ture obtained due to surrounding conditions. This is combustion in its simplest form. All solid, as well as liquid and even gaseous fuels generally contain several combustible elements in combination with others which, depending on their nature, affect oxygen requirements and thus govern the combustion process. For a continuous reaction, as in heating processes, it is necessary to establish an effective balance between rates of removing heat and of supplying fuel and air or oxygen to keep the reaction going. In establishing such a balance, consideration must be given to the removal or venting of products of combustion, so that the entire process is one of flow wherein draft conditions in the combustion space are important.

*Complete combustion* is obtained when all combustible elements in a fuel are oxidized by all of the oxygen with which they will combine. All oxygen or air supplied is generally not utilized, and this excess portion is commonly referred to as *excess oxygen* or *excess air*. Excess air is usually expressed as a percentage of the of air required for perfect combustion.

*Perfect combustion* results when the exact amount of oxygen required for complete combustion of all elements of a fuel is supplied and utilized. The percentage of carbon dioxide contained in the products of combustion from such a reaction is obviously the maximum attainable and is referred to as the ultimate $CO_2$ or *maximum theoretical percentage of carbon dioxide*. This condition of perfect combustion, without having excess air or oxygen left from the reaction, is seldom, if ever, realized in practice. Most types of heating equipment must be sufficiently flexible in performance to provide complete combustion with not only variations in the quality of a fuel but also changes in the rate at which it is supplied. This situation makes it advisable, from a practical standpoint, to insure *complete combustion* but not *perfect combustion* in the sense expressed above. To attempt to do so would undoubtedly result eventually in unsatisfactory performance especially from a safety standpoint. Consequently, common types of heating equipment are usually designed, installed, and adjusted to operate with some excess air. The exact percentage of such air depends on the type of fuel being utilized, as well as anticipated variations in its quantity and quality. Despite these practical limitations, however, it should not be inferred that common types of fuels cannot be utilized economically. Reference to flue loss charts such as Figs. 6 and 7 for gas burning equipment and to the air requirements discussion in Chapter 15 shows that reasonable quantities of excess air can be used without appreciable reductions in operating efficiencies.

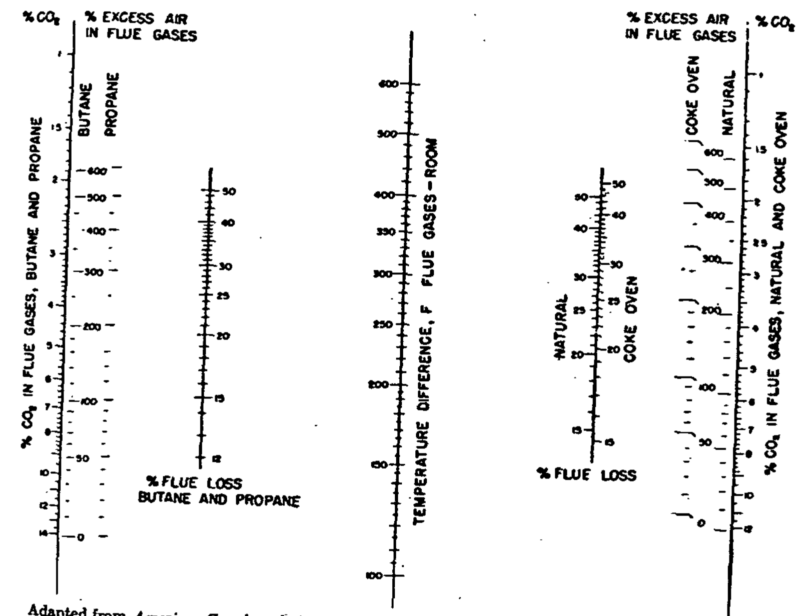
Oxygen combines with the combustible elements and compounds of any fuel in accordance with fixed laws. The reactions and resultant products of perfect combustion of common fuel constituents are set forth in Table 7. All of the oxygen required for combustion is normally obtained from the surrounding air, which is a mechanical mixture of nitrogen and oxygen with small amounts of carbon dioxide, water vapor and inert gases. For practical combustion calculations, air is considered to consist of 20.9 percent oxygen and 79.1 percent nitrogen by volume, and 23.15 percent oxygen and 76.85 percent nitrogen by weight. The nitrogen, being inert, passes through the reaction without change. Table 7 gives the air quantities corresponding to the oxygen required for perfect combustion.

Air supplied to the combustion reaction is in most instances introduced in two ways. *Primary air* is introduced through or with the fuel, and *secondary air* is supplied to the flames issuing from the fuel.

*Incomplete combustion* is obtained when any of the combustible elements are not completely oxidized in the combustion reaction. This condition



not only represents inefficient use of the fuel but also presents a hazard because carbon monoxide is usually one of the products of incomplete combustion. For example, a hydrocarbon may not oxidize completely to carbon dioxide and water, as indicated in Table 7, but may also form alcohols, ketones, aldehydes, or carbon monoxide depending on where and how the reaction is interrupted. Too low a temperature (such as may be caused by flame impingement on a cold surface), a poor oxygen supply to the flames (due to insufficient or poorly located air supply, or smothering




Adapted from *American Gas Association Laboratories Flue Loss Charts*.

Fig. 7. Alignment Chart for Calculation of Flue Losses for Butane, Propane, Coke Oven, and Natural Gases

by products of combustion not properly vented), or insufficient mixing of the air and fuel, are the primary causes of incomplete combustion.

## Heat of Combustion

As previously stated, the process of combustion results in the evolution of heat. The heat generated by the complete combustion of a unit of fuel is constant for a given combination of combustible elements and compounds, and is known as the *heat of combustion*, *calorific value*, or *heating value* of the fuel. The heat of combustion of the several substances found in the more common fuels is given in Table 7.

The calorific value of a fuel may be determined either by direct measurement of the heat evolved during combustion in a calorimeter, or it may be computed from the ultimate analysis and the heat of combustion of the several chemical elements in the fuel. When the heating value of a fuel is determined in a calorimeter, the water vapor is condensed and the latent heat of vaporization is included in the heating value of the fuel. The heat-