Table 1. Heats and products of combustion in oxygen.

Fuel	Atomic or molecular weight	Kcal/g of fuel	Kcal/g-atom or g-mole of fuel	Product of combustion
		Metals		
Mg	24.32	5.920	143.940	MgO
Al	26.97	7.410	199.525	Al_2O_3
Zr	91.22	2.840	258.800	ZrO_2
Fe	55.85	1.670	95.350	Fe_2O_3
		Nonmetals		
H_2	2.016	34.20	68.400	H_2O
C(graphite)	12.000	2.20	26.428	CO
C(graphite)	12.000	7.88	94.385	CO_2
CH_4	16.032	13.20	210.800	H_2O and CO_2
CO	28.000	2.42	67.797	CO_2

weights. However, on a molar basis, all the metals listed (with the exception, of course, of iron) generate more heat than either hydrogen or carbon, in accordance with their positions in the periodic system as electropositive elements. It is because the metals are much more costly than either coal or oil, since they have to be produced from their oxides by reduction, that we do not use them as fuel in our daily lives.

Methods were developed at our institute to burn many metals at atmospheric pressure. The metals were burned in the solid state (as rods, pipes, balls, sheets, and powders), in the liquid state, and in the vapor state. The expected adiabatic temperatures in the range of 3000° to 5000°K were reached (*2*). The highest temperature, close to 5000°K, was attained (*3*) through burning zirconium powder in a torch-type apparatus. Beryllium, at pressure of 1 atmosphere, in oxygen produces a temperature of 4300°K, and aluminum and magnesium, temperatures of 3800° and 3350°K, respectively.

Various types of apparatus have been developed for the combustion of metals (see *2–4*). A typical autoclave for the combustion of metals, either under pressure (up to 75 lb/in.^{2}) or in a vacuum (down to 4 mm-Hg) is shown in Fig. 1. Metals are fed in the form of a rod through the stuffing box at right or, as balls or small rods, by gravity through the side arm at left. The combustion phenomena may be observed through the sight glass (diameter, 4 in.) at the top of the autoclave. One combustion phenomenon of general interest is the so-called "skating sun" observed during the burning and boiling of aluminum metal (*5*); this was first observed on 29 December 1948. It was called a "sun" because of its brilliance and disk-like shape; the vapor of boiling aluminum burns in oxygen in a regular flame front, a fraction of a millimeter above the surface of the boiling metal. Suns up to 6 inches in diameter were observed; these burned down to minute drops if the metal was pure. The suns "skate" on the surface of the liquid alumina because of their lower density; because of their surface tension, thickness, and vapor pressure they have great mobility.

Whereas aluminum, as every housewife knows, does not burn in air, it does burn readily in the apparatus shown in Fig. 1, even at 4 mm-Hg oxygen pressure, a concentration of oxygen 35 times less than that in air.

The experiments on metal combustion gave the Institute valuable experience in containing and handling large quantities—1 or more liters—of liquid alumina, liquid magnesia, and other materials at high temperatures.

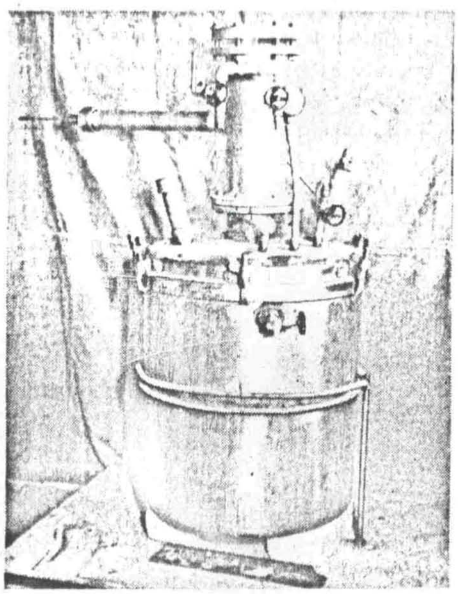

Fig. 1. Autoclave for the combustion of metals either under pressure (up to 75 lb/in.^{2}) or in a vacuum (down to 4 mm-Hg). Metals are fed either in the form of rod through the stuffing box or through the side arm by gravity feed. Observation is through the sight glass (diameter, 4 in.) at the top of the autoclave.

Combustion of Gases

While study of the combustion of metals was being continued, we turned our attention to conventional flames, with the objective of reaching higher temperatures. As I mentioned earlier, the production of very high temperatures depends in part on the thermal stability of the reaction product. Fluorine is the most electronegative element known, and thus many fluorine compounds are more stable than the corresponding oxides, because of the greater strength of the fluorine bond. A good example is hydrogen fluoride. When it is formed from hydrogen and fluorine a flame temperature of 4000°K is reached (*6, 7*). At a total pressure of 5 atmospheres the temperature is raised to 4200°K (*6*). In contrast, the maximum temperature of the hydrogen-oxygen flame is only 2930°K at atmospheric pressure.

Two of the most stable nondissociating, nonmetallic compounds are CO and N_2. Thus, if we can burn an organic compound (particularly an endothermic one) to form these products we will have attained high flame temperatures. Useful endothermic compounds are cyanogen and the carbon subnitrides (or dicyanoacetylenes) $N{\equiv}C{-}(C{\equiv}C)_n{-}C{\equiv}N$, for which the general formula is $C_{(2n+2)}N_2$.

When a mixture of cyanogen and oxygen was burned according to the equation $(CN)_2 + O_2 \longrightarrow 2CO + N_2$, one of the highest flame temperatures so far attained, 4800°K (at atmospheric pressure), was produced (*8*). By burning the same mixture under a total pressure of 100 pounds per square inch, a temperature of 5050°K was attained (*9*).

It was found that the unstable colorless liquid, carbon subnitride, C_4N_2—the first member of the dicyanoacetylene series—can be burned with oxygen (*10*) in either a diffusion flame or a flame of premixed type, according to the equation $C_4N_2 + 2O_2 \longrightarrow 4CO + N_2$. The calculated flame temperature is 5260°K at atmospheric pressure.

Since the flame temperature calculated for the cyanogen-oxygen flame has been checked experimentally (*8*), the enthalpy data for CO and N_2 may be used with confidence. The accuracy of the calculated flame temperatures is ±2°. In all these combustion studies ordinary oxygen, O_2, was used. It was recognized that significantly higher temperatures could be obtained if ozone, O_3, were substituted for O_2. The heat