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ANALYSES OF COMPLEX MIXTURES OF GASES

Application To Control and Extinguish Fires and To Prevent Explosions in Mines, Tunnels, and Hazardous Industrial Processes

By

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Application To Control and Extinguish Fires and To Prevent Explosions in Mines, Tunnels, and Hazardous Industrial Processes

By S. H. Ash[2] and E. W. Felegy[3]

PART I

INTRODUCTION

For many years the Federal Bureau of Mines has been investigating fires and explosions in mines, tunnels, buildings, and hazardous processes of various kinds.

Means and methods for controlling and extinguishing mine fires and preventing explosions and other accidents in many hazardous processes require the collection and analysis of samples of the atmospheres surrounding the sources of ignition.

Complex mixtures of gases often encountered in mines, tunnels, and industrial processes may well presage imminent danger from explosions. This report discusses some practicable methods of utilizing the analyses of samples of complex mixtures of gases in their application to the many problems that arise from their presence.

There is need for (1) greater appreciation of the hazards involved when dealing with complex-gas mixtures, (2) better understanding of means to extinguish fires and to prevent explosions, and (3) a clearer and more concise explanation of how analyses of gaseous mixtures often present the only dependable information for preventing accidents. This is evidenced by the continued occurrence of accidents during recovery operations and the interest shown in the subjects discussed in this report.

PURPOSE OF REPORT

The purpose of this report is to point out what the mine-management official, the safety engineer, and the chemist can do to utilize analyses of complex gas mixtures as a basis for safe procedure to (1) control and extinguish fires in mines, tunnels, and industrial plants and (2) prevent explosions when dealing with explosive mixtures and sources of ignition.

The report is designed to meet the needs of those desiring to utilize analyses of complex-gas mixtures for the above-mentioned purposes.

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Anyone who has knowledge of decimal fractions and simple graphs can learn to use the formulas discussed in this report. For educational use, the necessary theory and detail relating to the derivation of the formulas are given for technical men. Many typical examples are calculated and discussed in detail to show the application of material presented.

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VALUE OF GAS ANALYSES

Experiences at mine fires (*2*, *3*, *5*, *15*, *27*)[4] have proved conclusively that mine-air analyses furnish the only means of judging what is going on in a mine-fire area. Mine-air analyses give notice of conditions that require immediate protection, govern the order and control the manner by which a fire is being fought, show the necessity of bulkheads and establish the places to construct them, and indicate whether or not a fire is being controlled or is being extinguished.

In general, each fire should be investigated separately. Forbes, Grove, Maize, and Walsh (*13*, *24*) have discussed suggested procedure in sealing and unsealing mine fires in recovery operations.

When it is decided to seal a fire area, the success of the work will depend solely on the effectiveness of the methods and facilities utilized to seal and extinguish the fire; and the measure of ultimate success will be attained only when the carbon monoxide content of the atmosphere within the fire zone is reduced to zero. However, physical conditions and other features attending each individual fire must be considered in deciding positively, on the basis of the disappearance of carbon monoxide, that a fire has been extinguished. There is one conclusion that can be generally accepted—that with continued exclusion of oxygen and cooling of strata involved for some time after the carbon monoxide is gone, the fire will ultimately be extinguished. The matter of time is important.

A fire in a confined place presents a hazard from explosion wherever the fire occurs, whether in a building, a metal mine, a coal mine,

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[4] Italicized figures in parentheses refer to items in the Bibliography at the end of this report.

a tunnel, or an industrial plant. The degree of hazard depends on the gases that are present. As the greatest hazard from explosion exists where the most combustible gases are present, the method of dealing with a particular problem can be modified according to the gaseous constituents present.

When fighting a mine fire, the first consideration is to prevent an explosion. Explosions may occur while a fire is being fought directly, when a fire area is being sealed, after an area is sealed, or when a mine-fire area is unsealed. It is, finally, important to know when a mine fire has been extinguished, and if the mine-fire area can be unsealed safely.

In any coal-mine fire, knowledge of the volume of carbon monoxide and hydrogen present in the atmosphere is of far more value, for indicating the progress of the fire, than knowledge of the amount of oxygen present. The carbon monoxide and hydrogen contents of the mine-fire atmosphere follow fairly definite trends, whereas the oxygen content is variable.

The oxygen percentages of mine-fire gas samples taken at the same place vary markedly from day to day, although it is known that the heated area from which the gases come could not be affected appreciably in the time involved. In large sealed areas, in broken and fissured ground, in extensive workings, or in areas where many seals are present, infiltrations of air oftentimes cannot be prevented. Under such conditions a fire area will breathe, and it is necessary to correct this condition if a fire is to be suffocated. The two outstanding values of the oxygen content are (1) the knowledge that it is above or below the percentage (the critical oxygen value) at which an explosion can occur and (2) the indication given by decreasing oxygen content that an area is being sealed effectively.

Hydrogen does not appear in a subbituminous- or bituminous-coal mine-fire area until the temperature at some spot is approximately 480° F. (*6*) nor in an anthracite mine-fire area until the temperature at some spot is approximately 660° F. (*29, 31*). If hydrogen is present—and its presence or absence should be ascertained—it can be taken for granted that an active fire exists in the area at temperatures higher than the figures given above.

Carbon monoxide is a product of combustion, and it exists in a fire area only when an active fire is in progress or has been present, with or without flame. It is difficult to ascertain the exact conditions of a fire from the percentage of carbon monoxide present. The percentage of carbon monoxide is highest at high temperatures when the volatile constituents become active in combustion, and lowest either when there is no fire or when there is perfect combustion.

The carbon dioxide content of a mine-fire atmosphere is significant. For certain types of fires and mines it ultimately reaches a fairly constant high value during an active fire, as well as a fairly constant lower value after the fire is extinguished. It provides a valuable criterion on the progress of a fire in steeply dipping mine workings and in metal mines. When the fire is extinguished, the fire gases, on cooling, permit the carbon dioxide to settle into the lower workings and become fairly constant throughout the area under seal (*2*).

The carbon dioxide content of the air-free composition of a mine-fire atmosphere shows a definite trend downward when a fire is being extinguished. When the fire is out, a line constructed of points corresponding to the carbon dioxide content on an air-free basis flattens; and, in a tightly sealed area, the carbon dioxide content is almost constant. Because of its magnitude (as compared with the carbon monoxide content), the carbon dioxide content (air-free) can be the means of indicating whether or not a fire is out, after analyses show that carbon monoxide is absent. If methane is being generated, the carbon dioxide content on an air-free, methane-free basis can be used for the foregoing purpose.

It appears that too much stress is placed on analyses of samples "as received" to indicate either the progress of a fire or the atmospheric condition existing in a sealed area. A more accurate picture is presented by the compositions of the samples on an air-free basis. Samples highly contaminated with air give a reliable trend of the fire only by comparing the composition of the samples on an air-free basis.

SAMPLING AND ANALYZING ATMOSPHERES

Close relationship exists between the composition of the atmosphere and problems of health and safety in mines, tunnels, and other confined places where explosive or poisonous gases may be present. This interdependency makes the sampling and analysis of the atmosphere the most important part of the safety work in these places.

The collection of a representative sample and the preservation of that sample until it can be analyzed are the most important and most difficult parts of the procedure in determining the composition of a dangerous atmosphere. Inaccurate sampling gives erroneous results. Erroneous results, which lead to incorrect interpretations and conclusions, may cause a false sense of security and may be used as a basis for unsafe or unnecessary recommendations.

A complete description of the methods of sampling and analysis of mine, tunnel, or other atmospheres is given in publications of the Bureau of Mines (*4*, *7*, *34*). The correct method of analysis depends on the kinds and percentages of the combustible gases present in a sample, and the proper apparatus should be used for the job at hand; for example, the accuracy and precision attainable with the Haldane apparatus are essential in many instances to obtain analytical results of value. The Haldane apparatus, however, is limited to mixtures that do not contain enough combustible gases to be explosive; and the gas mixture undergoing analysis must contain no less than 75 percent of inert gas, such as nitrogen, which is not determined analytically. A sample of an atmosphere that is explosive or that is capable of forming explosive mixtures with air must be analyzed by other means.

SYMBOLS AND FORMULAS

Most of the rules dealing with gases are expressed by means of formulas, which show at a glance the relation of the several factors to each other. A comparatively few formulas form the basis from which practically all the other formulas relating to gases are derived. In this report, the methods of deriving the formulas and examples of their application are given in the body of the report in the same sequence as the presentation of the subject matter to which they relate.

As far as practicable, the same symbols are used to designate the same factors. A list of the symbols and their meanings and a summary showing the more important formulas are given on pages 189 to 200, inclusive.

ACCURACY OF FORMULAS

The accuracy of the result in the application of the formulas depends on (1) accuracy of the observed data, (2) accuracy of mathematical constants, (3) accuracy of physical constants, and (4) precision of the computation.

As the observed data depend on the reliability of the samples and analyses of the atmospheres under consideration, the accuracy attained in application of the formulas is limited by the care taken by the sampler and the chemist and by the percentage of error that accompanies efficient sampling and analytical procedure.

The mathematical constants have been carried to a degree of accuracy that is sufficiently accurate.

The physical constants used possess a variable accuracy but are correct in erring always on the safe side.

The accuracy of the computation depends on the engineer. The authors, by working many examples in detail, have computed the results arithmetically. In dealing with explosive atmospheres, a little more care and a little more time taken in performing the arithmetical calculations are worthwhile.

AIR-FREE ANALYSIS

In dealing with mine atmospheres consisting of mixed gases such as exist in a mine-fire area, it is sometimes necessary to know the composition of a "normal" mine atmosphere. It is often erroneously believed that the atmospheres in mines, tunnels, and other underground openings are, or can be expected to be, of the same quality as pure atmospheric air.

Changes occur in pure atmospheric air or "normal" air from various causes as it courses through underground passageways. The agencies contributing largely to these changes are the chemical and physical action between the oxygen of the air and the earth materials it contacts, the decay of mine timber, gas emanations from the strata, and the breathing of men. Normal mine air is air that is ordinarily classed as good air for underground atmospheres, or it is the air in a mine operating under normal conditions. Normal mine air varies in composition in different types of underground mines. The acceptable quality for normal mine air is determined by experience, mining practices, and the physiological effects of the air when breathed by the workmen.

The following analyses (*8, 14, 16, 27, 28, 30, 33*) are an average of the percentages of individual constituents composing mine atmospheres that were sampled and analyzed by the Bureau of Mines. They are representative of atmospheres that are considered to be normal mine air.

TABLE 1.—*Normal mine atmospheres (average analyses), percent*

Constituent	Normal atmospheric air	Subbituminous-coal mines	Bituminous-coal mines	Anthracite mines	Metal and noncoal mines
Oxygen	20.93	20.41	20.53	20.58	20.62
Nitrogen	78.10	79.21	79.12	79.03	79.19
Carbon dioxide	.03	.23	.17	.22	.19
Methane	.00	.15	.18	.17	.00
Other gases	[1].94	(2)	(2)	(2)	(2)

[1] Argon.
[2] Considered as nitrogen.

The average analysis, which consists of the average percentage of each individual gaseous constituent, does not necessarily indicate the normal mine air throughout the average mine, nor the most probable normal mine atmosphere in the ordinary coal mine, metal mine, or tunnel.

The most probable content (in percent) of the individual gaseous constituents of normal mine atmospheres is the percentage of each individual constituent that occurs in the greatest number of samples from representative mines. The most probable normal mine atmospheres of underground mines are shown in table 2.

TABLE 2.—*Most probable normal mine atmospheres in ordinary mines, percent*

Constituent	Normal atmospheric air	Subbituminous-coal mines	Bituminous-coal mines	Anthracite mines	Metal and noncoal mines
Oxygen	20.93	20.59	20.71	20.72	20.76
Nitrogen	78.10	79.22	79.14	79.14	79.16
Carbon dioxide	.03	.18	.13	.12	.08
Methane	.00	.01	.02	.03	.00
Other gases	[1].94	(2)	(2)	(2)	(2)

[1] Argon.
[2] Considered as nitrogen.

It can be seen from the data in table 2 that the composition of the mine air in the ordinary operating mine does not differ greatly from that of pure air. When dealing with a mine fire, the normal mine air can be determined only by analyses of representative samples of the atmosphere in the mine concerned.

The oxygen content of a mine atmosphere must come from the atmospheric air that enters the mine. For this reason mine air can be considered as consisting of air and other gases. Furthermore, it can be concluded that the gases generated or liberated in a mine, from whatever source, are diluted by air and that they existed originally in their pure state at some point in the mine.

In a tightly sealed mine-fire area the mine-fire atmosphere is depleted of oxygen by adsorption of oxygen by the mineral in contact with the air and by oxidation processes. The air remaining is diluted by gas emanations, if the strata contain gas under pressure.

In a newly sealed mine-fire area the atmosphere contains the least amount of oxygen at the place where the fire is burning. The rate at which the fire gases are diluted decreases with the distance from the fire because of dilution and diffusion of the fire gases by the surrounding mine air. If a sample of the mine-fire atmosphere is taken at any point within the sealed area, the maximum percentage of each simple gas as it existed before dilution with air is the percentage of the simple gas in the atmosphere when all the air is removed. This is the air-free analysis of the sample.

It has been observed (*27, 30, 33*) that the percentage of oxygen in the air contained in a mine-fire atmosphere or a normal mine atmosphere changes only slightly or not at all, when adsorption of the oxygen by the strata is completed and oxidation from heat ceases. Any change in the oxygen content at this point is accomplished by the dilution of the mine atmosphere by emanations of gas (*17, 18, 30, 33*), such as methane, carbon dioxide, or other gases. For this reason, the progress of a mine fire can best be analyzed and sometimes can only be determined by a study of the air-free analyses of the mine-fire atmosphere.

In sealed mine-fire areas that generate considerable methane, dilution of the mine-fire atmosphere by methane becomes an important consideration. If this is accomplished without an explosion, methane becomes the dominant constituent of the mine-fire atmosphere; and by reducing the oxygen content, it eventually creates a nonexplosive atmosphere and assists very materially in extinguishing the fire by depriving it of oxygen.

If considerable methane is present, the air-free, methane-free analyses will give information from which the most reliable trend of the fire can be determined (*30*).

Analyses of mine-fire atmospheres are made, and often little or no value is attached to them because of variations in the percentages of the constituents. In the vast majority of instances, it is found that the differences in the percentages of the constituents are a consequence of nothing more than variations in the air content of the samples. This may result from the admission of air during sampling or during analysis; or it may be the effect of barometric pressure on emanations of gas, such as methane, carbon dioxide, or nitrogen, and on breathing at seals. If the analyses of a series of samples taken at approximately the same time are calculated to an air-free basis, the percentages of the constituents are usually found to be approximately the same.

To ascertain the possibilities of an explosion in an atmosphere consisting of a mixture of gases, it is necessary to know: (1) If the mixture is or is not explosive. (2) If the mixture is not explosive, can it become so when admixed with air? (3) What are the possibilities of an explosion when the mixture is admixed with an inert gas or with blackdamp (*8*) (nitrogen and carbon dioxide in percentages more than those found in atmospheric air)? To determine these conditions by calculations, it is first necessary to calculate the air-free analysis of the atmosphere under consideration. Other factors relating to the explosibility of an atmosphere can then be determined by means of the methods described later in this report.

EXPLOSIVE LIMITS AND EXPLOSIVE RANGE

The term "gas" has a rather broad meaning, but in the mind of the average individual it usually means anything of an invisible gaseous nature other than pure air. All gases are harmful under some conditions. In this sense, any of the gaseous constituents that together compose an atmosphere can be classed as a noxious gas, unless some restriction is placed on the definition of a noxious gas.

Gas hazards may be divided into three principal classes: (1) Burns or explosion, (2) asphyxiation, and (3) poisoning.

A noxious gas is any gas that is directly or indirectly injurious or destructive to the health or life of human beings, if its presence in an otherwise respirable atmosphere presents a hazard from burns, violence, asphyxiation, or poisoning.

A gas may fall into one, two, or three of the above-stated classes of gas hazards. For example, nitrogen is innocuous, nonexplosive, and suffocating and falls into class 2; methane is innocuous, explosive, and suffocating and falls into classes 1 and 2; and carbon monoxide is explosive, suffocating, and poisonous and falls into classes 1, 2, and 3. Gases such as nitrogen and carbon dioxide are called inert gases only because they do not support combustion. Nitrogen and carbon dioxide actually extinguish the flames of burning gases, in part because of their heat capacity, and in part because their presence contributes to oxygen deficiency.

The burning of a gas may be regarded as a chemical reaction, which releases heat energy, regardless of the amount of heat liberated or of the size of the flame involved.

Every combustible gas burns when in contact with a flame, a spark, or a heated material having a temperature equal to or more than the ignition temperature of the gas, provided that there is enough oxygen present (by weight) for combustion. However, the heat energy released is not always capable of igniting the neighboring layers of gas, and therefore the mixture is nonexplosive (*19*).

The combustion of mixtures of a combustible gas, or combustible gases, and air is often visible as a cap of flame, such as in a flame safety lamp burning in a gassy atmosphere, provided that the products of combustion are removed by convection or otherwise from contact with the heat-activating agent (*19*). Such mixtures of gas or gases, and air, are not within the *explosive range* of the mixture of gas or gases, and air.

An explosion, when applied to gaseous-explosive reactions, may be regarded as a chemical reaction that exerts a sudden pressure on whatever surrounds the explosive mixture. The time required to complete the reaction may be very short or long, depending on the kind and percentage of the combustible gases that may be present in the mixture, and on the environment in which the reaction takes place (*20*).

Confusion has arisen regarding the meanings of the expressions "explosive limits," "inflammation limits," "inflammable limits," "limits of inflammability," and "flammable limits." All these terms mean the same thing (*20*). In this report the authors have used the term "explosive limits."

The reaction of a gas or mixture of gases with the oxygen of the air that results in progressive combustion, or propagation of flame, occurs only when the percentage of the combustible gases is within certain limits (*9*). The limits are usually expressed in terms of percentage of the gas or air-free original mixture in air, by volume. When the percentage of the combustible constituents is less or more (as the case may be) than the percentage of the combustible constituents in these limit mixtures, local combustion may occur at the source of ignition; however, there is no actual propagation of flame, and combustion ceases on removal of the source of ignition. The minimum and maximum percentages of the gas in a gas-air mixture, which, if ignited, propagates flame independently of an external source of ignition (heat), are known as the lower (L_L) and the upper (L_U) explosive limits. These limit mixtures are of border-line composition; a slight change in the percentage of combustible gas in one direction produces an explosive mixture—in the other direction, a nonexplosive mixture.

The gaseous mixtures within the border-line mixtures, or explosive limit mixtures, lie within the explosive range, and *the explosive range is said to be between the amount of the gaseous constituents other than air existing in the lower explosive-limit mixture and the amount of the same gases existing in the upper explosive-limit mixture, both expressed in percentage.* For example, the explosive range of methane in air is said to be 5 to 15 percent, of hydrogen 4.1 to 74 percent, and of carbon monoxide 12.5 to 74 percent. It is not enough to express the "explosive range" as the numerical difference in percentage between the lower and the upper explosive limits. For example, it is meaningless to state that methane has an explosive range of 10, obtained by subtracting 5 from 15, unless the numerical values of the explosive limits are known.

Some authorities (*20*) regard *explosive limits* as those limiting mixtures within which flame is propagated throughout the mixture, pressure is developed, and more or less violence produced, while *flammable limits* (limits of inflammability) refer only to the passage of flame through the mixture without regard to the development of pressure.

It is impossible to distinguish an ignition or a burning from an explosion by the amount of violence produced (*20*). Mixtures just within the zone of explosive mixtures (*see* fig. 1, pocket), if confined and ignited under some conditions, will propagate flame quietly and slowly throughout the mixture (usually at uniform speed).

CRITICAL GAS MIXTURE AND CRITICAL GAS-MIXTURE VALUE

To understand more clearly the effects of admixing a diluent, or additional inert gas, with an atmosphere, which may or may not have explosive limits with air, an atmosphere can be thought of as possibly consisting of three portions: (1) The gas portion (*Gas*), or a mixture of combustible gases and inert gases such as nitrogen and carbon dioxide; (2) a portion (*Air*) consisting of normal air; and (3) a portion considered as diluent that, unless stated otherwise, consists of additional inert gas ($Dil_{\text{inert gas}}$), which may be nitrogen or carbon dioxide.

In this report, an original atmosphere is considered as an atmosphere in which the additional inert-gas portion is absent, unless stated otherwise; that is, an original atmosphere is considered as diluent-free. An air-free original atmosphere, therefore, consists only of the gas portion.

Every air-free original atmosphere that has explosive limits with air will form mixtures if admixed with an inert gas, such as nitrogen, carbon dioxide, or blackdamp. Some of these mixtures will have explosive limits with air, and others will not.

Experimental data (*19*) establish the fact that the effect of the inert gas in a mixture that has explosive limits with air is to extinguish the flames of the combustible gases present. The severity of this reaction depends on the individual extinctive effect and the volume, in percent of the whole, of the inert gas in the mixture.

If an air-free mixture that has explosive limits is diluted, step by step, with diluent, or additional inert gas, each of the new mixtures formed will also be air-free and will consist of progressively less (in percent of the whole) of the air-free original mixture and progressively more diluent.

One of the air-free mixtures so formed will be just incapable of forming an explosive mixture with air. The authors have called this air-free mixture the "critical gas mixture." It has a gas-portion content (in percent) that is the maximum percentage of the air-free original atmosphere that can be present in any possible air-free original atmosphere-diluent mixture incapable of forming explosive mixtures with air. It has a diluent-portion content that is the minimum percentage of additional inert gas that can be admixed with the air-free original mixture to form a mixture just incapable of forming an explosive mixture with air.

The importance of the critical gas mixture becomes evident upon consideration of the character of it. The critical gas mixture will, if diluted step by step with air, form new mixtures that are just incapable of forming explosive mixtures with air until the "nose" limit mixture, discussed later, is formed. Such critical gas mixture—air mixtures, on a graph form such as figure 1, form a line that is a definite boundary between those mixtures that are capable of forming explosive mixtures with air, and those mixtures that are not.

The critical gas mixture has a combustible-gas content that is more than that of the lower explosive-limit mixture. It has, however, a total combustible-gas content (in percent) that may be either more or less than the total combustible-gas content of the upper explosive-limit mixture, depending on the kind and volume of gases present in the original mixture. (*See* fig. 9, pocket.)

The authors have called the numerical value signifying the gas-portion content (in percent) of the critical gas mixture, the critical gas-mixture value (*C. G. M. V.*). The percentage of diluent contained in the critical gas mixture is, therefore, 100 minus the critical gas-mixture value (*C. G. M. V.*).

If the air-free analysis of a mixture of the air-free original atmosphere, diluent, and air has a gas-portion content that is equal to or less than the critical gas-mixture value, that mixture is nonexplosive and incapable of forming an explosive mixture with air, regardless of the oxygen content of the mixture.

For any given diluent, the compositions of the critical gas mixtures are identical for a given air-free original atmosphere and for all possible mixtures of the given air-free original atmosphere and the specific inert gas used as the diluent, when such air-free mixtures are capable of forming explosive mixtures with air. On the other hand, the critical gas-mixture values of the air-free atmospheres will be different in each instance and will range in value from that of the critical gas-mixture value of the air-free original atmosphere, to just under 100.

It has been found experimentally (*19*) that 6 volumes of nitrogen must be admixed with 1 volume of methane to render it nonexplosive (*see* table 3). As 1 volume of methane is 14.285 percent of the whole, the critical gas-mixture value of methane-nitrogen-air mixtures is 14.285 percent. The critical gas mixtures of all air-free methane-nitrogen-air mixtures that can form explosive mixtures with air must, therefore, contain 14.285 percent of methane and 85.715 percent of nitrogen.

As the critical gas-mixture value of an atmosphere containing 100 percent methane is 14.285 percent when nitrogen is used as the diluent, an air-free atmosphere that contains, say, 14.287 percent methane and 85.713 percent nitrogen has a critical gas-mixture value of 99.991 percent. Such a mixture can form two borderline explosive mixtures with air that have approximately the same composition and explosive-limit value.

The methods of calculating the critical gas-mixture value (*C. G. M. V.*) and the composition of the critical mixture of complex mixtures of combustible gases, nitrogen, and carbon dioxide are discussed later.

NOSE-LIMIT MIXTURE AND NOSE LIMIT

If air is admixed step by step with a critical gas mixture, none of the successive mixtures formed will be either explosive or capable of forming explosive mixtures with air. Furthermore, as more and more air is added, each successive mixture consists of correspondingly less proportions (in percent of the whole) of the gas portion and diluent portion contained in the critical gas mixture, and correspondingly more air, the amount of which is expressed in percent of the whole.

Although none of the mixtures formed as stated above are capable of forming explosive mixtures with air, one of the mixtures is just nonexplosive. The authors have called this mixture the "nose"-limit mixture. It is seen from the manner in which the nose-limit mixture can be formed that the critical gas mixture is the air-free analysis of the nose-limit mixture.

The composition of the nose-limit mixture of any given air-free original atmosphere that has explosive limits depends on the kind and proportions of combustible gases and inert gases in the air-free original atmosphere and on the kind of inert gas used as a diluent.

When a definite volume of air is admixed with an air-free original atmosphere, an upper-explosive-limit mixture is formed that contains slightly more than the maximum amount of analogous proportions of the constituents of the gas portion and therefore more combustible gases than are present in any possible explosive-limit mixture of the air-free original atmosphere, air, and diluent. Similarly, a lower-explosive-limit mixture is formed in which slightly more air, and therefore more oxygen, is present than in any possible explosive-limit mixture of the air-free original atmosphere, air, and diluent.

If air is admixed with each of the air-free mixtures formed by admixing progressively more diluent with an air-free original atmosphere, each air-free mixture so formed will make an upper- and a lower-explosive-limit mixture with air until the air-free mixture is used that has a gas-portion content that is slightly more than, and a diluent-portion content that is slightly less than, those of the critical gas mixture. When a definite amount of air is admixed with this air-free mixture, a common explosive-limit mixture is formed, and the same real number defines both the upper and the lower explosive limits. In other words, a common explosive-limit mixture exists when the upper- and the lower-explosive-limit mixtures have the same chemical composition and are represented by the same point in a graph form such as figure 2 (pocket). A common explosive-limit mixture such as this (1) is just explosive, or capable of propagating flame; (2) represents the upper-explosive-limit mixture having the minimum gas-portion content and therefore the minimum combustible-gas content of any possible upper-explosive-limit mixture of the air-free original atmosphere, diluent, and air; (3) represents the lower-explosive-limit mixture having the minimum oxygen content of any possible lower-explosive-limit mixture of the air-free original atmosphere, diluent, and air; and (4) has the maximum diluent content of any possible explosive-limit mixture of the air-free original atmosphere, diluent, and air.

A relationship can be established between the compositions of the air-free original atmosphere, the nose-limit mixture, and the common explosive-limit mixture formed by admixing the air-free original atmosphere with diluent and air, and the analytical properties of the equations by which the foregoing factors are determined.

As the real number defining the explosive limit of an air-free mixture of gases also designates the total percentage (K) of the gas portion plus diluent, or total percentage (K) of gases other than air, that are present in the explosive-limit mixture, all explosive-limit mixtures having the same limit value have the same air content. Therefore, any complex-gas mixture, of which the real value of K is the real number defining the explosive limit of the common explosive-limit mixture, must have the same air content as the common explosive-limit mixture. Conversely, any mixture that has the same air content as the common explosive-limit mixture also contains a total percentage (K) of gases other than air that is equal numerically to the real number (in percent) defining the explosive limit of the common explosive-limit mixture.

If we now consider the definite mixture formed by admixing air with the critical gas mixture, until it has an air content that is the same as that of the common explosive-limit mixture, this definite mixture has a gas-portion content that is slightly less, and a diluent-portion content that is slightly more, than the proportions of these portions contained in the common explosive-limit mixture, which exists when the upper- and the lower-explosive-limit mixtures have the same chemical composition.

Because all mixtures of the critical gas mixtures and air are nonexplosive, an atmosphere having the composition of the definite mixture formed as stated above is just nonexplosive. The authors have called this atmosphere or mixture the "nose"-limit mixture. They have also called the real number designating the total percentage of gases other than air that are present in the nose-limit mixture, the nose limit (L_{nose}).

The nose-limit mixture can therefore be defined as that borderline extinctive mixture or atmosphere that is just nonexplosive and cannot form an explosive mixture with air because it lacks just enough combustible gas or oxygen or because it contains just too much inert gas. This definition can be verified mathematically by considering the nose-limit mixture as an original atmosphere and calculating the the critical gas-mixture value (*C. G. M. V.*) in the manner described later.

The importance of the nose-limit value, when nitrogen is used as the diluent, is that it is a safe and easily obtainable basic value by which the critical oxygen value can be determined for complex-gas mixtures. The nose-limit value furnishes a reliable numerical value for approximately determining the lower explosive limit of the air-free original atmosphere. In combination with the critical gas mixture and lower-explosive-limit values, the nose-limit value affords a practicable method by which the zones of explosive and potentially explosive atmospheres can be established. (*See* figs. 1 and 4, pocket.)

Strictly speaking, an atmosphere or portion of a mine-fire atmosphere corresponding to a nose-limit mixture may not exist in a mine-fire area. When dealing with potentially explosive atmospheres, it is the possibility that a nose-limit mixture may exist or can be formed that governs the safe procedure to follow under the existing conditions.

The composition of the nose-limit mixture and the real number defining the nose limit are always the same for both a given air-free original atmosphere and all possible mixtures of the given air-free original atmosphere and a given diluent, unless the diluent content (in percent) of the air-free mixture equals or exceeds the diluent content of the critical gas mixture. Such an air-free mixture will have neither a nose-limit mixture nor explosive limits if admixed with air. In other words, for a given diluent, the composition of the nose-limit mixture is the same for both the air-free original atmosphere and all air-free atmospheres that have explosive limits and are composed of analogous proportions of the constituents composing the air-free original atmosphere and different proportions of the given diluent. For example, the composition of the nose-limit mixture and the nose-limit value of an atmosphere that contains 10 percent each of carbon monoxide, methane, and hydrogen and 70 percent of nitrogen (diluent) are the same as the composition of the nose-limit mixture and the nose-limit value (62.7) of an air-free original atmosphere that contains 33⅓ percent each of carbon monoxide, methane, and hydrogen, when nitrogen is used as the diluent (*see* fig. 3, pocket).

The percentages of the gas portion and diluent contained in the nose-limit mixture can be calculated by multiplying the percentages of these portions contained in the critical gas mixture by the real number (L_{nose}) defining the nose limit, expressed as a decimal fraction. For example, the real number defining the nose limit (L_{nose}) of methane-air-nitrogen mixtures is considered by the authors as being 41.5 percent, which is the same as the real number defining the explosive limit of the upper explosive-limit mixture that contains the minimum possible percentage of methane (gas portion) (*19, p. 23*). The critical gas mixture has been found (*see* p. 11) to contain 14.285 percent of methane and 85.715 percent of nitrogen (diluent portion). Therefore, the composition of the nose-limit mixture for all possible mixtures of methane and nitrogen with air is (by portions) 5.93 percent of methane, 58.50 percent of air, and 35.57 percent of nitrogen, or (by constituents) 5.93 percent of methane, 81.93 percent of nitrogen, and 12.24 percent of oxygen. The nose-limit mixture shows that any possible explosive mixture of methane, nitrogen, and air must contain less than 81.93 percent of nitrogen.

The methods of calculating the nose limit (L_{nose}) and the composition of the nose-limit mixture of complex mixtures of combustible gases, nitrogen, and carbon dioxide are discussed later.

CRITICAL OXYGEN VALUE

The fact that a gaseous mixture that can burn or explode will not burn or explode when the oxygen content is reduced below a definite value affords a means by which explosions can be prevented.

Knowledge of the explosive limits of mixed gases is of fundamental importance in the study and prevention of fires and explosions in mines and industrial processes. Moreover, it is imperative to know and attain the critical oxygen value when dealing with atmospheres following fires and explosions or other accidents in mines, buildings, sewers, and industrial processes where sources of ignition are present or may be introduced. Atmospheres that are mixtures of gases must be dealt with and are the rule, not the exception.

In this report the critical oxygen value of an air-free original atmosphere having explosive limits is considered to be the oxygen percentage below which no mixture of the air-free original atmosphere, diluent, and air is explosive. The critical oxygen value for any given air-free original atmosphere that has explosive limits with air depends on whether nitrogen or carbon dioxide is used as the diluent.

If nitrogen is used as the diluent, the critical oxygen value may or may not be the same as the oxygen content (in percent) of the nose-limit mixture.

If, however, carbon dioxide is used as the diluent, the critical oxygen value of an air-free original atmosphere that has explosive limits and consists of carbon monoxide, methane, hydrogen, nitrogen, and carbon dioxide will be the oxygen content of the upper-explosive-limit mixture, except when methane constitutes a large proportion of the combustible gases. Such a condition can be verified only by determining the oxygen contents of the nose-limit mixture and the upper-explosive-limit mixture. The oxygen content of the upper-explosive-limit mixture may also be the critical oxygen value when nitrogen is used as the diluent and the zone of explosive mixtures is small and composed of explosive mixtures near the nose. This condition exists when the original atmosphere contains a large amount of inert gas (*see* fig. 9, pocket).

In an investigation of the explosibility of any mixture of the above-mentioned common gases, the oxygen content of the nose-limit mixture (when nitrogen is used as the diluent) should always be determined. For all practical purposes, and erring on the safe side, the critical oxygen value can be safely taken as 0.5 percent less than the oxygen content (in percent) of the nose-limit mixture, calculated with nitrogen as the diluent, regardless of whether nitrogen or carbon dioxide is used as the diluent.

For the reasons given above, it is apparent that, to determine a safe critical oxygen value relating to an atmosphere composed of mixtures of gases that are either explosive or capable of forming explosive mixtures with air, it is necessary to determine the nose-limit mixture of the air-free composition of a representative sample of each mixture being investigated. Furthermore, a method by which the real number defining the nose limit of complex-gas mixtures that have explosive limits can be readily calculated affords the only practicable means whereby the critical oxygen value can be determined.

Critical oxygen values and the oxygen contents of the nose-limit mixtures of the simple combustible gases—carbon monoxide, methane, hydrogen, ethylene, and propylene—when nitrogen and carbon dioxide are used as the diluents, are shown in table 3 (p. 19).

OXYGEN-CONTENT RANGE

The oxygen contents of the explosive-limit mixtures of the commonly known combustible gases and air are considerably higher, at times, than the critical oxygen value that must be attained, if explosions are to be prevented, when mine fires are fought in gassy mines. For example, the oxygen content of the lower-explosive-limit mixture of methane-air mixtures is 19.8 percent and of the upper-explosive-limit mixture, 17.7 percent (*9*). This signifies that, when a methane-air mixture contains just 5 percent of methane or just 15 percent of methane, 19.8 percent and 17.7 percent of oxygen, respectively, must be present; and an explosion can occur if the mixture is suitably ignited. However, when the methane content of a methane-air-nitrogen atmosphere is 6 percent and the oxygen content ranges from 12.1 to 19.6 percent, the atmosphere is explosive. Every mixture of combustible gases, inert gases, and air having an explosive range has an oxygen-content range within which the mixture is explosive; it is just as important as the explosive range. For methane-air-nitrogen mixtures the oxygen-content range is 12.1 to 19.8 percent; that is, all possible explosive mixtures of methane, air, and additional nitrogen contain more than 12.1 percent but less than 19.8 percent of oxygen.

CALCULATION OF FACTORS AFFECTING EXPLOSIBILITY OF COMPLEX-GAS MIXTURES

Whenever the explosibility of complex-gas mixtures is being considered, several factors are sometimes more important than others for indicating steps to be taken to lessen or prevent explosions where a source of ignition is present. These factors are: (1) The least volume (in percent) of the air-free original mixture that can be admixed with air to form an explosive mixture (lower explosive limit); (2) the maximum volume of the air-free original mixture that, when admixed with diluent (nitrogen or carbon dioxide) forms a mixture that is just incapable of forming an explosive mixture with air (critical gas mixture value); (3) the volume of oxygen below which no mixture is explosive, regardless of the proportions of the air-free original mixture and diluent present (critical oxygen value); and (4) the maximum volume of the air-free original mixture that is just explosive when admixed with air (upper explosive limit).

An infinite number of combinations of combustible gases, nitrogen, carbon dioxide, and air are possible; therefore, an infinite number of values of the factors relating to the explosibility of these mixtures must be considered in connection with mine fires and some industrial processes. Because the experimental determination of these values necessarily entails ignition of those mixtures that are explosive, it is obviously impossible to determine experimentally the factors relating to the explosibility of each mixture. Therefore, a method whereby the real values of the above-mentioned factors can be simply and quickly calculated is of paramount importance.

The experimental determination of the explosive limits, nose-limit mixture, critical oxygen value, and critical gas mixture of several simple combustible gases when admixed with air and with both nitrogen and carbon dioxide as diluents has been made by Coward, Jones, and others (*9, 19, 20*).

Some experimental work (*1, 9, 10, 21, 25, 26, 32, 35*) has been done to determine the explosive limits of complex-gas mixtures, or of mixed gases, likely to be encountered at mine fires and in some industrial processes.

The determination of the explosive limits of gases and vapors has been fully covered by Coward and Jones (*9, 20*), who also present the results of a critical review of all figures published, as of February 1938, on the limits of explosibility of combustible gases and vapors when admixed with air, oxygen, or other atmosphere (*9*).

The authors do not know of any experimental work that has been done on determination of the nose-limit mixture, the critical oxygen value, or the critical gas mixture of mixtures composed of combustible gases and inert gases; however, these factors are of paramount importance when dealing with complex-gas mixtures such as exist in every mine-fire area. Heretofore no formulas have been available whereby these factors can be calculated simply and quickly. Calculations have had to be made by the method of trial and error. The actual procedure by this method is long and complicated.

For the purpose of discussion, the methods of calculating the factors relating to the explosibility of mixed gases are given as follows in the order by which they can be calculated consecutively and in the order of their usual applicability, rather than in the order of their importance:

1. Calculation of air-free analysis.
2. Calculation of explosibility or nonexplosibility of complex gas-air mixtures.
3. Calculation of critical gas-mixture value.
4. Calculation of nose limit.
5. Calculation of critical oxygen value and nose-limit mixture.
6. Calculation of explosive limits.
7. Calculation of oxygen range.

For some purposes, the results of the calculations of the factors affecting the explosibility of gases are more useful and more clearly understood when expressed graphically by the method used by Coward and Jones (*9*), which has been amplified by the authors to include the graphic determination of the additional inert-gas portion. Figure 1 (pocket) shows the above-stated factors for a complex gas-air mixture consisting of equal proportions of hydrogen, methane, and carbon monoxide, when nitrogen is used as the diluent.

The methods of calculation given in this report are based on experimental data from references quoted and on original work by the authors. The data relating to the factors discussed and applied to complex mixtures of gases consisting of carbon monoxide, methane, hydrogen, ethylene, propylene, carbon dioxide, nitrogen, and air have been proved by experiment to apply to the gases stated. The formulas relating to the critical gas mixture, nose limit, and critical oxygen value are new and may be extended to include other combustible gases; however, such an arrangement cannot be applied indiscriminately to all combustible gases in the absence of test data to prove that the formula applies to the gases being investigated.

CALCULATION OF AIR-FREE ANALYSIS

The first step in determining any of the factors relating to the explosibility of complex gas–air mixtures is the calculation, to an air-free basis, of the analysis of the atmosphere sampled. This is done by first considering all the oxygen in the sample as a constituent of normal atmospheric air (*see* table 1, p. 6).

Normal atmospheric air contains 20.93 percent of oxygen, by volume. For all practical purposes, the other gases (carbon dioxide and argon) can be considered as nitrogen. The volume of air in the atmosphere sampled is expressed by the following formula:

$$Air_s=\frac{(O_2)_s\,(100)}{20.93}\text{ percent,} \tag{1}$$

where (Air_s) and $(O_2)_s$ are the volumes (in percent) of air and oxygen, respectively, in the atmosphere sampled.

As the atmosphere sampled consists of air and other gases, the volume of gases (K_s) other than air can be expressed, in percent, as follows:

$$K_s=(100-Air_s)\text{ percent.}$$

By substituting equation (1) in the expression above, the volume of the air-free mixture (gases other than air) can be determined by the following formula:

$$K_s=100-\frac{(O_2)_s\,(100)}{20.93}\text{ percent.} \tag{2}$$

When the respective volumes (in percent) of the individual constituents, except the nitrogen and the oxygen, composing the atmosphere sampled are divided by the total volume (K_s) of the individual constituents other than air, as obtained by equation (2), and each of these volumes is then multiplied by 100, the air-free volumes (in percent) of the individual constituents, except the nitrogen, are obtained.

The volume of nitrogen $(N_2)_1$ on an air-free basis is the difference between 100 and the sum (ϵ) of the volumes of the other individual constituents (air-free basis). The volume of nitrogen $(N_2)_1$ on an air-free basis can also be found by formula (4*b*), which has been derived by considering the total nitrogen $(N_2)_s$ as consisting of two parts—one $(N_2)_{air\text{-}s}$ derived from the air and the other $(N_2)_{gp\text{-}s}$ as a constituent of the gas portion (Gas_s) of the atmosphere sampled. Equations expressing the volume of each of the individual constituents, calculated to an air-free basis, are:

$$Constituent_{air\text{-}free}=\frac{Constituent_s}{K_s}(100), \tag{3}$$

and

$$(N_2)_1=100-\epsilon, \tag{4a}$$

or

$$(N_2)_1=\frac{[(N_2)_s-Air_s+(O_2)_s]\,(100)}{K_s}; \tag{4b}$$

where $Constituent_{air\text{-}free}$ is the volume of each of the constituents, except the nitrogen, on an air-free basis; $(N_2)_s$ is the total amount of nitrogen in the sample; ϵ is the total volume of the individual constituents, except the nitrogen, in the air-free analysis of the atmosphere sampled;
and the other symbols have the same meanings as before.

The method by which the air-free composition of a complex gas mixture is determined is shown below. An atmosphere beneath a building in which an explosion had occurred is used as an example. The sample represents the composition of the atmosphere (carbureted water gas and air) in a sealed area beneath the building.

The compositions of the atmosphere as sampled, and when calculated to an air-free basis, are as follows:

Constituent	Analysis of sample as collected		Air-free analysis	
	Percent	Symbol	Percent	Symbol
Carbon dioxide	3.90	D_s	4.00	D_1.
Ethylene	5.76	$(C_2H_4)_s$	5.92	$(C_2H_4)_1$.
Propylene	1.44	$(C_3H_6)_s$	1.48	$(C_3H_6)_1$.
Methane	11.25	B_s	11.55	B_1.
Hydrogen	42.95	$(H_2)_s$	44.11	$(H_2)_1$.
Carbon monoxide	31.30	A_s	32.14	A_1.
Oxygen	.55	$(O_2)_s$	.00	
Nitrogen, total	2.85	$(N_2)_s$	.80	$(N_2)_1$.
Air	2.63	$(Air)_s$	.00	
Nitrogen in air	2.08	$(N_2)_{air\text{-}s}$	.00	
Gases other than air	97.37	K_s	100.00	

The volume of air (Air_s) in the atmosphere sampled is found by substituting the volume of oxygen (0.55 percent) in the sample for the corresponding symbol in formula (1), as follows:

$$Air_s=\frac{(O_2)_s\,(100)}{20.93}=\frac{0.55\times 100}{20.93}=2.63 \text{ percent.}$$

From formula (2) we obtain the percentage (K_s) of the gases other than air in the atmosphere sampled; this is a constant that is used to determine the percentages of the constituents composing the atmosphere under consideration:

$$K_s=100-Air_s=100-2.63 \text{ percent}=97.37 \text{ percent.}$$

To determine the volume of each constituent of the air-free analysis, determination of the hydrogen $(H_2)_1$ (air-free) can be used as an example. By substituting the volume of hydrogen $(H_2)_s$ sampled for the corresponding symbol in formula (3), we find

$$(H_2)_1=\frac{(H_2)_s\,(100)}{K_s}=\frac{42.95\times 100}{97.37}=44.11 \text{ percent.}$$

The percentages of the other constituents, on an air-free basis, are found in a similar manner, with the exception of the percentage of nitrogen $(N_2)_1$, which is found by substituting the real values of the other constituents for the symbols in formula (4*a*), as follows:

$$\begin{aligned}(N_2)_1 &= 100-\epsilon, \qquad\qquad (4a)\\ &=100-D_1+(C_2H_4)_1+(C_3H_6)_1+B_1+(H_2)_1+A_1,\\ &=100-(4.00+5.92+1.48+11.55+44.11+32.14),\\ &=100-99.20=0.80 \text{ percent;}\end{aligned}$$

or from formula (4*b*)

$$\begin{aligned}(N_2)_1 &= \frac{[(N_2)_s-Air_s+(O_2)_s]\,(100)}{K_s},\\ &=\frac{(2.85-2.63+0.55)\times 100}{97.37}=0.80 \text{ percent.} \qquad (4b)\end{aligned}$$

CALCULATION OF EXPLOSIBILITY OR NONEXPLOSIBILITY OF COMPLEX GAS-AIR MIXTURES

Whether an air-free complex-gas mixture is explosive or nonexplosive when mixed with the suitable proportions of air can be determined by the method used by Jones (*19, 20*). Experimental data on the extinctive effect of both nitrogen and carbon dioxide on the flames of the combustible gases—carbon monoxide, methane, hydrogen, ethylene, and propylene—have been determined by Jones, Coward, Hartwell, and others (*6, 9, 19, 20*) and are given in table 3.

TABLE 3.—*Volumes of inert gas* (*nitrogen or carbon dioxide*) *required for extinction of hydrogen, methane, carbon, monoxide, ethylene, and propylene flames in the combustible gas–air–inert gas mixtures; critical gas-mixture values* (*C. G. M. V.*); *combustible gas, additional inert gas, and oxygen in nose-limit mixtures; and oxygen percentages, below which no mixture is explosive* (*critical oxygen values*)

Combustible gas	Diluent or additional inert gas	Volumes of inert gas required per volume of combustible gas	Critical gas mixture value (*C. G. M. V.*)[1] (percent)	Gases in nose-limit mixture[1] (percent by volume)			Critical oxygen value[2] (percent)
				Combustible gas	Additional inert gas	Oxygen	
Hydrogen (H_2)	Nitrogen	[3] 16.55	5.69	4.30	71.20	5.12	5.0
	Carbon dioxide	[3] 10.20	8.92	5.31	54.19	8.48	5.9
Methane (CH_4)	Nitrogen	[3] 6.00	14.28	5.93	35.57	12.24	12.1
	Carbon dioxide	[3] 3.20	23.80	6.66	21.34	15.07	14.6
Carbon monoxide (CO)	Nitrogen	[3] 4.15	19.41	13.78	57.22	6.07	5.6
	Carbon dioxide	[3] 2.16	31.64	18.35	39.65	8.79	5.9
Ethylene (C_2H_4)	Nitrogen	[4] 15.40	6.09	3.06	47.24	10.40	10.0
	Carbon dioxide	[4] 9.10	9.90	4.26	38.74	11.93	11.7
Propylene (C_3H_6)	Nitrogen	[4] 14.10	6.62	2.81	39.69	12.03	11.5
	Carbon dioxide	[4] 7.80	11.36	3.54	27.66	14.40	14.1

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[1] Calculated by authors from test data furnished by G. W. Jones, chemist, Bureau of Mines; and ref. *19*, table 7.

[2] Ref. *9*, table 33.

[3] Ref. *19*, table 7.

[4] Test data by G. W. Jones, chemist, Bureau of Mines.

Whether or not an air-free complex-gas mixture is explosive when admixed with air can be determined from the foregoing data. The volumes of the inert gases (nitrogen, carbon dioxide, or both) that must be admixed with the combustible gases in the air-free composition of the gas mixture to form a mixture incapable of forming an explosive mixture with air are calculated from table 3 and then compared with the volumes of inert gases in the air-free composition of the gas mixture. The procedure to determine this follows:

A bituminous-coal mine-fire atmosphere (example 1) and an anthracite mine-fire atmosphere (example 2), which were sampled after the fires had been sealed for several months, may be used as examples. The samples represent the compositions of atmospheres in sealed areas of large volumes. Both samples were taken on the return-air side of the fire; they represent portions of the mine-fire atmospheres that contain air, a large proportion of which entered the mine-fire areas through openings between the fires and the sampling points.

Procedure to determine whether or not air-free mine-fire atmosphere is explosive when admixed with air

Constituent	Analysis (percent by volume)		Ratio of inert gas (N_2 or CO_2) to combustible gas necessary to render combustible gas nonexplosive [1]		Amount (parts) of inert gas (N_2 or CO_2) that must be present to render combustible gas nonexplosive if air is admixed with air-free mixture	
	Sample	Air-free	N_2	CO_2	N_2	CO_2
Example 1						
Carbon monoxide	0.52	0.77	4.15	2.16	3.20	2.46
Methane	.16	.24	6.00	3.20	1.44	.77
Hydrogen	.03	.05	16.55	10.20	.83	.51
Oxygen	6.80	.00				
Nitrogen	82.65	84.36				
Carbon dioxide	9.84	14.58				
Total combustible gases	.71	1.06				
Total inert gases	92.49	98.94			5.47	3.74
Example 2						
Carbon monoxide	.78	3.54	4.15	2.16	14.69	7.65
Methane	.33	1.50	6.00	3.20	9.00	4.80
Hydrogen	1.07	4.86 {1.73 3.13	16.55 16.55	10.20 10.20	28.63 51.79	17.61 31.96
Oxygen	16.32	.00				
Nitrogen	77.62	72.49				
Carbon dioxide	3.88	17.61				
Total combustible gases	2.18	9.90				
Total inert gases	81.50	90.10			104.11	62.02

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[1] From table 3.

Example 1 of the foregoing tabulation shows that the presence of either 5.47 parts of nitrogen or 3.74 parts of carbon dioxide suffices to render the combustible gases in this atmosphere nonexplosive. The air-free analysis of the atmosphere shows that 84.36 parts of nitrogen and 14.58 parts of carbon dioxide are present. As it is known that the sample represents the most hazardous portion of the mine-fire atmosphere surrounding the active fire, it can be concluded that an explosion within the sealed area was impossible either under conditions as they were or if air were admitted at the time the sample was collected.

In example 2 either 104.11 parts of nitrogen or 62.02 parts of carbon dioxide is required to render the combustible gases in this atmosphere nonexplosive. If all the carbon dioxide (17.61 parts) in the air-free original atmosphere is used to render part (1.73 parts) of the hydrogen (4.86 parts, total) nonexplosive, then 75.48 parts of nitrogen and 17.61 parts of carbon dioxide will be required to render the combustible gases nonexplosive. The analysis of the air-free original atmosphere shows that 72.49 parts of nitrogen are available; therefore, this atmosphere can form explosive mixtures with air. Percautions must be taken to guard against an explosion, and the other factors relating to the explosibility of the mine-fire atmosphere should be investigated. Jones (*19*) describes in detail the conventional method used to determine the explosive limits of complex gas-air mixtures. The methods used to determine the other pertinent factors are described in this report.

Experience at fires emphasizes the need of a more simplified method that can be used to determine the explosiblity of mine-fire atmospheres. Accordingly, the authors have developed a method whereby the procedure shown in tabular form on page 20 can be simplified. Whether or not an air-free atmosphere containing combustible gases has explosive limits can be determined by using the critical gas mixture value formula that applies to the type of mixture being investigated.

If the real values of the various constituents composing the air-free original atmosphere are substituted for the symbols in the critical gas-mixture value formula, and the critical gas-mixture value is found to be less than 100, the air-free original atmosphere has explosive limits; if it is 100, more than 100, or has a minus value, both the original atmosphere and the air-free original atmosphere are nonexplosive and incapable of forming explosive mixtures with air. The reasons for these conclusions can be deduced from figures 1 and 4 (pocket).

Applying the critical gas-mixture value method to the two examples previously given, we first determine for example 1 that $[10.2(H_2)_1+3.2\,B_1]$, or 1.28, $<$ 14.58, or D_1, in which case we use formula (21A), as given on page 29, or

$$C.\,G.\,M.\,V._{N_2}=\frac{10{,}000}{5.15A_1+7.15B_1+20.6(H_2)_1-0.9213D_1}; \qquad (21A)$$

where $C.\,G.\,M.\,V._{N_2}$ is the critical gas-mixture value (in percent) of the air-free original atmosphere;

A_1 = the volume of carbon monoxide in the air-free original atmosphere;
B_1 = the volume of methane;
$(H_2)_1$ = the volume of hydrogen;
and
D_1 = the volume of carbon dioxide.

By substituting the real values for the symbols in formula (21*A*)—for example 1, when $A_1=0.77$, $B_1=0.24$, $(H_2)_1 = 0.05$, and $D_1=14.58$—we find

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{(5.15\times 0.77)+(7.15\times 0.24)+(20.6\times 0.05)-(0.9213\times 14.58)},$$

$$=\frac{10{,}000}{3.97+1.72+1.03-13.43}=\frac{10{,}000}{-6.71}=-1{,}490.$$

The critical gas-mixture value is a minus quantity; therefore, the air-free original atmosphere is incapable of forming explosive mixtures with air, and the original atmosphere is nonexplosive.

For example 2, in which $10.2(H_2)_1$, or 49.57, $>$ 17.61, or D_1, formula (10) applies when $A_1=3.54$, $B_1=1.50$, $(H_2)_1=4.86$, and $D_1=17.61$. By substituting the numerical values for the symbols in formula (10) (p. 25) we find

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{(5.15\times 3.54)+(7\times 1.50)+(17.55\times 4.86)-(0.6225\times 17.61)},$$

$$=\frac{10{,}000}{18.23+10.50+85.29-10.96}=\frac{10{,}000}{103.06}=97.02.$$

The critical gas-mixture value is less than 100; therefore, the air-free original atmosphere is capable of forming explosive mixtures with air. (*See* fig. 9, pocket.)

It needs to be repeated that whenever the critical gas-mixture value is a minus value, is 100, or exceeds 100, neither the original atmosphere nor the air-free original atmosphere is explosive; and they cannot become explosive, regardless of how much air is admixed with them. No further calculations on the explosibility of the atmosphere under consideration are necessary, except when the critical gas-mixture value equals or slightly exceeds 100. In such instances, the critical oxygen value should be determined.

The reason for determining the critical oxygen value of mixed gases that have a critical gas-mixture value slightly over 100 is that such mixtures are borderline mixtures. Although nose-limit values that exceed 75.5 percent and critical oxygen values that are less than 5 percent are impossible for complex mixtures composed of hydrogen, carbon monoxide, methane, ethylene, and propylene and although the nose-limit-mixture formulas and the critical-oxygen-value formulas are not strictly accurate and do not apply to complex mixtures having a critical gas-mixture value over 100, an approximate indication of the critical oxygen value for mixtures containing analogous proportions of the constituents composing the air-free analysis of the atmosphere under investigation is calculable and desirable. A change can occur in the composition of a mine-fire atmosphere by an increase of methane from various causes, or hydrogen and carbon monoxide may be increased materially by an increase in the temperature of some fires or by water coming in contact with hot materials in others (*3, 30*). (*See* fig. 9, pocket.)

CALCULATION OF CRITICAL GAS-MIXTURE VALUE

The critical gas mixture has been defined as that air-free atmosphere formed when an air-free original atmosphere that has explosive limits is diluted with an inert gas (such as nitrogen) until the composition of the mixture makes it just incapable of forming an explosive mixture with air. (*See* fig. 1, pocket.)

We have defined the critical gas-mixture value as the numerical value (in percent) that corresponds to the gas-portion content of the critical gas mixture (*see* p. 10).

As the respective volumes of the inert gases (nitrogen and carbon dioxide) required for the extinction of hydrogen, methane, carbon monoxide, ethylene, and propylene flames are known (table 3), we can determine the composition of an atmosphere that is just incapable of forming explosive mixtures with air, when that atmosphere has been formed by admixing an air-free atmosphere—composed of the foregoing combustible gases in varying proportions—with the required amount of diluent (nitrogen or carbon dioxide).

The manner in which the inert gases are combined with the different combustible gases affects to some extent the final calculated values of the factors relating to the explosibility of a complex-gas mixture. Experimental data (*9*, *19*, *20*) indicate that the carbon dioxide should be presumed to be used in rendering the hydrogen, in whole or in part, nonexplosive. If there is an excess of hydrogen for the carbon dioxide available, the remainder of the hydrogen is combined with nitrogen. If there is an excess of carbon dioxide for the hydrogen available, the carbon dioxide remaining is combined with the methane and the carbon monoxide, in the order named.

Relationships between the known amounts of each of the combustible gases and inert gases that compose an air-free original atmosphere and the unknown amounts of the corresponding constituents that compose the gas portion and the diluent portion of the critical gas mixture can be established as follows:

Let us consider a sample of an original atmosphere that, when calculated to an air-free basis, has explosive limits in air and is composed of carbon monoxide, methane, hydrogen, carbon dioxide, and nitrogen in such proportions that:

A_1 = the number of parts of carbon monoxide in the air-free original atmosphere;

B_1 = number of parts of methane;

$(H_2)_1$ = number of parts of hydrogen;

D_1 = number of parts of carbon dioxide;

$(N_2)_1$ = number of parts of nitrogen;

and

$A_1 + B_1 + (H_2)_1 + D_1 + (N_2)_1 = 100$ percent or parts.

To make the foregoing atmosphere incapable of forming explosive mixtures with air, it is necessary to add enough additional inert gas (table 3) to the air-free original atmosphere so that the following conditions exist:

$4.15A_1$ = the number of parts of nitrogen paired with the carbon monoxide;

and

$6.00B_1$ = the number of parts of nitrogen paired with the methane.

If all the carbon dioxide D_1 is paired with part of the hydrogen $(H_2)_1$, then

$\frac{D_1}{10.2}$ = the number of parts of hydrogen paired with the carbon dioxide;

and

$(H_2)_1-\frac{D_1}{10.2}$ = the number of parts of hydrogen paired with nitrogen.

Also

$16.55\left[(H_2)_1-\frac{D_1}{10.2}\right]$ = the number of parts of nitrogen paired with part of the hydrogen,

and

D_1 = the number of parts of carbon dioxide paired with the remainder of the hydrogen.

From the foregoing data, it can be deduced that the total volume of a mixture incapable of forming explosive mixtures, if admixed with air, is the sum of the number of parts of each combustible gas plus the number of parts of diluent paired with it.

Case 1

When all the carbon dioxide (D_1) can be paired with part of the hydrogen, as stated above, we have a condition where 10.2 times the amount of hydrogen $(H_2)_1$ in the air-free original atmosphere is more than the amount of carbon dioxide (D_1), or $10.2(H_2)_1>D_1$.

If V_1 = the total number of parts of combustible gases and inert gases composing the air-free original atmosphere, plus parts of inert gas necessary to form a mixture just incapable of forming an explosive mixture with air, then

$$V_1=\underbrace{(A_1+4.15A_1)}_{\substack{\text{carbon}\\ \text{monoxide}\\ \text{plus}\\ \text{nitrogen}}}+\underbrace{B_1+6B_1}_{\substack{\text{methane}\\ \text{plus}\\ \text{nitrogen}}}+\underbrace{\left[(H_2)_1-\frac{D_1}{10.2}\right]}_{\text{hydrogen}}\underset{\text{plus}}{+}\underbrace{16.55\left[(H_2)_1-\frac{D_1}{10.2}\right]}_{\text{nitrogen}}+\underbrace{\frac{D_1}{10.2}+D_1}_{\substack{\text{hydrogen}\\ \text{plus}\\ \text{carbon}\\ \text{dioxide}}};$$

or

$$V_1=5.15A_1+7B_1+17.55(H_2)_1-\frac{17.55D_1}{10.2}+\frac{D_1}{10.2}+D_1,$$

which, by clearing of fractions, can be written

$$V_1=5.15A_1+7B_1+17.55(H_2)_1-0.6225D_1. \qquad (5)$$

Similarly, if A, B, (H_2), D, (N_2), and $(N_2)_{dil}$ are the number of parts or percentages of carbon monoxide, methane, hydrogen, carbon dioxide, nitrogen, and additional nitrogen, respectively, that compose the critical gas mixture, it can be deduced that

$$V = A + B + (H_2) + D + (N_2) + (N_2)_{dil},$$

and

$$V = 5.15A + 7B + 17.55(H_2) - 0.6225D; \tag{6}$$

where V is the total volume (in parts) of the critical gas mixture.

Because analogous proportions of the constituents that compose the 100 parts of the air-free original atmosphere can be presumed to be replaced by a diluent (additional nitrogen) until the critical gas mixture is formed, the total volume (V) of the critical gas mixture must consist of 100 parts of the individual gases that compose this mixture, and the number of parts of each constituent can be expressed in percent. Substituting 100 for V in formula (6), we obtain

$$5.15A + 7B + 17.55(H_2) - 0.6225D = 100, \tag{7}$$

where the symbols have the same meanings as before.

The following relationships can be established from formulas (5), (6), (7), and other data previously given:

$$\frac{A}{A_1} = \frac{B}{B_1} = \frac{(H_2)}{(H_2)_1} = \frac{D}{D_1} = \frac{(N_2)}{(N_2)_1} = \frac{A + B + (H_2) + D + (N_2)}{A_1 + B_1 + (H_2)_1 + D_1 + (N_2)_1} =$$

$$\frac{C.\ G.\ M.\ V._{\mathrm{N}_2}}{100} = \frac{C.\ G.\ M.\ V._{N_2} + (N_2)_{dil}}{5.15A_1 + 7B_1 + 17.55(H_2)_1 - 0.6225D_1} = \frac{V}{V_1} =$$

$$\frac{5.15A + 7B + 17.55(H_2) - 0.6225D}{5.15A_1 + 7B_1 + 17.55(H_2)_1 - 0.6225D_1} =$$

$$\frac{100}{5.15A_1 + 7B_1 + 17.55(H_2)_1 - 0.6225D_1} = k. \tag{8}$$

From the foregoing equations, we obtain

$$k = \frac{100}{5.15A_1 + 7B_1 + 17.55(H_2)_1 - 0.6225D_1} = \frac{C.\ G.\ M.\ V._{N_2}}{100}, \tag{9}$$

where k is the critical gas-mixture value ($C.\ G.\ M.\ V.$) expressed as a decimal fraction, and the other symbols have the same meanings as before, and

$$C.\ G.\ M.\ V._{N_2} = 100\ k = \frac{100 \times 100}{5.15A_1 + 7B_1 + 17.55(H_2)_1 - 0.6225D_1},$$

or

$$C.\ G.\ M.\ V._{N_2} = \frac{10{,}000}{5.15A_1 + 7B_1 + 17.55(H_2)_1 - 0.6225D_1}. \tag{10}$$

Formula (10) is applicable when all the carbon dioxide D_1 is paired with part of the hydrogen, and the remainder of the hydrogen is paired with part of the available nitrogen, that is, where $10.2(H_2)_1 > D_1$.

We have considered the case that applies for calculating the critical gas-mixture value when all the carbon dioxide in the air-free original atmosphere is paired with part of the hydrogen, and the remainder of the hydrogen is paired with nitrogen (formula (10)). This has been called case 1.

If any of the gases represented by A_1, B_1, $(H_2)_1$, etc., in any of the formulas relating to the calculation of the "critical gas mixture" value are absent, the real value of the symbol expressing the missing gas becomes zero. For example, when carbon monoxide (A_1), hydrogen $(H_2)_1$, and carbon dioxide (D_1) are absent, formula (10) becomes

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{7B_1}.$$

We can now consider the formulas for calculating the critical gas-mixture values for other mixed-gas combinations likely to be met; and calculations similar to those given for deriving formulas (5) to (10), inclusive, can be made.

Case 2

When no hydrogen is present in an air-free original atmosphere that is composed of carbon monoxide, methane, carbon dioxide, and nitrogen, all the carbon dioxide is paired with part of the methane, and the remainder of the methane is paired with nitrogen. In this case, $3.2B_1 > D_1$, and it can be shown, when nitrogen is used as the diluent, that

$$V=\underbrace{(A+4.15A)}_{\substack{\text{carbon}\\ \text{monoxide}\\ \text{plus}\\ \text{nitrogen}}}+\underbrace{\left(B-\frac{D}{3.2}\right)+6\left(B-\frac{D}{3.2}\right)}_{\text{methane plus nitrogen}}+\underbrace{\frac{D}{3.2}+D_1}_{\substack{\text{methane}\\ \text{plus}\\ \text{carbon}\\ \text{dioxide}}}$$

or

$$V=5.15A+7B-0.875D, \tag{11}$$

$$5.15A+7B-0.875D=100, \tag{12}$$

and

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{5.15A_1+7B_1-0.875D_1}, \tag{13}$$

where 3.2 = a constant from table 3;

$\frac{D}{3.2}$ = the number of parts of methane in critical gas-mixture paired with carbon dioxide;

$B-\frac{D}{3.2}$ = the number of parts of methane in critical gas mixture paired with nitrogen;

V = the total volume of the critical gas mixture;

$C.\ G.\ M.\ V._{N_2}$ = the critical gas-mixture value, in percent;

and the other symbols have the same meanings as before.

Case 3

If an air-free original atmosphere is composed of carbon monoxide, methane, hydrogen, carbon dioxide, and nitrogen, and hydrogen and carbon dioxide are present in such volumes that 10.2 times the hydrogen is less than the total volume of carbon dioxide present, all the hydrogen is paired with part of the carbon dioxide and the remainder of the carbon dioxide is paired with part of the methane.

In this case, 10.2 $(H_2)_1 < D_1$, and it can be shown, when nitrogen is used as the diluent, that

$$V = \underbrace{(A+4.15A)}_{\substack{\text{carbon}\\\text{monoxide}\\\text{plus}\\\text{nitrogen}}} + \underbrace{\left(B-\frac{D-10.2(H_2)}{3.2}\right)}_{\text{methane}} \underset{\text{plus}}{+} \underbrace{6\left(B-\frac{D-10.2(H_2)}{3.2}\right)}_{\text{nitrogen}}$$

$$+\underbrace{\frac{D-10.2(H_2)}{3.2}}_{\text{methane}} \underset{\text{plus}}{+} \underbrace{D-10.2(H_2)}_{\substack{\text{carbon}\\\text{dioxide}}} + \underbrace{(H_2)}_{\text{hydrogen}} \underset{\text{plus}}{+} \underbrace{10.2(H_2)}_{\substack{\text{carbon}\\\text{dioxide}}}$$

or

$$V = 5.15A + 7B + 20.12(H_2) - 0.875D, \tag{14}$$

$$5.15A + 7B + 20.12(H_2) - 0.875D = 100, \tag{15}$$

and

$$C.\ G.\ M.\ V._{N_2} = \frac{10{,}000}{5.15A_1 + 7B_1 + 20.12(H_2)_1 - 0.875D_1}; \tag{16}$$

where 10.2 and 3.2 = constants from table 3;

$10.2(H_2)$ = the number of parts of carbon dioxide paired with hydrogen;

$D-10.2(H_2)$ = the number of parts of carbon dioxide paired with methane;

$\frac{D-10.2(H_2)}{3.2}$ = the number of parts of methane paired with carbon dioxide;

$B-\frac{D-10.2(H_2)}{3.2}$ = the number of parts of methane paired with nitrogen;

V = total volume of the critical gas mixture;

$C.\ G.\ M.\ V._{N_2}$ = critical gas-mixture value, in percent;

and the other symbols have the same meanings as before.

Case 4

If an air-free original atmosphere is composed of carbon monoxide, methane, hydrogen, carbon dioxide, nitrogen, ethylene, and propylene, such as in instances where producer gas or carbureted water gas may be used or at anthracite mine fires when slushing or use of water produces such gases, all the carbon dioxide is paired with part of the hydrogen, and the remainder of the hydrogen and the other combustible gases are paired with nitrogen.

In this case 10.2 $(H_2)_1 > D_1$, and, when nitrogen is used as the diluent, it can be shown that

$$V = \underbrace{A+4.15A}_{\substack{\text{carbon}\\\text{monoxide}\\\text{plus}\\\text{nitrogen}}} + \underbrace{B+6B}_{\substack{\text{methane}\\\text{plus}\\\text{nitrogen}}} + \underbrace{(H_2)-\frac{D}{10.2}}_{\text{hydrogen plus}} + \underbrace{16.55\left((H_2)-\frac{D}{10.2}\right)}_{\text{nitrogen}}$$

$$+\underbrace{\frac{D}{10.2}+D}_{\substack{\text{hydrogen}\\\text{plus}\\\text{carbon}\\\text{dioxide}}} + \underbrace{(C_2H_4)+15.4(C_2H_4)}_{\substack{\text{ethylene}\\\text{plus}\\\text{nitrogen}}} + \underbrace{(C_3H_6)+14.1(C_3H_6)}_{\substack{\text{propylene}\\\text{plus}\\\text{nitrogen}}},$$

or

$$V=5.15A+7B+17.55(H_2)-0.6225D+16.4(C_2H_4)+15.1(C_3H_6), \qquad (17)$$

$$5.15A+7B+17.55(H_2)-0.6225D+16.4(C_2H_4)+15.1(C_3H_6)=100, \qquad (18)$$

and

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{5.15A_1+7B_1+17.55(H_2)_1-0.6225D_1+16.4(C_2H_4)_1+15.1(C_3H_6)_1}; \qquad (19)$$

where A and A_1, B and B_1, (H_2) and $(H_2)_1$, D and D_1, (C_2H_4) and $(C_2H_4)_1$, (C_3H_6) and $(C_3H_6)_1$ are the carbon monoxide, methane, hydrogen, carbon dioxide, ethylene, and propylene composing the critical gas mixture and the air-free original atmosphere, respectively;
4.15, 6.00, 16.55, 10.2, 15.4, and 14.1 are constants from table 3;
V is the total volume of critical gas mixture,
and $C.\ G.\ M.\ V._{N_2}$ is the critical gas-mixture value, in percent.

Case 5

If carbon monoxide, methane, hydrogen, nitrogen, and carbon dioxide are present in an air-free original atmosphere in volumes such that 10.2 times the volume of hydrogen $(H_2)_1$ equals the volume of carbon dioxide (D_1), the critical gas-mixture value can be calculated in several ways.

In this case, $10.2\ (H_2)_1=D_1$, and when nitrogen is used as the diluent it can be shown that

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{5.15A_1+7B_1+(H_2)_1+D_1}, \qquad (20a)$$

or

$$=\frac{10{,}000}{5.15A_1+7B_1+11.2(H_2)_1}; \qquad (20b)$$

where A_1, B_1, $(H_2)_1$, and D_1 are the volumes of carbon monoxide, methane, hydrogen, and carbon dioxide, respectively, in the air-free original atmosphere;
and $C.\ G.\ M.\ V._{N_2}$ is the critical gas-mixture value, in percent.

However, if 10.2 times $(H_2)_1$ equals D_1, either formula (10), page 25, or formula (16), page 27, can also be used to calculate the critical gas-mixture value.

It is observed that there is a similarity in the forms of formulas (10), (13), (16), and (19), which are used to calculate the critical gas-mixture value. The differences in the constants and the presence or absence of some constituents depend on four things: (1) Absence of some of the combustible constituents in the original atmosphere under consideration; (2) whether the carbon dioxide is paired in whole or in part with the hydrogen or methane; (3) mathematical results in developing the formula; and (4) whether the carbon dioxide in the air-free original atmosphere is more or less than 10.2 times the amount of hydrogen when both are present.

If hydrogen and carbon dioxide are present and formula (16) is used instead of formula (10) when $10.2(H_2)_1$ is more than D_1, the critical gas-mixture value obtained would be on the safe side for borderline mixtures, but according to the experimental data (*19*) used to derive the formulas the results would not be strictly correct. For this reason, the formula applying to the case at hand should be used. If 10.2 times $(H_2)_1$ is more than D_1, formula (10) should be used, but if 10.2 times $(H_2)_1$ is less than D_1, formula (16) should be used.

Case 6

If carbon monoxide, methane, hydrogen, nitrogen, and carbon dioxide are present in an air-free original atmosphere in volumes such that all the hydrogen and methane can be paired with part of the carbon dioxide, the remainder of the carbon dioxide is paired with part of the carbon monoxide, and the carbon monoxide remaining is paired with nitrogen.

In this case

$$[10.2(H_2)_1+3.2B_1]<D_1,$$

and when nitrogen is used as the diluent the critical gas-mixture value can be shown to be

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{5.15A_1+7.15B_1+20.6(H_2)_1-0.9213D_1}, \qquad (21A)$$

where the symbols have the same meanings as before.

Case 6 is unusual, and it is unlikely that formula (21*A*) would have to be used in dealing with the usual mine fire, although atmospheres to which it is applicable are sometimes encountered at lignite-mine fires and subbituminous-coal-mine fires.

Case 7

If an air-free original atmosphere is composed of carbon monoxide, methane, hydrogen, ethylene, propylene, carbon dioxide, and nitrogen in volumes such that all the methane, hydrogen, ethylene, and propylene and part of the carbon monoxide can be paired with the carbon dioxide available, the carbon monoxide remaining is paired with nitrogen.

In this case,

$$[3.2B_1+10.2(H_2)_1+9.1(C_2H_4)_1+7.8(C_3H_6)_1]<D_1,$$

and when nitrogen is used as the diluent the critical gas-mixture value can be shown to be

$$C.G.M.V._{N_2}=\frac{10{,}000}{5.15A_1+7.15B_1+20.6(H_2)_1+18.48(C_2H_4)_1+15.98(C_3H_6)_1-0.9213D_1}, \qquad (21B)$$

Case 7 is an unusual case, and formula (21*B*) would not be employed when investigating mine fires; it is useful to determine whether or not some mixtures composed of carbureted water gas and carbon dioxide are nonexplosive or capable of forming explosive mixtures with air.

USE OF CRITICAL GAS-MIXTURE VALUE TO DETERMINE NONEXPLOSIBILITY OF ATMOSPHERE

It has been stated on page 21 that the critical gas-mixture value is an index showing whether an original atmosphere is nonexplosive, whether there is any possibility of an explosion if a source of ignition is present, or whether the air-free original atmosphere has explosive limits.

