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STUDY OF MINE FIRE FIGHTING USING INERT GASES

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16. Abstracts A theoretical evaluation was made of the usefulness of fighting coal mine fire with inert gases. A review is made of existing applications that indicate that inert gas methods of fighting mine fires are routine in Czechoslovakia and the U.S.S.R. Details are given of the calculation of inert gas requirements. If sudden ventilation changes can be avoided, the main inerting requirements are to prevent explosion hazards from methane, which is normally liberated in the mine. However, sudden ventilation changes during a fire complicate the inerting requirements owing to possible formation of flammable distillation products. Inert gas methods are considered for the prevention of explosion when fires are fought directly, during construction of seals and for extinction of mine fires. Calculations of the inerting requirements are presented and compared with observed data from actual applications. In some instances, it is believed that the use of inert gas could reduce sealing time requirements by an order of magnitude.

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FORWORD

This report was prepared by Michigan Technological University, College of Engineering, Department of Mining Engineering, Houghton, Michigan, under USBM Contract No. S0231075. The contract was initiated under the Coal Mine Health and Safety Program. It was administered under the technical direction of PMSRC with Dr. R. F. Chaiken acting as the technical project officer. Mr. R. J. Simonich was the contract administrator for the Bureau of Mines.

This report is a summary of the work recently completed as part of this contract during the period June 4, 1973 to December 4, 1974. This report was submitted by the author on October 24, 1974.
This technical report has been reviewed and approved.

It is hereby certified that no inventions have been made on this project.

The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies of the Interior Department's Bureau of Mines or of the U. S. Government.

CONTENTS

SUMMARY

This report contains a theoretical study on the usefulness of fighting mine fires with inert gases.

Four introductory chapters review the role of fires in the mining industry; the conventional fire fighting techniques, the influence of inert gases on the burning of gases and solids, and the well established inert gas fire extinguishing systems for buildings and machinery.

A large chapter describes the use which inert gas has found so far for fighting mine fires in major mining countries. More applications have occurred than generally expected and the inert gas method has in the last years become routine in Czechoslovakia and the USSR. This chapter is based on an evaluation of the extensive literature as well as on personal information obtained from leading experts.

To allow the precalculation of inert gas requirements for preventing the formation of explosive mixtures during fire fighting operations, the production of flammable gases by fires is investigated next. It is found that the explosive danger from these gases is small compared with the danger from methane, which is liberated in the mine. The exceptions are sudden reductions in the oxygen supply of the fire and the subsequent formation of distillation products. If such sudden ventilation changes are avoided, it is possible to base the inert gas requirements in coal mines on the normal evolution of methane.

Inert gases can be utilized for the prevention of gas explosions when fires are fought directly or seals are constructed or closed; for the extinction of fires by lowering the oxygen concentration of their atmospheres; for the effective sealing of fire zones by preventing air leakage. The inert gas requirements for these purposes are calculated in the next chapter. For the determination of extinctive atmospheres the oxygen consumption by combustion and sorption as well as the oxygen dilution by inert gases are taken into account. The calculated inert gas requirements are compared with observed data from actual inert gas applications.

It is then investigated how sealing times can be reduced if heat is extracted from the fire zone by ventilation with inert gases. Ordinarily a fire zone has to remain sealed over a time of 15 to 20 times the length of the active fire period. The calculations of this chapter

show that with the ventilation of sealed fire zones with inert gases the sealing times can be kept in the same order of magnitude as the active fire times. Although these calculations are based on many simplifying assumptions they show, nevertheless, that the ventilation of sealed fire zones with recirculated inert gases might be a promising method.

The mine ventilating system and the released inert gas will influence each other. Several aspects of this interaction are investigated and the obtained results compared with practical observations. These aspects are: reduction of air leakage in sealed fire zones by inert gas injection; mixing of inert gases and mine atmosphere; influence of inert gases on mine ventilating pressures; and the risks of inert gas use underground. It is found that problems, which can arise from this interaction can be overcome without greater difficulties, once they have been recognized.

The available inert gas sources are evaluated next. Design, functioning, and performance of available inert gas generators are described and their fuel consumption and heat development derived. The two most important sources for the supply of the generally needed large quantities of inert gases will be: liquefied nitrogen or carbon dioxide, delivered by tankers to the mine site; large capacity mobile or portable inert gas generators. Both methods are routinely used in the USSR, where delivery rates of 2,800 - 3,500 ft^3/min with tankers and 12,00 ft^3/min with portable underground inert gas generators are reached.

A final chapter tries to compare advantages and disadvantages of inert gas methods with conventional fire fighting methods under conditions prevailing in US coal mines. Since very few such applications have taken place on a larger scale, the records of five fires in one larger company were picked at random and the actual course of the fire was compared with its likely course, if inert gas had been used. The probable advantages and disadvantages found in this comparison together with those recognized in actual inert gas applications are summarized.

The conclusion reached is that inert gas methods will not be able to match direct fire fighting methods in effectiveness and economy. Their ability to cool fires is limited and the needed gas quantities to lower the oxygen concentrations of the atmosphere sufficiently over the required cooling

periods are prohibitively large, unless the fire is sealed or the inert gas is recirculated. Inert gas methods will therefore find their main application when a direct attack of the fire is no longer possible. They can permit the fast and close sealing of fire zones without danger of explosions, the fast buildup and maintenance of fire extinguishing atmospheres in the sealed area and the possible reduction of cooling times with a recirculated, cooled inert atmosphere. Inert gases can support the direct attack on the fire also by providing a nonexplosive atmosphere and clearing the fire site of smoke without fanning the fire.

The main competitor of inert gases will be high expansion (air) foam, which in the U.S. has become the preferred fire fighting method when a direct attack is no longer possible. The main advantages, which inert gases compared with high expansion foam offer, are: explosive atmospheres can be avoided at any phase of the fire fighting operations; no distance limitations exist; blocking of the flow by roof falls is negligible; the application requires less skill; weakened roofs and softened floors are avoided; and air leakage in sealed areas can be reduced or altogether avoided. The disadvantages are: sealing of the fire zone is required even where high expansion foam could be applied without it; the required large quantities of inert gas are, at present, difficult to provide; and inert gas generators will always be bulkier, heavier, and costlier than foam generators.

There is no justification to expect the inert gas method to become the standard method for fighting mine fires. There is however reason to expect its wider use, when sealing operations cannot be avoided and can cause explosion dangers.

I. INTRODUCTION

Although in the past years great efforts have been made to free mines, as far as possible, from fire hazards, approximately 50 large fires happen in U. S. coal mines per year.[149] Unreported smaller fires occur daily. The number of fatal injuries by fires in coal mines over the last years was:[31,32,33,114,115,116]

1968: 4 1969: 0 1970: 1 1971: 2 1972: 9 1973: 0

Several of these involved miners who were engaged in fighting the fires. The statistics for the 8 years between 1952 and 1960[112,113] show that of the 401 fires investigated by the U. S. Bureau of Mines (30 fatalities, 75 injuries) 50% burned longer than one shift and 20% could not be extinguished by direct attack but required sealing. No newer figures could be found in the literature but the ratio most probably will not have changed significantly.

Sealing the fire to extinguish it depends for success on the sealed fire zone becoming filled with inert gases which deprive the fire of oxygen and stop the combustion process. The idea of artificially flooding fires with inert gases obviously presents itself and has been proposed for more than one hundred years. Inert gases in this sense mean all gases which can replace the oxygen and are incombustible themselves. For the various attempts to extinguish fires with inert gases, all degrees of success have been claimed, from complete effectiveness to complete uselessness. The attitude of most mining engineers towards this method is therefore in most countries a rather cautious one.

A major handicap in the successful application of the inert gas method has, in the past, frequently been the limited and costly supply of inert gases. This difficulty seems to have been overcome in several countries with tank-trucks carrying liquid nitrogen to the fire site, or with large capacity portable inert gas generators. To reduce the risks in sealing fire zones and to shorten the time period before reopening the seals, the use of inert gas has become routine in these countries. In view of these recent successes, it seems worthwhile to make a new assessment of the usefulness of the inert gas method for fighting fires in underground mines.

II. FIRE FIGHTING TECHNIQUES IN MINES

A. General Review

For a comparison of the inert gas method with conventional fire fighting techniques, a short review of the latter seems appropriate. Since it will later in this report become obvious that inert gas should only be used in connection with sealing, the procedures followed in the sealing and unsealing of fire zones shall receive a more detailed description.

Fire may be described as a rapid oxidation process with the evolution of heat. The oxidation rate depends on the nature of the combustible material and the oxygen concentration and increases greatly with temperature. If the heat being generated by the oxidation is equal to the heat losses, the combustible material will maintain its oxidation rate and, once ignited, will continue to burn. At the same time, the heat losses to the surrounding have to be large enough to prepare new adjacent material for burning by raising its temperature to a sufficient high level. To extinguish a fire, the rapid oxidation rate has to be decreased. This is mainly done by:[168] cooling, lowering the oxygen concentration, separating the oxygen from the fuel, chemical extinguishment, dilution or removal of the fuel supply, or combinations of these methods. All of them are used to fight mine fires.

Following the classification of the National Fire Protection Association as to fuel type,[168] most mine fires fall into the following three categories: class A-fires, in which the fuel is coal, wood, rubber or other solid material which will burn; class B-fires, in which the fuel is liquid such as oil; and class C-fires, which occur in live electrical equipment during arcing. State and Federal laws require fire fighting equipment working with water rockdust, foam and dry chemicals.

Water, directly applied, is used for class A-fires and class B-fires of high flashpoint oil or grease. It extinguishes fires mainly by cooling. An additional effect is the lowering of the oxygen concentration by the developed steam. The specific and latent heats of water are higher than those of most other extinguishing agents; with the additional advantage of being cheap, abundant, easily distributed, and relatively harmless, it can be considered as the universal agent for fighting fires.[72]

Rock dust is used for class A-, B-, and C-fires. It is mainly effective in smothering them by separating the oxygen from the fuel, but has a cooling effect also. It is therefore suited only when the fires are small or the available rock dust quantities large enough to cover the fire.

Air foams (produced from a foaming agent, water and air) have a threefold action: preventing the air from reaching the fire and thus separating the oxygen from the fuel, producing steam and thus lowering the oxygen concentration at the fire site, and cooling the fire. Apart from being able to extinguish class B-fires, air foams are very well suited to fight class A-fires when the fire has spread beyond the reach of water hoses or fire extinguishers.

Chemical foams (produced from foaming agents and inert gases) prevent air from reaching the fire, dilute the oxygen at the fire site and have a certain cooling effect also, the latter being smaller than that of air foams. They can be used for class A-, B-, and C-fires. Their preferred application in the mining industry is in portable fire extinguishers to fight fires in their incipient stages.

The dry chemicals which are commonly used are monoammonium phosphate (ABC Powder), potassium bicarbonate (Purple K) and sodium bicarbonate (Standard Dry Chemical). They are based on the chemical reaction of the chemical with one of the intermediate products in the combustion process. The formation of CO_2 with its oxygen diluting effects may for the two metal salts support the extinguishing of fires. Besides reacting chemically, ABC Powder forms a glaze of phosphoric anhydride, which coats the combustible materials and separates them from the oxygen. All these dry chemicals can be used for class A-, B-, and C-fires, with ABC Powder for class A-fires and Purple K for class B-fires suited best.

Carbon dioxide fire extinguishers dilute or replace the oxygen. If discharged closely to the fire they have a cooling effect also. They are best suited to fight class B- and C-fires, although they are much less effective than the dry chemical extinguishers (Table 1) and therefore not listed as required fire fighting equipment in the Mandatory Safety Standards, Underground Coal Mines.

Table 1: Comparison of Agent Effectiveness for Equal Sized Extinguishers[72]

Agent	Size	Underwriters' Laboratories Rating
Water	2 1/2 gal	2 A
Standard DC	20 lb	40 B:C
Purple K	20 lb	60 B:C
ABC Powder	20 lb	10 A, 40 B:C
CO_2	15 lb	12 B:C

A-rating: effectiveness on wood fire; preceding number: relative size
B-rating: effectiveness of gasoline fire; preceding number: surface (sq. ft.)
C-rating: discharge on live electrical equipment permissible

Extinguishment of fires by dilution or removal of the fuel supply in mines is only possible in some rare cases. An example is the fire of a methane blower[150] extinguished by draining the gas through adjacent boreholes.

The last resort in fighting mine fires is sealing the fire zone or the whole mine. Sealing tries to interrupt the airflow through the fire zone and, with the consumption of the oxygen and the inflow of strata gases, to lower the oxygen concentration until the fire is extinguished. Ample time (an average of 100 days) has to be allowed for letting the fire zone sufficiently cool down to prevent rekindling or the ignition of flammable gas mixtures, which may have formed in the sealed area.

All the discussed fire fighting techniques have their shortcomings. Experience shows that mine fires, except in their incipient stages, can only be extinguished by large quantities of water, large quantities of air foam or by sealing. Water applied through fire hoses and nozzles has a range of usually less than 40 feet. Since the heat of the fire weakens the roof and lets part of it cave, it is necessary to clear the floor from burning material and to set up timber supports. This, usually, lets the fire extend away from the fire fighters faster than they can follow. Control of the smoke without fanning the fire is also difficult. Since high expansion foam does not carry much water it must be caused to flow through the fire area, which requires experienced fire fighters who understand how foam moves and how to control it. Actually, this should not be too serious a problem since it can be resolved by training under non-fire conditions.

Finally, sealing of underground mines can be hazardous and is always costly.

Miners are therefore still trying to improve their fire fighting techniques. After the successful introduction of foam generators in the fifties, and new, improved dry chemical extinguishers in the sixties, the usefulness of the new generation of halogenated hydrocarbons has been studied[21,134] lately; although, with the result that the toxic reaction products as well as the high costs make their application in mine fires inadvisable. The long and successful history of carbon dioxide extinguishing systems in other industries has over the years led to many attempts to fight mine fires with inert gases. The successes which are presently claimed in several countries for this method, has revived the interest in this method again.

