + 8\,O_2 = 5\,CO_2 + 6\,H_2O$	1,518,410	21,047	19,459	4010.71[d]	3708.01[d]	104,863	26.17
13	Neopentane	$C_5H_{12} + 8\,O_2 = 5\,CO_2 + 6\,H_2O$	1,513,440	20,978	19,390	3994	3692	104,603	26.19
14	*n*-Hexane	$C_6H_{14} + 9.5\,O_2 = 6\,CO_2 + 7\,H_2O$	1,806,620	20,966	19,415	4768.27[d]	4415.23[d]	108,806	22.82
15	Neohexane	$C_6H_{14} + 9.5\,O_2 = 6\,CO_2 + 7\,H_2O$	1,803,600	20,931	19,380	4760	4407		
16	*n*-Heptane	$C_7H_{16} + 11\,O_2 = 7\,CO_2 + 8\,H_2O$	2,089,530	20,854	19,329	5459	5056	108,907	19.95
17	Triptane	$C_7H_{16} + 11\,O_2 = 7\,CO_2 + 8\,H_2O$	2,086,520	20,824	19,299	5445	5042		
18	*n*-Octane	$C_8H_{18} + 12.5\,O_2 = 8\,CO_2 + 9\,H_2O$	2,375,400	20,796	19,291	6260	5806	111,240	17.77
19	*iso*-Octane	$C_8H_{18} + 12.5\,O_2 = 8\,CO_2 + 9\,H_2O$	2,372,430	20,770	19,265	6249	5795		
Olefin series									
20	Ethylene	$C_2H_4 + 3\,O_2 = 2\,CO_2 + 2\,H_2O$	606,910	21,636	20,275	1603.75[d]	1502.87[d]	71,504	44.33
21	Propylene	$C_3H_6 + 4.5\,O_2 = 3\,CO_2 + 3\,H_2O$	885,640	21,048	19,687	2339.70[d]	2188.40[d]	87,390	37.41
22	Butylene (*n*-Butene)	$C_4H_8 + 6\,O_2 = 4\,CO_2 + 4\,H_2O$	1,169,950	20,854	19,493	3084	2885		
23	*iso*-Butene	$C_4H_8 + 6\,O_2 = 4\,CO_2 + 4\,H_2O$	1,163,390	20,737	19,376	3069	2868	102,106	33.27
24	*n*-Pentene	$C_5H_{10} + 7.5\,O_2 = 5\,CO_2 + 5\,H_2O$	1,453,050	20,720	19,359	3837	3585		
Aromatic series									
25	Benzene	$C_6H_6 + 7.5\,O_2 = 6\,CO_2 + 3\,H_2O$	1,420,300	18,184	17,451	3751.68[d]	3600.52[d]	129,724	34.63
27	Toluene	$C_7H_8 + 9\,O_2 = 7\,CO_2 + 4\,H_2O$	1,704,530	18,501	17,672	4486.44[d]	4284.81[d]	129,003	28.68
27	*p*-Xylene	$C_8H_{10} + 10.5\,O_2 = 8\,CO_2 + 5\,H_2O$	1,978,040	18,633	17,734	5223	4971	127,988	24.50
Miscellaneous gases									
28	Acetylene	$C_2H_2 + 2.5\,O_2 = 2\,CO_2 + H_2O$	559,830	21,502	20,769	1476.55[d]	1426.17[d]		
29	Naphthalene	$C_{10}H_8 + 12\,O_2 = 10\,CO_2 + 4\,H_2O$	2,217,590	17,303[e]	16,708[e]	5854[e]	5654[e]		
30	Methyl alcohol	$CH_3OH + 1.5\,O_2 = CO + 2\,H_2O$	328,680	10,258	9,066	868	767	66,775	76.93
31	Ethyl alcohol	$C_2H_5OH + 3\,O_2 = 2\,CO_2 + 3\,H_2O$	606,290	13,161	11,917	1600	1449	85,360	53.35
32	Ammonia[f]	$NH_3 + 0.75\,O_2 = 0.5N_2 + 1.5\,H_2O$	164,640	9,667	7,985	441	364		
33	Sulfur	$S + O_2 = SO_2$	127,800	3,980	3,980	...	...		
34	Hydrogen sulfide	$H_2S + 1.5\,O_2 = SO_2 + H_2O$	241,840	7,097	6,537	646	595	46,822	72.48
35	Formaldehyde[g]	$HCHO + O_2 = CO_2 + H_2O$	209,540	6,980	6,344	643	593		
36	Formic acid[g]	$HCOOH + 0.5\,O_2 = CO_2 + H_2O$	112,700	2,450	2,035	301	251		
37	Acetaldehyde[g]	$CH_3CHO + 2.5\,O_2 = 2\,CO_2 + 2\,H_2O$	501,160	11,390	10,523	1360	1259		
38	Nitric oxide[b]	$NO + 0.5\,O_2 = NO_2$	128,800	4,270	4,270	339[i]	339		
39	Nitrogen tetroxide[h]	$N_2O_4 + 0.5\,O_2 = N_2O_5$	108,000	1,175	1,175	284[i]	284		