Because the numerator in the fractional expression of the critical-gas-mixture-value formulas is a constant (10,000), it follows that if the denominator, which is the total number of parts of the combustible constituents in the air-free original atmosphere plus the number of parts of inert gases (nitrogen and carbon dioxide) required to form an extinctive atmosphere, is less than 100 or a minus value, the original atmosphere is nonexplosive, and the air-free composition of it cannot form explosive mixtures with air. No further calculations are necessary unless the denominator is equal to or slightly less than 100. This condition indicates a nonexplosive borderline mixture, and a critical oxygen value should be calculated as explained on page 22.

The method of determining by this approach whether an explosion was likely to occur in an anthracite mine-fire area is used in the following instance.

A mine fire has existed for many years in the steeply dipping workings of an anthracite mine. It has been impossible to extinguish this fire by flooding or other conventional methods. The best that can be done to work the mine with safety is to keep the fire isolated, prevent excess infiltration of air, and take whatever precautions are possible as indicated by a systematic study of analyses of the mine-fire atmosphere. A representative sample of the mine-fire atmosphere may be used as an example. The composition of the normal mine air and of the mine-fire atmosphere as sampled is as follows:

Constituent	Symbol in formula used (air-free analysis)	Normal mine air (percent)	Mine-fire atmosphere (percent)	
			Sample	Air-free analysis
Carbon dioxide	D_1	0.14	13.22	16.79
Oxygen		20.70	4.46	.00
Hydrogen	$(H_2)_1$	.00	1.57	1.99
Carbon monoxide	A_1	.00	1.92	2.44
Methane	B_1	.02	.99	1.26
Nitrogen	$(N_2)_1$	79.14	77.84	77.52
Total		100.00	100.00	100.00
Normal atmospheric air		98.90	21.32	.00
Other gases		1.10	78.68	100.00

First, the analysis of the mine-fire atmosphere as sampled is calculated to an air-free basis by the method described in the section, Calculation of Air-Free Analysis.

Now we determine the relationship between the volume of hydrogen $(H_2)_1$ and the volume of carbon dioxide (D_1) in the air-free analysis. This relationship shows the critical-gas mixture-value formula that should be used.

From the above tabulation $(H_2)_1$ is 1.99 and D_1 is 16.79, from which the following relationship is established:

$$10.2(H_2)_1 = 10.2 \times 1.99 = 20.3;$$

therefore,

$$10.2(H_2)_1, \text{ or } 20.3, > 16.79, \text{ or } D_1,$$

and formula (10), page 25, should be used.

By substituting the real values for the symbols A_1, B_1, $(H_2)_1$, and D_1 in formula (10), which is

$$C.\,G.\,M.\,V._{N_2}=\frac{10{,}000}{5.15A_1+7B_1+17.55(H_2)_1-0.6225D_1}; \qquad (10)$$

where $C.\,G.\,M.\,V._{N_2}$ = the critical gas-mixture value;

we find $C.\,G.\,M.\,V._{N_2}=\dfrac{10{,}000}{(5.15\times2.44)+(7\times1.26)+(17.55\times1.99)-(0.6225\times16.79)}$,

$$=\frac{10{,}000}{45.86}=218.2.$$

As the denominator (45.86) in the above equation is less than 100, the critical gas-mixture value (218.2) is consequently more than 100, and it can be concluded (1) that the air-free original atmosphere cannot form explosive mixtures with air, (2) the original atmosphere is not explosive, (3) there is no possibility of an explosion in the mine-fire area, and (4) an explosion would not occur if air was admitted to the sealed mine-fire area at the time the atmosphere in the sealed area was sampled.

CALCULATION OF INDIVIDUAL CONSTITUENTS OF CRITICAL GAS MIXTURE

It is desirable to know the real values, or percentages, of the individual constituents composing the critical gas mixture.

It has been shown in formula (8), page 25, that

$$\frac{A}{A_1}=\frac{B}{B_1}=\frac{(H_2)}{(H_2)_1}=\frac{D}{D_1}=\frac{(N_2)}{(N_2)_1}=*\ *\ *=k;$$

where k = the critical gas-mixture value expressed as a decimal fraction;
A, B, (H_2), D, (N_2), ***= the volumes (in percent) of carbon monoxide, methane, hydrogen, carbon dioxide, nitrogen, and other constituents, except diluent, that compose the gas portion of the critical gas mixture;

and A_1, B_1, $(H_2)_1$, D_1, $(N_2)_1$, ***=the volumes (in percent) of the same constituents that compose the air-free original atmosphere.

From the above data, a general formula can be arranged by which the volume of each constituent of the critical gas mixture, except diluent, can be calculated when the volume of the same constituent present in the air-free original atmosphere and the critical gas-mixture value expressed as a decimal fraction are known.

A general expression of the foregoing data (formula 8) can be written as follows:

$$\frac{Constituent_{C.G.M.}}{Constituent_{air\text{-}free}}=k,$$

from which, by transposing factors, we obtain

$$Constituent_{C.G.M.}=k\ (Constituent_{air\text{-}free}); \qquad (22A)$$

where $Constituent_{C.G.M.}$ = the respective volume (in percent) of each of the simple gases, except diluent, composing the gas portion of the critical gas mixture;
$Constituent_{air\text{-}free}$ = the respective volume (in percent) of each of the same simple gases composing the air-free analysis of the original atmosphere;

and k = the critical gas-mixture value expressed as a decimal fraction, as calculated by the critical-gas-mixture-value formula applicable to the air-free original atmosphere under consideration.

The diluent content (in percent) of the critical gas mixture is found by subtracting the critical gas-mixture value from 100, or

$$Dil_{C.G.M.} = 100 - C.G.M.V.; \qquad (22B)$$

where $Dil_{C.G.M.}$ = the diluent content (nitrogen or carbon dioxide, as the case may be) of the critical gas mixture.

If the composition of the air-free original atmosphere includes an inert gas that is the same as the inert gas used as the diluent, the total volume of this inert gas in the critical gas mixture is the sum of the diluent content of the critical gas mixture and the volume of the same inert gas, as found in the gas portion of the critical gas mixture by formula (22*A*).

An example will serve to show the application of formulas (22*A*) and (22*B*) for calculating the volume of each constituent of the critical gas mixture.

For this purpose we can take example 2 (p. 20), in which the air-free original atmosphere in a sealed anthracite mine-fire area is composed of 3.54 percent carbon monoxide (A_1), 1.50 percent methane (B_1), 4.86 percent hydrogen $(H_2)_1$, 17.61 percent carbon dioxide (D_1), and 72.49 percent nitrogen $(N_2)_1$.

The critical gas-mixture value has been found to be 97.02 (see p. 22), which, expressed as a decimal fraction, is k in formula (22*A*).

By substituting the real values just given for the symbols in formula (22*A*), which is

$$Constituent_{C.G.M.} = k\ (Constituent_{air\text{-}free}),$$

we find

$$\begin{aligned}
A &= kA_1 &&= 0.9702 \times 3.54 = 3.43 \text{ percent of carbon monoxide,}\\
B &= kB_1 &&= 0.9702 \times 1.50 = 1.46 \text{ percent of methane,}\\
(H_2) &= k(H_2)_1 &&= 0.9702 \times 4.86 = 4.72 \text{ percent of hydrogen,}\\
D &= kD_1 &&= 0.9702 \times 17.61 = 17.08 \text{ percent of carbon dioxide,}\\
(N_2) &= k(N_2)_1 &&= 0.9702 \times 72.49 = 70.33 \text{ percent of nitrogen.}
\end{aligned}$$

The volume of diluent (additional nitrogen) is found by subtracting the critical gas-mixture value from 100; therefore, the volume of diluent ($Dil_{C.G.M.}$) is

$$\begin{aligned}
Dil_{C.G.M.} &= 100 - C.\ G.\ M.\ V._{N_2}, \qquad (22B)\\
&= 100 - 97.02 = 2.98 \text{ percent of nitrogen.}
\end{aligned}$$

Because 2.98 percent of additional nitrogen is used as diluent and 70.33 percent of nitrogen is derived from the air-free original atmosphere, the total volume of nitrogen in the critical gas mixture is

(70.33+2.98) percent, or 73.31 percent.

Summarizing the foregoing calculations, we find that the critical gas mixture is composed of 3.43 percent carbon monoxide, 1.46 percent methane, 4.72 percent hydrogen, 17.08 percent carbon dioxide, and 73.31 percent nitrogen.

The significance of the real values just given is that a mixture composed of 3.43 percent carbon monoxide, 1.46 percent methane, 4.72 percent hydrogen, 17.08 percent carbon dioxide, and 70.33 percent nitrogen is just incapable of forming explosive mixtures with air. However, any mixture that is formed by increasing the volume of any one of the combustible gases, which consequently decreases the inert-gas content, is capable of forming explosive mixtures with air. A mixture capable of forming explosive mixtures with air is formed if the volumes of the combustible gases composing the critical gas mixture are increased by increasing the gas-portion content; this decreases the inert-gas content of the resultant mixture.

CALCULATION OF NOSE LIMIT

The term "explosive limit," when applied to any simple combustible gas or a complex mixture of gases that have explosive limits when mixed with air, indicates a combustible gas-air or a complex gas-air mixture that is just explosive. It is defined by the real number that indicates the volume (in percent) of gases other than air present in the explosive-limit mixture.

In the section on the Nose-Limit Mixture and the Nose Limit the authors have defined the nose limit (1) as the numerical value designating the total percentage of gases other than air contained in the nose-limit mixture and (2) as having the same numerical value as the explosive limit of the common explosive-limit mixture that is present when the lower- and the upper-explosive-limit mixtures of an air-free complex-gas mixture have the same chemical composition.

In the section on Critical Gas Mixture and Critical Gas-Mixture Value and in the above-mentioned section, the authors have discussed the relationship between the nose limit, the critical gas mixture, the common explosive-limit mixture, the air-free original atmosphere, and the original atmosphere to which the foregoing factors apply.

LAW OF LE CHATELIER

The law of Le Chatelier, (*23*) which is used for calculating the explosive limits of any mixture of combustible gases that obey it, has been found to apply accurately for calculating both the upper and the lower explosive limits of complex gas-air mixtures (*9, 10*).

Briefly, the law of Le Chatelier states that when limit mixtures of two or more combustible gases are mixed, all the limit mixtures being of the same kind—all lower-explosive-limit or all upper-explosive-limit mixtures—a complex mixture will result that is just at its lower explosive limit or its upper explosive limit, correspondingly.

It follows that all explosive-limit mixtures remain as such in any proportion of explosive-limit mixtures that may constitute a complex gas-air mixture and that the new explosive-limit mixture resulting is that of the complex gas-air mixture. Therefore, the explosive-limit mixture of the complex gas-air mixture will consist of a number of similar explosive-limit mixtures of the individual combustible gases composing it.

Coward, Carpenter, and Payman (*9, 10*) rearranged the original statement of the law as given by Le Chatelier and put it in a more useful form for calculating the explosive limits of any mixture of combustible gases that obey it. Their formula is as follows:

$$L_U \text{ or } L_L = \frac{100}{\frac{p_1}{N_1}+\frac{p_2}{N_2}+\frac{p_3}{N_3}+*****},$$

where L_U=the upper and L_L the lower explosive limit;

p_1, p_2, and p_3 *****=the proportions of each combustible gas present in the original mixture, free from air and inert gases, so that

$$p_1+p_2+p_3+*****=100;$$

and N_1, N_2, and N_3=either all the upper or all the lower explosive limits in air for each combustible gas separately.

Payman (*9, 25*) in turn proposed and tested the accuracy of the application of Le Chatelier's law to other atmospheres such as those consisting of various amounts of oxygen by considering the inert gases as included with the "atmosphere" in which the air is present.

Jones (*19*) investigated the application of the law of Le Chatelier with reference to the three combustible gases—carbon monoxide, methane, and hydrogen—to which he added various volumes of the inert gases—nitrogen and carbon dioxide. Instead of considering the inert gases as included with the "atmosphere" in which the air is present, as proposed by Payman (*9, 25*), the atmosphere is always considered in the later investigations (*9, 19*) as normal air, and the added inert gases are considered in conjunction with the combustible gases. By this method, in conjunction with data on the extinctive action of both nitrogen and carbon dioxide on each of the above combustible gases, it is possible to apply the law of Le Chatelier to calculate the explosive limits of complex gas-air mixtures, such as a mixture composed of carbon monoxide, methane, hydrogen, nitrogen, and carbon dioxide (*19, 35*).

The formula under this arrangement has the same form as that previously given. The proportions (in percentages) of the combustible gases present in the air-free complex-gas mixture are paired with the appropriate amounts of the available inert gas to form mixtures having explosive limits. The formula is as follows:

$$L_U \text{ or } L_L = \frac{100}{\frac{p_1}{N_1}+\frac{p_2}{N_2}+\frac{p_3}{N_3}+*****};$$

where L_U = the upper and L_L the lower explosive limits of the air-free original atmosphere, when admixed with air;

p_1, p_2, p_3 ***** = the proportions of the dissected mixtures (each combustible gas plus inert gas paired with it), in percentages;

and N_1, N_2, and N_3 ***** = their respective explosive limits when admixed with air.

APPLICATION OF LAW OF LE CHATELIER TO DETERMINE NOSE LIMIT

The generalized formula applied to a complex-gas mixture composed of any number of combustible gases plus the inert gas paired with them has been shown to hold for both the lower- and the upper-explosive-limit mixtures of hydrogen, methane, carbon monoxide, carbon dioxide, and nitrogen and for coal gas (*19, 20*). Therefore, the authors believe that from the experimental data (*19*) and their own experience with complex-gas mixtures in the field, the law of Le Chatelier can be further generalized to apply to a complex gas of the above composition, when calculating the nose limit of such mixtures.

It follows that all mixtures in any proportion of nose-limit mixtures should remain nose-limit mixtures, the limiting nose-limit mixture being that of the complex gas. Conversely, any nose-limit mixture of a complex gas will consist of a number of nose-limit mixtures of the individual combustible gases composing it.

The authors have rearranged and inserted nose-limit values determined experimentally by Jones and others (*19, 20*) in the formula given above to fit the special case in which the nose limit of a complex-gas mixture is considered as having the same numerical value as the explosive limit of the common explosive-limit mixture defined on page 12. In other words, a formula has been arranged that expresses the nose limit of any complex mixture of gases that has been found to obey the law of Le Chatelier when applied to the lower and the upper explosive limits. The method of deriving the nose-limit formula follows:

DERIVATION OF NOSE-LIMIT FORMULA

If we consider the compositions of the critical gas mixture, which is just incapable of forming an explosive mixture with air, and the air-free common explosive-limit mixture, which is just capable of forming an explosive mixture with air, it is evident that these air-free mixtures differ minutely in composition. Furthermore, as air is admixed with each of these air-free mixtures until the nose-limit mixture is formed on the one hand and the common explosive-limit mixture on the other, these mixtures will differ in composition to even a lesser degree, although they have the same air content. Because a point has position only, the points representing the nose-limit mixture and the common explosive-limit mixture, respectively, occupy two minutely separated positions in a graph, such as figure 4 (pocket).

If we consider the air-free common explosive-limit mixture as an air-free original atmosphere and introduce the fact that the upper, the lower, and the common explosive limits of such an air-free mixture when admixed with air are equal, the generalized formula that applies to either the upper or the lower explosive limit of a complex-gas-air mixture can be written as follows:

$$\underset{C.E.M.}{L_{upper}} = \underset{C.E.M.}{L_{lower}} = L_{U=L} = \frac{100}{\frac{p_1}{N_1}+\frac{p_2}{N_2}+\frac{p_3}{N_3}+\frac{p_n}{N_n}}; \tag{23}$$

where $\underset{C.E.M.}{L_{upper}}$, $\underset{C.E.M.}{L_{lower}}$, and $L_{U=L}$ = the upper, lower, and common explosive limits, respectively, of the air-free common explosive-limit mixture when admixed with air, in percent;

p_1, p_2, p_3, and p_n = the respective proportions of each simple combustible gas plus the inert gas paired with it, in percentages;

and N_1, N_2, N_3, and N_n = the respective common explosive limits of these mixtures, in air.

Because by definition the nose limit numerically equals the explosive limit of the common explosive-limit mixture, and as it also signifies the percentage of the critical gas mixture existing in the nose-limit mixture, we can express this relationship by the following equation:

$$L_{U=L} = L_{nose};$$

where $L_{U=L}$ = the common explosive limit of the air-free mixture that is just capable of forming an explosive mixture with air;

and L_{nose} is the nose limit of the critical gas mixture formed by admixing a given diluent (additional inert gas) with the air-free original atmosphere.

To save repetition of words, the term "nose limit" will be called the nose limit of the air-free original atmosphere from which the critical gas mixture is derived.

We have shown in deriving formulas (6) and (7) relating to the critical gas mixture, when nitrogen is used as the diluent, that

$$5.15A+7B+17.55(H_2)+p_n=100;$$

where $5.15A$, $7B$, and $17.55(H_2)$ = the volumes of carbon monoxide (A), methane (B), and hydrogen (H_2) contained in the critical gas mixture plus their respective amounts of nitrogen required to form an atmosphere that would be just nonexplosive (nose-limit mixture) if admixed with the required amount of air;

and p_n = similar values for other simple combustible gases plus inert gas, as well as any proportion of either of the combustible gases present plus the carbon dioxide required to form a nose-limit mixture, if carbon dioxide is present and is paired with one or more of the combustible gases.

We have shown on page 33 that

$$p_1+p_2+p_3+p_n=100,$$

and on page 35 that

$$L_{U=L}=L_{nose}.$$

If for p_1, p_2, p_3, and p_n in formula (23) we substitute $5.15A$, $7B$, $17.55(H_2)$, and p_n, respectively, we can write

$$L_{nose-N_2}=\frac{100}{\frac{5.15A}{N_1}+\frac{7B}{N_2}+\frac{17.55(H_2)}{N_3}+\frac{p_n}{N_n}}; \qquad (23a)$$

where N_1, N_2, N_3, and N_n = the respective "nose" limits of each simple combustible gas plus the inert gas paired with it, when admixed with air,

and the other symbols have the same meanings as before.

The nose limits of many simple combustible gases, with both nitrogen and carbon dioxide as the diluent, have been determined by Jones and others (*9*, *19*, *20*, *22*). The nose limits of carbon monoxide, methane, hydrogen, ethylene, propylene, and ethane in nitrogen-air and carbon dioxide-air mixtures are given in table 4.

TABLE 4.—*Nose limits of carbon monoxide, methane, hydrogen, ethylene, propylene, and ethane in nitrogen-air and in carbon dioxide-air mixtures*

Combustible gas	Nose limits (percent)	
	Nitrogen-air mixtures	Carbon dioxide-air mixtures
Carbon monoxide	71.0	58.0
Methane	41.5	28.0
Hydrogen	75.5	59.5
Ethylene	50.3	43.0
Propylene	42.5	31.2
Ethane	45.4	35.7

If the real values of the nose limits of carbon monoxide, methane, and hydrogen given in table 4 are substituted for their respective symbols in formula (23*a*), a generalized formula can be written that expresses the relationship between the nose-limit value of the air-free original atmosphere and the nose-limit mixtures of the percentages of the gases composing the critical gas mixture plus the inert gas paired with them and their respective nose limits. The formula, when nitrogen is used as the diluent, is as follows:

$$L_{nose-N_2}=\frac{100}{\frac{5.15A}{71}+\frac{7B}{41.5}+\frac{17.55(H_2)}{75.5}+\frac{p_n}{N_n}}; \tag{24}$$

where L_{nose-N_2} = the nose limit of the air-free original atmosphere when nitrogen is used as the diluent;

A, B, and (H_2) = the amounts (in percent) of carbon monoxide, methane, and hydrogen contained in the critical gas mixture;

and $\frac{p_n}{N_n}$ has the same meaning as before.

Because the critical gas-mixture value is affected to some extent by the manner in which the combustible gases that compose an air-free original atmosphere are paired with the carbon dioxide (when present), the nose-limit formula to be used for determining the nose-limit value will depend on the case at hand and will be considered for each case separately, as was done previously to determine the critical gas-mixture value.

Because the above-given generalized equation (formula 24) expresses a relationship between the nose limit and the constituents of the critical gas mixture and both are unknown values, it is necessary to determine a relationship between the unknown nose-limit value and the known percentages of the constituents as they exist in the air-free original atmosphere.

The method of deriving the formulas used by the authors for calculating the nose limit when nitrogen is used as the diluent is the same for all the cases to which they are applicable, according to the manner in which the carbon dioxide available in the air-free original atmosphere is paired with the combustible gases. The method of deriving the formula applicable to case 1, page 24, follows:

Case 1

The method of deriving the nose-limit formula applicable in case 1 concerns a complex gas that consists of carbon monoxide, methane, hydrogen, nitrogen, and carbon dioxide in a volume such that 10.2 times the volume of hydrogen $(H_2)_1$ in the air-free analysis of the original atmosphere is more than the volume of carbon dioxide $(D)_1$, or

$$10.2(H_2)_1>D_1.$$

It has been shown on page 24 and in the derivation of formula (7), that the proportion of hydrogen plus the nitrogen paired with it is

$$(H_2)-\frac{D}{10.2}+16.55\left[(H_2)-\frac{D}{10.2}\right],$$

and the hydrogen remaining plus the carbon dioxide paired with it is

$$\frac{D}{10.2}+D, \text{ in case 1.}$$

If the terms just given for the proportions of hydrogen paired with the nitrogen and carbon dioxide, respectively, are substituted for $\frac{17.55\ (H_2)}{75.5}$ and $\frac{p_n}{N_n}$, respectively, in formula (23a), we obtain

$$L_{nose\text{-}N_2}=\frac{100}{\frac{5.15A}{71}+\frac{7B}{41.5}+\frac{17.55\left[(H_2)-\frac{D}{10.2}\right]}{75.5}+\frac{\frac{11.2D}{10.2}}{59.5}},$$

which, by clearing of fractions, becomes

$$L_{nose\text{-}N_2}=\frac{100}{\frac{5.15A}{71}+\frac{7B}{41.5}+\frac{17.55\left[(H_2)-\frac{D}{10.2}\right]}{75.5}+\frac{\frac{11.2D}{10.2}}{59.5}},$$

$$=\frac{100}{\frac{5.15A}{71}+\frac{7B}{41.5}+\frac{17.55(H_2)}{75.5}-\frac{17.55D}{10.2\times75.5}+\frac{11.2D}{10.2\times59.5}},$$

$$=\frac{100}{\frac{5.15A}{71}+\frac{7B}{41.5}+\frac{17.55(H_2)}{75.5}-\frac{198.625D}{45{,}820.95}},$$

$$=\frac{100}{\frac{5.15A}{71}+\frac{7B}{41.5}+\frac{17.55(H_2)}{75.5}-0.00434D};$$

where A, B, (H_2), and D = the percentages of carbon monoxide, methane, hydrogen, and carbon dioxide, respectively, present in the critical gas mixture;
71, 41.5, and 75.5 = the nose limits of carbon monoxide, methane, and hydrogen, respectively, in nitrogen-air mixtures;
59.5 = the nose limit of hydrogen in carbon dioxide-air mixtures (see table 4);
5.15, 7, and 17.55 = constants previously given;
and 0.00434 = a constant applicable when all the carbon dioxide is paired with part of the hydrogen (case 1).

From formula (7), we obtain

$$100=5.15A+7B+17.55(H_2)-0.6225D.$$

By substituting this value for 100 in the equation for the nose limit given above, the equation for the nose limit becomes

$$L_{nose\text{-}N_2}=\frac{5.15A+7B+17.55(H_2)-0.6225D}{\frac{5.15A}{71}+\frac{7B}{41.5}+\frac{17.55(H_2)}{75.5}-0.00434D},$$

where the symbols have the same meanings as before.

It has been shown in formula (8), page 25, that

$$\frac{A}{A_1}=\frac{B}{B_1}=\frac{(H_2)}{(H_2)_1}=\frac{D}{D_1}=***=k. \tag{8}$$

From formula (8), we can determine the value of any one of the constituents in terms of the others and deduce that

$$A=\frac{AA_1}{A_1},\ B=\frac{AB_1}{A_1},\ (H_2)=\frac{A(H_2)_1}{A_1},\text{ and }D=\frac{AD_1}{A_1}.$$

Substituting these values and reducing in the equation for the nose limit given above, we obtain

$$L_{nose-N_2}=\frac{\frac{A}{A_1}\,[5.15A_1+7B_1+17.55(H_2)_1-0.6225D_1]}{\frac{A}{A_1}\left[\frac{5.15A_1}{71}+\frac{7B_1}{41.5}+\frac{17.55(H_2)_1}{75.5}-0.00434D_1\right]}.$$

By cancellation of the common factor $\left(\frac{A}{A^1}\right)$, this expression becomes

$$L_{nose-N_2}=\frac{5.15A_1+7B_1+17.55(H_2)_1-0.6225D_1}{\frac{5.15A_1}{71}+\frac{7B_1}{41.5}+\frac{17.55(H_2)_1}{75.5}-0.00434D_1}, \tag{25}$$

where L_{nose-N_2} = the nose limit of the air-free original atmosphere as sampled and is applicable when all the carbon dioxide is paired with part of the hydrogen;

and A_1, B_1, $(H_2)_1$, and D_1 are the percentages of carbon monoxide, methane, hydrogen, and carbon dioxide, respectively, in the air-free original atmosphere, as sampled.

Other formulas for calculating the nose limit of an air-free original atmosphere, as sampled, have been derived in the same manner as that shown for case 1 and vary only according to the manner in which the carbon dioxide is combined with hydrogen or the other combustible gases, and as to whether any of the constituents are absent, or if ethylene and propylene are present. The symbols in the subsequent nose-limit formulas have the same meanings as previously given. These formulas are arranged according to the case to which they apply, and are as follows:

Case 2

When no hydrogen is present in an air-free original atmosphere that contains carbon monoxide, methane, carbon dioxide, and nitrogen, all the carbon dioxide is paired with part of the methane, and the methane remaining is paired with nitrogen.

In this case $3.2B_1>D_1$, and when nitrogen is used as the diluent, the nose-limit can be shown to be

$$L_{nose-N_2}=\frac{5.15A_1+7B_1-0.875D_1}{\frac{5.15A_1}{71}+\frac{7B_1}{41.5}-0.0065D_1}. \tag{26}$$

Case 3

If an air-free original atmosphere consists of carbon monoxide, methane, hydrogen, carbon dioxide, and nitrogen, and hydrogen and carbon dioxide are present in such volumes that

$$10.2(H_2)_1<D_1,$$

the hydrogen is paired with part of the carbon dioxide, and the carbon dioxide remaining is paired with part of the methane.

In this case, and when nitrogen is used as the diluent, the nose limit can be shown to be

$$L_{nose-N_2}=\frac{5.15A_1+7B_1+20.12(H_2)_1-0.875D_1}{\frac{5.15A_1}{71}+\frac{7B_1}{41.5}+0.2545(H_2)_1-0.0065D_1}. \tag{27}$$

Case 4

If an air-free original atmosphere consists of carbon monoxide, methane, hydrogen, ethylene, propylene, carbon dioxide, and nitrogen, and the carbon dioxide can be paired with part of the hydrogen, the hydrogen remaining and the other combustible gases are paired with nitrogen.

In this case $10.2(H_2)_1 > D_1$, and when nitrogen is used as the diluent, the nose limit can be shown to be

$$L_{\text{nose}-N_2}=\frac{5.15A_1+7B_1+17.55(H_2)_1+16.4(C_2H_4)_1+15.1(C_3H_6)_1-0.6225D_1}{\frac{5.15A_1}{71}+\frac{7B_1}{41.5}+\frac{17.55(H_2)_1}{75.5}+\frac{16.4(C_2H_4)_1}{50.3}+\frac{15.1(C_3H_6)_1}{42.5}-0.00434D_1}. \quad (28)$$

Case 5

If carbon monoxide, methane, hydrogen, carbon dioxide, and nitrogen are present in an air-free original atmosphere in volumes such that $10.2(H_2)_1=D_1$, all the hydrogen (H_2) is paired with all the carbon dioxide (D_1).

In this case, as in the derivation of formula (20) for calculating the critical gas-mixture value, either formula (25) or formula (27) can be used to calculate the nose limit.

However, when all the hydrogen is paired with all the carbon dioxide, and because the nose limit of hydrogen-carbon dioxide-air mixtures is 59.5 (*see* table 4), a formula for calculating the nose limit in this case can also be shown to be

$$L_{\text{nose}-N_2}=\frac{5.15A_1+7B_1+(H_2)_1+D_1}{\frac{5.15A_1}{71}+\frac{7B_1}{41.5}+\frac{(H_2)_1+D_1}{59.5}}, \quad (29a)$$

or

$$L_{\text{nose}-N_2}=\frac{5.15A_1+7B_1+11.2(H_2)_1}{\frac{5.15A_1}{71}+\frac{7B_1}{41.5}+\frac{11.2(H_2)_1}{59.5}}. \quad (29b)$$

Case 6

If carbon monoxide, methane, hydrogen, nitrogen, and carbon dioxide are present in an air-free original atmosphere in volumes such that all the hydrogen and methane can be paired with part of the carbon dioxide, the carbon dioxide remaining is paired with part of the carbon monoxide, and the carbon monoxide remaining is paired with nitrogen. (*See* p. 29.)

In this case,

$$[10.2(H_2)_1+3.2B_1] < D_1,$$

and when nitrogen is used as the diluent, the nose limit can be shown to be

$$L_{\text{nose}-N_2}=\frac{5.15A_1+7.15B_1+20.6(H_2)_1-0.9213D_1}{\frac{5.15A_1}{71}+0.1767B_1+0.2734(H_2)_1-0.00836D_1}. \quad (30A)$$

Case 7

If an air-free original atmosphere is composed of carbon monoxide, methane, hydrogen, ethylene, propylene, carbon dioxide, and nitrogen in volumes such that all the methane, hydrogen, ethylene, and propylene, and part of the carbon monoxide can be paired with the carbon dioxide available, the carbon monoxide remaining is paired with nitrogen. (*See* p. 29.)

In this case,

$$[3.2B_1+10.2(H_2)_1+9.1(C_2H_4)_1+7.8(C_3H_6)_1]<D_1,$$

and when nitrogen is used as the diluent, the nose limit can be shown to be

$$L_{nose-N_2}=\frac{5.15A_1+7.15B_1+20.6(H_2)_1+18.48(C_2H_4)_1+15.98(C_3H_6)_1-0.9213D_1}{\frac{5.15A_1}{71}+0.1767B_1+0.2734(H_2)_1+0.311(C_2H_4)_1+0.3472(C_3H_6)_1-0.00836D_1}. \tag{30B}$$

It need only be added that, if any of the gases expressed by A_1, B_1, $(H_2)_1$, etc., in any of the formulas relating to the calculation of the nose limit is absent, the real value of the symbol expressing the missing gas is zero. For example, when carbon monoxide (A_1) hydrogen $(H_2)_1$, and carbon dioxide (D_1) are absent, formula (25) becomes

$$L_{nose-N_2}=\frac{7B_1}{\frac{7B_1}{41.5}}.$$

An example will serve to show the application of the nose-limit formula for calculating the nose limit.

For this purpose we can take example 2 (p. 20), in which the air-free composition of an original atmosphere in a sealed anthracite-mine-fire area is 3.54 percent carbon monoxide (A_1), 1.50 percent methane (B_1), 4.86 percent hydrogen $(H_2)_1$, 17.61 percent carbon dioxide (D_1), and 72.49 percent nitrogen $(N_2)_1$.

Because $10.2(H_2)_1$, or 49.57, $>$ 17.61, or D_1, and nitrogen is used as a diluent, formula (25) is used, which is

$$L_{nose-N_2}=\frac{5.15A_1+7B_1+17.55(H_2)_1-0.6225D_1}{\frac{5.15A_1}{71}+\frac{7B_1}{41.5}+\frac{17.55(H_2)_1}{75.5}-0.00434D_1}, \tag{25}$$

where the symbols have the same meanings as before.

By substituting the above-given real values for the symbols, we find

$$L_{nose-N_2}=\frac{(5.15\times3.54)\times(7\times1.50)+(17.55+4.86)-(0.6225\times17.61)}{\frac{5.15\times3.54}{71}+\frac{7\times1.50}{41.5}+\frac{17.55\times4.86}{75.5}-(0.00434\times17.61)},$$

$$=\frac{18.231+10.500+85.293-10.962}{0.257+0.252+1.129-0.076}=\frac{103.062}{1.562}=65.98 \text{ percent.}$$

The significance of this nose-limit value is that the nose-limit mixture of the above-given air-free original atmosphere is composed of 65.98 percent of the percentages of the constituents composing the critical gas mixture (p. 32) and 34.02 percent of air, of which 7.12 percent is oxygen.

Because the critical gas mixture in this example is composed of 97.02 percent of the percentages of the constituents composing the air-free original atmosphere, plus 2.98 percent of nitrogen (diluent), the nose-limit mixture is composed of 64.01 percent (65.98 percent of 97.02 percent) of the percentages of the consituents composing the air-free original atmosphere, plus 1.97 percent (65.98 percent of 2.98 percent) of nitrogen (diluent) and 34.02 percent of air.

CALCULATION OF CRITICAL OXYGEN VALUE

Because the limit value expresses the volume of gases other than air in the limit mixture, the air content (in percent) can be calculated by substituting the pertinent limit value in the following formula:

$$Air_{limit}=100-L, \qquad (31A)$$

where Air_{limit} is the volume (in percent) of air in the lower explosive-limit mixture, the upper-explosive-limit mixture, or the nose-limit mixture, as the case may be;

and L is the limit value, or volume of gases other than air that are present in the limit mixture.

As pure atmospheric air is considered as being composed of 20.93 percent of oxygen and 79.07 percent of nitrogen (by volume), the volume of oxygen in a limit mixture and the nitrogen component of its air portion are calculated by the following formulas:

$$(O_2)_{limit}=0.2093\ (100-L), \qquad (31B)$$

$$(N_2)_{air\text{-}limit}=0.7907\ (100-L), \qquad (31C)$$

where $(O_2)_{limit}$ and $(N_2)_{air\text{-}limit}$ are the volumes (in percent) of oxygen and nitrogen, respectively, in the air portion of the limit mixture, 0.2093 and 0.7907 are the percentages (by volume) of oxygen and nitrogen, respectively, in normal atmospheric air, expressed as decimal fractions;

and L has the same meaning as before.

On page 14 it was stated that, for all practical purposes, the critical oxygen value (as defined) can be safely taken as 0.5 percent less than the oyxgen content of the nose-limit mixture when nitrogen is used as the diluent.

An example will serve to show the application of formula (31*B*) and the above statement for calculating the critical oxygen value, In example 2, page 41, the nose-limit value is shown to be 65.98 percent. If this value is substituted for the symbol in formula (31*B*), we find

$$(O_2)_{nose}=0.2093\times(100-65.98)=7.12\text{ percent.} \qquad (31B)$$

Applying the above-given statement, the critical oxygen value in this example can be safely taken as

$$(7.12-0.50),\text{ or }6.62\text{ percent.}$$

Although the air and oxygen contents of the nose-limit mixture can be calculated accurately by formulas (31*A*) and (31*B*), it is more convenient and usually sufficiently accurate to obtain the air and the oxygen contents of limit mixtures from table 5. The authors have also prepared a graph (fig. 2, pocket) that can be used for this purpose.

TABLE 5.—*Air and oxygen in limit mixtures, or mixtures that contain the same amount (K) of gases other than air, percent by volume*

Limit value	0.00	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50
Air percent	100.00	99.50	99.00	98.50	98.00	97.50	97.00	96.50	96.00	95.50
Oxygen do.	20.93	20.83	20.72	20.62	20.51	20.41	20.30	20.20	20.09	19.99
Limit value	5.00	5.50	6.00	6.50	7.00	7.50	8.00	8.50	9.00	9.50
Air percent	95.00	94.50	94.00	93.50	93.00	92.50	92.00	91.50	91.00	90.50
Oxygen do.	19.88	19.78	19.67	19.57	19.46	19.36	19.26	19.15	19.05	18.94
Limit value	10.00	10.50	11.00	11.50	12.00	12.50	13.00	13.50	14.00	14.50
Air percent	90.00	89.50	89.00	88.50	88.00	87.50	87.00	86.50	86.00	85.50
Oxygen do.	18.84	18.73	18.63	18.52	18.42	18.31	18.21	18.10	18.00	17.90
Limit value	15.00	15.50	16.00	16.50	17.00	17.50	18.00	18.50	19.00	19.50
Air percent	85.00	84.50	84.00	83.50	83.00	82.50	82.00	81.50	81.00	80.50
Oxygen do.	17.79	17.69	17.58	17.48	17.37	17.27	17.16	17.06	16.95	16.85
Limit value	20.00	20.50	21.00	21.50	22.00	22.50	23.00	23.50	24.00	24.50
Air percent	80.00	79.50	79.00	78.50	78.00	77.50	77.00	76.50	76.00	75.50
Oxygen do.	16.74	16.64	16.53	16.43	16.33	16.22	16.12	16.01	15.91	15.80
Limit value	25.00	25.50	26.00	26.50	27.00	27.50	28.00	28.50	29.00	29.50
Air percent	75.00	74.50	74.00	73.50	73.00	72.50	72.00	71.50	71.00	70.50
Oxygen do.	15.70	15.59	15.49	15.38	15.28	15.17	15.07	14.96	14.86	14.76
Limit value	30.00	30.50	31.00	31.50	32.00	32.50	33.00	33.50	34.00	34.50
Air percent	70.00	69.50	69.00	68.50	68.00	67.50	67.00	66.50	66.00	65.50
Oxygen do.	14.65	14.55	14.44	14.33	14.23	14.13	14.02	13.92	13.81	13.72
Limit value	35.00	35.50	36.00	36.50	37.00	37.50	38.00	38.50	39.00	39.50
Air percent	65.00	64.50	64.00	63.50	63.00	62.50	62.00	61.50	61.00	60.50
Oxygen do.	13.60	13.50	13.40	13.29	13.19	13.08	12.98	12.87	12.77	12.66
Limit value	40.00	40.50	41.00	41.50	42.00	42.50	43.00	43.50	44.00	44.50
Air percent	60.00	59.50	59.00	58.50	58.00	57.50	57.00	56.50	56.00	55.50
Oxygen do.	12.56	12.45	12.35	12.24	12.14	12.03	11.93	11.83	11.72	11.62
Limit value	45.00	45.50	46.00	46.50	47.00	47.50	48.00	48.50	49.00	49.50
Air percent	55.00	54.50	54.00	53.50	53.00	52.50	52.00	51.50	51.00	50.50
Oxygen do.	11.51	11.41	11.30	11.20	11.09	10.99	10.88	10.78	10.67	10.57
Limit value	50.00	50.50	51.00	51.50	52.00	52.50	53.00	53.50	54.00	54.50
Air percent	50.00	49.50	49.00	48.50	48.00	47.50	47.00	46.50	46.00	45.50
Oxygen do.	10.46	10.36	10.26	10.15	10.05	9.94	9.84	9.73	9.63	9.52
Limit value	55.00	55.50	56.00	56.50	57.00	57.50	58.00	58.50	59.00	59.50
Air percent	45.00	44.50	44.00	43.50	43.00	42.50	42.00	41.50	41.00	40.50
Oxygen do.	9.42	9.31	9.21	9.10	9.00	8.90	8.79	8.69	8.58	8.48
Limit value	60.00	60.50	61.00	61.50	62.00	62.50	63.00	63.50	64.00	64.50
Air percent	40.00	39.50	39.00	38.50	38.00	37.50	37.00	36.50	36.00	35.50
Oxygen do.	8.37	8.27	8.16	8.06	7.95	7.85	7.74	7.64	7.53	7.43
Limit value	65.00	65.50	66.00	66.50	67.00	67.50	68.00	68.50	69.00	69.50
Air percent	35.00	34.50	34.00	33.50	33.00	32.50	32.00	31.50	31.00	30.50
Oxygen do.	7.33	7.22	7.12	7.01	6.91	6.80	6.70	6.59	6.49	6.38
Limit value	70.00	70.50	71.00	71.50	72.00	72.50	73.00	73.50	74.00	74.50
Air percent	30.00	29.50	29.00	28.50	28.00	27.50	27.00	26.50	26.00	25.50
Oxygen do.	6.28	6.17	6.07	5.97	5.86	5.76	5.65	5.55	5.44	5.34
Limit value	75.00	75.50	76.00	76.50	77.00	77.50	78.00	78.50	79.00	79.50
Air percent	25.00	24.50	24.00	23.50	23.00	22.50	22.00	21.50	21.00	20.50
Oxygen do.	5.23	5.13	5.02	4.92	4.81	4.71	4.60	4.50	4.40	4.29

CALCULATION OF COMPOSITION OF NOSE-LIMIT MIXTURE

A nose-limit mixture consists of definite percentages of the constituents composing an air-free original atmosphere, of the inert gas used as the diluent, and of air. With the exception of the nitrogen, oxygen, carbon dioxide, and the diluent, the constituents will always exist in the same ratio in relation to each other as they exist in the air-free original atmosphere.

Formulas (31*A*) and (31*B*) are used to calculate the air-portion content and the oxygen content of the nose-limit mixture. Formula (31*C*) is used to calculate the nitrogen component of the air portion.

Formulas can be derived by which the volumes of the individual constituents composing the gas portion and the volume of the additional inert gas used as a diluent can be calculated.

It can be deduced from the definition of the nose-limit mixture and the derivation and application of formulas (22*A*) and (25) that the gas portion of the nose-limit mixture consists of analogous proportions of the constituents composing the air-free original atmosphere; consequently, the constituents composing the gas portion of the nose-limit mixture exist in volumes equal to their respective percentages in the critical gas mixture times the nose-limit value expressed as a decimal fraction, and the diluent content of the nose-limit mixture equals the diluent content of the critical gas mixture times the nose-limit value expressed as a decimal fraction. These statements can be expressed mathematically as follows:

In the derivation of formula (22*A*) it was shown that

$$Constituent_{\,C.G.M.}=k(Constituent_{\,air\text{-}free}), \tag{22A}$$

and from the statement just given we can write

$$\left[\frac{L_{nose}}{100}\right](Constituent_{\,C.G.M.})=\left[\frac{L_{nose}}{100}\right]k(Constituent_{\,air\text{-}free}),$$

but

$$\left[\frac{L_{nose}}{100}\right](Constituent_{\,C.G.M.})=Constituent_{\,nose};$$

therefore,

$$Constituent_{\,nose}=\left[\frac{L_{nose}}{100}\right]k(Constituent_{\,air\text{-}free}), \tag{32A}$$

where $Constituent_{\,nose}$ is the percentage of each gas existing in the gas portion ($Gas_{\,nose}$) of the nose limit mixture,
and the other symbols have the same meanings as before.

If we assume that an air-free original atmosphere consists of carbon monoxide, methane, hydrogen, ethylene, propylene, carbon dioxide, and nitrogen, by substituting the respective symbols for the constituents in formula (32A), we obtain

$$\left.\begin{aligned}
A_{nose} &= \left[\frac{L_{nose}}{100}\right][kA_1], \\
B_{nose} &= \left[\frac{L_{nose}}{100}\right][kB_1], \\
(H_2)_{nose} &= \left[\frac{L_{nose}}{100}\right][k(H_2)_1], \\
(C_2H_4)_{nose} &= \left[\frac{L_{nose}}{100}\right][k(C_2H_4)_1], \\
(C_3H_6)_{nose} &= \left[\frac{L_{nose}}{100}\right][k(C_3H_6)_1], \\
D_{1-nose} &= \left[\frac{L_{nose}}{100}\right][kD_1], \\
(N_2)_{1-nose} &= \left[\frac{L_{nose}}{100}\right][k(N_2)_1],
\end{aligned}\right\} \text{Gas}_{nose} \qquad (32B)$$

where A_{nose}, B_{nose}, $(H_2)_{nose}$, $(C_2H_4)_{nose}$, $(C_3H_6)_{nose}$, D_{1-nose}, and $(N_2)_{1-nose}$ are the percentages of carbon monoxide, methane, ethylene, propylene, carbon dioxide, and nitrogen, respectively, in the gas portion of the nose-limit mixture,

A_1, B_1, $(H_2)_1$, $(C_2H_4)_1$, $(C_3H_6)_1$, D_1, and $(N_2)_1$ are the percentages of the same constituents in the air-free original atmosphere;

L_{nose} is the nose-limit value;

and k is the critical gas-mixture value expressed as a decimal fraction.

Because the diluent content depends on the kind of inert gas used as the diluent, we can deduce that

$$Dil_{nose-N_2} = (L_{nose-N_2})(1-k), \qquad (33A)$$

and

$$Dil_{nose-CO_2} = (L_{nose-CO_2})(1-k), \qquad (33B)$$

where Dil_{nose-N_2} and $Dil_{nose-CO_2}$ are the diluent contents (nitrogen or carbon dioxide, whichever is used as the diluent) of the nose-limit mixture;

and k is the critical gas-mixture value that applies to the diluent used, expressed as a decimal fraction.

The total nitrogen content and the total carbon dioxide content of the nose-limit mixture depend on (1) which inert gas is used as the diluent, (2) the amounts of nitrogen and carbon dioxide present in the air-free original atmosphere, and (3) the amounts of nitrogen or carbon dioxide added as a diluent. The total amount of nitrogen also depends on the atmospheric-air content of the nose-limit mixture. These statements can be expressed mathematically as follows:

When nitrogen is the diluent we can deduce that

$$(N_2)_{nose} = 100 - Gas_{nose} - (O_2)_{nose} + (N_2)_{1-nose}, \qquad (34A)$$

or

$$(N_2)_{nose} = (N_2)_{air\text{-}nose} + (N_2)_{1-nose} + Dil_{nose-N2}, \qquad (34B)$$

and

$$D_{nose} = D_{1-nose}. \qquad (34C)$$

When carbon dioxide is the diluent, we can deduce that

$$(N_2)_{nose}=(N_2)_{1-nose}+(N_2)_{air-nose}, \qquad (35A)$$

and

$$D_{nose}=D_{1-nose}+Dil_{nose-CO2}, \qquad (35B)$$

where $(N_2)_{nose}$ and D_{nose} are the total percentages of nitrogen and carbon dioxide, respectively;
$(O_2)_{nose}$ is the oxygen content;
$(N_2)_{air-nose}$ is the percentage of nitrogen in the air portion of the nose-limit mixture,
and the other symbols have the same meanings as before.

In formulas (34*A*) to (35*B*), inclusive, the numerical values are found by the following formulas:

(31*B*) for $(O_2)_{nose}$, (31*C*) for $(N_2)_{air-nose}$;
(32*B*) for Gas_{nose}, $(N_2)_{1-nose}$, and D_{1-nose};
(33*A*) for Dil_{nose-N_2};
and (33*B*) for $Dil_{nose-CO_2}$.

By substituting the equivalent values for the symbols in equations (34*B*) and (35*B*), we obtain

$$(N_2)_{nose}=0.7907(100-L_{nose-N_2})+\left[\frac{L_{nose-N_2}}{100}\right][k(N_2)_2]+(L_{nose-N_2})(1-k), \qquad (36)$$

$$(D)_{nose}=0.7907(100-L_{nose-CO_2})+\left[\frac{L_{nose-CO_2}}{100}\right][k(N_2)_2]+(L_{nose-CO_2})(1-k), \qquad (37)$$

where the symbols have the same meanings as before.

Formulas (36) and (37) are sometimes more convenient to use than formulas (34*B*) and 35*B*).

An example will show the application of the formulas for calculating the composition of the nose-limit mixture. For this purpose we can use the example given on page 18, where the air-free original atmosphere is composed of 32.14 percent carbon monoxide (A_1), 11.55 percent methane (B_1), 44.11 percent hydrogen $(H_2)_1$, 5.92 percent ethylene $(C_2H_4)_1$, 1.48 percent propylene $(C_3H_6)_1$, 4.00 percent carbon dioxide (D_1), and 0.80 percent nitrogen $(N_2)_1$. (*See* fig. 10, pocket.)

From the foregoing data we find

$$10.2(H_2)_1, \text{ or } 10.2(44.11), >4, \text{ or } D_1.$$

Therefore, formula (19), page 28, for calculating the critical gas-mixture value, and formula (28), page 40, for calculating the nose limit, apply in this problem when nitrogen is the diluent.

Substituting the real values just given for the symbols in formulas (19) and (28), we find

$$C.G.M.V._{N_2}=\frac{10{,}000}{\left[\begin{array}{l}(5.15\times 32.14)+(7\times 11.55)+(17.55\times 44.11)-\\(0.6225\times 4)+(16.4\times 5.92)+(15.1\times 1.48)\end{array}\right]},$$

$$=\frac{10{,}000}{165.52+80.85+774.13-2.49+97.09+22.35}=\frac{10{,}000}{1137.45},$$

$=8.79$ percent, the critical gas-mixture value;

and

$$L_{nose-N_2}=\frac{\begin{bmatrix}(5.15\times 32.14)+(7\times 11.55)+(17.55\times 44.11)+\\(16.4\times 5.92)+(15.1\times 1.48)-(0.6225\times 4),\end{bmatrix}}{\begin{bmatrix}\frac{(5.15\times 32.14)}{71}+\frac{(7\times 11.55)}{51.5}+\frac{(17.55\times 44.11)}{75.5}+\\\frac{16{\cdot}4\times 5.92)}{50.3}+\frac{(15.1\times 1.48)}{42.5}-(0.00434\times 4)\end{bmatrix}}$$

$$=\frac{1{,}137.45}{\frac{165.52}{71}+\frac{80.85}{41.5}+\frac{774.13}{75.5}+\frac{97.09}{50.3}+\frac{22.35}{42.5}-0.01736},$$

$$=\frac{1137.45}{16.971}=67.02 \text{ percent, the nose limit.}$$

By substituting the above-given real values for the symbols in formula (32*B*), we find

$$A_{nose}=0.6702\times 0.088\times 32.14,$$
$$=1.90 \text{ percent of carbon monoxide;}$$
$$B_{nose}=0.6702\times 0.088\times 11.55,$$
$$=0.68 \text{ percent of methane;}$$
$$(H_2)_{nose}=0.6702\times 0.088\times 44.11,$$
$$=2.60 \text{ percent of hydrogen;}$$
$$(C_2H_4)_{nose}=0.6702\times 0.088\times 5.92,$$
$$=0.35 \text{ percent of ethylene;}$$
$$(C_3H_6)_{nose}=0.6702\times 0.088\times 1.48,$$
$$=0.09 \text{ percent of propylene;}$$
$$D_{1-nose}=0.6702\times 0.088\times 4.00,$$
$$=0.23 \text{ percent of carbon dioxide;}$$
$$(N_2)_{1-nose}=0.6702\times 0.088\times 0.8,$$
$$=0.05 \text{ percent of nitrogen.}$$

By substituting the real value of the nose limit (L_{nose-N_2}) in formulas (31*A*), (31*B*), and (31*C*), we find the air-portion and oxygen contents of the nose-limit mixture and the nitrogen component of the air portion:

$$Air_{nose}=100-67.02=32.98 \text{ percent of air;} \tag{31A}$$

$$(O_2)_{nose}=0.2093\times(100-67.02), \tag{31B}$$
$$=0.2093\times 32.98,$$
$$=6.90 \text{ percent of oxygen,}$$

$$(N_2)_{air-nose}=0.7907\ (100-67.02), \tag{31C}$$
$$=26.08 \text{ percent of nitrogen in the atmospheric air component of the nose-limit mixture.}$$

By adding the percentages of the various constituents of the nose-limit mixture obtained above by formula (32*B*), we find the gas-portion content, or

$$Gas_{nose}=1.90+0.68+2.60+0.35+0.09+0.23+0.05,$$
$$=5.90 \text{ percent of gases other than air and diluent.}$$

It is important to know the maximum volume (in percent) of diluent that can be present in any possible explosive mixture. This factor is found by determining the diluent content of the nose-limit mixture by substituting the real values previously determined for the symbols in formula (33*A*), or

$$Dil_{nose-N_2} = (L_{nose-N_2})(1-k); \tag{33a}$$

which gives $Dil_{nose-N_2} = 67.02 \times (1-0.088)$,

$= 67.02 \times 0.912$,

$= 61.12$ percent of nitrogen.

To determine the total nitrogen content, we substitute the real values found above for the symbols (Gas_{nose}, $(O_2)_{nose}$, and $(N_2)_{1-nose}$) in formula (34*A*), which gives

$$(N_2)_{nose} = 100 - 5.90 - 6.90 + 0.05,$$

$$= 87.25 \text{ percent of nitrogen.}$$

The total percentage of nitrogen in the nose-limit mixture can also be determined by substituting the real values previously determined for the symbols in formula (36) or

$$(N_2)_{nose} = 0.7907(100 - L_{nose-N_2}) + \left[\frac{L_{nose-N_2}}{100}\right][k(N_2)_1] + (L_{nose-N_2})(1-k), \tag{36}$$

which gives

$$\begin{aligned}(N_2)_{nose} &= 0.7907 \times (100-67.02) + (0.6702 \times 0.088 \times 0.8) + [67.02 \times (1-0.088)]\\ &= (0.7907 \times 32.98) + 0.05 + (67.02 \times 0.912)\\ &= 26.08 + 0.05 + 61.12\\ &= 87.25 \text{ percent of nitrogen.}\end{aligned}$$

Summarizing the foregoing calculations: The nose-limit mixture is composed (by portions) of

5.90 percent of gases other than air and diluent (gas portion),
32.98 percent of atmospheric air (air portion), and
61.12 percent of additional nitrogen (diluent portion);

and (by constituents) of

1.90 percent carbon monoxide,
.68 percent methane,
2.60 percent hydrogen,
.35 percent ethylene,
.09 percent propylene,
6.90 percent oxygen,
.23 percent carbon dioxide,
87.25 percent nitrogen.

The significance of the real values just given is that any mixture composed of the same constituents in the amounts given is just nonexplosive and incapable of forming an explosive mixture with air. Such a mixture is nonexplosive because just too much nitrogen and just too little oxygen are present for the given gas-portion content. It could form explosive mixtures with air if the gas-portion content were slightly increased by admixing a slight amount of the air-free original atmosphere with the mixture and thereby decrease the air and diluent contents correspondingly. An explosive mixture might be formed under such conditions if the critical oxygen value were not attained.

Because the oxygen content is 6.90 percent, the critical oxygen value can be safely taken as 0.5 percent less or 6.40 percent. No mixture composed of analogous proportions of the air-free original atmosphere, nitrogen, and air is explosive if the oxygen content of the mixture is less than 6.40 percent.

The nitrogen content of 87.25 percent signifies that any possible explosive mixture must contain less than 87.25 percent of nitrogen.

The gas-portion content of the nose-limit mixture can also be used as a basic value for quickly determining a safe approximate lower explosive-limit value. (*See* p. 52.)

The composition of the nose-limit mixture can also be determined graphically from figure 10 (pocket) by the graphic method that is explained later.

CALCULATION OF EXPLOSIVE LIMITS

The explosive limits of the simple combustible gas-air mixtures are familiar to those dealing with such mixtures. When dealing with mine fires where combustible gases may be present, the critical problems while men are in the mine are (1) to keep the combustible-gas content of any portion of the mine atmosphere, likely to come in contact with the fire, less than that of any possible lower explosive-limit mixture if such a portion of the mine atmosphere can reach the fire; and (2) to form an atmosphere that, on the return-air side of the fire, has an oxygen content that is less than the critical oxygen value.

If the combustible-gas content of the mine atmosphere cannot be kept less than that of the lower-explosive-limit mixture while the fire is being fought, and it is decided to seal the part of the mine that is on fire, the problems are to seal the fire area before this happens and to surround the active fire with an atmosphere having an oxygen content that is less than the critical oxygen value. The combustible-gas content can then be allowed to increase in the sealed area until it is more than that of the upper-explosive-limit mixture when, as a consequence, an explosion could not occur unless air is allowed to enter into the sealed area and reduce the combustible-gas content to less than that of the upper-explosive-limit mixture.

It is important to know whether or not the complex-gas mixture that may be formed in a mine-fire area has explosive limits, so that necessary precautions can be taken. As little can be done after a lower-explosive-limit mixture is formed, it is vitally important to withdraw the men fighting a fire from the mine before this happens. Furthermore, it is important to know the lower explosive limit of the air-free original atmosphere being investigated.

It is possible to calculate closely the lower and the upper explosive limits of complex mixtures of gases and air, or complex-gas mixtures. The actual procedure is rather long and complicated and is discussed in detail by Jones and others (*19*). Because it is necessary to know the explosive limits of the examples given in this report to show the relationships between the various factors relating to the explosibility of the complex-gas mixtures and the equations by which the real values of the factors are found, a brief discussion of the method used to calculate explosive limits is given.

The calculation of the explosive limits of complex-gas mixtures is made by using the equation given on page 34, or

$$L=\frac{100}{\frac{p_1}{N_1}+\frac{p_2}{N_2}+\frac{p_3}{N_3}+\frac{p_n}{N_n}},$$

where the symbols have the same meanings as before.

If for p_1, p_2, p_3, and p_n in the above equation we substitute the symbols that represent the percentage of each simple combustible gas present in an air-free original atmosphere plus the percentage of inert gas (nitrogen or carbon dioxide) paired with the combustible gas, so that $p_1+p_2+p_3+p_n=100$; and for N_1, N_2, N_3, and N_n, we substitute their respective explosive limits (lower or upper), then the equation can be used to calculate the explosive limits.

By applying this procedure, a general equation that is applicable to the example discussed on page 46 can be written for the above equation:

$$L_L \text{ or } L_U=\frac{100}{\left[\begin{array}{l}\frac{A_1+(N_2)_{A_1}}{\text{limit}_{l \text{ or } u}}+\frac{B_1+(N_2)_{B_1}}{\text{limit}_{l \text{ or } u}}+\frac{(H_2)^a_1+(N_2)_{(H_2)^a_1}}{\text{limit}_{l \text{ or } u}}+\\ \frac{(H_2)^b_1+D_1}{\text{limit}_{l \text{ or } u}}+\frac{(C_2H_4)_1+(N_2)_{(C_2H_4)_1}}{\text{limit}_{l \text{ or } u}}+\frac{(C_3H_6)_1+(N_2)_{(C_3H_6)_1}}{\text{limit}_{l \text{ or } u}}.\end{array}\right]}$$

where L_L or L_U is the lower or the upper explosive limit, as the case may be, of the air-free original atmosphere;

A_1, B_1, D_1, $(C_2H_4)_1$, $(C_3H_6)_1$, and $(N_2)_1$ are the volumes (in percent) of carbon monoxide, methane, carbon dioxide, ethylene, propylene, and nitrogen, respectively, that compose the air-free original atmosphere;

$H_2)^a_1$ is the volume of hydrogen paired with nitrogen, and $(H_2)^b_1$ is the volume of hydrogen paired with the total carbon dioxide (D_1);

$(N_2)_{A_1}$, $(N_2)_{B_1}$, $(N_2)_{(H_2)^a_1}$, $(N_2)_{(C_2H_4)_1}$, and $(N_2)_{(C_3H_6)_1}$ are the proportions (in percent of the whole) of the total nitrogen $(N_2)_1$ paired with the respective combustible gas;

and limit $_{l \text{ or } u}$ is the lower or the upper explosive limit, as the case may be, of each combustible-gas inert-gas mixture taken from tabulated values of the explosive limits of mixtures of the different combustible gases and definite proportions of the inert gases (*19*).

The following table summarizes the calculations for determining the explosive limits of the air-free original atmosphere, of which the composition is given on page 46:

Summary of calculations applied to air-free carbureted water gas-air mixture to determine its explosive limits

Symbol in formula	Constituent [1]	Air-free combustible gases (percent) [1]	Inert gases paired with combustible gases (percent)		Total amount of inert gas plus combustible gas (percent) [2]	Ratio of inert gas to combustible gas [2]	Explosive limits (percent of air-free gas mixture in air) [3]		Oxygen in limit mixtures [4]	
			CO_2, (D_1)	(N_2), $(N_2)_1$			Lower	Upper	Lower	Upper
A_1	CO	32.14		0.53	32.67	0.016	13.24	72.08	18.16	5.84
$(C_2H_4)_1$	C_2H_4	5.92		.00	5.92	.000	2.75	28.60	20.35	14.94
$(C_3H_6)_1$	C_3H_6	1.48		.00	1.48	.000	2.00	11.10	20.51	18.61
B_1	CH_4	11.55		.20	11.75	.017	5.09	14.17	19.86	17.96
$(H_2)_1$	H_2	4.11		.07	4.18	.017	4.09	72.09	20.07	5.84
		40.00	4.00		44.00	.100	4.50	71.50	19.99	5.97
Total		95.20	4.00	.80	100.00		[2] 5.41	[2] 43.55	19.80	11.81

[1] Pp. 18 and 46.

[2] Calculated.

[3] Ref. *19*, tables 8 to 13, inclusive; ref. *20*, table 1.

[4] Table 5.

By substituting the real values in the table on page 50 for the symbols in the equation given on page 50, we find

$$L_L=\frac{100}{\frac{32.67}{13.24}+\frac{11.75}{5.09}+\frac{4.18}{4.09}+\frac{44.00}{4.50}+\frac{5.92}{2.75}+\frac{1.48}{2.00}},$$

$$=\frac{100}{2.468+2.308+1.024+9.778+2.152+0.740},$$

$$=\frac{100}{18.470}=5.41 \text{ percent, the lower explosive limit,}$$

which means that 5.41 parts of the air-free original atmosphere is explosive when admixed with 94.59 parts of atmospheric air and that the lower-explosive-limit mixture formed consists of 5.41 percent of the percentages of the constituents composing the air-free original atmosphere, 19.80 percent of oxygen, and 74.79 percent of nitrogen derived from atmospheric air.

The air-free original atmosphere has a nitrogen content of 0.8 percent; therefore, the total nitrogen content of the lower-explosive-limit mixture is:

$$\text{Total nitrogen}=(0.0541\times 0.8)+74.79,$$
$$=0.04+74.79=74.83 \text{ percent.}$$

By a similar procedure, the upper explosive limit (L_U) is calculated as follows:

$$L_U=\frac{100}{\frac{32.67}{72.08}+\frac{11.75}{14.17}+\frac{4.18}{72.09}+\frac{44.00}{71.50}+\frac{5.92}{28.60}+\frac{1.48}{11.10}},$$

$$=\frac{100}{0.453+0.830+0.058+0.615+0.207+0.133},$$

$$=\frac{100}{2.296}=43.55 \text{ percent, the upper explosive limit,}$$

which means that 43.55 parts of the air-free original atmosphere is explosive when admixed with 56.45 parts of atmospheric air and that the upper-explosive-limit mixture formed consists of 43.55 percent of the percentages of the constituents composing the air-free original atmosphere, 11.81 percent of oxygen, and 44.64 percent of nitrogen derived from atmospheric air.

The air-free original atmosphere has a nitrogen content of 0.8 percent; therefore, the total nitrogen content of the upper-explosive-limit mixture is:

$$\text{Total nitrogen}=(0.4355\times 0.8)+44.64,$$
$$=0.35+44.64=44.99 \text{ percent.}$$

By calculating the percentages of the constituents composing the gas portions of the lower- and the upper-explosive-limit mixtures in the manner shown for the nose-limit mixture, and combining these percentages with the respective amounts of oxygen and nitrogen derived from air, we find the composition of the explosive-limit mixtures to be:

Constituent	Percent by volume	
	Lower-limit mixture	Upper-limit mixture
Carbon monoxide	1.74	14.00
Methane	.62	5.03
Hydrogen	2.39	19.21
Ethylene	.32	2.58
Propylene	.08	.64
Carbon dioxide	.22	1.74
Nitrogen	74.83	44.99
Oxygen	19.80	11.81

Calculation of the explosive limits of a complex-gas mixture is complicated, whereas the calculation of the nose-limit mixture is comparatively simple; consequently, an easily applied method to determine a safe value of the lower explosive limit is available.

The difference between the total volume of combustible gases present in the lower-explosive-limit mixture of any air-free atmosphere that consists of carbon monoxide, methane, hydrogen, ethylene, propylene, carbon dioxide, and nitrogen or in the lower explosive-limit mixture of any air-free atmosphere that consists of varying amounts of nitrogen and carbon dioxide and any one or more of the foregoing combustible gases, except carbon monoxide taken singly, and the total volume of combustible gases present in the nose-limit mixture when nitrogen is used as the diluent is less than 1 percent. For this reason and for all practical purposes and safe procedure, the lower explosive limit, which is the gas-portion content (in percent) of the lower-explosive-limit mixture, can be taken as 1 percent less than the gas-portion content of the nose-limit mixture when nitrogen is used as the diluent, except when the carbon monoxide content of the air-free original atmosphere is more than 80 percent.

A practical application of the above-given statement can be shown by using the data given on pages 48 and 50. The gas-portion content of the nose-limit mixture is 5.90 percent and that of the lower-explosive-limit mixture is 5.41 percent, a difference of 0.49 percent. By applying the above statement, we find that the lower-explosive-limit mixture has a gas-portion content of (5.90—1.00) percent, or 4.90 percent. Therefore, the lower explosive limit would be 4.90, as compared with 5.41, the actual value calculated by the conventional method (*19*). This value, only 0.51 percent different from the actual calculated value, is on the safe side and is in as close agreement, as should be expected between values determined in this manner and values determined experimentally.

The air-free original atmosphere being discussed consists partly of 44.11 percent of hydrogen and 32.14 percent of carbon monoxide. This is an extreme case involving a high percentage of carbon monoxide, which, when compared with the other common simple combustible gases, has the most difference (1.3 percent) between the combustible-gas content of the lower-explosive-limit mixture and that of the nose-limit mixture when nitrogen is used as the diluent.

CALCULATION OF OXYGEN RANGE

Because an explosion is possible in the part of a mine that may be sealed to extinguish a fire, if the air-free composition of any portion of the mine-fire atmosphere has explosive limits, it is not enough to know only the volumes of combustible gases, inert gases, and oxygen present in the lower- and the upper-explosive-limit mixtures of the portion of the mine-fire atmosphere having the widest explosive range. The critical oxygen value must also be known so that all precautions possible can be taken to avert an explosion of any dangerous portion of either the mine atmosphere or the mine-fire atmosphere. The critical oxygen value expresses the minimum volume of oxygen required to have an explosion, whereas the oxygen content of the lower-explosive-limit mixture of the air-free original atmosphere expresses the maximum volume of oxygen required for this purpose. As these percentages of oxygen are limiting values that apply to definite mixtures of gases, they define the oxygen range of all possible explosive mixtures of a given air-free original atmosphere, a given diluent, and air.

Therefore, *the oxygen range can be said to be between the critical oxygen value, as defined on page 14, and the oxygen content of the lower-explosive-limit mixture of the air-free original atmosphere*, both expressed in percent. For example, the oxygen range of methane-air-nitrogen mixtures is said to be from 12.1 to 19.9 percent.

It was stated on page 14 that the critical oxygen value of complex-gas mixtures can be safely taken as 0.5 percent less than the oxygen content (in percent) of the nose-limit mixture only when calculated with nitrogen as the diluent.

From the data given on pages 47 and 51, relating to a carbureted water gas-air-nitrogen mixture, and the above-given statement, we can write

$$\begin{aligned}\text{Critical oxygen value} &= (O_2)_{nose} - 0.5,\\ &= 6.9 - 0.5,\\ &= 6.4 \text{ percent.}\end{aligned}$$

Because the oxygen content of the lower-explosive-limit mixture is 19.8 percent, the oxygen range is considered as being 6.4 to 19.8 percent.

USE OF CHARTS TO DETERMINE EXPLOSIBILITY OF COMPLEX GAS-INERT GAS-AIR MIXTURES

Real values of the factors relating to the explosibility of complex gas–air mixtures can be shown graphically, as in figure 1 (pocket). Some of the values can be obtained without calculations from the graph itself.

A graph form for use when dealing with a simple combustible gas is easily constructed. It is a standard form that can be utilized for any simple combustible gas and is useful for showing at a glance information that would otherwise have to be calculated for a problem that deals with a simple combustible gas (*9*). However, when complex-gas mixtures are being investigated, and particularly when the mixtures are changing (almost constantly) in composition, it becomes necessary to have available a graph form readily adaptable to any complex gas mixture as well as to any simple combustible gas–air–diluent mixture. The authors have used blueprint copies of a graph form, figure 2 (pocket), when conducting investigations at mine fires and at some industrial-plant accidents.

In the following description of the graph form the term "gas" will be considered (where convenient) as the air-free original atmosphere.

Any scheme by means of which a geometric figure may be represented by an equation is called a system of coordinates. The coordinates of a point are the quantities that determine the position of the point. If we consider a definite point in a line or a graph as corresponding to a definite atmosphere, we can express the position of the point by means of coordinates corresponding to real numbers that determine the position of the point in the graph. We then have a "1-to-1 correspondence" between real numbers and the points, or atmospheres, they represent, within the limits of the graph.

The authors have considered an atmosphere, or complex-gas mixture, as consisting of three portions, namely: (1) The gas portion, or volume of gases derived from an air-free original atmosphere; (2) the air portion, or atmospheric-air content; and (3) the diluent portion, or additional inert-gas content. If we let the definite real numbers that express the quantities (in percent) of the three portions composing a definite atmosphere correspond to the definite real numbers that determine the position of a definite point in a graph by expressing the distance from fixed lines to the point, we then have a means of plotting the point in the graph.

To avoid repetition of words when referring to an atmosphere that corresponds to a definite point, such as point *P*, for example, the term "atmosphere *P*" will be understood to mean "the atmosphere that corresponds to (or is represented by) point *P*."

The graph form shown in figure 2 (pocket) consists essentially of a right triangle, the sides of which form a boundary of points representing all possible mixtures of an air-free original atmosphere, air, and diluent.

The left side of the graph form is the leg of the triangle and the ordinate axis (*O–A*), which is a line representing all possible gas-free mixtures, or all mixtures composed of air and additional nitrogen (diluent). These mixtures vary from pure air to pure nitrogen. The ordinate axis is graduated to show the volume of oxygen in all possible mixtures. A graduated scale shows the air content (in percent) of the atmosphere that has the specified oxygen content, as well as the volume of diluent present in the atmosphere.

The base of the right triangle is the abscissa axis (*O–J*), which is a line representing all possible air-free gas–air–nitrogen mixtures. These mixtures vary from 100 percent of the percentages of the constituents composing the air-free original atmosphere to pure nitrogen (diluent). This boundary line (as graduated) shows the total volume of gases, less air and diluent, present in the atmosphere, as well as the volume of additional nitrogen (diluent) in the atmosphere.

The hypotenuse of the right triangle is a line representing all possible diluent-free gas-air mixtures. Such mixtures are considered as original mixtures, or original atmospheres. These mixtures vary in composition from 100 percent pure air to 100 percent of the percentages of the constituents composing the air-free original atmosphere. The volumes of oxygen and nitrogen that compose the air in any possible mixture of the air-free original atmosphere, air, and diluent are shown on a graduated scale opposite the hypotenuse of the triangle, and this scale forms the right-hand side of the graph-form.

The origin (point *O*) of the ordinate and abscissa axes represents a gas-free, air-free mixture consisting of 100 percent of nitrogen or other inert gas, if it is used as the diluent.

CONSTRUCTION OF A GRAPH

Figures 3 and 4 (pocket) have been constructed to show the "damping" effect of methane on mixtures composed of equal proportions of carbon monoxide, methane, and hydrogen, as well as to show the method of constructing a graph. These figures show the relationship between the composition and the explosibility of mixtures of analogous proportions of the combustible gases with air and nitrogen; they also show similar factors for mixtures of each of the simple gases—carbon monoxide, methane, and hydrogen—with air and nitrogen.

The procedure to employ in constructing a graph in any problem is to calculate (1) the atmosphere, as sampled, to an air-free basis, (2) the critical gas-mixture value (*C. G. M. V.*), and (3) the nose limit if the real value of *C. G. M. V.* is less than 100. If the critical gas-mixture value is 100, or more than 100, or has a minus value, the air-free original atmosphere is incapable of forming explosive mixtures with air, and the construction of a graph is unnecessary.

The calculations for determining the various factors relating to the explosibility of the combustible gas–air–nitrogen mixtures shown in figures 1, 3, and 4 (pocket) are not included but have been determined by the formulas given in this report and are summarized in table 6, which also gives some real values of the factors as determined experimentally.

The methods of utilizing a graph form, such as figure 2, and the graphic determination of the explosive limits, nose limit, critical oxygen value, critical gas-mixture value, and related factors are shown in figures 3 and 4 and in the following explanation:

EXPLANATION OF FIGURE 4

Figure 4 specifically explains figure 3 (pocket), as well as the procedure employed to construct figures 1 and 6 to 10 (pocket), inclusive. The straight line *AJ* (fig. 4) represents the composition of all mixtures of air with hydrogen, carbon monoxide, and methane, taken singly or combined in equal proportions of one-third each. The combustible-gas content of these mixtures can range from 0 to 100 percent hydrogen, carbon monoxide, or methane, as the case may be, or from 0 to 33⅓ percent hydrogen, 33⅓ percent carbon monoxide, and 33⅓ percent methane. No mixture, composed of either of the simple combustible gases and air or of the equally proportioned mixture of the combustible gases and air, can fall above line *AJ*. All mixtures of the combustible gases taken singly or in equal proportions, air, and nitrogen must fall below it.