B. Procedures Followed in the Sealing and Unsealing of Mine Fire Zones

The majority of mine fires in accessible workings, when detected early enough, can be fought and extinguished directly. During the direct attack, the ventilation of the fire site is reduced to a minimum; large enough to keep the intake side reasonably free of smoke and fire gases and to prevent flammable gas mixtures from forming, but small enough to avoid unnecessary intensification of the fire.[49] When it becomes obvious that a fire can not be extinguished by fighting it directly or when the accumulation of flammable gas mixtures or other circumstances create dangerous conditions in the neighborhood of the fire, it is necessary to withdraw and to isolate the fire site by sealing. The purpose of sealing is to prevent access of air to the fire and to stifle it in the oxygen deficient atmosphere, which gradually forms in the sealed off area. The atmosphere must be held in this oxygen deficient state until the fire zone has cooled enough to prevent reignition after the seals are opened.

When constructing the seals, the air flow through the fire zone is reduced and after the seals have been completed, interrupted. This can result in explosion hazards caused either by accumulations of methane or of flammable combustion or distillation products. As in the direct fighting of fires it is sound practice to reduce the air flow to avoid unnecessary fanning of the fire, but to maintain a ventilation which is large enough for the prevention of explosive gas mixtures until the seals can be closed. The USBM Miner's Circular 36[49] recommends for gassy sections of mines to erect tight temporary seals but to close the last seals only after all men, except those immediately involved, have

left the mine. Remote or automatic closing is preferred. At least 24 hours should elapse before the mine is entered again. Dougherty[41] states that "while sealing work is in progress, the volume of intake air coursed to and over the fire should be reduced to sufficiency to keep the products of combustion moving away from the fire to the return. In the absence of ventilation controls, fighting or sealing an underground fire is too hazardous to contemplate". He recommends a waiting period of 72 hours after the simultaneous closing of the temporary seals. Only when the gas analysis confirms that an explosion is impossible, work on the permanent seals may be started.

The memorandum on the sealing of underground fires by the British Institution of Mining Engineers[189] states that "wherever there is the possibility of such accumulations near the fire or of migration of firedamp to the seat of the fire, the ventilation should be maintained as nearly as possible at its normal rate, or at least reduced under control only to a still safe rate, during the operation of building the seals". The seals should be of explosion proof construction, closed simultaneously and a waiting period of 24 hours should be observed before approaching them after closing.

The West German Guidelines for Fire Protection Underground[125] demand that the fire zone be ventilated during construction of the seals to avoid explosive gas mixtures. Where such mixtures are possible temporary seals have to be erected, closed simultaneously and a waiting period of 8 hours has to be observed before they may be approached again for taking gas samples. Where no explosion danger exists the intake seals may be closed first. The temporary seals have to be supplemented by permanent seals of explosion proof construction, but work on these may start only when no explosive gas mixtures behind the temporary seals are found.

The earlier expressed opinion[4,146] that sealing the return airways first helps to extinguish the fire due to the backing of CO_2 finds little support nowadays, because of the explosion danger from flammable combustion and distillation products.

Explosions in a sealed off area are prevented when the oxygen is consumed faster and inert gases are produced faster than flammable gases can accumulate. This process is frequently compared to a race between the gases involved[49,146,148] and has been simulated experimentally.[102,103] It has been suggested [106,146,148] that one should let the fire reach a certain intensity before sealing it to guarantee a fast oxygen depletion. Scott [148] calculates the combustion rate

a fire should have before sealing. Another approach is to make the sealed off space the larger, the larger the production of flammable gases is, in order to allow enough time to elapse before an explosive concentration is formed.[49,146,189] This contributes additionally to the safety of the miners constructing the seals by removing them from the fire or the center of a prospective explosion and protects the seals from destruction. Both methods, intense fires and large sealed spaces, make the extinction of the fire more difficult, however, since intense fires require longer cooling periods, and larger spaces provide more oxygen for the fire and are frequently more difficult to keep tight.

The distances between seals and fires are therefore in most cases compromises which take the gas production, ventilation, rock conditions, number of openings to be sealed, haulage system and many other factors into account.[41,49,189] As a rule one tries in metal mines or coal mines without CH_4 evolution in the fire zone, to erect the seals as close as possible to the fire to facilitate a rapid oxygen depletion and fast extinction of the fire.[49,189] In gassy sections of mines the distance from the fire should depend on the gas liberation,[189] although the practice varies.[146] The literature is full of fire descriptions where seals were originally constructed as close as possible to the fire and after destruction by explosions were rebuilt at greater distances. The USBM Miner's Circular 36[49] recommends that in gassy mine sections the seals should be placed as far as possible from the fire (1000 feet or more).

Mines are nowhere allowed to return to production until the fire zones have been sealed permanently with explosion proof seals. As long as explosive gas mixtures exist in the sealed off areas, an opening of the seals is not permitted. If nonexplosive gas mixtures, which in dilution with air can become explosive, exist, the seals can be opened through airlocks,[48,49,125] but a wide margin of safety should be observed. The USBM Miner's Circular 36[49] recommends that, although there is little likelihood of gas explosions at oxygen concentrations of 4% or less, with combinations of different flammable gases the oxygen content should be 2% or less, with CH_4 as the only significant flammable gas, it should be 3% or less before seals are opened.

III. INFLUENCE OF INERT GASES ON THE BURNING OF GASES AND SOLIDS

Combustion processes in mine fires can be divided into

two categories, which follow different physical laws and shall therefore be treated separately: the burning of gaseous combustibles, and the burning of solid combustibles. This division is not based on the original state of aggregation of the combustibles before burning starts. All solid fuels contain substances which decompose and form combustible gases, the volatiles. Volatile contents range between 5% for anthracite, 40% for high volatile C bituminous coal, and 75 - 85% for timber. Only the residual carbon represents a solid and burns as such.

Liquid fuels, burning from an open surface, likewise have for their combustion to evaporate and their burning takes place in the gas phase.

A. Combustion of Gases; Flammability Limits

The combustion of gases usually involves complicated reactions, consisting of many steps.[176] Although several theories for these chain reactions have been developed, it is customary to use experimentally determined overall kinetic equations, which allow the calculation of reaction products yield and liberated heat in narrowly defined ranges.

It is possible to derive the influence of inert admixtures qualitatively by considering the combustion in a simplified way as a bimolecular reaction, in which a combustible A and an oxidizer B react chemically with one another and form the combustion product M under liberation of the heat Q:

$$A + B \rightarrow M + Q$$

If $\bar{a}$, $\bar{b}$, and $\bar{m}$ are the molar concentrations (numbers of moles per unit volume) of A, B, and M, the reaction rate is

$$\frac{d\bar{m}}{d\tau} = k\,\bar{a}\,\bar{b} \qquad \tau = \text{time}$$

where k is called the reaction rate constant. If instead of molar concentrations volume concentrations a, b, and m shall be used, one obtains from the equation of state and the fact that partial pressure ratios in mixtures are equal to volume fractions

$$\bar{a} = \frac{p}{\bar{R}T}\,a \; ; \; \bar{b} = \frac{p}{\bar{R}T}\,b$$

where p is the total gas pressure, T is the absolute temperature and $\bar{R}$ the universal gas constant. Consequently:

$$\frac{d\bar{m}}{d\tau} = k \left(\frac{p}{\bar{R}T}\right)^2 a\, b$$

This indicates that the reaction rate is proportional to the product a*b of the volume concentration and the square of the total pressure p. It is however, not inversely proportional to the square of the temperature, but increases greatly with T, since the reaction rate constant k, according to Arrhenius' theory of molecular activation, follows the equation

$$K = \text{constant} * \exp\left(-\frac{E}{\bar{R}T}\right)$$

E is called the activation energy of the reaction and has usually numerical values of the order of tens of thousands of Btu/lb-mole, which explains the rapid increase of k with T.

Combustion starts through the transition from a slow, almost imperceptible reaction to a rapid reaction. This transition is by most researchers explained by a change in the chemical process in the presence of chain reactions. It can however be explained as caused by the intensification of the reaction due to thermal stimulation also.[86] When the heat generation of the reaction exceeds the heat necessary to maintain the temperature, at which this heat generation takes place, gas temperature and reaction rate rise rapidly and this leads to the phenomenon of combustion.

The lowest temperature at which heat is generated faster than heat is lost to the surroundings, is called the ignition temperature. Below this temperature the gas mixture will not burn without a heat supply. Since the rate of heat generation is proportional to the reaction rate and the latter proportional to the product of the volume concentrations of the reactants, this product must not be below certain values, expressed by the limits of flammability, if the gas mixture shall ignite and once ignited continue to burn, without external heat supply. The lower limit of flammability indicates the lowest volume concentration of the combustible in the mixture, the upper limit the highest volume concentration.

Since heat generation and heat losses depend on many different factors, like - concentrations, pressures, temperature gradients, heat capacities, heat conductivities, flow conditions, size and wall properties of reaction volume spaces - ignition temperatures and limits of flammability are no fixed properties for a mixture of a combustible and an oxidizer. If numerical values have been determined, they are valid only for the conditions under which they were determined.

Since limits of flammability are of great practical importance in the technical combustion of gases and in safety considerations, ample experimental data exist for them.[36,193] Most have been determined under the condition of forced ignition, when ignition occurs only within a small portion of the gas whereas the rest remains cold. Table 2[176] gives an example of the flammability limits of methane, hydrogen, carbon monoxide, and ethylene in mixture with air and of the variation of these limits with initial gas temperatures.

Table 2 shows that an increase in temperature widens the range of flammability, as can be expected from the fact that less heat is needed to raise the temperature of the gas mixture to the ignition temperature. A variation in pressure has the same influence, as can be expected from the increase in reaction rate with pressure, although the influence on the lower limit is small.[78] With the small pressure changes encountered in mine ventilation systems, the effect of initial pressures on flammability limits can be neglected.

Inert admixtures exert several influences in a flammable gas mixture. They lower the reaction rate by lowering the concentrations of combustible and oxidizer, absorb heat due to their own heat capacity and change the heat conductivity within the gas mixture. Changed diffusion constants can have an influence also. Lowering the concentrations and absorbing heat narrows the flammability range. Increasing the heat conductivity can widen it since the propagation of flames is supported - can narrow it since the heat transfer to the walls is increased. Which influence prevails, depends on the geometry and the volume of the space filled with the gas mixture. The difference in values obtained for the upper limits can be considerable,[109] for the lower limit it seems to be less significant.

The different effects of inert admixtures upon lower and upper limits may be explained in the following way.[86] At the lower limit the combustible gas is completely consumed by the reaction, and the amount of combustible gas which is present determines the quantity of generated heat. The excess air, which does not take part in the reaction, plays the role of an essentially inert admixture. Replacing this excess air with a different inert gas has, therefore, no influence on the heat generation and only a minor influence on the burning properties of the mixture. At the upper limit exists an excess of combustible gas, and the amount of oxygen which is present determines the heat generation. Replacing this oxygen by an inert admixture will have a large effect.

Table 2: Variation of Flammability Limits with Initial Gas Temperature[176]

Initial Gas Temperature (°F)	Fuel in Mixture with Air (%) Methane	Hydrogen	Carbon Monoxide	Ethylene
63	6.3 -12.9	9.4-71.5	16.3-70.0	3.45-13.7
212	5.95-13.7	8.8-73.5	14.8-71.5	3.20-14.1
392	5.50-14.6	7.9-76.0	13.5-73.0	2.95-14.9
572	5.10-15.5	7.1-79.0	12.4-75.0	2.75-17.9
752	4.80-16.6	6.3-81.5	11.4-77.5	2.50-...

Conditions: vertical tube, downward flame propagation, atmospheric pressure

Table 3: Zero Pressure Molar Specific Heats at 80°F[177]

Gas	C_p (Btu/lb-mole °F)
Carbon Dioxide	8.93
Steam	8.02
Nitrogen	6.95
Helium	5.00
Argon	5.00
Air	6.95

Table 4: Volume of Inert Gas Required for the Extinction of Hydrogen, Methane, and Carbon Monoxide Flames[76]

Combustible Gas	Added Inert Gas	Vol. Ratio Inert Gas / Comb. Gas	Concentrations at Extinction Point (% Vol.) Comb. Gas	Oxygen
Hydrogen	Nitrogen	16.55	4.3	5.1
	Carbon Dioxide	10.20	5.3	8.4
Methane	Nitrogen	6.00	6.1	12.1
	Carbon Dioxide	3.20	7.3	14.6
Carbon Monoxide	Nitrogen	4.12	13.9	6.0
	Carbon Dioxide	2.16	18.6	8.6

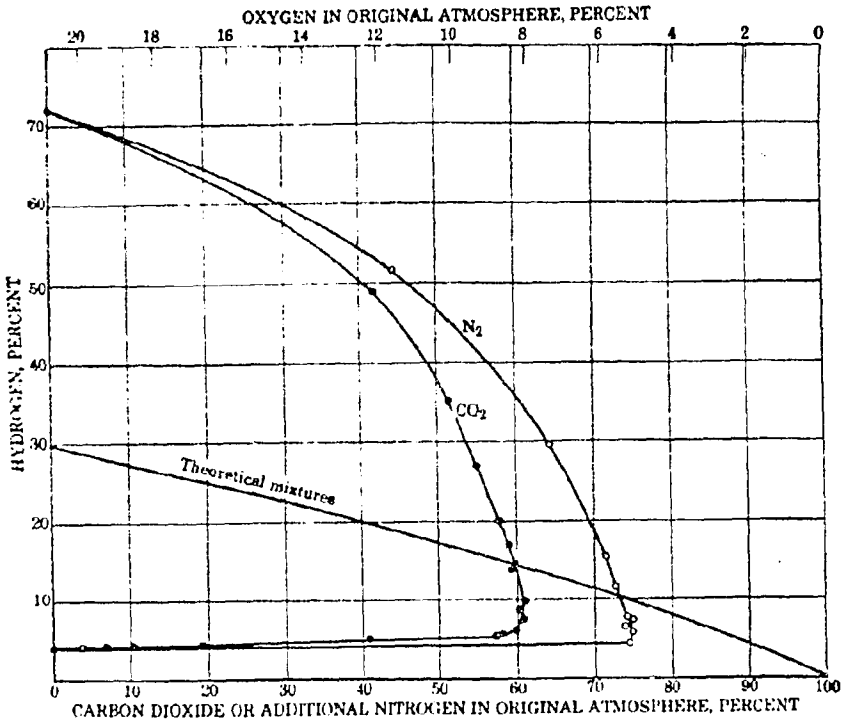


Fig. 1: Limits of Flammability of hydrogen in air and carbon dioxide or nitrogen.[36]