[a] All values corrected to 60 F, 30 in. Hg dry. For gases saturated with water vapor at 60 F, deduct 1.74 per cent of the Btu value. Rossini, F. D., and others. *Selected Values of Physical and Thermodynamic Properties of Hydrocarbons and Related Compounds.* (Res. Proj. 44) Pittsburgh, Pa., Am. Petrol. Inst., 1953. Estimated uncertainty of values varies from <0.01 to 0.1 per cent [Rossini, F. D., and others. *Tables of Selected Values of Properties of Hydrocarbons.* (U.S. Nat.Bur. Std. C461), 1947].

[b] Addition from net to gross heating value determined by adding 19,095 Btu per lb-mole of water in the products of combustion. Keenan, J. H., and Keyes, F. G. *Thermodynamic Properties of Steam.* New York, Wiley, 1936.

[c] "Actual" volume of gas at 60 F and 760 mm formed upon vaporization; considered deviation from perfect gas laws. Matteson, R., and Hanna, U. S. "Physical Constants of Low Boiling-Point Hydrocarbons." *Oil & Gas J.* 41:33–7, 1942.

[d] Mason, D. McA., and Eakin, E. E. "Proposed Standard Method for Calculating Heating Value and Specific Gravity from Gas Composition." *A.G.A. Proc.* 1961: CEP-61-11.

[e] A.G.A. *Combustion*, 3rd ed., rev. New York, A.G.A., 1938.

[f] Does not readily react in air; reaction takes place in pure oxygen. In presence of platinum catalyst: $4\,NH_3 + 5\,O_2 = 4\,NO + 6\,H_2O$.

[g] Calculated from *Handbook of Chemistry and Physics*, 28th ed., p. 1436–44. Cleveland, Ohio, Chemical Rubber Co., 1945.

[h] Shnidman, L., ed. *Gaseous Fuels*, 2nd ed., p. 273. New York, A.G.A., 1954.

[i] Btu per lb-mole divided by 380.

Table 2-60 Chemical Reactions and Heats of Combustion Involved in the Incomplete Combustion of Pure Combustible Materials

		Heat of combustion,* Btu per		
Combustible material	Reaction	lb-mole gross	lb gross	cu ft† gross
Carbon to carbon monoxide	$C + {}^1/_2\,O_2 = CO$	‡	‡	‡
Methane to CO and water	$CH_4 + {}^3/_2\,O_2 = CO + 2\,H_2O$	260,580	16,245	691.0
Methane to CO and H_2	$CH_4 + {}^1/_2\,O_2 = CO + 2\,H_2$	14,380	896	41.0
Methane to formaldehyde	$CH_4 + O_2 = HCHO + H_2O$	173,440	10,812	369.8
Methane to formic acid	$CH_4 + {}^3/_2\,O_2 = HCOOH + H_2O$	270,280	16,849	711.8
Methane to methyl alcohol	$CH_4 + {}^1/_2\,O_2 = CH_3OH$	54,300	3,385	144.8
Ethane to CO	$C_2H_6 + {}^5/_2\,O_2 = 2\,CO + 3\,H_2O$	426,390	14,181	1148.4
Ethane to acetaldehyde	$C_2H_6 + O_2 = CH_3CHO + H_2O$	170,030	5,655	432.0
Ethane to ethyl alcohol	$C_2H_6 + {}^1/_2\,O_2 = C_2H_5OH$	64,900	2,159	192.0

* Calculated by subtracting the heat of combustion of the unburned product of reaction from the heat of reaction to complete combustion.
† All volumes corrected to 60 F, 30-in. Hg dry.
‡ See Table 2-59.

the temperature and pressure of the gas, composition of the gas, and amount of heat lost thru the compressor walls.