Consider the air-free complex-gas mixture composed of one-third each of hydrogen, carbon monoxide, and methane. Points *D* and *G*

TABLE 6.—*Observed and calculated explosive limits of hydrogen, methane, and carbon monoxide, and a complex-gas mixture composed of equal proportions of these gases; also nose-limit and critical gas-mixture values of same gases*

Item	Composition of gas before mixing with air (percent)			Explosive limits in air (percent)			Critical gas mixture value[1] (percent)
	H_2	CH_4	CO	Observed	Calculated	Difference	
				Lower			
Simple gases	100.0	----------	----------	[2] 4.1	----------	----------	----------
	----------	100.0	----------	[2] 5.0	----------	----------	----------
	----------	----------	100.0	[2] 12.5	----------	----------	----------
Complex-gas mixture	33.3+	33.3+	33.3+	[3] 5.7	[1] 5.72	−0.02	----------
				Upper			
Simple gases	100.0	----------	----------	[2] 74.0	----------	----------	----------
	----------	100.0	----------	[2] 14.0	----------	----------	----------
	----------	----------	100.0	[2] 74.0	----------	----------	----------
Complex-gas mixture	33.3+	33.3+	33.3+	[3] 29.9	[1] 30.47	−.57	----------
	Composition of air-free original mixtures (percent)			Nose limit (nitrogen as diluent)			
Simple gases	100.0	----------	----------	[4] 75.5	----------	----------	5.69
	----------	100.0	----------	[4] 41.5	----------	----------	14.28
	----------	----------	100.0	[4] 71.0	----------	----------	19.41
Complex-gas mixture	33.3+	33.3+	33.3+	----------	[1] 62.7	----------	10.10

[1] Calculated by authors.
[2] Ref. *9*.
[3] Ref. *10*.
[4] Ref. *19*.

correspond to the lower- and the upper-explosive-limit mixtures, respectively. Line *DL* represents the compositions of all possible lower-explosive-limit mixtures of the air-free original mixture, air, and nitrogen and line *GL* the compositions of all possible upper-explosive-limit mixtures. If the oxygen content falls, points *D* and *G* approach each other until they meet at the point representing the common explosive-limit mixture, or the nose of the zone of explosive mixtures. In other words, the combustible-gas content and the oxygen content of the explosive-limit mixtures at *D* (5.72 percent of combustible gases and 19.72 percent oxygen) and *G* (30.5 percent of combustible gases and 14.55 percent oxygen) decrease, while the nitrogen content increases until the explosive limits are identical in composition. As stated on page 35, the point corresponding to this mixture is minutely separated from point *L*, which corresponds to the nose-limit mixture. For graphic purposes, these points will be considered as the same point. The composition of the nose-limit mixture has been found to be 6.33 percent of combustible gases (2.11 percent each of hydrogen, carbon monoxide, and methane), 85.87 percent nitrogen, and 7.80 percent oxygen. Because the nose-limit mixture is just nonexplosive, the common explosive-limit mixture is just explosive and is composed of 2.11+ percent of each of the combustible gases, 85.87− percent nitrogen, and 7.80 percent oxygen.

We have stated on page 14 that no mixture having an oxygen content 0.5 percent less than that of the mixture corresponding to point *L* (nose-limit mixture) is explosive. However, all mixtures within the area *DLG* have explosive limits and are explosive. The same line of reasoning can be followed to explain the common explosive-limit mixtures and the nose-limit mixtures (*N*, *M*, and *K*, fig. 4) of hydrogen, carbon monoxide, and methane, respectively, when they are taken singly.

Let us now consider an atmosphere having the composition corresponding to point *L* (fig. 4). If this atmosphere is diluted, step by step, with normal air (ratio of oxygen to combustible gas, 13.13 : 6.33) because of leakage or otherwise, the resultant mixtures will correspond to points in line *LA* until point *A* is reached, when the atmosphere will be normal air (20.93 percent oxygen). By the same line of reasoning, if the oxygen (7.8 percent of the mixture) existing in the nose-limit mixture corresponding to point *L* is replaced, step by step, with the combustible gases in the same ratio (ratio of oxygen to combustible gas, 13.13 : 6.33) as they exist at point *L*, the resultant mixtures will correspond to points in line *LQ* until the critical gas mixture, or point *Q* in the abscissa axis, is reached. The critical gas mixture will have a composition consisting of 10.10 percent combustible gases and 89.90 percent nitrogen. The critical gas-mixture value is 10.10 percent.

From the foregoing, it can be deduced that any mixture consisting of equal proportions of hydrogen, carbon monoxide, and methane, and nitrogen can form explosive mixtures with air when the mixture has a combustible content that is more than 10.10 percent (3.36 + percent each of hydrogen, carbon monoxide, and methane) and a nitrogen content less than 89.90 percent. It follows that the position of line *AQ* is exactly defined by drawing a straight line from point *A* to point *L* (nose-limit mixture) and extending same to point *Q* in the abscissa axis. Because any mixture to the right of the line *GLQ* has a combustible-gas content of more than 6.33 percent, on dilution of such a mixture with air the resultant mixture becomes explosive when its composition reaches the point in the line of upper-explosive-limit mixtures (*GL*) and remains so until it passes the point in the line of lower-explosive-limit mixtures (*DL*).

Points *P*, *R*, and *S* (fig. 4, pocket) correspond to the critical gas mixtures of any mixture of hydrogen, of methane, and of carbon monoxide, respectively, and nitrogen. The fact that these mixtures are just incapable of forming explosive mixtures with air can be established in the manner previously described.

The critical gas-mixture values relating to the critical gas mixtures that correspond to the above-given points are, in the same order, 5.69, 14.28, and 19.41, respectively (table 6). Because these real values define the combustible-gas content of their corresponding critical gas mixtures, the compositions of these mixtures are: 5.69 percent hydrogen and 94.31 percent nitrogen, 14.28 percent methane and 85.72 percent nitrogen, and 19.41 percent carbon monoxide and 80.69 percent nitrogen, respectively.

It can also be deduced that no mixture composed of equal proportions of hydrogen, methane, and carbon monoxide, and nitrogen, falling to the left of line *LQ*, can form explosive mixtures with air. Similarly, no mixture of hydrogen, methane, or carbon monoxide, and nitrogen, falling to the left of line *NP*, or line *KR*, or line *MS*, respectively, can form explosive mixtures with air.

Let us now consider any mixture composed of hydrogen, methane, or carbon monoxide taken singly, nitrogen, and air or any mixture composed of equal proportions of these combustible gases, nitrogen, and air that is represented by some point in the areas *JINP*, *JFKR*, *JHMS*, and *JGLQ* (fig. 4), respectively. Such a mixture can form explosive mixtures when admixed with air in suitable proportions. It is of interest to know the explosive range of the air-free compositions of all mixtures capable of forming explosive mixtures with air.

Let us assume that a mixture formed by admixing nitrogen and air with any of the foregoing combustible gases, taken singly or with an equally proportioned mixture of them, is represented by point P_1, which has an oxygen content of 3 percent. The straight line P_1A therefore corresponds to all possible mixtures of P_1 and air. As mixture P_1 is diluted step by step with air, the composition of the new mixture is represented by points farther and farther from point P_1 until point *A* is reached and the new mixture becomes pure air (20.93 percent oxygen). Considering each mixture separately, the new mixture for hydrogen first becomes explosive at point *W* (upper-explosive-limit mixture) and remains so until it reaches and passes point *V* (lower-explosive-limit mixture); for carbon monoxide the explosive range exists between points *Y* and *X;* for the equally proportioned mixture of combustible gases between points *ZZ* and *Z;* and for methane between points *U* and *T*.

GRAPHIC DETERMINATION OF NOSE-LIMIT MIXTURE, CRITICAL GAS MIXTURE, AND CRITICAL OXYGEN VALUE

It is obvious from the above-given explanation of figure 4 that if the position of point *L* (the nose-limit mixture of any combination of equal proportions of hydrogen, carbon monoxide and methane, air, and nitrogen) and the position of point *Q* (corresponding critical gas mixture) can be found simply, a method is available for quickly determining critical factors relating to the explosibility of mine-fire atmospheres and other potentially explosive mixtures.

The air and the oxygen contents of the nose-limit mixture can be found directly from the graph after calculating the nose limit (L_{nose-N_2}). Point *L* is found graphically to be the point of intersection of line *de* drawn parallel to the abscissa axis (*O–J*) through the points corresponding to all mixtures having the same oxygen content as the nose-limit mixture, and line *AQ* drawn between point *A*, which corresponds to pure air, and point *Q*, which corresponds to the critical gas mixture.

Having determined the position of point *L*, which corresponds to the nose-limit mixture, we can determine the gas-portion and the diluent-portion contents of it by means of the graph. The mathematical basis for and the details of the procedure to employ in the graphic determination of the foregoing factors are as follows:

Consider any mixture consisting of equal proportions of hydrogen, methane, and carbon monoxide, and air. Such a mixture corresponds to some point in line *AJ* (the hypotenuse). At point *A* the mixture is pure air, and at point *J* it consists of 33⅓ percent each of hydrogen $(H_2)_1$, methane (B_1), and carbon monoxide (A_1). Point *J*, therefore, corresponds to the air-free original mixture of this combination.

The nose limit (L_{nose-N_2}) is 62.7 percent, which is found by substituting the composition values of point *J* for the symbols in formula (25), page 39.

In figure 4 (pocket) it is observed that the abscissa axis (*O–J*) is divided into 100 parts by definite points; these points correspond to definite mixtures of the air-free original mixture and diluent. By geometrical construction, the hypotenuse (*A–J*) is divided into similar proportional parts by lines drawn parallel to the ordinate axis (*O–A*) from these points. Furthermore, any other line, such as *AQ*, drawn from point *A* to line *O–J* (the abscissa axis) is divided proportionally into 100 parts by lines drawn parallel to the abscissa axis from the above-mentioned points in the hypotenuse to the ordinate axis, such as line *ed*, *fb*, or *O–J*. Therefore, the following ratios are equal:

$$\frac{Ae}{A\text{–}O}=\frac{Ad}{A\text{–}J}=\frac{Oc}{O\text{–}J}=\frac{AL}{AQ}=\frac{eL}{OQ}.$$

By construction, we make

$$Oc=L_{nose-N_2},\ OQ=C.\ G.\ M.\ V._{N_2},\ \text{and } O\text{–}J=100.$$

Therefore, we can write

$$\frac{L_{nose-N_2}}{100}=\frac{eL}{C.\ G.\ M.\ V._{N_2}},$$

which, by transposition of terms, becomes

$$eL=\left[\frac{L_{nose-N_2}}{100}\right][C.\ G.\ M.\ V._{N_2}].$$

Line *eL* corresponds to the gas-portion content of the nose-limit mixture and is expressed in percent of the percentages of the constituents composing the air-free original mixture. Point *L*, which corresponds to the nose-limit mixture, can be determined by means of a graph, such as figure 2 (pocket), by drawing the pertinent straight lines from definite points, the positions of which are known. To determine the position of point *L*, we proceed as follows:

We have previously found the critical gas-mixture value ($C.\ G.\ M.\ V._{N_2}$) to be 10.10 percent by substituting the known composition values of point *J* for the symbols in formula (10), page 25. Point *Q*, which corresponds to a critical gas mixture having a gas-portion content of 10.10 percent (the critical gas-mixture value), is plotted in line *O–J* (the abscissa axis). Line *QA* is then drawn, thus defining all possible mixtures of the critical gas mixture and air, of which one must be the nose-limit mixture.

Point *c*, which corresponds to a mixture having a gas-portion content of 62.7 percent (the nose limit), is now plotted in the abscissa axis (*O–J*). Line *cd* is then drawn parallel to the ordinate axis (*O–A*) and intersects the hypotenuse (*A–J*) at point *d*, which corresponds to a mixture having an air content of 37.3 percent. Line *de*, drawn parallel to the abscissa axis (*O–J*), intersects the ordinate axis at point *e*. Line *de*, therefore, represents all possible mixtures that have an air content and an oxygen content of 37.3 percent and 7.8 percent, respectively; one of these mixtures must be the nose-limit mixture. Because line *de* intersects line *QA* at point *L*, which is common to both line *QA* and line *de*, point *L* must, therefore, correspond to the nose-limit mixture.

The composition of the critical gas mixture (point *Q*) is found in figure 4 (pocket) to be 10.10 percent of the composition of point *J* and 89.90 percent nitrogen, or 3.366+ percent each of hydrogen, carbon monoxide, and methane, and 89.90 percent nitrogen.

To find the composition of the nose-limit mixture, we proceed as follows: A line drawn parallel to the ordinate axis (*O–A*) from point *L* intersects the abscissa axis (*O–J*) at point *g*. This shows that the nose-limit mixture has a gas-portion content of 6.33 percent of the composition of point *J*, or 2.11 percent each of hydrogen, carbon monoxide, and methane. A line drawn parallel to the hypotenuse (*A–J*) from point *L* intersects the abscissa axis at point *h*. This shows that the nose-limit mixture has a diluent content of 56.37 percent nitrogen. The air content has been given above as 37.3 percent. Summarizing, the composition of the nose-limit mixture is 2.11 percent each of hydrogen, carbon monoxide, and methane, 7.8 percent oxygen, and 85.87 percent nitrogen, of which 29.5 percent is the nitrogen component of air and 56.37 percent is diluent.

The critical oxygen value in this example could be safely considered as 7.3 percent, which is 0.5 percent less than the oxygen content of the nose-limit mixture. Line d_1e_1, drawn parallel to the abscissa axis, represents all possible mixtures having an oxygen content of 7.3 percent.

The construction lines that determine point *N*, which corresponds to the nose-limit mixture of all possible mixtures of hydrogen and nitrogen, are shown in figure 4. The procedure described above is applicable to a mixture of any simple combustible gas and inert gas or of any complex-gas mixture and inert gas that has explosive limits with air and has been tested and found to obey the law of Le Chatelier.

GRAPHIC DETERMINATION OF EXPLOSIVE LIMITS

The explosive limits of an air-free original atmosphere (*J*, fig. 4) that relates to any original atmosphere corresponding to some point in line *A–J* cannot be determined graphically. However, having determined mathematically the explosive limits, nose limit, and critical gas-mixture value corresponding to atmospheres *D* and *G*, *L*, and *Q*, respectively, whereby the graph (fig. 4) can be constructed, the real values of the explosive limits of the air-free atmosphere relating to any atmosphere lying in the plane of the graph can be determined graphically.

Let us consider atmosphere P_1 (fig. 4) as an example. The air-free composition of atmosphere P_1 corresponds to atmosphere *k*. The mathematical basis for determining graphically the real values of the explosive limits of atmosphere *k* is the same as that for determining the position of point *L* corresponding to the nose-limit mixture. However, the graphic procedure is reversed.

To find the real value of the lower explosive limit of atmosphere *k*, draw line Z–Z_1 parallel to the abscissa axis to intersect line *A–J* at point Z_1. Draw a line from point Z_1 parallel to the ordinate axis to intersect the abscissa axis at a point corresponding to an atmosphere having a gas-portion content of 14.66 percent; therefore, the real value of the lower explosive limit is 14.66 percent.

As the upper explosive-limit mixture of atmosphere *k* corresponds to point ZZ_1, we draw line ZZ–ZZ_1 parallel to the abscissa axis to find the real value of the upper explosive limit. We then draw a line from point ZZ_1 parallel to the ordinate axis to intersect the abscissa axis at a point corresponding to an atmosphere having a gas-portion content of 46.30 percent, which is also the real value of the upper explosive limit.

Figure 5 (pocket) shows the relationship between the factors just discussed when atmosphere P_1 (fig. 4), is considered as an original atmosphere corresponding to atmosphere P_2 (fig. 5).

CALCULATION OF ADDITIONAL INERT GAS IN ATMOSPHERES CONTAINING DILUENT

A mine atmosphere can be considered as pure atmospheric air, to which other gases such as methane, carbon dioxide, nitrogen, or mine-fire gases have been added. The resultant original atmosphere, calculated to an air-free basis, can be considered as the air-free original atmosphere of any mixture that may be formed by admixing air and an inert gas, such as nitrogen if used as the diluent, with the original atmosphere. In such a mixture, the nitrogen over and above that present in the air portion and in the gas portion of the mixture is considered as diluent.

There are times when practical considerations make it desirable to know the effect on an original atmosphere, such as mentioned above, of a portion of the mine atmosphere that may have a low oxygen content, a high nitrogen content, and a small carbon dioxide content, which, for all practical purposes, can be considered as nitrogen. It is often possible to obtain samples of the resultant atmosphere formed by admixing such atmospheres. Furthermore, it is desirable (1) to know the volume of available nitrogen that is affecting the original atmosphere and (2) to determine the position of the point that corresponds to the atmosphere sampled, in a graph form such as figure (2 pocket).

The volume of nitrogen (diluent) and the volumes of nitrogen existing in the gas and the air portions of the atmosphere sampled can be expressed mathematically and therefore be designated in or obtained from a graph.

Formulas (38), (39), and (40) can be used to determine real values for the factors just mentioned. The method of deriving these formulas follows. The methods of determining the composition of any possible mixture that can be used to dilute a definite original atmosphere, as well as methods to determine other factors relating to such a mixture, are given later.

Let us assume that the atmosphere sampled has been formed from an original atmosphere that has a known composition and corresponds to some point in line *A–J* (the hypotenuse), figure 2 (pocket), except point *A*, which corresponds to pure air. Point *J*, therefore, corresponds to the air-free original atmosphere.

First, we establish the following relationship between known real values of factors relating to the air-free original atmosphere and the atmosphere sampled:

$$C=\frac{(Comb)_s}{\left[\frac{K_s}{100}\right]\left[\frac{(Comb)_1}{100}\right]}, \qquad (38)$$

where C = a factor (in percent) that expresses the percentage of the air-free original atmosphere existing in the air-free composition of the atmosphere sampled;
$(Comb)_1$ = the combustible-gas content (in percent) of the air-free original atmosphere.
$(Comb)_s$ = the combustible-gas content (determined by analysis) of the atmosphere sampled,
and K_s is the amount (in percent) of gases other than air that is present in the atmosphere sampled. (*See* formula (2), p. 17.)

A relationship between the inert-gas and the combustible-gas contents of both the atmosphere sampled and the air-free original atmosphere can be expressed as follows:

$$(Inert)_{gp-s}=\frac{\left[\frac{(Inert)_1}{100}\right][Comb_s]}{\frac{(Comb)_1}{100}}, \qquad (39)$$

where $(Inert)_{gp-s}$ is the inert-gas content (nitrogen plus carbon dioxide) of the gas portion of the atmosphere sampled,
$(Inert)_1$ is the inert-gas content (nitrogen plus carbon dioxide) of the air-free original atmosphere;
and $(Comb)_1$ and $(Comb)_s$ have the same meanings as before.

Because the nitrogen content of atmospheric air is 79.07 percent, and the oxygen content is 20.93 percent, it can be established that the volume of nitrogen ($(N_2)_{air-s}$) derived from the air present in the atmosphere sampled is 3.78 times the oxygen content $(O_2)_s$, in percent.

Because the volume (in percent) of nitrogen reported in an analysis of a sample of an atmosphere is the total amount of nitrogen, we can express the relationship between the inert-gas components of the atmosphere sampled, as follows:

$$(N_2)_{add-s}=(N_2)_{ts}+(CO_2)_{ts}-(Inert)_{gp-s}-3.78(O_2)_s; \qquad (40)$$

where $(N_2)_{add-s}$ = the additional nitrogen, or diluent, content (in percent) of the atmosphere sampled;
$(N_2)_{ts}$ = the total nitrogen content (in percent) of the atmosphere sampled;
$(CO_2)_{ts}$ = the total carbon dioxide content (in percent) of the atmosphere sampled;
$3.78\ (O_2)_s$ = the volume of nitrogen derived from the atmospheric air contained in the atmosphere sampled;
and $(Inert)_{gp-s}$ and $(O_2)_s$ have the same meanings as before.

The following example will show the application of formulas (38), (39), and (40):

Let us assume that an original atmosphere is diluted with either nitrogen or nitrogen and air, as the case may be. Samples of the resultant atmosphere formed are analyzed.

The first step in the procedure to determine the additional nitrogen (diluent) content of the atmosphere sampled is to calculate (1) the composition of the original atmosphere to an air-free basis and (2) the air content of the atmosphere sampled, by means of formulas (1) to (4*b*), inclusive.

The arithmetical calculations of the foregoing factors are not given. The composition of the air-free original atmosphere, the composition of the atmosphere sampled, and the symbols applicable for use in formulas (1) to (4*b*), inclusive, and (38), (39), and (40) are shown in the following table:

Item	Amount of constituent (in percent) and symbols used in formulas	
	Air-free original atmosphere	Atmosphere sampled
Combustible gases	40.85 $(Comb)_1$	14.30 $(Comb)_s$.
Oxygen	.00	3.00 $(O_2)_s$.
Carbon dioxide (total)	2.00 D_1	.07 $(CO_2)_{ts}$.
Nitrogen (total)	57.15 $(N_2)_1$	82.63 $(N_2)_{ts}$.
Total	100.00	100.00.
Air portion:		
Oxygen	None	3.00 $(O_2)_s$.
Nitrogen	None	11.33 $(N_2)_{air-s}$.
Total	None	14.33 Air_s.
Total inert gases	59.15 $D_1+(N_2)_1$	82.70 $(N_2)_{ts}+(CO_2)_{ts}$.
Gases other than air	100.00	85.67 K_s.
Inert gas in gas portion	59.15 $(Inert)_1$	? $(Inert)_{gp-s}$.
Diluent (nitrogen)	None	? $(N_2)_{add-s}$.

Substituting the real values given in this table for the symbols in formulas (38), (39), and (40) (pp. 61, and 62), we find

$$C = \frac{14.30}{0.8567 \times 0.4085} = 40.85 \text{ percent} \tag{38}$$

$$(Inert)_{gp-s} = \frac{0.5915 \times 14.30}{0.4085}, \tag{39}$$

$=20.70$ percent of inert gases, of which 20.63 percent is nitrogen and 0.07 percent is carbon dioxide, determined by analysis,

$$\text{and } (N_2)_{add-s} = 82.63 + 0.07 - 20.70 - 11.33, \tag{40}$$

$=50.67$ percent of additional nitrogen, or diluent.

We have just found that the additional nitrogen content of the atmosphere sampled is 50.67 percent. The significance of this value is: Any possible atmosphere that could be admixed with any possible mixture of the given air-free original atmosphere and air to form the given atmosphere sampled must contain 50.67 percent of additional nitrogen.

We find from the above table that the air content of the atmosphere sampled is 14.33 percent, of which 3 percent is oxygen. Therefore, the gas-portion content of the atmosphere sampled must have a real value of

$$(100 - 50.67 - 14.33) \text{ percent, or 35 percent.}$$

The real values of the coordinates that determine the position of the point in a graph applicable to the atmosphere sampled are: 35 percent (gas-portion content), 14.33 percent (air content), and 50.67 percent (diluent content).

Several methods may be used to determine graphically the position of the point corresponding to the atmosphere sampled. Because of its composition (by portions), this point in figure 4 (pocket) corresponds only in position to point P_1. The various factors relating to the explosibility of the atmospheres shown in figure 4, which is an explanation of figure 3, do not apply to the above-mentioned atmosphere, and point P_1 has only the same position in both instances. The position of point P_1 is determined as follows:

1. Because the atmosphere sampled has a diluent content of 50.67 percent, a line drawn parallel to the hypotenuse (*A–J*) from point *j* (fig. 4) in the abscissa axis (*O–J*) intersects the ordinate axis (*O–A*). This line represents all possible mixtures having an additional nitrogen content of 50.67 percent. It intersects the line drawn parallel to the abscissa axis that represents all mixtures having an oxygen content of 3 percent, at point P_1.
2. Because the gas-portion content of the atmosphere sampled is 35 percent, a line drawn parallel to the ordinate axis from point *i* in the abscissa axis represents all possible mixtures having a gas portion that consists of 35 percent of the percentages of the constituents composing the air-free original atmosphere. This line intersects the line representing all possible mixtures having an oxygen content of 3 percent at point P_1.
3. Another method of finding the point corresponding to the atmosphere sampled is to determine first the real value of *C* by formula (38). By plotting this value, which in this instance is 40.85 percent, in a graph (fig. 4) as shown at point *k* in the abscissa axis, a line can be drawn from point *k* to point *A*, which represents pure atmospheric air (20.93 percent oxygen). This line represents all possible mixtures formed by admixing air with an atmosphere having a gas portion that consists of 40.85 percent of the composition of the air-free original atmosphere. One of these mixtures corresponds to point P_1, which is the point of intersection of the foregoing line and the line representing all mixtures having an oxygen content of 3 percent.

The method just described for determining the position of point P_1, (fig. 4), is preferable when determining graphically the position of point P_1 and the composition of the atmosphere it represents. If the oxygen content of the atmosphere sampled and the gas-portion content of its air-free composition are known, the composition (by constituents) of the atmosphere represented by the point sought can be readily determined graphically by this method.

CALCULATION OF VOLUME OF ADDITIONAL INERT GAS NECESSARY TO RENDER AN ATMOSPHERE NONEXPLOSIVE

It has been shown in figure 4 (pocket) that if an atmosphere is either explosive or capable of forming explosive mixtures with air, such an atmosphere can be rendered nonexplosive and incapable of forming explosive mixtures with air if the required volume of inert gas, such as nitrogen or carbon dioxide, is admixed with it.

It is important to know how much inert gas must be used for the above-stated purpose (condition 1) when the line corresponding to all possible mixtures formed by admixing a given inert gas with a given atmosphere passes below the point corresponding to the nose-limit mixture, and (condition 2) when the line of mixtures formed intersects the line of lower explosive-limit mixtures.

The volume of inert gas that must be admixed with a given atmosphere to yield an atmosphere incapable of forming explosive mixtures with air can be determined by either mathematical calculations or graphically. To determine the volume of diluent required when condition 1, given above, applies, it is necessary to (1) consider the given atmosphere as an original atmosphere, of which the air-free analysis is taken as 100 percent in the graph-form (*see* fig. 5 (pocket) and p. 61), (2) calculate the composition of the original atmosphere to an air-free basis, and (3) calculate the real values of the critical gas mixture value, nose limit, and oxygen content of the nose-limit mixture.

It is not necessary to know the lower explosive limit when the line corresponding to all possible mixtures formed, as stated above, passes below the point corresponding to the nose-limit mixture (condition 1). It is not necessary to know the upper explosive limit in either condition 1 or condition 2. It is necessary to know the lower explosive limit if condition 2 applies.

Whether condition 1 or condition 2 applies can only be determined by calculating the nose limit and the oxygen content of the nose-limit mixture. If the oxygen content of the given atmosphere (P_2, fig. 5) being diluted is less than the oxygen content of the nose-limit mixture, condition 1 applies. Condition 1 also applies if the angle (θ) included between the abscissa axis and the line drawn from the origin (O) through the point corresponding to atmosphere P_2 is less than the angle (θ_{nose}) included between the abscissa axia and the line drawn from the origin through the point corresponding to the nose-limit mixture. (*See* angle θ_{nose}, fig. 6.)

In the section immediately following this discussion we will consider condition 1 (p. 64) when the oxygen content of the atmosphere sampled is less than the oxygen content of the nose-limit mixture. The method of procedure in condition 1, when the oxygen content of the atmosphere sampled is more than the oxygen content of the nose-limit mixture, is discussed on pages 87 and 88.

Formulas for calculating the amount of inert gas required under condition 2 are derived and discussed on pages 112 to 113, inclusive.

Let us consider an atmosphere having a chemical composition identical to that of atmosphere P_1 (fig. 4). It is desired to know the minimum volume of a given diluent that must be admixed with this atmosphere to form a mixture incapable of forming an explosive mixture with air. On the basis of requirement 1, given above, this atmosphere can be represented by point P_2 (fig. 5). Atmospheres represented by points P_1 (fig. 4) and P_2 (fig. 5), therefore, have identical chemical compositions and express the same mixture in two different graphs in which points J correspond to two different air-free original atmospheres.

The relationship between points P_1 (fig. 4) and P_2 (fig. 5) to their corresponding air-free original atmospheres is shown in figure 5 by superimposing part of figure 4 on figure 5. Although atmospheres P_1 and P_2 have identical chemical compositions, atmosphere P_1 has been formed from an original atmosphere (P_3, fig. 4) by admixing nitrogen with atmosphere P_3, whereas atmosphere P_2 (fig. 5) is an original atmosphere in which no additional nitrogen (diluent) is present. This satisfies requirement 1 given above. Requirement

1 must be complied with when determining graphically the amount of inert gas (nitrogen) required to form a mixture incapable of forming an explosive mixture with air.

MATHEMATICAL METHOD OF CALCULATING VOLUME OF INERT GAS REQUIRED TO RENDER AN ATMOSPHERE NONEXPLOSIVE IF ADMIXED WITH AIR

General formulas can be derived for calculating the minimum volume of a given inert gas (nitrogen or carbon dioxide) required to render a given mixture nonexplosive if admixed with air.

As stated on page 65, it is not necessary to know the explosive limits to calculate the volume of inert gas required when condition 1 applies. To find graphically the relationship existing between the compositions of all possible mixtures and the various factors applying to their explosibility, the explosive limits of atmosphere J, example 1, page 71, are determined by the method described on page 50. The arithmetical calculations are not given; however, the lower explosive limit of atmosphere *J* (fig. 5) is 14.66 percent and the upper explosive limit 46.30 percent.

Referring to figure 5, the following relations, existing between the geometric properties of the figure and the analytic properties of the equations to determine the above-mentioned factors, can be established when the line corresponding to all possible mixtures formed by admixing a given inert gas with a given atmosphere passes below the point corresponding to the nose limit mixture (condition 1, p. 64).

Consider the abscissa axis (*O–J*) as the *X* axis, and the ordinate axis (*O–A*) as the *Y* axis. Then x and y are the rectangular coordinates of any point (x, y) in the portion of the *XY* plane that lies within the boundaries of triangle *AOJ*. Therefore, there is a "1—to—1 correspondence" between the symbol (x, y) and the points within the triangular portion of the *XY* plane.

Because the rectangular coordinates of point x, y are x and y, the real value (in percent) of the gas-portion content of a given atmosphere is the real value of x, which corresponds to the length of the line drawn normal to the ordinate axis (*O–A*) from point x, y. The real value (in percent) of either the air-portion content or the oxygen content of the given atmosphere, as the case may be, is the real value of y, which corresponds to the length of a line drawn normal to the abscissa axis (*O–J*) from point x, y.

Let us now assume that point x, y corresponds to an atmosphere that is just incapable of forming an explosive mixture with air and that atmosphere x, y is formed by admixing nitrogen with an original atmosphere that (1) can form explosive mixtures with air and (2) has an air-free composition identical to that of atmosphere *J* (fig. 5).

If point P_2 corresponds to the original atmosphere to which nitrogen is added as a diluent, and point *O* corresponds to an atmosphere composed of pure nitrogen, then line P_2–*O* represents all possible mixtures of atmosphere P_2 and nitrogen. One of these mixtures is represented by point x, y, the coordinates of which are unknown. Because the real numbers determining the positions of points P_2 and *O* in figure 5 are known, line P_2–*O* can be plotted without calculations.

If we now assume that points *C. G. M. V.*, *A*, and *Nose* (fig. 5) represent the critical gas mixture, pure air, and the nose-limit mixture, respectively, then the portion of line *C. G. M. V.–A* between point *C. G. M. V.* and point *Nose* represents mixtures that are just incapable of forming an explosive mixture with air.

Because the position of point A is known, to plot line *C. G. M. V.–Nose* it is necessary to determine the real numbers that determine the position of point *C. G. M. V.* On page 10 it was shown that the real number defining the gas-portion content (in percent) of the critical gas mixture is the critical gas-mixture value. Therefore, to plot point *C. G. M. V.* we determine the critical gas-mixture value ($C.\ G.\ M.\ V._{N_2}$) and plot point *C. G. M. V.* in the abscissa axis at the position corresponding to an atmosphere having a gas-portion content, the real value of which is the critical gas-mixture value ($C.\ G.\ M.\ V._{N_2}$).

We now draw line *C. G. M. V.–A*, which intersects line P_2–O at point $(P_4)_2$. Because point $(P_4)_2$ is common to line P_2–O and line *C. G. M. V.–Nose*, atmosphere $(P_4)_2$ is the atmosphere formed by admixing the minimum amount of nitrogen with atmosphere P_2 to form an atmosphere that is just incapable of forming an explosive mixture with air. Therefore, atmosphere $(P_4)_2$ and atmosphere x, y are identical, and the real values of x and y correspond to the gas-portion content and the oxygen content, respectively, of atmosphere $(P_4)_2$. To determine the minimum amount of nitrogen $(N_2)_{dil}$ that must be admixed with the original atmosphere (P_2) to form atmosphere $(P_4)_2$, we first establish a relationship between the unknown values of x and y (rectangular coordinates of point $(P_4)_2$) and known or determinable values relating to the atmosphere sampled, or atmosphere P_2.

A line, $(P_4)_2$–$(l_4)_2$, drawn from point $(P_4)_2$ parallel to line A–J intersects the abscissa axis at point $(l_4)_2$, which corresponds to an atmosphere having an additional nitrogen content the same as the diluent content $(N_2)_{dil}$ of atmosphere $(P_4)_2$. The length of line J–$(l_4)_2$, therefore, corresponds to the diluent content of atmosphere $(P_4)_2$. Moreover, the real value of the diluent content of atmosphere $(P_4)_2$ is the minimum amount (in percent) of nitrogen that must be admixed with atmosphere P_2 to form a mixture $(P_4)_2$ just incapable of forming an explosive mixture with air.

If in figure 5 (pocket) we designate angle $OA(C.\ G.\ M.\ V.)$ as ϕ, angle P_2OJ as θ, and angle $O(P_4)_2A$ as Δ, the following trigonometric relationships can be established:

$$\phi=\tan^{-1}\frac{C.\ G.\ M.\ V._{N_2}}{20.93}, \tag{41}$$

$$\theta=\tan^{-1}\frac{(O_2)_s}{100-Air_s-(N_2)_{add-s}}, \tag{42a}$$

$$=\tan^{-1}\frac{(Comb_1)\ [(O_2)_s]}{100\ (Comb_s)}, \tag{42b}$$

$$=\tan^{-1}\frac{(O_2)_s}{Gas_s}, \tag{42c}$$

$$\text{and } \Delta=180°-90°+\theta-\phi,$$

which by simplifying becomes

$$\Delta=90°-\phi+\theta. \tag{43}$$

By denoting the length of line $O-(P_4)_2$ as w, we can deduce the following equations:

$$w=\frac{\sin \phi\ (20.93)}{\sin \Delta}, \tag{44}$$

$$x=w \cos \theta, \tag{45a}$$

$$\text{and } y=w \sin \theta. \tag{46a}$$

If the expression for w as given by formula (44) is substituted in formulas (45a) and (46a), respectively, we obtain

$$x=\frac{\cos \theta \sin \phi\ (20.93)}{\sin \Delta}, \tag{45b}$$

$$\text{and } y=\frac{\sin \theta \sin \phi\ (20.93)}{\sin \Delta}. \tag{46b}$$

It has been shown that the length of line $J-(l_4)_2$ (fig. 5) is a measure of the minimum volume of nitrogen that must be admixed with atmosphere P_2 to form a mixture $(P_4)_2$ just incapable of forming an explosive mixture with air.

If we denote the diluent content of atmosphere $(P_4)_2$ as $(N_2)_{dil}$, which is also the volume (in percent) of nitrogen required to form atmosphere $(P_4)_2$ from atmosphere P_2, expressions whereby the value of $(N_2)_{dil}$ can be calculated are derived as follows:

If we let

$$(N_2)_{dil}=\text{the length of line } J-(l_4)_2, \text{ (fig. 5)},$$

then

$$(N_2)_{dil}=100-y \tan \tan^{-1} \frac{100}{20.93}-x,$$

which by simplifying becomes

$$(N_2)_{dil}=100-\frac{100y}{20.93}-x. \tag{47a}$$

By substituting the values of the x and y obtained in formulas (45b) and (46b) in formula (47a) and then simplifying, we obtain

$$(N_2)_{dil}=100-\frac{\sin \phi\ (100 \sin \theta+20.93 \cos \theta)}{\sin \Delta}. \tag{47b}$$

It needs to be added that if carbon dioxide is used as the diluent instead of nitrogen, the symbols $C.\ G.\ M.\ V._{N_2}$, $(N_2)_{add-s}$, and $(N_2)_{dil}$ in formulas (41), (42a), (47a), and (47b) become $C.\ G.\ M.\ V._{CO_2}$, $(CO_2)_{add-s}$, and $(CO_2)_{dil}$, respectively.

By calculating the real values of ϕ, θ, and Δ by formulas (41), (42a), and (43), and by substituting the trigonometric functions then obtainable, for the symbols in formula (44), and formulas (45a) and (46a) or (45b) and (46b), we can obtain real values for x, y, and $(N_2)_{dil}$ or $(CO_2)_{dil}$, as the case may be.

If the real value of the oxygen content (y) of any mixture that can be formed by admixing a given inert gas with a given original atmosphere is known or has been determined by formula (46*a*) or formula (46*b*), it is usually convenient to find the volume of inert gas required to form the mixture by means of formula (47*c*), which is given below.

Because the oxygen content (y) of a mixture formed by admixing a given inert gas with a given atmosphere is the volume of oxygen remaining after the inert gas is added, the following expression can be written whereby the amount of inert gas admixed with the given atmosphere to form the resultant mixture can be determined.

$$Inert\ gas_{dil}=\frac{[(O_2)_s-y]100}{(O_2)_s}. \qquad (47c)$$

where *inert gas*$_{dil}$=the volume (in percent) of inert gas (nitrogen or carbon dioxide) admixed with the given atmosphere to form the final mixture,

and the other symbols have the same meanings as before.

When formula (47*c*) is used to determine the volume of inert gas required to form an atmosphere from a given atmosphere, the difference between the real value of $(O_2)_s$ and the real value of y should be determined to at least two decimal places. Formula (47*c*) is useful for many practical purposes, particularly when determining graphically the volume of inert gas required to reduce the oxygen content of an atmosphere to any amount desired.

To form a definite atmosphere from a given atmosphere, we have considered the use of the given inert $_{gas}$ that is used as the diluent. As stated previously, the terms "additional inert gas" and "diluent" are synonomous. We will now consider formulas that have been derived for use when air or other possible gas mixtures are used for the foregoing purpose.

To avoid confusion, the term "*diluent*" will be understood to mean some other gas or gas mixture, such as is described below, that may be used to form a definite atmosphere from a given atmosphere.

Formulas having the same form as formula (47*c*) can be used, if applicable, to determine the volume of *diluent* or given inert gas that must be admixed with a given atmosphere to form a final atmosphere (*f. a.*), when the *diluent* is composed of (1) pure air, (2) pure gas having the composition of the air-free original atmosphere (atmosphere *J*, as in fig. 2), (3) a given inert gas (diluent), or (4) any combination of definite proportions of any two of the three portions that, by definition, constitute an atmosphere.

If a given inert gas (diluent) is used, or if the *diluent* is composed of fixed proportions of the given inert gas and pure gas ($Dil_{inert\ gas+gas}$), or if the pure gas (Dil_{gas}) is used, we can deduce from the graph form that

$$Inert\ gas_{dil}\text{ or }Dil_{inert\ gas+gas}\text{ or }Dil_{gas}=\frac{[(O_2)_s-(O_2)_{f.\ a.}]100}{(O_2)_s}, \qquad (47c\text{-}1)$$

where $(O_2)_{f.\ a.}$ is the oxygen content of the final atmosphere formed.

If the *diluent* is composed of the pure gas (Dil_{gas}), the pure gas plus air ($Dil_{gas+air}$), or pure air (Dil_{air}), we have

$$Dil_{gas}\text{ or }Dil_{gas+air}\ on\ Dil_{air}=\frac{(Inert\ gas_{add-s}-Inert\ gas_{add-f.\ a.})100}{Inert\ gas_{add-s}}, \qquad (47c\text{-}2)$$

where $Inert\ gas_{add-s}$ and $Inert\ gas_{add-f.\ a.}$ = the additional inert-gas (diluent) contents of the given atmosphere and final atmosphere, respectively.

If the *diluent* is composed of pure air (Dil_{air}), additional inert gas plus air ($Dil_{inert\ gas+air}$), or the given diluent ($Inert\ gas_{dil}$), we have

$$Dil_{air} \text{ or } Dil_{inert\ gas+air} \text{ or } Inert\ gas_{dil} = \frac{(Gas_s - Gas_{f.\ a.})100}{Gas_s}, \qquad (47c\text{-}3)$$

where $Gas_{f.\ a.}$ = the gas-portion content (in percent) of the final atmosphere formed.

It will be observed that the volume of inert gas necessary to form an atmosphere from a given atmosphere can be determined by formula (*47c*), (*47c–1*), or (*47c–3*) when the inert gas used ($Inert\ gas_{dil}$) is the same kind as the diluent.

The following examples will serve to show the application of formulas (41) to (47*c*), inclusive.

Example 1.—An original atmosphere as sampled is composed (by constituents) of 35 percent of combustible gases consisting of 11.67 percent each of carbon monoxide, methane, and hydrogen, 3 percent of oxygen, and 62 percent of nitrogen. This atmosphere corresponds to point P_2 (fig. 5, pocket) and is composed (by portions) of 11.67 percent each of carbon monoxide, methane, and hydrogen and 50.67 percent nitrogen (the gas portion), and 14.33 percent air (the air portion).

Example 2.—An atmosphere as sampled is composed of 35 percent of combustible gases consisting of 11.67 percent each of carbon monoxide, methane, and hydrogen; 14.33 percent of air, of which 3 percent is oxygen and 11.33 percent nitrogen; and 50.67 percent of additional nitrogen (diluent). This atmosphere corresponds to point P_1 (figs. 3 and 4, pocket) and has been formed by admixing 50.67 percent of nitrogen with atmosphere P_3 (fig. 4).

It is observed that although atmosphere P_2 (fig. 5) and atmosphere P_1 (fig. 4) have identical chemical compositions, they have been formed from different air-free original atmospheres. Figures 4 and 5 therefore represent different sets of conditions in which the air-free original atmospheres have different compositions, are considered as 100 percent, and correspond to atmosphere J in the graphs.

We desire to know the minimum volume of a given inert gas (nitrogen) that must be admixed with a given atmosphere to form an atmosphere just incapable of forming explosive mixtures with air. The first step in the procedure is to determine the composition of the air-free original atmosphere (J) relating to the given atmosphere, as follows:

Example 1.—Because the atmosphere sampled (P_2, fig. 5) is an original atmosphere formed by admixing air with the air-free original atmosphere (J), atmosphere P_2 is diluent-free.

By substituting the real values given above for the symbols in formulas (1), (2), (3), and (4*b*), we find

$$Air_s = \frac{3 \times 100}{20.93} = 14.33 \text{ percent of air,} \qquad (1)$$

$$K_s = 100 - 14.33 = 85.67 \text{ percent of gases other than air,} \quad (2)$$

$$Combustible\ gases_{air\text{-}free} = \frac{35 \times 100}{85.67} = 40.85$$ percent of combustible gases consisting of equal percentages of carbon monoxide, methane, and hydrogen, 13.62 percent each of carbon or monoxide, methane, and hydrogen,

$$\text{and}\quad Nitrogen_{air\text{-}free}=\frac{(62.00-14.33+3.00)\times100}{85.67}, \tag{4b}$$

$$=\frac{50.67\times100}{85.67}=59.15 \text{ percent of nitrogen.}$$

Summarizing the above data, the composition of the air-free original atmosphere (*J*, fig. 5) is 13.62 percent each of carbon monoxide, methane, and hydrogen, and 59.15 percent nitrogen.

EXAMPLE 2.—The atmosphere sampled (P_1, fig. 4) consists of 35 percent of combustible gases, 3 percent of oxygen, and 62 percent of nitrogen. By calculations similar to those used for example 1, atmosphere P_1 is found to consist of 14.33 percent of air, of which 11.33 percent is nitrogen; and 85.67 percent of other gases, of which 35 percent is combustible gas and 50.67 percent is additional nitrogen (diluent).

According to the composition (by portions) of atmosphere P_1, as shown in figure 4, it can be assumed to be formed by admixing nitrogen with an original atmosphere (P_3) consisting of combustible gases and air.

Therefore, the air-free original atmosphere (*J*) must have a composition identical to that of atmosphere P_1 calculated to a diluent-free air-free basis.

Because the diluent-portion content of atmosphere P_1 is 50.67 percent of the whole, the diluent-free composition of atmosphere P_1 and the composition of atmosphere P_3 are identical.

We now find the composition (by portions) of atmosphere P_3 by dividing the real values of the gas-portion and air-portion contents of atmosphere P_1 by (100−50.67) percent and then multiplying each of the quotients by 100. The gas-portion content of atmosphere P_3 is

$$\frac{35\times100}{49.33}=70.95 \text{ percent of combustible gases,}$$

or 23.65 percent each of carbon monoxide, methane, and hydrogen; and the air-portion content is

$$\frac{14.33\times100}{49.33}=29.05 \text{ percent of air, of which 7.08 percent is oxygen and 21.97 percent is nitrogen.}$$

The composition of the air-free original atmosphere (*J*, figs. 3 and 4) is found by substituting the real values of the air-portion and gas-portion contents of atmosphere P_3, found above, for the symbols in formulas (2) and (3), or

$$K_s=100-29.05=70.95 \text{ percent,} \tag{2}$$

$$\text{and}\quad Atmosphere\ (P_3)_{air\text{-}free}=\frac{70.95\times100}{70.95}, \tag{3}$$

$$=100 \text{ percent of combustible gases, or 33.33+ percent each of carbon monoxide, methane, and hydrogen.}$$

Summarizing the above data, the composition (by portions) of atmosphere P_3 (fig. 4) is 70.95 percent of the composition of atmosphere *J* (the gas portion) and 29.05 percent of air (the air portion). Its composition (by constituents) is 23.65 percent each of carbon monoxide, methane, and hydrogen, 7.08 percent of oxygen, and 21.97 percent of nitrogen. The composition (by portions) of the air-free original atmosphere (*J*, fig. 4) is 100 percent of combustible gases (the gas portion). Because the air-portion and diluent-portion contents are zero, the composition (by constituents) of atmosphere *J* is 33.33+ percent each of carbon monoxide, methane, and hydrogen.

The next step in the procedure is to calculate the critical gas-mixture values ($C.\ G.\ M.\ V._{N_2}$) relating to their respective air-free original atmospheres.

Because no carbon dioxide is present in either atmosphere P_2, (fig. 5) or atmosphere P_1, (fig. 4) all the combustible gases are paired with nitrogen, and formula (10), page 25, is used in the following form:

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{5.15A_1+7B_1+17.55(H_2)_1}\ .$$

By substituting the real values applying to the air-free original atmospheres for the symbols in formula (10), we find for example 1, page 70, when $A_1=B_1=(H_2)_1=13.62$ percent, that

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{(5.15\times 13.62)+(7\times 13.62)+(17.55\times 13.62)},$$

$$=\frac{10{,}000}{404.34}=24.73$$ percent, the critical gas mixture value, relating to atmosphere *J* (fig. 5);

and for example 2, when $A_1=B_1=(H_2)_1=33.33+$ percent, that

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{(5.15\times 33.33)+(7\times 33.33)+(17.55\times 33.33)},$$

$$=\frac{10{,}000}{989.90}=10.10$$ percent, the critical gas-mixture value, relating to atmosphere *J* (fig. 4).

It is of interest to show that the critical gas mixtures relating to the above-given critical gas-mixture values must have the same chemical composition, although the critical gas-mixture values are expressed by different real numbers, because each belongs to a different air-free original atmosphere and is shown in a different figure (figs. 4 and 5).

The composition of the gas portion of the critical gas mixture for both examples can be calculated by substituting the real values given above for the symbols in formula (22*A*), page 31, which is

$$Constituent\ C.\ G.\ M.=k\ (Constituent_{air-free}). \qquad (22A)$$

The arithmetical calculations are omitted, but the results of them and related factors are tabulated on page 74.

The nitrogen content of the gas portion of the critical gas mixture can also be calculated directly by formula (39), page 62, if no carbon dioxide is present in the air-free original atmosphere.

Because no carbon dioxide is present in both air-free original atmospheres (*J*, figs. 4 and 5), and both critical gas mixtures are considered as the atmospheres sampled, the nitrogen content of the gas portion of both critical gas mixtures is found as follows:

Example 1.—From the data previously determined and summarized on page 74, we obtain
$(Inert)_1=59.15$, $(Comb)_s=10.10$, and $(Comb)_1=40.85$ percent.
Substituting these real values for the symbols in formula (39), we find

$$(Inert)_{gp-s}=\frac{\left[\frac{(Inert)_1}{100}\right][(Comb)_s]}{\frac{(Comb)_1}{100}}, \qquad (39)$$

$$=\frac{0.5915\times 10.10}{40.85}=14.63$$ percent of nitrogen, the nitrogen content of the gas portion of the critical gas mixture (atmosphere *C. G. M. V.*, fig. 5).

EXAMPLE 2.—From page 74, we obtain

$(Inert)_1=0.00$, $(Comb)_s=10.10$, and $(Comb)_1=100.00$ percent.

Substituting these real values for the symbols in formula (39), we find

$(Inert)_{gv-s}=\frac{0.00\times 10.10}{100}=0.00$ percent, which signifies that no nitrogen is present in the gas portion of the critical gas mixture (atmosphere Q, fig. 4).

The diluent content of the critical gas mixture can often by obtained from data such as that previously determined and tabulated on page 74. However, this factor can always be calculated by means of formula (22*B*) or by formulas (39) and (40) when the critical gas mixture is considered as the atmosphere sampled. The following calculations show the procedure employed to determine the diluent content of the critical gas mixture by formula (22*B*) and by formulas (39) and (40).

From the data previously determined and summarized on page 74, we obtain, for example 1,

$(Inert)_{gv-s}=14.63$, $C.\ G.\ M.\ V._{N2}=24.73$, $(N_2)_{ts}=89.90$,

$(CO_2)_{ts}=0.00$, and $(O_2)_s=0.00$ percent.

By substituting the real values for the symbols in formula (22*B*), we find

$$Dil_{C.\ G.\ M.}=100-C.\ G.\ M.\ V._{N_2}, \qquad (22B)$$

$=100-24.73=75.27$ percent of nitrogen, the diluent content of the critical gas mixture (atmosphere *C. G. M. V.*, fig. 5).

By means of formula (40), we find

$$(N_2)_{add-s}=Dil_{C.\ G.\ M.}=(N_2)_{ts}+(CO_2)_{ts}-(Inert)_{gv-s}-3.78\ (O_2)_s, \qquad (40)$$

$$=89.90+0.00-14.63-(3.78\times 0.00),$$

$=75.27$ percent of nitrogen, as above.

In the same manner, for example 2, we find by substituting the pertinent real values for the symbols in formula (22*B*),

when $(Inert)_{gv-s}=0.00$, $C.\ G.\ M.\ V._{N2}=10.10$, $(N_2)_{ts}=89.90$, $(CO_2)_{ts}=0.00$, and

$(O_2)_s=0.00$ percent,

that $Dil_{C.\ G.\ M.}=100-10.10=89.90$ percent of nitrogen, the diluent content of the critical gas mixture (atmosphere Q, fig. 4).

By means of formula (40), we find

$$(N_2)_{add-s}=Dil_{C.\ G.\ M.}=89.90+0.00-0.00-(3.78\times 0.00), \qquad (40)$$

$=89.90$ percent of nitrogen, as above.

It was stated on page 65 that to determine whether the line corresponding to mixtures formed by admixing a given inert gas with a given atmosphere passes above or below the point corresponding to the nose-limit mixture, it is necessary to calculate the oxygen content of the nose-limit mixture.

Because the chemical compositions of the nose-limit mixtures relating to the atmospheres given in examples 1 and 2 (p. 70) are identical, the oxygen content of both nose-limit mixtures is 7.8 percent. (*See* pp. 60 and 61.)

Because the oxygen content of atmospheres P_1 (fig. 4) and P_2 (fig. 5) is 3 percent, the lines corresponding to the mixtures formed by admixing nitrogen with each of these atmospheres pass below the nose, and the procedure described on pages 64 to 69, inclusive, is employed.

The following table summarizes the calculations made on pages 70 to 74, inclusive, in the procedure employed to determine the respective minimum amounts of nitrogen that must be admixed with atmospheres P_2 (fig. 5) and P_1 (fig. 4) to form atmospheres $(P_4)_2$ (fig. 5) and $(P_4)_1$ (fig. 4), respectively, which have identical chemical compositions and are incapable of forming explosive mixtures with air.

Composition of atmospheres sampled, of air-free original atmospheres, and of critical gas mixtures and related critical gas-mixture values

Constituent	Composition of atmospheres (percent)					
	Example 1 (see fig. 5)			Example 2 (see fig. 4)		
	Atmosphere sampled (P_2)	Air-free original atmosphere (J)	Critical gas mixture ($C. G. M. V.$)	Atmosphere sampled (P_1)	Air-free original atmosphere (J)	Critical gas mixture (Q)
Gas portion:						
Carbon monoxide	11.67−	13.62−	3.37−	11.67−	33.33+	3.37−
Methane	11.67−	13.62−	3.37−	11.67−	33.33+	3.37−
Hydrogen	11.67−	13.62−	3.37−	11.67−	33.33+	3.37−
Total combustible gases	35.00	40.85	10.10	35.00	100.00	10.10
Nitrogen (total inert gas)	50.67	59.15	14.63	.00	.00	.00
Total	85.67	100.00	24.73	35.00	100.00	10.10
Air portion:						
Air	14.33	.00	.00	14.33	.00	.00
Oxygen	3.00	.00	.00	3.00	.00	.00
Nitrogen	11.33	.00	.00	11.33	.00	.00
Diluent portion: Additional nitrogen	.00	.00	75.27	50.67	.00	89.90
Total nitrogen	62.00	59.15	89.90	62.00	.00	89.90
Critical gas-mixture value ($C. G. M. V._{N_2}$)			24.73			10.10
k			.2473			.1010

Having determined the critical gas-mixture values and other related factors shown in the preceding table, the next step in the procedure is to determine the real values of the rectangular coordinates (x and y) that determine the positions of the points corresponding to atmosphere $(P_4)_2$, (fig. 5) and atmosphere $(P_4)_1$, (fig. 4). Formulas (41) to (44), inclusive (45*a*), and (46*a*) are used for this purpose. The detailed arithmetical calculations are omitted; however, the following table summarizes the calculated data:

Summary of calculations to determine real values of rectangular coordinates (x and y) establishing positions of atmospheres $(P_4)_2$, (fig. 5) and $(P_4)_1$ (fig. 4), respectively, which are incapable of forming explosive mixtures with air and have been formed by admixing minimum amount of nitrogen with atmospheres sampled

Symbol	Formula used, or number designating same	Example 1 (fig. 5)		Example 2 (fig. 4)	
		Calculations	Real value[1]	Calculations	Real value[1]
$C.G.M.V._{N_2}$	(10)	See table, p. 74	24.73	See table, p. 74	10.10.
$(O_2)_s$	(by analysis)		Atmos. P_2 3.00		Atmos. P_1 3.00.
Air_s	(1)		14.33		14.33.
$(N_2)_{add-s}$	(40)		.00		50.67.
ϕ	$=\tan^{-1}\frac{C.G.M.V._{N_2}}{20.93}$ (41)	$\tan^{-1}\frac{24.73}{20.93}$	49°45½′	$\tan^{-1}\frac{10.10}{20.93}$	25°45′40″.
θ	$=\tan^{-1}\frac{(O_2)_s}{100-Air_s-(N_2)_{add-s}}$ (42a)	$\tan^{-1}\frac{3}{85.67}$	2°00′20″	$\tan^{-1}\frac{3}{35}$	4°54′.
Δ	$=90°-\phi+\theta$ (43)	90°−49°45½′+2°00′20″	42°14′50″	90°−25°45′40″+4°54′	69°08′20″.
w	$=\frac{\sin\phi\,(20.93)}{\sin\Delta}$ (44)	$\frac{0.76332\times20.93}{0.67233}$	23.76	$\frac{0.43458\times20.93}{0.93445}$	9.74.
x	$=w\cos\theta$ (45a)	23.76×0.99939	Atmos. $(P_4)_2$ 23.74	9.74×0.99635	Atmos. $(P_4)_1$ 9.70.
y	$=w\sin\theta$ (46a)	23.76×0.035	.83	9.74×0.08542	.83.

---

[1] Real value in percent, unless shown otherwise.

Having determined the above-given real values of x and y, it is not strictly necessary to know the chemical compositions of atmospheres $(P_4)_2$ and $(P_4)_1$ to calculate the volumes of nitrogen required to form these atmospheres from atmospheres P_2 (fig. 5) and P_1, (fig. 4), respectively However, it is necessary to know the compositions of atmospheres $(P_4)_2$ and $(P_4)_1$, particularly by portions, to understand clearly the mathematical procedure on which the graphic determination of the above factors is based; this is simple once understood. For these reasons, the procedure employed to calculate the compositions of atmospheres $(P_4)_2$ (fig. 5), and $(P_4)_1$, (fig. 4), is discussed in detail.

It was shown on page 66 that the real values of x and y, as given on page 75, express the gas-portion and oxygen contents (in percent) of atmospheres $(P_4)_2$, (fig. 5) and $(P_4)_1$, (fig. 4). Therefore, the gas-portion contents (x) of atmospheres $(P_4)_2$ and $(P_4)_1$ are 23.74 and 9.70 percent, respectively, and the oxygen content (y) of both atmospheres is 0.83 percent.

Because the real value of the gas-portion content of an atmosphere defines the volume (in percent) of the air-free original atmosphere present in that atmosphere, we find the composition (by constituents) of the gas portion by multiplying the percentages of the constituents composing the air-free original atmosphere by the real value of the gas-portion content, expressed as a decimal fraction.

Applying the foregoing procedure to example 1 by using the above-given real value of the gas-portion content and the composition values of the air-free original atmosphere given on page 74, we find the composition of the gas portion of atmosphere $(P_4)_2$ (fig. 5), as follows:

$$\begin{aligned}\text{Carbon monoxide} &= 0.2374\times 13.62 = 3.23+ \text{ percent.}\\ \text{Methane} &= 0.2374\times 13.62 = 3.23+ \text{ percent.}\\ \text{Hydrogen} &= 0.2374\times 13.62 = 3.23+ \text{ percent.}\\ \text{Nitrogen} &= 0.2374\times 59.15 = 14.04 \text{ percent.}\end{aligned}$$

Similarly, for example 2, we find the composition of the gas portion of atmosphere $(P_4)_1$ (fig. 4) to be

$$\begin{aligned}\text{Carbon monoxide} &= 0.097\times 33.33+ = 3.23+ \text{ percent.}\\ \text{Methane} &= 0.097\times 33.33+ = 3.23+ \text{ percent.}\\ \text{Hydrogen} &= 0.097\times 33.33+ = 3.23+ \text{ percent.}\\ \text{Nitrogen} &= 0.097\times 0.00 \text{ percent.}\end{aligned}$$

Because the oxygen content of both atmosphere $(P_4)_2$ and atmosphere $(P_4)_1$ is 0.83 percent, the air-portion contents of these atmospheres are identical and are found by formula (1) to be

$$\text{Air} = \frac{0.83\times 100}{20.93} = 3.97 \text{ percent, of which 0.83 percent is oxygen and 3.14 percent is nitrogen.}$$

Finally, having determined the real values of x and y, the diluent contents of atmospheres $(P_4)_2$ and $(P_4)_1$ can be calculated by means of formula (47*a*), page 68.

By substituting the real values of x and y, as given on page 75, for the symbols in formula (47*a*), we find the diluent content of atmosphere $(P_4)_2$, example 1, to be

$$(N_2)_{dil} = 100 - \frac{100\ (0.83)}{20.93} - 23.74 \qquad (47a)$$

$$= 100 - 3.96 - 23.74 = 72.29 \text{ percent of nitrogen (diluent);}$$

and for atmosphere $(P_4)_1$, example 2,

$$(N_2)_{dil}=100-\frac{100\ (0.83)}{20.93}-9.70$$

$$=86.33 \text{ percent of nitrogen (diluent).}$$

A summary of the foregoing calculations relating to the compositions of atmospheres $(P_4)_2$ and $(P_4)_1$ as well as other factors is given on page 79.

It is observed in that summary and the calculations just given that, although atmospheres $(P_4)_2$ and $(P_4)_1$ have identical chemical compositions (by constituents), atmosphere $(P_4)_2$ (fig. 5) has a diluent content of 72.29 percent of nitrogen, whereas atmosphere $(P_4)_1$, (fig. 4) has a diluent content of 86.33 percent of nitrogen. This difference in the diluent content of atmospheres that have identical chemical compositions is a fundamental in the graphic method of determining the various factors on explosibility pertaining to such atmospheres. This is discussed later in detail.

As the final step in the procedure employed to determine the volumes of nitrogen that must be admixed with atmosphere P_2 (fig. 5) to form atmosphere $(P_4)_2$, and with atmosphere P_1 (fig. 4) to form atmosphere $(P_4)_1$, we first recognize the following relationships pertaining to these atmospheres:

As the atmospheres sampled (P_2 and P_1) have identical chemical compositions, it is obvious that the same volume of a given inert gas must be admixed with each to form atmospheres that have identical chemical compositions and that cannot form explosive mixtures with air.

Having previously determined the real values of the gas-portion content (x) and the oxygen content (y), respectively, of both atmosphere $(P_4)_2$ and atmosphere $(P_4)_1$, which have identical chemical compositions and are incapable of forming explosive mixtures with air, we can determine the respective volumes of the given inert gas (nitrogen) that must be admixed with atmospheres P_2 (fig. 5) and P_1 (fig. 4) to form them. Formula (47*c*), (47*c*–1), or (47*c*–3) can be used for this purpose.

We next obtain the real values pertaining to example 1 and atmospheres P_2 and $(P_4)_2$ (fig. 5) from the data tabulated on pages 74 and 75 as follows:

$y=0.83$ percent, the oxygen content of atmosphere $(P_4)_2$;

$x=Gas_{f.a.}=23.74$ percent, the gas-portion content of atmosphere $(P_4)_2$;

$(O_2)_s=3.00$ percent, the oxygen content of atmosphere P_2;

$Gas_s=85.67$ percent, the gas-portion content of atmosphere P_2.

By substituting the pertinent real values for the symbols in formulas (47*c*) or (47*c*–3), we find

$$Inert\ gas_{dil}=\frac{[(O_2)_s-y]\ 100}{(O_2)_s}, \qquad (47c)$$

$$=\frac{(3-0.83)\times 100}{3},$$

$$=72.29 \text{ percent of nitrogen,}$$

or

$$Inert\ gas_{dil} = \frac{(Gas_s - Gas_{f.a.})\ 100}{Gas_s}, \qquad (47c\text{–}3)$$

$$= \frac{(85.67 - 23.74) \times 100}{85.67},$$

= 72.29 percent of nitrogen, the volume of nitrogen that must be admixed with atmosphere P_2 (fig. 5) to form atmosphere $(P_4)_2$.

Similarly, for example 2 and atmospheres P_1 and $(P_4)_1$ (fig. 4) we obtain

$y = 0.83$ percent, the oxygen content of atmosphere $(P_4)_1$;

$x = Gas_{f.a.} = 9.70$ percent, the gas-portion content of atmosphere $(P_4)_1$;

$(O_2)_s = 3.00$ percent, the oxygen content of atmosphere P_1;

$Gas_s = 35.00$ percent, the gas-portion content of atmosphere P_1.

Because the oxygen contents of both atmosphere P_2 and atmosphere P_1 are the same, and because the oxygen contents of both atmosphere $(P_4)_2$ and atmosphere $(P_4)_1$ are also the same, the calculations and result by formula (47*c*) when applied to example 2 would be the same as shown for example 1.

By substituting the pertinent real values for the symbols in formula (47*c*–3), we find

$$Inert\ gas_{dil} = \frac{(35.00 - 9.70) \times 100}{35}, \qquad (47c\text{–}3)$$

= 72.29 percent of nitrogen, the volume of nitrogen that must be admixed with atmosphere P_1 (fig. 4) to form atmosphere $(P_4)_1$.

The foregoing calculations and data tabulated previously show that the chemical compositions of atmospheres $(P_4)_2$ and $(P_4)_1$, formed by admixing 72.29 percent of nitrogen with atmospheres P_2 and P_1, respectively, are identical.

The following summary shows the relations existing between the atmospheres as sampled, or P_2 (fig. 5, example 1) and P_1 (fig. 4, example 2), and the final atmospheres [$(P_4)_2$, fig. 5] and [$(P_4)_1$, fig. 4], respectively, when the final atmospheres are formed by admixing the same volume of nitrogen with the atmosphere sampled in each example.

Relationship between atmospheres sampled (P_2 and P_1) and final atmospheres formed by admixing a definite amount (72.29 percent) of nitrogen with each atmosphere sampled

Constituent	Composition of atmospheres (percent)					
	Example 1			Example 2		
	Atmosphere sampled (P_2, fig. 5)	Nitrogen added (effect + or −)	Atmosphere formed by adding nitrogen ($(P_4)_2$, fig. 5)	Atmosphere sampled (P_1, fig. 4)	Nitrogen added (effect + or −)	Atmosphere formed by adding nitrogen ($(P_4)_1$, fig. 4)
Gas portion:						
Carbon monoxide	11.67	−8.43	3.23+	11.67	−8.43	3.23+
Methane	11.67	−8.43	3.23+	11.67	−8.43	3.23+
Hydrogen	11.67	−8.43	3.23+	11.67	−8.43	3.23+
Nitrogen	50.67	−36.63	14.04	.00	.00	.00
Total	85.67	−61.93	23.74 = x	35.00	−25.30	9.70 = x
Air portion:						
Air	14.33	−10.36	3.97	14.33	−10.36	3.97
Oxygen	3.00	−2.17	.83 = y	3.00	−2.17	.83 = y
Nitrogen	11.33	−8.19	3.14	11.33	−8.19	3.14
Diluent portion:						
Additional nitrogen from diluent in atmosphere sampled	.00	.00	.00	50.67	−36.63	14.04
Nitrogen added	.00	+72.29	72.29	.00	+72.29	72.29
Total	.00	+72.29	72.29	50.67	+35.66	86.33
Total nitrogen	62.00	+27.47	89.47	62.00	+27.47	89.47

RELATIONSHIP BETWEEN DILUENT CONTENT OF ATMOSPHERE FORMED FROM ANOTHER AND VOLUME OF GIVEN INERT GAS USED FOR THAT PURPOSE

A study of the data on page 74 and above and of figures 4 and 5 (pocket) shows that the mathematical and graphic methods for determining the composition of an atmosphere formed from a given atmosphere (atmosphere sampled) as well as those for determining the volume of a given inert gas required to form that atmosphere depend on the diluent-free air-free composition of the atmosphere sampled, or composition of the air-free original atmosphere.

The relations between the analytical properties of the formulas for determining the above-mentioned factors and the geometrical properties of the figures furnish the fundamental basis for establishing the position of an atmosphere in the graph, regardless of whether the factors relating to the composition of the atmosphere are given or are determined mathematically or graphically. Furthermore, the diluent content of an atmosphere formed by admixing a given inert gas with a given atmosphere may or may not be the volume of inert gas used for that purpose. It is understood in this discussion that the inert gas used as the diluent of the air-free original atmosphere and the given inert gas admixed with a given atmosphere to form another are of the same kind.

A question frequently asked is: Why can formula (47*a*) or formula (47*b*) be used to calculate the volume of inert gas required to form an atmosphere from another in some problems and not be used for this purpose in others? As an explanation of the reasons for this is also the explanation of the mathematical basis of the procedure for using a graph to determine the volume of inert gas required to form an atmosphere from another, a discussion on these reasons is given in detail.

The reasons why neither formula (47*a*) nor formula (47*b*) can always be used to determine the volume of inert gas required to form an atmosphere from another are because of (1) the different ways by which the atmosphere sampled may be formed and (2) the design of the graph form used to derive the formulas for determining the factors relating to the composition of an atmosphere as well as used to express these factors graphically. Formulas (47*a*) and (47*b*), page 68, are used specifically to determine the diluent content of an atmosphere and can be used whenever the gas-portion content and the oxygen content of the atmosphere are known. They cannot be used to calculate the volume of inert gas required to form an atmosphere from a given atmosphere, unless the given atmosphere is considered as an original atmosphere, which, be definition, is diluent-free.

To clarify the foregoing statements, we can use example 2, page 74, relating to atmospheres P_1 and $(P_4)_1$ (figure 4). If it is desired to use either formula (47*a*) or formula (47*b*) to determine the diluent content of atmosphere $(P_4)_1$ so that it will also be the volume of nitrogen that must be admixed with atmosphere P_1 to form atmosphere $(P_4)_1$, the procedure employed is to consider point P_1, (figs. 3 and 4) as occupying the position of point P_2 in figure 5. When this is done, the volume of diluent determined by formula (47*a*) or formula (47*b*) is the volume of nitrogen required to form atmosphere $(P_4)_2$ from atmosphere P_2 or to form atmosphere $(P_4)_1$ from atmosphere P_1, as well as being the volume of diluent present in either atmosphere $(P_4)_2$ or atmosphere $(P_4)_1$. This relationship applies specifically to example 1, p. 74), where the volume of inert gas required to form atmosphere $(P_4)_2$ from atmosphere P_2 is 72.29 percent of nitrogen, which is also the diluent content of atmosphere $(P_4)_2$ (fig. 5).

If the procedure just stated is not employed and the atmosphere sampled (example 2) is considered as occupying the position of point P_1 (figs. 3 and 4), the volume of nitrogen required to form atmosphere $(P_4)_1$ from atmosphere P_1 would not be 86.33 percent of nitrogen, found by using formula (47*a*), page 68. The volume of nitrogen required for this purpose is 72.29 percent, as found on page 78 by formula (47*c*-3). In this instance, 86.33 percent of nitrogen is the diluent content of atmosphere $(P_4)_1$, and also the minimum volume of nitrogen that must be admixed with original atmosphere P_3 (fig. 4) to form an atmosphere having the same chemical composition as either atmosphere $(P_4)_1$ (fig. 4) or atmosphere $(P_4)_2$ (fig. 5). The result obtained by using formula (47*a*) is not an error. The foregoing explanation demonstrates the necessity of interpreting the calculations correctly and explains the utility of a graph for determining graphically (1) the diluent content of an atmosphere and (2) the volume of diluent required to form that atmosphere from a given atmosphere.

METHOD OF CALCULATING VOLUME OF CARBON DIOXIDE REQUIRED AS A DILUENT

The danger from explosions at coal-mine fires is present to some degree during the early stages of an active fire and when a mine-fire area is being sealed. The possibility of an explosion constitutes an ever-present hazard while the seals are being constructed and after the area is sealed, until the oxygen content of the portion of the atmosphere surrounding the active fire is reduced to less than the critical oxygen value of the air-free original atmosphere.

In a gassy mine in which a fire is burning, the race between methane accumulation and oxygen depletion often cannot be controlled with any degree of certainty. When it does appear possible, the problem of control constantly faces those fighting a fire.

Displacement of mine-fire gases, a potentially explosive mixture, or an explosive atmosphere by an inert gas is something to be desired (*3*, *24*). Carbon dioxide (*11*, *12*) is desirable for this purpose, and it appears possible that many mine fires can be controlled or even extinguished; and explosions can be prevented in many instances (*20*) by the use of "dry ice," if enough carbon dioxide can be placed in the fire area at the critical time. (See p. 93.)

For the above-given reasons, the authors have derived the formulas necessary for calculating the various factors relating to the explosibility of atmospheres consisting of carbon monoxide, methane, hydrogen, nitrogen, carbon dioxide, and air, when carbon dioxide is used as the diluent. The procedure employed to derive the formulas is the same as that employed when nitrogen is used as the diluent.

DETERMINATION OF CRITICAL GAS-MIXTURE VALUE AND NOSE LIMIT WITH CARBON DIOXIDE AS DILUENT

The formulas for calculating the critical gas-mixture value ($C.\ G.\ M.\ V._{CO_2}$) and the nose limit ($L_{nose\text{-}CO_2}$) when carbon dioxide is used as the diluent follow. The symbols have the same meanings as before:

Case 1

When neither nitrogen nor carbon dioxide is present in an air-free original atmosphere that consists of carbon monoxide, methane, and hydrogen, we deduce that

$$C.\ G.\ M.\ V._{CO_2}=\frac{10{,}000}{3.16A_1+4.20B_1+11.20(H_2)_1}, \tag{48}$$

and

$$L_{nose\text{-}CO_2}=\frac{3.16A_1+4.20B_1+11.20(H_2)_1}{\frac{3.16A_1}{58.0}+\frac{4.20B_1}{28.0}+\frac{11.20(H_2)_1}{59.5}}. \tag{49}$$

Whether or not carbon dioxide is present in the air-free original atmosphere in case 1 or in the subsequent cases makes no difference in the derivation or application of the formulas. The net effect of the presence of carbon dioxide in the air-free original atmosphere is to decrease the amount of carbon dioxide required as diluent.