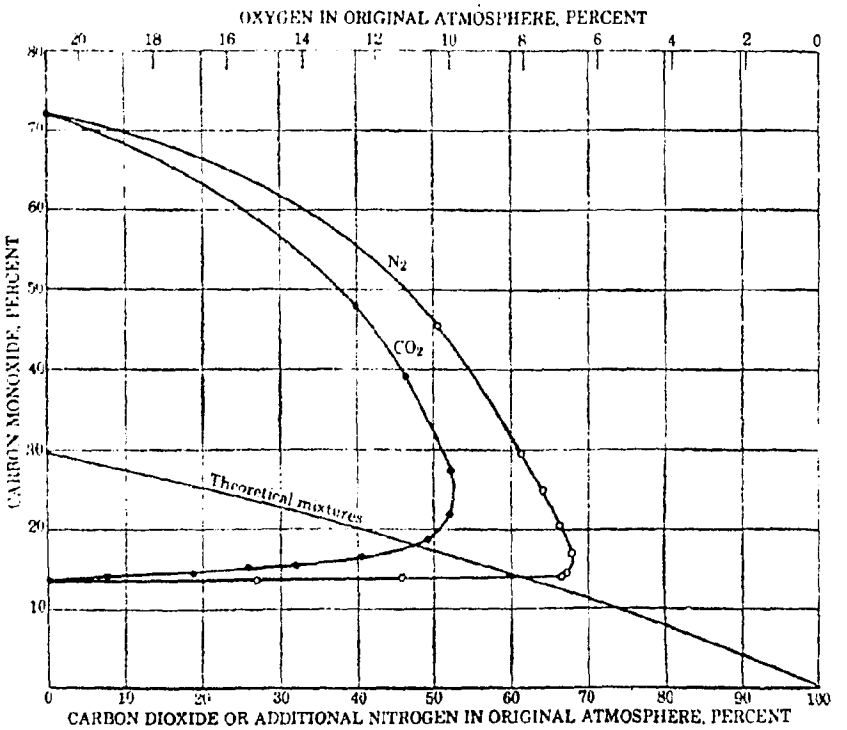


Fig. 2: Limits of flammability of carbon monoxide in air and carbon dioxide or nitrogen.[36]

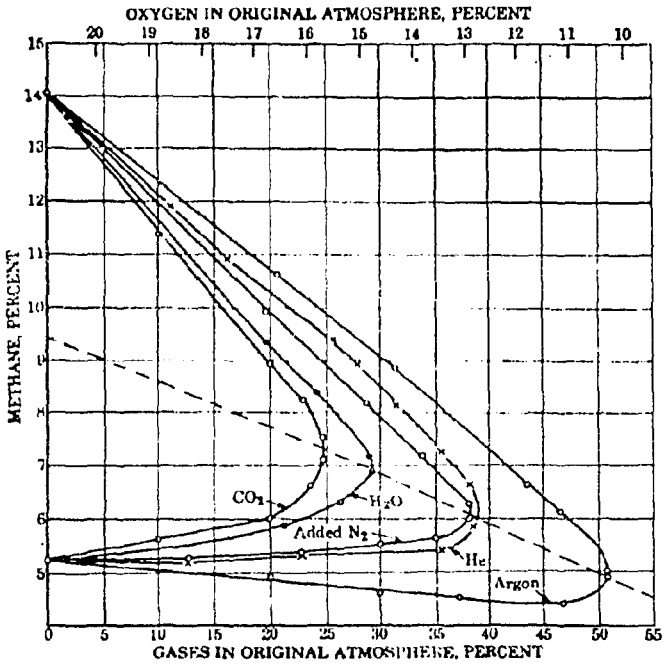


Fig. 3: Limits of flammability of methane in separate mixtures of air with carbon dioxide, water vapor, nitrogen, helium, and argon.[36]

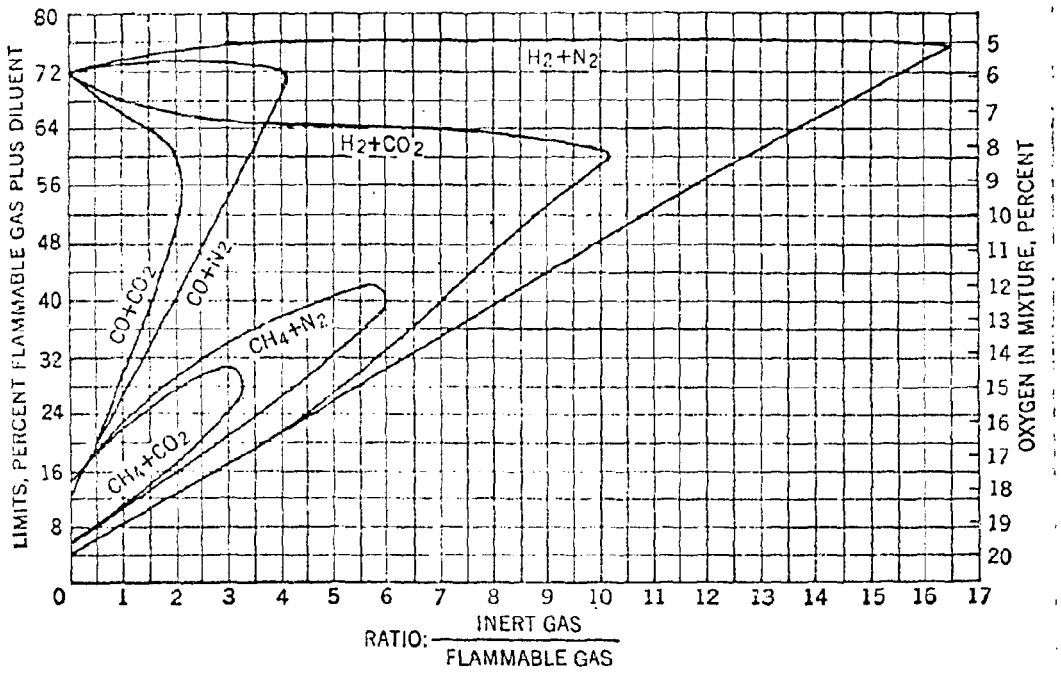


Fig. 4: Limits of flammability of hydrogen, carbon monoxide, and methane containing various amounts of carbon dioxide and nitrogen.[36]

Figure 3 shows a comparison of the effectiveness of CO_2, H_2O, N_2, He, and A, obtained in a tube of 5 inches diameter. This tube diameter is large enough to let the heat conductivity support the flame propagation and widen the flammability range. Since the heat capacity narrows it, it has been suggested that the amount of inert admixture - necessary for the same phlegmatizing effect - must be proportional to the ratio heat conductivity λ divided by the constant pressure specific heat c_p. These ratios λ/c_p have for CO_2, N_2, He, and A relative values of 15, 23, 27, and 33. Other authors [168] make the effectiveness of inert admixtures proportional to their constant pressure molar specific heats C_p, which for the diluents of Fig. 3 are listed in Table 3. One sees that both opinions are supported by Fig. 3.

There is in all reported test results general agreement about the order CO_2, N_2, and A with respect to their phlegmatizing effectiveness. The position of He changes, [36,109] most probably because He has thermal conductivities, specific heats and diffusion coefficients so much different from those of the other inert admixtures that the type of experiment has a large bearing on the results.

The flammability limits of complex gases, which are mixtures of several flammable gases, can be derived with the help of Le Chatelier's rule. This rule is based on the assumption that the individual flammable constituents do not react with one another nor do have any catalytic influence upon each other. Mixtures of complex gases with other noncombustible gases can then be considered as systems comprising simple mixtures, formed by one flammable constituent with a fraction of the remaining nonflammable gases. When each one of the so dissected simple mixtures is at its lower or upper flammability limit, the total mixture will be at its lower or upper flammability limit also.

For mixtures of complex gases with air, the lower and upper limits of the mixture can be determined as follows. If N_1, N_2, ..., N_n are the flammability limits of the individual constituents and p_1, p_2, ..., p_n are their volume percentages in the complex gas, the flammability limits L of the complex gas will be

$$L = \frac{100}{\frac{p_1}{N_1} + \frac{p_2}{N_2} + \ldots + \frac{p_n}{N_n}}$$

It has been shown experimentally [36,76] that this formula shows sufficient accuracy for mixtures of hydrogen, carbon monoxide, and methane and many other, although not all gases.

For mixtures of complex gases with air and inert diluents the influence of the ratio inert gas:flammable gas on the flammability limits has to be taken into account. Figure 4 [36] shows these limits for hydrogen, carbon monoxide and methane diluted with nitrogen or carbon dioxide when mixed with air. The upper and lower limits of mixtures of complex gases with inert gases in mixture with air can then be determined as follows. [36,76,176] The mixture of the complex gas with the inert gases is dissected into simpler mixtures, each of which contains only one flammable gas and one inert gas. The flammability limits N of these simpler mixtures are determined from tables or graphs like Fig. 4. If p_1 are the volume percentages of the dissected mixtures, the flammability limits L of the total mixture of complex and inert gases when mixed with air can again be calculated from

$$L = \frac{100}{\frac{p_1}{N_1} + \frac{p_2}{N_2} + \ldots\ldots + \frac{p_n}{N_n}}$$

It has been shown [36,76] that this procedure shows sufficient accuracy for mixtures of hydrogen, carbon monoxide and methane with air, nitrogen, and carbon dioxide and can therefore be used for mine fire gases.

From curves like those in Fig. 4 or the experimental results on which they are based, [76] one can determine the minimum volume of inert diluent that must be mixed with a combustible gas in order to assure that none of its possible mixtures with air is flammable. These volumes, together with the concentrations of combustible gas and oxygen at the extinction or nose point - the point where lower and upper flammability limit meet - are contained in Table 4. [76]

There exists an abundance of literature on the flammability of gas mixture which can be encountered in mine fires. For a fast determination if such mixtures are flammable or if they can become flammable when diluted with air or if flammable mixtures can form when the ventilation is reduced, a great variety of diagrams have been developed in almost all mining countries. A large number of them are found in the English literature. [2,3,35,36,67,71,76,151,189,192]

One type of these diagrams, suggested by Zabetakis, Stahl, and Watson[192,193] is later in this report used to visualize the changes which the composition and the flammability of fire gases experience when mixed with air and inert gases. It shall, therefore, be described more in detail.

Figure 5 shows as an example an explosibility diagram for methane-nitrogen-air mixtures.[192] It contains three distinguished regions of gas composition. A: mixtures, which are already explosive in their present state. B: mixtures, that will become explosive when mixed with air. And C: mixtures, that will not become explosive when air is added. The remaining area (D), the triangle between the ordinate, the lower flammability curve and the diagonal inerting boundary indicates mixtures of methane and nitrogen, which upon less dilution with air would become explosive.

If to a gas mixture of a given composition, indicated by the composition point, methane, nitrogen, or air are added, the composition shifts towards the 100% methane-, 100% nitrogen-, or 100% air-concentration points, respectively. If mixtures of these gases are added, the new composition can be found by considering this addition as a sequence of admixtures of the individual constituents of the addition.

Similar diagrams, like Fig. 5, can be plotted for mixtures of combustible gases mixed with mixtures of inert gases and with air. Flammability limits and inerting boundaries can without difficulty be determined with the help of Le Chatelier's rule.

B. Combustion of Solids; Minimum Oxygen Concentrations for Support of Combustion

The basis of almost all types of solid fuels is carbon. The combustion of these fuels is a very complex process which can be considered in two stages: combustion through volatilization, and combustion of the solid carbon residue through surface oxidation. The former is a reaction in the gaseous phase, the latter is a reaction between a solid and a gas. Burning of the solid carbon can be considered as a sequence of two different processes:

a) the chemical reaction of the carbon at the surface of the solid with the gaseous oxygen,

b) the transfer of oxygen from the gas surrounding the carbon to the place of its consumption.

