of formation of ozone from oxygen is +33.98 kilocalories per mole of ozone; thus, the amount of heat liberated is increased, and, provided the stoichiometry of the combustion is adjusted to produce the same reaction products as with oxygen, the flame temperature is also increased.

However, pure ozone in either gaseous, liquid, or solid form may detonate with great violence to molecular oxygen, although with proper handling it can be made to burn in a regular, but faint and nonluminous, blue flame (*11*) to oxygen, according to the equation $2O_3 \longrightarrow 3O_2$. Because of the experience we had gained in handling and burning 100-percent ozone we were able to premix and burn various mixtures of hydrogen (*12*) and cyanogen (*13*) with ozone. The mixture $3(CN)_2 + 2O_3$ burns uniformly, noiselessly, as brightly as an electric arc, and with a pink-violet color: $3(CN)_2 + 2O_3 \longrightarrow 6CO + 3N_2$. At pressures of 1 and 10 atmospheres, its calculated temperatures are 5208° and 5506°K (±2°), respectively. The temperatures of the corresponding oxygen flame, $3(CN)_2 + 3O_2 \longrightarrow 6CO + 3N_2$, are 4856° and 5025°K, respectively.

The cyanogen-ozone and the carbon subnitride-oxygen flames, with temperatures of 5208° and 5260°K, respectively, produce the highest chemical-flame temperatures achieved to date at pressure of 1 atmosphere. Calculations indicate (*10*) that substitution of ozone for oxygen in the carbon subnitride-oxygen flame, provided explosions and detonations could be avoided, particularly under pressure, would produce a temperature higher than 6000°K (see Table 2). These flame temperatures represent the ultimate goals with chemical reactions.

Table 2. Temperature attainable through substitution of ozone for oxygen in the carbon subnitride-oxygen flame.

Reaction	Flame temperature (deg K)		
	1.0 atm	10.0 atm	600 lb/in.² (atmospheric)
$(C_4N_2)g + 2O_2 \longrightarrow 4CO + N_2$ $\Delta H_{298°} = 254.6$ kcal	5,261	5,573	5,748
$(C_4N_2)g + 4/3\ O_3 \longrightarrow 4CO + N_2$ $\Delta H_{298°} = 299.9$ kcal	5,516	5,936	6,100

Plasma Jets

We recognized long before our flame studies were completed that to achieve higher temperatures and to be able to heat gases of low molecular weight for extended periods, in order to get high specific impulses, other means of generating energy were necessary. As a parallel project, it was necessary to develop new methods of confining or containing chemical substances at high temperatures.

In 1958 the Institute started research on plasma jets (*14, 15*). The use of electrical energy, particularly in the form of the well-known electric arc, offers great possibilities for chemical research.

Plasma is often referred to as the "fourth state of matter," since in a plasma the number of positive ions and electrons exceeds the number of neutral atoms or molecules.

The development of plasma jets resulted from the work of various investigators, primarily in Germany. In 1910 Beck described the high-current carbon arc. Next came Gerdien's researches in 1923 on the steam arc. Having improved the Gerdien arc, Maecker and Peters, in 1951, were able to attain a plasma temperature of 50,000°K, using currents of 1500 amperes. In 1954 Peters inserted a nozzle into the anode of a steam arc burning under pressure and produced a high-temperature plasma jet which emerged from the nozzle at supersonic velocity; thus, the prototype of the modern plasma jet flame was created (*16*).

Use of the noble gases helium and argon makes it possible to produce a chemically inert "flame" of temperature up to 25,000°K. The ionization of argon to $A^+ + e^-$ begins to occur at 10,000°K; due to the rapid increase in ionization between 15,000° and 20,000°K, the heat content rises sharply. The first ionization potential of argon is 15.68 volts, equivalent to 362 kilocalories per gram atom; that of helium is 24.46 volts or 565 kilocalories per gram atom. Helium begins to ionize appreciably only in the 20,000° to 25,000°K range, and therefore its heat content is lower than that of argon. Up to 10,000°K both gases exist as neutral atoms.

Liquid Metals as High-Temperature Substances

Let me emphasize the difference between the problem of containing hot gases and that of containing hot liquids or solids. The densities of liquids or solids at high temperatures are about 100,000 times greater than the densities of gases at pressure of 1 atmosphere, and consequently the concentrations of energy are that many times greater. For this reason, to confine hot gases is comparatively easy.

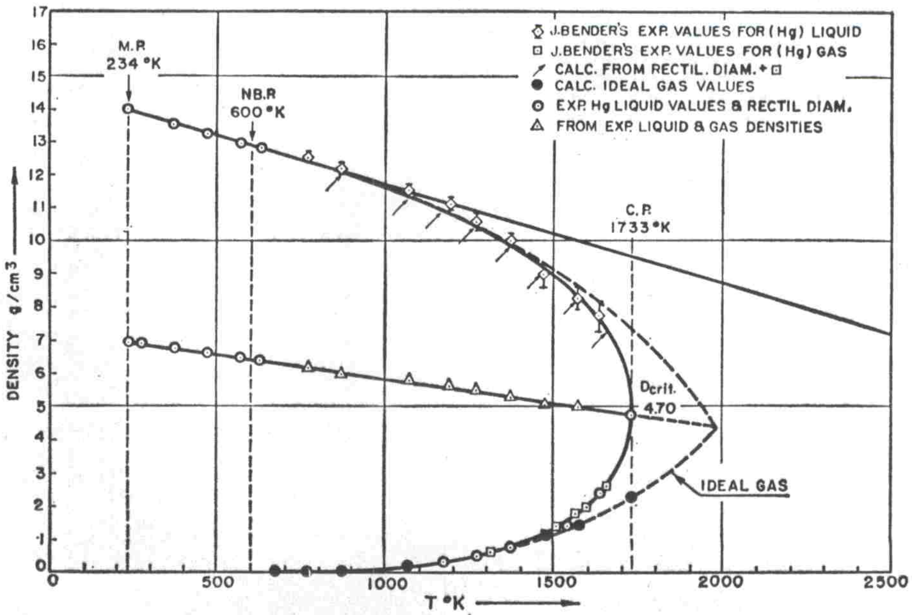

Fig. 2. Temperature-range diagram for liquid mercury.