Case 2

When nitrogen is present in the air-free original atmosphere in an amount such that $4.15A_1 < (N_2)_1$, part of the nitrogen $(N_2)_1$ is paired with all the carbon monoxide (A_1) and the nitrogen remaining is paired with part of the methane (B_1). The methane remaining is paired with carbon dioxide. In this case

$$C.\ G.\ M.\ V._{CO_2}=\frac{10{,}000}{3.21A_1+4.2B_1+11.2(H_2)_1+0.467(N_2)_1}, \tag{50}$$

and

$$L_{nose-CO_2}=\frac{3.21A_1+4.2B_1+11.2(H_2)_1+0.467(N_2)_1}{0.0596A_1+\frac{4.2B_1}{28.0}+\frac{11.2(H_2)_1}{59.5}+0.00311(N_2)_1}. \tag{51}$$

Case 3

When nitrogen is present in the air-free original atmosphere in an amount such that $4.15A_1 > (N_2)_1$, all the nitrogen $(N_2)_1$ is paired with part of the carbon monoxide (A_1) and the carbon monoxide remaining is paired with carbon dioxide. In this case

$$C.\ G.\ M.\ V._{CO_2}=\frac{10{,}000}{3.16A_1+4.2B_1+11.2(H_2)_1+0.479(N_2)_1}, \tag{52}$$

and

$$L_{nose-CO_2}=\frac{3.16A_1+4.2B_1+11.2(H_2)_1+0.479(N_2)_1}{\frac{3.16A_1}{58.0}+\frac{4.2B_1}{28.0}+\frac{11.2(H_2)_1}{59.5}+0.00435(N_2)_1}. \tag{53}$$

If carbureted water gas is the original atmosphere under consideration, this fuel gas may contain ethylene, propylene, and ethane in addition to the above-named gases. To determine the critical gas-mixture value ($C.\ G.\ M.\ V._{CO_2}$) and the nose limit ($L_{nose-CO_2}$) of an atmosphere having the air-free composition of this fuel gas when

$$4.15A_1 > (N_2)_1,$$

the formulas applying to such an atmosphere have the form of formulas (52) and (53) and are

$$C.\ G.\ M.\ V._{CO_2}=\frac{10{,}000}{3.16A_1+4.2B_1+11.2(H_2)_1+10.1(C_2H_4)_1+8.8(C_3H_6)_1+8.4(C_2H_6)_1+0.479(N_2)_1}, \tag{52a}$$

and

$$L_{nose-CO_2}=\frac{3.16A_1+4.2B_1+11.2(H_2)_1+10.1(C_2H_4)_1+8.8(C_3H_6)_1+8.4(C_2H_6)_1+0.479(N_2)_1}{\frac{3.16A_1}{58.0}+\frac{4.2B_1}{28.0}+\frac{11.2(H_2)_1}{59.5}+\frac{10.1(C_2H_4)_1}{43.0}+\frac{8.8(C_3H_6)_1}{31.2}+\frac{8.4(C_2H_6)_1}{35.7}+0.00435(N_2)_1}. \tag{53a}$$

Case 4

Although it is desirable first to pair the nitrogen in the air-free original atmosphere with carbon monoxide if carbon monoxide is present, there may be occasions when nitrogen is present in such volume that $6B_1 < (N_2)_1$ and $(6B_1 + 4.15A_1) > (N_2)_1$, in which case all the methane (B_1) is paired with part of the nitrogen $(N_2)_1$, and the nitrogen remaining is paired with part of the carbon monoxide (A_1). The carbon monoxide remaining is paired with carbon dioxide. In this case

$$C.\ G.\ M.\ V._{CO_2} = \frac{10{,}000}{3.16A_1 + 4.12B_1 + 11.2(H_2)_1 + 0.479(N_2)_1}, \tag{54}$$

and

$$L_{nose-CO_2} = \frac{3.16A_1 + 4.12B_1 + 11.2(H_2)_1 + 0.479(N_2)_1}{\frac{3.16A_1}{58.0} + 0.1426B_1 + \frac{11.2(H_2)_1}{59.5} + 0.00435(N_2)_1}. \tag{55}$$

Case 5

When nitrogen is present in the air-free original atmosphere in such an amount that $6B_1 > (N_2)_1$, and carbon monoxide is absent or present in very small volume, all the nitrogen $(N_2)_1$ is paired with part of the methane (B_1), and the methane remaining and all the carbon monoxide are paired with carbon dioxide. In this case

$$C.\ G.\ M.\ V._{CO_2} = \frac{10{,}000}{3.16A_1 + 4.2B_1 + 11.2(H_2)_1 + 0.467(N_2)_1}, \tag{56}$$

and

$$L_{nose-CO_2} = \frac{3.16A_1 + 4.2B_1 + 11.2(H_2)_1 + 0.467(N_2)_1}{\frac{3.16A_1}{58.0} + \frac{4.2B_1}{28.0} + \frac{11.2(H_2)_1}{59.5} + 0.00311(N_2)_1}. \tag{57}$$

Case 6

When nitrogen is present in the air-free original atmosphere in such volume that $(4.15A_1 + 6B_1) < (N_2)_1$, all the carbon monoxide (A_1) and methane (B_1) are paired with part of the nitrogen $(N_2)_1$. The nitrogen remaining is paired with part of the hydrogen $(H_2)_1$, and the hydrogen remaining is paired with carbon dioxide. In this case

$$C.\ G.\ M.\ V._{CO_2} = \frac{10{,}000}{3.56A_1 + 4.70B_1 + 11.2(H_2)_1 + 0.3836(N_2)_1}, \tag{58}$$

and

$$L_{nose-CO_2} = \frac{3.56A_1 + 4.70B_1 + 11.2(H_2)_1 + 0.384(N_2)_1}{0.0614A_1 + 0.1526B_1 + \frac{11.2(H_2)_1}{59.5} + 0.00267(N_2)_1}. \tag{59}$$

Formulas (58) and (59) are particularly applicable to many anthracite mine fires that produce mine-fire atmospheres in which hydrogen and nitrogen are present in large volumes, and the carbon dioxide content is more than that of the average mine-fire atmosphere. In "nongassy" anthracite mines the methane content of the mine-fire gases often will be less than either the hydrogen content or the carbon monoxide content.

If a fire is inactive or if the fire gases are diluted to some degree by methane, hydrogen may be absent or the percentage may be too small to be determined by chemical analysis. As stated previously, if any gas is absent the term in the formula in which it occurs becomes zero, and the formula is applied accordingly.

DETERMINATION OF CARBON DIOXIDE REQUIRED TO RENDER A POTENTIALLY EXPLOSIVE ATMOSPHERE NONEXPLOSIVE

An example will serve to show the method of calculating the minimum volume of carbon dioxide that must be admixed with a given atmosphere to form an atmosphere just incapable of forming an explosive mixture with air, as well as to show the determination of other related factors.

For this purpose we will consider the original atmosphere, example 1, page 74, which corresponds in composition and position to atmosphere P_2, (figs. 5, 6, and 7, pocket). As sampled, this atmosphere consists of 11.67 percent each of carbon monoxide, methane, and hydrogen, 50.67 percent of nitrogen, and 14.33 percent of air of which 3 percent is oxygen and 11.33 percent nitrogen. The analysis of atmosphere P_2 calculated to an air-free basis has been found on page 74 to be 13.62 percent carbon monoxide (A_1), 13.62 percent methane (B_1), 13.62 percent hydrogen $(H_2)_1$, and 59.15 percent nitrogen $(N_2)_1$. It corresponds to atmosphere J (fig. 6).

Because the composition of the original atmosphere (P_2) is the same in both figure 5 and figure 6, the explosive limits of the air-free original atmosphere (J) are the same, regardless of the kind of inert gas used as the diluent. By means of the methods discussed on page 49, the lower explosive limit is found to be 14.66 percent and the upper explosive limit, 46.30 percent.

The relationships between the factors relating to the explosibility of atmosphere P_2 and those of atmospheres $(P_2)_2$ and $(P_4)_2$, which are formed by admixing carbon dioxide and nitrogen, respectively, with atmosphere P_2, are shown graphically in figure 6. A portion of figure 5 is superimposed by dotted lines on figure 6 to show the abovementioned relationships when nitrogen is used as the diluent (fig. 5), and when carbon dioxide is used as the diluent (fig. 6).

The next step in the procedure to determine the minimum volume of carbon dioxide that must be admixed with atmosphere P_2 (fig. 6) to form an atmosphere $(P_2)_2$ incapable of forming explosive mixtures with air, is to calculate the critical gas-mixture value ($C.\ G.\ M.\ V._{CO_2}$) relating to the air-free original atmosphere (J):

Because carbon monoxide (A_1) and nitrogen $(N_2)_1$ are present in atmosphere J in volumes of 13.62 and 59.15 percent, respectively, we have

$$4.15A_1 = 4.15 \times 13.62 = 56.52 \text{ percent},$$

and

$$(N_2)_1 = 59.15 \text{ percent},$$

from which

$$4.15A_1, \text{ or } 56.52, < 59.15, \text{ or } (N_2)_1.$$

Therefore, case 2 applies, and we use formula (50), page 82, to determine the critical gas-mixture value.

By substituting the real values given above for the symbols in formula (50), we find

$$C.\ G.\ M.\ V._{CO_2} = \frac{10{,}000}{3.21A_1 + 4.2B_1 + 11.2(H_2)_1 + 0.467(N_2)_1}, \qquad (50)$$

$$= \frac{10{,}000}{(3.21 \times 13.62) + (4.2 \times 13.62) + (11.2 \times 13.62) + (0.467 \times 59.15)},$$

$$= \frac{10{,}000}{43.72 + 57.20 + 152.54 + 27.62},$$

$$= 35.57 \text{ percent}.$$

Having determined the real value (35.57) of the critical gas-mixture value, the next step in the procedure is to determine whether or not the line (P_2–O, fig. 6) corresponding to all possible mixtures formed by admixing carbon dioxide with atmosphere P_2 (fig. 6) passes below the point corresponding to the nose-limit mixture (condition 1, p. 64). This condition is verified by determining the limiting value of angle θ, figure 6.

DETERMINATION OF LIMITING VALUE OF ANGLE θ

In figures 5 and 6 it will be observed that the limiting value of angle θ when the real values of x and y are calculated by means of formulas (45*a*) and (46*a*), which apply to condition 1, page 64, is an angle of which the tangent is the oxygen content of the nose-limit mixture divided by the gas-portion content (Gas_{nose}) of that mixture. This statement can be expressed mathematically as follows:

$$\theta_{nose}=\tan^{-1}\frac{(O_2)_{nose}}{kL_{nose}}, \qquad (60A)$$

where θ_{nose} is the angle included between the abscissa axis ($O-J$) and a line drawn from the origin (O) through the point corresponding to the nose-limit mixture.

We can also deduce from figures 5 and 6 an expression for calculating the limiting value of angle θ that applies to condition 2, page 64. When the line corresponding to all possible mixtures of a given atmosphere and a given inert gas intersects the line corresponding to all possible lower-explosive-limit mixtures, the limiting value of angle θ is an angle of which the tangent is the oxygen content $[(O_2)_{L-L}]$ of the lower-explosive-limit mixture divided by its gas-portion content (Gas_{L-L}). This statement can be expressed mathematically as follows:

$$\theta_{L-L}=\tan^{-1}\frac{(O_2)_{L-L}}{Gas_{L-L}}, \qquad (60B)$$

where θ_{L-L} is the angle included between the abscissa axis (O–J) and a line drawn from the origin (O) to the point corresponding to the lower-explosive-limit mixture.

The application of formula (60*B*) to atmosphere P_2 (fig. 6) is more a matter of interest than of practical importance for the reason that, when the oxygen content of a given atmosphere exceeds that of the lower-explosive-limit mixture, such an atmosphere is nonexplosive. Consequently, comparison of the real values of the oxygen contents of a given atmosphere and the lower-explosive-limit mixture suffices to establish whether or not it is feasible or necessary to admix an inert gas with a given atmosphere either to render it nonexplosive or to form a mixture incapable of forming explosive mixtures with air. However, formula (60*B*) is useful for other purposes, which are discussed later.

A definite relationship exists between angles ϕ and θ, as shown in figures 5 or 6, and the atmospheres that are just incapable of forming explosive mixtures with air, when these atmospheres are formed by admixing a given diluent with the given atmosphere that determines the real value of angle θ. A statement of this relationship is necessary to avoid unnecessary calculations.

From figures 5 and 6 it can be deduced that the real value of angle ϕ is constant for all air-free complex-gas mixtures, regardless of their composition, when (1) they have explosive limits in air and (2) their critical gas-mixture values are the same. Furthermore, the real value of angle θ is constant for all complex-gas mixtures, regardless of their chemical composition, when the real values of their respective gas-portion and air contents are the same. For this reason, angle θ relating to atmosphere P_2 has the same real value in both figure 5 and figure 6.

The next step in the procedure is to establish the fact that the line corresponding to all mixtures formed by admixing carbon dioxide with atmosphere P_2 (fig. 6) passes below the nose. To do this, we determine (1) the nose limit, (2) the oxygen content of the nose-limit mixture, and (3) the limiting value of angle θ, as follows:

We have found on page 84 that case 2 applies to atmosphere J, figure 6; therefore, we use formula (51), page 82, to determine the nose limit.

By substituting the real values given on page 84 for the symbols in formula (51), we find

$$L_{nose-CO_2}=\frac{3.21A_1+4.2B_1+11.2(H_2)_1+0.467(N_2)_1}{0.0596A_1+\frac{4.2B_1}{28.0}+\frac{11.2(H_2)_1}{59.5}+0.0031(N_2)_1}, \qquad (51)$$

$$=\frac{(3.21\times 13.62)+(4.2\times 13.62)+(11.2\times 13.62)+(0.467\times 59.15)}{(0.0596\times 13.62)+\frac{4.2\times 13.62}{28.0}+\frac{11.2\times 13.62}{59.5}+(0.0031\times 59.15)},$$

$$=\frac{43.72+57.20+152.54+27.62}{0.812+2.043+2.563+0.183},$$

$$=\frac{281.09}{5.60}=50.18 \text{ percent.}$$

By substituting this value of the nose limit for the symbol (L) in formula (31B), page 42, we find the oxygen content of the nose-limit mixture to be

$$(O_2)_{limit}=0.2093\times(100-50.18)=0.2093\times 49.82,$$

$$=10.43 \text{ percent of oxygen}$$

Because the oxygen content of the nose-limit mixture is 10.43 percent and the oxygen content of atmosphere P_2, (fig. 6) is 3 percent, the line corresponding to the successive mixtures formed by admixing carbon dioxide with atmosphere P_2 must pass below the nose. However, it is of interest to know the limiting value of angle θ (fig. 6), which can now be determined.

By substituting real values for the symbols in formula (60A), page 85, when

$C.\ G.\ M.\ V._{CO_2}=35.57$, $k=0.3557$, $L_{nose-CO_2}=50.18$, ano $(O_2)_{nose-CO_2}=10.43$, we find

$$\theta_{nose-CO_2}=\tan^{-1}\frac{(O_2)_{nose-CO_2}}{k(L_{nose-CO_2})}, \qquad (60A)$$

$$=\tan^{-1}\frac{10.43}{0.3557\times 50.18},$$

$$=\tan^{-1}\frac{10.43}{17.85}=\tan^{-1}0.58431=30°18'.$$

The significance of the real value of $\theta_{nose=CO2}$, or 30° 18′, is that if the angle having a tangent obtained by dividing the oxygen content $(O_2)_s$ of a given atmosphere, figure 6, by its gas-portion content (Gas_s), is more than 30° 18′, that is, when

$$\tan^{-}{}_1\frac{(O_2)_s}{Gas_s}>\theta_{nose-CO_2},$$

the line corresponding to the successive mixtures formed by admixing carbon dioxide with the given atmosphere passes above the nose (condition 2, p. 64).

When

$$\tan^{-1}\frac{(O_2)_s}{Gas_s}>\theta_{nose-CO_2},$$

formulas (41) to (46*a*), inclusive, cannot be used to calculate the real values of the rectangular coordinates (x and y) determining the position of the point corresponding to the atmosphere formed by admixing the minimum amount of carbon dioxide with a given atmosphere so as to form an atmosphere just incapable of forming explosive mixtures with air; instead, formulas (75) to (79), inclusive (pp. 112 and 113), would have to be used for that purpose. However, the position of the point corresponding to such an atmosphere and the factors relating to it are readily determined without calculations by the graphic method described in the section given on pages 94 to 98.

Conversely, if

$$\tan^{-1}\frac{(O_2)_s}{Gas_s}<\theta_{nose-CO_2},$$

formulas (41) to (46*a*), inclusive, can be used to calculate the coordinates (x and y) of the point corresponding to the atmosphere formed by admixing carbon dioxide with the given atmosphere.

Because angle θ_s is the angle included between the abscissa axis (O–J) and a line drawn from the origin through the point corresponding to any given atmosphere in the graph, formula (42*c*), page 67, or

$$\theta_s=\tan^{-1}\frac{(O_2)_s}{Gas_s}, \qquad (42c)$$

may be used to determine whether θ_s is more or less than θ_{nose}. This will establish whether the line of successive mixtures formed by admixing a given inert gas with a given atmosphere passes below or above the nose (condition 1 or 2, p. 64).

Applying the foregoing procedure to atmosphere P_2 (fig. 6), when

$(O_2)_s=3$ percent, $Air_s=14.33$ percent, and $Gas_s=85.67$ percent, we find, by substituting these real values for the symbols in formula (42*c*), that

$$\theta_s = \tan^{-1} \frac{3}{85.67} = 2°00'20''.$$

We have found on page 87 that

$$\theta_{nose-CO_2} = 30°18';$$

therefore,

$$\theta_{nose-CO_2}, \text{ or } 30°18', > \theta_s, \text{ or } 2°00'20'',$$

and the line corresponding to the successive mixtures formed by admixing carbon dioxide with atmosphere P_2 (fig. 6) passes below the nose.

DETERMINATION OF COMPOSITION OF ATMOSPHERE FORMED BY ADMIXING CARBON DIOXIDE WITH A GIVEN ATMOSPHERE

Having determined the real values of the critical gas-mixture value, nose limit, and oxygen content of the nose-limit mixture and having established the fact that the line corresponding to the successive mixtures formed by admixing carbon dioxide with atmosphere P_2 (fig. 6) passes below the nose, the next step in the procedure to determine the minimum volume of carbon dioxide that must be admixed with atmosphere P_2, to form an atmosphere $[(P_2)_2]$ just incapable of forming explosive mixtures with air, is to determine the real values of the rectangular coordinates (x and y) that determine the position of atmosphere $(P_2)_2$ (fig. 6).

Formulas (40), (41), (42*c*), (43), (44), (45*a*), and (46*a*) are used for the above-mentioned purpose, except that, because carbon dioxide is used as the diluent instead of nitrogen, the term $(CO_2)_{add-s}$ and its real value are substituted for $(N_2)_{add-s}$ in formula (40).

The detailed arithmetical calculations are omitted; however, the following tables summarize the calculated and related data:

Composition of original atmosphere (P_2, fig. 6) and of air-free original atmosphere (J); and real values of factors used in formulas (40) and (42c)

Constituent	Composition			
	Original atmosphere (P_2)		Air-free original atmosphere (J)	
	Symbol	Percent	Symbol	Percent
Gas portion:				
Carbon monoxide	A_s	11.67—	A_1	13.62—
Methane	B_s	11.67—	B_1	13.62—
Hydrogen	$(H_2)_s$	11.67—	$(H_2)_1$	13.62—
Nitrogen	$(N_2)_{gp-s}$	50.67		59.15
Carbon dioxide	D_s	.00		.00
Total combustible gas	$Comb_s$	35.00	$Comb_1$	40.85
Total inert gas	$Inert_{gp-s}$	50.67	$Inert_1$	59.15
Total	Gas_s	85.67		100.00
Air portion:				
Nitrogen	$(N_2)_{air-s}$	11.33		.00
Oxygen	$(O_2)_s$	3.00		.00
Total	$(Air)_s$	14.33		.00
Diluent portion: Carbon dioxide	$(CO_2)_{add-s}$	.00		.00
Total (all portions)		100.00		100.00
Total nitrogen	$(N_2)_{ts}$	50.67	$(N_2)_1$	59.15
Total carbon dioxide	$(CO_2)_{ts}$	.00	D_1	.00
Total gases other than air and diluent	K_s	85.67		100.00

Summary of calculations to determine real values of rectangular coordinates (x and y) establishing position of atmosphere $(P_2)_2$ (fig. 6), which is incapable of forming explosive mixtures with air and has been formed by admixing minimum volume of carbon dioxide with atmosphere sampled (P_2)

Symbol	Formula used or number designating it	Calculations	Real value [1]
$C.G.M.V._{CO_2}$	(50)	(See p. 84)	Atmos. P_2 35.57
$(O_2)_s$	By analysis	(See above tabulation)	3.00
Air_s	$=\frac{(O_2)_s(100)}{20.93}$ (1)	$\frac{3.00\times100}{20.93}$	14.33
$(CO_2)_{add-s}$	$=(N_2)_{ts}+(CO_2)_{ts}-Inert_{gp-s}-3.78(O_2)_s$ (40)	$62.00+0.00-50.67-(3.78\times3.00)$	.00
ϕ	$=\tan^{-1}\frac{C.G.M.V._{CO_2}}{20.93}$ (41)	$\tan^{-1}\frac{35.57}{20.93}$	59°31′36″
θ	$=\tan^{-1}\frac{(O_2)_s}{Gas_s}$ (42c)	$\tan^{-1}\frac{3}{85.67}$	2°00′20″
Δ	$=90°-\phi+\theta$ (43)	$90°-59°31'36''+2°00'20''$	32°28′44″
w	$=\frac{\sin\phi\ (20.93)}{\sin\Delta}$ (44)	$\frac{0.86185\times20.93}{0.53699}$	33.59
x	$=w\cos\theta$ (45a)	33.59×0.99939	Atmos. $(P_2)_2$ 33.57
y	$=w\sin\theta$ (46a)	33.59×0.035	1.176

[1] Real value in percent, unless shown otherwise.

Having calculated the real values of x and y that correspond to the gas-portion content and oxygen content, respectively, of atmosphere $(P_2)_2$ (fig. 6) we determine the diluent content of this atmosphere by substituting the real values of x and y in formula (47*a*), page 68, as follows:

$$(CO_2)_{dil}=100-\frac{100\ y}{20.93}-x, \qquad (47a)$$

$$=100-\frac{100\times1.176}{20.93}-33.57,$$

$$=100-5.62-33.57,$$

$=60.81$ percent of carbon dioxide, the diluent content of atmosphere $(P_2)_2$.

Finally, as atmosphere P_2 (fig. 6) is an original atmosphere that is diluent-free, the diluent content (60.81 percent carbon dioxide) of atmosphere $(P_2)_2$ is also the volume of carbon dioxide that must be admixed with atmosphere P_2 to form atmosphere $(P_2)_2$.

The volume of carbon dioxide required to form atmosphere $(P_2)_2$ from atmosphere P_2 can also be calculated by substituting the real values of the oxygen contents [$(O_2)_s$ and y] of atmospheres P_2 and $(P_2)_2$, respectively, for the symbols in formula (47*c*), page 69, when

$(O_2)_s=3$ percent, and $y=1.176$ percent,

or

$$(CO_2)_{dil}=\frac{[(O_2)_s-y]100}{(O_2)_s}, \qquad (47c)$$

$$=\frac{(3.00-1.176)\times100}{3.00},$$

$=60.81$ percent of carbon dioxide required to form atmosphere $(P_2)_2$ from atmosphere P_2.

The relationships between the original atmosphere (P_2, figs. 5 and 6) and the final atmospheres [$(P_4)_2$, fig. 5, and $(P_2)_2$, fig. 6], formed by admixing nitrogen and carbon dioxide, respectively, with atmosphere P_2, are shown in figure 6 and the following table:

Relationships between atmosphere P_2, figures 5 and 6, and atmospheres $(P_4)_2$, figure 5, and $(P_2)_2$, figure 6, formed by admixing a definite volume of nitrogen (72.29 percent) or carbon dioxide (60.81 percent) with atmosphere P_2

Item	Compsotion of atmospheres (percent by volume)				
	Original atmosphere sampled (P_2, figs. 5 and 6)	Nitrogen added (Effect: + or −)[1]	Atmosphere formed by adding nitrogen ($(P_4)_2$, fig. 5)[1]	Carbon dioxide added (Effect: + or −)	Atmosphere formed by adding carbon dioxide ($(P_2)_2$, fig. 6)
Gas portion:					
Carbon monoxide	11.67	−8.43	3.23+	−7.10	4.57
Methane	11.67	−8.43	3.23+	−7.10	4.57
Hydrogen	11.67	−8.43	3.23+	−7.10	4.57
Nitrogen	50.67	−36.63	14.04	−30.81	19.86
Total	85.67	−61.93	$23.74=x$	−52.10	$33.57=x$
Air portion:					
Air	14.33	−10.36	3.97	−8.714	5.616
Oxygen	3.00	−2.17	$.83=y$	−1.824	$1.176=y$
Nitrogen	11.33	−8.19	3.14	−6.890	4.440
Diluent portion:					
Additional nitrogen from diluent in atmosphere sampled	.00	.00	.00	.00	.00
Additional carbon dioxide from diluent in atmosphere sampled	.00	.00	.00	.00	.00
Nitrogen added	.00	+72.29	72.29	.00	.00
Carbon dioxide added	.00	.00	.00	+60.81	60.81
Total	.00	+72.29	72.29	+60.81	60.81
Total nitrogen	62.00	+27.47	89.47	−37.70	24.30
Total carbon dioxide	.00	.00	.00	+60.81	60.81

[1] From tabulation, p. 79.

The foregoing table shows that if 60.81 volumes of carbon dioxide gas are used to displace the same number of volumes of an atmosphere consisting of 11.67 percent each of carbon monoxide, methane, and hydrogen, 50.67 percent of nitrogen, and 14.33 percent of air, of which 3 percent is oxygen and 11.33 percent is nitrogen, an atmosphere will be formed that is incapable of forming explosive mixtures with air. The chemical composition of that atmosphere will be 4.57 percent each of carbon monoxide, methane, and hydrogen, 1.18 percent of oxygen, 24.30 percent of nitrogen, and 60.81 percent of carbon dioxide.

The table also shows that, whereas 72.29 percent of nitrogen must be admixed with atmosphere P_2 (figs. 5 and 6) to form atmosphere $(P_4)_2$ (fig. 5), which is just incapable of forming explosive mixtures with air, it is necessary to use only 60.81 percent of carbon dioxide to accomplish the same purpose by forming atmosphere $(P_2)_2$ (fig. 6).

METHOD OF VERIFYING CALCULATIONS ON EXPLOSIBILITY OF ATMOSPHERES

It was shown on pages 57 and 58 that atmospheres corresponding to points lying in or to the left of line *LQ*, figure 4, or corresponding to points lying in the area to the left of line *DL* are nonexplosive and incapable of forming explosive mixtures with air.

Referring to figure 6, we can deduce that no atmosphere is explosive or can form explosive mixtures with air when (1) the point corresponding to that atmosphere lies in line *C. G. M. V.–A* or in the area to the left of that line, or (2) when the point corresponding to an atmosphere lies in the triangular area enclosed by lines *A–Nose, Nose–Lower Limit,* and *Lower Limit–A.* However, air-free mixtures of atmospheres corresponding to points lying in the area just mentioned can form explosive mixtures with air, whereas air-free mixtures of atmospheres corresponding to points in line *C. G. M. V.–A* or to points to the left of that line cannot form explosive mixtures with air (condition 1 above).

Therefore, if we find that the air-free composition of a given atmosphere is capable of forming explosive mixtures with air, the given atmosphere itself may or may not be explosive, or it may or may not be capable of forming explosive mixtures with air. The explosibility of the given atmosphere can be verified only by determining the explosive limits of the air-free composition of the given atmosphere and then comparing the composition of the given atmosphere with the compositions of the explosive-limit mixtures. The method of procedure in such problems is discussed on pages 145 to 148, inclusive.

On pages 21 and 22 it has been shown that if the critical gas-mixture value (*C. G. M. V.*) of the air-free composition of a given mixture is 100, over 100, or a minus value, both the given mixture and its air-free composition are incapable of forming explosive mixtures with air.

By determining the critical gas-mixture value, we obtain (1) a check on the accuracy of the calculations determining the explosibility of the atmosphere formed by admixing an inert gas with a given atmosphere and (2) a check on the volume of inert gas found necessary to form a mixture just incapable of forming explosive mixtures with air.

It is immaterial which formula is used to calculate the critical gas-mixture value of the air-free mixture insofar as selecting the formula according to the inert gas used as the diluent is concerned. It is only necessary to select the pertinent case and use the pertinent formula as determined by the relationship between the volumes of hydrogen and carbon dioxide, carbon monoxide and nitrogen, or methane and nitrogen. Therefore, if atmosphere $(P_2)_2$, figure 6, is considered as an original atmosphere and calculated to an air-free basis, the critical gas-mixture value ($C.\ G.\ M.\ V._{N_2}$ or $C.\ G.\ M.\ V._{CO_2}$) of the air-free composition of atmosphere $(P_2)_2$ must be 100 or more than 100.

To prove whether or not atmosphere $(P_2)_2$, figure 6, or its air-free composition is explosive or can form explosive mixtures with air, we proceed as follows:

On page 90, atmosphere $(P_2)_2$ is shown to consist of 4.57 percent each of carbon monoxide, methane, and hydrogen; 1.18 percent of oxygen; 24.30 percent of nitrogen; and 60.81 percent of carbon dioxide.

It can be seen in figure 6 that the air-free composition of atmosphere $(P_2)_2$ and the composition of the critical gas mixture relating to the air-free original atmosphere (*J*) are identical; therefore, the air-free composition of atmosphere $(P_2)_2$ can be determined as follows:

On page 84 we found the critical gas-mixture value ($C.\ G.\ M.\ V._{CO_2}$)

to be 35.57 percent. By substituting the real values of the constituents of atmosphere *J*, as given on page 74, for the symbols in formula (22*A*), page 31, we find, when *C. G. M. V.*$_{CO_2}$=35.57, $k=0.3557$, $A_1=B_1=(H_2)_1=13.62$, and $(N_2)_1=59.15$ that the gas-portion content of the critical gas mixture is

$$\begin{aligned} \text{Carbon monoxide} &= k(A_1) = 0.3557\times 13.62 = 4.84+ \text{ percent}, && (22A)\\ \text{Methane} &= k(B_1) = 0.3557\times 13.62 = 4.84+ \text{ percent}, && (22A)\\ \text{Hydrogen} &= k(H_2)_1 = 0.3557\times 13.62 = 4.84+ \text{ percent}, && (22A)\\ \text{Nitrogen} &= k(N_2)_1 = 0.3557\times 59.15 = 21.04 \text{ percent}; && (22A) \end{aligned}$$

and, by formula (22*B*), page 32, that the diluent content is

$$\begin{aligned} Dil_{C.G.M.} &= 100 - \text{C. G. M. V.}_{CO_2}, && (22B)\\ &= 100 - 35.57,\\ &= 64.43 \text{ percent of carbon dioxide.} \end{aligned}$$

Summarizing the above-given calculations, the composition of the critical gas mixture (of atmosphere *J*, fig. 6), which is also the air-free composition of atmosphere $(P_2)_2$, is 4.84+ percent each of carbon monoxide, methane, and hydrogen; 21.04 percent of nitrogen; and 64.43 percent of carbon dioxide.

If we now consider the air-free composition of atmosphere $(P_2)_2$ as an air-free original atmosphere, we have the following relationships when

$$(H_2)_1 = 4.84 \text{ percent, and } D_1 = 64.43 \text{ percent, } 10.2(H_2)_1 = 10.2\times 4.84 = 49.37,$$

and

$$10.2(H_2)_1, \text{ or } 49.37, < 64.43, \text{ or } D_1.$$

Therefore, to find the critical gas-mixture value when nitrogen is used as the diluent, case 3, page 27, applies, and we use formula (16).

By substituting the real values of A_1, B_1, $(H_2)_1$, $(N_2)_1$, and D_1, given above, for the symbols in formula (16), we find

$$\begin{aligned} C.\ G.\ M.\ V._{N_2} &= \frac{10{,}000}{5.15A_1 + 7B_1 + 20.12(H_2)_1 - 0.875D_1}, && (16)\\ &= \frac{10{,}000}{(5.15\times 4.84) + (7\times 4.84) + (20.12\times 4.84) - (0.875\times 64.43)},\\ &= \frac{10{,}000}{99.81} = 100.1. \end{aligned}$$

If carbon dioxide is used as the diluent with the same air-free original atmosphere (atmosphere $(P_2)_2$, air-free), we have the following relationships when

$$A_1 = 4.84 \text{ percent and } (N_2)_1 = 21.04 \text{ percent, } 4.15A_1 = 4.15\times 4.84 = 20.09,$$

and

$$4.15A_1, \text{ or } 20.09, < 21.04, \text{ or } (N_2)_1.$$

Therefore, to find the critical gas-mixture value, case 2, page 82, applies, and we use formula (50).

By substituting the real values, previously found, for the symbols in formula (50), we find

$$C.\ G.\ M.\ V._{CO_2}=\frac{10{,}000}{3.21A_1+4.2B_1+11.2(H_2)_1+0.467(N_2)_1}, \qquad (50)$$

$$=\frac{10{,}000}{(3.21\times4.84)+(4.2\times4.84)+(11.2\times4.84)+(0.467\times21.04)},$$

$$=\frac{10{,}000}{99.90}=100.1.$$

From both calculations it is seen that the critical gas-mixture value is 100.1; therefore, both atmosphere $(P_2)_2$ and its air-free composition are nonexplosive and incapable of forming explosive mixtures with air, thus proving that atmosphere $(P_2)_2$, which is formed by admixing 60.81 percent of carbon dioxide with atmosphere P_2 (fig. 6), is incapable of forming explosive mixtures with air.

VOLUME OF CARBON DIOXIDE REQUIRED TO DILUTE A GIVEN ATMOSPHERE

The volume of carbon dioxide gas required to form a definite atmosphere in a confined place containing the original atmosphere depends on the volume of the confined original atmosphere. If a sealed area is assumed to contain 1,000 cubic feet of an original atmosphere having the same composition as atmosphere P_2 (figs. 5 and 6), then 608.1 cubic feet of carbon dioxide gas at the same temperature and atmospheric pressure as those of the original atmosphere will be required to form an extinctive atmosphere that is just incapable of forming an explosive mixture when admixed with air. One pound of carbon dioxide or "dry ice" evolves 8.57 cubic feet of carbon dioxide gas at 60° F. and 760 millimeters pressure (normal atmospheric conditions); therefore, 71 pounds of dry ice is required to produce 608.1 cubic feet of carbon dioxide gas. In other words, to form 1,000 cubic feet of an atmosphere having the composition of atmosphere $(P_2)_2$ (fig. 6) from atmosphere P_2 requires 71 pounds of dry ice.

If a limestone consisting of approximately 97.7 percent $CaCO_3$ could be completely calcined, 1 ton (2,000 pounds) of such limestone would yield 7.540 cubic feet of carbon dioxide gas at 60° F. and 760 millimeters pressure. Rock dust made from limestone of this quality is used in many coal mines to reduce the explosion hazard.

COMPARISON BETWEEN CONTINUOUS AND INTERMITTENT DILUTING OPERATIONS

Carbon dioxide gas has been used in attempts to extinguish mine fires or to form nonexplosive atmospheres in mine-fire areas. An analysis of the atmosphere formed in the mine-fire area often has shown that the results were not as anticipated. Probably one of the important reasons for such failure is the means by which the carbon dioxide gas was introduced.

Effectual steps for the best results in the use of a diluent (inert gas) to extinguish a fire or prevent an explosion are: (1) The volume of diluent introduced into a sealed area should displace an equal volume of the given atmosphere being displaced; (2) the diluent should be allowed to mix with the portion of the given atmosphere remaining; and (3) once a diluent is being introduced, the operation should be continuous. If the diluting operation is not continuous and the resultant atmosphere in the sealed area is allowed to stand for even a day, it is not only necessary to displace a proportional part of the given atmosphere remaining after the diluting operation is discontinued, but when the diluting operation is resumed it is also necessary to displace the diluent that has become diffused or admixed with the proportional part of the given atmosphere remaining.

The difference between the volume of diluent required to form a definite atmosphere from a given atmosphere when the diluting operation is intermittent and the volume when it is continuous can be explained by the data shown in figure 4 (pocket), which represents a given atmosphere and related factors when nitrogen is used as the diluent.

If nitrogen were introduced into a sealed area containing atmosphere P_3, 50.67 percent of nitrogen would be required to form a mixture having the composition corresponding to point P_1. If conditions were then allowed to remain static until the nitrogen and the portion of atmosphere P_3 remaining become diffused, 72.29 percent of nitrogen would be required to form atmosphere $(P_4)_1$ from atmosphere P_1. In other words, nitrogen in a volume equal to 122.96 percent of the volume of the sealed area would have to be used to form atmosphere $(P_4)_1$ (fig. 4) from atmosphere P_3 by the intermittent diluting operation, whereas, had the diluting operation been continuous, 86.33 percent of nitrogen would have accomplished the purpose. (*See* pp. 76 and 77.)

GRAPHIC METHOD OF DETERMINING MINIMUM VOLUME OF INERT GAS NECESSARY TO RENDER A GIVEN ATMOSPHERE INCAPABLE OF FORMING EXPLOSIVE MIXTURES WITH AIR

Figure 7 (pocket) has been constructed to show the graphic method of determining the volumes of diluent (carbon dioxide) that must be admixed with given atmospheres to form final atmospheres incapable of forming explosive mixtures with air. It also shows the graphic method of determining the composition of the atmospheres concerned. The data used to construct figure 6 are used to construct figure 7, which shows the relationship between the factors relating to the explosibility of atmospheres to be considered and the air-free original atmosphere *J* (figs. 6 and 7). From page 88, we find that atmosphere *J* consists of 13.62 percent each of carbon monoxide, methane, and hydrogen and 59.15 percent of nitrogen.

Because point *J* corresponds to the same atmosphere in figure 6 and figure 7 and carbon dioxide is used as the diluent in both figures, the lines defining the boundaries of the zones of explosive mixtures, mixtures capable of forming explosive mixtures with air, and mixtures incapable of forming explosive mixtures with air are the same in both figures.

It must be explained that, although point P_2 in figures 5, 6, and 7 corresponds to an atmosphere having the same chemical composition in each figure, points P_1 and P_3 in figure 7 correspond to atmospheres having chemical compositions different from atmospheres P_1 and P_3 in figure 4.

When the composition of an atmosphere corresponding to some definite point in a graph, such as figure 7, is determined graphically, the atmosphere is considered as consisting of three portions, each of which can be called a coordinate of the point corresponding to the atmosphere. The real values of the portions, or coordinates, are the percentages (1) of the air-free original atmosphere (gas-portion content), (2) of air, and (3) of diluent (additional nitrogen or carbon dioxide) that are present in the atmosphere being considered.

If the chemical composition of the atmosphere being considered has been determined by an analysis of a sample, the portions, or coordinates, can be established readily; however, if the composition (by constituents or by portions) of the atmosphere is to be determined either mathematically or graphically, it is necessary to know the real value of one of the portions and a mathematical relationship between this portion and another before the third portion, or coordinate, can be determined.

If the objective of obtaining real values for the three portions, or coordinates, rather than for the individual constituents composing a definite atmosphere, is kept in mind the procedure to be employed and the formulas to be used to determine the real values of the components of the three portions will be readily recognizable.

It is well-known that, in order to solve problems readily, an essential requirement is practice in solving many examples. For this reason, the solutions of several specific examples are given in detail.

The graphic method for determining the volume of carbon dioxide required to form a definite atmosphere from a given atmosphere can be shown by the following examples, which show the application of a graph to problems likely to be found at mine fires.

To avoid repetition of words, the words "volume of diluent required" will be used to mean the volume (in percent of the volume of the atmosphere under seal) of carbon dioxide that must be admixed with a given atmosphere to form an atmosphere incapable of forming explosive mixtures with air; the words "final atmosphere," to mean the resultant atmosphere formed; and the words "atmosphere *J*," to mean the air-free original atmosphere corresponding to point *J* (fig. 7).

EXAMPLE 1. A given atmosphere corresponding to point P_1 (fig. 7) consists of 35 percent of the percentages of the constituents composing atmosphere *J*, 14.33 percent of air, and 50.67 percent of carbon dioxide (diluent), or 4.77 percent each of carbon monoxide, methane, and hydrogen; 3 percent of oxygen; 32.03 percent of nitrogen; and 50.67 percent of carbon dioxide.

To find the volume of diluent required to form the final atmosphere, draw line P_1–P_2 parallel to the abscissa axis (line *O*–*J*) and intersecting line *J*–*A* at point P_2. This establishes a point that, although coinciding with point P_2, corresponds to an original atmosphere having the same chemical composition as P_1 when atmosphere P_1 is considered as an original atmosphere. Draw line P_2–*O*, which corresponds to the successive mixtures formed by admixing carbon dioxide with such an original atmosphere. Draw line P_1–*O*, which corresponds to the successive mixtures formed by admixing carbon dioxide with atmosphere P_1. Line P_1–*O* intersects line *C. G. M. V.*–*A* at point *a*, the final atmosphere desired. Draw line *a*–*g* parallel to the abscissa axis and intersecting line P_2–*O* at point *g*. Draw line *g*–*h* parallel to line *A*–*J* and intersecting the abscissa axis at point *h*, which represents the volume of diluent required, or 11.28 percent of carbon dioxide. In other words, 11.28 percent of carbon dioxide will, when admixed with atmosphere P_1, form atmosphere *a*, the final atmosphere desired.

The composition of atmosphere *a* is found as follows: Draw a line parallel to the ordinate axis (line *O–A*) from point *a* and intersecting the abscissa axis at the point corresponding to a gas-portion content of 31.05 percent of the percentages of the constituents composing atmosphere *J*. By drawing line *a–j* parallel to line *A–J*, the diluent content of atmosphere *a* is found to be 56.23 percent of carbon dioxide. Line *a–g* extended to the ordinate axis shows that atmosphere *a* contains 12.72 percent of air, of which 2.66 percent is oxygen and 10.06 percent is nitrogen. Therefore, the final atmosphere corresponding to point *a* is composed of 4.23 percent each of carbon monoxide, methane, and hydrogen; 2.66 percent of oxygen; 28.43 percent of nitrogen; and 56.23 percent of carbon dioxide.

EXAMPLE 2. An original atmosphere corresponding to point P_2, (fig. 7) consists of 85.67 percent of the percentages of the constituents composing atmosphere *J*, and 14.33 percent of air, or 11.67 percent each of carbon monoxide, methane, and hydrogen; 3 percent of oxygen; and 62 percent of nitrogen. (See p. 90.)

To find the volume of diluent required to form the final atmosphere, draw or follow line P_2–*O* to where it intersects line *C. G. M. V.–A* at point *b*, the final atmosphere desired. Draw line *b–i* parallel to line *A–J* and intersecting the abscissa axis at point *i*, which represents the volume of diluent required, or 60.81 percent of carbon dioxide. In other words, 60.81 percent of carbon dioxide will, when admixed with atmosphere P_2, form atmosphere *b*, the final atmosphere desired.

The composition of atmosphere *b* is found as follows: Draw a line from point *b* parallel to the ordinate axis and intersecting the abscissa axis at the point corresponding to a gas-portion content of 33.57 percent of the percentages of the constituents composing atmosphere *J*. The volume (60.81 percent) of carbon dioxide required to form atmosphere *b* from atmosphere P_2 is also the diluent content of atmosphere *b*. A line drawn from point *b* parallel to the abscissa axis (*O–J*) and extended to the ordinate axis (*O–A*) shows that atmosphere *b* contains 5.62 percent of air, of which 1.18 percent is oxygen and 4.44 percent is nitrogen. Therefore, the final atmosphere corresponding to point *b* is composed of 4.57 percent each of carbon monoxide, methane, and hydrogen; 1.18 percent of oxygen; 24.30 percent of nitrogen; and 60.81 percent of carbon dioxide.

EXAMPLE 3. An original atmosphere corresponding to point P_3 (fig. 7) consists of 70.95 percent of the percentages of the constituents composing atmosphere *J*, and 29.05 percent of air, or 9.66 percent each of carbon monoxide, methane, and hydrogen; 6.08 percent of oxygen; and 64.94 percent of nitrogen.

The composition of atmosphere P_3, (fig. 7) and the composition of the atmosphere P_1 calculated to a diluent-free basis (carbon dioxide-free basis) are identical.

To find the amount of diluent required to form the final atmosphere, draw line P_3–*O* to where it intersects line *C. G. M. V.–A* at point *a*, the final atmosphere desired. It is observed that line P_3–*O* passes through point P_1 and that point *a* has the same composition as found in example 1, page 95. By following line *a–j*, as in example 1, the amount (56.23 percent) of carbon doxide required to form atmosphere *a* from atmosphere P_3 is found to be the diluent content of atmosphere *a*. In other words, 56.23 percent of carbon dioxide will, when admixed with atmosphere P_3, form atmosphere *a*, the final atmosphere desired.

Example 3 is given to show the effect of admixing a given inert gas (diluent) in a continuous operation with atmosphere P_3 in order to form the same final atmosphere (*a*) as is formed by admixing the same kind of inert gas (carbon dioxide) with atmosphere P_1. The effects are similar to those obtained when nitrogen is used as the diluent, as discussed on page 94.

It is observed from the data given above and in example 1, page 95, that when carbon dioxide is admixed with atmosphere P_3 in a continuous operation to form atmosphere *a*, 56.23 percent of carbon dioxide is required. If, however, only 50.67 percent of carbon dioxide is introduced into a sealed space containing atmosphere P_3, and conditions are allowed to remain static until the gases become mixed, atmosphere P_1 is formed. To form atmosphere *a* would then necessitate admixing 11.28 percent of carbon dioxide with atmosphere P_1 thus making a total of 61.95 percent of carbon dioxide required to be admixed with atmosphere P_3 to form atmosphere *a* by the intermittent operation, whereas, only 56.23 percent is required by the continuous operation.

EXAMPLE 4. A given atmosphere corresponding to point P_4 (fig. 7) consists of 60.00 percent of the percentages of the constituents composing atmosphere *J*, 14.33 percent of air, and 25.67 percent of carbon dioxide (diluent), or 8.17 percent each of carbon monoxide, methane, and hydrogen; 3.00 percent of oxygen; 46.82 percent of nitrogen; and 25.67 percent of carbon dioxide.

To find the volume of diluent required to form the final atmosphere, draw line P_4–P_2 parallel to the abscissa axis and intersecting line *J–A* at point P_2. This establishes a point that, although coinciding with point P_2, corresponds to an original atmosphere having the same chemical composition as P_4 when atmosphere P_4 is considered as an original atmosphere. Line P_2–*O*, as in example 1, corresponds to the successive mixtures formed by admixing carbon dioxide with such an original atmosphere. Draw line P_4–*O*, which corresponds to the successive mixtures formed by admixing carbon dioxide with atmosphere P_4. Line P_4–*O* intersects line *C. G. M. V.–A* at point *c*, the final atmosphere desired. Draw line *c-k* parallel to the abscissa axis and intersecting line P_2–*O* at point *k*. Draw line *k-l* parallel to line *A–J* and intersecting the abscissa axis at point *l*, which shows the volume of diluent required, or 45.40 percent of carbon dioxide. In other words, 45.40 percent of carbon dioxide will, when admixed with atmosphere P_4, form atmosphere *c*, the final atmosphere desired.

The composition of atmosphere *c* is found as follows: Draw a line from point *c* parallel to the ordinate axis and intersecting the abscissa axis at the point corresponding to a gas-portion content of 32.78 percent of the percentages of the constituents composing atmosphere *J*. A line drawn parallel to line *A–J* from point *c* intersects the abscissa axis at a point that shows that the diluent content of atmosphere *c* is 59.4 percent of carbon dioxide. A line drawn from point *c* parallel to the abscissa axis (*O–J*) and extended to the ordinate axis (*O–A*) shows that atmosphere *c* contains 7.83 percent of air, of which 1.64 percent is oxygen and 6.19 percent is nitrogen. Therefore, the final atmosphere corresponding to point *c* is composed of 4.46 percent each of carbon monoxide, methane, and hydrogen; 1.64 percent of oxygen; 25.58 percent of nitrogen; and 59.4 percent of carbon dioxide.

Example 5. An original atmosphere corresponding to point P_5, (fig. 7) consists of 26.38 percent of the percentages of the constituents composing atmosphere *J* and 73.63 percent of air, or 3.59 percent each of carbon monoxide, methane, and hydrogen; 15.41 percent of oxygen; and 73.82 percent of nitrogen.

To find the volume of diluent required to form the final atmosphere, draw line P_5–*O*, which intersects line *C. G. M. V.–A* at point *d*, the final atmosphere desired. Draw line *d–m* parallel to line *A–J* and intersecting the abscissa axis at point *m*, which shows that the volume of diluent required is 32.34 percent of carbon dioxide. In other words, 32.34 percent of carbon dioxide will, when admixed with atmosphere P_5, form atmosphere *d*, the final atmosphere desired.

The composition of atmosphere *d* is found as follows: Draw a line from point *d* parallel to the ordinate axis and intersecting the abscissa axis at the point corresponding to a gas-portion content of 17.85 percent of the percentages of the constituents composing atmosphere *J*. The volume (32.34 percent) of carbon dioxide required to form atmosphere *d* from atmosphere P_5 is also the diluent content of atmosphere *d*. A line drawn from point *d* parallel to the abscissa axis and extended to the ordinate axis shows that atmosphere *d* contains 49.82 percent of air, of which 10.43 percent is oxygen and 39.39 percent nitrogen. Therefore, the final atmosphere corresponding to point *d* is composed of 2.43 percent each of carbon monoxide, methane, and hydrogen; 10.43 percent of oxygen; 49.95 percent of nitrogen; and 32.34 percent of carbon dioxide.

On page 86, the real value of the nose limit relating to atmosphere *J* (fig. 7) was found to be 50.18 percent, which shows that the real value of the gas-portion content of the nose-limit mixture is 50,18 percent of the gas-portion content (35.57 percent) of the critical gas mixture, or 17.85 percent. Because atmosphere *d* has a gas-portion content of 17.85 percent and an oxygen content of 10.43 percent, atmosphere *d* must be the nose-limit mixture.

Example 6. A given atmosphere corresponding to point P_6 (fig. 7) consists of 20 percent of the percentages of the constituents composing atmosphere *J*, 66.88 percent of air, and 13.12 percent of carbon dioxide (diluent), or 2.72 percent each of carbon monoxide, methane, and hydrogen; 14.00 percent of oxygen, 64.71 percent of nitrogen; and 13.12 percent of carbon dioxide.

To find the volume of diluent required to form the final atmosphere, draw line P_6–*n* parallel to the abscissa axis and intersecting line *J–A* at point *n*. This establishes point *n* as corresponding to an original atmosphere having the same chemical composition as atmosphere P_6 when it is considered as an original atmosphere. Draw line *n–O*, which corresponds to the successive mixtures formed by admixing carbon dioxide with such an original atmosphere. Draw line P_6–*O*, which corresponds to the successive mixtures formed by admixing carbon dioxide with atmosphere P_6. Line P_6–O interests line d–L_L at point e, the final atmosphere desired. Line d–L_L corresponds to all possible lower-explosive-limit mixtures that could be formed by admixing carbon dioxide and air with atmosphere J. Draw line e–q parallel to the abscissa axis and intersecting line n–O at point q. Draw line q–r parallel to line A–J and intersecting the abscissa axis at point r, which shows that the volume of diluent required is 13.92 percent of carbon dioxide. In other words, 13.92 percent of carbon dioxide will, when admixed with atmosphere P_6, form atmosphere e, the final atmosphere desired.

The composition of atmosphere e is found as follows: Draw a line from point e parallel to the ordinate axis and intersecting the abscissa axis at the point correponding to a gas-portion content of 17.22 percent of the percentages of the constituents composing atmosphere J. A line drawn parallel to line A–J from point e intersects the abscissa axis at a point that shows that the diluent content of atmosphere e is 25.21 percent of carbon dioxide. A line drawn from point e parallel to the abscissa axis (O–J) and extended to the ordinate axis (O–A) shows that atmosphere e contains 57.57 percent of air, of which 12.05 percent is oxygen and 45.52 percent is nitrogen. Therefore, the final atmosphere corresponding to point e is composed of 2.34 percent each of carbon monoxide, methane, and hydrogen; 12.05 percent of oxygen; 55.71 percent of nitrogen; and 25.21 percent of carbon dioxide.

EXAMPLE 7. An original atmosphere corresponding to point P_7, (fig. 7) consists of 20.00 percent of the percentages of the constituents composing atmosphere J and 80.00 percent of air, or 2.72 percent each of carbon monoxide, methane, and hydrogen; 16.74 percent of oxygen; and 75.09 percent of nitrogen.

To find the volume of diluent required to form the final atmosphere, draw line P_7–O, which intersects line d–L_L (line of lower-explosive-limit mixtures) at point f, the final atmosphere desired. Draw line f–s parallel to line A–J and intersecting the abscissa axis at point s, which shows that the volume of diluent required is 18.16 percent of carbon dioxide. In other words, 18.16 percent of carbon dioxide will, when admixed with atmosphere P_7, form atmosphere f, the final atmosphere desired.

The composition of atmosphere f is found as follows: Draw a line from point f parallel to the ordinate axis and intersecting the abscissa axis at the point corresponding to a gas-portion content of 16.37 percent of the percentages of the constituents composing atmosphere J. The volume (18.16 percent) of carbon dioxide required to form atmosphere f from atmosphere P_7 is also the diluent content of atmosphere f. A line drawn from point f parallel to the abscissa axis and extended to the ordinate axis shows that atmosphere f contains 65.47 percent of air, of which 13.70 percent is oxygen and 51.77 percent is nitrogen. Therefore, the final atmosphere corresponding to point f is composed of 2.23 percent each of carbon monoxide, methane, and hydrogen; 13.70 percent of oxygen; 61.45 percent of nitrogen; and 18.16 percent of carbon dioxide.

In the foregoing examples carbon dioxide is used to form the final atmospheres desired. Carbon dioxide is easily obtained and in practice is likely to be used as the diluent instead of nitrogen. However, if calculations are made to determine the volume of nitrogen required as diluent, and instead of nitrogen an equal volume of carbon dioxide is used, the final atmosphere formed will be on the safe side because of the greater extinctive effect of carbon dioxide over nitrogen. This is because of the higher specific heat of carbon dioxide (*19*).

In general, each problem if investigated thoroughly will suggest the procedure that should be employed. Where methane is the principal or the only combustible gas present, more carbon dioxide than is necessary would be used if carbon dioxide were substituted for nitrogen on the basis of calculations made for nitrogen.

USE OF MIXTURE OF AIR AND INERT GAS AS A *DILUENT*

Practical considerations in the use of an inert gas to displace all or a portion of an atmosphere that is potentially explosive do not always permit the use of a pure inert gas for that purpose. This circumstance in some instances can prove to be an asset rather than a dangerous liability, as when a mixture of an inert gas, such as carbon dioxide, and air is used as a *diluent* instead of the pure inert gas. The net effect is that less inert gas is required.

It is immaterial whether air is admitted inadvertently with the inert gas as it is introduced into a sealed area, or a mixture of the inert gas and air is prepared beforehand and then used, so long as the *diluent* is such that an explosive atmosphere is not formed when a means of ignition is present, and an excess of air is not introduced until after the borderline of possible nonexplosive atmospheres is reached. (*See* line *C. G. M. V.–d–Lower limit*, fig. 7, pocket.)

USE OF *DILUENT* TO FORM A NOSE-LIMIT MIXTURE

From the examples shown in figure 7, it can be seen that the nose-limit mixture can be formed from a given atmosphere that either is explosive or can form explosive mixtures with air, by admixing the given atmosphere with one of the following: (1) A mixture (inert gas plus gas or gases) corresponding to one of a limited number of points in the abscissa axis (line *O–J*), (2) pure inert gas corresponding to point *O*, the origin; or (3) a mixture (inert gas plus air) corresponding to one of the points in the ordinate axis (line *O–A*). The composition of the mixture that can be used to form the nose-limit mixture will depend on whether angle θ is less than, equal to, or more than angle θ_{nose}. (See figs. 5 and 6 and pp. 65, 67, 68, and 85.)

Instances in which the above-stated mixtures may be employed as a *diluent* are possible not only by mixtures made artificially, but they may be formed by natural processes such as emanations of gas or the generation of gases in a sealed place.

In any event, if the potentially explosive atmosphere being diluted is considered as diluent-free and therefore corresponds to some point in line *A–J* of the graph, the volume (in percent) of inert gas used singly or as a portion of a *diluent* (inert gas plus air or inert gas plus other gases) to form the nose-limit mixture is the volume of inert gas considered as the diluent content of the nose-limit mixture.

Furthermore, the use of a *diluent*, composed of a given inert gas and air, to form the nose-limit mixture from potentially explosive atmospheres is restricted to those atmospheres satisfying condition 1, page 64, or when angle θ is less than angle θ_{nose}, and the gas-portion content (in percent) of the air-free composition of the given atmosphere is more than the critical gas-mixture value of the air-free original atmosphere (*J*, fig. 6).

The use of a mixture of carbon dioxide and air instead of pure carbon dioxide to form the nose-limit mixture when angle θ, as defined on page 65, is less than angle θ_{nose} (condition 1, p. 64), can best be shown by examples of the application of such a *diluent* to given atmospheres such as those represented by points P_2 and P_4, (fig. 7).

It can be seen in figure 7 that if a *diluent* composed of carbon dioxide and air is prepared and admixed with atmospheres P_2 and P_4, the successive mixtures formed correspond to points in lines P_2–*t* and P_4–*v*, respectively, and one of these mixtures, which is common to both lines, is the nose-limit mixture. Furthermore, these lines can be considered as tangent to the zone of explosive mixtures at point *d*, which corresponds to the nose-limit mixture.

DETERMINATION OF VOLUME AND COMPOSITION OF *DILUENT*

Both the composition and the amount of *diluent* required to form the nose-limit mixture from a given atmosphere can be determined either mathematically or graphically.

Because the compositions of atmospheres P_2 and P_4, (fig. 7), and of the nose-limit mixture (d) are known, formulas can be derived for the above-mentioned purposes by utilizing the relations existing between the analytic properties of these formulas and the geometric properties of figure 7, in which the atmospheres corresponding to points P_2, d, and t or points P_4, d, and v can be considered, as follows:

If we let

Gas_s = the gas-portion content (in percent) of the given atmosphere (P_2 or P_4),

Gas_{nose} = the gas-portion content (in percent) of the nose-limit mixture (d),

and

Diluent mixture$_{nose}$ = the total amount (in percent) of the *diluent* (t or v) that is composed of definite proportions of a given inert gas and air and that must be admixed with the given atmosphere to form the nose-limit mixture,

then

$$Diluent\ mixture_{nose} = \frac{(Gas_s - Gas_{nose})100}{Gas_s}\ \text{percent.} \qquad (61)$$

Also, if we let

$Atmos_{diluent}$ = the mixture composed of definite proportions of an inert gas and air, used as a *diluent*,

$Atmos_{air}$ = the air content (in percent) of the *diluent*,

and

$Atmos_{inert\ gas}$ = the inert-gas content (in percent) of the *diluent*,

then

$$Atmos_{diluent} = Atmos_{air} + Atmos_{inert\ gas} = 100\ \text{percent;}$$

or

$$Atmos_{inert\ gas} = 100 - Atmos_{air}.$$

From figure 7 it can be deduced that

$$\frac{(O_2)_{atmos} - (O_2)_s}{Gas_s} = \frac{(O_2)_{nose} - (O_2)_s}{Gas_s - Gas_{nose}},$$

where

$(O_2)_{atmos}$ is the oxygen content (in percent) of the *diluent*,

and

$(O_2)_{nose}$, $(O_2)_s$, Gas_s, and Gas_{nose} have the same meanings as before.

By transposition of the terms in the foregoing equation, we obtain

$$(O_2)_{atmos}=\frac{Gas_s[(O_2)_{nose}-(O_2)_s]}{Gas_s-Gas_{nose}}+(O_2)_s, \qquad (62A)$$

from which we can deduce

$$Atmos_{air}=\frac{100}{20.93}\left[\frac{Gas_s[(O_2)_{nose}-(O_2)_s]}{Gas_s-Gas_{nose}}+(O_2)_s\right]\text{ percent.} \qquad (62B)$$

Substituting the above-given value for the term $Atmos_{air}$ in the equation

$$Atmos_{inert\ gas}=100-Atmos_{air} \qquad (62C\text{–}1)$$

we obtain

$$Atmos_{inert\ gas}=100-\frac{100}{20.93}\left[\frac{Gas_s[(O_2)_{nose}-(O_2)_s]}{Gas_s-Gas_{nose}}+(O_2)_s\right]\text{ percent.} \qquad (62C\text{–}2)$$

It was shown on page 100 that the *diluent* being considered is composed of definite amounts (in percent) of the given inert gas and air. Therefore, the ratio of the real values of the components ($Atmos_{air}$ and $Atmos_{inert\ gas}$) of the *diluent* ($Atmos_{diluent}$) is a constant that expresses the mathematical ratio of these components in any proportion of the *diluent* that may be used to form a definite mixture from the given atmosphere.

On page 100, the volume (in percent of the whole) of the *diluent* used to form the nose-limit mixture from the given atmosphere was designated as *Diluent* $Mixture_{nose}$.

If we designate

Diluent $Mixture_{inert\ gas}$ = the inert-gas content (in percent) of *Diluent* $Mixture_{nose}$,

and

Diluent $Mixture_{air}$ = the air content (in percent) of *Diluent* $Mixture_{nose}$,

we can deduce from the above-stated relationships and in the derivation of formulas (61) and (62*B*) that

$$Diluent\ Mixture_{air}=\frac{(Diluent\ Mixture_{nose})\,(Atmos_{air})}{100}, \qquad (63a)$$

which can be used if the factors sought by formula (61) and (62B) have been determined, or formula (63) can be written as follows:

$$Diluent\ Mixture_{air}=\frac{100}{20.93}\left[(O_2)_{nose}-(O_2)_s+\frac{(O_2)_s(Gas_s-Gas_{nose})}{Gas_s}\right], \qquad (63b)$$

where *Diluent* $Mixture_{air}$ is the air content [in percent of the *diluent* (*Diluent* $Mixture_{nose}$)] admixed with the given atmosphere to form the nose-limit mixture.

The total volume (in percent) of *diluent,* or inert gas-air mixture (*Diluent* $Mixture_{nose}$), used to form the nose-limit mixture from a given atmosphere is composed of definite volumes of a given inert gas and air; the volume of either component is the difference between the total volume of *diluent* used and the volume of the other component; therefore, we can write

$$\textit{Diluent Mixture}_{nose} = \textit{Diluent Mixture}_{inert\ gas} + \textit{Diluent Mixture}_{air}, \qquad (63c)$$

from which we obtain

$$\textit{Diluent Mixture}_{inert\ gas} = \textit{Diluent Mixture}_{nose} - \textit{Diluent Mixture}_{air}, \qquad (64a)$$

which can be used when real values for the symbols, *Diluent Mixture*$_{nose}$ and *Diluent Mixture*$_{air}$, have been determined by formulas (61) and (63*a*) or (63*b*), respectively.

Formula (64*a*) can also be written as follows:

$$\textit{Diluent Mixture}_{inert\ gas} = \left[\frac{100(Gas_s - Gas_{nose})}{Gas_s}\right]\left[1 - \frac{(O_2)_s}{20.93}\right] - \frac{100}{20.93}\left[(O_2)_{nose} - (O_2)_s\right], \qquad (64b)$$

where the symbols have the same meanings as before.

Attention is called to the fact that the components (*Diluent Mixture*$_{air}$ and *Diluent Mixture*$_{inert\ gas}$) of the mixture *Diluent Mixture*$_{nose}$ can always be calculated by formulas (63*a*) to (64*b*), inclusive, and (66), regardless of the position of the point (in the graph) corresponding to the given atmosphere, as, for example, point P_2 or point P_4 (fig. 7).

If the given atmosphere with which a given *diluent* is admixed is either an original atmosphere or an atmosphere that contains diluent and is treated as an original atmosphere, the real value of *Diluent Mixture*$_{inert\ gas}$ is also the diluent content of the nose-limit mixture relating to the air-free composition of the given atmosphere; consequently, it is unnecessary to calculate the real value of *Diluent Mixture*$_{inert\ gas}$ by either formula (64*a*) or formula (64*b*) if the diluent content of the nose-limit mixture is known. It is also unnecessary to calculate the real value of *Diluent Mixture*$_{air}$ by either formula (63*a*) or formula (63*b*); instead, having determined the amount of *diluent* or real value of *Diluent Mixture*$_{nose}$, by formula (61), the following formula, which applies only to the special case mentioned, can be used:

$$\textit{Diluent Mixture}_{air} = \frac{(Gas_s - Gas_{nose})100}{Gas_s} - Dil_{nose}, \qquad (65)$$

where Gas_s is the gas-portion content (in percent) of the given atmosphere when considered as an original atmosphere (diluent-free),

and Gas_{nose} and Dil_{nose} are the gas-portion content and the diluent content, respectively, of the nose-limit mixture relating to the air-free composition of the given atmosphere.

Formula (65) can be used to determine the real value of *Diluent Mixture*$_{air}$ that concerns any original atmosphere corresponding to some point in the portion of line A–J intercepted by angle θ, as explained on page 65; for example, atmosphere P_2 (fig. 7).

If the given atmosphere, from which the nose-limit mixture can be formed by using a *diluent* composed of a given inert gas and air, corresponds to some point lying in either the zone of explosive mixtures or the zone of mixtures capable of forming explosive mixtures with air; for example, atmosphere P_4 (fig. 7), the real value of *Diluent Mixture*$_{air}$

cannot be determined by formula (65); instead, formulas (61), (62*B*), and (63*a*) or (63*b*) are used.

However, if atmosphere P_4 is considered as an original atmosphere corresponding to a point occupying the position of point P_2 in the graph, and the composition (by portions) of the nose-limit mixture relating to the air-free composition of atmosphere P_4 is determined, formula (65) can then be used. Calculations for that purpose have been made but are not given. Instead, the points corresponding to such a nose-limit mixture and the related critical gas mixture, or points d_1 and *w*, respectively, are shown in figure 7.

The application of formulas (61) to (65), inclusive, to determine the volume and composition of a *diluent* that contains the minimum volume of a given inert gas, and the maximum volume of air required to form a safe atmosphere (the nose-limit mixture) from an atmosphere capable of forming explosive mixtures with air, can be shown by the following example:

The procedure employed to determine the volume of *diluent* required to form the nose-limit mixture from a given atmosphere depends on whether the given atmosphere is diluent-free (an original atmosphere) or whether it contains diluent.

We will now consider the use of a *diluent* with an original atmosphere:

EXAMPLE 1. An original atmosphere (example 1, p. 70) corresponding to point P_2, (fig. 7) consists of a gas portion (Gas_s) composed of 85.67 percent of the percentages of the constituents composing atmosphere *J*, 14.33 percent of air (Air_s), and no diluent ($Inert\ gas_{add-s}$), or 11.67 percent each of carbon monoxide, methane, and hydrogen; 3.00 percent of oxygen $(O_2)_s$; and 62.00 percent of nitrogen $(N_2)_{ts}$. (See p. 96.)

The nose-limit mixture (*d*, fig. 7) relating to atmosphere P_2 has been found on page 97 to consist of a gas portion (Gas_{nose}) composed of 17.85 percent of the percentages of the constituents composing atmosphere *J*, 49.82 percent of air (Air_{nose}), and 32.34 percent of carbon dioxide ($Dil_{nose-CO_2}$), or 2.43 percent each of carbon monoxide, methane, and hydrogen; 10.43 percent of oxygen $[(O_2)_{nose}]$; 49.95 percent of nitrogen $[(N_2)_{t-nose}]$; and 32.34 percent of carbon dioxide $[(CO_2)_{t-nose}]$.

To find the volume of *diluent* composed of air and the minimum volume of carbon dioxide that, when admixed with atmosphere P_2, (fig. 7) will form an atmosphere (the nose-limit mixture) incapable of forming explosive mixtures with air, we use formula (61), or

$$Diluent\ Mixture_{nose}=\frac{(Gas_s-Gas_{nose})100}{Gas_s}\text{ percent.} \qquad (61)$$

Substituting the above-given real values for the symbols, we find

$$Diluent\ Mixture_{nose}=\frac{(85.67-17.85)\times 100}{85.67}\text{ percent,}$$

$$=79.16 \text{ percent of } \textit{diluent} \text{ composed of carbon dioxide and air.}$$

To find the volumes (in percent) of inert gas and air composing the atmosphere used as a *diluent*, we substitute the above-given real values for the symbols in formula (62*B*):

$$Atmos_{air}=\frac{100}{20.93}\left[\frac{Gas_s[(O_2)_{nose}-(O_2)_s]}{Gas_s-Gas_{nose}}+(O_2)_s\right]\text{ percent,} \qquad (62B)$$

$$=\frac{100}{20.93}\left[\frac{85.67\times(10.43-3)}{85.67-17.85}+3\right],$$

$$=\frac{100}{20.93}\left[\frac{85.67\times 7.43}{67.82}+3\right],$$

$$=59.14 \text{ percent of air, of which 12.38 percent is oxygen and 36.76 percent is nitrogen.}$$

Because the air content ($Atmos_{air}$) of the *diluent* is 59.14 percent, the inert-gas content (in percent) is found by formula (62C–1):

$$\begin{aligned} Atmos_{inert\ gas} &= 100 - Atmos_{air}, \qquad (62C\text{-}1)\\ &= (100-59.14)\text{ percent},\\ &= 40.86\text{ percent of carbon dioxide.} \end{aligned}$$

It has been shown on page 103 that the total volume ($Diluent\ Mixture_{nose}$) of *diluent* required to form the nose-limit mixture from atmosphere P_2 is 79.16 percent; and because 59.14 percent of the *diluent* used is air, we find the volume ($Diluent\ Mixture_{air}$) of air by formula (63*a*), or

$$\begin{aligned} Diluent\ Mixture_{air} &= \frac{(Atmos_{air})\ (Diluent\ Mixture_{nose})}{100}, \qquad (63a)\\ &= \frac{(59.14)(79.16)}{100}\text{ percent},\\ &= 46.82\text{ percent of air.} \end{aligned}$$

To determine the real value of the inert-gas component of the total volume of *diluent* mixed with atmosphere P_2 to form the nose-limit mixture, we can use formula (64*a*), or

$$\begin{aligned} Diluent\ Mixture_{inert\ gas} &= Diluent\ Mixture_{nose} - Diluent\ Mixture_{air}, \qquad (64a)\\ &= (79.16-46.82)\text{ percent},\\ &= 32.34\text{ percent of carbon dioxide.} \end{aligned}$$

It is observed that the inert-gas component (32.34 percent carbon dioxide) of the total volume of *diluent* admixed with atmosphere P_2 is also the diluent content of the nose-limit mixture, for the reason that atmosphere P_2 (fig. 7) is diluent-free (see p.103).

Having previously determined the real value (79.16) of $Diluent\ Mixture_{nose}$, formula (65) can also be used to determine the real value of $Diluent\ Mixture_{air}$ instead of formula (63*a*).

By substituting the real values of $Diluent\ Mixture_{nose}$ and $Dil_{nose-CO_2}$ for the symbols in formula (65), we find

$$\begin{aligned} Diluent\ Mixture_{air} &= Diluent\ Mixture_{nose} - Dil_{nose-CO_2}, \qquad (65)\\ &= (79.16-32.34)\text{ percent},\\ &= 46.82\text{ percent of air.} \end{aligned}$$

Summarizing the foregoing data, we find that a mixture consisting of 59.14 percent of air and 40.86 percent of carbon dioxide and corresponding to point *t*, figure 7, will, if introduced into the place occupied by atmosphere P_2 in the amount of 79.16 percent of the volume of this atmosphere and allowed to mix with the gas remaining, form atmosphere *d* (nose-limit mixture), which is just incapable of forming an explosive mixture with air.

The actual volume of *diluent* necessary to form the nose-limit mixture (*d*) from atmosphere P_2 has been found to be 79.16 percent of the total volume of the place occupied by atmosphere P_2. The volume of air required for the mixture used as a *diluent* would be 46.82 percent, and the volume of carbon dioxide, 32.34 percent of the volume of the place occupied by atmosphere P_2.

Reducing the foregoing figures to a volumetric yardstick, we find that for every 1,000 cubic feet of the place occupied by atmosphere P_2, there would be required 791.6 cubic feet of *diluent,* of which 468.2 cubic feet is air and 323.4 cubic feet is carbon dioxide. It is interesting to observe at this point that, whereas 791.6 cubic feet of the *diluent* composed of 468.2 cubic feet of air and 323.4 cubic feet of carbon dioxide is required to form atmosphere *d,* figure 7, from atmosphere

P_2, if pure carbon dioxide were used, 608.1 cubic feet of this inert gas would be necessary to form atmosphere *b*, which is just incapable of forming explosive mixtures with air. (See p. 96.)

GRAPHIC METHOD OF DETERMINING *DILUENT* REQUIRED TO FORM NOSE-LIMIT MIXTURE FROM ORIGINAL ATMOSPHERES

To determine graphically from figure 7 the factors relating to the formation of the nose-limit mixture by admixing a *diluent* composed of air and carbon dioxide with an original atmosphere, we can use atmosphere P_2 and the above-given *diluent* as an example.

Draw line P_2–t through point *d*, the nose-limit mixture. Point *t* corresponds to the given mixture used as a *diluent* ($Atmos_{dil}$). The real values of the air component ($Atmos_{air}$) and oxygen content ($(O_2)_{atmos}$) are seen at once to be 59.14 percent and 12.38 percent, respectively. To find the real value of the inert-gas component ($Atmos_{inert\ gas}$) we draw line *t*–*u* parallel to line *A*–*J* and intersecting the abscissa axis *O*–*J* at point *u*, which shows that the inert-gas component is 40.86 percent of carbon dioxide.

To find the volume of *diluent* ($Diluent\ Mixture_{nose}$) required to form the nose-limit mixture (*d*) from atmosphere P_2, the real value of the inert-gas component is first found by drawing line *d*–*m* parallel to line *A*–*J* and intersecting the abscissa axis *O*–*J* at point *m*, which shows that the inert-gas component is 32.34 percent of carbon dioxide.

The real values of the volume ($Diluent\ Mixture_{nose}$) of *diluent* and the air component ($Diluent\ Mixture_{air}$) of it cannot be determined graphically but can be calculated by either formula (66) or formula (67) and formula (63*c*), page 102.

We have shown on page 101 that the air component and the inert-gas component of the total volume of *diluent* used to form the nose-limit mixture from a given atmosphere exist in the same ratio as they exist in the mixture used as a *diluent*. Therefore, we can write

$$\frac{Diluent\ Mixture_{air}}{Diluent\ Mixture_{inert\ gas}}=\frac{Atmos_{air}}{Atmos_{inert\ gas}}, \tag{66}$$

which, by clearing of fractions, becomes

$$Diluent\ Mixture_{air}=\frac{(Atmos_{air})\,(Diluent\ Mixture_{inert\ gas})}{Atmos_{inert\ gas}}. \tag{67}$$

By substituting the real values (obtained graphically) for the symbols in formula (67), we find

$$Diluent\ Mixture_{air}=\frac{59.14\times 32.34}{40.86}\text{ percent,}$$

$$=46.82\text{ percent of air.}$$

The total volume ($Diluent\ Mixture_{nose}$) of *diluent* required is then found by substituting the foregoing real values for the symbols in formula (63*c*), or

$$Diluent\ Mixture_{nose}=Diluent\ Mixture_{inert\ gas}+Diluent\ Mixture_{air}, \tag{63c}$$

$$=(32.34+46.82)\text{ percent,}$$

$$=79.16\text{ percent of } \textit{diluent}\text{, or carbon dioxide plus air.}$$

MATHEMATICAL METHOD OF DETERMINING VOLUME OF *DILUENT* REQUIRED TO FORM NOSE-LIMIT MIXTURE FROM ATMOSPHERES CONTAINING DILUENT

To determine the volume of *diluent* required to form the nose-limit mixture from a given atmosphere containing diluent, or that has been formed by admixing air and carbon dioxide with atmosphere *J* (fig. 7), we can consider the following example:

Example 2. A given atmosphere (example 4, p. 96) corresponding to point P_4 (fig. 7) consists of a gas portion (Gas_s) composed of 60.00 percent of the percentages of the constituents composing atmosphere *J*, 14.33 percent of air (Air_s), and 25.67 percent of carbon dioxide (diluent), or 8.17 percent each of carbon monoxide, methane, and hydrogen; 3.00 percent of oxygen ($(O_2)_s$); 46.82 percent of nitrogen ($(N_2)_{ts}$); and 25.67 percent of carbon dioxide ($(CO_2)_{ts}$).