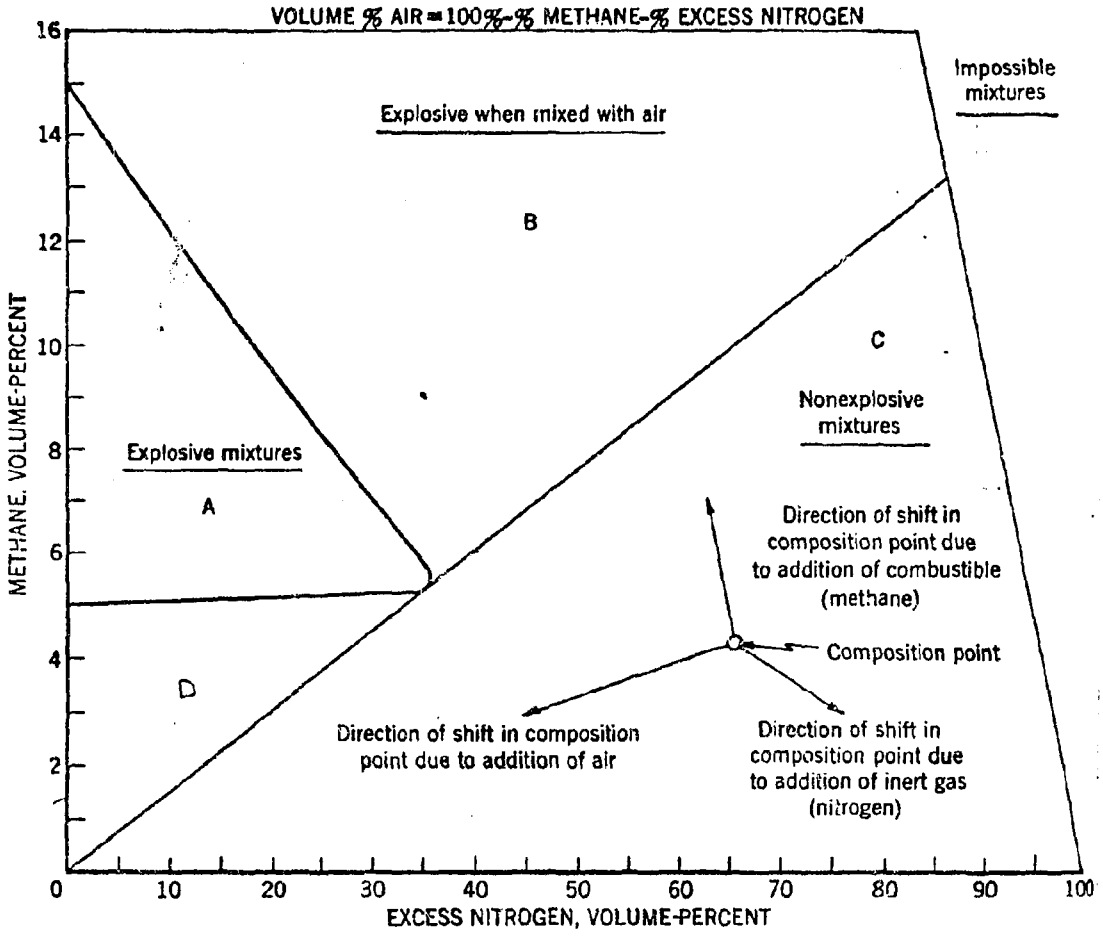


Fig. 5: Explosibility Diagram for Methane-Nitrogen-Air Mixtures at 80°F. and Atmospheric Pressure.[192]

The chemical reaction proceeds according to the formula

$$xC + yO_2 = mCO + nCO_2$$

and is accompanied by the secondary reaction

$$2CO + O_2 = 2CO_2$$

when the ignition temperature of CO is exceeded. When the temperature of the carbon is sufficiently high and the oxygen concentration low, another secondary reaction proceeds:

$$C + CO_2 = 2CO$$

Unlike the reaction of gases where the concentration of all reactants influence the reaction rate, the oxygen concentration is the overriding determining factor in the combustion of solid carbon. This is because the carbon is always present in great excess in the reaction area. Experiments have shown that the reaction rate per unit surface area is well described by an equation of the form[86]

$$w = \frac{k\,c}{A+c} \quad \left(\frac{ft^3}{ft^2 sec}\right)$$

where k = reaction rate constant $\left(\frac{ft^3}{ft^2 sec}\right)$

A = characteristic constant

c = O_2 concentration $\left(\frac{ft^3}{ft^3}\right)$

When the O_2 concentration is small ($c \ll A$), as happens close to the reaction surface, this equation can be written as

$$\dot{w} = \frac{k\,c}{A} = \alpha c$$

α = effective reaction rate constant ($ft^3/ft^2 sec$)

α can be regarded as a scale of the reactive properties of the solid carbon under consideration. It takes the chemical properties as well as physical properties, like an increased reaction surface due to porosity, into account. Since heterogeneous reaction between gases and solids follow Arrhenius' theory in the same way as homogeneous reactions between gases, α increases very rapidly with temperature.

The transport of oxygen to, and the transport of reaction products from the reaction surface, takes place by means of diffusion. The transport rate depends on diffusion constants of the gases involved, and in the case of moving gases, on the hydrodynamic state of the gases at the surface. The ash content of the solid coal may have an influence also. It has become customary to describe the rate of gas transport by diffusion per unit surface area analogous to heat transfer by the equation

$\dot{q} = \alpha_{dif} (c_a - c_s)$ $\quad \alpha_{dif}$ = diffusion coefficient $(\frac{ft^3}{ft^2 sec})$

$(\frac{ft^3}{ft^2} sec)$ $\quad c_a$ = concentration in general body of gas

c_s = concentration at reacting surface

α_{dif} is, like its thermal analogue the heat transfer coefficient α_{th}, a very complex quantity. For rough calculations one can, due to the analogy between mass and heat transfer, derive α_{dif} from Lewis' law

$$\alpha_{dif} = \alpha_{th}/\rho c_p$$

ρ = density of gas

c_p = specific heat of gas

In an equilibrium state the rate of oxygen consumption

$$\dot{w} = \alpha c_s$$

is equal to the rate of oxygen supply

$$\dot{q} = \alpha_{dif} (c_a - c_s)$$

From $\dot{w} = \dot{q}$ and by combining the two equations, one obtains

$$\dot{q} = \frac{1}{\frac{1}{\alpha} + \frac{1}{\alpha_{dif}}} \quad c_a = \alpha^* c_a \qquad (\frac{ft^3}{ft^2 sec})$$

The amount of carbon oxidized $\dot{g}$ corresponds to the amount of oxygen consumed. If the ratio of both, the stoichometric factor is called β, one obtains from

$$\beta = \dot{g}/\dot{q}$$

the rate of carbon oxidized per unit surface area

$$\dot{g} = \beta \frac{1}{\frac{1}{\alpha} + \frac{1}{\alpha_{dif}}} \quad c_a \qquad (\frac{ft^3}{ft^2 sec})$$

Although derived under simplifying assumptions, this equation expresses the fundamental properties of the oxidation process of coke comparatively well. Its rate is described as depending both on purely chemical reaction properties and on the factors determining the oxygen supply to the surface of the coal. When the temperatures are low, the effective reaction rate constant is small and $\frac{1}{\alpha} >> \frac{1}{\alpha_{dif}}$. In this

case the process is mainly controlled by the rate of the chemical reaction and can be described by

$$\dot{g} \approx \beta \alpha c_a \qquad \text{"quasikinetic range"}$$

For high temperatures, $\frac{1}{\alpha} << \frac{1}{\alpha_{dif}}$ and the process is mainly controlled by the diffusive resistance the oxygen supply encounters. It is practically independent of the reactive properties of the coal and can be described by

$$\dot{g} \approx \beta \alpha_{dif} c_a \qquad \text{"diffusion range"}$$

Between these two limiting cases exists a transition region where α and α_{dif} are both of essential importance.

For the ignition of coal, it is necessary as for the ignition of gases, to reach a certain temperature at which the heat generation of the oxidation process is larger than the heat losses to the surrounding.

Accurate calculations have to take into account that surface temperatures and gas concentrations are interdependent and show considerable local variations. A great amount of theoretical and experimental work has gone into exact descriptions of the burning process of spherical particles and circular channels.[52,86] Burning channels, which resemble fuel rich fires in mine workings (see chapter VI B.), are distinguished by the formation of two consecutive zones, an oxygen zone and a reduction zone. In the former, a rapid consumption of the oxygen is observed and the combustion products are mainly CO_2; in the latter, a progressive reduction of CO_2 to CO takes place. Since these zones are separated in space, they can for approximative calculations be considered separately. Although exact solutions for the channel burning of solid carbon exist[86,159] which take all chemical reactions simultaneously into account, they are little suited for practical purposes.

A simple approximation for the change of the oxygen concentration along a channel can be obtained under the assumption of a steady state process, constant O_2 concentrations c_a across every cross section except for the boundary layer, where it drops from c_a to c_s, and constant wall temperatures. For a channel with the perimeter P, the cross sectional area A, and an airflow velocity $\bar{V}$ the rate of oxygen consumption over a length dL is

$$d\dot{Q} = \dot{q} \, P \, dl = \alpha^* c_a \, P \, dL \qquad \left(\frac{ft^3}{sec}\right)$$

This changes the oxygen concentration of the gas flow through the channel by

$$- dc_a = \frac{d\dot{Q}}{\bar{V} A}$$

From

$$- \frac{dc_a}{c_a} = \frac{P}{A \bar{V}} \alpha^* dL$$

one obtains with $c_a = c_o$ for $L = 0$

$$c_a = c_o \exp(- \frac{P}{A \bar{V}} \alpha^* L) = c_o \exp(- \frac{P}{A \bar{V}} \frac{1}{\frac{1}{\alpha} + \frac{1}{\alpha_{dif}}} L)$$

This can for low temperatures ($\frac{1}{\alpha} >> \frac{1}{\alpha_{dif}}$, quasikinetic range) furthermore be simplified to

$$c_a = c_o \exp(- \frac{P}{A \bar{V}} \alpha L)$$

and for high temperatures ($\frac{1}{\alpha} << \frac{1}{\alpha_{dif}}$, diffusion range) to

$$c_a = c_o \exp(- \frac{P}{A \bar{V}} \alpha_{dif} L)$$

For turbulent flow, α_{dif} can be approximated by[86]

$$\alpha_{dif} \approx \bar{V} \, 18 * 10^{-3} \, N_R^{-0.16} \qquad \text{for Reynolds' numbers } N_R = 10^4 - 10^5$$

$$\alpha_{dif} \approx \bar{V} \, 2.2 * 10^{-3} \qquad \text{for } N_R > 10^5$$

Admixture of inert gases to the gas stream flowing over the burning solid surface has the effect of reducing the oxygen concentration, which reduces the rate of carbon oxidation and consequently the rate of heat generation. How high the oxygen concentrations are which can no longer support combustion, depends on the factors determining the rate of carbon oxidation and on the heat transfer from the burning surfaces. Theoretical calculations and experiments have been performed for solid particles[86,119,120] in gases of different temperatures. Their results are important for dust ignitions but are not directly applicable to ordinary mine fires. The ASTM oxygen index flammability test[70] bears too little resemblance with burning conditions in mines also, to give useful results. One has, therefore, to rely on observations in real mine fires. For the sake of completeness, observations on flaming combustion - which is

actually a reaction in the gaseous phase - shall be quoted, also.

In the discussion of a paper by Spencer[154] it is maintained that gob fires were kept alive by O_2 concentrations of 1.31%. Walsh[181] recommends that the O_2 content of inert gases should not exceed 4 - 5%. Rice and colleagues[139] state that active flaming stops below 12 - 15%, combustion below 5 - 6% oxygen.

Mason and Tideswell[102] conclude from their experiments that at oxygen concentrations of 5% dying fire may be maintained or it may develop further activity. "Under the good conditions of heat insulation that occur underground the continued presence of only 1 or 2% of oxygen in the atmosphere of a sealed off waste might maintain a heating indefinitely".

Willett and coauthors[189] state that "flaming combustion normally ceases when the oxygen content in the surrounding atmosphere is reduced below 12%, but this dying out of open flames is only the first stage in extinguishing of the fire. Atmospheres of much lower oxygen content may suffice to maintain incandescence of solid combustible material, whilst slow smouldering may persist at very low oxygen percentages".

Kukuczka[91] is of the opinion that below 5% down to 3% the combustible material stops to smoulder. Below 3% the combustion process stops completely and after extraction of the heat developed during the fire period, the fire is extinguished. Krotkiewski states[90] that any combustion process is arrested when the oxygen content drops to 3%. Ratuskov and coauthors[138] write that after a reduction of the oxygen content to 3 - 5% combustion and smouldering come to an end. Hajek[60] states that the oxygen content has to be lowered to 3% to extinguish fires.

Stark[156] found in large scale tests that flaming combustion of wood and liquid fuels could be extinguished with inert gases containing 12% oxygen, but that smouldering combustion continued. Superficial smouldering is extinguished at 8 - 10%. Extinction of the fires could only be accomplished with certainty by the use of gas containing less than 2 - 5% oxygen, and by leaving the fire zone filled with this gas for very long periods. For atmospheres of oxygen and nitrogen with up to 20% water vapor, Stark characterizes the effect of reduced oxygen contents on combustion as compiled in Table 5.[157] For dry gas the oxygen content would be slightly lower. Other authors put the limit of flaming combustion at 5 - 12% O_2,[91] 10% O_2,[103] 12 - 14% O_2,[16] > 12.5% O_2.[136]

Table 5: Effect of Reduced Oxygen Concentrations on Combustion[157]

O_2 Concentration (%)	Nature of Combustion
21	Normal burning or smouldering
* 17	Rate or burning and flame spread reduced by about 50%
* 16	Wick lamps and candles extinguished
* 14	Flames of several ft diameter extinguished but lower O_2 concentrations needed for extinction, if the ambient temperature is high
17	Smouldering reduced by about 25%
13	Smouldering stops in a 1-in layer of cork dust
5	Smouldering stops in a 6-in layer of cork dust

*obtained with gas containing up to 20% water vapor; O_2 content would be lower for dry gas

Table 6: Volume Factors[121]

Volume of Space ft^3	Volume Factor $ft^3/lb\ CO_2$	Volume Factor $lb\ CO_2/ft^3$	Calc. Quantity Not Less Than lb
Up to 140	14	.072	-
141 - 500	15	.067	10
501 - 1600	16	.063	35
1601 - 4500	18	.056	100
4501 - 500000	20	.050	250
Over 500000	22	.046	2500

A rule of thumb in the chemical industry is that all dangers of explosions from gases, vapors and solids are avoided, when the oxygen concentration is kept below 3%.[14]

Experiments showed that ignition of carbonaceous dusts in a furnace was prevented in all instances when the O_2 content was reduced to 3%.[119] Except for dusts,[119] where one obtains the same results as for gas mixtures, there are no data on the different effectiveness of the various inert gases in the extinguishing of solid fires. Since the diffusion constants for oxygen in inert gases decrease from Helium over Argon and nitrogen to carbon dioxide, which makes the oxygen supply to the burning surface decrease in the same order, one should observe the same results in solid fires as in gas mixtures. In turbulent flow the influence of the diffusion constants should have a minor role anyway.

IV. INERT GAS FIRE EXTINGUISHING SYSTEMS FOR BUILDINGS AND MACHINES

Inert gases are preferred for extinguishing

a) flammable liquid fires, because they can rapidly separate the surface of the liquid from the oxygen of the air;

b) fires of electrical equipment, because they are electrically nonconductive;

c) fires in rooms of high value contents or whose downtime after a fire shall be kept to a minimum, because they have no residue.