Atomic or Nuclear Energy.[7] The energy released in a nuclear pile appears as the kinetic energy of the fragments of the **fission** of uranium and thorium atoms. The fragments are charged electrically and give off a portion of their energy to the negative particles of each of the atoms thru which they travel. Their kinetic energy is dissipated in speeding up the atoms surrounding them and is converted to heat. It is this heat which is utilized in generating power from nuclear reactions.

Combustion Reactions

Combustion data presented in Tables 2-59, 2-63, and 2-89 are based on perfect combustion. In practical applications, excess air is usually present, and therefore complete combustion is the more appropriate term. Gas appliance performance standards as established in American Standard Approval Requirements, ASA Committee Z21, permit slight but stated departures from "complete combustion." For most appliances, the limit of carbon monoxide which may be present in the dry, air-free flue products is 0.04 per cent. Some types of appliances have limits which vary slightly above or below this figure because of low input rates, intermittent operation, and general operating conditions. These limits for flue gas composition ensure that the maximum amounts of CO which may develop in room air from the use of unvented gas appliances will be far below levels which might be harmful to the occupants. Vented appliances are subject to similar CO limits because of the possibility that the venting system might fail to function properly.

Incomplete or Partial Combustion. In certain industrial operations incomplete or partial combustion of the gas fuel is required; the resultant products of combustion are primarily carbon monoxide and hydrogen.

Table 2-60 presents representative chemical reactions of carbon, methane, and ethane when they are burned *incompletely*, as well as their respective calculated **heats of combustion.** Other hydrocarbons would react in the partial combustion process in a manner similar to methane and ethane. Products of incomplete combustion of carbon monoxide or hydrogen are not found by ordinary methods of analysis. Reactions in the combustion of hydrogen[2,8] involve chain carriers, of which the hydroxyl radical OH is very prominent. How the first OH radical is formed is not known; probably hydrogen peroxide forms on the walls of the containing vessel and then decomposes with subsequent conversion of hydrogen to water as follows:

$$H_2O_2 + M \rightarrow 2\,OH + M$$

where M = any third body, such as a wall or a gas molecule

$$OH + H_2 \rightarrow H_2O + H$$

$$H + O_2 \rightarrow OH + O$$

$$O + H_2 \rightarrow OH + H$$

Table 2-61 Products of Incomplete Combustion[9] of Three Gases With Limited Air Supply, Self-Supporting Flame, and No External Heat

(at one atmosphere pressure)

	Natural	Coke oven	Butane
Heating value of gas, Btu per cu ft	1108	534	3207
Specific gravity of gas	0.63	0.404	2.0
Aeration (100 per cent required for complete combustion)	67.5%	49.5%	49.0%
Products of combustion on dry, air-free basis, per cent			
Orsat analysis:			
Carbon dioxide	3.4	4.6	4.3
Unsaturated hydrocarbons	0.1	0.3	2.0
Carbon monoxide	9.6	11.4	13.5
Hydrogen	9.9	15.4	9.6
Methane	0.3	0.4	3.5
Nitrogen (100 minus sum of above)	76.7	67.9	67.1
Total	100.0	100.0	100.0
Chemical analysis:			
Formaldehyde	0.0133	0.00302	0.0842
Acetaldehyde	.00008	.0002	.0052
Clyoxal	.0005	.00009	.0023
Formic acid	.00282	.00097	.0028
Methyl alcohol	< .0004	< .00025	< .006
Combined nitrogen	0.00106	0.00046	0.00106
Total	0.01816	0.00499	0.11956

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