By substituting the above-given real values for the symbols in formulas (2), (3), and (4*b*), we find that the air-free composition of atmosphere P_4 is 9.54 percent each of carbon monoxide, methane, and hydrogen; 41.43 percent of nitrogen; and 29.96 percent of carbon dioxide. Such an air-free atmosphere is shown in figure 7 as the point in the abscissa axis (*O–J*) corresponding to the atmosphere having a gas-portion content of 70.04 percent and a diluent content of 29.96 percent of carbon dioxide.

The data relating to the nose-limit mixture (*d*, fig. 7) are given on page 103 and show that the real values of Gas_{nose} and O_{2nose} are 17.85 and 10.43 percent, respectively. The real values of the diluent content of the nose-limit mixture and the inert-gas component ($Diluent\ Mixture_{inert\ gas}$) of the total volume of *diluent* required to form the nose-limit mixture from atmosphere P_4 are not the same, for the reason that atmosphere P_4 is not diluent-free. Therefore, formula (65), page 102, does not apply for determining the real value of $Diluent\ Mixture_{air}$, and the following formulas are used in the order given to determine the real values of the factors desired.

Substituting the known real values and those now determined for the symbols in formulas (61), (62*B*), (62*C*–1), (63*a*), and (64*a*) in the order given, we find

$$Diluent\ Mixture_{nose}=\frac{(Gas_s-Gas_{nose})100}{Gas_s}\text{ percent,} \tag{61}$$

$$=\frac{(60-17.85)\times 100}{60},$$

$$=70.25\text{ percent of } diluent \text{ composed of carbon dioxide and air;}$$

$$Atmos_{air}=\frac{100}{20.93}\left[\frac{Gas_s[(O_2)_{nose}-(O_2)_s]}{Gas_s-Gas_{nose}}+(O_2)_s\right]\text{ percent,} \tag{62B}$$

$$=\frac{100}{20.93}\left[\frac{60\times(10.43-3)}{60-17.85}+3\right],$$

$$=\frac{100}{20.93}\left[\frac{445.80}{42.15}+3\right],$$

$$=\frac{100\times 13.58}{20.93}=64.87\text{ percent of air;}$$

$$Atmos_{inert\ gas}=100-Atmos_{air}, \tag{62C-1}$$

$$=100-64.87,$$

$$=35.13\text{ percent of carbon dioxide;}$$

$$Diluent\ Mixture_{air}=\frac{(Diluent\ Mixture_{nose})(Atmos_{air})}{100}, \tag{63a}$$

$$=\frac{70.25\times 64.87}{100},$$

$$=45.57\text{ percent of air;}$$

and

$$\text{Diluent Mixture}_{inert\ gas} = \text{Diluent Mixture}_{nose} - \text{Diluent Mixture}_{air}, \quad (64a)$$
$$= 70.25 - 45.57,$$
$$= 24.68 \text{ percent of carbon dioxide.}$$

Summarizing the above-given data, we find that, if a mixture composed of 35.13 percent of carbon dioxide and 64.87 percent of air is used as a *diluent* to displace 70.25 percent of the volume of the place occupied by atmosphere P_4 (fig. 7) and allowed to mix with the remainder portion of atmosphere P_4, atmosphere d (nose-limit mixture), which is just incapable of forming an explosive mixture with air, will be formed. The volume of *diluent* (carbon dioxide plus air) required is therefore 702.5 cubic feet for every 1,000 cubic feet of the place occupied by atmosphere P_4. This volume of *diluent* is composed of 246.8 cubic feet (24.68 percent) of carbon dioxide and 455.7 cubic feet (45.57 percent) of air.

Furthermore, if we consider atmosphere P_4 as an original atmosphere, the volume of carbon dioxide required for the foregoing purpose is also the diluent content of a nose-limit mixture corresponding to point d_1, which is superimposed on figure 7 to show the relationship between atmosphere d_1 and atmosphere P_4 calculated to an air-free basis. The point corresponding to the air-free composition of atmosphere P_4 in relation to point d_1 then corresponds in position to point J in a graph. Atmosphere d_1 consists of 25.5 percent of the percentages of constituents composing atmosphere P_4 calculated to an air-free basis (see p. 106), 49.82 percent of air, and 24.68 percent of carbon dioxide (diluent).

It is observed that the diluent content (24.68 percent of carbon dioxide) of atmosphere d_1 is the same as the carbon dioxide content of the *diluent* that, when admixed with atmosphere P_4, forms atmosphere d (fig. 7). This verifies the results obtained when atmosphere P_4 is considered as an original atmosphere. (See example 4, p. 96.)

GRAPHIC METHOD OF DETERMINING VOLUME OF *DILUENT* REQUIRED TO FORM NOSE-LIMIT MIXTURE FROM ATMOSPHERES CONTAINING DILUENT

To determine graphically the factors relating to the use of a given *diluent* to form the nose-limit mixture from atmosphere P_4 (fig. 7) and claculated by formulas (61), (62*B*), (62*C*-1), (63*a*), and (64*a*), we proceed as follows:

Draw line P_4–v through point d, the nose-limit mixture. Point v corresponds to the atmosphere used as the *diluent*, and the air component ($Atmos_{air}$) is seen at once to be 64.87 percent. The inert-gas component ($Atmos_{inert\ gas}$) is also shown to be 35.13 percent of carbon dioxide on the ordinate-axis (O–A) scale; however, this factor is usually determined by drawing line v–x parallel to line A–J and intersecting the abscissa axis (O–J) at point x, which shows that the inert-gas component ($Atmos_{inert\ gas}$) is 35.13 percent of carbon dioxide.

To find the volume ($Diluent\ Mixture_{nose}$) of *diluent* required to form atmosphere d from atmosphere P_4, the inert-gas component ($Diluent\ Mixture_{inert\ gas}$) is first found by drawing line P_4–P_2 parallel to the abscissa axis; we then consider atmosphere P_4 as occupying the position shown as point P_2 but having the same chemical composition as atmosphere P_4. A line drawn through point d parallel to the abscissa axis consists of points corresponding to atmospheres having the same oxygen content as atmosphere d. Line P_2–v is now drawn intersecting line d–d_1 at point d_1. Point d_1 therefore corresponds to an atmosphere having the same oxygen content (10.43 percent) as point d and consequently has a nose-limit value of the same magnitude, or 50.18 percent. The diluent content of atmosphere d_1 is found by drawing line d_1–y parallel to line A–J and intersecting the abscissa axis at point y, which shows that the diluent content is 24.68 percent of carbon dioxide, which is also the real value of the inert-gas component ($Diluent\ Mixture_{inert\ gas}$) desired.

As stated on page 105, the total volume ($Diluent\ Mixture_{nose}$) of *diluent* and the volume ($Diluent\ Mixture_{air}$) of its air component cannot be calculated directly by a graphic method from figure 7. Formulas (67), page 105, and (63*c*), page 102, are used for this purpose, as follows:

By substituting the above-determined real values (in percent) for the symbols in formulas (67) and (63*c*) when

$$Atmos_{air}=64.87,\ Diluent\ Mixture_{inert\ gas}=24.68,$$

and

$$Atmos_{inert\ gas}=35.13,$$

we find

$$Diluent\ Mixture_{air}=\frac{(Atmos_{air})(Diluent\ Mixture_{inert\ gas})}{Atmos_{inert\ gas}}, \quad (67)$$

$$=\frac{64.87\times 24.68}{35.13}\ \text{percent},$$

$$=45.57\ \text{percent of air;}$$

and

$$Diluent\ Mixture_{nose}=Diluent\ Mixture_{inert\ gas}+Diluent\ Mixture_{air}, \quad (63c)$$

$$=(24.68+45.57)\ \text{percent},$$

$$=70.25\ \text{percent of } \textit{diluent}, \text{ or carbon dioxide plus air.}$$

It is of interest to note that the critical gas-mixture value of atmosphere P_4 calculated to an air-free basis (see p. 106) is determined graphically in figure 7 by extending line A–d_1 to intersect the abscissa axis (O–J) at point *w*, which corresponds to a critical gas mixture having a gas-portion content of 50.75 percent, the critical gas-mixture value. The composition (by portions) of the critical gas mixture is 50.75 percent of the percentages of the constituents composing atmosphere P_4 calculated to an air-free basis and 49.25 percent of carbon dioxide (diluent); or (by constituents) 4.84-percent each of carbon monoxide, methane, and hydrogen; 21.03 percent of nitrogen; and 63.45 percent of carbon dioxide.

USE OF DIFFERENT VOLUMES OF *DILUENT* TO FORM SAFE FINAL ATMOSPHERES

Attention is called to the fact that inert gas-air mixtures cannot be used indiscriminately with safety to form a line of successive mixtures that passes through the point corresponding to the nose-limit mixture. If a portion of the atmosphere under seal can form explosive mixtures with air and contains more oxygen than the portion considered as the given atmosphere and less but analogous proportions of the other constituents, that portion of the atmosphere under seal can become explosive if the same *diluent* (inert gas plus air) that is safe to use with the given atmosphere is admixed with the portion containing more oxygen. This condition arises because that particular portion of the atmosphere initially contains too much air. Such a condition is illustrated in figure 8 (pocket) by considering the atmosphere corresponding to point *P* as the portion containing more oxygen than is contained in sample 65 (the given atmosphere), when both of these portions of the atmosphere under seal are admixed with a *diluent* having the composition of atmosphere *k*.

If a portion of the atmosphere under seal contains less oxygen than the portion considered as the given atmosphere and correspondingly larger proportions of the other constituents, the same unsafe conditions will prevail if the same volume of *diluent* (inert gas plus air) is used as was used with safety for the given atmosphere. The unsafe condition is because the portion of the atmosphere containing less oxygen than the given atmosphere also contains too much combustible gas, and the final atmosphere formed can form explosive mixtures with air. (See points *J* and *n*, fig. 8, pocket.)

The minimum volume of inert gas that can be admixed with air to form a *diluent* that cannot form an explosive mixture with a given atmosphere is found mathematically by formula (64*a*) or formula (64*b*). The air component of such a *diluent* is the maximum volume of air that can be used for the above purpose. The real value of the air component is determined mathematically by formula (63*a*) or formula (63*b*).

METHOD OF CALCULATING COMPOSITION OF ATMOSPHERES FORMED BY ADMIXING DIFFERENT VOLUMES OF *DILUENT* WITH GIVEN ATMOSPHERES

Because the successive mixtures formed when a *diluent* is admixed with a given atmosphere correspond to definite points in a straight line, a general equation can be written expressing a relationship between the geometric properties of the coordinates corresponding to the three portions that compose any final atmosphere formed and the analytic properties of the equation. (See pp. 94 and 95.)

$$Inert\ gas_{add-f.a.} = 100 - Air_{f.a.} - Gas_{f.a.}, \tag{68}$$

where $Inert\ gas_{add-f.a.}$, $Air_{f.a.}$, and $Gas_{f.a.}$ are the contents (in percent) of the diluent, air, and gas portions, respectively, of the final atmosphere formed by admixing a *diluent* with a given atmosphere.

If we assume that successive mixtures are formed by admixing a *diluent* with a given atmosphere such that one of them is the nose-limit mixture, a *diluent* having a definite composition must be used, and we can deduce that

$$Air_{f.a.} = \frac{100}{20.93}\left[(O_2)_s + \frac{(Gas_s - Gas_{f.a.})\,[(O_2)_{nose} - (O_2)_s]}{Gas_s - Gas_{nose}}\right], \tag{69}$$

where the symbols have the same meaning as before.

The real values of the three portions composing a final atmosphere can be determined mathematically by substituting known real values for the symbols in formulas (68) and (69) if the real value of any one of the three portions of the final atmosphere and the compositions (by portions) of the nose-limit mixture and given atmosphere are known.

Formula (62*B*), page 101, is a special case of formula (69) in which the factor, $Gas_{f.a.}$, is zero, and the factor, $Air_{f.a.}$, is equivalent to $Atmos_{air}$.

In order that the nose-limit mixture of atmosphere *J* in a graph can be formed by admixing a *diluent* composed of a given inert gas and air with a given atmosphere that is either explosive or capable of forming explosive mixtures with air, the given atmosphere must correspond to some point in the portions of the zones of explosive mixtures and atmospheres capable of forming explosive mixtures with air that are included by angle θ_{nose}.

Furthermore, the percentage of the inert gas present in the *diluent* used to form the nose-limit mixture is zero when the given atmosphere has the same composition as the critical gas mixture of atmosphere J and 100 percent when angle θ_{nose} equals angle θ. (See fig. 6, (pocket) and p. 99.)

It may sometimes be desirable to dilute an atmosphere that already contains additional inert gas (diluent) and corresponds in a graph to some point in the zone of mixtures capable of forming explosive mixtures with air. Examples of such atmospheres are represented by points P_1 and P_4 (fig. 7). Point sample 65 (fig. 8) corresponds to a diluent-free atmosphere.

DETERMINATION OF VOLUME OF *DILUENT* REQUIRED TO FORM MIXTURES JUST INCAPABLE OF FORMING EXPLOSIVE MIXTURES WITH AIR

When dealing with a potentially explosive atmosphere in a sealed area in which a source of ignition may be present, a common problem is to deal safely with portions of the atmosphere under seal that are capable of forming explosive mixtures with air.

Formulas (70) to (74), inclusive, have been derived to calculate the minimum volume of a given *diluent* that can be admixed with any given atmosphere capable of forming explosive mixtures with air to form a borderline extinctive mixture, where the *diluent* contains a given inert gas and air in such proportions that the final atmosphere formed is one of the atmospheres that corresponds to some point in the line of borderline extinctive mixtures. Such lines are *C. G. M. V.-d* (fig. 7) and $C.\,G.\,M.\,V._{CO_2}\text{-}nose_{CO_2}$ (fig. 8).

If a given inert gas ($Atmos_{inert\ gas}$) and air ($Atmos_{air}$) are admixed in known proportions to form a definite *diluent* ($Atmos_{dil}$), and real values for the critical gas-mixture value (*C. G. M. V.*), and oxygen content $(O_2)_s$ relating to the given atmosphere to be diluted are also known, we can assume that the appropriate conditions exist and deduce from a completed graph, such as figure 8, that

$$\frac{z}{\sin\tan^{-1}\dfrac{C.\,G.\,M.\,V.}{20.93}}=\frac{20.93-(O_2)_{atmos}}{\sin\left[90^\circ-\tan^{-1}\dfrac{C.\,G.\,M.\,V.}{20.93}-\tan^{-1}\dfrac{(O_2)_{atmos}-(O_2)_s}{Gas_s}\right]},$$

from which, by transposition, we obtain

$$z=\frac{[20.93-(O_2)_{atmos}]\left[\sin\tan^{-1}\dfrac{C.\,G.\,M.\,V.}{20.93}\right]}{\sin\left[90^\circ-\tan^{-1}\dfrac{C.\,G.\,M.\,V.}{20.93}-\tan^{-1}\dfrac{(O_2)_{atmos}-(O_2)_s}{Gas_s}\right]},\tag{70}$$

where z is the real number defining the length of the line (t–u) drawn between point t, which corresponds to a definite atmosphere ($Atmos_{dil}$) used as a *diluent* (inert gas plus air), and point u, which corresponds to the final atmosphere formed by admixing the *diluent* with the original atmosphere corresponding to point sample 65.

The final atmosphere (u) desired contains the minimum amount of the *diluent* necessary to form an atmosphere incapable of forming explosive mixtures with air.

If the real value of $(O_2)_{atmos}$ is less than the real value of $(O_2)_s$, $\tan^{-1} \frac{(O_2)_{atmos}-(O_2)_s}{Gas_s}$ in formula (70) is a minus angle and consequently must be added instead of subtracted in the portion of the formula within the parentheses.

In order to determine the composition of the final atmosphere (u) we can also deduce from figure 8 and the above data that

$$Gas_{f.a.}=z \cos \tan^{-1} \frac{(O_2)_{atmos}-(O_2)_s}{Gas_s}, \tag{71}$$

and

$$Air_{f.a.}=Atmos_{air}-\left[\left(z \sin \tan^{-1} \frac{(O_2)_{atmos}-(O_2)_s}{Gas_s}\right)\left(\frac{100}{20.93}\right)\right], \tag{72a}$$

or

$$Air_{f.a.}=\left[(Gas_s-Gas_{f.a.})\left(\frac{(O_2)_{atmos}-(O_2)_s}{Gas_s}\right)\left(\frac{100}{20.93}\right)\right]+Air_s. \tag{72b}$$

We have previously shown that

$$Inert\ gas_{add-f.a.}=100-Air_{f.a.}-Gas_{f.a.}, \tag{68}$$

from which, by substituting the real values found by formulas (71) and (72*a*) or (72*b*) for the symbols, we can find the diluent content ($Inert\ gas_{add\text{-}f.a.}$) of the final atmosphere desired.

To determine how much *diluent* (inert gas plus air) to admix with a given atmosphere to form a final atmosphere we have shown on page 70 that

$$Dil_{inert\ gas+air}=\frac{(Gas_s-Gas_{f.a.})100}{Gas_s}. \tag{47c–3}$$

Because the total amount of *diluent* ($Dil_{inert\ gas+air}$) admixed with the given atmosphere to form a final atmosphere is composed of an inert-gas component ($Inert\ gas_{Dil\text{-}inert\ gas+air}$) and an air component ($Air_{Dil\text{-}inert\ gas+air}$), and because the amounts (in percent of the whole) of these components exist in the same ratio as the inert-gas ($Atmos_{inert\ gas}$) and air ($Atmos_{air}$) components of the mixture ($Atmos_{Dil}$) used as a *diluent*, we can determine their real values by substituting the real value of $Dil_{inert\ gas+air}$ as determined by formula (47*c*–3) and known real values of $Atmos_{inert\ gas}$ and $Atmos_{air}$ for the symbols in the following formulas:

$$Inert\ gas_{dil\text{-}inert\ gas+air}=Dil_{inert\ gas+air}\left[\frac{Atmos_{inert\ gas}}{100}\right], \tag{73}$$

and

$$Air_{dil\text{-}inert\ gas+air}=Dil_{inert\ gas+air}\left[\frac{Atmos_{air}}{100}\right]. \tag{74}$$

DETERMINATION OF VOLUME OF *DILUENT* REQUIRED TO FORM LOWER-EXPLOSIVE-LIMIT MIXTURES

There may be occasions when it is not possible, necessary, or desirable to use a pure inert gas or a mixture of an inert gas and air (*diluent*) to form a line of successive mixtures that always passes below the nose.

If the inert gas or a *diluent* composed of that inert gas and air is admixed with a given atmosphere to form a final atmosphere just incapable of forming explosive mixtures with air, and the line corresponding to the successive mixtures formed passes through the line of lower-explosive-limit mixtures, such as line *Lower Limit–d* (fig. 7, pocket), the diluent content (in percent) of the final atmosphere is always less than the diluent content of the nose-limit mixture.

Conditions such as just stated exist when carbon dioxide is admixed with given atmospheres corresponding to points such as P_6 and P_7 (fig. 7); or when a *diluent* (k) composed of carbon dioxide and air is admixed with an original atmosphere corresponding to a point such as P (fig. 8, pocket). The compositions of the final atmospheres corresponding to points e and f (fig. 7) and point l_1 (fig. 8) can be determined from the graphs or calculated mathematically.

The line of lower-explosive-limit mixtures, such as *Nose*$_{CO_2}$—*Lower Limit* (fig. 8) is not strictly a straight line, and it is impracticable to determine exactly the compositions of all the mixtures that correspond to the points in a line of lower-explosive-limit mixtures because an infinite number of combinations are possible. The lower explosive limit of any mixture of a given air-free original atmosphere and additional inert gas (diluent), with air can be calculated in the manner that has been described.

As will be shown and for all practical purposes, the line of lower-explosive-limit mixtures in a graph can be assumed to be a straight line. The important fact is that when the composition of a final atmosphere, which is presumed to be a lower-explosive-limit mixture, is determined, the explosibility of that atmosphere can be readily verified in the manner shown and possibly determined experimentally.

The following formulas have been derived to determine the composition of the final atmosphere formed in the line of lower-explosive-limit mixtures when a *diluent* composed of a given inert gas and air is admixed with a given atmosphere. From figure 8 we can establish the mathematical relationships of the factors expressed by the symbols, which have the same meanings as before or are designated as follows:

z_1, z_2, and z_3 = symbols expressing mathematical relationships established by the factors shown in the formulas when the final atmosphere formed (*f. a.*) is a lower-explosive limit-mixture.

From a completed graph form such as figure 8 we can deduce that

$$z_1=[(O_2)_{L-L}-(O_2)_{atmos}]+(Gas_{L-L})\tan\tan^{-1}\frac{(O_2)_{atmos}-(O_2)_s}{Gas_s}, \tag{75}$$

$$z_2=\frac{(z_1)\left[\sin\tan^{-1}\dfrac{Gas_{nose}-Gas_{L-L}}{(O_2)_{L-L}-(O_2)_{nose}}\right]}{\sin\left[90^\circ-\tan^{-1}\dfrac{Gas_{nose}-Gas_{L-L}}{(O_2)_{L-L}-(O_2)_{nose}}-\tan^{-1}\dfrac{(O_2)_{atmos}-(O_2)_s}{Gas_s}\right]}, \tag{76}$$

$$z_3=z_2\sin\tan^{-1}\frac{(O_2)_{atmos}-(O_2)_s}{Gas_s}, \tag{77}$$

$$(O_2)_{f.\ a.}=(O_2)_{L-L}-z_l-z_3, \tag{78}$$

and

$$Gas_{f.\ a.}=Gas_{L-L}+z_2\cos\tan^{-1}\frac{(O_2)_{atmos}-(O_2)_s}{Gas_s}, \tag{79}$$

where the final atmosphere (*f. a.*) is a lower-explosive-limit mixture.

Having determined the oxygen content $(O_2)_{f.a.}$ of the final atmosphere, the air content $(Air_{f.a.})$ of that atmosphere can be determined by means of formula (1). The diluent content $(Inert\ gas_{add-f.a.})$ can then be determined by substituting the real values for $(Air)_{f.a.}$ and $(Gas_{f.a.})$ in formula (68).

If the oxygen content $(O_2)_{atmos}$ of the mixture used as a *diluent* is less than the oxygen content $(O_2)_s$ of the given atmosphere, the angles that these factors affect in the above formulas are minus angles, and as a consequence both the tangent and the sine functions of these angles have minus values. If the angle, tangent, or sine is a minus value, the terms that the function affects or in which it is present in formulas (75), (76), (77), and (78) are changed from plus (+) or minus (—) to the opposite sign, as the case may be. Furthermore, if the *diluent* consists of air or an inert gas, the real value of $(O_2)_{atmos}$ becomes 20.93 or zero, as the case may be.

Having found the real values of the three portions $(Gas_{f.a.}, Air_{f.a.},$ and $Dil_{add-inert\ gas-f.a.})$, we can determine the chemical composition of the final atmosphere, which should also be the chemical composition of the lower-explosive-limit mixture of the final atmosphere calculated to an air-free basis. To verify this assumption, we first calculate the air-free analysis of the final atmosphere and then determine the actual lower explosive limit of the air-free composition of the final atmosphere. (See pp. 49, 50, 52, and ref. 19.)

As the final atmosphere is supposed to be a lower-explosive-limit mixture, the percentage (K) of gases other than air in the final atmosphere should equal the real number defining the lower explosive limit of the final atmosphere calculated to an air-free basis. If the real value of K is less than the lower explosive limit (L_L), the final atmosphere is nonexplosive and cannot form explosive mixtures with air. If the real value of K is more than the lower explosive limit, the final atmosphere is either explosive or capable of forming explosive mixtures with air; therefore, to obtain a safe atmosphere more *diluent* must be admixed with either the above-mentioned final atmosphere or the above-mentioned given atmosphere to form a mixture having a real value of K that is less than the actual lower explosive limit (L_L) of the air-free composition of that mixture.

An example of the application of formulas (75) to (79), inclusive, and the determination of the explosibility of the final atmosphere formed are given on pages 156 to 158, inclusive, which refer to atmosphere 1_1 (fig. 8).

MAXIMUM SAFETY IN USE OF *DILUENT*

Maximum safety is assured when the *diluent* consists entirely of an inert gas (diluent) and when a sufficient volume is admixed with the given atmosphere to form a final atmosphere that (1) cannot form explosive mixtures with air and (2) has a diluent content (in percent) the same as the diluent content of the critical gas mixture or a gas-portion content $(Gas_{f.a.})$ the same as the gas-portion content (Gas_{L-L}) of the lower explosive-limit mixture. The same conditions regarding the composition of the final atmosphere should also be effected if the *diluent* consists of an inert gas and air.

It is desirable to use an inert gas, either singly or with air, in the safest manner possible to form a final atmosphere from a given atmosphere. However, the final atmosphere should contain enough but not an unnecessary volume of the given inert gas. Therefore, the final atmosphere selected should be the one that contains the least volume of additional inert gas. The right selection is governed by (1) the magnitude of the oxygen and gas-portion contents of the given atmosphere, which should be the critical portion of the sealed atmosphere, and (2) the relationships existing between the factors just given and similar factors of the critical gas mixture, nose-limit mixture, and lower-explosive-limit mixture. For example, in figure 8, when atmosphere r, which is composed of air and carbon dixoide, is used as a *diluent* of atmosphere J, the final atmosphere sought is atmosphere q instead of atmosphere q_1.

The use of air as part of a *diluent* to form extinctive atmospheres and atmospheres that are both nonexplosive and incapable of forming explosive mixtures with air has been discussed in detail for the reasons that there are times when it is advantageous to use such a *diluent*, impossible todo otherwise, or dangerous to do so. Such instances may arise when storage-battery equipment is present in an explosive atmosphere or in an atmosphere that may become explosive, and such equipment might cause an explosion by creating an electric arc; or when, if an active fire exists or a source of ignition is present, air is admitted inadvertently into dangerous sealed mine-fire areas. Again, there is the possibility that no source of ignition is present; or the possibility that blackdamp mixtures from old workings can be employed for fire-fighting purposes or that flue gases can be utilized for such purposes. In any event, it is dangerous to use a *diluent* containing oxygen when dealing with a potentially explosive atmosphere if a source of ignition is present or is likely to be introduced, unless the explosibility of the atmosphere, as well as the composition of the *diluent* and limitations on the use of same, are known, and the procedure employed is governed by safety considerations.

PART II. EXAMPLES OF PRACTICAL APPLICATIONS OF DATA RELATING TO EXPLOSIBILITY FACTORS OF MIXED GASES

AN ANTHRACITE MINE FIRE

On May 13, 1940, a fire was discovered in the Continental mine of the Hazle Brook Coal Co., Centralia, Pa. The mine could not be flooded with water. The fire could not be fought directly or sealed off by any method other than slushing with water and culm through boreholes. The history of this mine fire has been described by Ash, Jones, and Felegy (*3*).

The Continental mine fire is an outstanding example of (1) a mine fire that produced fire gases that, although highly explosive, contained little methane and (2) isolating a fire by means of a concrete tube (Schaefer lining) and ultimately extinguishing the fire by slushing the fire area with water and culm.

CONTROL OF FIRE-FIGHTING PROCEDURE

It has been stated that no laboratory work has been conducted to test the formulas used to calculate the critical gas-mixture value, the critical oxygen value, and the nose limit. However, these formulas were tested time and again in their application to the mine-fire atmosphere at this mine under actual mining conditions.

The experience at the Continental mine fire and at subsequent mine fires has proved that the formulas apply to atmospheres that consist of carbon monoxide, methane, hydrogen, oxygen, nitrogen, and carbon dioxide. At the Continental mine fire, explosions did not occur when the oxygen content of the mine-fire atmosphere was less than the critical oxygen value calculated by the pertinent formulas; when it was more, explosions did occur. Several hundred samples of the mine-fire atmosphere were taken and analyzed, and the procedure followed at the fire was governed by the conditions indicated by the analyses.

The following data show the application of the formulas to determine the real values of the factors on explosibility that relate to the mine-fire atmosphere at the Continental mine.

Analyses of typical samples of the mine-fire atmosphere at the Continental mine fire are shown in table 7.

CALCULATIONS TO CONTROL ATMOSPHERES CONTACTING ACTIVE FIRE

Borehole 22, table 7, connected directly with the active fire, and samples 62, 63, and 65 are typical of the mine-fire atmosphere from which sample 25 was formed. Calculations based on sample 65, which has a gas-portion content of 96.656 percent and an air content of 3.344 percent, were used to control the procedure employed to slush the mine-fire area as long as the calculations indicated that this sample represented the most hazardous conditions. A graph was prepared by plotting the results on a graph form similar to figure

TABLE 7.—*Analyses of typical samples of the mine-fire atmosphere at Continental mine*

Sample No.	Date, 1940	Composition of atmosphere, percent by volume							Ratio H_2: Total combustible gases (percent)
		CO_2	O_2	CO	CH_4	H_2	N_2	Total combustible gases	
65721	May 19	9.53	8.13	0.91	0.08	0.41	80.94	1.40	29.25
8	May 21	3.7	15.3	.6	.00	.6	79.8	1.20	45.00
21	May 24	6.5	11.5	1.1	.00	1.5	79.4	2.60	57.70
25	May 24	6.9	10.3	1.4	.00	1.9	79.5	3.30	57.60
60	June 4	12.3	2.9	1.0	.10	1.5	82.2	2.60	57.70
62	June 5	13.0	.4	4.5	.90	7.0	74.2	12.40	56.45
63	June 5	12.6	.2	6.6	1.00	8.8	70.8	16.40	53.65
65	June 5	12.5	.7	6.6	.80	9.9	69.5	17.30	57.20
67	June 5	11.1	4.3	2.3	.00	2.7	79.6	5.00	54.00
72	June 7	2.2	18.0	.3	.10	1.0	78.4	1.40	71.40
76	June 8	14.0	2.6	.4	1.00	8.3	73.7	9.70	85.60

Sample No.	Date, 1940	Air-free composition, percent by volume					Ratio H_2: CO	Calculated limits of explosibility air-free mixture		Oxygen content within which air-free mixtures are explosive with air (percent)		Location of sampling station
		CO_2	CO	CH_4	H_2	N_2		Lower	Upper	From—	To—	
65721	May 19	15.6	1.5	0.1	0.7	82.1	0.47	(1)	(1)	-------	------	Fire seal, 1st level, rock tunnel.
8	May 21	13.7	2.2	.0	2.2	81.9	1.00	(1)	(1)	-------	------	Do.
21	May 24	14.4	2.4	.0	3.3	79.9	1.37	(1)	(1)	-------	------	At fissure in Mammoth-bed stripping.
25	May 24	13.6	2.8	.0	3.7	79.9	1.32	(1)	(1)	-------	------	Do.
60	June 4	14.2	1.2	.1	1.7	82.8	1.42	(1)	(1)	-------	------	At top of borehole 20 (upcasting).
62	June 5	13.2	4.6	.9	7.1	74.2	1.54	48.1	69.9	6.3	10.9	At top of borehole 22 (upcasting).
63	June 5	12.7	6.7	1.0	8.9	70.7	1.33	37.0	69.5	6.4	13.2	Do.
65	June 5	12.9	6.8	.8	10.2	69.3	1.50	33.5	70.0	6.3	13.9	Do.
67	June 5	14.0	2.9	.0	3.4	79.7	1.17	(1)	(1)	-------	------	Same as sample 60.
72	June 7	15.7	2.1	.7	7.1	74.4	3.38	54.4	69.9	6.3	9.4	In back chute, No. 10 tunnel, 2d level.
76	June 8	16.0	.5	1.1	9.5	72.9	19.00	42.6	68.7	6.6	12.0	Do.

[1] Nonexplosive with air.

2 (pocket). Figure 8 (pocket) shows graphically the data derived from the following calculations and was prepared in the manner that has been described.

Sample 65, which corresponds to point sample 65, (fig. 8), is calculated to an air-free basis (atmosphere *J*) by means of formulas (2), (3), and (4). The chemical composition of atmosphere *J* is carbon monoxide (A_1) 6.8 percent, methane (B_1) 0.8 percent, hydrogen $(H_2)_1$ 10.2 percent, nitrogen $(N_2)_1$ 69.3 percent, and carbon dioxide (D_1) 12.9 percent. (See table 7.)

$$\text{As } 10.2(H_2)_1 = 10.2 \times 10.2 = 104.04, \text{ and } D_1 = 12.9;$$

therefore,

$$10.2(H_2)_1, \text{ or } 104.04, > 12.9, \text{ or } D_1,$$

and formula (10) (p. 25) is used to calculate the real value of $C.\,G.\,M.\,V._{N_2}$.

By substituting the foregoing real values for A_1, B_1, $(H_2)_1$, and D_1 in formula (10), we find:

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{5.15A_1+7B_1+17.55(H_2)_1-0.6225D_1}, \qquad (10)$$

$$=\frac{10{,}000}{(5.15\times 6.8)+(7\times 0.8)+(17.55\times 10.2)-(0.6225\times 12.9)},$$

$$=\frac{10{,}000}{211.60}=47.26 \text{ percent.}$$

Because the critical gas-mixture value, or 47.26, is less than 100, the mine-fire atmosphere corresponding to point *J* (fig. 8), has explosive limits with air. It can be readily seen in figure 8 that the original atmosphere, sample 65, can also form explosive mixtures with air.

The significance of the critical gas-mixture value ($C.\ G.\ M.\ V._{N_2}$) lies in the fact that any air-free mixture containing more than 47.26 percent of the percentages of the constituents composing atmosphere *J* is capable of forming explosive mixture with air. The composition of the critical gas mixture can be determined by formula (22*A*), page 31, or found directly from figure 8; it is given in table 9, page 120.

The upper and the lower explosive limits of sample 65 calculated to an air-free basis (point *J*, fig. 8) were determined according to the method described on pages 49 to 52, inclusive. The calculations are summarized in table 8.

TABLE 8.—*Summary of calculations applied to mine-fire atmosphere, sample 65, to determine limits of explosibility*

Symbol in formula	Constituent	Air-free combustible gases (percent)	Inert gases paired with combustible gases (percent)		Total amount of inert gas plus combustible gas (percent)	Ratio of inert gas to combustible gas [1]	Explosive limits (percent of air-free gas mixture in air) [1]		Oxygen in limit mixtures		
			$CO_2(D_1)$	$(N_2)(N_2)_1$			Lower	Upper	Lower	Upper	Nose
A_1	CO	6.8		23.80	30.60	3.50	61.5	72.5			
B_1	CH_4	.8		4.00	4.80	5.00	33.0	40.5			
$(H_2)_1$	H_2	8.05		41.50	49.55	5.18	26.4	76.0			
		2.15	12.90		15.05	6.00	33.0	64.0			
Total		[2] 17.8	[2] 12.90	[2] 69.30	100.00		[2] 33.5	[2] 70.0	[2] 13.92	[2] 6.28	[2] 5.88

[1] Tables 6 and 7; and ref. 19, tables 8 to 13, inclusive.
[2] Calculated.

The upper explosive limit of atmosphere *J* (fig. 8) is found to be 70 percent and the lower explosive limit 33.5 percent. The upper explosive limit consists of 70 percent of the percentages of the constituents composing atmosphere *J* and 30 percent of air, of which 6.28 percent is oxygen; and the lower explosive limit consists of 33.5 percent of the percentages of the constituents composing atmosphere *J* and 66.5 percent of air, of which 13.92 percent is oxygen. (See table 9.)

DETERMINATION OF NOSE LIMIT AND CRITICAL OXYGEN VALUE

To determine the critical oxygen value relating to all possible mixtures of atmosphere *J*, air, and nitrogen, it is necessary to calculate the nose limit.

It was shown on page 116 that

$$10.2(H_2)_1 > D_1;$$

therefore, formula (25), page 39, is used.

By substituting the real values of A_1, B_1, $(H_2)_1$, and D_1, in table 8, for the symbols in formula (25), we find

$$L_{nose-N_2}=\frac{5.15A_1+7B_1+17.55(H_2)_1-0.6225D_1}{\frac{5.15A_1}{71}+\frac{7B_1}{41.5}+\frac{17.55(H_2)_1}{75.5}-0.00434D_1}, \qquad (25)$$

$$=\frac{(5.15\times6.8)+(7\times0.8)+(17.55\times10.2)-(0.6225+12.9)}{\frac{5.15\times6.8}{71}+\frac{7\times0.8}{41.5}+\frac{17.55\times10.2}{75.5}-(0.00434\times12.9)},$$

$$=\frac{211.60}{2.943},$$

$=71.90$ persent, the nose limit.

We now find the air and oxygen contents of the nose-limit mixture by substituting the real value (71.9) of the nose limit (L_{nose-N_2}) for that symbol in formulas (31*A*) and (31*B*) (p. 42):

$$Air_{nose-N_2}=100-L_{nose-N_2}, \qquad (31A)$$

$=(100-71.9)$ percent,

$=28.1$ percent, air content;

and

$$(O_2)_{nose-N_2}=0.2093\ (100-L_{nose-N_2}), \qquad (31B)$$

$=0.2093\ \ (100-71.9)$,

$=0.2093\times28.1$,

$=5.88$ percent, oxygen content of the nose-limit mixture.

The air and oxygen contents can also be found from table 5, page 43, which gives the air and oxygen contents of limit mixtures. The real value of the nose limit is 71.9 percent, and from the table the air and oxygen contents of a limit mixture having a limit value of 71.9 percent are found to be 28.1 and 5.88 percent, respectively.

The air and oxygen contents of the nose-limit mixture can be determined graphically from figure 8 as follows: Plot point *a* in the abscissa axis (*O–J*) at the point corresponding to an atmosphere having a gas-portion content of 71.9 percent (the nose limit). Draw line *a–b* parallel to the ordinate axis (*O–A*) and intersecting line *J–A* at point *b* corresponding to an original atmosphere that has a gas-portion content of 71.9 percent and an air content of 28.1 percent, of which 5.88 percent is oxygen.

The volume of air in any limit mixture is also equivalent to the real value expressing the volume of diluent contained in any air-free atmosphere having a gas-portion content (in percent) that is the same as the real number defining the limit value. Therefore, the volume of air in a limit mixture of 71.9 percent is found to be 28.1 percent, from figure 8, by referring to the scale on the abscissa axis (*O–J*).

It was shown in the section on the Critical Oxygen Value (pp. 14 and 15) that a safe real value for this factor can be taken as 0.5 percent less than the oxygen content (in percent) of the nose-limit mixture, considering nitrogen as the diluent.

Having found the oxygen content of the nose-limit mixture to be 5.88 percent, the critical oxygen value can be safely taken as

$$(5.88-0.50)\text{ percent,}$$

or

$$5.38\text{ percent of oxygen.}$$

The significance of the critical oxygen value of 5.38 percent is that an explosion could not, and did not, occur in the fire area at the Continental mine, regardless of the presence of an active fire, as long as the oxygen contents of the potentially explosive portions of the mine-fire atmosphere in contact with the fire were maintained less than 5.38 percent.

The point corresponding to the nose-limit mixture and the composition of this mixture are found from figure 8, as follows: Draw line *b–c* parallel to the abscissa axis (*O–J*) and intersecting the ordinate axis (*O–A*) at point *c*. Line *b–c* corresponds to all possible mixtures of atmosphere *J*, air, and nitrogen that contain 5.88 percent of oxygen. One of these mixtures is the nose-limit mixture. Draw line *C. G. M. V.–A*, which corresponds to all possible mixtures of the critical gas mixture and air. One of these mixtures is also the nose-limit mixture. The point of intersection of lines *b–c* and *C. G. M. V.–A*, therefore is the point corresponding to the nose-limit mixture.

To determine graphically the composition of the nose-limit mixture, draw line *Nose–d* parallel to the ordinate axis and intersecting the abscissa axis at point *d*, which corresponds to a mixture containing 33.98 percent (gas-portion content) of the percentages of the constituents composing atmosphere *J*. The diluent content is found by drawing line *Nose–e* parallel to line *A–J* and intersecting the abscissa axis at point *e*, which shows that the diluent content is 37.92 percent of nitrogen. The air content (28.1 percent) of the nose-limit mixture has been found on page 118.

The composition of the nose-limit mixture can also be determined mathematically by means of formulas (31*A*), (31*B*), (31*C*), (32*B*), (33*A*), and (34*B*). Formula (36) can also be used instead of formula (34*B*). The compositions of the lower- and the upper-explosive-limit mixtures and the compositions of the critical gas mixture and the nose-limit mixture when nitrogen is considered as the diluent are given in table 9.

DETERMINATION OF LOWER EXPLOSIVE LIMIT FROM NOSE LIMIT

It was stated on page 52 that, for all practical purposes and erring on the safe side, the gas-portion content of the lower-explosive-limit mixture can be taken as 1 percent less than the gas-portion content of the nose-limit mixture when nitrogen is used as the diluent.

Applying the above statement when the gas-portion content of the

TABLE 9.—*Composition (in percent) of lower-, and upper-explosive-limit mixtures, critical gas mixture, nose-limit mixture, and atmosphere J (fig. 8) when nitrogen is used as diluent*

Constituent	Explosive limits		Nose-limit mixture	Critical gas mixture	Air-free original atmosphere (*J*, fig. 8)
	Lower	Upper			
Gas portion:					
Carbon monoxide	2.28	4.76	2.31	3.21	6.8
Methane	.27	.56	.27	.38	.8
Hydrogen	3.42	7.14	3.47	4.82	10.2
Carbon dioxide	4.32	9.03	4.38	6.10	12.9
Nitrogen	23.21	48.51	23.55	32.75	69.3
Total	33.50	70.00	33.98	47.26	100.0
Air portion:					
Oxygen	13.92	6.28	5.88	.00	.0
Nitrogen	52.58	23.72	22.22	.00	.0
Total	66.50	30.00	28.10	.00	.0
Diluent: Nitrogen	.00	.00	37.92	52.74	.0
Total nitrogen	75.79	72.23	83.69	85.49	.0
Total	100.00	100.00	100.00	100.00	100.0

nose-limit mixture is 33.98 percent (table 9), we find that the gas-portion content of the lower-explosive-limit mixture is

$$(33.98-1.00) \text{ percent}=32.98 \text{ percent.}$$

Because the real value of the gas-portion content of the lower-explosive-limit mixture is also the real number defining the lower explosive limit, the lower explosive limit is 32.98 as compared with 33.50, the actual real value calculated by the conventional method explained on pages 49 to 52, inclusive. This value, only 0.52 percent different from the actual value, is on the safe side.

A reliable and safe real value of the lower explosive limit, the position of the point that corresponds to the lower-explosive-limit mixture in figure 8, and the composition of that mixture are determined graphically as follows:

Having plotted the point corresponding to the nose-limit mixture as explained on page 119, we plot the point in line *b–c* at a distance from the nose-limit mixture equivalent to 1 percent on the abscissa axis. This point corresponds to a mixture having a gas-portion content of 32.98 percent and an oxygen content of 5.88 percent. A line drawn through this point parallel to the ordinate axis (*O–A*) corresponds to all mixtures having a gas-portion content of 32.98 percent; it intersects the hypotenuse (*A–J*) at the point that corresponds to the lower-explosive-limit mixture, the limit value of which is 32.98 percent. The composition (by portions) of the lower-explosive-limit mixture is then found by the manner previously given to be: Gas portion 32.98 percent and air 67.02 percent, of which 14.03 percent is oxygen. The actual oxygen content is 13.92 percent (table 9, above).

MAINTAINING AND VERIFYING NONEXPLOSIBILITY OF FIRE GAS-AIR-BLACKDAMP MIXTURES

To prevent dangerous accumulations of mine-fire gases in adjacent old workings, the effluent gases from the fire were allowed to escape through a caved chute to the surface after being admixed with the blackdamp-air mixture that was bleeding from the adjacent old workings. This procedure was followed only when it was known that the highly heated fire gases could not form an explosive mixture with the blackdamp-air mixture. That an explosive mixture did not form can be shown by considering sample 25, table 7, as an original atmosphere and calculating the critical gas-mixture value of its air-free composition, which is: Carbon monoxide (A_1) 2.8 percent, methane (B_1) none, hydrogen $(H_2)_1$ 3.7 percent, nitrogen $(N_2)_1$ 79.9 percent, and carbon dioxide (D_1) 13.6 percent.

Because 10.2 $(H_2)_1$, or 37.74, $>$13.6, or D_1, case 1, page 24, applies, and we find the real value of $C.\ G.\ M.\ V._{N_2}$ by substituting the foregoing real values for the symbols in formula (10):

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{5.15A_1+7B_1+17.55(H_2)_1-0.6225D_1}, \qquad (10)$$

$$=\frac{10{,}000}{(5.15\times2.8)+(7\times0)+(17.55\times3.7)-(0.6225\times13.6)},$$

$$=\frac{10{,}000}{14.42+0.00+64.94-8.47}=\frac{10{,}000}{70.89}=141.6.$$

Because the critical gas-mixture value (141.6) is more than 100, neither atmosphere sample 25 nor its air-free composition can form explosive mixtures with air. Furthermore, no other calculations are necessary with regard to the portion of the atmosphere in the mine-fire area represented by sample 25. No explosions resulted when this atmosphere was admixed with air.

When a mine-fire area is sealed, the experience of the authors supports the advisability of maintaining a nonexplosive atmosphere on the return-air side of a mine fire by allowing, and aiding if possible, the inert gases from the fire to increase until the oxygen content of the atmosphere on that side is less than the critical oxygen value of that atmosphere. This is accomplished by (1) sealing first the openings on the return-air side of a fire area, (2) maintaining a nonexplosive atmosphere on the intake-air side of the fire, and (3) sealing the intake-air openings last.

At the Continental mine fire a fan was used as a force fan to keep positive pressure on the intake-air side of the fire and as a consequence prevent the formation of an explosive atmosphere while the fire was being fought directly, while the seals were being constructed, and until the last intake opening into the fire area was closed. (See p. 122.) In order to ascertain whether or not the above-mentioned conditions regarding nonexplosibility were in effect and thereby avert explosions, the atmosphere surrounding the active fire was sampled frequently. Calculations were made from the analyses to determine the factors relating to the explosibility of the atmosphere at the sampling points.

Sample 60, table 7, represents a typical return-air portion of the mine-fire atmosphere. It was taken in a borehole that was driven from the surface into the mine-fire area on the return-air side of the fire. Sample 60 was collected in a part of the fire area that was very hot and adjoined old workings. The atmosphere in the old workings, although deficient in oxygen, had an oxygen content more than that defining the critical oxygen value of the mine fire gas-air-nitrogen mixtures that were potentially explosive. Blackdamp and less than

0.02 percent of methane were present in the atmosphere contained in the old workings. It was extremely necessary to maintain a nonexplosive atmosphere wherever a source of ignition was present because of the existent conditions.

That the procedure adopted was effective was proved by the fact that no explosions occurred as long as the atmospheric conditions represented by sample 60 were maintained. That the atmosphere represented by sample 60 is nonexplosive is determined mathematically, as follows:

The composition of sample 60 calculated to an air-free basis is: Carbon dioxide (D_1) 14.2 percent, carbon monoxide (A_1) 1.2 percent, methane (B_1) 0.1 percent, hydrogen $(H_2)_1$ 1.7 percent, and nitrogen $(N_2)_1$ 82.8 percent.

We determine that

$$10.2(H_2)_1=10.2\times 1.7=17.34.$$

Because 10.2 $(H_2)_1$, or 17.34,>14.2, or D_1, we use formula (10), page 25, to determine the real value of $C.\ G.\ M.\ V._{N_2}$.

By substituting the real values given above for A_1, B_1, $(H_2)_1$, and D_1 in formula (10), we find

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{5.15A_1+7B_1+17.55(H_2)_1-0.6225D_1}, \qquad (10)$$

$$=\frac{10{,}000}{(5.15\times 1.2)+(7\times 0.1)+(17.55\times 1.7)-(0.6225\times 14.2)},$$

$$=\frac{10{,}000}{6.180+0.700+29.835-8.840},$$

$$=\frac{10{,}000}{27{,}875}=358.7.$$

Because the real value of $C.\ G.\ M.\ V._{N_2}$, or 358.7, is more than 100, the atmosphere represented by sample 60 cannot form explosive mixtures with air.

When conditions were in readiness to seal the fire area on the intake-air side of the fire, it was necessary to employ several men to complete placement of the fire stoppings quickly and safely. A highly explosive atmosphere, as shown by sample 63, table 7, could reach the fire if the ventilation was not controlled.

To protect the men and the mine at all times, fresh air was forced into the fire area (see p. 121). This maintained positive pressure on the normal intake-air side of the fire, prevented potentially explosive fire gases from backing over the fire and becoming explosive, and maintained an intake atmosphere represented by sample 72, table 7. This atmosphere was nonexplosive because it contained too much air. On the other hand, it is observed that the air-free composition of sample 72 is highly explosive when admixed with air.

Special precautions were taken to prevent a serious explosion when the last intake-air opening to the fire area was closed. A 6-inch pipe was led from the surface into the last intake-air opening to be sealed and in which a door, which could be closed automatically, had been placed. The men were removed from the mine, the forced-draft fan was stopped, the door in the stopping was closed, and a mixture of culm and water was forced into the fire area through the 6-inch pipe.

Sample 76, table 7, taken 24 hours later at the same sampling point as sample 72, showed that the oxygen content of the atmosphere behind the seal had been reduced from 18 percent to 2.6 percent. The critical oxygen value of 5.38 percent, page 119, was passed, and no danger from an explosion existed. The fire was then successfully extinguished by slushing with culm and water.

USE OF CARBON DIOXIDE GAS

To prevent the possibility of an explosion if the fan stopped, as well as to retard or extinguish the fire, an attempt was made to form an extinctive atmosphere on the intake-air side of the fire. This was done by forcing limestone dust into the highly heated fire area by means of a compressed-air-operated rock-dusting apparatus. This method was partly successful, but caving ground prevented the limestone dust from reaching the desired places and consequently from being calcined effectively.

The authors believe that this fire probably could have been extinguished in its early stages if an inert gas such as carbon dioxide had been available and was used.

It is of interest to know how much carbon dioxide would have been necessary to form mixtures that were nonexplosive and incapable of forming explosive mixtures with air under the conditions that existed at this fire after it had become widespread.

To determine the volume of carbon dioxide required for the above-stated purpose, it is necessary first to determine the critical gas-mixture value ($C.\ G.\ M.\ V._{CO_2}$), the nose limit ($L_{nose-CO_2}$), and the oxygen content $[(O_2)_{nose-CO_2}]$ of the nose-limit mixture when carbon dioxide instead of nitrogen is used as the diluent of the air-free original atmosphere being considered. Having determined these factors, a graph can be prepared and the volume of carbon dioxide determined either graphically or mathematically.

Figure 8 (pocket) shows the zones of explosive mixtures when either nitrogen or carbon dioxide is used as the diluent of the original atmosphere represented by sample 65, table 7.

The following procedure and calculations show the method of determining the factors relating to the use of carbon dioxide as the diluent.

DETERMINATION OF FACTORS IN EXPLOSIBILITY, USING CARBON DIOXIDE AS DILUENT

From table 7 we find that the composition of sample 65 calculated to an air-free basis is: Carbon monoxide (A_1) 6.8 percent, methane (B_1) 0.8 percent, hydrogen $(H_2)_1$ 10.2 percent, carbon dioxide (D_1) 12.9 percent, and nitrogen $(N_2)_1$ 69.3 percent. In figure 8 this atmosphere corresponds to point J.

As carbon dioxide is used as the diluent and 69.3 percent of nitrogen $(N_2)_1$ is present in the air-free original atmosphere, we determine the following relationships:

$$4.15A_1 = 4.15 \times 6.8 = 28.22,$$

and

$$4.15A_1, \text{ or } 28.22, < 69.3, \text{ or } (N_2)_1.$$

$$6B_1 = 6 \times 0.8 = 4.8,$$

and

$$6B_1, \text{ or } 4.8, < 69.3, \text{ or } (N_2)_1.$$

$$4.15A_1 + 6B_1 = 28.22 + 4.8 = 33.02,$$

and

$$(4.15A_1 + 6B_1), \text{ or } 33.02, < 69.3, \text{ or } (N_2)_1.$$

We have shown on page 83 that when such a relationship exists case 6 applies, and we use formula (58) to determine the critical gas-mixture value ($C.\ G.\ M.\ V._{CO_2}$) and formula (59) to determine the nose limit ($L_{nose-CO_2}$).

By substituting the real values given on page 123 for the symbols in formulas (58) and (59), which are

$$C.\ G.\ M.\ V._{CO_2} = \frac{10{,}000}{3.56A_1 + 4.70B_1 + 11.2(H_2)_1 + 0.3836(N_2)_1}, \tag{58}$$

and

$$L_{nose-CO_2} = \frac{3.56A_1 + 4.70B_1 + 11.2(H_2)_1 + 0.384(N_2)_1}{0.0614A_1 + 0.1526B_1 + \frac{11.2(H_2)_1}{59.5} + 0.00267(N_2)_1}; \tag{59}$$

we find

$$C.\ G.\ M.\ V._{CO_2} = \frac{10{,}000}{(3.56 \times 6.8) + (4.7 \times 0.8) + (11.2 \times 10.2) + (0.384 \times 69.3)},$$

$$= \frac{10{,}000}{168.82} = 59.23 \text{ percent;}$$

and

$$L_{nose-CO_2} = \frac{(3.56 \times 6.8) + (4.7 \times 0.8) + (11.2 \times 10.2) + (0.384 \times 69.3)}{(0.0614 \times 6.8) + (0.1526 \times 0.8) + \frac{(11.2 \times 10.2)}{59.5} + (0.00267 \times 69.3)},$$

$$= \frac{168.82}{2.645} = 63.83 \text{ percent.}$$

As the real values for $C.\ G.\ M.\ V._{CO_2}$ and $L_{nose-CO_2}$ have been found, the compositions of the critical gas mixture and the nose-limit mixture can be determined either mathematically by the formulas previously given or graphically in figure 8.

We have shown on page 31 that the real number defining the critical gas-mixture value is the real value of the gas-portion content (in percent). Expressed as a decimal fraction, it is the real value of symbol k, therefore,

$$\frac{C.\ G.\ M.\ V._{CO_2}}{100} = \frac{59.23}{100} = k = 0.5923.$$

To find the composition of the gas portion and the diluent content of the critical gas mixture, we substitute the above-given real values for the symbols in formulas (22*A*) and (22*B*), which are

$$Constituent_{C.\ G.\ M.} = k(Constituent_{air-free}), \tag{22A}$$

and

$$Dil_{C.\ G.\ M.} = 100 - C.\ G.\ M.\ V., \tag{22B}$$

and find

$A = kA_1 = 0.5923 \times 6.8 = 4.03$ percent of carbon monoxide,
$B = kB_1 = 0.5923 \times 0.8 = 0.47$ percent of methane,
$H_2 = k(H_2)_1 = 0.5923 \times 10.2 = 6.04$ percent of hydrogen,
$D_1 = kD_1 = 0.5923 \times 12.9 = 7.64$ percent of carbon dioxide,
$N_2 = k(N_2)_1 = 0.5923 \times 69.3 = 41.05$ percent of nitrogen,

and

$$Dil_{C.\ G.\ M.} = 100 - 59.23 \tag{22B}$$

$= 40.77$ percent of carbon dioxide, the diluent content of the critical gas mixture.

By definition, the critical gas mixture contains no air, and its diluent content can be found by substituting the real values of x and y in formula (47*a*), as follows, when $x = 59.23$ and $y = 0.00$:

$$(CO_2)_{dil} = 100 - \frac{100\ y}{20.93} - x, \tag{47a}$$

$= 100 - 0.00 - 59.23,$

$= 40.77$ percent of carbon dioxide.

By summarizing the foregoing data, we find that when carbon dioxide is used as the diluent, the critical gas mixture consists of 4.03 percent carbon monoxide, 0.47 percent methane, 6.04 percent hydrogen, 41.05 percent nitrogen, and 48.41 percent carbon dioxide, of which 7.64 percent is derived from atmosphere *J* and 40.77 percent is diluent.

The real values of the constituents of the gas portion of the critical gas mixture can be obtained directly from figure 8 by drawing line $C.\ G.\ M.\ V._{CO_2}$–J parallel to the ordinate axis (*O–A*).

To determine the composition, by portions and by constituents, of the nose-limit mixture, we substitute the real values already known or calculable for the symbols in the following formulas in the order given:

$$Air_{nose} = 100 - L_{nose-CO_2}, \tag{31A}$$

$= 100 - 63.83,$

$= 36.17$ percent, air content of nose-limit mixture;

$$(O_2)_{nose} = 0.2093\ (Air_{nose}), \tag{31B}$$

$= 0.2093 \times 36.17,$

$= 7.57$ percent of oxygen;

$$(N_2)_{air-nose} = 0.7907\ (Air_{nose}), \tag{31C}$$

$= 0.7907 \times 36.17,$

$= 28.60$ percent of nitrogen.

The gas-portion content of the nose limit mixture is the percentage of the gas-portion content of the critical gas mixture existing in the nose-limit mixture; therefore, to find its real value we use formula (32*A*) in the following form:

$$Gas_{nose}=\frac{(L_{nose-CO_2})\ (C.\ G.\ M.\ V._{CO_2})}{100}, \qquad (32A)$$

$$=\frac{63.83\times 59.23}{100},$$

$$=37.81 \text{ percent, gas-portion content of nose-limit mixture}$$

To find the composition of the gas portion we substitute the foregoing real value of Gas_{nose} and the real value of each constituent of atmosphere *J*, given on page 123, for the symbols in formula (32*A*), in the following form:

$$Constituent_{nose}=\frac{Gas_{nose}}{100}\ (Constituent_{air-free}), \qquad (32A)$$

$A_{nose}=0.3781\times 6.8=2.57$ percent of carbon monoxide,

$B_{nose}=0.3781\times 0.8=0.30$ percent of methane,

$(H_2)_{nose}=0.3781\times 10.2=3.86$ percent of hydrogen,

$D_{1-nose}=0.3781\times 12.9=4.88$ percent of carbon dioxide,

and

$(N_2)_{1-nose}=0.3781\times 69.3=26.20$ percent of nitrogen.

To find the diluent content we substitute the real values of the diluent content (40.77 percent) of the critical gas mixture and of $L_{nose-CO_2}$ for the symbols in formula (32*A*) in the following form:

$$Dil_{nose-CO_2}=\frac{(L_{nose-CO_2})\ (Dil_{C.\ G.\ M.-CO_2})}{100}, \qquad (32A)$$

$$=\frac{63.83\times 40.77}{100},$$

$$=26.02 \text{ percent of carbon dioxide.}$$

The diluent content can also be determined by substituting the real values, previously determined, for the symbols in formulas (33*B*), (47*a*), or (68) as follows, when

$y=(O_2)_{nose}$, $x=Gas_{nose}$, and

$Dil_{nose-CO_2}=(CO_2)_{dil}=Dil_{add-inert\ gas}$.

$$Dil_{nose-CO_2}=(L_{nose-CO_2})(1-k), \qquad (33B)$$

$$=63.83\times(1-0.5923),$$

$$=26.02 \text{ percent of carbon dioxide;}$$

$$(CO_2)_{dil}=100-\frac{100\ y}{20.93}-x, \qquad (47a)$$

$$=100-\frac{100\times 7.57}{20.93}-37.81,$$

$$=100-36.17-37.81,$$

$$=26.02 \text{ percent of carbon dioxide;}$$

$$Dil_{add-inert\ gas}=100-Air_{nose}-Gas_{nose}, \qquad (68)$$

$$=100-36.17-37.81,$$

$=26.02$ percent of carbon dioxide, diluent content of nose-limit mixture.

Summarizing the foregoing data, we find that the composition (by portions) of the nose-limit mixture is: 37.81 percent of the percentages of the constituents composing atmosphere *J*, figure 8 (gas portion), 36.17 percent of air (air portion), and 26.02 percent of carbon dioxide (diluent portion); and, by constituents: Carbon monoxide 2.57 percent, methane 0.30 percent, hydrogen 3.86 percent, oxygen 7.57 percent, nitrogen 54.80 percent, and carbon dioxide 30.90 percent.

The foregoing real values relating to the composition of the nose-limit mixture can be obtained graphically by the methods previously given and shown by the construction lines in figure 8.

DETERMINATION OF MINIMUM VOLUME OF CARBON DIOXIDE REQUIRED TO FORM ATMOSPHERE INCAPABLE OF FORMING EXPLOSIVE MIXTURES

Having determined real values for the critical gas-mixture value ($C.\ G.\ M.\ V._{CO_2}$) and nose limit ($L_{nose-CO_2}$) when carbon dioxide is used as the diluent, we can determine mathematically the minimum volume of carbon dioxide that must be admixed with the atmosphere represented by sample 65, table 7, to form a mixture (*g*, fig. 8) that is just incapable of forming explosive mixtures with air.

The first step in the procedure is to determine the composition, by portions, of the final atmosphere formed from the atmosphere sampled.

DETERMINATION OF COMPOSITION OF FINAL ATMOSPHERE

As atmosphere *g* (fig. 8) is to be formed from atmosphere sample 65 (table 7), atmosphere *g* is considered as the final atmosphere formed; and sample 65, which is diluent-free, is considered as an original atmosphere.

From table 7 and the data on page 125, we find that the oxygen content $(O_2)_{nose-CO_2}$ of the nose-limit mixture is 7.57 percent, which is more than the oxygen content $(O_2)_s$, or 0.7 percent, of atmosphere sample 65. Therefore, the line of successive mixtures formed by admixing carbon dioxide with sample 65 passes below the nose (condition 1, p. 64). One of these mixtures is atmosphere *g*.

To find the real values of the rectangular coordinates, *x* and *y*, which correspond to the gas-portion and oxygen contents, respectively, of atmosphere *g*, we substitute real values for the symbols in formulas (41) to (46*a*), inclusive, page 67, in the order given.

When

$C.\ G.\ M.\ V._{CO_2}=59.23$, $(O_2)_s=0.7$, and $Gas_s=96.656$ percent,

we find

$$\phi=\tan^{-1}\frac{C.\ G.\ M.\ V._{CO_2}}{20.93}, \qquad (41)$$

$$=\tan^{-1}\frac{59.23}{20.93},$$

$$=70°32'17''.$$

$$\theta=\tan^{-1}\frac{(O_2)_s}{Gas_s}, \qquad (42c)$$

$$=\tan^{-1}\frac{0.7}{96.656},$$

$$=0°24'54''.$$

$$\Delta = 90° + \theta - \phi, \tag{43}$$
$$= 90° + 0°24'54'' - 70°32'17'',$$
$$= 19°52'37''.$$

$$w = \frac{\sin\phi(20.93)}{\sin\Delta}, \tag{44}$$
$$= \frac{\sin 70°32'17''(20.93)}{\sin 19°52'37''},$$
$$= \frac{0.9428 \times 20.93}{0.34},$$
$$= 58.04.$$

$$x = w \cos\theta, \tag{45a}$$
$$= 58.04 (\cos 0°24'54''),$$

$= 58.04 \times 1 = 58.04$ percent, gas-portion content of final atmosphere (g, fig. 8).

$$y = w \sin\theta, \tag{46a}$$
$$= 58.04 (\sin 0°24'54''),$$
$$= 58.04 \times 0.00724,$$

$= 0.4203$ percent of oxygen, oxygen content.

To find the air content we substitute the real value of the oxygen content for the symbol $(O_2)_{f.a.}$ in formula (1), page 17, or

$$Air_{f.a.} = \frac{(O_2)_{f.a.}(100)}{20.93}, \tag{1}$$
$$= \frac{0.4203 \times 100}{20.93},$$

$= 2.01$ percent of air, air content.

To find the diluent content of atmosphere g, we substitute the real values for the symbols in formula (47a), or

$$(CO_2)_{dil} = 100 - \frac{100y}{20.93} - x, \tag{47a}$$
$$= 100 - \frac{42.03}{20.93} - 58.04,$$
$$= 100 - 2.01 - 58.04,$$

$= 39.95$ percent of carbon dioxide, diluent content.

Summarizing the data determined by formulas (41), (42c), (43), (44), (45a), (46a), (1), and (47a), we find that atmosphere g, figure 8, is composed (by portions) of 58.04 percent of the percentages of the constituents composing atmosphere J (p. 123), 2.01 percent of air; and 39.95 percent of carbon dioxide.

By calculating the chemical compositions of the gas portion and the air portion of atmosphere g and then combining and adding the percentages of the constituents, thus found, with the real value of the diluent portion given above, we find the chemical composition of atmosphere *g* (the extinctive atmosphere desired) to be:

	Percent
Carbon monoxide	3. 95
Methane	. 46
Hydrogen	5. 92
Oxygen	. 42
Nitrogen	41. 81
Carbon dioxide	47. 44

DETERMINATION OF CARBON DIOXIDE REQUIRED TO FORM BORDERLINE EXTINCTIVE ATMOSPHERES

Atmosphere *g* (fig. 8) can be considered a borderline extinctive atmosphere if we define such an atmosphere as one that is nonexplosive and just incapable of forming explosive mixtures with air.

As atmosphere sample 65 is diluent-free and considered as an original atmosphere, the diluent content (39.95 percent of carbon dioxide) of atmosphere *g* is also the amount of carbon dioxide required to form atmosphere *g* from atmosphere sample 65. (See pp. 127 and 128).

However, the amount of carbon dioxide required for this purpose can be determined by substituting the known real values for the symbols in formula (47*c*), page 69, or

$$\begin{aligned} Inert\ gas_{dil} &= \frac{[(O_2)_s - y]100}{(O_2)_s}, \qquad (47c) \\ &= \frac{(0.7-0.4203)\times 100}{0.7}, \\ &= 39.95 \text{ percent of carbon dioxide.} \end{aligned}$$

The practical significance of the foregoing data is that if carbon dioxide is introduced into the sealed mine-fire area in a proportion no less than 39.95 percent of the volume (250,000 cubic feet) of the confined mine-fire atmosphere, an extinctive atmosphere having the composition of atmosphere *g* will be formed from that portion of the mine-fire atmosphere represented by sample 65, table 7; furthermore, as sample 65 represents the portion of the atmosphere containing the maximum percentage of the air-free original atmosphere (*J*, fig. 8), a nonexplosive atmosphere that is incapable of forming explosive mixtures with air will exist throughout the sealed area.

The effect of admixing definite quantities of a given inert gas with different portions of the mine-fire atmosphere, when such portions differ in composition, is discussed later.

GRAPHIC DETERMINATION OF CARBON DIOXIDE REQUIRED TO FORM BORDERLINE EXTINCTIVE ATMOSPHERES

Having determined the real value (59.23 percent) of $C.\ G.\ M.\ V._{CO_2}$, the volume ($Inert\ gas_{dil}$) of carbon dioxide that must be admixed with atmosphere sample 65, table 7, to form the borderline extinctive atmosphere desired and the composition of that atmosphere are determined graphically as follows:

Points sample 65 and $C.\ G.\ M.\ V._{CO_2}$, which correspond to the original atmosphere (sample 65) and the critical gas mixture, respecttively, are plotted in line *J–A* and the abscissa axis *J–O*, respectively, in figure 8. Draw line sample 65–*O*, which corresponds to all possible mixtures formed by admixing carbon dioxide with the original atmosphere. Draw line *C. G. M.* $V._{CO_2}$–*A*, which corresponds to all possible mixtures formed by admixing air with the critical gas mixture. These lines intersect at point *g*, which corresponds to the final atmosphere desired.

The air and oxygen contents, the diluent content $(CO_2)_{dil}$, and the gas-portion content of atmosphere *g* can be found directly from figure 8 by drawing lines *g–j*, *g–h*, and *g–i*, respectively. The air and oxygen contents of the final atmosphere (*g*) are the same as those of atmosphere *j*, the diluent content the same as that of atmosphere *h*, and the gas-portion content the same as that of atmosphere *i*. The composition of the final atmosphere is found by combining and adding the percentages of the various constituents thus obtained and is given on page 129.

DETERMINATION OF VOLUME OF CARBON DIOXIDE REQUIRED TO FORM BORDERLINE EXTINCTIVE MIXTURES

Because the volume of carbon dioxide gas required to form a definite atmosphere from a given atmosphere in a confined place depends on the volume of the place in which the atmosphere is confined, the volume of carbon dioxide required to form atmosphere *g* from an atmosphere having the composition of sample 65, table 7, and figure 8, is determined as follows:

The volume of the sealed mine-fire area at the time sample 65 was taken was 250,000 cubic feet. It has been shown that 39.95 percent of carbon dioxide is required to form atmosphere *g*; therefore,

$$0.3995 \times 250{,}000 \text{ cubic feet,}$$

or

$$99{,}875 \text{ cubic feet of carbon dioxide,}$$

is required to form atmosphere *g* from atmosphere sample 65.

One pound of carbon dioxide, or dry ice, produces 8.57 cubic feet of carbon dioxide gas at 60° F. and 760 millimeters pressure (normal temperature and pressure); therefore, $\frac{99{,}875}{8.57}$ or 11,654 pounds, or 5.82 net tons, of carbon dioxide is required to form atmosphere *g* from atmosphere sample 65.

When limestone of the quality often used for rock dusting is completely calcined, 1 net ton yields 7,540 cubic feet of carbon dioxide gas at normal temperature and pressure; therefore, to obtain 99,875 cubic feet of carbon dioxide requires 13.23 net tons of limestone.

DETERMINATION OF MINIMUM VOLUME OF CARBON DIOXIDE REQUIRED FOR CARBON DIOXIDE–AIR MIXTURES USED AS *DILUENT*

The extinguishment of the Continental mine fire after it had advanced into caved areas adjacent to the place where the fire started was impossible by any means other than slushing with culm and water. Slushing could have been done with less risk and quicker if the fire area could have been blanketed on the intake-air side of the fire with either an inert gas or a mixture of inert gas and air that would have formed an atmosphere incapable of forming an explosive mixture with air. Furthermore, the final sealing operations could have been prosecuted with more vigor and would have been both cheaper and less hazardous. The foregoing statements are based on the experience gained at this and subsequent fires.

We have found that 39.95 percent, or 99,875 cubic feet (the minimum volume), of carbon dioxide gas has to be admixed with atmosphere sample 65 to form atmosphere *g* (fig. 8). It is of interest to know the minimum volume of carbon dioxide contained in a *diluent* composed of carbon dioxide and air that, if admixed with atmosphere sample 65, would safely form a borderline extinctive atmosphere and thereby accomplish the same purpose.

The composition and amount of *diluent* required to form the desired extinctive atmosphere from atmosphere sample 56 can be determined mathematically by means of formulas (61) to (67), inclusive, or graphically in figure 8. The final atmosphere desired is the nose-limit mixture corresponding to point $Nose_{CO_2}$. (See p. 127.)

The graphic method of determining the foregoing factors in figure 8 is as follows:

Draw line sample 65–*k* through the point corresponding to the nose-limit mixture ($Nose_{CO_2}$) and intersecting the ordinate axis (*O–A*) at point *k*, which corresponds to the atmosphere used as the *diluent.* We find in figure 8 that atmosphere *k* is composed of 57.26 percent of air and 42.74 percent of carbon dioxide.

Because atmosphere sample 65 is an original atmosphere, the real value of the inert-gas component ($Diluent\ Mixture_{inert\ gas}$) of the given *diluent* that must be admixed with atmosphere sample 65 to form the nose-limit mixture is also the diluent content ($Dil_{nose-CO_2}$) of the nose-limit mixture. The diluent content has been found to be 26.02 percent of carbon dioxide. (See p. 127.)

Having found that the atmosphere used as the *diluent* is composed of 57.26 percent of air ($Atmos_{air}$) and 42.74 percent of carbon dioxide ($Atmos_{inert\ gas}$), and that the real value of $Diluent\ Mixture_{inert\ gas}$ is 26.02 percent of the whole, we can find the air content ($Diluent\ Mixture_{air}$) of the total volume of *diluent* required by substituting real values for the symbols in formula (67) as follows:

$$Diluent\ Mixture_{air} = \frac{(Atmos_{air})\ (Diluent\ Mixture_{inert\ gas})}{Atmos_{inert\ gas}}, \qquad (67)$$

$$= \frac{57.26 \times 26.02}{42.74},$$

$$= 34.86 \text{ percent of air.}$$

The total amount of *diluent* ($Diluent\ Mixture_{nose\text{-}CO_2}$), or carbon dioxide–air mixture, required to form the nose-limit mixture from atmosphere sample 65 is composed of definite amounts of carbon dioxide and air; therefore, we find the real value of *Diluent Mixture*

$_{nose-CO_2}$ by substituting the above-given real values for the symbols in formula (63*c*), or

$$\mathit{Diluent\ Mixture}_{nose-CO_2} = \mathit{Diluent\ Mixture}_{inert\ gas} + \mathit{Diluent\ Mixture}_{air},$$

$$= (26.02 + 34.86) \text{ percent},$$

$$= 60.88$$ percent of the volume of the mine-fire atmosphere under seal, the volume of the *diluent* required to form atmosphere $Nose_{CO_2}$ (fig. 8).