Their modes of application are local application, where inert gas is discharged directly onto the surface of the burning material; and, total flooding, where all of the air in the room at fire is diluted with inert gas.

The first method requires that the fire can be approached closely enough for the inert gas discharge or that the location of possible fires is known for the permanent installation of discharge nozzles. All portable fire extinguishers are, for instance, locally applied. Due to their limited content it is very important that they are used as early as possible so that the fire is completely extinguished before the fire zone is heated to temperatures which allow rekindling.

Total flooding requires that enough inert gas is available to be built up and maintain the inert gas or reduce the oxygen concentration to a level, where burning cannot continue. Recommendations exist for carbon dioxide. The Standards of the National Fire Protection Association[121] distinguish, for total flooding extinguishing systems, between requirements for surface fires and deep seated fires. They list for surface fires theoretical minimum carbon dioxide concentrations, which are the values of USBM Bulletin 503,[36] and suggested minimum design concentrations, which are approximately 1.2 times the theoretical figures. Recommended volume factors of the Standards, indicating the ratio weight of carbon dioxide to be discharged:volume of space to be flooded, are for a design concentration of 34% CO_2 given in Table 6.[121] These figures take the fact into account that in buildings small spaces have proportionately more wall area per enclosed volume than larger spaces and have therefore proportionately greater leakages. Since under the assumption of a free efflux the volume of carbon dioxide required to develop a certain concentration can be calculated from: (Chapter VII. A. 2.)

$$\exp(x) = \frac{100}{100 - \%\ CO_2}$$

x = volume of CO_2 added per volume of space

the volume factors from Table 6 have for other design concentrations y to be multiplied by a factor F

$$F = \log\left(\frac{100}{100 - y}\right) / \log\left(\frac{100}{100 - 34}\right)$$

The Flooding Factors of these Standards for deep seated fires are given in Table 7.[121] They have been determined by practical tests and contain no allowance for possible leakage. The pertinent oxygen concentrations for 50, 65, and 75 % CO_2 are 10.5, 7.4, and 5.3% O_2. The length of time over which the inert atmosphere has to be maintained is variable. According to the Fire Protection Handbook,[168] time periods of 30 to 60 minutes may in many cases be adequate. In extreme cases, days or weeks with CO_2 concentrations of practically 100% may be required. This is especially the case when charcoal or char are formed, which are subject to spontaneous ignition as long as the temperatures are higher than 200 - 300°F.

The U.S. Coast Guard[105] requires for boiler room protection with carbon dioxide bilge flooding systems a volume factor of 22 ft^3/lb, corresponding to 33.5% CO_2 or 13.9% O_2. These systems are designed for fighting fires of fuel oils and have been shown to be adequate when the air intakes are closed prior to release of the CO_2.

Table 7: Flooding Factors for Specific Hazards[121]

Design Concentration %	Flooding Factor $ft^3/lb\ CO_2$	Flooding Factor $lb\ CO_2/ft^3$	Specific Hazard
50	12	0.083	Dry electrical, wiring insulation hazards in general.
50	10	0.100	Small elec. machines, wire enclosures, under 2000 cu. ft.
65	8	0.125	Record (bulk paper) storage, ducts, and mechanically ventilated covered trenches.
75	6	0.166	Fur storage vaults, dust collectors.

A different use of inert gases for fighting building fires has been tested in Great Britain and in the USSR.[96,117,137,156,185] Large flowrates of jet engine exhausts mixed with water vapor are used to ventilate buildings at fire and clear them from smoke. The oxygen concentration of the mixture is low enough to extinguish flaming combustion. A description of the appliances used will be given in chapter X. C. 1.

V. INERT GAS USE IN MINE FIRES APPLICATIONS AND PREVAILING OPINIONS ABOUT THE USEFULNESS OF THIS METHOD IN MAJOR MINING COUNTRIES

A. United States

Rothwell[144] mentions already in 1875 that steam, carbon dioxide, and mixtures of carbon dioxide with nitrogen have been injected into sealed off areas to hasten the cooling and the expulsion of the air from the enclosed space. Carbon dioxide was usually generated from mixing limestone or marble dust with sulphuric or muriatic acid or from passing air through a bed of incandescent coal, mixed with limestone. He states that the use of carbon dioxide has not been too satisfactory, but blames the defective manner of application and particularly the shortness of time allowed for the cooling of the heated fire zone for it. He feels that the district on fire should be hermetically sealed.

Spencer[154] describes in 1898 a fire in a heading, which after sealing, kept burning slowly. He claims that the discharge of 150 lbs CO_2 into the sealed area supported the extinction of the fire greatly.

Walsh[181,182] suggested in 1919 an inert gas generator based on an ordinary coal boiler furnace for fire fighting purposes. He sees the main advantage of inert gases, when applied with a positive gage pressure in sealed areas, in keeping the air out. This is especially beneficial for fighting fires in difficult to seal outcrop or other inaccessible regions.

Jones[75] describes the extinction of a fire in the Bitner Mine, a drift mine under very light and leaky cover. The fire was caused by a grounded trolley on Nov. 16, 1922 and had reached an extension of 1400 ft. by Dec. 16, when the application of CO_2 was commenced. Injected into the sealed fire zone were a total of 36 tons of liquefied CO_2,

equivalent to 650,000 ft^3, the major part of it between Dec. 16 and Dec. 25 with a maximum rate of 17,750 lb/day (160,000 ft^3/day) on Dec. 24. From Dec. 26 till March 26 the the CO_2 supply was continued at a reduced rate of several hundred lbs/day to make up partly for the leakage losses. After Jan. 5, when gas analyses indicated that the fire had been extinguished, the mine was partly flooded with water to accelerate the cooling process. The CO_2 concentration inside the sealed area reached a peak of 24% on Dec. 25 and was allowed to taper off to 11%, when the fire zone was opened on March 26. The cost of injected CO_2 was estimated to be less than 10% of the total fire fighting cost. The main advantage of the CO_2 application was seen in the prevention of inward leakage of air due to pressure fluctuation and the cooling of the sealed atmosphere.

Strange[161] reports that on Feb. 28, 1924 a fire was discovered at the Pine Hill Coal Comp near Minersville, Pa. in old workings. Sealing was completed after 4 days, but due to faulty geological conditions was not effective enough. Injection of CO_2 began March 26. Within 4 1/2 hours 194 cylinders with 50 lbs of CO_2 each were discharged, within the next 11 hours another 242, and finally within the next 10 hours an additional 122 cylinders. In May it was felt that the fire was extinguished.

Rice, Paul, and von Bennewitz report[139] that carbon dioxide has been used at the end of the last century at the Engleville Mine in Colorado to extinguish a mine fire, but without success since the fire zone couldn't be sealed well enough. The gas was generated by mixing limestone with sulphuric acid in closed vats. In another mine, the fire was extinguished by blackdamp evolving from the strata. After sealing off the whole mine with an excavated volume of $96*10^6$ ft^3, the O_2 content dropped to 5% after 21 days and to 0.66% after 39 days. The authors state that they learned of other inert gas applications in mine fires also. They see the only advantage of inert gases in keeping external gases from entering. Otherwise, the rapid absorption of O_2 in a reasonably well sealed area makes the use of inert gases, according to their opinion, unnecessary.

Forbes and Grove[49] mention in 1948 that CO_2 is used by forcing it with perforated pipes through burning or smouldering material.

Westfield, Brumbaugh, and Whittaker[186] describe the successful use of CO_2 for fighting a coal fire of electrical origin in an intake airway. When discovered, rockfalls impeded direct fighting, so sealing was decided upon and completed 14 hours later. Only 4 seals were necessary,

of which two were destroyed twice and rebuilt within the next 5 days. The sea ed off area was approximately 30,000 ft^3 large. To prevent further explosions it was decided to inject carbon dioxide, which was shipped in tanktrucks to the mine, gasified at the surface and introduced through the existing waterline. A total of 5 tons or 85,700 ft^3 were introduced at an original rate of 8000 ft /hr. After 1 hour the oxygen and carbon dioxide concentrations were 6.8 and 39.5%, respectively, after 10 hours, 1.2 and 73.3%, respectively. Fifteen days later the sealed area was inspected and no fire being detected, ventilated. Remarkable was an increase in the CO concentration from 0.03 to 2.0% after the CO_2 injection, which had decreased to 0.23% only at the time of ventilation.

Haller and Michels[61] report that in 1957 a fire in a timbered raise of the Penokee Iron Ore Mine near Ironwood, Michigan was extinguished with CO_2. Immediately after the fire was detected, the airflow through the raise was interrupted with temporary seals of timber and brattice cloth. Since water from the top of the raise could not extinguish the fire, the injection of bottled CO_2 into the raise from its top was begun 18 hours after the fire detection. After the introduction of some 4000 ft^3 during the next 3 hours, one ton of dry ice was dumped into the raise while the release of bottled CO_2 was continued at a reduced rate. Samples taken from behind the seals 33 hours after the detection of the fire showed that the fire had been extinguished. The CO_2 introduction was stopped after an additional 24 hours, the seals were opened 3 days later. The total CO_2 consumption was 10,000 lbs from bottles and 1 ton of dry ice. The sealed volume was approximately 18,000 - 20,000 ft^3, the length of the fire zone 40 ft.

Heers and Dennison[64] describe the application of CO_2 to fight a fire in the Koehler Coal Mine near Raton, N.M. The fire was discovered on the morning of June 8, 1958. By 11:00 p.m., the seals in the intake and return airways to the fire zone were completed, the total sealed off volume was approximately 28,000,000 ft^3. To cool the sealed area, a closed ventilation circuit was constructed of 2 ft diam. corrugated culvert, with which gas was withdrawn from the sealed area, passed over dry ice and introduced back into the sealed area again. Liquid CO_2 was injected into the sealed area also. Over a period of 7 months, a total of 1302.5 tons of liquid and solid CO_2 were consumed. Due to cracks to the surface, the O_2 content in the sealed area never fell below 3%. The fire could not be extinguished but it was possible to explore the sealed off area, drive bypass entries and to advance the seals to the edge of the fire zone. These seals were then strengthened in preparation

for flooding with water, which was started on June 29, 1959. On August 11, 1959, the mine was released from the Withdrawal Order of June 1958.

Dougherty reports[41] that during recovery operations of a caved entry section, three blocks long, indication of rekindling occurred. The entry was resealed and "a dozen or more bottles of CO_2 were discharged into the enclosure", and the fire was extinguished. He mentions another case where 49 tons of CO_2 were pumped into a sealed area, in which rekindling during recovery operations occurred. It was, however, difficult to keep the CO_2 contained and after 10 days the seals were reopened. From his experiences with mine fires he takes the stand that the first case offered ideal conditions for the injection of CO_2 into a sealed area. "If the area involved is of any appreciable size, the quantity and cost is prohibitive. It has been tried as an adjunct in seals on occasions, but was unsuccessful".[41]

McElroy[106] concludes in 1938: "Although a number of attempts have been made to extinguish large fires in anthracite mines by the use of steam and, in at least three instances, CO_2, the results appear to have been practically nil, or at least indeterminate". The Miner's Circular 36 from 1948[49] summarizes: "Inert gas such as CO_2 occasionally may be used to advantage in cooling or extinguishing a mine fire, however, the use of inert gases is a laborious, expensive, and often unsuccessful method. If effective seals are erected and the fire area is airtight, enough inert gases will be produced by the fire and by the consumption of oxygen to extinguish the fire within a short time. If the fire area is not sealed tightly or seals are erected, it is questionable whether the use of inert gas will be effective. Where claims of the effective use of carbon dioxide have been made, it is likely that conditions have been especially favorable, as its use is known to have been unsuccessful in several attempts".

B. Great Britain

The usefulness of inert gases for extinguishing mine fires was already being seriously discussed in the last century, and several applications are reported - the first one as early as 1849.[46] Walker[180] reports that in 1851 a fire in a coal mine at Clackmannan, Scotland, which had burned in a 9 ft seam for 30 years, was extinguished within 3 weeks with a mixture of carbon dioxide and steam. The carbon dioxide was generated in a coke furnace, cooled by water jets and then forced into the sealed fire zone with

steam jets. In 1874 the Wynnstay Colliery, North Wales, was sealed after a fire broke out. Carbon dioxide was generated by mixing limestone with sulphuric acid and a total volume of 164,000 ft^3 was within 4 months forced into the downcast shaft. The atmosphere behind the seals was found to contain 5% CO_2, 25% air and 70% CH_4.[144] Walker[180] mentions that in 1885 one engineer claims to have used carbon dioxide on several occasions to extinguish mine fires. The carbon dioxide was generated by mixing chalk with acid in barrels and piped through the seals into the fire area. Several months of application were usually necessary.

In 1913 carbon dioxide was used to fight a fire at the Senghenydd Colliery since due to the heavy leakage, it seemed impossible to extinguish the fire by sealing it.[46] The carbon dioxide introduction was started eight weeks after closing the seals at a rate of 400 ft^3/hr and was continued for 15 weeks. The fire could not be extinguished but sufficiently slowed down to fight it directly with water. The carbon dioxide was produced from bicarbonate of soda and sulphuric acid in a commercial generator otherwise used in the mineral water industry.

A detailed description of the use of nitrogen for fighting a coal fire in a heading, ignited by a methane explosion on July 24, 1962, has been given by Vaughan-Thomas.[178] Due to the fact that the heading passed over a total distance of 360 ft through old workings and was exerted to large ventilation pressure fluctuations, sealing was unsuccessful. The leakage rate outbye through the seal was at first 1,700 cfm - and even after concrete spraying and building of a pressure balancing chamber, did not drop below 900 cfm. The oxygen concentration in the sealed off space of 400,000 ft^3 could not be reduced below 15.3%. On August 10 the injection of nitrogen through the seal commenced and within 60 hours a total of 1.87 Million ft^3 had been introduced. The nitrogen was transported in road tankers to the mine, evaporated in steam-heated evaporators at the surface, and piped through the compressed air lines into the fire zone. Between August 15 and October 10 efforts concentrated on reducing the leakage with additional concrete spraying and better pressure balancing while nitrogen was supplied in variable quantities. Between October 10 and November 7 the oxygen concentration could be kept at an average of 1.8% with a nitrogen input of 25,000 ft^3/hr. After a stop in the nitrogen injection between November 7 and 10, which let the O_2 and CO concentration at once rise again, nitrogen pumping was continued at 25,000 ft^3/hr till November 14, and at 40,000 ft^3/hr thereafter. Between November 16 and 18 inspection teams entered the sealed area and installed

water nozzles in the fire zone. On November 25 the nitrogen flow was stopped and the heading again ventilated. When resurgence of the heating took place, a new seal, 95 yd back from the face of the heading was constructed, which was completed on November 27. Nitrogen was introduced behind this seal until December 11 at an initial rate of 40,5000 ft^3/hr and at a total volume of 8 Million ft^3. A reinforced concrete dam was built 5 yd outbye the second seal to flood the fire zone. Build up of an extinctive atmosphere made flooding superfluous, however. In the twenty weeks of fighting this fire, a total of 85 Million ft^3 of gaseous nitrogen had been consumed. It was possible to keep the atmosphere behind the seals nonexplosive, however not possible to extinguish the fire.

Notman[123] mentions that two and a half tons of dry ice were in another case transported into a sealed fire area to support the formation of an extinctive atmosphere.

Tideswell[167] sees in the use of inert gases as a buffer between the air and the gas while clearing areas of potential dangers, not an unpromising approach to greater safety.

The opinion of the National Coal Board is that the use of inert gases for combatting underground fires has potentially a wide application, which is in practice, however, limited by the problem associated with supplying the gas at a sufficiently high flow rate. This opinion is currently being reexamined, and the results of the present investigations should be available shortly.[190] The Safety in Mines Research Establishment takes the same stand. In their opinion there appears no doubt that inert gases can be used to control large underground fires and to enable the rapid reopening of sealed districts. In view of the heavy leakage which usually exists, large sources of inert gases must be available if the method is to be used successfully. Recently, SMRE have started small scale experiments to investigate the effects of reduced oxygen concentrations on a fire in a duct, with nitrogen being the diluent.[184]

C. Germany

Inert gas use was more popular in the thirties than now. Bredenbruch[18] reports in 1939 that sealed fire areas, when an interest in their fast reopening exists, are flooded with carbon dioxide. This method had been used for several years. Prequisite is a good sealing of the area and a limited extension. The carbon dioxide is always introduced at the highest point. He quotes the example of a backfilled, abandoned longwall face where spontaneous ignition caused

a concealed fire. Pipes were driven into the backfill and 20,000 ft^3 of carbon dioxide sufficed to extinguish the fire. Smaller concealed heatings were frequently fought with perforated injection lances. In one case an initial quantity of 7,000 ft^3 and continuing injections of 2,300 - 3,700 ft^3/week of carbon dioxide over a period of 8 weeks extinguished the fire.

Both[16] reports that in the only case of inert gas application during the last decades - a rate of 35,000 ft^3/hr over several weeks - was not capable of extinguishing the fire, but allowed to advance the seals and tc reduce the sealed area. The inert gas was generated in a mobile plant from heating oil, and had a composition of ≈ 15% CO_2, 80% N_2, 0.5% O_2, and 5% H_2O.

The Mine Rescue Center of the Ruhr Coal Mines[17] is of the opinion that fighting fires with inert gases is suited only for small, well sealed fires. In other cases the required inert gas flow rates are larger than presently available. Besides using larger portable inert gas generators, thought is given to use in future liquid carbon dioxide or nitrogen in tank cars; which due to the proximity of the Ruhr mines to the producers of these gases, could be delivered in larger quantities than were available in the past.

The East German Institute for Mine Safety takes the stand[122] that inert gas use is justified when a large mine fire shall be extinguished in the shortest time possible, without consideration of cost. During the last years inert gases have, however, not been used - high expansion foam is preferred.[79]

D. Mainland China

Wang Tie-Sin[183] describes two coal mine fires, which could be extinguished with inert gases. The first fire (Colliery No. 1 Tchegan Division) started in June 1959 and required the sealing of a whole mine level with a volume of 3.5 Million ft^3. Injection of a mixture of carbon dioxide and nitrogen started in March 1960, and by July 3.5 Million ft^3 had been forced into the sealed area. Gas samples taken in June behind two seals showed carbon dioxide concentrations of 10.25% and 9.50%, oxygen concentrations of 5.1% and 6.7%, methane concentrations of 1.0%. The carbon monoxide concentration in the fire area was in July, 0.03%. After inspecting the sealed area in September 1960, the seals were opened.

The second fire (Dalu Colliery No. 1 Tchegan Division)

Table 8: Characteristic Data of Two Fires Described by Wang Tie-Sin[183]

Fire No.	V ft^3	$\dot{q}_h$ ft^3/hr	$\dot{q}_m$ $ft^3/month$	Q ft^3	Intensity of Forcing 1/month	Fire Exting. Index ft^3/hr
1	$3.5*10^6$	$18.2*10^3$	$1.16*10^6$	$3.5*10^6$	0.33	$18.2*10^3$
2	$1.6*10^6$	$8.0*10^3$	$1.10*10^6$	$3.5*10^6$	0.69	$17.5*10^3$

started in August 1960 and was immediately sealed. Injection of a mixture of carbon dioxide and nitrogen started in September 1960. After 3.5 Million ft^3 had been introduced within the next 3 months into the sealed area with a volume of 1.6 Million ft^3, the carbon monoxide content in the sealed atmosphere disappeared. Gas samples taken at three different seals showed carbon dioxide concentrations of 6.9, 9.1, and 10.0% oxygen concentrations of 2.7, 1.0, and 0.9%.

Wang Tie-Sin introduces two scales for the inert gas application:

the "intensity of forcing" = $\dot{q}_m/V$

the "fire extinguishing index" = $Q*\dot{q}_h/V$

where V = volume of sealed area (ft^3)

Q = total injection of inert gas (ft^3)

$\dot{q}_m$ = rate of inert gas injection (ft^3/month)

$\dot{q}_h$ = rate of inert gas injection (ft^3/hr)

The intensity of forcing obviously is some measure for the fraction of the sealed volume which is filled within one month with inert gases. The fire extinguishing index $Q*\dot{q}_h/V = Q/(V/\dot{q}_h)$ relates the total quantity of inert gases Q to the time $V/\dot{q}_h$ required to fill the volume V. For the two fires under discussion, Wang Tie-Sin gives the data compiled in Table 8. He concludes that for the successful fighting of mine fires the intensity of forcing should be higher than 0.3 and the index of extinguishing the fire should exceed $14*10^3$.

The inert gas was in both fires generated with an intermittently operating coal furnace, charged with 1,760 lbs of coal which were consumed in 12 - 14 hours. The combustion gases contained: $CO_2 > 16\%$, $CO = 0\%$, $O_2 < 3\%$. It is claimed by Ratuskov and colleagues[138] that this inert gas generator is based on work done by the Russian Research Institute for Workprotection in the Mines of the Eastern District (VostNII).

E. Poland

The Polish Coal Mines use inert gases for two different purposes: to support the build up of a non-explosive atmosphere in sealed areas, and to prevent air leakage through the seals.

The inert gas requirements for extinguishing fires by lowering the oxygen concentration to approximately 3% are considered to be too large for practical applications.[90]

Air leakage through seals is prevented by so-called insulation locks - consisting of a group of 2 - 4 stoppings, erected adjoining to the seals, and forming an inert gas filled chamber of 1500 - 3000 ft^3 volume. The inert gas is kept at an overpressure of 0.4 - 0.8 in. wg. The stoppings have well fitting doors to allow fire fighting teams to penetrate into the fire zone.

The inert gas source is a truck mounted West German built generator of the type Mahler-Exo-I 200/s, with a capacity of 120 ft^3/min.[60,90] The inert gas composition is 85% N_2, 13% CO_2, 2% O_2 maximal.

F. Czechoslovakia

A thorough review of inert gas methods is given in a paper by Hajek.[60] It contains a list of all inert gas application in Czechoslovakia up until 1969 (Table 9).

The first large scale use took place in 1949 at the Doubrava Colliery, where a series of methane explosions had caused widespread fires. When sealing was not able to extinguish these fires, an improvised nitrogen plant of the Claude system with a capacity of 25,000 ft^3/hr was set up at the mine. A total volume of 178.6 Million ft^3 had to be released into the mine before it could be reopened.

Three more fires were fought in 1951, 1955, and 1956 with bottled CO_2, mine-site produced and trucked N_2. In 1957 three truck trailers carrying bottled nitrogen at 5,100 psi and with a capacity of 21,000 ft^3/trailer were put into service for routine use in mine fires by the Central Rescue Station in Orlava-Lazy. In 1965 two trailers with a capacity of 25,000 ft each were added so that now delivery rates of several 100,000 ft^3/day can be maintained in the Ostrava-Karvina Coal Basin. Where no discharge of the gas through pipelines is possible, bottles of 10 gal volume are used for the transport between trailers and fire zone. They have a capacity of 210 ft^3 each at 2,200 psi.

Experiences with CO_2 have not been favorable. When blown into the fire, the CO content rose to 5 - 6%.[179] Nitrogen can furthermore be obtained in larger quantities.[132]

Table 9: Inert Gas Applications in Czechoslovakia (60)

Year	Plant	Cause	Use	Transport	Volume (10^3 ft^3)
1949	Doubrava	expl. & fire	extinct. & inert.	produced at mine site	178,570
1951	Zápotocky	fire	extinction	bottled CO_2	
1955	Č S A	fire	extinction	piped N_2	
1956	Hlubina	fire	extinct. & inert.	produced at mine site	
1958	Zápotocky	fire	extinction	piped N_2	
1959	Mszana PLR	fire	inertization	bottled N_2	10.6
1959	Gottwald	fire	inertization	piped N_2	
1960	El. Č S A	fire	inertization	piped N_2	24.7
1960	Kovokutě	fire prevent.	inertization	piped N_2	21.2
1961	Dukla	fire	extinction	piped N_2	10,219.9
1961	Č S A	fire	extinction	piped N_2	
1961	Koks. V. Únor	fire	inertization	piped N_2	
1961	Plynárna Suchu	fire	inertization	piped N_2	
1961	Sídliště	fire	inertization	piped N_2	
1962	Žafie	fire	extinction	bottled N_2	392.0
1962	Sídliště	surf. fire	inertization	piped N_2	
1963	Doubrava	fire	extinct. & inert.	piped N_2	7,532.5
1963	Václav	fire	extinction	piped N_2	423.8
1963	Dukla	fire	extinction	piped N_2	
1963	Suchá	surf. fire	inertization	piped N_2	
1964	Fučik II	fire	extinction	bottled and piped N_2	988.8
1964	Č S A	expl. & fire	extinction	bottled N_2	81.2
1964	Sídliště	surf. fire	inertization	piped N_2	
1965	Č S M	fire	extinct. & inert.	piped N_2	1,013.5
1966	Zárnbek	expl. & fire	extinction	piped N_2	476.7
1967	Zápotocky	fire	extinction	piped N_2	2,464.9

Year	Plant	Cause	Use	Transport	Volume (10^3 ft^3)
1967	Koks. Karolina	fire	extinction	piped N_2	21.2
1967	Koks. Sverma	fire	inertization	piped N_2	24.7
1969	Jeremenko	fire	extinction	piped N_2	1,617.4
1969	ZKL Brno	fire in bunker	inertization	piped N_2	21.2
1969	Rekultivace	fire in bunker	inertization	piped N_2	21.2
1969	Studenka	fire in bunker	inertization	piped N_2	21.2
1969	Plynárna Suchá	fire prevention	inertization	piped N_2	74.2
1969	Koks. V. Ú.	fire prevention	inertization	piped N_2	194.2
1969	Koks. Karolina	pressure test	inertization	piped N_2	51.8

To limit the gas consumption only smaller sealed spaces are flooded with nitrogen to extinguish the fire. In the majority of fires, low-volume nitrogen pressure chambers are employed.[60,131,179] These are two, nitrogen filled chambers, 10 - 17 ft. long and fitted with well sealing doors, which are built after the waiting period has passed outside each seal of the fire zone. The nitrogen is kept at a pressure approximately 0.4 in. wg. higher than that of the sealed atmosphere or mine atmosphere - whichever is higher. This requires a nitrogen supply of 35 - 70 ft^3/min per seal.

Pressure chambers have two purposes: they shall prevent a leakage of other gases than nitrogen through the seals, and they shall permit an opening of the seals to allow fire fighting teams to advance towards the seat of the fire under the cover of a nitrogen curtain. If the whole sealed area cannot be inerted, new seals are built at the farthest point of advance.

Wald[179] brings an example for the rapid extinction of a mine fire with the aid of pressure chambers (Fig. 6). It is estimated that the reduced air leakage through the seals allows to shorten the sealing periods from 4 - 6 months to 1 - 2 months.[131]

In 1967 an inert gas generator, based on the thermal dissociation of ammonia and subsequent combustion of hydrogen with a capacity of 650 ft^3/min, was developed by the Mine Rescue Center. It is, however, contemplated to use in the future the generator GIG-4, developed in the Soviet Union.

G. U. S. S. R.

Osipov and colleagues[128] mention that inert gases for fighting mine fires have been used since the beginning of the century. They report that in the years 1963 - 1965 nine large mine fires in the gassy mines of the Donetsk district alone were sealed with simultaneous injections of carbon dioxide to prevent explosions, and that the total amount of CO_2 consumed was higher than 3.5 Million ft^3.