The volume of the mine-fire atmosphere under seal has been given as 250,000 cubic feet. From the foregoing data we can determine that:

$$\text{Volume of carbon dioxide} = 0.2602 \times 250{,}000 \text{ cubic feet}, = 65{,}050 \text{ cubic feet}.$$

$$\text{Volume of air} = 0.3486 \times 250{,}000 \text{ cubic feet}, = 85{,}150 \text{ cubic feet}.$$

$$\text{Volume of } \mathit{diluent} \text{ required} = 0.6088 \times 250{,}000 \text{ cubic feet}, = 152{,}200 \text{ cubic feet}.$$

One pound of carbon dioxide gas has a volume of 8.57 cubic feet at normal temperature and pressure; therefore, the quantity of carbon dioxide required to form the extinctive atmosphere (nose-limit mixture) desired is 65,050÷8.57, or 7,590 pounds (3.795 net tons) of carbon dioxide.

Summarizing the above data, we find that, if 3.795 net tons of carbon dioxide, or dry ice, is used to produce 65,050 cubic feet of carbon dioxide gas at normal temperature and pressure and this gas is then admixed with 87,150 cubic feet of air, 152,200 cubic feet of *diluent* having the chemical composition of atmosphere *k* is formed. If this volume of *diluent k* is admixed with the mine-fire atmosphere under seal, extinctive final mixtures having a chemical composition the same as that of the nose-limit mixture (CO_2 as diluent) will be formed with all portions of the mine-fire atmosphere having the same composition as sample 65, table 7.

It is observed that, whereas 5.82 net tons of carbon dioxide are required to form atmosphere *g* (fig. 8) when pure carbon dioxide is admixed with atmosphere sample 65, only 3.795 net tons, or 65,050 cubic feet, are required if a *diluent* composed of this quantity of carbon dioxide gas and 87,150 cubic feet of air is used. In other words, 65,050 cubic feet (26.02 percent of the volume of the mine-fire atmosphere under seal) is the minimum quantity of carbon dioxide that can be used safely as the inert-gas portion of the *diluent* required to form a borderline extinctive mixture (nose-limit mixture) when the *diluent* consists of 42.74 percent of carbon dioxide and 57.26 percent of air. (See p. 131.)

LIMITATIONS IN USE OF CARBON DIOXIDE–AIR MIXTURES AS *DILUENT*

It has been shown on pages 109 to 112, inclusive, that, if a source of ignition is present, inert gas–air mixtures (*diluents*) cannot be indiscriminately admixed with mine-fire atmospheres to form extinctive atmospheres. The following examples show the discrimination that must be exercised in the use of a *diluent* (carbon dioxide plus air) when applied to the Continental mine-fire problem.

EFFECT WHEN USING *DILUENTS* CONTAINING DIFFERENT QUANTITIES OF AIR AND FIXED QUANTITY OF GIVEN INERT GAS

We have shown above that, if 152,200 cubic feet of *diluent* composed of 87,150 cubic feet of air and 65,050 cubic feet of carbon dioxide were admixed with the mine-fire atmosphere under seal, an extinctive atmosphere would be formed safely with the portion of the mine-fire atmosphere represented by sample 65, table 7.

If more than 87,150 cubic feet of air were admixed with 65,050 cubic feet of carbon dioxide to form a *diluent*, a final atmosphere corresponding to point *l* (fig. 8) would be one of the final atmospheres that could be formed if the required volume of such a *diluent* were admixed with atmosphere sample 65, figure 8; furthermore, some of the successive mixtures formed would be explosive.

If less than 87,150 cubic feet of air were admixed with 65,050 cubic feet of carbon dioxide to form a *diluent* and the required volume of such a *diluent* were admixed with atmosphere sample 65, the final atmosphere formed would fall short of being the nose limit mixture and could correspond to point *n* (fig. 8). If air were then admixed with the atmosphere under seal, some of the successive mixtures formed with atmosphere *n* would be explosive. It is thus seen that the final atmospheres formed by admixing *diluents* containing 65,050 cubic feet of carbon dioxide and different volumes of air that range from 0 to 184,950 cubic feet (73.98 percent) with atmosphere sample 65 would correspond to the points in line w-w_1. One of these final atmospheres is the nose-limit mixture when carbon dioxide is used as the diluent.

EFFECT WHEN USING *DILUENTS* CONTAINING DIFFERENT QUANTITIES OF GIVEN INERT GAS AND FIXED QUANTITY OF AIR

If progressively more than 65,050 cubic feet (26.02 percent of the mine-fire atmosphere under seal, fig. 8) of carbon dioxide were used with 87,150 cubic feet (34.86 percent) of air to form a series of *diluents*, and each of these *diluents* were admixed with atmosphere sample 65, a series of extinctive final atmospheres would be formed safely; these final atmospheres would correspond to points in line $Nose_{CO_2}$-t. As the air content of each of the *diluents* is 34.86 percent of the volume of the mine-fire atmosphere under seal, the maximum carbon dioxide content of any possible *diluent* is 65.14 percent (162,850 cubic feet). We will designate this *diluent* as *diluent t*, which corresponds to point *t* (fig. 8).

It can be seen in figure 8 that, if the above-mentioned series of *diluents* were admixed with atmosphere sample 65, the borderline extinctive mixtures formed would correspond to points in line $Nose_{CO_2}$–u; that the air content of the borderline extinctive mixtures would decrease progressively as the carbon dioxide content increased; and that it would not be necessary to admix as much of *diluent t* with atmosphere sample 65 to form a borderline extinctive mixture as would be required if *diluent k* were used. If *diluent t* were used, the borderline extinctive atmosphere formed with atmosphere sample 65 would correspond to point *u*, which is the point of intersection of line $C.\ G.\ M.\ V_{CO_2}$–$Nose_{CO_2}$ and line sample 65–*t*.

The composition of atmosphere *u*, the volume of *diluent* that must be admixed with atmosphere sample 65 to form atmosphere *u*, and the percentages of carbon dioxide and air composing the *diluent* can be determined graphically or calculated mathematically as follows:

By substituting real values for the symbols in formula (70)

when

$(O_2)_{atmos-dil}=7.30$ percent, oxygen content of the *diluent* (atmosphere *t*),
$C.\ G.\ M.\ V.=59.23$ percent,
$(O_2)_s=0.70$ percent, oxygen content of atmosphere sample 65,

and

$Gas_s=96.66$ percent, gas-portion content of atmosphere sample 65;

we find

$$z=\frac{[20.93-(O_2)_{atmos}]\left(\sin\tan^{-1}\frac{C.\ G.\ M.\ V.}{20.93}\right)}{\sin\left(90°-\tan^{-1}\frac{C.\ G.\ M.\ V.}{20.93}-\tan^{-1}\frac{(O_2)_{atmos}-(O_2)_s}{Gas_s}\right)}, \tag{70}$$

$$=\frac{(20.93-7.30)\left(\sin\tan^{-1}\frac{59.23}{20.93}\right)}{\sin\left(90°-\tan^{-1}\frac{59.23}{20.93}-\tan^{-1}\frac{7.30-0.70}{96.66}\right)},$$

$$=\frac{13.63\ (\sin 70°32'17'')}{\sin\left(90°-70°32'17''-\tan^{-1}\frac{6.60}{96.66}\right)},$$

$$=\frac{13.63\ (\sin 70°32'17'')}{\sin\ (90°-70°32'17''-3°54'22'')}=\frac{13.63\ (\sin 70°32'17'')}{\sin 15°33'21''},$$

$$=\frac{13.63\times 0.94287}{0.26818}=47.92.$$

By substituting the real values of *z* and other factors, just obtained, and pertinent known real values for the symbols in formulas (71), (72*a*) or (72*b*), and (68) in the order given, we can determine the composition (by portions) of atmosphere *u*, as follows:

$$Gas_{f.a.}=z\cos\tan^{-1}\frac{(O_2)_{atmos}-(O_2)_s}{Gas_s}, \tag{71}$$

$$=47.92\ (\cos 3°54'22''),$$

$$=47.92\times 0.99767,$$

$=47.81$ percent of percentages of constituents composing atmosphere *J* (fig. 8).

$$Air_{f.a.}=Atmos_{air}-\left[\left(z\sin\tan^{-1}\frac{(O_2)_{atmos}-(O_2)_s}{Gas_s}\right)\left(\frac{100}{20.93}\right)\right], \tag{72a}$$

$$=34.86-\left[47.92(\sin 3°54'22'')\left(\frac{100}{20.93}\right)\right],$$

$$=34.86-\left[\frac{47.92\times 0.06813\times 100}{20.93}\right],$$

$=34.86-15.60=19.26$ percent of air;

or

$$Air_{f.a.}=\left[(Gas_s-Gas_{f.a.})\left(\frac{(O_2)_{atmos}-(O_2)_s}{Gas_s}\right)\left(\frac{100}{20.93}\right)\right]+Air_s, \qquad (72b)$$

$$=\left[(96.66-47.81)\left(\frac{6.60}{96.66}\right)\left(\frac{100}{20.93}\right)\right]+3.34,$$

$$=\frac{48.85\times6.60\times100}{96.66\times20.93}+3.34,$$

$$=15.93+3.34=19.27 \text{ percent of air.}$$

$$Inert\ gas_{add-f.a.}=100-Air_{f.a.}-Gas_{f.a.}, \qquad (68)$$

$$=100-19.26-47.81,$$

$$=32.93 \text{ percent of carbon dioxide (diluent).}$$

Summarizing the foregoing data: The borderline extinctive atmosphere corresponding to point *u* (fig. 8) consists (by portions) of:

47.81 percent of percentages of constituents composing atmosphere *J*, page 116 (gas portion),
19.26 percent of air, of which 4.03 percent is oxygen and 15.23 percent is nitrogen (air portion),
32.93 percent of additional carbon dioxide (diluent portion).

By calculating the composition of the gas portion and combining the percentages of the constituents composing the three portions, we find that atmosphere *u* consists (by constituents) of:

	Percent
Carbon monoxide	3. 25
Methane	. 38
Hydrogen	4. 88
Oxygen	4. 03
Nitrogen	48. 36
Carbon dioxide	39. 10

To find the volume of *diluent* ($Dil_{inert\ gas+air}$) required to form atmosphere *u* from atmosphere sample 65, we substitute the real values determined previously for the symbols in formula (47*c*–3), or

$$Dil_{inert\ gas+air}=\left(\frac{Gas_s-Gas_{f.a.}}{Gas_s}\right)100, \qquad (47c\text{-}3)$$

$$=\left(\frac{96.66-47.81}{96.66}\right)100 \text{ percent,}$$

$$=\frac{48.85\times100}{96.66} \text{ percent,}$$

$$=50.53 \text{ percent of } diluent \text{ composed of air plus carbon dioxide.}$$

Because atmosphere sample 65 is diluent-free, the real value of the inert-gas component ($Inert\ gas_{Dil-inert\ gas+air}$) of the *diluent* ($Dil_{inert\ gas+air}$) required to form atmosphere *u* is the same as the diluent content of atmosphere *u*, or 32.93 percent of carbon dioxide; therefore, the air component ($Air_{Dil-inert\ gas+air}$) is

$$Air_{dil-inert\ gas+air}=Dil_{inert\ gas+air}-Dil_{add-inert\ gas-f.a.},$$

$$=(50.53-32.93) \text{ percent,}$$

$$=17.60 \text{ percent of air.}$$

The real values of the components composing the *diluent* ($Dil_{inert\ gas+air}$) required to form atmosphere *u* can also be determined by formulas (73) and (74), as follows:

$$Inert\ gas_{Dil-inert\ gas+air} = Dil_{inert\ gas+air}\left(\frac{Atmos_{inert\ gas}}{100}\right), \tag{73}$$

$$= \frac{50.53 \times 65.14}{100} \text{ percent,}$$

$$= 32.93 \text{ percent of carbon dioxide;}$$

and

$$Air_{Dil-inert\ gas+air} = Dil_{inert\ gas+air}\left(\frac{Atmos_{air}}{100}\right), \tag{74}$$

$$= \frac{50.53 \times 34.86}{100} \text{ percent,}$$

$$= 17.60 \text{ percent of air.}$$

The significance of the data just given is that, if a *diluent* composed of 82,325 cubic feet (32.93 percent) of carbon dioxide and 44,000 cubic feet (17.60 percent) of air were admixed with atmosphere sample 65 (fig. 8), atmosphere *u*, which is a borderline extinctive mixture, would be formed safely. Furthermore, although 60.88 percent of the mine-fire atmosphere under seal would have to be replaced by a *diluent* corresponding to atmosphere *k* to form an extinctive atmosphere (the nose-limit mixture), only 50.53 percent of the atmosphere under seal would have to be replaced if a *diluent* corresponding to atmosphere *t* were used; however, to form safely an extinctive atmosphere having the same composition as the nose-limit mixture would require but 65,050 cubic feet (26.02 percent) of carbon dioxide, whereas, to form the extinctive atmosphere corresponding to point *u* would require 82,325 cubic feet (32.93 percent) of carbon dioxide.

From the previous statement the question may arise that if a *diluent* composed of 65,050 cubic feet of carbon dioxide and air serves the same purpose as a *diluent* composed of 82,325 cubic feet of carbon dioxide and considerably less air, why not use the lesser volume of inert gas? The answer is that greater safety is obtained by using the larger volume of carbon dioxide, and considerably less work is required to put the *diluent* into the mine-fire area. (See pp. 109 to 112.)

EFFECT OF ADMIXING A DEFINITE VOLUME OF GIVEN *DILUENT* WITH PORTIONS OF MINE-FIRE ATMOSPHERE UNDER SEAL THAT CONTAIN MORE OR LESS OXYGEN THAN PORTION OF ATMOSPHERE SAMPLED

Some portions of a mine-fire atmosphere under seal usually contain more or less oxygen than the portion of the atmosphere sampled and on which the calculations on explosibility are based. Such portions of the mine-fire atmosphere can be represented by points in a graph, such as figure 8.

The composition of each of the different final atmospheres formed by admixing a definite volume of a given *diluent* with a mine-fire atmosphere composed of portions having different compositions would be the same as it would be if the entire mine-fire atmosphere were (1) considered in each instance as having the same composition as the portion from which the final atmosphere was formed and (2) diluted in the manner stated. The reason that the composition of each final atmosphere would be the same in both instances is that the ratio of the volume of *diluent* that would be admixed with a definite portion of the mine-fire atmosphere to the volume of that portion is the same as the ratio of the total volume of *diluent* to the volume of the mine-fire atmosphere under seal.

EFFECT OF ADMIXING A DEFINITE VOLUME OF GIVEN *DILUENT* WITH AN ATMOSPHERE HAVING PORTIONS CONTAINING MORE OXYGEN THAN PORTION SAMPLED

We have shown on page 132 that 152,200 cubic feet of *diluent k* will, if admixed with the mine-fire atmosphere under seal, form the nose-limit mixture with that portion of the mine-fire atmosphere represented by sample 65, table 7. The successive mixtures formed correspond to points in line sample 65–$Nose_{CO_2}$ (fig. 8). Furthermore, each of the portions of the mine-fire atmosphere corresponding to points lying in the area above line sample 65–$Nose_{CO_2}$ forms successive mixtures, some of which are explosive.

To verify whether or not a line of successive mixtures formed, as stated above, passes through the zone of explosive mixtures, and in order to determine the composition of the final atmosphere formed, let us assume that a portion of the mine-fire atmosphere under seal corresponds to point *P*, which is diluent-free; has an air content of 15 percent, of which 3.14 percent is oxygen; has a gas-portion content of 85 percent, composed of 85 percent of the percentages of the constituents composing atmosphere *J*, and contains no additional carbon dioxide (diluent).

If we now assume that the mine-fire atmosphere under seal corresponds to point *P* and that 152,200 cubic feet of *diluent k* is admixed with atmosphere *P*, successive mixtures will be formed. These mixtures correspond to points in line *P–l* (fig. 8), in which point *l* corresponds to the final mixture formed.

Because atmosphere *l* is formed by admixing 152,200 cubic feet of *diluent k* with atmosphere *P* and because *diluent k* has a carbon dioxide content of 26.02 percent of the volume of the mine-fire atmosphere under seal, point *l* is one of the points in line w–w_1, which represents all atmospheres containing 26.02 percent of additional carbon dioxide (diluent). Point *l* is established graphically as the point of intersection of lines *P–k* and w–w_1.

We have shown on page 100 that, when

$$\tan^{-1}\frac{(O_2)_{atmos}-(O_2)_s}{Gas_s}=\tan^{-1}\frac{(O_2)_{nose}-(O_2)_s}{Gas_s-Gas_{nose}},$$

the final mixture formed by admixing a definite amount of a given *diluent* with a given atmosphere is the nose-limit mixture; consequently, none of the successive mixtures formed lie in the zone of explosive mixtures.

On pages 127, 131, and 134, the real values of the symbols in the foregoing equation that relate to the nose-limit mixture, *diluent k*, and atmosphere sample 65 are given as follows:

$(O_2)_{nose-CO2}=7.57$ percent, $Gas_{nose-CO_2}=37.81$ percent;

$(O_2)_{atmos-k}=11.98$ percent,

and

$(O_2)_{sample\ 65}=0.70$ percent, $Gas_{sample\ 65}=96.66$ percent, respectively.

By substituting the real values for the symbols in the foregoing equation, we find

$$\tan^{-1}\frac{11.98-0.70}{96.66}=\tan^{-1}\frac{7.57-0.70}{96.66-37.81}=\tan^{-1} 0.11669.$$

If, by applying data relating to *diluent k* and atmosphere *P*, page 137, we find that

$$\tan^{-1}\frac{(O_2)_{atmos-k}-(O_2)_{sample\ 65}}{Gas_{sample\ 65}}>\tan^{-1}\frac{(O_2)_{atmos-k}-(O_2)_{s-P}}{Gas_{s-P}},$$

where

$(O_2)_{s-P}$ is the oxygen content,

and

Gas_{s-P} is the gas-portion content of atmosphere *P*,

we can infer that line *P–l* (fig. 8) passes through the zone of explosive mixtures. Line *P–l* corresponds to the successive mixtures formed by admixing 152,200 cubic feet (60.88 percent of the volume of the mine-fire atmosphere under seal) of *diluent k* with the mine-fire atmosphere when it corresponds to point *P*.

By substituting real values for the symbols in the expression

$$\tan^{-1}\frac{(O_2)_{atmos-k}-(O_2)_{s-P}}{Gas_{s-P}},$$

when

$(O_2)_{atmos-k}=11.98$ percent, $(O_2)_{s-P}=3.14$ percent, and $Gas_{s-P}=85.00$ percent,

we find

$$\tan^{-1}\frac{11.98-3.14}{85.00}=\tan^{-1} 0.10400.$$

Consequently,

$$\frac{(O_2)_{atmos-k}-(O_2)_{sample\ 65}}{Gas_{sample\ 65}},\text{ or } 0.11669, >0.10400,\text{ or }\frac{(O_2)_{atmos-k}-(O_2)_{s-P}}{Gas_{s-P}},$$

and line *P–l*, which corresponds to the successive mixtures formed by admixing 152,200 cubic feet of *diluent k* with atmosphere *P*, passes through the zone of explosive mixtures. Furthermore, although atmosphere *l* is nonexplosive, all mixtures corresponding to points in line *P–l* between points l_2 and l_1 are explosive. If a source of ignition were present, an explosion would occur before atmosphere *l* could be formed.

The mathematical method of verifying the explosibility of explosive-limit mixtures such as atmosphere l_1 and l_2 is given on pages 156 to 168, inclusive.

To find the composition of atmosphere *l*, or the final atmosphere formed by admixing 152,200 cubic feet of *diluent k* with atmosphere *P*, we substitute the known real values for the symbols in formula (47*c*–3), page 70, as follows:

$$Dil_{inert\ gas+air}=\frac{(Gas_s-Gas_{f.\ a.})100}{Gas_s}, \tag{47c–3}$$

or

$$60.88=\frac{(85.00-Gas_{f.\ a.})100}{85.00},$$

from which, by transposition, we find

$$\begin{aligned} Gas_{f.\ a.}&=\frac{(85.00\times 100)-(60.88\times 85.00)}{100},\\ &=\frac{8{,}500-5{,}174.80}{100}\text{ percent},\\ &=33.25\text{ percent, gas-portion content of atmosphere } l. \end{aligned}$$

The diluent content of atmosphere *l* was found on page 137 to be 26.02 percent of carbon dioxide; the air content is found by substituting the above-given real values for the symbols in formula (68), as follows:

$$\begin{aligned} Inert\ gas_{add-f.\ a.}&=100-Air_{f.\ a.}-Gas_{f.\ a.},\\ 26.02&=100-Air_{f.\ a.}-33.25, \end{aligned} \tag{68}$$

from which, by transposition, we find

$$\begin{aligned} Air_{f.\ a.}&=100-26.02-33.25,\\ &=40.73\text{ percent, air content of atmosphere } l. \end{aligned}$$

The compositions of atmospheres l, l_1, and l_2, can be determined graphically in figure 8. The composition of atmosphere l_1 has been determined mathematically and is given on page 159.

The composition and volume of a *diluent* composed of carbon dioxide and air that could be used safely to form the nose-limit mixture from atmosphere *P* (fig. 8) can be determined graphically or mathematically.

Summarizing the data determined above: The final atmosphere corresponding to point *l* (fig. 8) is formed by admixing 152,200 cubic feet (60.88 percent of the volume of the mine-fire atmosphere under seal) of *diluent* composed of 87,150 cubic feet (34.86 percent) of carbon dioxide and 65,050 cubic feet (26.02 percent) of air, with atmosphere *P*. Atmosphere *l* consists (by portions) of:

33.25 percent of percentages of the constituents composing atmosphere *J*
40.73 percent of air, of which 8.52 percent is oxygen and 32.21 percent is nitrogen
and 26.02 percent of additional carbon dioxide (diluent)

By calculating the composition of the gas portion and combining the percentages of the constituents composing the three portions, we find that atmosphere *l* (fig. 8) consists (by constituents) of:

	Percent
Carbon monoxide	2. 26
Methane	. 26
Hydrogen	3. 39
Oxygen	8. 52
Nitrogen	55. 25
Carbon dioxide	30. 32

EFFECT OF ADMIXING A DEFINITE VOLUME OF GIVEN *DILUENT* WITH AN ATMOSPHERE HAVING PORTIONS CONTAINING LESS OXYGEN THAN PORTION SAMPLED

We have shown on pages 137 and 138, inclusive, that, although 152,200 cubic feet of *diluent k* (fig. 8) can be used safely to form a borderline extinctive atmosphere (the nose-limit mixture) with atmosphere sample 65, this volume of *diluent k* could not be used safely to form extinctive final atmospheres with mixtures corresponding to points lying above line sample 65—$Nose_{CO_2}$, when a source of ignition is present.

Because all mixtures corresponding to points in the portion of the zone of mixtures capable of forming explosive mixtures with air that lies below line sample 65—$Nose_{CO_2}$ (fig. 8) are nonexplosive, *diluent k* can be used safely in any volume to form a final atmosphere with any of these mixtures; however, whether the final atmosphere formed by admixing *diluent k* with any one of the mixtures defined above is either capable or incapable of forming explosive mixtures with air depends on (1) the diluent (additional carbon dioxide) content of the given mixture and (2) the volume of *diluent k* admixed with that mixture. The composition of the final atmosphere formed and the factors relating to its explosibility are determined as follows:

Let us assume that the composition of the mine-fire atmosphere under seal is that of the atmosphere corresponding to point *J* (fig. 8) and consists of no air, no diluent and a gas-portion content of 100 percent. As atmosphere *J* obviously contains less oxygen than sample 65, the maxiumm volume of *diluent k* would be required to form a borderline extinctive atmosphere from atmosphere *J*.

If 152,200 cubic feet of *diluent k* is admixed with atmosphere *J*, the successive mixtures (line *J–n*, fig. 8) formed, although nonexplosive, are capable of forming explosive mixtures with air. The final mixture formed is atmosphere *n*, which is the point of intersection of lines *J–k* and w–w_1. As line w–w_1 corresponds to all mixtures that contain 26.02 percent of additional carbon dioxide (diluent), the composition of atmosphere *n* can be obtained from figure 8 or determined mathematically as follows:

We have shown on page 132 that 152,200 cubic feet of *diluent k* is equivalent to 60.88 percent of the volume of the mine-fire atmosphere under seal and is composed of 65,050 cubic feet (26.02 percent) of carbon dioxide and 87,150 cubic feet (34.86 percent) of air; therefore, we can write

$$Dil_{inert\ gas+air} = 60.88 \text{ percent},$$

and

$$Inert\ gas_{add-f.\ a.} = 26.02 \text{ percent, diluent content of atmosphere } n.$$

As the mixture being diluted is atmosphere *J*, the real value of the symbol Gas_s is 100 percent.

By substituting the real values, just given, for the symbols in formulas (47*c*–3) and (68) in the order given, we find

$$Dil_{inert\ gas+air} = \frac{(Gas_s - Gas_{f.\ a.})(100)}{Gas_s}, \qquad (47c\text{-}3)$$

which, by substitution and transposition, becomes

$$60.88=\frac{(100-Gas_{f.\ a.})\times 100}{100},$$

or

$$Gas_{f.\ a.}=100-60.88,$$

$$=39.12 \text{ percent, gas-portion content of atmosphere } n \text{ (fig. 8).}$$

$$Inert\ gas_{add-f.\ a.}=100-Air_{f.\ a.}-Gas_{f.\ a.}, \qquad (68)$$

which, by substitution and transposition, becomes

$$26.02=100-Air_{f.\ a.}-39.12,$$

$$Air_{f.\ a.}=100-26.02-39.12,$$

$$=34.86 \text{ percent of air, air content of atmosphere } n.$$

By summarizing the above data we find that atmosphere *n* is composed, by portions, of

39.12 percent of percentages of constituents composing atmosphere *J* (gas portion),
34.86 percent of air, of which 7.30 percent is oxygen,
and
26.02 percent of carbon dioxide (diluent);

and, by constituents, of

	Percent
Carbon monoxide	2. 66
Methane	. 31
Hydrogen	3. 99
Oxygen	7. 30
Nitrogen (of which 27.11 percent is derived from atmosphere *J* and 27.56 percent from air)	54. 67
Carbon dioxide (of which 5.05 percent is derived from atmosphere *J* and 26.02 percent is diluent)	31. 07

That atmosphere *n* can form explosive mixtures with air can be verified mathematically by the procedure shown for atmospheres *m* and *h* on pages 142 to 145, inclusive.

EFFECT OF ADMIXING A DEFINITE VOLUME OF GIVEN *DILUENT* (CARBON DIOXIDE) WITH PORTIONS OF MINE-FIRE ATMOSPHERE UNDER SEAL THAT EITHER CONTAIN MORE OR LESS OXYGEN THAN PORTION OF ATMOSPHERE SAMPLED

When a definite volume of carbon dioxide is admixed with the mine-fire atmosphere under seal, it is important to know the facts regarding the explosibility of the mixtures formed with those portions of the mine-fire atmosphere that have oxygen contents that are greater or less than the oxygen content (0.70 percent) of sample 65, table 7, which represents the portion of the mine-fire atmosphere sampled.

Regardless of the oxygen content of any one of the portions defined above, the process of admixing carbon dioxide with the mine-fire atmosphere could not cause an explosion unless an explosive mixture was forced over the fire.

Whether or not the final atmosphere formed by admixing a given volume of carbon dioxide with any given portion of the mine-fire atmosphere under seal is capable of forming explosive mixtures with air or is explosive depends on (1) whether the given portion of the mine-fire atmosphere is explosive or nonexplosive, (2) the diluent (additional carbon dioxide) content of the given portion, and (3) the volume of carbon dioxide admixed with the given portion.

We have shown on page 131 that, when 99,875 cubic feet of carbon dioxide (39.95 percent of the mine-fire atmosphere under seal) is admixed with the mine-fire atmosphere, a borderline extinctive atmosphere (*g*, fig. 8) is formed with that portion of the mine-fire atmosphere represented by sample 65, table 7.

Let us assume that atmosphere *P*, which contains 3.14 percent oxygen, and atmosphere *J*, which contains no oxygen, represent portions of the mine-fire atmosphere under seal that contain more oxygen and less oxygen, respectively, than the percentage (0.70 percent) contained in sample 65, which represents the portion of the mine-fire atmosphere sampled. (See pp. 116 and 137.)

If 99,875 cubic feet (39.95 percent of the mine-fire atmosphere under seal) of carbon dioxide is admixed with the mine-fire atmosphere, the final atmospheres formed with the portions corresponding to atmospheres *P* and *J*, which are diluent-free, contain analogous proportions of 99,875 cubic feet of carbon dioxide.

For the foregoing reason, we can consider that the final atmospheres formed with atmospheres *P* and *J* have a diluent content of 39.95 percent of carbon dioxide and that line h–h_1, (fig. 8) corresponds to all possible mixtures containing 39.95 percent of additional carbon dioxide (diluent). Furthermore, this proportion (39.95 percent) of carbon dioxide is the volume that must be admixed with any given atmosphere corresponding to some point in line *A*–*J* (fig. 8) to form a final atmosphere that contains 39.95 percent of additional carbon dioxide. Given atmospheres corresponding to points in line *A*–*J* are atmosphere *P*, which contains more oxygen than sample 65, and atmosphere *J*, which contains no oxygen.

Because atmosphere *P* is diluent-free, the diluent content of the final atmosphere formed by admixing 39.95 percent of carbon dioxide with atmosphere *P* (fig. 8) is 39.95 percent. The final atmosphere corresponds to point *m*, which is the point of intersection of lines *P*–*O* and h–h_1. Similarly, the final atmosphere formed by admixing 39.95 percent of carbon dioxide with atmosphere *J* corresponds to point *h*, which is the point of intersection of lines *J*–*O* and h–h_1.

The compositions of the final atmospheres corresponding to points *m* and *h* can be determined graphically in figure 8 or determined mathematically by substituting real values for the symbols in formulas (47*c*–1), (1), and (68) in the order given, or

$$Inert\ gas_{dil}=\frac{[(O_2)_s-(O_2)_{f.\ a.}]100}{(O_2)_s}, \qquad (47c\text{-}1)$$

$$Air_{f.\ a.}=\frac{(O_2)_{f.\ a.}\ (100)}{20.93}, \qquad (1)$$

and

$$Inert\ gas_{add-f.\ a.}=100-Air_{f.\ a.}-Gas_{f.\ a.}, \qquad (68)$$

where

$Inert\ gas_{add-f.\ a.}=Inert\ gas_{dil}$=diluent content of final atmosphere,

$(O_2)_{f.\ a.}$=oxygen content of final atmosphere,

$Air_{f.\ a.}$=air content of final atmosphere,

$Gas_{f.\ a.}$=gas-portion content of final atmosphere,

and

$(O_2)_s$=oxygen content of given atmosphere.

To determine the composition of atmosphere *m*, formed from atmosphere *P*,

when

$Inert\ gas_{add-f.\ a.}=Inert\ gas_{dil}=39.95$ percent, diluent content of atmosphere *m*,

and

$(O_2)_s=3.1395$ percent, oxygen content of atmosphere *P*,

we have

$$39.95=\frac{[3.1395-(O_2)_{f.\ a.}]\times 100}{3.1395}, \qquad (47c\text{-}1)$$

which, by clearing of fractions and transposing of terms, becomes

$$(O_2)_{f.\ a.}=\frac{313.95-125.42}{100}$$

=1.885 percent of oxygen, oxygen content of atmosphere *m*.

$$Air_{f.\ a.}=\frac{1.885\times 100}{20.93} \qquad (1)$$

=9.01 percent, air content of atmosphere *m*.

$$39.95=100-9.01-Gas_{f.\ a.}, \qquad (68)$$

which, by transposition, becomes

$$Gas_{f.\ a.}=100-9.01-39.95,$$

=51.04 percent of percentages of constituents composing atmosphere *J*, gas-portion content of atmosphere *m*.

Summarizing the data determined above: The final atmosphere corresponding to point *m* (fig. 8) is formed by admixing 99,875 cubic feet (39.95 percent of the volume of the mine-fire atmosphere under seal) of carbon dioxide with the mine-fire atmosphere corresponding to point *P*. Atmosphere *m* is extinctive; it cannot form explosive mixtures with air and consists (by portions) of:

51.04 percent of percentages of constituents composing atmosphere *J*
9.01 percent of air, of which 1.89 percent is oxygen and 7.12 percent is nitrogen
39.95 percent of carbon dioxide (diluent)

By calculating the composition of the gas portion and combining the percentages of the constituents composing the three portions, we find that atmosphere *m* (fig. 8) consists (by constituents) of:

	Percent
Carbon monoxide	3.47
Methane	.41
Hydrogen	5.20
Oxygen	1.89
Nitrogen	42.50
Carbon dioxide (of which 39.95 percent is diluent)	46.53

To determine the composition of atmosphere *h*, formed from atmosphere *J* (fig. 8 and page 116), we substitute real values for the symbols in formulas (47*c*–1), (1), and (68) and find when

$Inert\ gas_{add-f.\ a.} = Inert\ gas_{dil} = 39.95$ percent, diluent content of atmosphere *h*,

$(O_2)_s = 0.00$ percent, oxygen content of atmosphere *J*,

$Air_{f.\ a.} =$ air content (in percent) of atmosphere *h*,

and

$Gas_{f.\ a.} =$ gas-portion content (in percent) of atmosphere *h*,

that

$$39.95 = \frac{[0.00 - (O_2)_{f.\ a.}] \times 100}{0.00}, \tag{47c–1}$$

from which, by transposition, we find

$(O_2)_{f.\ a.} = 0.00$ percent, oxygen content of atmosphere *h*,

and consequently

$$Air_{f.\ a.} = \frac{0.00 \times 100}{20.93} = 0.00 \text{ percent, air content of atmosphere } h. \tag{1}$$

$$39.95 = 100 - 0.00 - Gas_{f.\ a.}, \tag{68}$$

from which, by transposition, we find

$Gas_{f.\ a.} = 100 - 39.95,$

$= 60.05$ percent of percentages of constituents composing atmosphere *J*, gas-portion content of atmosphere *h*.

Summarizing the data determined above: The final atmosphere corresponding to point *h* (fig. 8) is formed by admixing 99,875 cubic feet (39.95 percent of the volume of the mine-fire atmosphere under seal) of carbon dioxide with a mine-fire atmosphere corresponding to point *J*. Atmosphere *h* is nonexplosive because oxygen is lacking; it can form explosive mixtures with air and consists (by portions) of:

60.05 percent of percentages of constituents composing atmosphere *J*
.00 percent of air
39.95 percent of carbon dioxide (diluent)

By calculating the composition of the gas portion and combining the percentages of the constituents composing the three portions, we find that atmosphere *h* (fig. 8) consists (by constituents) of:

	Percent
Carbon monoxide	4. 08
Methane	. 48
Hydrogen	6. 13
Oxygen	. 00
Nitrogen	41. 61
Carbon dioxide (of which 39.95 percent is diluent)	47. 70

It can be deduced from figure 8 that atmosphere *m*, which is formed by admixing 39.95 percent of carbon dioxide with atmosphere *P*, cannot form explosive mixtures with air, whereas, atmosphere *h*, which is formed by admixing the same amount of carbon dioxide with atmosphere *J*, can form explosive mixtures with air.

It can be concluded that any diluent-free atmosphere that contains more oxygen than atmosphere sample 65—for example, atmosphere *P* (fig. 8)—will, if admixed with 39.95 percent of carbon dioxide, form an extinctive atmosphere; moreover, any diluent-free atmosphere that contains less oxygen than atmosphere sample 65—for example, atmosphere *J*—will, if admixed with 39.95 percent of carbon dioxide, form a final atmosphere that is capable of forming explosive mixtures with air.

Whether or not a given atmosphere will, if admixed with 39.95 percent of carbon dioxide, form a final atmosphere that is incapable of forming explosive mixtures with air depends on the diluent (additional carbon dioxide) content and the oxygen content of the given atmosphere.

To verify mathematically whether or not a final atmosphere, formed as above, is explosive or capable of forming explosive mixtures with air, we determine the explosibility of the final atmosphere by means of the critical gas-mixture value formulas, as shown on pages 90 to 93.

DETERMINATION OF EXPLOSIBILITY OF FINAL ATMOSPHERES FORMED BY ADMIXING INERT GAS WITH MINE-FIRE ATMOSPHERE

To determine the explosibility of the final atmospheres *m* and *h*, we first determine the air-free analysis of each atmosphere by means of formulas (1), (2), (3), and (4*b*). The arithmetical calculations are not given; however, the air-free analyses (in percent, by volume) are shown in the following table:

Constituent	Final atmosphere		Air-free analysis		
	m	*h*	*m*	*h*	Symbol
Gas portion:					
Carbon monoxide	3. 47	4. 08	3. 81	4. 08	A_1
Methane	. 41	. 48	. 45	. 48	B_1
Hydrogen	5. 20	6. 13	5. 72	6. 13	$(H_2)_1$
Carbon dioxide	6. 58	7. 75	7. 23	7. 75	
Nitrogen	35. 38	41. 61	38. 88	41. 61	
Total	51. 04	60. 05	56. 09	60. 05	
Air portion:					
Oxygen	1. 89	. 00	. 00	. 00	
Nitrogen	7. 12	. 00	. 00	. 00	
Total	9. 01	. 00	. 00	. 00	
Diluent portion: Carbon dioxide	39. 95	39. 95	43. 91	39. 95	
Total carbon dioxide	46. 53	47. 70	51. 14	47. 70	D_1
Total nitrogen	42. 50	41. 61	38. 88	41. 61	$(N_2)_1$
Total	100. 00	100. 00	100. 00	100. 00	

We determine now the critical gas-mixture value formulas that apply to atmospheres *m* and *h*. We have shown on page 91 that it is immaterial which formula is used to calculate the critical gas-mixture value as long as the case defining the formula applies to both the given air-free atmosphere and the diluent (nitrogen or carbon dioxide) selected.

We have determined that both atmosphere *m* and atmosphere *h* contain carbon monoxide, methane, hydrogen, carbon dioxide, and nitrogen; to determine the case that is applicable when nitrogen is used as the diluent, we establish the relationship existing between the extinctive combination of the hydrogen content (in percent) of the air-free given atmosphere and carbon dioxide, and the carbon dioxide content of that atmosphere.

To determine the case that is applicable when carbon dioxide is used as the diluent, we establish the relationship existing between the extinctive combination of the carbon monoxide content (in percent) of the air-free given atmosphere and nitrogen plus the extinctive combination of the methane content and nitrogen, and the total nitrogen content of the air-free given atmosphere.

Applying the foregoing procedure to atmosphere *m* (fig. 8) we obtain from the air-free analysis given in the table on page 145:

$$(H_2)_1=5.72 \text{ percent, and } D_1=51.14 \text{ percent,}$$

from which we deduce, when nitrogen is used as the diluent, that

$$10.2(H_2)_1=10.2\times 5.72=58.34,$$

and

$$10.2(H_2)_1, \text{ or } 58.34, >51.14, \text{ or } D_1.$$

As all the carbon dioxide (D_1) can be paired with part of the hydrogen $(H_2)_1$, and the hydrogen remaining can be paired with nitrogen, case 1, page 24, applies, and formula (10), page 25, is used to calculate the real value of $C.\ G.\ M.\ V._{N_2}$.

Applying the procedure to determine the case in which carbon dioxide is used as the diluent, we obtain from the table on page 145:

$$A_1=3.81 \text{ percent, } B_1=0.45 \text{ percent, and } (N_2)_1=38.88 \text{ percent,}$$

from which we deduce that

$$4.15A_1=4.15\times 3.81=15.81,$$

$$6B_1=6\times 0.45=2.70,$$

$$4.15A_1+6B_1=15.81+2.70=18.51,$$

and

$$(4.15A_1+6B_1), \text{ or } 18.51, <38.88, \text{ or } (N_2)_1.$$

As all the carbon monoxide (A_1) and all the methane (B_1) contained in the air-free composition of atmosphere *m* can be paired with part of the nitrogen $(N_2)_1$, and the nitrogen remaining can be paired with part of the hydrogen, case 6, page 83, applies; and formula (58), page 83, is used to calculate the critical gas-mixture value when carbon dioxide is used as the diluent.

By substituting the real values for the symbols in formulas (10) and (58), which are

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{5.15A_1+7B_1+17.55(H_2)_1-0.6225D_1}, \tag{10}$$

and

$$C.\ G.\ M.\ V._{CO_2}=\frac{10{,}000}{3.56A_1+4.70B_1+11.2(H_2)_1+0.3836(N_2)_1}, \tag{58}$$

we find

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{(5.15\times 3.81)+(7\times 0.45)+(17.55\times 5.72)-(0.6225\times 38.88)}, \tag{10}$$

$$=\frac{10{,}000}{19.62+3.15+100.39-31.83},$$

$$=\frac{10{,}000}{91.33}=109.49, \text{ critical gas-mixture value when nitrogen is used as diluent;}$$

and

$$C.\ G.\ M.\ V._{CO_2}=\frac{10{,}000}{(3.56\times3.81)+(4.7\times0.45)+(11.2\times5.72)+(0.3846\times38.88)},\qquad(58)$$

$$=\frac{10{,}000}{13.56+2.12+64.06+14.91},$$

$$=\frac{10{,}000}{94.65}=105.65,\ \text{critical gas-mixture value when carbon dioxide is used as diluent.}$$

As the critical gas-mixture values relating to the air-free composition of atmosphere m (fig. 8) are more than 100, neither atmosphere m nor its air-free composition can form explosive mixtures with air or is explosive.

Applying the same procedure to determine the critical gas-mixture values relating to atmosphere h (fig. 8) we deduce from the data given in the table on page 145 that

$$10.2(H_2)_1=10.2\times6.13=62.53,$$

and

$$10.2(H_2)_1,\ \text{or}\ 62.53,\ >\ 47.70,\ \text{or}\ D_1.$$

Therefore, formula (10) is used to determine the critical gas-mixture value relating to atmosphere h when nitrogen is used as the diluent.

To determine the critical gas-mixture value relating to atmosphere h when carbon dioxide is used as the diluent, we determine that

$$4.15A_1=4.15\times4.08=16.93,$$

$$6B_1=6\times0.48=2.88,$$

and

$$4.15A_1+6B_1=16.93+2.88=19.81.$$

As $(4.15A_1+6B_1)$, or 19.81, <41.61, or $(N_2)_1$, case 6, page 83, applies, and formula (58), page 83, is used for the same reason that governed the use of formula (58) with atmosphere m.

By substituting the real values given in the table on page 145 for the symbols in formulas (10) and (58), we find

$$C.\ G.\ M.\ V._{N2}=\frac{10{,}000}{(5.15\times4.08)+(7\times0.48)+(17.55\times6.13)-(0.6225\times47.70)},\qquad(10)$$

$$=\frac{10{,}000}{21.01+3.36+107.58-29.69},$$

$$=\frac{10{,}000}{102.26}=97.78,\ \text{critical gas-mixture value when nitrogen is used as diluent;}$$

and

$$C.\ G.\ M.\ V._{CO_2}=\frac{10{,}000}{(3.56\times4.08)+(4.7\times0.48)+(11.2\times6.13)+(0.3836\times41.61)},\qquad(58)$$

$$=\frac{10{,}000}{14.52+2.26+68.66+15.96},$$

$$=\frac{10{,}000}{101.40}=98.62,\ \text{critical gas-mixture value when carbon dioxide is used as diluent.}$$

Because the critical gas-mixture values relating to atmosphere *h* (fig. 8) are less than 100, atmosphere *h* can form explosive mixtures with air.

The significance of the foregoing data relating to atmospheres *m* and *h* is: If 99,875 cubic feet (39.95 percent) of carbon dioxide is admixed with the mine-fire atmosphere under seal, a borderline extinctive mixture (*g*, fig. 8 and p. 130) is formed from that portion of the mine-fire atmosphere represented by sample 65; however, those portions that contain less oxygen than sample 65 and correspond to some point that lies below line sample 65–*g* and in the portion of the zone of mixtures capable of forming explosive mixtures with air, may or may not form final mixtures that can form explosive mixtures with air; furthermore, those portions of the mine-fire atmosphere that contain more oxygen than atmosphere *g* and correspond to some point in line sample 65–*g*, or to some point in the zone of explosive mixtures, or to some point that lies above line sample 65–*g* and in the portion of the zone of mixtures capable of forming explosive mixtures with air, form final mixtures that cannot form explosive mixtures with air and are nonexplosive.

Although the factors relating to the explosibility of atmospheres *m* and *h* can be determined graphically, the seriousness of errors justifies the time expended to determine by both graphic and mathematical methods the explosibility of mixtures formed by admixing a diluent with a mine-fire atmosphere.

DETERMINATION OF VOLUME OF INERT GAS REQUIRED TO FORM A SAFE FINAL ATMOSPHERE WITH PORTION OF MINE-FIRE ATMOSPHERE THAT MAY CONTAIN MORE OXYGEN THAN PORTION SAMPLED

It has been shown that atmosphere *m* is formed from the portion of the mine-fire atmosphere corresponding to point *P* when 39.95 percent of carbon dioxide is introduced into the mine-fire area under seal and that atmosphere *m* is well on the safe side. As a matter of fact, it is not necessary to use 39.95 percent of carbon dioxide to form nonexplosive and extinctive mixtures, as the case may be, throughout the mine-fire area if atmosphere *P* represents the portion of the mine-fire atmosphere under seal that has the widest explosive range. If this condition exists, 36.91 percent of carbon dioxide suffices, and the desired final atmosphere formed from atmosphere *P* corresponds to point m_1 (fig. 8). (See p. 150.)

It is seen in figure 8 that the points composing line *P–O* correspond to the successive mixtures formed by admixing carbon dioxide with atmosphere *P*. The compositions of these mixtures range from that of atmosphere *P* to pure carbon dioxide (point *O*). Point m_1 in line *P–O* corresponds to atmosphere m_1.

The composition of atmosphere m_1, which is a borderline extinctive mixture, can be determined in the usual manner. The volume of carbon dioxide that must be admixed with atmosphere *P* to form atmosphere m_1 can be determined from figure 8 or calculated either by formulas (41) to (46*c*), inclusive, or by formulas (70), (71), (72*a*), and (68), as follows:

We have determined the following real values of the symbols that apply to atmospheres P and O and all possible mixtures of atmosphere J (fig. 8), air, and carbon dioxide:

$$C.\ G.\ M.\ V._{co_2}=59.23 \text{ (see p. 124).}$$

$$\phi=\tan^{-1}\frac{C.\ G.\ M.\ V._{co_2}}{20.93}=\tan^{-1}\frac{59.23}{20.93}=70°32'17'' \text{ (see p. 127).}$$

$$\sin\tan^{-1}\frac{C.\ G.\ M.\ V._{co_2}}{20.93}=\sin\tan^{-1}\frac{59.23}{20.93}=\sin 70°32'17''=0.94287 \text{ (see p. 127).}$$

Atmosphere P (see p. 137):
Air content $= Air_s = 15.00$ percent.
Oxygen content $= (O_2)_s = 3.1395$ percent.
Gas-portion content $= Gas_s = 85.00$ percent.
Diluent content $= (CO_2)_{add-s} = 0.00$ percent.
Atmosphere O (see fig. 8):
Air content $= Atmos_{air} = 0.00$ percent.
Oxygen content $= (O_2)_{atmos} = 0.00$ percent.
Gas-portion content $= Atmos_{g.\ p.} = 0.00$ percent.
Diluent content $= 100.00$ percent.

By substituting the above-given real values for the symbols in formulas (70), (71), (72a), and (68), in the order given, we find

$$z=\frac{[20.93-(O_2)_{atmos}]\left[\sin\tan^{-1}\frac{C.\ G.\ M.\ V.}{20.93}\right]}{\left[\sin\left(90°-\tan^{-1}\frac{C.\ G.\ M.\ V.}{20.93}-\tan^{-1}\frac{(O_2)_{atmos}-(O_2)_s}{Gas_s}\right)\right]}, \qquad (70)$$

$$=\frac{(20.93-0.00)\times\sin 70°32'17''}{\left[\sin\left(90°-70°32'17''-\tan^{-1}\frac{0.00-3.1395}{85.00}\right)\right]},$$

$$=\frac{20.93\times 0.94287}{\sin(90°-70°32'17''+2°06'54'')}=\frac{20.93\times 0.94287}{\sin 21°34'37''},$$

$$=\frac{19.73406}{0.36779}=53.66.$$

$$Gas_{f.\ a.}=z\cos\tan^{-1}\frac{(O_2)_{atmos}-(O_2)_s}{Gas_s}, \qquad (71)$$

$$=53.66\times\cos\tan^{-1}\frac{0.00-3.1395}{85.00},$$

$$=53.66\times\cos 2°06'54'',$$

$$=53.66\times 0.9993,$$

$=53.63$ percent, gas-portion content of atmosphere m_1.

$$Air_{f.\ a.}=Atmos_{air}-\left[\left(z\sin\tan^{-1}\frac{(O_2)_{atmos}-(O_2)_s}{Gas_s}\right)\left(\frac{100}{20.93}\right)\right], \qquad (72a)$$

$$=0.00-\left[53.66\ (-\sin 2°06'54'')\left(\frac{100}{20.93}\right)\right],$$

$$=\frac{53.66\times 0.03687\times 100}{20.93}=\frac{197.90}{20.93},$$

$=9.46$ percent, air content of atmosphere m_1.

$$Inert\ gas_{add-f.\ a.}=100-Air_{f.\ a.}-Gas_{f.\ a.}, \qquad (68)$$

$$=100-9.46-53.63,$$

$=36.91$ percent of additional carbon dioxide, diluent content of atmosphere m_1.

Summarizing the above data: Atmosphere m_1 is composed (by portions) of 53.63 percent of the percentages of the constituents composing atmosphere J (fig. 8); 9.46 percent of air; and 36.91 percent of additional carbon dioxide (diluent). As atmosphere P is diluent-free, the diluent content of atmosphere m_1, or 36.91 percent of carbon dioxide, is also the volume of carbon dioxide that must be admixed with atmosphere P to form atmosphere m_1.

As atmosphere m_1 is a borderline extinctive mixture, it is just incapable of forming explosive mixtures with air. This condition can be seen in figure 8; however, to verify this conclusion regarding the explosibility of atmosphere m_1, we follow the procedure that was used to ascertain the explosibility of atmospheres m and h.

Let us assume that atmosphere m_1 is an original atmosphere, which is diluent-free by definition. As atmosphere m_1 corresponds to a definite point in line $C.\ G.\ M.\ V._{CO_2}\text{-}Nose_{CO_2}$ (fig. 8), the air-free composition of atmosphere m_1 is identical to the composition of the critical gas mixture that corresponds to point $C.\ G.\ M.\ V._{CO_2}$.

We have shown above that atmosphere m_1 consists of 9.46 percent of air and (100—9.46) percent, or 90.54 percent of other gases (see p. 17).

As atmosphere m_1 is assumed to be an original atmosphere, the critical gas mixture (atmosphere $C.\ G.\ M.\ V._{CO_2}$, fig. 8) must be equivalent to an air-free original atmosphere in relation to atmosphere m_1, and the gas-portion content (in percent) and the diluent content of atmosphere m_1 must equal 90.54 percent of the gas-portion content and the diluent content, respectively, of the critical gas mixture. This relationship can be expressed mathematically by formula (3), page 18, which is

$$Constituent_{air\text{-}free}=\frac{Constituent_s}{K_s}(100), \tag{3}$$

in which

$Constituent_{air\text{-}free}$ = gas-portion content, or diluent content (in percent), as the case may be, of atmosphere m_1 calculated to an air-free basis;

$Constituent_s$ = gas-portion content, or diluent content, as the case may be, of atmosphere m_1;

and

K_s = volume of gases, other than air, contained in atmosphere m_1.

By substituting the real values, found on page 149, for the symbols in formula (3), when

$Constituents_s$ = 53.63 percent, gas-portion content, and
36.91 percent, diluent content of atmosphere m_1,

and

K_s = 90.54 percent,

we find

$$Constituent_{air\text{-}free}=\frac{53.63\times 100}{90.54},$$

$=59.23$ percent, gas-portion content of air-free composition of atmosphere m_1;

and

$$Constituent_{air\text{-}free}=\frac{36.91\times 100}{90.54},$$

$=40.77$ percent of carbon dioxide, diluent content of air-free composition of atmosphere m_1.

We have found, on page 124, that the real value of $C.\ G.\ M.\ V._{CO_2}$ is 59.23 percent, which is also the gas-portion content of the critical gas mixture. As the gas-portion contents of the critical gas mixture and air-free composition of the gas portion of atmosphere m_1 are the same (59.23 percent), the chemical compositions of the gas portions of the critical gas mixture and air-free composition of atmosphere m_1 must be identical, and it can be concluded that the calculations made on page 149 to determine the composition of atmosphere m_1 are correct.

The chemical composition of the critical gas mixture is given on page 125, from which we obtain the air-free composition of atmosphere m_1 as follows:

	Percent
Carbon monoxide (A_1)	4.03
Methane (B_1)	.47
Hydrogen $(H_2)_1$	6.04
Nitrogen $(N_2)_1$	41.05
Carbon dioxide (D_1)	48.41

As the next step in the procedure to verify whether or not atmosphere m_1 is both incapable of forming explosive mixtures with air and nonexplosive, we determine the case and the critical gas-mixture value formulas that are applicable when either nitrogen or carbon dioxide is used as the diluent of atmosphere m_1 calculated to an air-free basis.

From the above-given air-free analysis of atmosphere m_1, we obtain the following real values:

$$(H_2)_1=6.04 \text{ percent, and } D_1=48.41 \text{ percent,}$$

from which we deduce, when nitrogen is the diluent,

$$10.2(H_2)_1=10.2\times 6.04=61.61,$$

and

$$10.2(H_2)_1, \text{ or } 61.61, >48.41, \text{ or } D_1.$$

As all the carbon dioxide (D_1) can be paired with part of the hydrogen $(H_2)_1$ and the hydrogen remaining can be paired with nitrogen, case 1, page 24, applies, and formula (10), page 25, is used to calculate the real value of $C.\ G.\ M.\ V._{N_2}$.

By substituting real values (see above) for the symbols in formula (10), which is

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{5.15A_1+7B_1+17.55(H_2)_1-0.6225D_1}, \tag{10}$$

we find

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{(5.15\times 4.03)+(7\times 0.47)+(17.55\times 6.04)-(0.6225\times 48.41)},$$

$$=\frac{10{,}000}{20.76+3.29+106.00-30.14},$$

$$=\frac{10{,}000}{99.91}=100.08.$$

To determine the case and the critical gas-mixture value formula that are applicable when carbon dioxide is used as the diluent of atmosphere m_1 calculated to an air-free basis, we obtain the following real values from the data given on page 151:

$$A_1=4.03 \text{ percent, } B_1=0.47 \text{ percent, and } (N_2)_1=41.05 \text{ percent,}$$

from which we deduce

$$4.15A_1=4.15\times 4.03=16.72,$$

$$6B_1=6\times 0.47=2.82,$$

$$4.15A_1+6B_1=16.72+2.82=19.54,$$

and

$$(4.15A_1+6B_1), \text{ or } 19.54, <41.05, \text{ or } (N_2)_1.$$

As all the carbon monoxide (A_1) and all the methane (B_1) can be paired with part of the nitrogen $(N_2)_1$, and the nitrogen remaining can be paired with part of the hydrogen $(H_2)_1$, case 6, page 83, applies, and formula (58), page 83, is used to calculate the real value of $C.\,G.\,M.\,V._{CO_2}$.

By substituting real values (see p. 151) for the symbols in formula (58), which is

$$C.G.M.V._{CO_2}=\frac{10{,}000}{3.56A_1+4.70B_1+11.2(H_2)_1+0.3836(N_2)_1}, \tag{58}$$

we find

$$C.G.M.V._{CO_2}=\frac{10{,}000}{(3.56\times 4.03)+(4.7\times 0.47)+(11.2\times 6.04)+(0.3836\times 41.05)},$$

$$=\frac{10{,}000}{14.35+2.21+67.65+15.75},$$

$$=\frac{10{,}000}{99.96}=100.04.$$

Because the critical gas-mixture values relating to the air-free composition of atmosphere m_1 (fig. 8) are more than 100, neither atmosphere m_1 nor its air-free composition can form explosive mixtures with air or is explosive.

DETERMINATION OF BOTH VOLUME OF INERT GAS AND VOLUME OF *DILUENT* (CARBON DIOXIDE PLUS AIR) REQUIRED TO FORM A SAFE FINAL ATMOSPHERE WITH PORTION OF MINE-FIRE ATMOSPHERE THAT MAY CONTAIN LESS OXYGEN THAN PORTION SAMPLED

It has been stated on page 114 that maximum safety is assured in the use of a given inert gas (diluent) to form a safe final atmosphere when enough inert gas is admixed with the given atmosphere to form a final atmosphere that (1) cannot form explosive mixtures with air and (2) has a diluent content (in percent) the same as the diluent content of the critical gas mixture or a gas-portion content the same as the gas-portion content of the lower-explosive-limit mixture. However, the final atmosphere containing the least amount of diluent should be selected.

Let us suppose that atmosphere *J* (fig. 8) represents a portion of the mine-fire atmosphere under seal that contains less oxygen than the portion represented by sample 65. As the composition of atmosphere *J* is the same as the air-free composition of sample 65, the volume of carbon dioxide necessary to form a safe final mixture with atmosphere *J*, when that volume of carbon dioxide is admixed with the mine-fire atmosphere under seal, also suffices to form a safe final mixture with every portion of the mine-fire atmosphere under seal that contains more oxygen.

If carbon dioxide is introduced into the mine-fire area, or if a *diluent* composed of carbon dioxide and air is used instead, and the volume of either the carbon dioxide or the *diluent* is such that the diluent content (in percent) of the final atmosphere formed with the air-free original atmosphere is equal to the diluent content (40.77 percent of additional carbon dioxide) of the critical gas mixture, every other possible final mixture that contains 40.77 percent of additional carbon dioxide corresponds to some point in line *C.G.M.V.* $_{co_2}$–*s* (fig. 8).

Let us now assume that pure carbon dioxide in an amount equal to 40.77 percent of the total volume of the mine-fire area under seal is introduced into the mine-fire area. A final atmosphere having the composition of the critical gas mixture is formed with that portion of the mine-fire atmosphere corresponding to point *J* (fig. 8). If, however, 4.78 percent of air be admixed with 40.77 percent of carbon dioxide so as to form a *diluent* having a total volume equal to 45.55 percent of the volume of the mine-fire area under seal, and this mixture is introduced into the mine-fire area, the resultant successive mixtures formed with atmosphere *J* will have chemical compositions that differ from those formed with pure carbon dioxide. These mixtures correspond to points in line *J*–*r* between point *J* and point *q*, which corresponds to the final atmosphere formed. In other words, if 113,875 cubic feet (45.55 percent) of a *diluent* having the composition of atmosphere *r* (89.51 percent carbon dioxide plus 10.49 percent air) is admixed with atmosphere *J*, a final atmosphere corresponding to point *q* is formed.

The composition of atmosphere *q* can be determined graphically in figure 8, in which point *q* is the point of intersection of line *J*–*r* and line *C.G.M.V.* $_{co_2}$–*s*. The composition (by portions) of atmosphere *q* is calculated by formulas (47*c*–3) and (68) and is:

54.45 percent, the gas-portion content,
4.78 percent of air,
40.77 percent of carbon dioxide (diluent).

It is obvious that carbon dioxide, in a proportion equal to 40.77 percent of the volume (250,000 cubic feet) of the mine-fire atmosphere under seal, can be admixed with different volumes of air to form a *diluent* until an amount of air equal to 59.23 percent of the volume of the mine-fire atmosphere under seal is used. In the last instance the *diluent* corresponds to point *s* (fig. 8) and consists of 101,825 cubic feet (40.77 percent) of carbon dioxide and 148,175 cubic feet of air. If a *diluent* having this composition is introduced into the mine-fire area, successive mixtures are formed with each definite portion of the mine-fire atmosphere under seal. However, every series of successive mixtures that is formed by admixing *diluent* s with any portion corresponding to a definite point in line A–J between **point** J **and** point *Lower Limit* contains some explosive mixtures.

It can be seen in figure 8 and verified by calculations **that:** (1) The air component of the *diluent* containing 101,825 cubic feet (40.77 percent) of carbon dioxide is limited by the condition that none of the successive mixtures formed by admixing the *diluent* with the mine-fire atmosphere be explosive; (2) the *diluent* is not safe if any point in the line corresponding to the successive mixtures intersects the line of upper-explosive-limit mixtures ($Upper\ Limit\text{–}Nose_{CO_2}$) or passes above point $Nose_{CO_2}$), which corresponds to the nose-limit mixture; and (3) the volume of air that can be used safely as the air component of the *diluent* must be determined for every portion of the mine-fire atmosphere in order to insure that an explosive mixture is not formed by use of the *diluent* where a source of ignition is present.

Applying the above statements specifically to atmosphere J (fig. 8) the maximum volume of air that can be admixed with 101,825 cubic feet (40.77 percent) of carbon dioxide to form a safe *diluent* is the air component of the *diluent* that will, when admixed with atmosphere J, form atmosphere s_1.

Point s_1, which corresponds to an atmosphere having a diluent content of 40.77 percent of carbon dioxide, is the point of intersection of line $C.\ G.\ M.\ V._{CO_2}\text{–}s$ and line J–v. Line J–v, which contains the point corresponding to the nose-limit mixture, corresponds to the successive mixtures formed by admixing *diluent* v (fig. 8) with atmosphere J.

The composition of *diluent* v, the volume (in percent of the volume of the mine-fire atmosphere under seal) of *diluent* v that must be admixed with atmosphere J to form admosphere s_1, and the composition of atmosphere s_1 can be determined graphically from figure 8 or calculated mathematically as follows:

As atmosphere s_1, the final atmosphere formed, must contain 40.77 percent of additional carbon dioxide, and as atmosphere J is diluent-free, we can write

$$Inert\ gas_{Dil-inert\ gas+air} = Inert\ gas_{add-f.\ a.}$$

$$= 40.77 \text{ percent carbon dioxide, the diluent content of atmosphere } s_1.$$

From the compositions of atmosphere J and the nose-limit mixture given on pages 116 and 127, respectively, we obtain

$Gas_s = 100.00$ percent, gas-portion content of atmosphere J

$(O_2)_s = .00$ percent, oxygen content of atmosphere J

$Gas_{nose} = 37.81$ percent, gas-portion content of nose-limit mixture

$(O_2)_{nose} = 7.57$ percent, oxygen content of nose-limit mixture

By substituting the above-given real values and those determined here for the respective symbols in formulas (62*B*), (62*C*–1), (73), (68), and (47*c*–3), we find:

$$Atmos_{air}=\frac{100}{20.93}\left[\frac{Gas_s[(O_2)_{nose}-(O_2)_s]}{Gas_s-Gas_{nose}}+(O_2)_s\right] \text{ percent,} \qquad (62B)$$

$$=\frac{100}{20.93}\left[\frac{100\times(7.57-0.00)}{100-37.81}+0.00\right],$$

$$=\frac{100\times757}{20.93\times62.19}=\frac{75{,}700}{1{,}301.64},$$

$$=58.16 \text{ percent, air content of atmosphere } v.$$

$$Atmos_{inert\ gas}=100-Atmos_{air}, \qquad (62C\text{-}1)$$

$$=100-58.16,$$

$$=41.84 \text{ percent carbon dioxide, diluent content of atmosphere } v.$$

$$Inert\ gas_{Dil-inert\ gas+air}=(Dil_{inert\ gas+air})\left[\frac{Atmos_{inert\ gas}}{100}\right], \qquad (73)$$

$$40.77=(Dil_{inert\ gas+air})\left(\frac{41.84}{100}\right);$$

which, by transposition, gives

$$Dil_{inert\ gas+air}=\frac{40.77\times100}{41.84},$$

$=97.44$ percent, amount of *diluent* v (carbon dioxide plus air), which, when admixed with atmosphere J, forms atmosphere s_1 (fig. 8).

As atmosphere J (fig. 8) is air-free and diluent-free, the real values of the air content and the diluent content (40.77 percent) of atmosphere s_1 are also the respective volumes of air and carbon dioxide composing the volume (97.44 percent) of *diluent* v that must be admixed with atmosphere J to form atmosphere s_1; therefore,

$$Air_{f.\ a.}=Dil_{inert\ gas+air}-Inert\ gas_{Dil-inert\ gas+air},$$

$$=97.44-40.77,$$

$$=56.67 \text{ percent, the air content of atmosphere } s_1.$$

By substituting real values for the symbols in formula (68), arranged as follows:

$$Gas_{f.\ a.}=100-Inert\ gas_{add-f.\ a.}-Air_{f.\ a.}, \qquad (68)$$

we find

$$Gas_{f.\ a.}=100-40.77-56.67,$$

$$=2.56 \text{ percent, gas-portion content of atmosphere } s_1.$$

The gas-portion content of atmosphere s_1 can also be found by substituting real values for the symbols in formula (47*c*–3) as follows:

$$Dil_{inert\ gas+air}=\frac{(Gas_s-Gas_{f.\ a.})100}{Gas_s}, \qquad (47c\text{-}3)$$

$$97.44=\frac{(100-Gas_{f.\ a.})100}{100},$$

from which, by transposition, we find

$Gas_{f.\ a.}=100-97.44=2.56$ percent, gas-portion content of atmosphere s_1.

Summarizing the foregoing data relating to atmospheres *J* and s_1 and *diluent v* (fig. 8), we find that 141,675 cubic feet (56.67 percent of the volume of the mine-fire atmosphere under seal) of air is the maximum volume that can be admixed with 101,825 cubic feet (40.77 percent) of carbon dioxide to form a *diluent* having a composition in which the ratio of air to carbon dioxide is the same as that of *diluent v*. *Diluent v* is composed of 58.16 percent of air and 41.84 percent of carbon dioxide. Furthermore, if 243,500 cubic feet of *diluent v* is admixed with atmosphere *J*, the line of successive mixtures formed contains point $Nose_{CO_2}$, which corresponds to the nose-limit mixture. Atmosphere s_1, which is the final mixture formed, is composed (by portions) of

	Percent
Percentages of constituents composing atmosphere *J*	2. 56
Air	56. 67
Carbon dioxide (diluent)	40. 77

By calculating the chemical composition of the gas portion and the air portion of atmosphere s_1, in the manner shown previously, and then combining and adding the percentages of the constituents and the above-given real value of the diluent portion, we find the chemical composition of atmosphere s_1 to be:

	Percent
Carbon monoxide	0. 17
Methane	. 02
Hydrogen	. 26
Oxygen	11. 86
Nitrogen	46. 59
Carbon dioxide	41. 10

VERIFICATION OF EXPLOSIBILITY OF EXPLOSIVE-LIMIT MIXTURES FORMED BY ADMIXING A GIVEN *DILUENT* WITH MINE-FIRE ATMOSPHERE UNDER SEAL

There are instances when it may not be possible to admix a pure inert gas with portions of a given mine-fire atmosphere under seal to form successive mixtures corresponding to lines that always pass below the nose. It is sometimes impossible to prevent these portions of a given mine-fire atmosphere from becoming admixed with air or blackdamp, which is equivalent to admixing air or blackdamp with the given mine-fire atmosphere insofar as results are concerned. If the line of successive mixtures formed with any given portion of the mine-fire atmosphere enters into or passes through the zone of explosive mixtures, and a source of ignition is present, an explosion will occur; if no source of ignition is present, a final atmosphere will be formed as a result of the given portion of the mine-fire atmosphere being admixed with a proportional part of the *diluent*. Whether or not such a final atmosphere is safe depends on its composition.

Conditions, such as just mentioned, prevailed at times in the Continental mine-fire area; a portion of the mine-fire atmosphere, as represented by sample 65, was admixed with blackdamp-air mixtures that contained 10 to 19 percent of oxygen and considerable nitrogen. The fire had not progressed to the part of the sealed area that contained the blackdamp-air mixtures; and, as no source of ignition was present, explosions did not occur when the mixtures formed were within the explosive range. The extinguishment of the fire by "slushing" was controlled; this resulted in formation of safe final atmospheres before the fire reached the places in the sealed area where explosive mixtures existed. Examples of final atmospheres formed under such conditions are shown in figure 8.

The construction of stoppings and bulkheads was governed by atmospheric conditions in the sealed area, as shown by analyses of samples of the mine-fire atmosphere.

It is important to know the composition of the borderline mixtures, or lower-explosive-limit mixtures, that were formed. The borderline mixtures were made nonexplosive before "slushing" operations were permitted, thereby preventing explosions if these mixtures were forced into the active fire area.

As it was known that successive mixtures were being formed in the sealed mine-fire area, the lines that corresponded to the successive mixtures were plotted in the graph, such as figure 8 (pocket), to establish the points of intersection of these lines and the line of lower explosive limits (*Lower Limit–Nose*$_{N_2}$) and line *Lower Limit-Nose* $_{CO_2}$. The composition of the final atmospheres that corresponded to points in the line of lower explosive limits was calculated and checked against the analyses of samples of the mine-fire atmosphere. These samples were obtained through boreholes that connected the surface to the mine-fire area.

It was stated on page 138 that point l_1 (fig. 8) corresponds to one of the successive mixtures formed when a definite volume of *diluent k*, which is composed of 42.74 percent of carbon dioxide and 57.26 percent of air, is admixed with atmosphere *P*.

As the line of lower explosive limits is assumed to be a straight line, and point l_1 is the point of intersection of the line of lower limits and line *P–k*, we can assume that point l_1 corresponds to a definite lower-explosive-limit mixture.

To determine whether or not atmosphere l_1 is a lower-explosive-limit mixture, we first determine the composition of it. The composition of atmosphere l_1 can be determined either graphically in figure 8 or mathematically as follows:

From the compositions of *diluent k*, atmosphere *P*, the lower-explosive-limit mixture, and the nose-limit mixture given on pages 131, 137, 120, and 127, respectively, we obtain

$Atmos_{air}=57.26$ percent, air content of *diluent k*,
$Atmos_{inert\ gas}=42.74$ percent carbon dioxide, diluent content of *diluent k*,
$(O_2)_{atmos}=11.98$ percent, oxygen content of *diluent k*,
$Gas_s=85.00$ percent, gas-portion content of atmosphere *P*,
$(O_2)_s=3.14$ percent, oxygen content of atmosphere *P*,
$Gas_{L-L}=33.50$ percent, gas-portion content of lower-explosive-limit mixture,
$(O_2)_{L-L}=13.92$ percent, oxygen content of lower-explosive-limit mixture,
$Gas_{nose}=37.81$ percent, gas-portion content of nose-limit mixture,
$(O_2)_{nose}=7.57$ percent, oxygen content of nose-limit mixture.

By substituting the above-given real values for the symbols in formulas (75) to (79), inclusive, (1), and (68) in the order given, we find

$$z_1=[(O_2)_{L-L}-(O_2)_{atmos}]+(Gas_{L-L})\tan\tan^{-1}\frac{(O_2)_{atmos}-(O_2)_s}{Gas_s},\qquad(75)$$

$$=(13.92-11.98)+\left[33.50\times\tan\tan^{-1}\frac{11.98-3.14}{85.00}\right],$$

$$=1.94+\frac{33.50\times8.84}{85}=1.94+\frac{296.14}{85},$$

$$=1.94+3.48=5.42.$$

$$z_2=\frac{(z_1)\left[\sin\tan^{-1}\dfrac{Gas_{nose}-Gas_{L-L}}{(O_2)_{L-L}-(O_2)_{nose}}\right]}{\sin\left[90^\circ-\tan^{-1}\dfrac{Gas_{nose}-Gas_{L-L}}{(O_2)_{L-L}-(O_2)_{nose}}-\tan^{-1}\dfrac{(O_2)_{atmos}-(O_2)_s}{Gas}\right]},\qquad(76)$$

$$=\frac{5.42\times\sin\tan^{-1}\dfrac{37.81-33.50}{13.92-7.57}}{\sin\left[90^\circ-\tan^{-1}\dfrac{37.81-33.50}{13.92-7.57}-\tan^{-1}\dfrac{11.98-3.14}{85}\right]},$$

$$=\frac{5.42\times\sin\tan^{-1}\dfrac{4.31}{6.35}}{\sin\left[90^\circ-\tan^{-1}\dfrac{4.31}{6.35}-\tan^{-1}\dfrac{8.84}{85}\right]},$$

$$=\frac{5.42\times\sin\tan^{-1}0.67874}{\sin[90^\circ-\tan^{-1}0.67874-\tan^{-1}0.10400]},$$

$$=\frac{5.42\times\sin 34^\circ09'59''}{\sin[90^\circ-34^\circ09'59''-5^\circ56'15'']},$$

$$=\frac{5.42\times0.56160}{\sin 49^\circ53'46''}=\frac{3.0461}{0.76488}=3.98.$$

$$z_3=z_2\sin\tan^{-1}\frac{(O_2)_{atmos}-(O_2)_s}{Gas_s},\qquad(77)$$

$$=3.98\sin\tan^{-1}\frac{11.98-3.14}{85},$$

$$=3.98\times\sin 5^\circ56'15'',$$

$$=3.98\times0.10344=0.41.$$

$$(O_2)_{f.\ a.}=(O_2)_{L-L}-z_1-z_3,\qquad(78)$$
$$=13.92-5.42-0.41,$$
$=8.09$ percent, the oxygen content of atmosphere l_1.

$$Gas_{f.\ a.}=Gas_{L-L}+z_2\cos\tan^{-1}\frac{(O_2)_{atmos}-(O_2)_s}{Gas_s},\qquad(79)$$

$$=33.50+\left(3.98\times\cos\tan^{-1}\frac{11.98-3.14}{85}\right),$$

$$=33.50+(3.98\times\cos 5^\circ56'15''),$$
$$=33.50+(3.98\times0.99464),$$
$$=33.50+3.96,$$
$=37.46$ percent, gas-portion content of atmosphere l_1.

$$Air_{f.\,a.}=\frac{[(O_2)_{f.\,a.}](100)}{20.93}, \qquad (1)$$

$$=\frac{8.09\times 100}{20.93},$$

$$=38.65 \text{ percent, air content of atmosphere } l_1.$$

$$Inert\ gas_{add-f.\,a.}=100-Air_{f.\,a.}-Gas_{f.\,a.}, \qquad (68)$$

$$=100-38.65-37.46,$$

$$=23.89 \text{ percent of carbon dioxide, diluent content of atmosphere } l_1.$$

As the gas-portion content of atmosphere l_1 is 37.46 percent, we can find the volume of *diluent k* that must be admixed with atmosphere *P* to form atmosphere l_1 by substituting the real values of $Gas_{f.\,a.}$ and Gas_s for these symbols in formula (47*c*–3) as follows:

$$Dil_{inert\ gas+air}=\frac{(Gas_s-Gas_{f.\,a.})(100)}{Gas_s}, \qquad (47c\text{–}3)$$

$$=\frac{(85.00-37.46)\times 100}{85.00},$$

$$=55.93 \text{ percent of } diluent\ k.$$

As atmosphere *P* is diluent-free, the diluent content of atmosphere l_1 is the volume of carbon dioxide composing the volume (55.93 percent) of *diluent k* that must be admixed with atmosphere *P* to form atmosphere l_1; therefore, the air component of the volume of *diluent k* used must be

$$(55.93-23.89) \text{ percent}=32.04 \text{ percent.}$$

By summarizing the foregoing data, we find that atmosphere l_1, fig. 8, is formed by admixing *diluent k*, which is composed of 42.74 percent of carbon dioxide and 57.26 percent of air, with atmosphere *P* in a volume (23.89 percent of carbon dioxide plus 32.04 percent of air) equal to 55.93 percent of the volume of the mine-fire atmosphere under seal; also that atmosphere l_1 is composed (by portions) of:

	Percent
Percentages of constituents composing atmosphere *J*	37. 46
Air	38. 65
Carbon dioxide	23. 89

and (by constituents) of:

	Percent
Carbon monoxide	2. 55
Methane	. 30
Hydrogen	3. 82
Oxygen	8. 09
Nitrogen	56. 52
Carbon dioxide	28. 72

As the next step in the procedure to determine whether or not atmosphere l_1 is a lower-explosive-limit mixture, we consider atmosphere l_1 as an original atmosphere and (1) calculate atmosphere l_1 to an air-free basis, (2) determine the critical gas-mixture value (*C. G. M. V.*) of the air-free composition of atmosphere l_1, and (3) determine the lower and the upper explosive limits of the air-free compostion of atmosphere l_1 and of atmosphere l_1 itself. (See pp. 49, 50, 52, and 53, and ref. *19*.)