The first detailed description of the extinction of a mine fire which could be found in the literature is from 1960[163] and deals with the injection of bottled carbon dioxide into a sealed area of 210,000 ft^3. Within 2 days a total of 195,000 ft^3 were released, but due to considerable leakage, the gas composition in the sealed area changed only

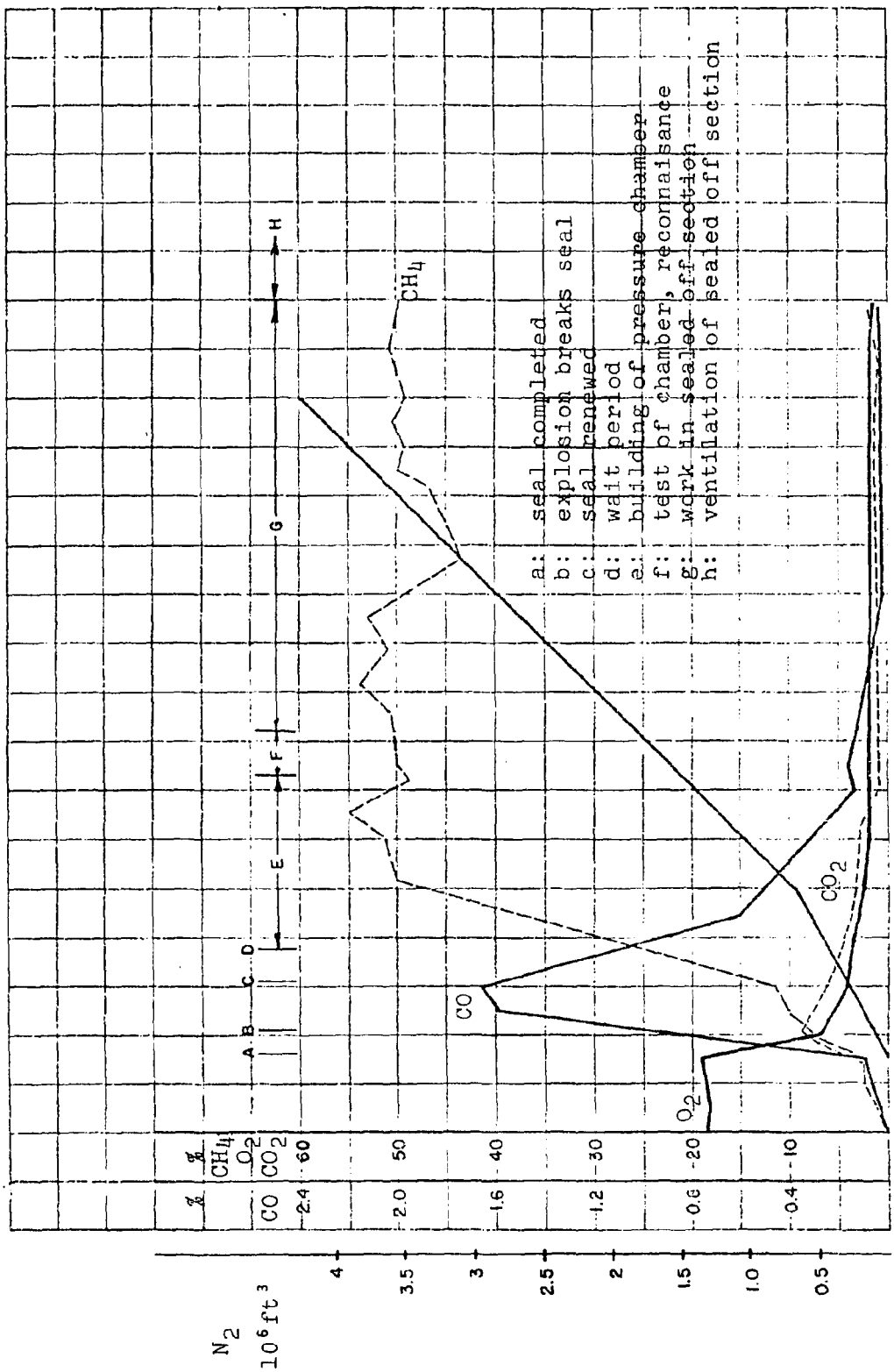


Fig. 6: Example for the Use of Pressure Chambers[179]

to 13.6% CO_2, 3.1% CH_4, 12.0% O_2, and 0.03% CO. Much more carbon dioxide had to be used before the fire could be extinguished.

Ratuskov and colleagues[138] report that inert gas methods found - till 1964 - no wide application due to the limited gas supply. The Research Institute for Work-protection in Mines of the Eastern Districts (VostNII) therefore developed a mobile inert gas generator with a capacity of 17,700 ft^3/hr, which consumes approximately 90 lbs/hr of heating oil and produces a gas with 1.5 - 2.5% O_2, 12.5 - 14.0% CO_2, and only traces of CO. This generator was successfully used to extinguish a fire in the gob of the Mine No. 3/4 "Ziminka" (Kombinat Kuzbassugol). After sealing a mine area of 106,000 ft^3 a total of 1.1 Million ft^3 inert gas was injected over a period of 3 months in rates of 17,700 - 21,200 ft^3/hr intermittently. One month after stopping the inert gas introduction, the seals were opened. The gas inside contained 5% O_2 and 4% CO_2, CO was missing. The authors see the special advantage of the inert gas application in the fact that a nonexplosive atmosphere behind the seals is established quickly so that interference of the fire with the rest of the mine is minimal.

Sevostjanov[150] describes a mine fire where inert gas application did not have the desired result. In the Mine No. 12 "Osnovnaja" (Kombinat Donbassantracit) a methane blower was ignited by shotfiring in a longwall face and produced a flame of 100 ft. length and 28 - 33 ft. width. Soon the timber lagging of the return airway burned over a length of 100 ft. With ample use of water the fire could be reduced to the gas flame alone. The latter was fought with water, carbon dioxide, and chemicals from hand extinguishers - but without success. To avoid the formation of explosive mixtures, it was decided to refrain from sealing or reducing the airflow, but rather to employ the inert gas generator GIG-2. This generator produces a mixture of steam and inert gas at a rate of 635,000 ft^3/hr. Although the O_2 content could be reduced to 15% and the CO_2 content increased to 5% (after 1 hour), the operation of the generator had the effect of increasing the airflow through the fire zone and the temperature of the combustion products, so that the fire started to spread again. After several hours the use of the inert gas generator was therefore suspended and the fire fought again with water. The fire was finally extinguished by draining the CH_4 into gas boreholes and cooling the rock with water brought in through other boreholes.

Osipov and Orlov[130] report that a fire which had been

started by a methane ignition could in the accessible parts of a longwall coal face be extinguished by conventional means but continued to burn in the waste area. After sealing, nitrogen from liquid gas containers at the surface and four AGU-2m evaporators with a combined capacity of 1,400 ft^3/min was piped into the gob through two 4 inch pipelines at a rate of 1130 ft^3/min over the first 64 hours and at a rate of 370 ft^3/min over the next 99 hours. The total volume of nitrogen injected was 6.3 Million ft^3 or 1.9 times the volume of the sealed off space. After 40 - 50 hours, the oxygen concentration had dropped to 1%. Four months after the nitrogen injection, the carbon monoxide had disappeared. After allowing an additional 2 months for cooling, the sealed area was inspected and reopened. The cooling times were calculated from heat transfer considerations, which gave an answer of 6 - 8 months.

Belik and colleagues[10] describe the successful use of carbon dioxide to extinguish a spontaneous coal fire in the gob area of a steep longwall face. After sealing, the carbon dioxide was released from the top entry in a quantity of 165,000 ft^3 over 12 hours and at a rate of 10 ft^3/sec. The composition of the atmosphere along the face and the entries was recorded over a period of 100 hours. Although the seam had a dip of 60°, the carbon dioxide filled all mine workings and diluted the oxygen to less than 3%.

Sobolev brings in his book Mine Rescue[159] an example for the use of nitrogen. At the Mine No. 23 of the Karaganda Coal District, a fire in a longwall face, which gradually spread into the return airways, was discovered April 19, 1969. After 4 hours of attempts to extinguish the fire with water and foam it had to be decided to seal the fire zone. Explosion proof seals were completed in April 23 in two intake and three return airways. Gas samples showed

7.5% CO_2, 8.4% CH_4, 6.9% O_2, 1.4% CO, 1.6% H_2 behind return seals and 1.0% CO_2, 4.2% CH_4, 16.8% O_2, 0.7% CO, 0.3% H_2 behind intake seals.
After 25 hours the composition had changed to

6.5% CO_2, 21% CH_4, 2.6% O_2, 1.2% CO, 1.1% H_2 behind return seals and 1.5% CO_2, 18% CH_4, 5.5% O_2, 1.0% CO, 1.2% H_2 behind intake seals, and miners were allowed to reenter the mine.

To stop active burning and to create a stable non-explosive atmosphere, the injection of inert gas was decided upon. Used was liquid nitrogen from railroad tank-cars, which was evaporated in gasification plants of the

type AGU-2m at the surface and piped through gas drainage and water lines of 6 and 5 inches diameter, and a total length of approximately 1.5 miles. Four plants AGU-2m could under these conditions feed an average of 1240 ft^3/min into the fire zone. Between May 3 and May 7, 1969, a total of 6,000,000 ft N_2 were released, or 1.24 times the sealed volume of 4,850,000 ft^3. An additional 940 ft^3 of liquid nitrogen, corresponding to another 650,000 ft^3 of gas, were poured through a borehole into the fire zone. This changed the composition of the sealed atmosphere from 3 - 4% CO_2, 36 - 49% CH_4, 6.5% O_2, 0.07 - 0.2% CO before the N_2 release to 0.5% CO_2, 41% CH_4, 0.9 - 1.9% O_2, and 0.0% CO. after the release of the nitrogen.

An unpublished report[175] describes 7 applications of the inert gas generator GIG-2 through the years 1969 - 1972 in coal mines. It is summarized in Table 10. In all cases, the ventilation of the fire zones was maintained to such an extent that no explosive mixtures could form and was cut off only after the fire zone had been filled with an inexplosive atmosphere.

The transport of the inert gases into the fire zone has been studied by several researchers. Kessariiskii[83] investigates the usefulness of existing pipeline systems in mines for piping nitrogen from the surface to the prospective fire sites and comes to the conclusion that the dimensions of the existing systems (water, compressed air, gas drainage) suffice. Osipov and colleagues[128] describe an experiment to study the carbon dioxide flow within a sealed longwall face of 360 ft. length, 3 ft. height, and 23° dip. The pertinent haulage and ventilation roadways had cross sectional areas of 54 ft^2, the ventilation was ascensional. Both roadways were sealed in a distance of 1150 ft. from the face, the airflow was regulated at 105 ft^3/sec or 2 ft/sec. Over a period of 90 minutes, carbon dioxide was released through the lower seal at a rate of 35 ft^3/sec. This caused the airflow to drop to 18 ft^3/sec after 20 minutes and to 3 - 5 ft^3/sec when the ventilation pressure, acting at the face, was further reduced. Airflow rates, methane, carbon dioxide, and oxygen concentrations were monitored along the roadways and the face. The results showed the following peak values of gas concentrations:

200 ft from lower seal:	62% CO_2, 8% O_2
1100 ft from lower seal:	45% CO_2, 11% O_2
100 ft inside longwall face:	30% CO_2, 14% O_2, 5% CH_4
top of longwall face:	12% CO_2, 16% O_2, 14% CH_4

Table 10: Examples for the Use of the Inert Gas Generator GIG-2 (175)

Name of Plant	Fire			Inert Gas Application				
	Time	Location	Sealed Vol. (ft^3)	Start	Duration (minutes)	Flowrate (ft^3/min)	O_2 (%)	Final Conc. at Return Seal
Berestovskaja 2	9-16-69	gob area	$1.4 * 10^6$	10-6-69	95	10,600	0.4	9.0 % CO_2 1.8 % CH_4 6.0 % O_2 0.2 % CO
Gorskaja 1 - 2	1-30-71	longwall	$0.81 * 10^6$	2-1-71	615	12,000 Total of $4.24*10^6$ ft^3	1.0	10.0 % CO_2 3.2 % CH_4 1.8 % O_2 0.0 - 0.4% CO
Ilijic	4-29-71	return of longwall	$0.5 * 10^6$	5-1-71	295	11,300	0.8	9.5 % CO_2 0.5 % CH_4 8.0 % O_2 0.004 % CO
Butovka Donetskaja	8-30-71	longwall	$0.35 * 10^5$	9-25-71	315	12,000	1.8	10.0 % CO_2 0.0 % CH_4 2.4 % O_2 0.02 % CO
Butovka Donetskaja	12-22-71	longwall	$0.53 * 10^6$	12-30-71	150			11.4 % CO_2 0.1 % CH_4 5.6 % O_2 0.01 % CO
Krasnyj Proletar	1-9-72	longwall	$0.32 * 10^6$	1-11-72	30	12,000		12.7 % CO_2 2.5 % CH_4 2.5 % O_2 0.3 % CO
Bazanova	8-28-72	gob area		8-31-72	4240			

This indicates that the ventilating pressure acting at the longwall face was too small to move the carbon dioxide up the face. To guarantee mixing of the CO_2 with air, the authors recommend that Reynold's numbers, larger than 50,000, should be maintained.

A similar experiment was conducted with nitrogen by Gorb and Stalerov.[53] A longwall face of 640 ft. length, 3 ft. height, 10 - 11° dip, which had advanced approximately 1000 ft. from a raise and been worked with full caving, was sealed in its pertinent haulage and ventilation roadway close to the raise. The total sealed space was estimated to be approximately 920,000 ft^3. Nitrogen was released through the lower seal over a time period of 260 minutes and a rate of 2000 ft^3/min, which amounts to a total nitrogen quantity of 0.57 times the sealed volume. The airflow had been reduced by the sealing from 19,500 ft^3/min to 5,600 ft^3/min and fell to 2,300 ft^3/min after the nitrogen release. Monitored were nitrogen, oxygen and methane concentrations in 90, 880, 1400, 2150, and 2460 ft from the point of nitrogen release. The results showed that the nitrogen moved with the ventilating air and filled the sealed space, which required approximately 3 hours. Due to the low air velocity, considerable methane layering was, however, observed along the upper entry.

The losses, which are caused by leakage through the gob area when inert gas is released into the roadways of a longwall face, have been estimated by Abramov and colleagues.[1] The results of the calculations show that the main factors are the backfill method, the height of the seam, and the length of the entries. The length of the longwall face is less significant. As is to be expected, the losses can be considerable.