We determine the air-free composition of atmosphere l_1 by substituting the real values relating to the constituents of atmosphere l_1 for the symbols in formula (3), page 18. The calculations are not given; however, the results are shown in the following table:

Constituent	Volume of constituent (in percent)			
		Atmosphere l_1		
			Air-free basis	
	Atmosphere J	Original atmosphere	Analysis	Symbol used in formulas
Gas portion:				
Carbon monoxide	6.80	2.55	4.15	A_1.
Methane	.80	.30	.49	B_1.
Hydrogen	10.20	3.82	6.23	$(H_2)_1$.
Carbon dioxide	12.90	4.83	7.88	----------
Nitrogen	69.30	25.96	42.31	
Total	100.00	37.46	61.06	----------
Air portion:				
Oxygen	.00	8.09	.00	----------
Nitrogen	.00	30.56	.00	----------
Total	.00	38.65	.00	----------
Diluent portion: Carbon dioxide	.00	23.89	38.94	----------
Total carbon dioxide	12.90	28.72	46.82	D_1.
Total nitrogen	69.30	56.52	42.31	$(N_2)_1$.
Total	100.00	100.00	100.00	----------

That the air-free composition of atmosphere l_1 has explosive limits can be seen in figure 8; the real values defining the explosive limits as well as the compositions of the limit mixtures can be determined graphically. To determine mathematically whether or not the air-free composition of atmosphere l_1 has explosive limits, we calculate the critical gas-mixture value by the formula that is applicable to the diluent selected. As stated on page 91, it is immaterial which diluent is selected as long as the correct formula is used to calculate the critical gas-mixture value. (*See* p. 145.)

From the above-given table we obtain

$$10.2(H_2)_1=10.2\times 6.23=63.55, \text{ and } D_1=46.82,$$

from which we deduce that

$$10.2(H_2)_1, \text{ or } 63.55, >46.82, \text{ or } D_1.$$

From this relationship we find, when nitrogen is used as the diluent, that case 1, page 24, applies, and formula (10), page 25, is used to calculate the critical gas-mixture value ($C.\ G.\ M.\ V._{N_2}$).

We find from the above-given table that

$$4.15A_1=4.15\times 4.15=17.22,$$

$$6B_1=6\times 0.49=2.94,$$

and

$$(N_2)_1=42.31;$$

from which we can deduce that

$$(4.15A_1+6B_1),\text{ or }20.16,\ <42.31,\text{ or }(N_2)_1.$$

From this relationship we find, when carbon dioxide is used as the diluent, that case 6, page 83, applies, and formula (58), page 83, is used to calculate the critical gas-mixture value ($C.\ G.\ M.\ V._{CO_2}$).

By substituting the real values in the table, page 160, for the symbols in formula (10), which is

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{5.15A_1+7B_1+17.55(H_2)_1-0.6225D_1},\qquad (10)$$

we find

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{(5.15\times 4.15)+(7\times 0.49)+(17.55\times 6.23)-(0.6225\times 46.82)},$$

$$=\frac{10{,}000}{21.37+3.43+109.34-29.15},$$

$$=\frac{10{,}000}{104.99}=95.25,$$ critical gas-mixture value relating to atmosphere l_1, when nitrogen is used as diluent.

By substituting the real values given in the table, page 160, for the symbols in formula (58), which is

$$C.\ G.\ M.\ V._{CO_2}=\frac{10{,}000}{3.56A_1+4.7B_1+11.2(H_2)_1+0.3836(N_2)_1},\qquad (58)$$

we find

$$C.\ G.\ M.\ V._{CO_2}=\frac{10{,}000}{(3.56\times 4.15)+(4.7\times 0.49)+(11.2\times 6.23)+(0.3836\times 42.31)},$$

$$=\frac{10{,}000}{14.77+2.30+69.78+16.23},$$

$$=\frac{10{,}000}{103.08}=97.01,$$ critical gas-mixture value relating to atmosphere l_1, when carbon dioxide is used as diluent.

Because the critical gas-mixture values are less than 100, the air-free composition of atmosphere l_1 has explosive limits.

As the first step in the procedure to determine the explosive limits of the air-free composition of atmosphere l_1, we pair the combustible gases with the available inert gases (*19*) as shown in the following table:

Combustible constituents	Volume (percent) of combustible gases	Ratio of inert gas to combustible gas	Combustible gas and inert gas paired with it (percent by volume)						Explosive limits[1]	
			CO_2	CO	CH_4	H_2	N_2	Total	Lower	Upper
Carbon monoxide	4.15	3.28		4.15			13.62	17.77	58.2	73.0
Methane	.49	5.00			0.49		2.45	2.94	33.0	40.5
Hydrogen:										
Paired with nitrogen	1.64	16.00				1.64	26.24	27.88	73.5	75.5
Paired with carbon dioxide	4.59	10.20	46.82			4.59		51.41	59.5	59.5
Total	10.87		46.82	4.15	.49	6.23	42.31	100.00		

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[1] Limits from tables 8, 9, 10, and 12, Bureau of Mines Tech. Paper 450.

We can calculate the explosive limits of the air-free composition of atmosphere l_1 by applying the rearrangement of the law of Le Chatelier (*23*), which can be written as follows:

$$L_L \text{ or } L_U=\frac{100}{\dfrac{A_1+(N_2)_{A_1}}{limit_{l \text{ or } u}}+\dfrac{B_1+(N_2)_{B_1}}{limit_{l \text{ or } u}}+\dfrac{(H_2)_1{}^a+(N_2)_{(H_2)_1{}^a}}{limit_{l \text{ or } u}}+\dfrac{(H_2)_1{}^b+D_1}{limit_{l \text{ or } u}}},$$

in which the symbols have the same meanings as given on page 50.

By substituting the real values given above for the symbols in the foregoing formula, we find

$$L_L=\frac{100}{\dfrac{17.77}{58.2}+\dfrac{2.94}{33.0}+\dfrac{27.88}{73.5}+\dfrac{51.41}{59.5}},$$

$$=\frac{100}{0.305+0.089+0.379+0.864},$$

$$=\frac{100}{1.637}=61.09, \text{ lower explosive limit.}$$

$$L_U=\frac{100}{\dfrac{17.77}{73}+\dfrac{2.94}{40.5}+\dfrac{27.88}{75.5}+\dfrac{51.41}{59.5}},$$

$$=\frac{100}{0.243+0.073+0.369+0.864},$$

$$=\frac{100}{1.549}=64.56, \text{ upper explosive limit.}$$

We have shown on page 160 that the air-free composition of atmosphere l_1 consists of 61.06 percent of the percentages of the constituents composing atmosphere *J* (fig. 8) and 38.94 percent of additional carbon dioxide (diluent); therefore, the lower explosive-limit mixture (point $l_{1\text{-}L}$, fig. 8) consists of

$0.6109\times 61.06=37.30$ percent of percentages of constituents composing atmosphere *J*,

$0.6109\times 38.94=23.79$ percent of additional carbon dioxide (diluent),

$100-61.09=38.91$ percent of air.

Similarly, the upper explosive-limit mixture (point l_{1-U}, fig. 8) consists of

$0.6456\times61.01=39.42$ percent of percentages of the constituents composing atmosphere J,

$0.6456\times38.94=25.14$ percent of additional carbon dioxide (diluent),

$100-64.56=35.44$ percent of air.

If atmosphere l_1 is a lower-explosive-limit mixture, the real value (61.35) of K, or the volume of gases other than air contained in atmosphere l_1, will be equal to the real number defining the lower explosive limit (L_L) of atmosphere l_1 calculated to an air-free basis, because

$$K=100-38.65=61.35 \text{ percent.}$$

The following table shows the compositions (by portions) of atmosphere l_1 and the explosive-limit mixtures, which correspond to points l_{1-L} and l_{1-U}, of the air-free composition of atmosphere l_1 (fig. 8).

Portion	*Atmos* l_1 (percent)	*Atmos* l_{1-L} (L_L) (percent)	*Atmos* l_{1-U} (L_U) (percent)
Gas portion	37.46	37.30	39.42
Additional carbon dioxide (diluent)	23.89	23.79	25.14
Air	38.65	38.91	35.44
Oxygen	8.09	8.14	7.42
Nitrogen	30.56	30.77	28.02
Total gases other than air (K)	61.35	61.09	64.56

This table shows that the real value (61.35) of K relating to atmosphere l_1 is more than the real number (61.09) defining the lower explosive limit and less than the real number (64.56) defining the upper explosive limit of the air-free composition of atmosphere l_1; consequently, atmosphere l_1 is explosive.

Two conclusions that can be drawn from the foregoing data are (1) the line of lower limits (*Lower Limit—Nose*$_{CO_2}$, fig. 8) is not strictly a straight line; and (2), although the gas-portion content of atmosphere l_1 is only 0.16 percent more than the gas-portion content of the lower-explosive-limit mixture, atmosphere l_1 is nevertheless explosive and capable of forming a few explosive mixtures with air. The successive mixtures formed by admixing air with atmosphere l_1 are explosive within the oxygen-content range of 8.09 to 8.14 percent.

It has been proved by laboratory experiments (*9*) that all possible mixtures that contain less oxygen than the lower-explosive-limit mixture are nonexplosive when the gas portions of these mixtures are identical with respect to each other and the lower-explosive-limit mixture.

Therefore, atmosphere l_1, which has a gas-portion content of 37.46 percent, can be made nonexplosive and incapable of forming explosive mixtures with air by reducing its gas-portion content from 37.46 to 37.30 percent, the gas-portion content of the lower-explosive-limit mixture. This can be done by admixing with atmosphere l_1 the same definite volume of carbon dioxide or *diluent* composed of carbon dioxide and air. We accomplish the same purpose by admixing just more than this amount of air with atmosphere l_1; this decreases the gas-portion content of the final atmosphere to just less than 37.30 percent.

As the volume of air, carbon dioxide, or carbon dioxide plus air required to displace an equal volume of the gas portion of atmosphere l_1 is the same, the volume of either of these gases that must be admixed with atmosphere l_1 to form final atmospheres having a gas-portion content of 37.30 percent can be determined by formula 47*c*–3), which is

$$Dil_{air} \text{ or } Inert\ gas_{dil} \text{ or } Dil_{inert\ gas+air} = \frac{(Gas_s - Gas_{f.a.})100}{Gas_s}. \qquad (47c\text{–}3)$$

By substituting the real values given on page 163, for the symbols in formula (47*c*–3), when

$$Gas_s = Gas_{l_1} = \text{gas-portion content of atmosphere } l_1,$$
$$= 37.46 \text{ percent},$$

and

$$Gas_{f.a.} = Gas_{l_1-L} = \text{gas-portion content of lower-explosive-limit mixture},$$
$$= 37.30 \text{ percent},$$

we find

$$\left.\begin{array}{l} Dil_{air}, \\ Inert\ gas_{dil}, \text{ or} \\ Dil_{inert\ gas+air} \end{array}\right\} = \frac{(37.46 - 37.30) \times 100}{37.46} \text{ percent},$$
$$= \frac{16.00}{37.46} \text{ percent},$$
$$= 0.43 \text{ percent of air, carbon dioxide, or carbon dioxide plus air, as the case may be.}$$

In other words, by admixing 0.43 percent of air with atmosphere l_1 we obtain atmosphere l_{1-L}, the lower-explosive-limit mixture shown in the table on page 163; by admixing 0.43 percent of carbon dioxide with atmosphere l_1 we obtain atmosphere l_{1-CO_2}, (fig. 8); and by admixing 0.43 percent of *diluent k*, which is composed of 42.74 percent of carbon dioxide and 57.26 percent of air, with atmosphere l_1 we obtain atmosphere l_3.

Whenever a gas having the same chemical composition as the air-free original atmosphere, pure air, or diluent is admixed with the atmosphere under seal to form a definite final atmosphere, and the volume (in percent of the volume of the atmosphere under seal) of that gas and the volume of one of the portions of the final atmosphere are known, the volume of another of the three portions composing the final atmosphere can be determined by formula (47*c*–1), (47*c*–2), or (47*c*–3), whichever is applicable, provided the chemical compositions of the unknown portions of the final atmosphere and the known portion of the atmosphere under seal are different from the chemical composition of the above-defined gas that is admixed with the atmosphere under seal. When the volumes of two of the portions of the final atmosphere have been ascertained, the volume of the remainder portion can be determined by formula (68).

Whenever a *diluent* is used for the foregoing purpose and it consists of definite amounts (in percent) of the air-free original atmosphere and air, of the air-free original atmosphere and the diluent, or of the diluent and air, the composition of none of the portions of the final atmosphere can be determined by formula (47*c*–1), (47*c*–2), or (47*c*–3) even though the volume of *diluent* is known; instead, we determine first the real values of the components composing that volume of *diluent* and the respective volumes of the *diluent* that become admixed with the three portions composing the atmosphere under seal; the composition of the final atmosphere is then determined.

We have established on page 164 that the gas-portion contents of the final atmospheres l_{1-L}, l_{1-CO_2}, and l_3 are the same, or 37.30 percent. To determine the compositions (by portions) of atmospheres l_{1-L} and l_{1-CO_2}, which are formed by admixing 0.43 percent of air and 0.43 percent of carbon dioxide, respectively, with atmosphere l_1 (fig. 8), we apply formulas (47*c*–2), (47*c*–1), and (68), as follows:

By substituting real values for the symbols,

when

$Dil_{air}=0.43$ percent of air,

$Inert\ gas_{dil}=0.43$ percent of carbon dioxide,

$Inert\ gas_{add-s}=23.89$ percent of carbon dioxide, diluent content of atmosphere l_1,

and

$Air_s=38.65$ percent of air, the air content of atmosphere l_1, we find for atmosphere l_{1-L} that

$$Dil_{air}=\frac{(Inert\ gas_{add-s}-Inert\ gas_{add-f\cdot a\cdot})100}{Inert\ gas_{add-s}}, \qquad (47c\text{–}2)$$

$$0.43=\frac{(23.89-Inert\ gas_{add-f\cdot a\cdot})100}{23.89},$$

which by clearing and transposition, becomes

$$Inert\ gas_{add-f\cdot a\cdot}=\frac{(23.89\times 100)-(23.89\times 0.43)}{100},$$

$$=23.79 \text{ percent of carbon dioxide, the diluent content of atmosphere } l_{1-L};$$

$$Inert\ gas_{add-f\cdot a\cdot}=100-Air_{f\cdot a\cdot}-Gas_{f\cdot a\cdot}, \qquad (68)$$

$$23.79=100-Air_{f\cdot a\cdot}-37.30,$$

which, by transposition, becomes

$$Air_{f.a.}=100-37.30-23.79,$$

$$=38.91 \text{ percent of air, air content of atmosphere } l_{1-L};$$

similarly, we find for atmosphere l_{1-CO_2}:

$$Inert\ gas_{dil}=\frac{[(O_2)_s-(O_2)_{f\cdot a\cdot}]100}{(O_2)_s}=\frac{(Air_s-Air_{f\cdot a\cdot})100}{Air_s}, \qquad (47c\text{–}1)$$

$$0.43=\frac{(38.65-Air_{f\cdot a\cdot})100}{38.65},$$

which, by clearing and transposition, becomes

$$Air_{f.a.}=\frac{(38.65\times 100)-(38.65\times 0.43)}{100},$$

$$=38.48 \text{ percent of air, air content of atmosphere } l_{1-CO_2};$$

$$Inert\ gas_{add-f\cdot a\cdot}=100-Air_{f\cdot a\cdot}-Gas_{f\cdot a\cdot}, \qquad (68)$$

$$=100-38.48-37.30,$$

$$=24.22 \text{ percent of carbon dioxide, diluent content of atmosphere } l_{1-CO_2}.$$

Because atmosphere l_3 (fig. 8) is formed by admixing 0.43 percent (of the volume of the mine-fire atmosphere under seal) of *diluent k* with atmosphere l_1, and because *diluent k* is composed of 42.74 percent of carbon dioxide and 57.26 percent of air, a mixture that is composed of 0.25 percent of air and 0.18 percent of carbon dioxide must be admixed with atmosphere l_1 to form atmosphere l_3. (See p. 131.) Because atmosphere l_3 is formed by the use of a *diluent* containing both air and carbon dioxide (diluent) neither formula (47*c*–2) nor formula (47*c*–1) is applicable to calculate the composition (by portions) of atmosphere l_3. For this purpose we establish the following relationships:

Because atmosphere l_1 has a gas-portion content of 37.46 percent, an air content of 38.65 percent, and a diluent content of 23.89 percent of carbon dioxide, 0.43 percent of *diluent k* must replace

(0.3746×0.43) percent, or 0.16 percent of original gas portion,
(0.3865×0.43) percent, or 0.17 percent of original air portion,

and

(0.2389×0.43) percent, or 0.10 percent of the original diluent portion of atmosphere l_1;

consequently, atmosphere l_3 must consist of

$(37.46-0.16)$ percent$=37.30$ percent, the gas-portion content,
$(38.65-0.17+0.25)$ percent$=38.73$ percent of air,

and

$(23.89-0.10+0.18)$ percent$=23.97$ percent of carbon dioxide (diluent).

The calculations to determine the compositions of atmospheres l_{1-L}, l_{1-CO_2}, and l_3 are best shown and summarized in tabular form as follows:

Procedure to determine the compositions (by portions, in percent) of atmospheres l_{1-L}, l_{1-CO_2}, and l_3 (fig. 8)

Portion of atmosphere	Atmos. l_1 (see p. 160)	Kind and amount of gas admixed with atmos. l_1	Amt. of portion of atmos. l_1 replaced by gas (air, carbon dioxide, or air $+CO_2$)	Amt. of portion of atmos. l_1 remaining after addition of gas	Amt. of gas added to (+) or subtracted from (−) original portion of atmos. l_1	Final atmosphere formed (see fig. 8)		
						l_{1-L}	l_{1-CO_2}	l_3
Gas portion	37.46		−0.16	37.30	−0.16	37.30		
Air	38.65	+0.43	−.17	38.48	+.26	38.91		
Diluent (carbon dioxide)	23.89		−.10	23.79	−.10	23.79		
Total	100.00	+.43	−.43	99.57	.00	100.00		
Gas portion	37.46		−.16	37.30	−.16		37.30	
Air	38.65		−.17	38.48	−.17		38.48	
Diluent (carbon dioxide)	23.89	+.43	−.10	23.79	+.33		24.22	
Total	100.00	+.43	−.43	99.57	.00		100.00	
Gas portion	37.46		−.16	37.30	−.16			37.30
Air	38.65	+.25	−.17	38.48	+.08			38.73
Diluent (carbon dioxide)	23.89	+.18	−.10	23.79	+.08			23.97
Total	100.00	+.43	−.43	99.57	.00			100.00

We have shown on page 162 that atmosphere l_{1-L} is a lower-explosive-limit mixture and therefore just explosive. Although atmospheres l_{1-CO_2} and l_3 contain the same amount (6.64 percent) of combustible gases as atmosphere l_{1-L}, they contain less air and more carbon dioxide. Furthermore; both atmosphere l_{1-CO_2} and atmosphere l_3 are nonexplosive and incapable of forming explosive mixtures with air. This can be verified by comparing atmospheres l_{1-CO_2} and l_3 with the respective lower-explosive-limit mixtures of the air-free compositions of these atmospheres in the manner shown for comparing armosphere l_1 with atmosphere l_{1-L}, the lower-explosive-limit mixture. (See p. 163.)

We have shown on page 166 that the real value of symbol K, which relates to atmosphere l_3, is 61.27. The lower explosive limit (l_{3-L}) of the air-free composition of atmosphere l_3 can be determined in the conventional manner (*19*) and is found to be 61.35. As the real value (61.27) of K, which relates to atmosphere l_3, is less than the real number (61.35) defining the lower explosive limit of the air-free composition of atmosphere l_3, atmosphere l_3 is nonexplosive and incapable of forming explosive mixtures with air.

The composition (by portions) of the lower-explosive-limit mixture (atmosphere l_{3-L}) has been found by calculations, which are not included, to be: Gas portion 37.34 percent, additional carbon dioxide (diluent) 24.01 percent;, and air 38.65 percent, which is the same as the air content of atmosphere l_1

The accuracy of the procedure and formulas used to determine the various factors relating to the explosibility of mixtures of the mine-fire gases, air, and inert gases is indicated by comparing the compositions of atmospheres l_1 and l_3 with the composition of atmospheres l_{1-L} and l_{3-L}, the lower-explosive-limit mixtures. Such a comparison is shown in the following table:

Portion of mine-fire atmosphere and other factors	Atmosphere, and volume (percent) of factor			
	l_1[1]	l_{1-L}[2]	l_3[3]	l_{3-L}[2]
Gas portion	37.46	37.30	37.30	37.34
Air	38.65	38.91	38.73	38.65
Additional carbon dioxide (diluent)	23.89	23.79	23.97	24.01
Value of K and of lower explosive limit, as the case may be	61.35	61.09	61.27	61.35
Oxygen	8.09	8.14	8.10	8.09

[1] Explosive.
[2] Lower-explosive-limit mixture.
[3] Nonexplosive.

From figure 8 and the foregoing table it can be seen that, for all practical purposes, the line of lower limits (line *Lower Limit–Nose*$_{CO_2}$) can be taken as a straight line and that atmosphere l_1, which is just explosive, has a gas-portion content that is 0.16 percent more than the gas-portion content of atmosphere l_3, which is just nonexplosive. The difference in the combustible-gas contents of these two atmospheres, between which the lower-explosive-limit mixture lies, is only 0.03 percent, which is as slight as can be expected either from the calculations or from the experimental data on which derivation of the formulas is based.

Inasmuch as atmosphere l_1 is explosive and atmosphere l_3 is nonexplosive, atmosphere l_3 is the final atmosphere desired; however, it should not be obtained in practice by admixing 0.43 percent of *diluent k* with the mine-fire atmosphere under seal after atmosphere l_1 has been formed; instead, the required volume of *diluent k* should be admixed with atmosphere P (fig. 8), from which atmospheres l_1 and

l_3 are derived. (See p. 164.) To find the volume of *diluent k* required to form atmosphere l_3 from atmosphere P, we apply formula (47c–3), page 70, which is

$$Dil_{inert\ gas+air}=\frac{(Gas_s-Gas_{f.\ a.})100}{Gas_s}. \qquad (47c\text{–}3)$$

By substituting real values for the symbols when

$Gas_s=85.00$ percent, the gas-portion content of atmosphere P,
and
$Gas_{f.\ a.}=37.30$ percent, the gas-portion content of atmosphere l_3,
we find

$$Dil_{inert\ gas+air}=\frac{(85-37.3)\times 100}{85}\text{ percent,}$$

$=56.12$ percent, the amount of *diluent k* required to form atmosphere l_3 from atmosphere P.

We have found on page 159 that, whereas 55.93 percent of *diluent k* must be admixed with atmosphere P to form atmosphere l_1, which is explosive, only 0.19 percent (56.12—55.93) more *diluent* is required to form atmosphere l_3, which is nonexplosive. As *diluent k* is composed of 42.74 percent of carbon dioxide and 57.26 percent of air; an increase of only 0.08 percent of carbon dioxide and 0.11 percent of air in the volume (55.93 percent) of *diluent k* admixed initially with atmosphere P to form atmosphere l_1 determines whether or not the final atmosphere is explosive.

As the procedure in the use of *diluents*, when dealing with potentially explosive mixtures, must be controlled so as to form safe final atmospheres, the common-sense thing to do is to make the calculations in the manner shown for the foregoing examples and then allow an adequate factor of safety.

It can be seen from the detailed discussion and application to the Continental mine fire of the formulas relating to the use of *diluents* that an important question before the engineer or chemist is: What is the minimum volume of inert gas or *diluent* that can be introduced into a sealed mine-fire area containing potentially explosive mixtures whereby safe mixtures are formed from all portions of the mine-fire atmosphere under seal, under any conditions that may arise?

The use of carbon dioxide singly and as a component of a *diluent* so as to form safe atmospheres has been covered in detail to show the effect of admixing this inert gas with a potentially explosive atmosphere, such as the Continental mine-fire atmosphere. Under normal conditions nitrogen would be the natural diluent, and it is on this basis that the initial calculations relating to a mine-fire atmosphere should be made. Use of carbon dioxide instead of nitrogen as the diluent increases the margin of safety, if the calculations are based on the use of nitrogen as the diluent.

ESTABLISHMENT OF A ZONE OF DESIRABLE ATMOSPHERES

The composition of the portions of the mine-fire atmosphere under seal in the Continental mine-fire area that were in contact with the fire or likely to come in contact with it was controlled so that such portions were either (1) nonexplosive or (2) incapable of forming explosive mixtures with air.

A zone of desirable atmospheres was established by controlling (1) the ventilation and (2) the extinguishment of the fire when "slushing" the fire area with water and culm. A planned procedure to maintain a zone of nonexplosive atmospheres, which were incapable of forming explosive mixtures with air, was based on the desire to obtain maximum safety. (See p. 114.)

The composition of the nonexplosive final atmospheres corresponding to points in the boundary line of the zone of desirable atmospheres was established so that the final atmospheres had either (1) a diluent content (in percent) the same as the diluent content of the critical gas mixture calculated with nitrogen as the diluent and a gas-portion content equal to or more than the gas-portion content of the lower-explosive-limit mixture or (2) a gas-portion content (in percent) the same as the gas-portion content of the lower-explosive-limit mixture and a diluent content equal to or less than the diluent content of the critical gas mixture. (See p. 152.) Obviously, any final atmosphere was acceptable and well on the safe side when it had either a gas-portion content less than the gas-portion content of the lower-explosive-limit mixture or a diluent content more than the diluent content of the critical gas mixture.

For any diluent-free limit mixture, the value of *K*, or the volume of gases other than air, the limit value, and the gas-portion content of the limit mixture are all expressed by numerically equal real values. Table 9, page 120, shows that the gas-portion content (Gas_{L-L}) of the lower-explosive-limit mixture is only 0.48 percent less than the gas-portion content of the nose-limit mixture (nitrogen used as the diluent).

As the gas-portion content of the lower-explosive-limit mixture of an air-free original atmosphere is expressed by the same real number, regardless of the kind of inert gas (nitrogen or carbon dioxide) used as the diluent to form the critical gas mixture, we can readily establish the boundary line of the zone of desirable final atmospheres if the lower explosive limit is known. This is done by considering that nitrogen is used as the diluent and calculating the critical gas-mixture value ($C.\ G.\ M.\ V._{N_2}$).

In figure 8 the boundary line established by points corresponding to desirable final atmospheres, which are safe, is the angular line consisting of line *Lower limit–z*, which corresponds to mixtures having a gas-portion content the same as that of the lower-explosive-limit mixture, and line z–$C.\ G.\ M.\ V._{N_2}$, which corresponds to mixtures having a diluent content the same as that of the critical gas mixture ($C.\ G.\ M.\ V._{N_2}$). The critical gas mixture corresponding to point $C.\ G.\ M.\ V._{N_2}$ consists of 47.26 percent of the percentages of the constituent composing atmosphere *J* and 52.74 percent of additional nitrogen. Atmosphere *z* consists of 33.50 percent of the percentages of the constituents composing atmosphere *J*, 52.74 percent of additional nitrogen, and 13.76 percent of air.

If the boundary line of desirable final atmospheres is established when carbon dioxide is used as the diluent, the portion of the boundary line limiting the diluent component of such a line is line $C.\ G.\ M.\ V._{CO_2}$–z_2 (fig. 8), and the portion limiting the gas-portion component is line z_2–*Lower Limit*. The critical gas mixture corresponding to point $C.\ G.\ M.\ V._{CO_2}$ consists of 59.23 percent of the percentages of the constituents composing atmosphere *J* and 40.77 percent of additional carbon dioxide (diluent). Atmosphere s_2 consists of 33.50 percent of the percentages of the constituents composing atmosphere *J*, 40.77 percent of carbon dioxide (diluent), and 25.73 percent of air.

It is apparent from discussion of the Continental mine fire that if enough of either an inert gas (nitrogen or carbon dioxide or both) or a mixture of this inert gas and air is admixed with the mine-fire atmosphere under seal, safe final atmospheres are formed; furthermore, if any of the final atmospheres formed from any portion of the mine-fire atmosphere corresponds to some point in the angular line *C. G. M* $V._{N_2}$*–z–Lower Limit* (fig. 8) and if the inert gas used as the diluent is considered as nitrogen, such a final atmosphere is safe, regardless of which of the above-mentioned gases is admixed with the mine-fire atmosphere.

Applications of the statements just given, when applied to atmosphere *P* (fig. 8), are as follows: If a mixture of carbon dioxide and nitrogen is used as the diluent, the minimum safe atmosphere corresponds to some point in the portion of line *P–O* between points m_1 and m_2. A safe final atmosphere, regardless of the inert gas (carbon dioxide or nitrogen) used as the diluent, corresponds to point m_3. If a *diluent* having the composition of atmosphere *k* is used, point *l* corresponds to a safe final atmosphere if either nitrogen or carbon dioxide is used as the diluent. The real number expressing the diluent content (in percent) of atmosphere *l* is the same and obviously can be either nitrogen or carbon dioxide; this depends on which inert gas is used as the diluent.

The matter of using pure inert gas or *diluents* to form nonexplosive or safe atmospheres at the Continental mine fire has been discussed in considerable detail for the reasons stated on page 114. The discussion furthermore shows application of the data to an actual mine fire and points out the precautions that must be exercised when dealing with explosive atmospheres, even though the explosibility of the atmospheres and the composition of the *diluent* and the limitations in its use are known. Numerous examples have been given to illustrate application of the fundamental data to any question or condition that might arise when dealing with potentially explosive atmospheres, such as those at the Continental mine fire.

FIRE IN INACCESSIBLE OLD MINE WORKINGS

A fire has burned for many years in inaccessible, steeply dipping workings of an anthracite mine. Because of the nature of the pillar workings in which the fire started, it was impossible to extinguish the fire by flooding, suffocation, or hydraulic backfilling. Furthermore, although the fire was isolated, air could not be excluded from the fire; and, as the mine workings progressed downward, the fire also traveled downward. The best that can be done to work a mine, with safety, under such circumstances is to keep the fire isolated, prevent excess air from reaching the fire, and take whatever precautions are necessary, as indicated by a study of analyses of representative samples of the mine-fire atmosphere.

Experience has demonstrated that sometimes such fire areas can be cooled off or the fire extinguished by slushing the fire area with culm or other similar-size materials and water or by extracting the unburned coal by open-cut methods, particularly if the bed is steeply inclined and the mine-fire area is near the surface or has shallow cover (*3*).

The fire mentioned above produced fire gases and created a mine-fire atmosphere that, in some portions, represented borderline explosive mixtures. These were composed of carbon monoxide, methane, hydrogen, oxygen, nitrogen, and carbon dioxide. Because of the composition of this mine-fire atmosphere, a slight change in either the combustible-gas content or the inert-gas content could form mixtures that were either potentially explosive or incapable of forming explosive mixtures with air. For the foregoing reasons, a discussion of the mine-fire atmosphere at this fire will point out some of the hazards to be dealt with under similar circumstances.

COMPOSITION OF MINE-FIRE ATMOSPHERE

Pertinent data relating to representative samples of the mine-fire atmosphere are given in the following tables:

Composition of air-free original atmosphere and explosive-limit mixtures, and real values of explosive limits, critical gas-mixture values, nose limits, and critical oxygen value (in percent)

Constituent or item	Constituent, percent			Real value
	Air-free original atmosphere (*J*, fig. 9)	Lower-explosive-limit mixture	Upper-explosive-limit mixture	
Gas portion:				
Carbon monoxide	3. 54	2. 24	2. 35	
Methane	1. 50	. 95	. 99	
Hydrogen	4. 86	3. 08	3. 22	
Carbon dioxide	17. 61	11. 14	11. 66	
Nitrogen	72. 49	45. 88	48. 00	
Total	100. 00	63. 29	66. 22	
Air portion:				
Oxygen	. 00	7. 68	7. 07	
Nitrogen	. 00	29. 03	26. 71	
Total	. 00	36. 71	33. 78	
Diluent portion: Nitrogen or carbon dioxide	. 00	. 00	. 00	
Total nitrogen	72. 49	74. 91	74. 71	
Total	100. 00	100. 00	100. 00	
Explosive limits:				
Lower				63. 29
Upper				66. 22
Critical gas-mixture values:				
Nitrogen used as diluent				97. 02
Carbon dioxide used as diluent				98. 14
Nose limits:				
Nitrogen used as diluent				65. 98
Carbon dioxide used as diluent				65. 54
Critical oxygen value: Nitrogen or carbon dioxide used as diluent				6. 62

Composition of critical gas mixture and nose-limit mixture when nitrogen or carbon dioxide is used as diluent

Constituent	Constituent, percent			
	Critical gas mixture		Nose-limit mixture	
	Nitrogen used as diluent	Carbon dioxide used as diluent	Nitrogen used as diluent	Carbon dioxide used as diluent
Gas portion:				
Carbon monoxide	3.43	3.48	2.27	2.28
Methane	1.46	1.47	.96	.96
Hydrogen	4.72	4.77	3.11	3.12
Carbon dioxide	17.08	17.28	11.27	11.33
Nitrogen	70.33	71.14	46.40	46.63
Total	97.02	98.14	64.01	64.32
Air portion:				
Oxygen	.00	.00	7.12	7.21
Nitrogen	.00	.00	26.90	27.25
Total	.00	.00	34.02	34.46
Diluent portion:				
Nitrogen	2.98	.00	1.97	.00
Carbon dioxide	.00	1.86	.00	1.22
Total	2.98	1.86	1.97	1.22
Total nitrogen	73.31	71.14	75.27	73.88
Total carbon dioxide	17.08	19.14	11.27	12.55
Total	100.00	100.00	100.00	100.00

The calculated data in the above tables that pertain to factors obtained when nitrogen is considered as the diluent are given in this report. (See pp. 20, 22, 32, 41, and 42.) Calculations of the data pertaining to factors obtained when carbon dioxide is considered as the diluent, except the critical gas-mixture value, are not given but have been computed by the methods shown in this report.

Figure 9 (pocket) has been constructed from the data shown in the tabular matter above and shows the relation between the quantitative composition and explosibility of mixtures of the mine-fire atmosphere, air, and nitrogen or carbon dioxide (diluent).

It is observed in figure 9 that the zone of explosive mixtures is small and confined to mixtures near the nose. The inert-gas content of such mixtures is large in comparison with the combustible-gas content.

When making calculations to determine the explosive limits of mixtures that have a high inert-gas content, the inert gases should be combined with the combustible gases in proportions that are near the maximum ratios. The greatest errors introduced in the calculated explosive limits of a mixture of combustible gases and inert gases occur when the maximum ratios of inert gas to combustible gas are approached (*21*). Because of the foregoing reasons, the calculated data represented graphically in figure 9 have been computed to the nearest thousandth. The zone of explosive mixtures is also shown on an enlarged scale in figure 9.

DISCUSSION OF MINE-FIRE ATMOSPHERE

The chemical composition of the fire gases indicates that the temperature of the fire area was intensely high. This is shown by the ratio of the hydrogen content to the carbon monoxide content of the mine-fire atmosphere (*29, 31*). However, this fact is known because of the hot gases that escaped from the mine-fire area through holes at the outcrop.

Because of the thickness of the bed on fire, the height of the mine workings in the fire area, the large volume of the steeply dipping mine workings that composed the fire area, and leakage of air into the part of the mine-fire area below the active fire, the mine-fire atmosphere consisted of portions that ranged in composition from normal mine air to almost that of the air-free original atmosphere (*J*, fig. 9).

The mine-fire atmosphere was heated throughout to very high temperatures because of radiation, extent of the active fire, and recirculation of hot fire gases within the sealed area. Furthermore, because of the number of openings (even though restricted to fissures) that afforded a way of escape for the fire gases, a portion of the mine-fire atmosphere in the lowest part of the sealed area was nonexplosive and incapable of forming explosive mixtures with air. This portion contained too much air, no determinable hydrogen or carbon monoxide, and a small percentage of methane.

Experience has shown that if enough air is admitted below the fire in a fire area, such as this one, an explosion will occur (*3*). This happens if an opening is made into the sealed fire area by caving, by blasting, or in some other manner. The violence or effect of the explosion will depend on the explosibility of the various portions composing the mine-fire atmosphere and the chance for expansion and escape of the mine-fire atmosphere.

The chemical composition of the portion of the mine-fire atmosphere corresponding to the zone of explosive mixtures shown in figure 9 and that could be formed by admixing air with the mine-fire gases generated in the active fire area is typical of explosive mixtures near the nose. These mixtures, if ignited, would not explode violently but would be a slow, expanding combustion. Because of the composition of the surrounding portions of this mine-fire atmosphere that either contained too much or not enough air, the explosion would only propagate a short distance. However, the hot gases in the fire area, heated further by the explosion, would escape through available openings with little or no violence, without flame, and envelop anyone who happened to be in places into which the hot gases would be forced (*3*).

Experience has shown that relatively brief exposure of persons to gases of such high temperatures, as would be formed under the abovementioned circumstances, would result in death due to pulmonary edema, which is caused by breathing intensely hot gases. Such persons would not show any evidence of violence, nor would their bodies, face, hair, or clothing necessarily show any visual effect of flame. However, the skin of victims of such intense dry heat can be baked in a short time.

DETERMINATION OF VOLUME OF INERT GAS REQUIRED TO FORM NONEXPLOSIVE MIXTURES

From the data expressed graphically in figure 9, we can determine the minimum volume of inert gas (nitrogen or carbon dioxide) that must be introduced into the sealed mine-fire area to form mixtures that would be nonexplosive regardless of how much air was later admitted into the fire area.

By referring to the points corresponding to the critical gas mixtures when nitrogen and carbon dioxide, respectively, are used as the diluent, we find that if 2.98 percent of nitrogen or 1.86 percent of carbon dioxide is admixed with the mine-fire atmosphere, all portions of this atmosphere that are either explosive or capable of forming explosive mixtures with air will be rendered nonexplosive and incapable of forming explosive mixtures with air. The volume of inert gas required for this purpose is 29.80 cubic feet of nitrogen or 18.60 cubic feet of carbon dioxide for each 1,000 cubic feet of the sealed mine-fire area (see p. 93).

The above-given volumes (in percent of the volume of the sealed mine-fire atmosphere) of nitrogen or carbon dioxide required to form an atmosphere of which no portion is explosive or capable of forming an explosive mixture with air are the diluent contents (percentage of nitrogen or carbon dioxide, as the case may be) of the respective critical gas mixtures. The diluent contents of these mixtures are given in the table on page 172.

The arithmetical calculations to determine the diluent content of the critical gas mixture when nitrogen is used as the diluent are given on pages 22 and 32. To determine mathematically the volume (1.86 percent) of carbon dioxide required for the foregoing purpose, we first ascertain from the composition of the air-free original atmosphere, page 171, that its carbon monoxide content (A_1) is 3.54 percent, its methane content (B_1) 1.50 percent, and its nitrogen content $(N_2)_1$ 72.49 percent. From these data we establish the relationship between the nitrogen content and the proportions thereof that can be combined with the available carbon monoxide and methane, as follows:

$$4.15A_1 = 4.15\times 3.54 = 14.69.$$
$$6B_1 = 6\times 1.50 = 9.00.$$
$$4.15A_1 + 6B_1 = 14.69 + 9.00 = 23.69.$$

As

$$(4.15A_1 + 6B_1),\text{ or } 23.69, < 72.49,\text{ or } (N_2)_1,$$

case 6, page 83, applies, and to determine the critical gas-mixture value we use formula (58), or

$$C.G.M.V._{CO_2} = \frac{10{,}000}{3.56A_1 + 4.70B_1 + 11.2(H_2)_1 + 0.3836(N_2)_1}, \qquad (58)$$

By substituting the real values given on page 171 for the symbols, we find

$$C.G.M.V._{CO_2} = \frac{10{,}000}{(3.56\times 3.54) + (4.70\times 1.5) + (11.2\times 4.86) + (0.3836\times 72.49)},$$

$$= \frac{10{,}000}{12.60 + 7.05 + 54.43 + 27.81} = \frac{10{,}000}{101.89},$$

$= 98.14$, critical gas-mixture value when carbon dioxide is used as diluent.

By substituting the critical gas-mixture value (98.14) for the symbol in formula (22*B*), or

$$Dil_{C.G.M.} = 100 - (C.G.M.V.)_{CO_2}, \qquad (22B)$$

we find

$$Dil_{C.G.M.} = 100 - 98.14,$$

$= 1.86$ percent of carbon dioxide, diluent content of critical gas mixture when carbon dioxide is used as diluent.

It is only by careful study of the analyses of representative samples of a mine-fire atmosphere, such as has been described, that the hazards can be ascertained and explosions averted by creating or maintaining in the sealed mine-fire area an atmosphere that is nonexplosive and incapable of forming explosive mixtures with air. It is not difficult to utilize an inert gas, such as carbon dioxide, for this purpose when the composition of a mine-fire atmosphere is restricted to mixtures near the nose. Furthermore, if the fire is relatively small, utilization of dry ice to form enough carbon dioxide will cool the area and extinguish the fire by cooling and suffocation.

EXPLOSION CAUSED BY FUEL GAS IN A MANUFACTURING PLANT

Fuel gases are used throughout the United States. These gases may be classed as natural gas and artificial gas. Explosions frequently happen in places where fuel gas is used. Investigations are made, and the lessons learned as to the cause and prevention of such explosions are much the same; to state them here would therefore be a repetition of available material.

A gas explosion, which was investigated by the authors, occurred in a manufacturing plant, injured two men, and caused considerable damage.

At the time of the explosion, 18 persons were in the plant, which was idle; however, no one was in the room that was damaged most.

This explosion is discussed because it is an example of circumstances that are unusual, and knowledge regarding the application of subject matter given in this report may aid in preventing such explosions.

CAUSE OF EXPLOSION

The explosion resulted when a relatively small volume (approximately 650 cubic feet) of an explosive mixture of carbureted water gas and air was ignited by an electric arc formed when a foot-operated starting switch was closed.

The explosive mixture was trapped between a concrete floor, which was resting on soil composed mostly of cinders, and a tight wooden floor, which was constructed of 2-inch plank flooring (grooved) on which was nailed tongue-and-grove flooring. The wooden floor was laid diagonally on 4- by 6-inch planks. These were laid on the concrete floor and spaced so as to support the wooden floor rigidly and provide a passageway, 4 inches in height, for conduit and power lines by which electricity was conducted to the electric equipment.

A small volume of the explosive mixture of carbureted water gas and air entered the housing of the starting switch through a hollow pedestal, which served as a passageway for the power wires that led to the terminals of the switch. The flames from the explosion within the housing of the switch were propagated by the explosive gas mixture in the pedestal to the explosive mixture that was trapped in the voids between the above-mentioned floors.

SOURCE OF FUEL GAS

Fuel gas was not used for any purpose in the building or on the premises. No gas-service pipes were in the building, and gas had not been used in the building for more than 2 years. The assistance of the

Bureau of Mines was requested to determine the cause of the explosion and the source of the gas.

The kind of gas that caused the explosion was determined by taking samples of the atmosphere in different parts of the building. Analyses of these samples indicated that the offending gas had to be fuel gas. A comparison of the analyses of these samples with an analysis of a sample of the fuel gas in use in the city revealed that the air-free analyses of the different samples were similar in composition. (*See* fig. 10, pocket.)

An abandoned gas-service pipe that led to a point under the building was discovered by digging a trench around the building. The section of the gas-service pipe that was under the concrete floor of the building was found to be wide open and to contain several holes that had been made by corrosion. The fuel gas, or carbureted water gas, leaked into the soil under the concrete floor, through cracks in the concrete floor, and into the space between it and the wooden floor.

The above-mentioned gas pipe had formerly given gas service to a dwelling house that occupied the site before the plant was erected, which was 14 years before the date of the explosion. As a consequence, the presence of the abandoned section of pipe was unknown, and leakage of the fuel gas was not suspected or detected, although the investigation showed that the gas could escape through some small cracks in the wooden floor into the rooms on the first floor of the building.

PROPERTIES OF FUEL-GAS—AIR MIXTURES

If fuel gas had been used recently in the building or was in use at the time of the explosion, persons employed therein would have suspected fuel gas if they had detected any unusual odor. No unusual odor was detected before the explosion; consequently, no investigation was made.

Usually, one gives little consideration to the composition of the atmosphere he is breathing if it has no unusual odor and is comfortable to breathe. Because no one detected or suspected the presence of a harmful gas or felt any ill effects, it is apparent that the quantity of carbureted water gas that was entering the occupied parts of the building was small, or this fuel gas did not have an odor intensity that indicated its presence under existent conditions.

For precautions to be taken that give ample warning before a hazard of asphyxiation or of explosion is created by a fuel gas, it is necessary to know the properties of the fuel gas. Where natural gas is used, the hazard of explosion takes precedence, and no danger exists from toxic poisoning by natural gas; however, where carbureted water gas is used, a greater hazard of explosion exists because of the high combustible-gas content, particularly of hydrogen, and the wide explosive range of mixtures of this fuel gas and air. Furthermore, the danger of toxic gas poisoning is great because of the high carbon monoxide content of carbureted water gas.

Because of the unusual circumstances surrounding this particular explosion, to avert a major disaster under similar circumstances it is necessary to know both the properties of carbureted water gas and the composition of the resultant atmospheres that are formed when this fuel gas is admixed with air.

Analyses of samples of carbureted water gas, taken from gas mains, show that its composition changes from time to time. As this fuel gas is an artificial gas, the simple gases composing it can exist in proportions that vary in different parts of the atmosphere with which the fuel gas is admixed.

For the foregoing reasons, it is advisable to collect samples both of the carbureted water gas in use in the neighborhood and of the atmosphere being investigated and to determine the chemical composition of these samples. It is also advisable to ascertain the specific gravity and the odor intensity of the fuel gas.

COMPOSITION OF FUEL GAS AND OF MIXTURES OF FUEL GAS AND AIR

An analysis of a typical sample of the carbureted water gas in use in 1931 and an analysis of a sample of the fuel gas in use at the time of the explosion in 1942, are shown in the following table:

Chemical composition of fuel gas in use in 1931 and in 1942

Constituent	Percentage of constituent				
	Fuel gas in use in 1931		Fuel gas in use in 1942		
			Analysis as sampled	Analysis	
	Analysis as sampled	Air-free analysis		Air-free (J, fig. 10)	Symbol used in formula
Gas portion:					
Carbon monoxide	30.93	31.69	31.30	32.14	A_1.
Methane	10.23	10.48	11.25	11.55	B_1.
Hydrogen	38.57	39.51	42.95	44.11	$(H_2)_1$.
Ethylene	9.03	9.25	5.76	5.92	$(C_2H_4)_1$.
Propylene			1.44	1.48	$(C_3H_6)_1$.
Ethane	.00	.00	.00	.00	$(C_2H_6)_1$.
Carbon dioxide	4.07	4.17	3.90	4.00	D_1.
Nitrogen	4.78	4.90	.77	.80	$(N_2)_1$.
Total	97.61	100.00	97.37	100.00	---------
Air portion:					
Oxygen	.50	.00	.55	.00	---------
Nitrogen	1.89	.00	2.08	.00	---------
Total	2.39	.00	2.63	.00	---------
Diluent portion:					
Nitrogen or carbon dioxide	.00	.00	.00	.00	---------
Total nitrogen	6.67	4.90	2.85	.80	---------
Total	100.00	100.00	100.00	100.00	---------

The analyses given above show that the fuel gas in use at the time (1942) of the explosion was better, or had a higher heating value, than in 1931; however, the fuel gas in use in 1942 has a wider explosive range and is more toxic than the fuel gas in use in 1931.

COMPOSITION OF ATMOSPHERE IN BUILDING AFTER EXPLOSION

Samples were collected (by the authors) of the atmosphere in the room in which the explosion caused the most damage. Analyses of typical samples are shown in the following table:

Analyses of typical samples collected after explosion in room in which explosion was most violent

Constituent	Percentage of constituent					
	Sample 1		Sample 2		Sample 3	
	Analysis as sampled	Air-free analysis	Analysis as sampled	Air-free analysis	Analysis as sampled	Air-free analysis
Gas portion:						
Carbon monoxide	0.40	36.04	0.37	27.61	1.30	11.20
Methane	.13	11.71	.16	11.94	.80	6.89
Hydrogen	.39	35.14	.24	17.91	2.10	18.09
Ethylene	.06	5.41	.08	5.97	.22	1.89
Propylene	.02	1.80	.03	2.24	.08	.69
Carbon dioxide	.04	3.60	.05	3.73	.16	1.38
Nitrogen	.01	.90	.01	.75	.03	.26
Total	1.05	94.60	.94	70.15	4.69	40.40
Air portion:						
Oxygen	20.70	.00	20.65	.00	18.50	.00
Nitrogen	78.19	.00	78.01	.00	69.89	.00
Total	98.89	.00	98.66	.00	88.39	.00
Diluent portion:						
Nitrogen	.01	.90	.30	22.39	6.08	52.37
Carbon dioxide	.05	4.50	.10	7.46	.84	7.23
Total	.06	5.40	.40	29.85	6.92	59.60
Total nitrogen	78.21	1.80	78.32	23.14	76.00	52.63
Total carbon dioxide	.09	8.10	.15	11.19	1.00	8.61
Total	100.00	100.00	100.00	100.00	100.00	100.00

In the above-given table, sample 1 was collected 30 hours; sample 2, 54 hours; and sample 3, 78 hours after the explosion. It is not within the scope of this report to discuss the details concerned with these samples; however, it was the analyses of these samples and the significant data developed from them that showed what had to be done to remove the dangerous conditions.

Pertinent data relating to factors bearing on the explosibility of the above-stated samples are given in the following tables:

Composition of air-free original atmosphere and explosive-limit mixtures, and real values of explosive limits, critical gas-mixture values, nose limits, and critical oxygen value (percent)

Constituent or item	Percentage of constituent			Real value
	Air-free original atmosphere (*J*, fig. 10)	Lower-explosive-limit mixture	Upper-explosive-limit mixture	
Gas portion:				
Carbon monoxide	32.14	1.74	14.00	
Methane	11.55	.62	5.03	
Hydrogen	44.11	2.39	19.21	
Ethylene	5.92	.32	2.58	
Propylene	1.48	.08	.64	
Carbon dioxide	4.00	.22	1.74	
Nitrogen	.80	.04	.35	
Total	100.00	5.41	43.55	
Air portion:				
Oxygen	.00	19.80	11.81	
Nitrogen	.00	74.79	44.64	
Total	.00	94.59	56.45	
Diluent portion: Nitrogen or carbon dioxide	.00	.00	.00	
Total nitrogen	.80	74.83	44.99	
Total	100.00	100.00	100.00	
Explosive limits:				
Lower				5.41
Upper				43.55
Critical gas-mixture values:				
Nitrogen used as diluent				8.79
Carbon dioxide used as diluent				13.94
Nose limits:				
Nitrogen used as diluent				67.02
Carbon dioxide used as diluent				52.75
Critical oxygen value: Nitrogen used as diluent				6.40

Compositions of critical gas mixture and nose-limit mixture when nitrogen or carbon dioxide is used as diluent

Constituent	Percentage of constituent			
	Critical gas mixture		Nose-limit mixture	
	Nitrogen used as diluent	Carbon dioxide used as diluent	Nitrogen used as diluent	Carbon dioxide used as diluent
Gas portion:				
Carbon monoxide	2.82	4.48	1.90	2.36
Methane	1.02	1.61	.68	.85
Hydrogen	3.88	6.15	2.60	3.25
Ethylene	.52	.82	.35	.43
Propylene	.13	.21	.09	.11
Ethane	.00	.00	.00	.00
Carbon dioxide	.35	.56	.23	.29
Nitrogen	.07	.11	.05	.06
Total	8.79	13.94	5.90	7.35
Air portion:				
Oxygen	.00	.00	6.90	9.89
Nitrogen	.00	.00	26.08	37.36
Total	.00	.00	32.98	47.25
Diluent portion:				
Nitrogen	91.21	.00	61.12	.00
Carbon dioxide	.00	86.06	.00	45.40
Total	91.21	86.06	61.12	45.40
Total nitrogen	91.28	.11	87.25	37.42
Total carbon dioxide	.35	86.62	.23	45.69
Total	100.00	100.00	100.00	100.00

Explosive limits of mixtures formed by admixing increasing proportions of diluent (nitrogen or carbon dioxide) with air-free carbureted water gas, or air-free original atmosphere

Composition (by portions) of air-free mixtures		Limit values and oxygen contents (in percent) of explosive-limit mixtures when nitrogen is used as diluent				Limit values and oxygen contents (in percent) of explosive-limit mixtures when carbon dioxide is used as diluent			
Gas portion (percentage of air-free original atmosphere)	Diluent portion (percentage of additional nitrogen or carbon dioxide)	Lower-explosive-limit mixtures		Upper-explosive-limit mixtures		Lower-explosive limit mixtures		Upper-explosive-limit mixtures	
		Limit value	Oxygen content	Limit value	Oxygen content	Limit value	Oxygen content	Limit value	Oxygen content
100	0	5.41	19.80	43.55	11.81	5.41	19.80	43.55	11.81
95	5	5.78	19.72	44.07	11.71	5.81	19.71	43.76	11.76
90	10	6.15	19.64	44.89	11.53	6.20	19.63	44.27	11.66
85	15	6.58	19.55	45.74	11.35	6.64	19.54	44.80	11.55
80	20	7.04	19.44	46.62	11.17	7.16	19.43	45.44	11.42
75	25	7.57	19.34	47.57	10.97	7.68	19.37	45.45	11.42
70	30	7.92	19.27	48.68	10.73	7.91	19.27	46.04	11.28
65	35	8.46	19.16	49.81	10.50	8.62	19.12	46.80	11.13
60	40	9.28	18.97	51.09	10.23	9.46	18.94	47.60	10.97
55	45	10.28	18.77	51.88	10.07	10.46	18.73	48.04	10.87
50	50	11.14	18.60	53.12	9.81	11.24	18.57	48.79	10.72
45	55	12.47	18.31	54.13	9.55	12.73	18.27	49.41	10.58
40	60	14.65	17.85	55.98	9.21	14.62	17.86	50.02	10.46
35	65	16.20	17.53	57.31	8.93	16.73	17.42	50.46	10.37
30	70	19.12	16.92	58.87	8.60	20.08	16.73	50.70	10.32
25	75	21.70	16.37	60.74	8.21	24.63	15.77	50.72	10.31
20	80	28.85	14.88	62.02	7.94	32.73	14.08	52.54	9.93
15	85	39.45	12.67	64.45	7.44	48.35	10.81	53.90	9.65
14	86	42.21	12.19	64.91	7.34	51.90	10.07	52.88	9.86
13.94	86.06					nonexplosive			
13	87	45.39	11.43	65.55	7.21				
12	88	49.16	10.63	66.18	7.08				
11	89	53.70	9.69	66.81	6.94				
10	90	58.73	8.64	67.23	6.86				
9	91	65.12	7.30	66.92	6.91				
8.79	91.21	nonexplosive							

The calculations of the data tabulated above that pertain to factors obtained when nitrogen is used as the diluent, except the data relating to mixtures of the air-free carbureted water gas (*J*, fig. 10) and diluent, are given in this report. (See pp. 18, 19, 46 to 48, 50 to 52, and 53.) Calculations of the data pertaining to factors obtained when carbon dioxide is used as the diluent are not given but have been computed by the methods described in this report. (*See* p. 82.)

Figure 10 (pocket) has been constructed from the data given in the foregoing tables and shows the relation between the quantitative composition and explosibility of mixtures of the carbureted water gas, air, and nitrogen or carbon dioxide (diluent).

It is observed in figure 10 that the zone of explosive mixtures is large, that the nose-limit mixture has a high inert-gas content, and that the critical oxygen value is low. These conditions are primarily because of the high hydrogen and carbon monoxide contents of the carbureted water gas.

Carbureted water gas has a wide explosive range and is composed of a number of simple combustible gases. The points corresponding to the explosive-limit mixtures of several mixtures of the air-free carbureted water gas and diluent (both nitrogen and carbon dioxide), with air, have been plotted in figure 10, which shows the relative positions of the points corresponding to the explosive-limit mixtures as calculated by the standard method (*19*) and the straight lines corresponding to the explosive-limit mixtures when such lines are drawn from the point corresponding to the nose-limit mixture to the points corresponding to the lower and the upper explosive-limit mixtures, respectively, of the air-free carbureted water gas.

A study of the data in figure 10 relating to the two methods of determining the position of the points corresponding to the explosive-limit mixtures, and consequently their composition, shows clearly the efficiency and utility of the method that utilizes the nose-limit mixture in conjunction with only the explosive-limit mixtures of the air-free original atmosphere.

DETERMINATION OF SPECIFIC GRAVITY OF A COMPLEX MIXTURE OF GASES

Because of the differences in magnitude of the specific gravity and percentage of the respective gases composing the carbureted water gas, the air-free compositions of different portions of an atmosphere confined in a place into which the carbureted gas is leaking differ from each other and from the air-free carbureted gas. For this reason, it is desirable to know the specific gravity of the carbureted gas.

The weight of a liter of a given gas at 0° C. and 760 mm. pressure is found by the following formula:

$$\text{Wt. of 1 liter of given gas}=\frac{(\text{Molecular wt. of given gas})\ (1.42904)}{32}. \qquad (80)$$

The specific gravity of a given gas, when the specific gravity of air is 1, is found by the following formula:

$$\text{Specific gravity of given gas}=\frac{\text{Weight of 1 liter of given gas}}{1.2929}. \qquad (81)$$

The arithmetical calculations concerning the specific gravity of the carbureted water gas are not given; however, the specific gravity has been found to be 0.5659, and the procedure employed to determine this real value is summarized in the following table:

Physical qualities [1] of constituents of the carbureted water gas and procedure to determine specific gravity of this gas

Gas	Formula	Molecular weight (based on atomic weights as of 1941)	Weight at 0° C. at 760 mm. (in grams per liter)	Specific gravity; air=1	Composition of carbureted water gas (in percent by volume)	Weight of respective volume of each constituent contained in 1 liter of carbureted water gas (in grams)
Carbon monoxide	CO	28.01	1.2504	0.9671	31.30	0.39138
Methane	CH_4	16.04	.7168	.5544	11.25	.08064
Hydrogen	H_2	2.0162	.08988	.06952	42.95	.03860
Ethylene	C_2H_4	28.05	1.2604	.9749	5.76	.07260
Propylene	C_3H_6	42.08	1.937	[2] 1.498	1.44	.02789
Ethane	C_2H_6	30.07	1.3566	1.0493	.00	.00000
Carbon dioxide	CO_2	44.01	1.9769	1.5290	3.90	.07710
Nitrogen	N_2	28.02	1.25055	.96724	2.85	.03564
Oxygen	O_2	32.00	1.42904	1.10527	.55	.00786
Carbureted water gas	Mixture of gases given above.	----------	.73171	.5659	100.00	.73171

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[1] Handbook of Chemistry and Physics, 28th ed., 1944.

[2] Lange's Handbook of Chemistry, 1946.

DETERMINATION OF VOLUME OF WARNING AGENT REQUIRED TO GIVE ADEQUATE WARNING

The gas industry has always been aware that the odor of carbureted water gas is generally accepted as being perceptible in an atmosphere composed of this fuel gas and air before such an atmosphere becomes dangerous to life from consideration of both carbon monoxide asphyxia and explosion.

When carbureted water gas passes through soil or earth, after it escapes from a gas pipe, tank, or other container and before it enters into the surrounding atmosphere or enclosure, the odor of normally odorous carbureted water gas can be reduced by the retention of its odorous constituents by the soil.

No unusual odor was detected by persons in the plant before or at the time of the explosion under discussion. This would indicate that the natural odor of carbureted water gas cannot always be depended upon to give adequate warning of its presence. No warning agent was in use to odorize the carbureted water gas that caused the explosion.

The subject of warning agents is covered in detail in Bureau of Mines Monograph 4, entitled "Warning Agents for Fuel Gases," by A. C. Fieldner and others. After considering the practical aspects desired of warning agents so that they could give ample warning of both carbon monoxide and explosion hazards, these investigators decided that enough suitable warning agent should be present in a fuel gas to give a distinct warning against these hazards.

As an aid to avert carbon monoxide poisoning, the above-mentioned investigators decided that a warning agent should be present in a fuel gas in an amount adequate to give a distinct odor when the percentage of carbon monoxide in the atmosphere containing the fuel gas is not more than 0.1 percent by volume. Although an atmosphere containing 0.1 percent of carbon monoxide can be breathed for a short period without causing death, this atmosphere will, if breathed, cause unconsciousness in less than 1 hour and death within 1½ hours.

As an aid to avert an explosion, the above-mentioned investigators decided that enough warning agent should be present in the fuel gas to give a distinct odor when the percentage of the fuel gas in the atmosphere equals one-fifth of the percentage defining the lower explosive limit of the air-free fuel gas in air.

In laboratory tests, odors were not found to awaken sleeping persons unless the odors were present in high, impracticable, and sometimes nauseating proportions. It is obvious, therefore, that the absence of a warning agent in carbureted water gas would only create less likelihood of a sleeping person being awakened in an atmosphere containing this fuel gas. However, where persons are conscious, the usefulness of a warning agent for detecting leaks in a fuel-gas distributing system is apparent.

The minimum amounts at which some substances used as warning agents attract the attention of persons breathing atmospheres containing them have been determined and are given in the following table:

Approximate minimum warning concentrations of materials used in field tests (pounds per million cubic feet of air)[1]

Material	Concentration	Remarks
Crotonaldehyde	0.5	Positive warning through irritation of eyes, nose, and throat.
	[2] 1.0	No significant disagreeable warning odor.
Ethyl mercaptan	.01	Disagreeable odor. Very striking in character, even when present in high dilution.
Amyl acetate	.10	Pleasant odor to most persons, mild in character and not striking.
Pyridine	.10	Moderately disagreeable and striking.
Butylene from cracked petroleum products	[3] 2.0	Not unplesaant, suggestive of manufactured gas.
Amylene from cracked petroleum products	[3] .08	Do.
Mixture hydrocarbons, paraffins, and olefins from cracking petroleum products.	[4] 2.4	Do.
Pintsch-gas condensate	.75	Do.

[1] Fieldner, A. C., and others. Warning Agents for Fuel Gases: Bureau of Mines Mon. 4, 1931, p. 152.

[2] For sleeping persons; all other values for conscious persons.

[3] Calculated on basis of olefin content of a mixture of paraffins and olefins.

[4] Mixture considered as a whole.

The quantity of a warning agent that must be admixed with a given fuel gas so as to give ample warning against both the carbon monoxide hazard and the explosion hazard can be calculated by means of the following formulas (see pp. 150–52, Bureau of Mines Monograph 4):

To determine the carbon monoxide hazard

$$Q=1000\ q\ A_s, \tag{82}$$

and to determine the explosion hazard

$$Q=\frac{500\ q}{L_L}, \tag{83}$$

where Q=quantity of warning agent that must be admixed with a unit volume of given fuel gas so as to produce desired warning, expressed as parts per million, milligrams per liter, or pounds per million cubic feet;

q=minimum quantity of warning agent required in an atmosphere so as to produce distinct warning, expressed in units the same as desired for Q;

A_s=percentage of carbon monoxide in given fuel gas, expressed as a decimal fraction;

L_L=lower explosive limit of air-free fuel gas, in air;

1000=constant for calculating carbon monoxide hazard;

500=constant for calculating explosion hazard.

Ethyl mercaptan has been found to be a suitable warning agent for giving ample warning under conditions such as existed in the plant where the explosion occurred.

From the table above we find that

q=0.01 pound, quantity of ethyl mercaptan required per million cubic feet of given atmosphere;

from the table on page 177, that

A_s=0.313, the percentage of carbon monoxide in fuel gas, expressed as a decimal fraction;

and from the table on page 179, that

$L_L = 5.41$ percent, lower explosive limit of air-free fuel gas, in air.

The quantity of warning agent that must be admixed with the carbureted water gas under discussion can be determined by substituting the above-given real values for the symbols in formulas (82) and (83) as follows:

$$Q = 1000\ q\ A_s, \tag{82}$$

$$= 1000 \times 0.01 \times 0.313,$$

$= 3.13$ pounds of ethyl mercaptan per million cubic feet of carbureted water gas containing 31.3 percent carbon monoxide;

and

$$Q = \frac{500\ q}{L_L}, \tag{83}$$

$$= \frac{500 \times 0.01}{5.41},$$

$= 0.924$ pound of ethyl mercaptan required per million cubic feet of carbureted water gas having a lower explosive limit of 5.41 percent.

As 3.13 pounds of ethyl mercaptan per million cubic feet of the fuel gas is required to give ample warning against the carbon monoxide hazard and only 0.924 pound is required to protect against the explosion hazard, carbon monoxide poisoning is the controlling hazard, and the larger quantity (3.13 pounds) of ethyl mercaptan should be utilized to protect against both hazards.

DETERMINATION OF VOLUME OF GAS DISCHARGED FROM GAS PIPE OF GIVEN SIZE

Fuel gas wasted by leakage from gas mains represents a loss in dividends to the utility-service company and a higher cost to the consumer of the fuel gas. This in itself justifies efficient inspections and dependable records of gas-service facilities.

Explosions and asphyxiations are caused by leakage of fuel gas from gas-service pipes into enclosed places or into the soil and eventually into enclosures in which the gas can accumulate.

The volume of gas that is discharged from a pipe of given size may be determined by the following formula:

$$Q = 1{,}350\ D^2 \sqrt{\frac{HD}{GL}}, \tag{84}$$

where

Q = volume of fuel gas discharged from pipe, expressed in cubic feet per hour;

D = diameter of pipe, expressed in inches;

H = difference in pressure of fuel gas in gas main and outside atmosphere, expressed in inches of water;

L = length of pipe through which gas will flow due to pressure H, expressed in linear yards;

G = specific gravity of fuel gas when specific gravity of air is 1.

The above-mentioned difference in pressure (H) was ascertained to be equivalent to 6 inches water gage at the time of the explosion. The diameter (D) and the length (L) of the gas pipe are 1¼ inches and 30 yards, respectively. The specific gravity (G) of the fuel gas is 0.5659 (see p. 181).

The real value of Q is found by substituting the above-given real values for the symbols in formula (84), or

$$Q=1{,}350D^2\sqrt{\frac{HD}{GL}}, \tag{84}$$

$$=1{,}350\times 1.25^2\times\sqrt{\frac{6\times 1.25}{0.5659\times 30}},$$

$$=1{,}402 \text{ cubic feet per hour.}$$

Because the gas pipe under the concrete floor was covered with porous dirt to a depth of 9 feet, we can assume that the end of the pipe was open, and under such conditions the carbureted water gas could escape from the gas pipe at the rate of approximately 1,400 cubic feet per hour.

The above-mentioned gas pipe gave gas service to a dwelling house on the premises before construction of the building in which the explosion occurred. This gas pipe was overlooked when the building was constructed. For this reason the carbureted water gas had been escaping into the dirt fill under the building for at least 14 years. This gas did not accumulate in the enclosure between the wooden floor and concrete floor until a large crack occurred in the concrete floor.

DISCUSSION OF IGNITION OF EXPLOSIVE MIXTURE OF CARBURETED WATER GAS, AIR, AND DILUENT (NITROGEN OR CARBON DIOXIDE)

In searching for the source of ignition of the explosive mixture of fuel gas and air, the fact that the plant was not operating at the time of the explosion focused attention on the acts of the 18 persons in the building. Furthermore, whatever occurred had to take place somewhere on the first floor of the building, either in the room occupied by the repairmen or in the room in which most of the damage was done by the explosion. The sources of ignition that could be assumed to be present were as follows:

(*a*) The building is heated by steam radiators supplied with steam from a furnace that burns anthracite and is in a small basement. The basement was flooded at the time of the explosion and showed no evidence of an explosion; therefore, the heating plant was not the source of ignition.

(*b*) Someone could have been using smokers' articles. Although smoking itself may not cause an explosion, the ignition of a match or a lighter could ignite any explosive mixture. The workmen stated that no one was smoking; also, the lower-explosive-limit mixture of the carbureted water gas and air contains 1.74 percent of carbon monoxide (see p. 179.) A person on breathing such an atmosphere would collapse immediately and die from carbon monoxide poisoning in a few minutes. Therefore, smoking or a flame from a match or a lighter did not cause the explosion.

(*c*) Electrical energy was used for lighting and for operating mechanical equipment in the building. Events concerning the explosion lead to the conclusion that an electric arc caused the explosion, and it was only necessary to ascertain where the explosive mixture was ignited (see p. 175.)

DETERMINATION OF VOLUME OF INERT GAS REQUIRED TO FORM NONEXPLOSIVE MIXTURES

All possible mixtures of the carbureted water gas, air, and diluent (nitrogen or carbon dioxide) are shown graphically in figure 10 (pocket).

From figure 10 we can determine graphically the minimum amount of inert gas (nitrogen or carbon dioxide), of air, or of a mixture of air and inert gas (*diluent*) that is necessary to purge a gas tank or other receptacle containing the carbureted water gas (*P*) so as to render nonexplosive all mixtures of this fuel gas, the inert gas, and air.

If conditions are such that pure air or a mixture of air and an inert gas, or *diluent*, can be used safely or is desirable for purging the container, the minimum volume of air required to form a nonexplosive mixture or a mixture incapable of forming an explosive mixture with air can be determined by means of figure 10 and formula (47*c*–2) or formula (47*c*–3), whichever is applicable. The minimum volume of *diluent* required can be determined by the methods described on pages 98 to 114.

For all practical purposes and erring on the side of safety, the carbureted water gas, which contains but 0.55 percent of oxygen and corresponds to point *P*, can be considered as the air-free original atmosphere (*J*, fig. 10). As the critical gas mixtures relating to atmosphere *J* represent the desirable final atmospheres when nitrogen and carbon dioxide, respectively, are used as the diluent, we find that if 91.21 percent of nitrogen or 86.06 percent of carbon dioxide is admixed with the carbureted water gas or with any potentially explosive mixture of this fuel gas and air, all the mixtures formed will be nonexplosive and incapable of forming explosive mixtures with air. The volume of inert gas required for this purpose is 912.1 cubic feet of nitrogen or 860.6 cubic feet of carbon dioxide for each 1,000 cubic feet of the volume of the sealed enclosure or container in which the final mixture is confined.

The volumes of nitrogen or carbon dixide given above, required to form a mixture that is nonexplosive and incapable of forming an explosive mixture with air, are the diluent contents (percentage of nitrogen or carbon dioxide) of the respective critical gas mixtures. The diluent contents of these mixtures are given in the table on page 179.

Because the fuel gas, or original atmosphere, contains 2.63 percent of air (see p. 177), it is logical to assume that the sample contains air that was admixed with fuel gas that had the same composition as atmosphere *J*. The potentially explosive mixtures and explosive mixtures formed by admixing air with atmosphere *J* correspond to the points comprising line *J–Lower Limit*. These mixtures are diluent-free, and the volume of inert gas required to form desirable extinctive mixtures from them ranges from 91.21 percent of nitrogen or 86.06

percent of carbon dioxide to just a trace of either nitrogen or carbon dioxide.

Atmosphere P, or the carbureted water gas, is one of the foregoing mixtures. To determine graphically the volume of inert gas required to form the desirable final atmosphere from atmosphere P, we draw line P–O. Points P_1 and P_2 correspond to the desirable final atmospheres when the diluent is nitrogen and carbon dioxide, respectively. The requisite volume of inert gas is the diluent content of atmosphere P_1 or P_2, as the case may be and depends on whether nitrogen or carbon dioxide is used as the diluent. The volume of inert gas is found to be 91.0 percent of nitrogen or 85.8 percent of carbon dioxide. The requisite volume of inert gas, therefore, is 910 cubic feet of nitrogen or 858 cubic feet of carbon dioxide for each 1,000 cubic feet of the total volume of whatever contains the final mixture, which is nonexplosive and incapable of forming an explosive mixture with air.

The volume of inert gas (nitrogen or carbon dioxide) that must be admixed with atmosphere P to form atmosphere P_1 or P_2, as the case may be, can be calculated by substituting the known real values for the symbols in formulas (41), (42*c*), (43), (46*b*), and (47*c*) in the order given.

When nitrogen is used as the diluent, we find

$$\phi = \tan^{-1}\frac{C.\ G.\ M.\ V._{N_2}}{20.93}, \qquad (41)$$

$$= \tan^{-1}\frac{8.79}{20.93},$$

$$= 22°46'51''.$$

$$\theta = \tan^{-1}\frac{(O_2)_s}{Gas_s}, \qquad (42c)$$

$$= \tan^{-1}\frac{0.55}{97.37},$$

$$= 0°19'25''.$$

$$\Delta = 90° - \phi + \theta, \qquad (43)$$

$$= 90° - 22°46'51'' + 0°19'25'',$$

$$= 67°32'34''.$$

$$y = \frac{\sin\theta \sin\phi\ (20.93)}{\sin\Delta}, \qquad (46b)$$

$$= \frac{(\sin 0°19'25'')\times(\sin 22°46'51'')\times 20.93}{\sin 67°32'34''},$$

$= 0.04953$ percent of oxygen, the oxygen content of atmosphere P_1.

$$Inert\ gas_{dil} = \frac{[(O_2)_s - y]100}{(O_2)_s}, \qquad (47c)$$

$$= \frac{(0.55-0.04953)\times 100}{0.55},$$

$= 90.995$ percent of nitrogen, volume required to form atmosphere P_1 from atmosphere P (fig. 10).

When carbon dioxide is used as the diluent, we find

$$\phi = \tan^{-1} \frac{C.\ G.\ M.\ V._{CO_2}}{20.93}, \tag{41}$$

$$= \tan^{-1} \frac{13.94}{20.93},$$

$$= 33°39'53''.$$

$$\theta = \tan^{-1} \frac{(O_2)_s}{Gas_s}, \tag{42}$$

$$= \tan^{-1} \frac{0.55}{97.37},$$

$$= 0°19'25''.$$

$$\Delta = 90° - \phi + \theta, \tag{43}$$

$$= 90° - 33°39'53'' + 0°19'25'',$$

$$= 56°39'32''.$$

$$y = \frac{\sin\theta \sin\phi\ (20.93)}{\sin\Delta}, \tag{46b}$$

$$= \frac{(\sin 0°19'25'') \times (\sin 33°39'53'') \times 20.93}{\sin 56°39'32''},$$

$= 0.07844$ percent of oxygen, oxygen content of atmosphere P_2.

$$Inert\ gas_{dil} = \frac{[(O_2)_s - y]100}{(O_2)_s}, \tag{47c}$$

$$= \frac{(0.55 - 0.07844) \times 100}{0.55},$$

$= 85.738$ percent of carbon dioxide, volume required to form atmosphere P_2 from atmosphere P (fig. 10).

The graphic method of determining the minimum volume of inert gas needed to render a given atmosphere nonexplosive and incapable of forming an explosive mixture with air is described on pages 94 to 98, inclusive. Whether an atmosphere is potentially explosive or explosive can be ascertained by plotting the point corresponding to it on a completed graph, such as figure 10.

When dealing with a fuel gas that can form explosive mixtures with air and the composition of the fuel gas is known definitely, the establishment of a zone of desirable atmospheres and the attainment of the final mixtures it defines will protect against explosions. The procedure by which this is done is described on pages 168 to 170.

APPENDIX

SUMMARY OF FORMULAS FOR REFERENCE

The following summary gives the most important formulas occurring in the preceding subject matter. The formulas are here grouped under the principal subject to which they apply. Following each formula is its number.

A symbol and its meaning apply to all formulas in which it occurs; consequently, the meaning of a symbol is given only once.

Because some of the simple gases are discussed frequently, the meanings of the symbols distinguishing the percentages of these gases are explained so as to avoid repetition; for example: The letter A is used to distinguish the percentage of carbon monoxide in a critical gas mixture. A small letter s affixed below to the symbol A distinguishes it as the carbon monoxide content of an atmosphere as sampled or original atmosphere. The subscript 1 distinguishes the symbol as a constituent of an air-free original atmosphere; thus, A_1 distinguishes the symbol as the carbon monoxide content of an air-free original atmosphere.

The following symbols and their meanings apply to the formulas in which they occur:

Item	Original atmosphere, or atmosphere as sampled	Air-free original atmosphere	Critical gas mixture	Nose-limit mixture	Final atmosphere formed from another atmosphere
Gas portion:					
Carbon monoxide	A_s	A_1	A	A_{nose}	$A_{f.a.}$
Methane	B_s	B_1	B	B_{nose}	$B_{f.a.}$
Hydrogen	$(H_2)_s$	$(H_2)_1$	H_2	$(H_2)_{nose}$	$(H_2)_{f.a.}$
Ethylene	$(C_2H_4)_s$	$(C_2H_4)_1$	C_2H_4	$(C_2H_4)_{nose}$	$(C_2H_4)_{f.a.}$
Propylene	$(C_3H_6)_s$	$(C_3H_6)_1$	C_3H_6	$(C_3H_6)_{nose}$	$(C_3H_6)_{f.a.}$
Ethane	$(C_2H_6)_s$	$(C_2H_6)_1$	C_2H_6	$(C_2H_6)_{nose}$	$(C_2H_6)_{f.a.}$
Nitrogen	$(N_2)_{gp-s}$	$(N_2)_1$	N_2	$(N_2)_{1-nose}$	$(N_2)_{gp-f.a.}$
Carbon dioxide	D_s	D_1	D	D_{1-nose}	$D_{1-f.a.}$
Any constituent	$Constituent_s$	$Constituent_{air-free}$	$Constituent_{C.G.M}$	$Constituent_{nose}$	$Constituent_{f.a.}$
Gas-portion content	Gas_s	Gas_1	$C.G.M.V$	Gas_{nose}	x, or $Gas_{f.a.}$
Inert-gas content	$Inert_{gp-s}$	$Inert_1$	$Inert_{C.G.M}$	$Inert_{gp-nose}$	$Inert_{gp-f.a.}$
Air portion:					
Oxygen	$(O_2)_s$			$(O_2)_{nose}$	y, or $(O_2)_{f.a.}$
Nitrogen	$(N_2)_{air-s}$			$(N_2)_{air-nose}$	$(N_2)_{air-f.a.}$
Air	Air_s			Air_{nose}	$Air_{f.a.}$
Diluent portion:					
Nitrogen	$(N_2)_{add-s}$		$(N_2)_{dil-C.G.M}$	Dil_{nose-N_2}	$(N_2)_{add-f.a.}$
Carbon dioxide	$(CO_2)_{add-s}$		$(CO_2)_{dil-C.G.M}$	$Dil_{nose-CO_2}$	$(CO_2)_{add-f.a.}$
Diluent content	$Inert\ gas_{add-s}$		$Inert\ gas_{add-C.G.M}$	$Inert\ gas_{add-nose}$	$Inert\ gas_{add-f.a.}$
Total nitrogen	$(N_2)_{ts}$	$(N_2)_1$	$(N_2)_{C.G.M}$	$(N_2)_{nose}$	$(N_2)_{t\,f.a.}$
Total carbon dioxide	$(CO_2)_{ts}$	D_1	$D_{C.G.M}$	D_{nose}	$(CO_2)_{t\,f.a.}$
All gases except air	K_s			L_{nose}	$K_{f.a.}$
Combustible gas content	$Comb_s$	$Comb_1$	$Comb_{C.G.M}$	$Comb_{nose}$	$Comb_{f.a.}$

The following symbols and their meanings cannot be shown suitably in the foregoing table:

$k=\frac{C.\,G.\,M.\,V.}{100}$, or critical gas-mixture value expressed as a decimal fraction.
L_L, L_U, and L_{nose}=lower explosive limit, upper explosive limit, and nose limit, respectively, of the air-free original atmosphere.
Air_{limit}=percentage of air in a limit mixture.
$(N_2)_{dil}$=additional nitrogen (diluent) content of any atmosphere.
$(CO_2)_{dil}$=additional carbon dioxide (diluent) content of any atmosphere.
$\mathit{Inert\ gas}_{dil}$=volume of inert gas (nitrogen or carbon dioxide) admixed with a given atmosphere to form a final mixture.
$\mathit{Dil}_{inert\ gas+air}$=total volume of a *diluent*, composed of definite proportions of air and inert gas used as diluent, that must be admixed with a given atmosphere to form a final mixture.
$\mathit{Inert\ gas}_{Dil-inert\ gas+air}$=volume of inert-gas component of $\mathit{Dil}_{inert\ gas+air}$.
$\mathit{Air}_{Dil-inert\ gas+air}$=volume of air component of $\mathit{Dil}_{inert\ gas+air}$.
$\mathit{Diluent\ Mixture}_{nose}$=total volume of a definite *diluent* composed of definite proportions of a given inert gas and air that must be admixed with a given atmosphere to form nose-limit mixture.
$\mathit{Diluent\ Mixture}_{inert\ gas}$=volume of inert-gas component of $\mathit{Diluent\ Mixture}_{nose}$.
$\mathit{Diluent\ Mixture}_{air}$=volume of air component of $\mathit{Diluent\ Mixture}_{nose}$.
$\mathit{Atmos}_{diluent}$=mixture composed of definite proportions of an inert gas and air, used as a *diluent.*
Atmos_{air}=percentage of air composing $\mathit{Atmos}_{diluent}$.
$\mathit{Atmos}_{inert\ gas}$=percentage of inert gas (same kind as diluent) composing $\mathit{Atmos}_{diluent}$.
$(O_2)_{atmos}$=oxygen content of $\mathit{Atmos}_{diluent}$.

DETERMINATION OF AIR-FREE ANALYSIS

AIR CONTENT OF AN ATMOSPHERE

$$\mathit{Air}_s=\frac{(O_2)_s\ (100)}{20.93}\ \text{percent.} \tag{1}$$

AIR-FREE ANALYSIS

To determine the air-free composition of an atmosphere, the following formulas are applied in the order given:

$$K_s=100-\frac{(O_2)_s\ (100)}{20.93}\ \text{percent.} \tag{2}$$

$$\mathit{Constituent}_{air\text{-}free}=\frac{\mathit{Constituent}_s}{K_s}\ (100). \tag{3}$$

$$(N_2)_1=\frac{[(N_2)_s-\mathit{Air}_s+(O_2)_s]\ (100)}{K_s}. \tag{4b}$$

$$(N_2)_{add-s}=(N_2)_{ts}+(CO_2)_{ts}-(\mathit{Inert})_{gp-s}-3.78\ (O_2)_s. \tag{40}$$

DETERMINATION OF CRITICAL GAS-MIXTURE VALUE AND NOSE LIMIT

NITROGEN USED AS DILUENT

Case 1

If carbon dioxide, methane, hydrogen, nitrogen, and carbon dioxide are present in the air-free original atmosphere, and

$$10.2(H_2)_1 > D_1 \text{ (see p. 24)},$$

$$C.\ G.\ M.\ V._{N_2} = \frac{10{,}000}{5.15A_1 + 7B_1 + 17.55(H_2)_1 - 0.6225D_1}, \tag{10}$$

$$L_{nose-N_2} = \frac{5.15A_1 + 7B_1 + 17.55(H_2)_1 - 0.6225D_1}{\frac{5.15A_1}{71} + \frac{7B_1}{41.5} + \frac{17.55(H_2)_1}{75.5} - 0.00434D_1}. \tag{25}$$

Case 2

If hydrogen is absent, and

$$3.2B_1 > D_1 \text{ (see p. 26)},$$

$$C.\ G.\ M.\ V._{N_2} = \frac{10{,}000}{5.15A_1 + 7B_1 - 0.875D_1}, \tag{13}$$

$$L_{nose-N_2} = \frac{5.15A_1 + 7B_1 - 0.875D_1}{\frac{5.15A_1}{71} + \frac{7B_1}{41.5} - 0.0065D_1}. \tag{26}$$

Case 3

If hydrogen is present, and

$$10.2(H_2)_1 < D_1 \text{ (see p. 26)},$$

$$C.\ G.\ M.\ V._{N_2} = \frac{10{,}000}{5.15A_1 + 7B_1 + 20.12(H_2)_1 - 0.875D_1}, \tag{16}$$

$$L_{nose-N_2} = \frac{5.15A_1 + 7B_1 + 20.12(H_2)_1 - 0.875D_1}{\frac{5.15A_1}{71} + \frac{7B_1}{41.5} + 0.2545(H_2)_1 - 0.0065D_1}. \tag{27}$$

Case 4

If ethylene and propylene also are present, and

$$10.2(H_2)_1 > D_1 \text{ (see p. 27),}$$

$$C.\,G.\,M.\,V._{N_2} = \frac{10{,}000}{5.15A_1 + 7B_1 + 17.55(H_2)_1 - 0.6225D_1 + 16.4(C_2H_4)_1 + 15.1(C_3H_6)_1}, \tag{19}$$

$$L_{nose-N_2} = \frac{5.15A_1 + 7B_1 + 17.55(H_2)_1 + 16.4(C_2H_4)_1 + 15.1(C_3H_6)_1 - 0.6225D_1}{\frac{5.15A_1}{71} + \frac{7B_1}{41.5} + \frac{17.55(H_2)_1}{75.5} + \frac{16.4(C_2H_4)_1}{50.3} + \frac{15.1(C_3H_6)_1}{42.5} - 0.00434D_1} \tag{28}$$

Case 5

If $10.2(H_2)_1 = D_1$ (see p. 28),

$$C.\,G.\,M.\,V._{N_2} = \frac{10{,}000}{5.15A_1 + 7B_1 + (H_2)_1 + D_1}, \tag{20a}$$

$$L_{nose-N_2} = \frac{5.15A_1 + 7B_1 + (H_2)_1 + D_1}{\frac{5.15A_1}{71} + \frac{7B_1}{41.5} + \frac{(H_2)_1 + D_1}{59.5}}. \tag{29a}$$

Case 6

If $[10.2(H_2)_1 + 3.2B_1] < D_1$ (see p. 29),

$$C.\,G.\,M.\,V._{N_2} = \frac{10{,}000}{5.15A_1 + 7.15B_1 + 20.6(H_2)_1 - 0.9213D_1}, \tag{21A}$$

$$L_{nose-N_2} = \frac{5.15A_1 + 7.15B_1 + 20.6(H_2)_1 - 0.9213D_1}{\frac{5.15A_1}{71} + 0.1767B_1 + 0.2734(H_2)_1 - 0.00836D_1}. \tag{30A}$$

Case 7

If ethylene and propylene also are present, and

$$[3.2B_1 + 10.2(H_2)_1 + 9.1(C_2H_4)_1 + 7.8(C_3H_6)_1] < D_1 \text{ (see p. 29),}$$

$$C.\ G.\ M.\ V._{N_2}=\frac{10{,}000}{5.15A_1+7.15B_1+20.6(H_2)_1+18.48(C_2H_4)_1+15.98(C_3H_6)_1-0.9213D_1}. \qquad (21B)$$

$$L_{nose-N_2}=\frac{5.15A_1+7.15B_1+20.6(H_2)_1+18.48(C_2H_4)_1+15.98(C_3H_6)_1-0.9213D_1}{\frac{5.15A_1}{71}+0.1767B_1+0.2734(H_2)_1+0.311(C_2H_4)_1+0.3472(C_3H_6)_1-0.00836D_1}. \qquad (30B)$$

CARBON DIOXIDE USED AS DILUENT

Whether or not carbon dioxide is present in the air-free original atmosphere in cases in which carbon dioxide is used as the diluent makes no difference in application of the formulas (see p. 81).

Case 1

When neither nitrogen nor carbon dioxide is present in an air-free original atmosphere consisting of carbon monoxide, methane and hydrogen (see p. 81),

$$C.\ G.\ M.\ V._{CO_2}=\frac{10{,}000}{3.16A_1+4.20B_1+11.20(H_2)_1}, \qquad (48)$$

$$L_{nose-CO_2}=\frac{3.16A_1+4.20B_1+11.20(H_2)_1}{\frac{3.16A_1}{58.0}+\frac{4.20B_1}{28.0}+\frac{11.20(H_2)_1}{59.5}}. \qquad (49)$$

Case 2

If nitrogen also is present, and

$$4.15A_1<(N_2)_1,$$

$$C.\ G.\ M.\ V._{CO_2}=\frac{10{,}000}{3.21A_1+4.2B_1+11.2(H_2)_1+0.467(N_2)_1}, \qquad (50)$$

$$L_{nose-CO_2}=\frac{3.21A_1+4.2B_1+11.2(H_2)_1+0.467(N_2)_1}{0.0596A_1+\frac{4.2B_1}{28.0}+\frac{11.2(H_2)_1}{59.5}+0.00311(N_2)_1}. \qquad (51)$$

Case 3

If $4.15A_1 > (N_2)_1$,

$$C.\,G.\,M.\,V._{CO_2} = \frac{10{,}000}{3.16A_1 + 4.2B_1 + 11.2(H_2)_1 + 0.479(N_2)_1}, \tag{52}$$

$$L_{nose-CO_2} = \frac{3.16A_1 + 4.2B_1 + 11.2(H_2)_1 + 0.479(N_2)_1}{\frac{3.16A_1}{58.0} + \frac{4.2B_1}{28.0} + \frac{11.2(H_2)_1}{59.5} + 0.00435(N_2)_1}. \tag{53}$$

If ethylene, propylene, and ethane also are present, and

$$4.15A_1 > (N_2)_1,$$

$$C.\,G.\,M.\,V._{CO_2} = \frac{10{,}000}{3.16A_1 + 4.2B_1 + 11.2(H_2)_1 + 10.1(C_2H_4)_1 + 8.8(C_3H_6)_1 + 8.4(C_2H_6)_1 + 0.479(N_2)_1}, \tag{52a}$$

$$L_{nose-CO_2} = \frac{3.16A_1 + 4.2B_1 + 11.2(H_2)_1 + 10.1(C_2H_4)_1 + 8.8(C_3H_6)_1 + 8.4(C_2H_6)_1 + 0.479(N_2)_1}{\frac{3.16A_1}{58.0} + \frac{4.2B_1}{28.0} + \frac{11.2(H_2)_1}{59.5} + \frac{10.1(C_2H_4)_1}{43.0} + \frac{8.8(C_3H_6)_1}{31.2} + \frac{8.4(C_2H_6)_1}{35.7} + 0.00435(N_2)_1}. \tag{53a}$$

Case 4

If $6B_1 < (N_2)_1$, and $(6B_1 + 4.15A_1) > (N_2)_1$,

$$C.\,G.\,M.\,V._{CO_2} = \frac{10{,}000}{3.16A_1 + 4.12B_1 + 11.2(H_2)_1 + 0.479(N_2)_1}, \tag{54}$$

$$L_{nose-CO_2} = \frac{3.16A_1 + 4.12B_1 + 11.2(H_2)_1 + 0.479(N_2)_1}{\frac{3.16A_1}{58.0} + 0.1426B_1 + \frac{11.2(H_2)_1}{59.5} + 0.00435(N_2)_1}. \tag{55}$$

Case 5

If carbon monoxide is absent or present in a very small amount, and

$$6B_1 > (N_2)_1,$$

$$C.\ G.\ M.\ V._{CO_2}=\frac{10{,}000}{3.16A_1+4.2B_1+11.2(H_2)_1+0.467(N_2)_1}, \tag{56}$$

$$L_{nose-CO2}=\frac{3.16A_1+4.2B_1+11.2(H_2)_1+0.467(N_2)_1}{\frac{3.16A_1}{58.0}+\frac{4.2B_1}{28.0}+\frac{11.2(H_2)_1}{59.5}+0.00311(N_2)_1}. \tag{57}$$

Case 6

If $(4.15A_1+6B_1)<(N_2)_1$,

$$C.\ G.\ M.\ V._{CO2}=\frac{10{,}000}{3.56A_1+4.70B_1+11.2(H_2)_1+0.3836(N_2)_1}, \tag{58}$$

$$L_{nose-CO2}=\frac{3.56A_1+4.70B_1+11.2(H_2)_1+0.384(N_2)_1}{0.0614A_1+0.1526B_1+\frac{11.2(H_2)_1}{59.5}+0.00267(N_2)_1}. \tag{59}$$

DETERMINATION OF COMPOSITION OF CRITICAL GAS MIXTURE

$$Constituent_{C.\ G.\ M.}=k\ (Constituent_{air-free}), \tag{22A}$$

$$Dil_{C.\ G.\ M.}=100-C.\ G.\ M.\ V. \tag{22B}$$

DETERMINATION OF COMPOSITION OF NOSE-LIMIT MIXTURE

$$Air_{limit}=100-L, \tag{31A}$$

$$(O_2)_{limit}=0.2093(100-L), \tag{31B}$$

$$(N_2)_{air-limit}=0.7907(100-L), \tag{31C}$$

$$Constituent_{nose}=\left[\frac{L_{nose}}{110}\right]k\ (Constituent_{air-free}), \tag{32A}$$

$$Dil_{nose-N_2}=(L_{nose-N_2})\ (1-k), \tag{33A}$$

$$(N_2)_{nose}=0.7907(100-L_{nose-N_2})+\left[\frac{L_{nose-N_2}}{100}\right][k(N_2)_1]+(L_{nose-N_2})(1-k), \tag{36}$$

$$(D)_{nose}=0.7907(100-L_{nose-CO2})+\left[\frac{L_{nose-CO2}}{100}\right][k(N_2)_1]+(L_{nose-CO2})(1-k). \tag{37}$$

DETERMINATION OF CRITICAL OXYGEN VALUE

Having found the real value of $(O_2)_{nose-N_2}$ when nitrogen is used as the diluent, the critical oxygen value for practical purposes can be determined by the following formula (see pp. 42 and 44):

$$Critical\ Oxygen\ Value=(O_2)_{nose}-0.50.$$

DETERMINATION OF EXPLOSIVE LIMITS

Having found the gas-portion content of the nose-limit mixture when nitrogen is used as the diluent, a safe real value of the lower explosive limit can be determined by the following formula (see pp. 52, 119, and 120):

$$L_L=Gas_{nose-N_2}-1.00.$$

The explosive limits are found by the method described on pages 49 to 52.

DETERMINATION OF DILUENT CONTENT OF ANY ATMOSPHERE CONTAINING DILUENT

Having determined the air-free analysis of the atmosphere sampled (see p. 191) and the composition of the air-free original atmosphere, the diluent content of the atmosphere sampled can be determined by applying the following formulas in the order given:

$$C = \frac{(Comb)_s}{\left[\frac{K_s}{100}\right]\left[\frac{(Comb)_1}{100}\right]} \qquad (38)$$

$$(N_2)_{add-s} = (100 - C)\left[\frac{K_s}{100}\right].$$

Having determined the real value of C by formula (38), the diluent content can be determined as follows:

$$Gas_s = \frac{CK_s}{100} = x,$$

and

$$(N_2)_{dil} = 100 - \frac{100y}{20.93} - x. \qquad (47a)$$

DETERMINATION OF COMPOSITION (BY PORTIONS) OF ANY ATMOSPHERE

Having determined the real values of two of the portions of any atmosphere (see pp. 94 and 95), the real value of the third portion is determined by substituting the known real values for the symbols in formula (68), or

$$Inert\ gas_{add-f.\ a.} = 100 - Air_{f.\ a.} - Gas_{f.\ a.}. \qquad (68)$$

DETERMINATION OF EXPLOSIBILITY OF A GIVEN ATMOSPHERE

To determine whether a given atmosphere is nonexplosive, explosive, or capable of forming an explosive mixture with air (see pp. 145 to 148):

(*a*) Determine the air-free composition of the given atmosphere (see p. 191).

(*b*) Determine the critical gas-mixture value ($C.\ G.\ M.\ V._{N_2}$) that is applicable to the air-free given atmosphere (see p. 91).

(*c*) If the critical gas-mixture value is found to be 100, is more than 100, or has a minus value, both the given atmosphere and its air-free composition are nonexplosive and incapable of forming explosive mixtures with air, and further calculations are unnecessary (see p. 147).

(*d*) If the critical gas-mixture value is less than 100, the air-free composition of the given atmosphere has explosive limits (see p. 148).

(*e*) Determine the real value of K_s by formula (2), page 17.

(*f*) Determine the nose limit (L_{nose-N_2}) that is related to the critical gas-mixture value given above.

(*g*) Determine the real value of Gas_{nose-N_2}.

(*h*) Determine the lower explosive limit by means of the following formula (see p. 119).

$$L_L = Gas_{nose-N_2} - 1.00.$$

If K_s is less than L_L, the given atmosphere is nonexplosive and incapable of forming an explosive mixture with air.

If the given atmosphere represents all portions of the atmosphere under consideration or is known to represent the portion having an air-free composition that has the widest explosive range and the maximum real value of K_s, no further calculations are necessary.

If K_s is equal to or more than the real value of L_L as determined above, the given atmosphere should be examined further.

(*i*) Determine the explosive limits (L_L and L_U) of the air-free composition of the given atmosphere by the method described on pages 49 to 52.

(*j*) If K_s is equal to or more than L_L and equal to or less than L_U, the given atmosphere is explosive; if K_s is more than L_U, the given atmosphere is capable of forming explosive mixtures with air.

DETERMINATION OF MINIMUM VOLUME OF GIVEN INERT GAS TO BE ADMIXED WITH A GIVEN ATMOSPHERE TO FORM AN ATMOSPHERE THAT IS NONEXPLOSIVE AND INCAPABLE OF FORMING AN EXPLOSIVE MIXTURE WITH AIR

To determine the minimum volume of a given inert gas that must be admixed with a given atmosphere to form an atmosphere that is both nonexplosive and incapable of forming an explosive mixture with air, the following formulas are applied in the order given:

$$\phi=\tan^{-1}\frac{C.G.M.V.}{20.93}, \qquad (41)$$

$$\theta=\tan^{-1}\frac{(O_2)_s}{Gas_s}, \qquad (42c)$$

$$\Delta=90^\circ-\phi+\theta, \qquad (43)$$

$$x=\frac{\cos\theta\sin\phi\ (20.93)}{\sin\Delta}, \qquad (45b)$$

$$y=\frac{\sin\theta\sin\phi\ (20.93)}{\sin\Delta}, \qquad (46b)$$

$$Inert\,gas_{dil}=\frac{[(O_2)_s-y]100}{(O_2)_s}. \qquad (47c)$$

The minimum amount of inert gas required to form an atmosphere that is both nonexplosive and incapable of forming an explosive mixture with air where the inert gas and the diluent are alike, can be determined by the following formulas:

$$Inert\ gas_{dil}\text{ or }Dil_{inert\ gas+gas}\text{ or }Dil_{gas}=\frac{[(O_2)_s-(O_2)_{f.a.}]100}{(O_2)_s}, \qquad (47c\text{–}1)$$

$$Dil_{air}\text{ or }Dil_{inert\ gas+air}\text{ or }Inert\ gas_{dil}=\frac{(Gas_s-Gas_{f.a.})100}{Gas_s}, \qquad (47c\text{–}3)$$

DETERMINATION OF VOLUME OF *DILUENT* (INERT GAS PLUS AIR) AND PERCENTAGES OF ITS COMPONENTS REQUIRED TO FORM THE NOSE-LIMIT MIXTURE FROM A GIVEN ATMOSPHERE

The procedure to determine the volumes of *diluent* and its respective components required to form the nose-limit mixture from a given atmosphere depends on whether the given atmosphere is diluent-free or whether it contains diluent (see p. 103).

If the given atmosphere is diluent-free, the following formulas are applied in the order given:

$$\mathit{Diluent\ Mixture}_{nose}=\frac{(\mathit{Gas}_s-\mathit{Gas}_{nose})100}{\mathit{Gas}_s}\ \text{percent}, \tag{61}$$

$$\mathit{Diluent\ Mixture}_{air}=\mathit{Diluent\ Mixture}_{nose}-\mathit{Dil}_{nose}. \tag{65}$$

If the given atmosphere contains diluent, the following formulas are applied in the order given (see p. 106):

$$\mathit{Diluent\ Mixture}_{nose}=\frac{(\mathit{Gas}_s-\mathit{Gas}_{nose})100}{\mathit{Gas}_s}\ \text{percent}, \tag{61}$$

$$\mathit{Atmos}_{air}=\frac{100}{20.93}\left[\frac{\mathit{Gas}_s\,[(O_2)_{nose}-(O_2)_s]}{\mathit{Gas}_s-\mathit{Gas}_{nose}}+(O_2)_s\right]\ \text{percent}, \tag{62B}$$

$$\mathit{Atmos}_{inert\ gas}=100-\mathit{Atmos}_{air}, \tag{62C–1}$$

$$\mathit{Diluent\ Mixture}_{air}=\frac{(\mathit{Diluent\ Mixture}_{nose})(\mathit{Atmos}_{air})}{100}, \tag{63a}$$

$$\mathit{Diluent\ Mixture}_{inert\ gas}=\mathit{Diluent\ Mixture}_{nose}-\mathit{Diluent\ Mixture}_{air}. \tag{64a}$$

DETERMINATION OF VOLUME OF *DILUENT* REQUIRED TO FORM A BORDERLINE EXTINCTIVE MIXTURE

A borderline extinctive mixture can be formed from an explosive mixture or a mixture capable of forming explosive mixtures with air by admixing a suitable *diluent* with it (see p. 110).

To determine the minimum amount of a given *diluent* required to form a borderline extinctive mixture where the *diluent* contains an inert gas (same as diluent) and air in suitable proportions (see p. 110), the following formulas are applied in the order given:

$$z=\frac{[20.93-(O_2)_{atmos}]\left[\sin\tan^{-1}\frac{C.\ G.\ M.\ V.}{20.93}\right]}{\sin\left[90°-\tan^{-1}\frac{C.\ G.\ M.\ V.}{20.93}-\tan^{-1}\frac{(O_2)_{atmos}-(O_2)_s}{\mathit{Gas}_s}\right]}, \tag{70}$$

$$\mathit{Gas}_{f.\ a.}=z\cos\tan^{-1}\frac{(O_2)_{atmos}-(O_2)_s}{\mathit{Gas}_s}, \tag{71}$$

$$\mathit{Air}_{f.\ a.}=\left[(\mathit{Gas}_s-\mathit{Gas}_{f.\ a.})\left(\frac{(O_2)_{atmos}-(O_2)_s}{\mathit{Gas}_s}\right)\left(\frac{100}{20.93}\right)\right]+\mathit{Air}_s, \tag{72b}$$

$$\mathit{Inert\ gas}_{add-f.\ a.}=100-\mathit{Air}_{f.\ a.}-\mathit{Gas}_{f.\ a.}, \tag{68}$$

$$\mathit{Dil}_{inert\ gas+air}=\frac{(\mathit{Gas}_s-\mathit{Gas}_{f.\ a.})100}{\mathit{Gas}_s}, \tag{47c–3}$$

$$\mathit{Inert\ gas}_{Dil-inert\ gas+air}=\mathit{Dil}_{inert\ gas+air}\left[\frac{\mathit{Atmos}_{inert\ gas}}{100}\right], \tag{73}$$

$$\mathit{Air}_{Dil-inert\ gas+air}=\mathit{Dil}_{inert\ gas+air}\left[\frac{\mathit{Atmos}_{air}}{100}\right]. \tag{74}$$

DETERMINATION OF VOLUME OF AIR, INERT GAS, OR *DILUENT* REQUIRED TO FORM A NONEXPLOSIVE MIXTURE THAT IS JUST NOT A LOWER-EXPLOSIVE-LIMIT MIXTURE

A nonexplosive mixture that is just not a lower-explosive-limit mixture can be formed from a given atmosphere by admixing with it air, an inert gas (same as diluent), or a *diluent* composed of that inert gas and air, if the line corresponding to the successive mixtures formed passes through the line of lower-explosive-limit mixtures (see p. 112).

To determine the volume of air, of the given inert gas, or of the given *diluent* required for the above-mentioned purpose (see pp. 159 and 164), the following formulas are applied in the order given:

$$z_1 = [(O_2)_{L-L} - (O_2)_{atmos}] + (Gas_{L-L}) \tan \tan^{-1} \frac{(O_2)_{atmos} - (O_2)_s}{Gas_s}, \qquad (75)$$

$$z_2 = \frac{(z_1)\left[\sin \tan^{-1} \dfrac{Gas_{nose} - Gas_{L-L}}{(O_2)_{L-L} - (O_2)_{nose}}\right]}{\sin\left[90^\circ - \tan^{-1} \dfrac{Gas_{nose} - Gas_{L-L}}{(O_2)_{L-L} - (O_2)_{nose}} - \tan^{-1} \dfrac{(O_2)_{atmos} - (O_2)_s}{Gas_s}\right]}, \qquad (76)$$

$$z_3 = z_2 \sin \tan^{-1} \frac{(O_2)_{atmos} - (O_2)_s}{Gas_s}, \qquad (77)$$

$$(O_2)_{f.\ a.} = (O_2)_{L-L} - z_1 - z_3, \qquad (78)$$

$$Gas_{f.\ a.} = Gas_{L-L} + z_2 \cos \tan^{-1} \frac{(O_2)_{atmos} - (O_2)_s}{Gas_s}, \qquad (79)$$

$$Dil_{air} \text{ or } Inert\ gas_{dil} \text{ or } Dil_{inert\ gas+air} = \frac{(Gas_s - Gas_{f.\ a.})100}{Gas_s}. \qquad (47c\text{–}3)$$

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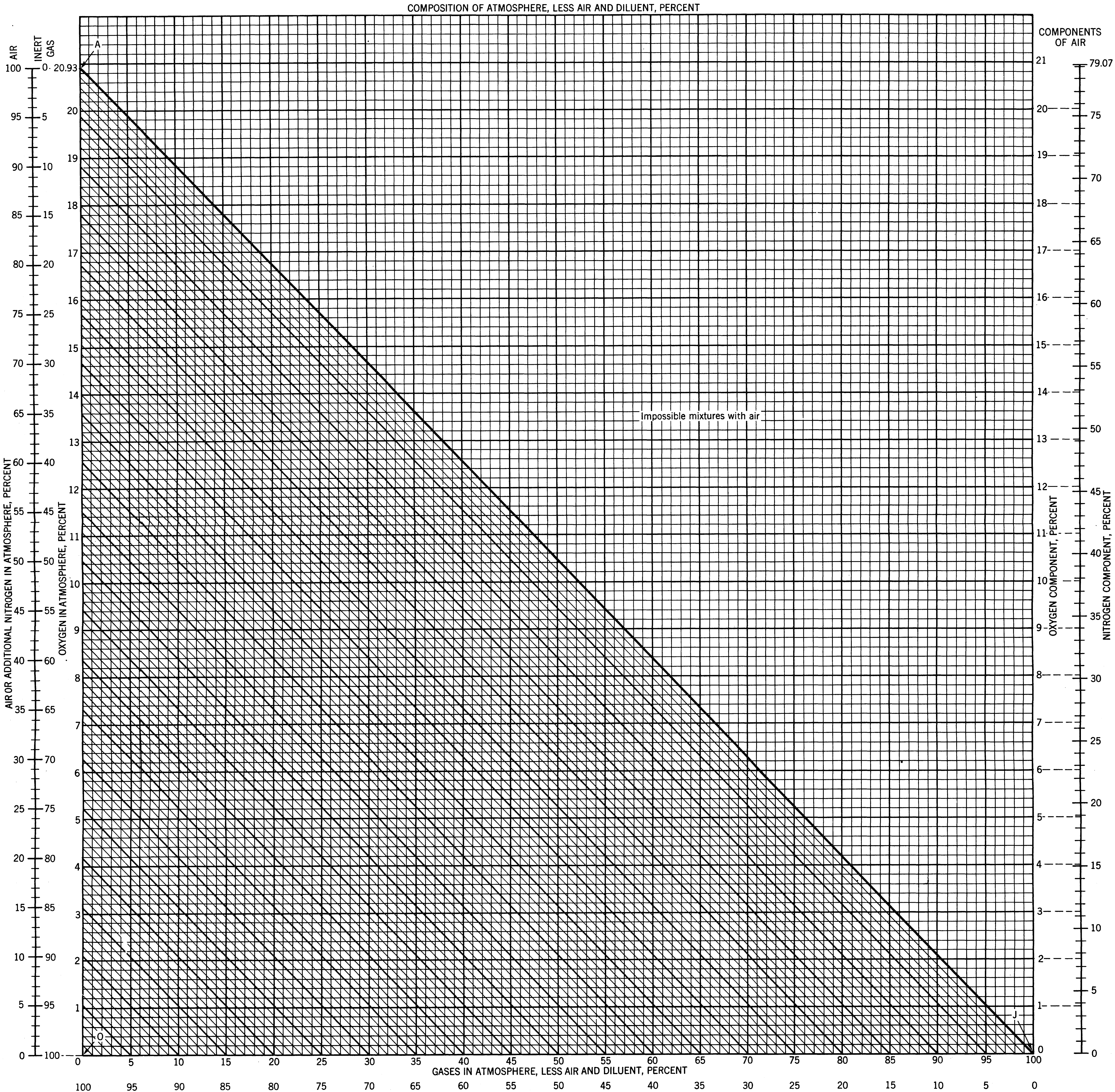

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FIGURE 2.—Relation between various constituents of any possible gaseous mixture composed of a combustible gas or combustible gases, different volumes of carbon dioxide and nitrogen, and air.

COMPOSITION OF ATMOSPHERE, LESS AIR AND DILUENT, PERCENT (GAS PORTION)

CO	0	1.61	3.21	4.82	6.43	8.03	9.64	11.25	12.86	14.46	16.07	17.68	19.28	20.89	22.50	24.11	25.71	27.32	28.93	30.53	32.14
CH_4	0	0.58	1.16	1.73	2.31	2.89	3.47	4.04	4.62	5.20	5.77	6.35	6.93	7.51	8.08	8.66	9.24	9.82	10.39	10.97	11.55
H_2	0	2.20	4.41	6.62	8.82	11.03	13.23	15.44	17.64	19.85	22.06	24.26	26.47	28.67	30.88	33.08	35.29	37.49	39.70	41.91	44.11
C_2H_4	0	0.30	0.59	0.89	1.18	1.48	1.78	2.07	2.37	2.66	2.96	3.26	3.55	3.85	4.14	4.44	4.74	5.03	5.33	5.62	5.92
C_3H_6	0	0.07	0.15	0.22	0.30	0.37	0.44	0.52	0.59	0.67	0.74	0.81	0.89	0.96	1.04	1.11	1.18	1.26	1.33	1.41	1.48
CO_2	0	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	2.00	2.20	2.40	2.60	2.80	3.00	3.20	3.40	3.60	3.80	4.00
N_2	0	0.04	0.08	0.12	0.16	0.20	0.24	0.28	0.32	0.36	0.40	0.44	0.48	0.52	0.56	0.60	0.64	0.68	0.72	0.76	0.80

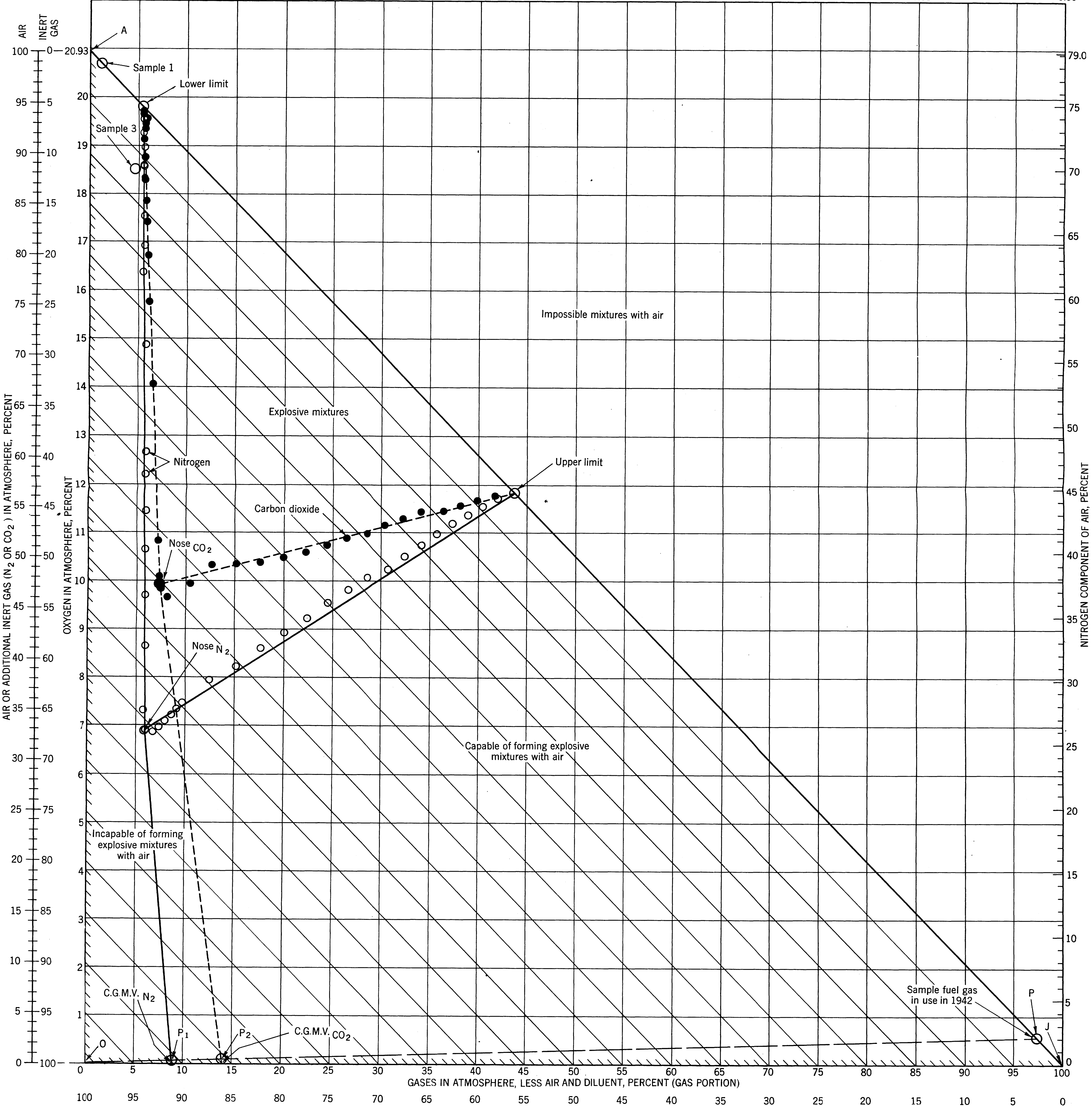

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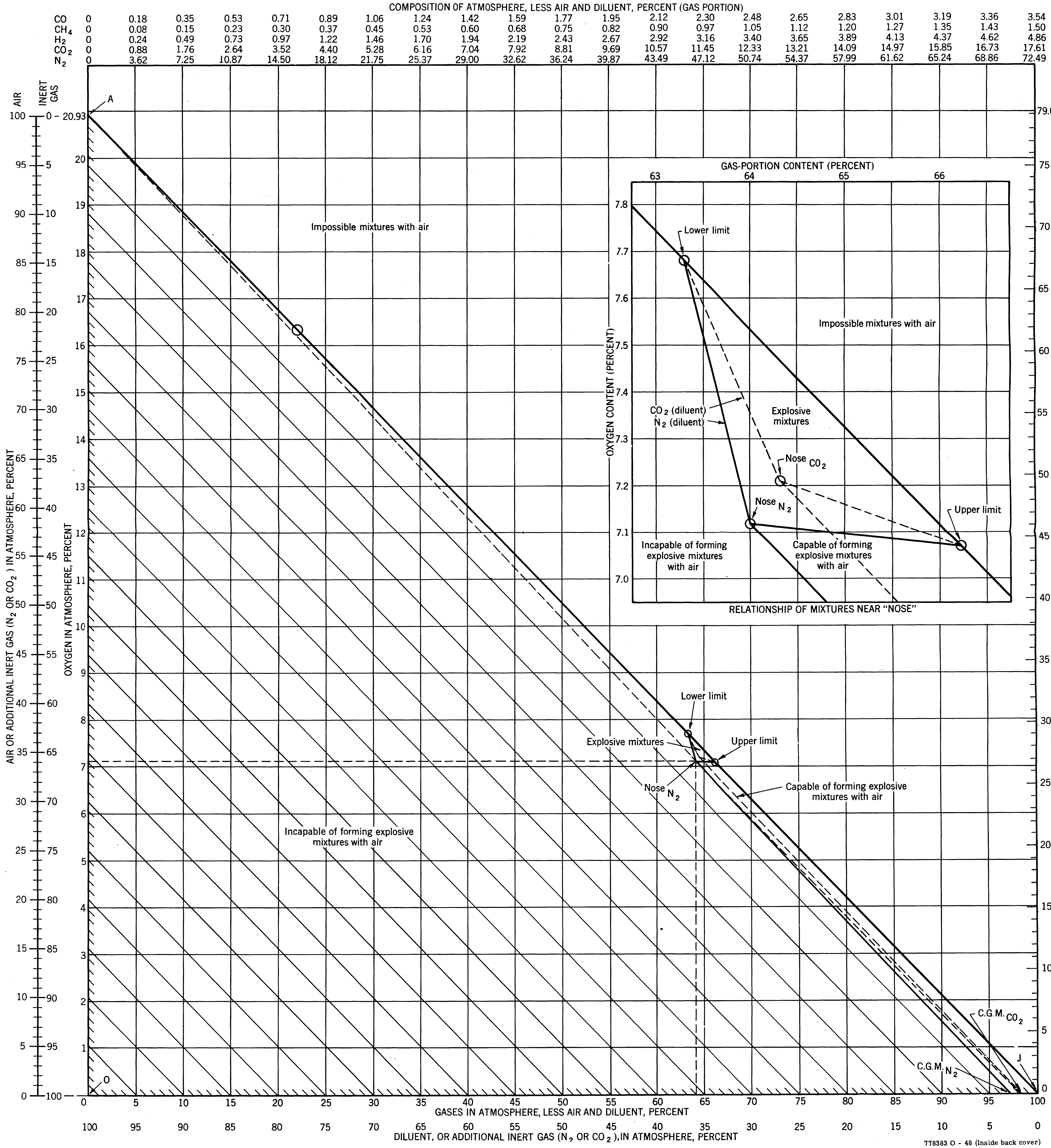
FIGURE 10.—Relation between composition and explosibility of mixtures of a given carbureted water gas, air, and diluent (nitrogen or carbon dioxide).



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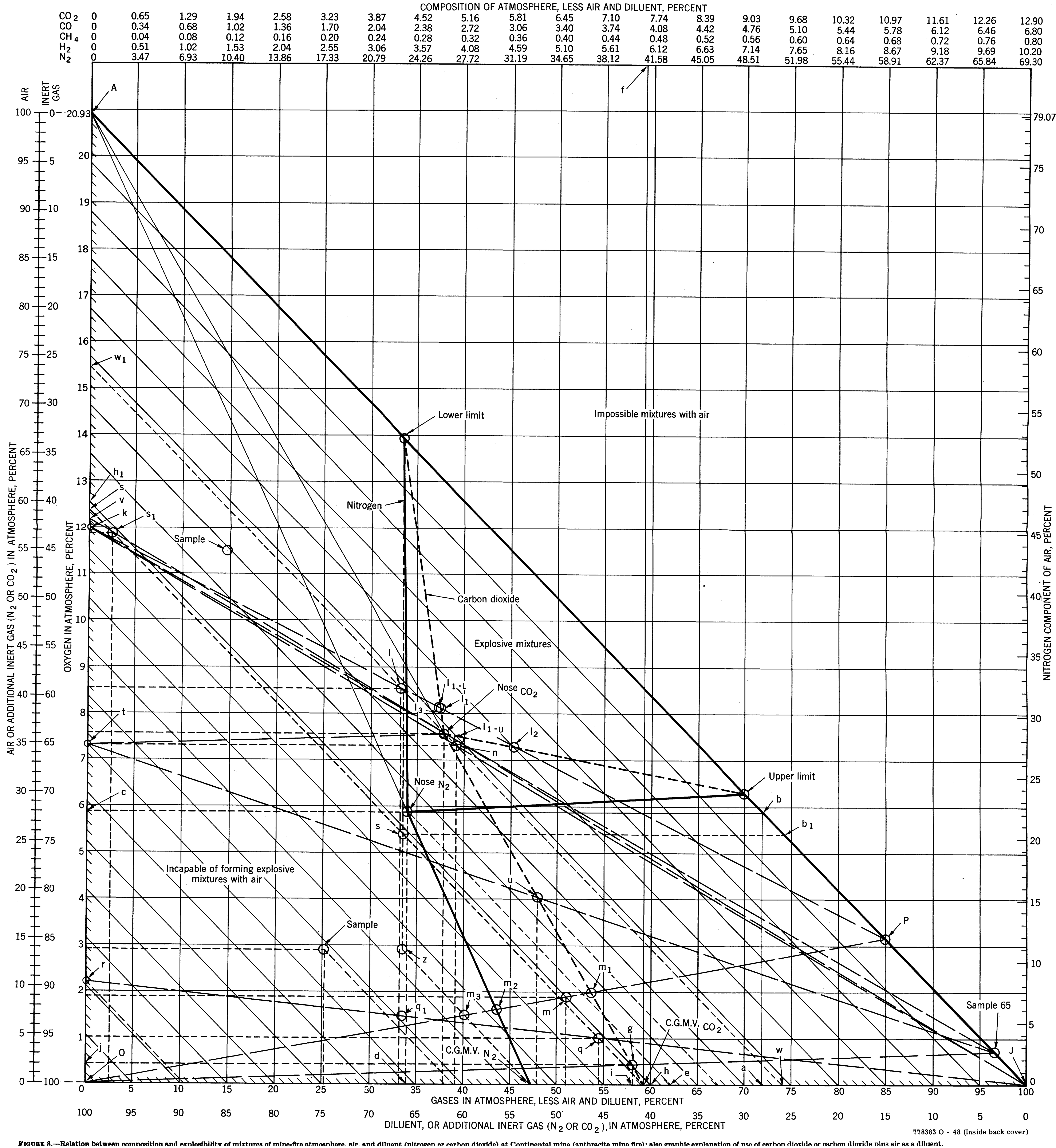

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FIGURE 8.—Relation between composition and explosibility of mixtures of mine-fire atmosphere, air, and diluent (nitrogen or carbon dioxide) at Continental mine (anthracite mine fire); also graphic explanation of use of carbon dioxide or carbon dioxide plus air as a diluent.

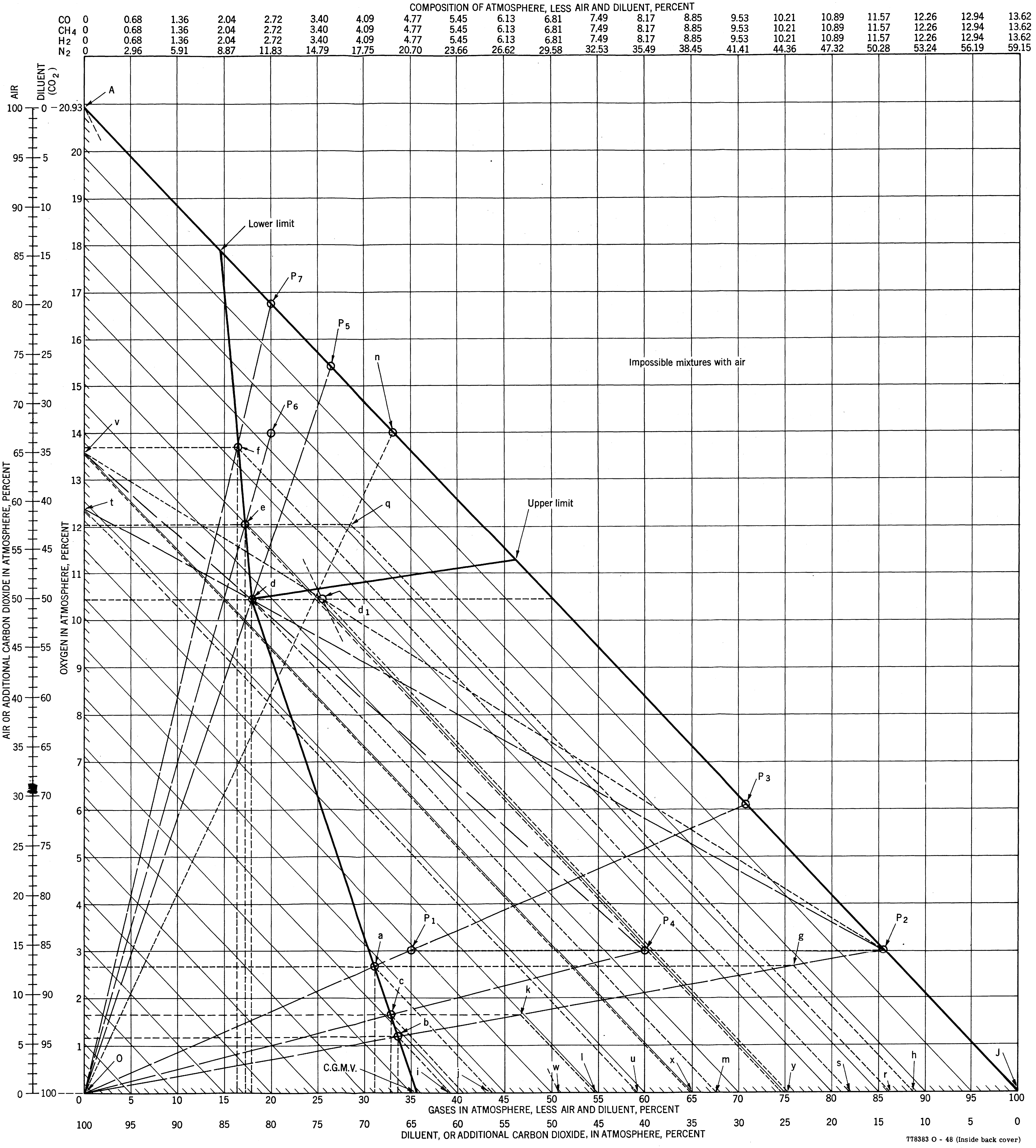

FIGURE 7.—Relation between composition and explosibility of a mixture of nitrogen and equal proportions of carbon monoxide, methane, and hydrogen, in air and carbon dioxide; composition of mixtures formed from given atmospheres by adding minimum volume of carbon dioxide necessary as a diluent to form mixtures incapable of becoming explosive when mixed with air; and minimum volume of carbon dioxide necessary to form such mixtures.

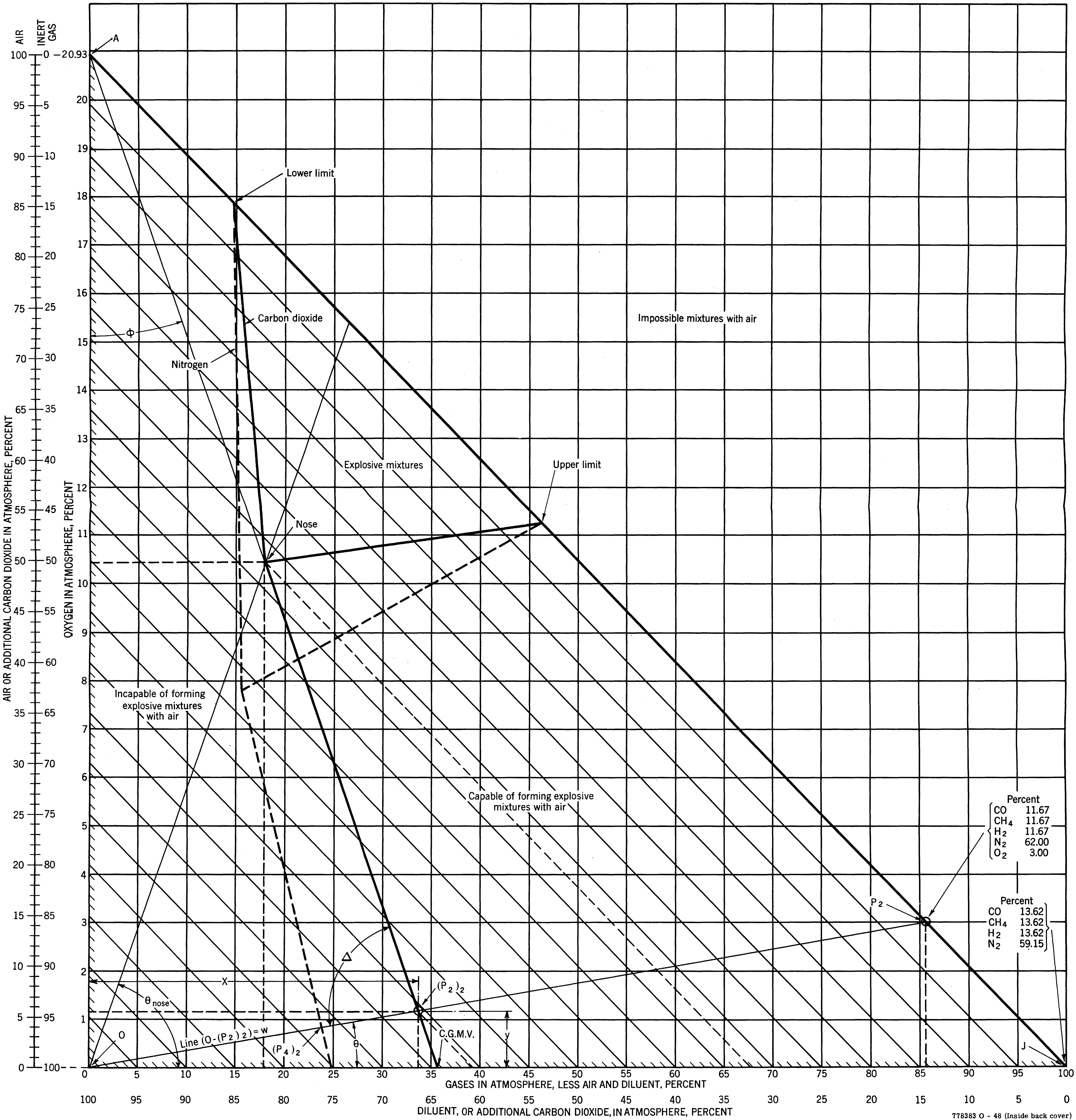

FIGURE 6.—Relation between composition and explosibility of a mixture of nitrogen and equal proportions of carbon monoxide, methane, and hydrogen, in air and carbon dioxide, and mixture formed from an original atmosphere by adding minimum volume of carbon dioxide necessary as a diluent to form a mixture incapable of forming an explosive mixture with air.

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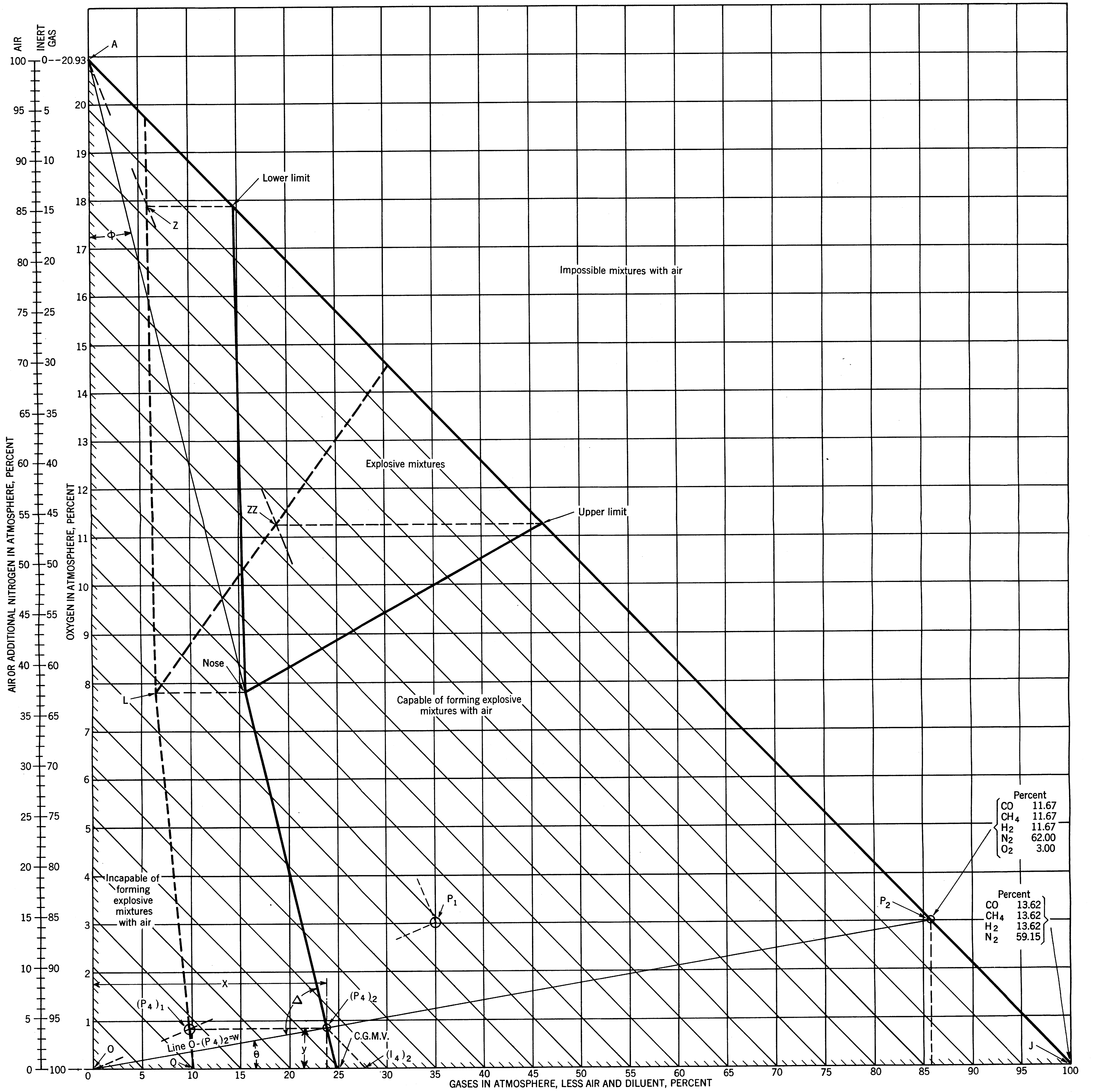

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FIGURE 5.—Relation between composition and explosibility of a mixture of nitrogen and equal proportions of carbon monoxide, methane, and hydrogen, in air and nitrogen, and mixture formed from an original atmosphere by adding the minimum volume of nitrogen necessary as a diluent to form a mixture incapable of forming an explosive mixture with air.

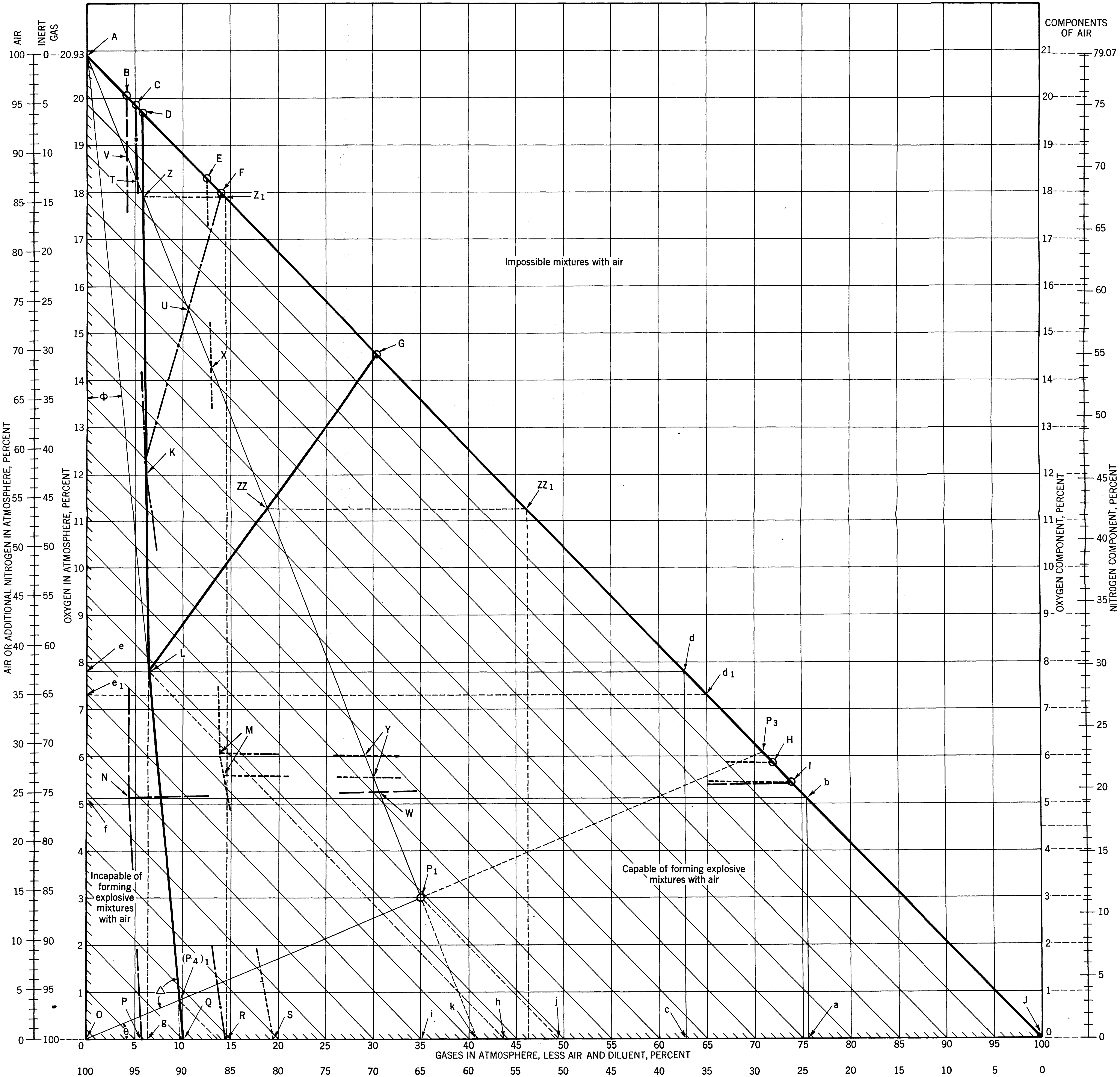

FIGURE 4.—Explanation of figure 3.

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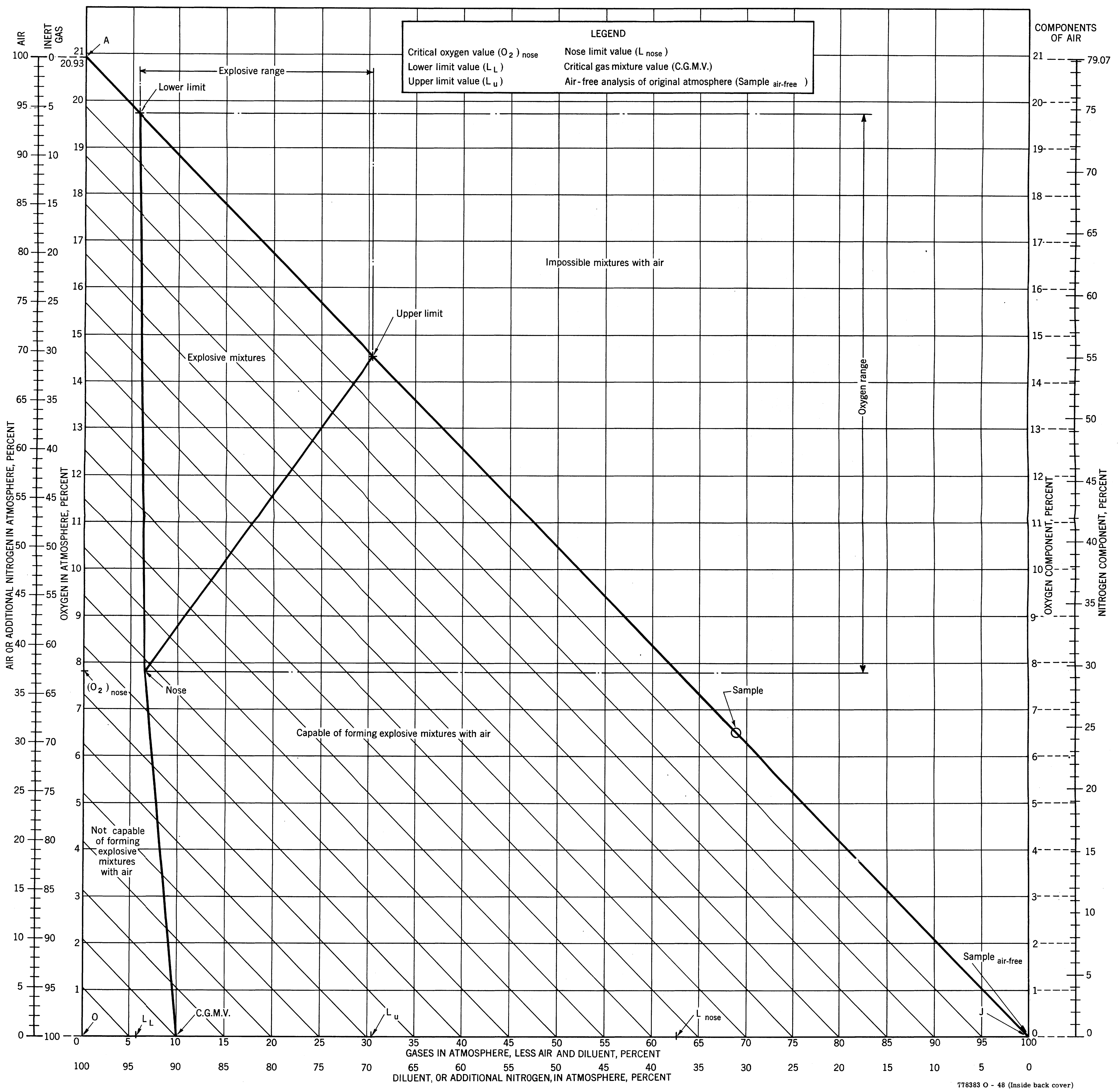

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FIGURE 1.—Relation between factors expressing composition and explosibility of a mixture composed of equal proportions of carbon monoxide, methane, and hydrogen, and nitrogen and air.

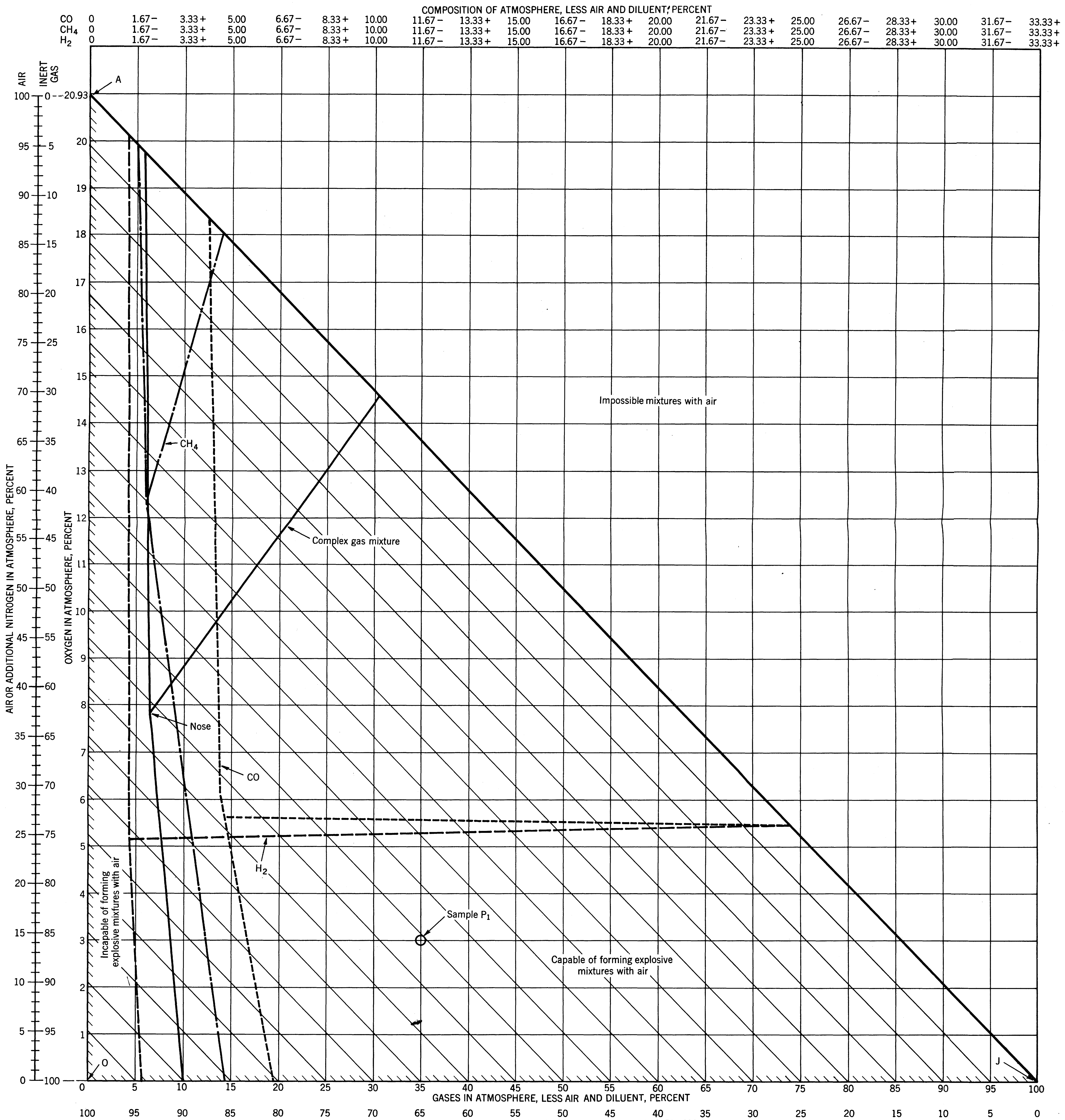

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FIGURE 3.—Relation between composition and explosibility of mixtures of gas mixture, air, and nitrogen when gas mixture contains equal proportiions of methane, carbon monoxide, and hydrogen, or when mixture contains only a single combustible gas—methane, carbon monoxide, or hydrogen.