Osipov and colleagues[129] measured the changes of carbon dioxide concentrations in sealed longwall faces and pertinent roadways after the gas introduction had been stopped. They found that up to 75% of the CO_2 disappeared within 3.5 to 14 hours and explain this fact mainly by absorption by the coal.

Grekov and Gorb[58] bring, without an explanation of their origin, two graphs for the concentration change of CO_2 and N_2 along airways for different flow velocities. Since these changes are much larger for CO_2 than for N_2 they might be based on absorption losses. Under the assumption that a CO_2 flow rate of 1060 ft^3/min (120 cylinders per hour) is the practical maximum, that the oxygen concentration should be lowered to at least 13.5% to establish a nonexplosive atmosphere and that due to air leakage only a 60 - 70% CO_2

concentration can be expected at the intake seals, they conclude that CO_2 should be used only in sealed spaces below 140,000 ft^3 volume or 1300 ft distance between intake and return seals. For N_2, with lower concentration changes and much larger possible flow rates, there is no limitation except for dead end workings.

The limitations in the application of carbon dioxide in non-horizontal mine workings have been investigated by Belik.[12] To reduce the large gas quantities needed for inerting the atmosphere in sealed off fire areas, the admixture of Freon 12 and Freon 114 V2 to nitrogen and carbon dioxide has been tried in laboratory tests.[127]

Additional experiences with the use of inert gases are contained in the Handbook for M ine Rescue, Vol. 3 and 4,[110] guidelines for the application of inert gases in the book Mine Rescue by Sobolev[159] and the Manual on the Isolation of Fires in Mines with Gas Hazards.[111]

Sobolev,[175] head of the Department Mine Rescue in the USSR Ministry of Coal Production sees as the main advantage of the inert gas method that it allows to prevent the formation of explosive mixtures while the fire is sealed. If a direct attack is possible, water with its large heat binding property is a better means of fire extinction. The fast filling of a sealed area with an inert atmosphere allows to reduce the sealing time by approximately 50%. Three inert gas sources are used: CO_2 from cylinders - maximum delivery rate 1250 - 1400 ft^3/min; liquid N_2 from tankcars - transported and evaporated at the mine site in evaporator trucks - like the type AGU-2m with a transport capacity of 50 ft^3 liquid nitrogen and a delivery rate of 2800 - 3500 ft^3/min gaseous nitrogen, which is piped from the surface into the fire zone; (another evaporator frequently used is the type PeEAS-100); and, inert gas from portable generators. The latest development is the type GIG-4 of which presently 4 are used mainly in the Donjetsk District. It has a capacity of 12,000 ft^3/min, weighs 2000 lbs. and can be dissembled and assembled for underground transport and used in a very short time. The composition of the generated inert gas is

1% O_2, 8% CO_2, 500 ppm CO, 51% N_2, rest H_2O,

the discharge temperature is 175 - 195°F, the gauge pressure 40 in. wg. Series production of this generator is under discussion. A smaller generator with 1750 ft^3/min capacity for replacing inert gas losses in sealed areas is under construction.

Right now liquid nitrogen is still the inert gas source mainly used in the USSR. If the inert gas is applied early enough, the seals of open fires can be opened after 2 - 3 weeks. For concealed fires, up to 6 months may be necessary. No forced recirculation of inert gases in used.

A foreign expert[131] estimates the number of inert gas generator uses in the USSR to be approximately equal to 60.

An unpublished report[17] of a visit to the Donetsk District in 1971 states that every mine rescue center is equipped with 4 trucks loaded with liquid nitrogen and 1 evaporator. The nitrogen is mainly used to inert explosive gases. The capacity of each truck is 7.5 tons, the rate of discharge 350 ft^3/min. Additional nitrogen is usually transported by rail to the mine. It is planned to acquire 15 ton trucks for mines without railroad connections. The report furthermore gives some technical data on the inert gas generator GIG-4, described in chapter X. C. 2.

VI. PROBABLE COMBUSTION PRODUCTS OF MINE FIRES

A. General Discussion

When coal or timber are burned at temperatures above 1200°F, the products of combustion are primarily CO_2, H_2O, and CO. They may be accompanied by small quantities of SO_2 and N_2 from the sulphur and free nitrogen in the fuel. Since mine fires usually comprise zones of widely changing temperatures and air supply, the combustion is in practice seldom complete and the fire gases may contain unburnt distillation products also. Additionally, secondary processes, like producer and water gas reactions, may take place. CO_2 may be adsorbed on the coal[56,129,148,152] or dissolved in water. Hydrogen and carbon monoxide may be oxidized by bacteria, if oxygen is present.[77,148]

1. Ventilation of Fires With An Excess Supply of Air

A thorough review of the literature on the oxidation of coal has been given by Scott.[148] Coal oxidizes at every temperature, the rate of oxidation increasing with temperature. Up to approximately 400 - 500°C for anthracite and 300 - 400°C for bituminous coal, the oxidation products are mainly CO_2, CO, H_2O and a solid coal-oxygen complex. The latter consumes up to half of the oxygen and has a retarding effect on the oxidation process. When the amount of complex present decreases the oxidation rate more than the temperature increase from the oxidation is able to increase it, the coal cannot ignite spontaneously.[37] If the temperature continues to rise,

further oxidation starts to destroy the complex, and at about the ignition temperature, it has practically disappeared. Fig. 7a[148] shows the distribution of consumed oxygen for anthracite after 72 hours at various temperatures.

Both CO_2 and CO production increase with temperature. Without excess air, CO_2 reaches a peak before the reduction by carbon becomes appreciable. This is the case at approximately 500 - 600°C for anthracite, and at lower temperatures for bituminous coal. With excess air, the CO_2 will continue to increase once the ignition temperature of CO and the hydrocarbons has been reached at 600 - 700°C.

Below its ignition temperature, CO appears in the oxidation products in greater quantities than the equilibrium state between C-CO_2-CO calls for. As soon as the two gases have been formed, they begin to change their ratios toward the equilibrium values. Above its ignition temperature, CO is burned to CO_2 and the CO-CO_2 ratio is therefore smaller than the equilibrium value. Fig. 7b[148] shows the ratio $CO/(CO + CO_2)$ for an anthracite sample as a function of temperature and contact time between gases and coal.

Hydrogen does not appear in the combustion products of coal until the temperature is approximately 250°C for subbituminous or bituminous coal fires and approximately 350°C for anthracite fires.[2] It appears usually in low concentrations, except as the product of a water gas secondary reaction or distillation. In the presence of excess air it is burned at temperatures between 600 and 700°C.

When wood is heated, it emits mainly carbon dioxide and water vapor at temperatures below 280°C. Between 280 and 320°C decomposition of lignin and pyrolysis of cellulose produce flammable gases and vapors, the latter in exothermic secondary reactions being transformed to char, carbon dioxide, and water. The ignition temperature of freshly formed charcoal is in the range of 200 - 250°C, the ignition temperature of the gases due to the presence of volatile tars at a little over 300°C. Underground timber fires with an excess of air produce up to 5% CO_2, 0.5 - 1% CO, and little H_2, timber fires with complete oxygen vitiation up to 21% CO_2, 18% CO, and 4% H_2.[187] Fig. 8[4] shows on an air free basis a suggestion for the fire gas composition of a typical timber fire.

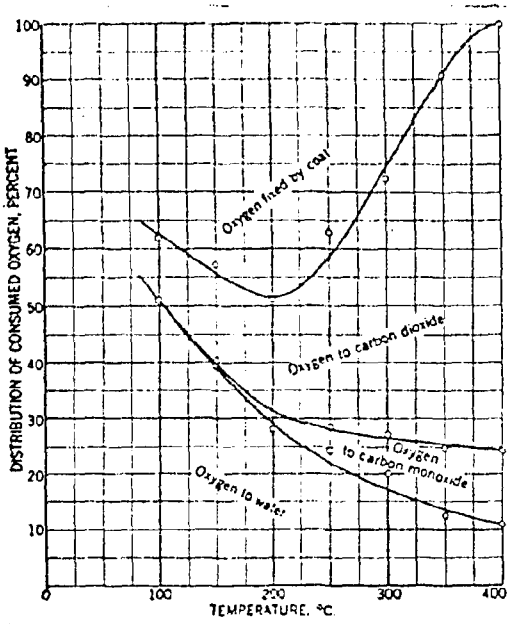


Fig. 7a : Distribution of consumed oxygen for anthracite.[148]

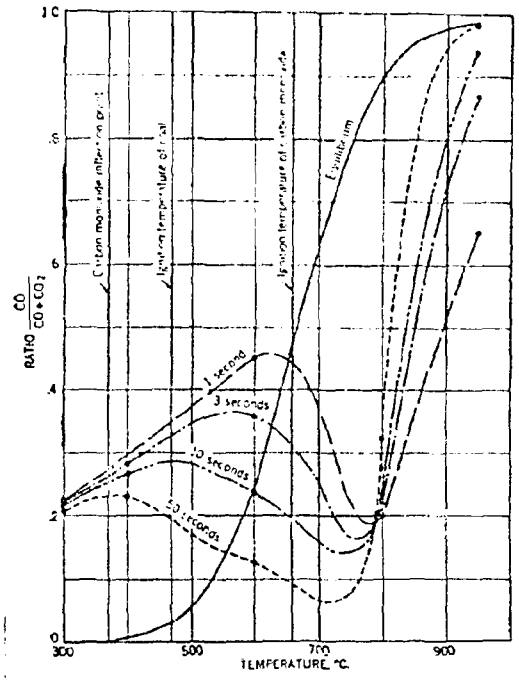


Fig. 7b : Ratios CO:(CO + CO_2) from oxidizing anthracite sample.[148]

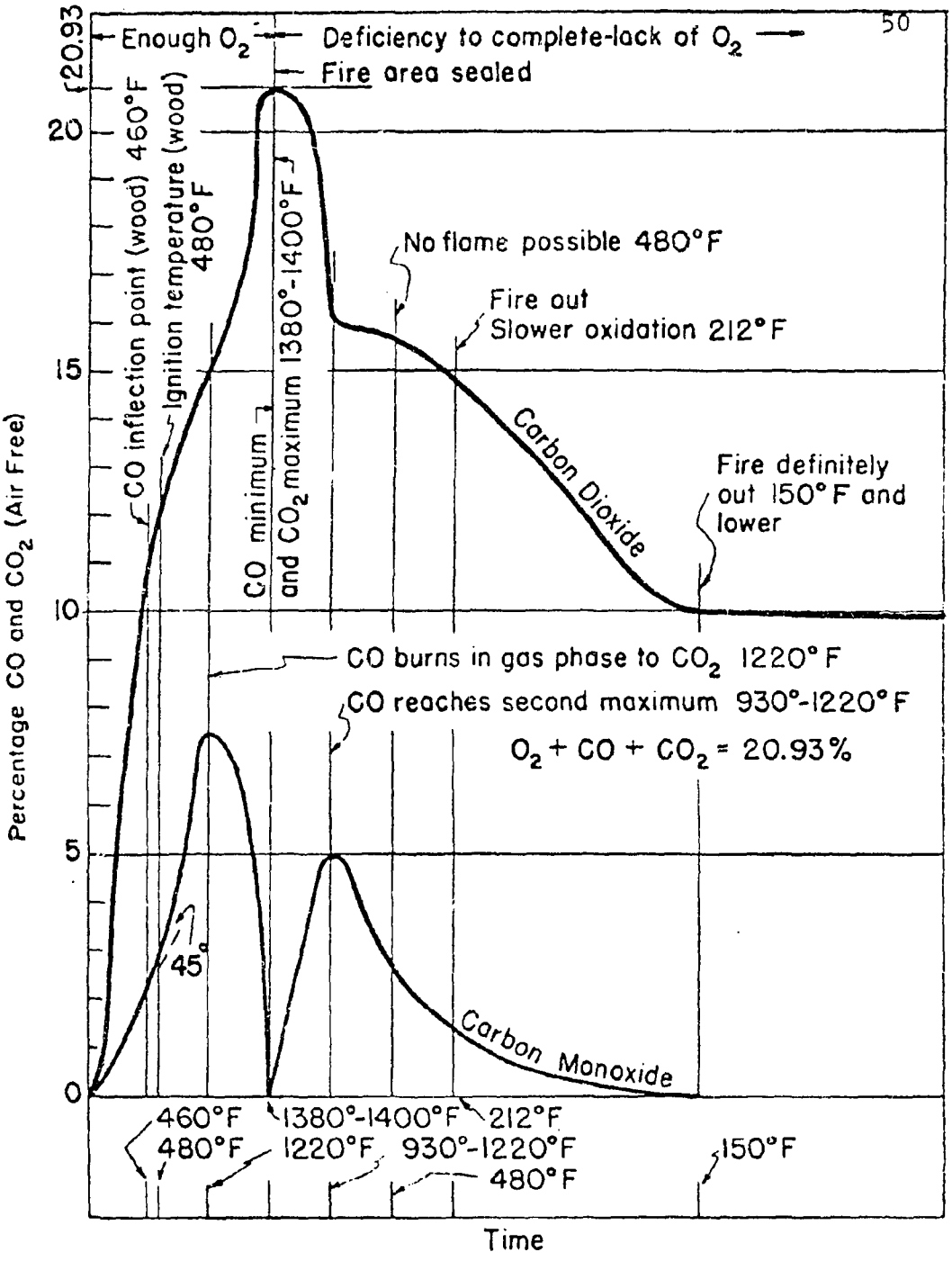


Fig. 8: Time-percent curves (carbon dioxide and carbon monoxide) under ideal conditions of wood fire, before sealing mine fire area and after sealing it. (not to scale)[4]

2. Ventilation With a Reduced Air Supply

If a mine fire, which has been burning and heating the fire zone for some time, is cut off from its oxygen supply, it will produce gases of a similar composition as those generated by destructive distillation. Ventilation standstills, either by sealing or by ventilation forces developed by the fire itself, can cause such oxygen cut offs. The composition of distillation products depends mainly on the substance to be distilled and the temperature. As examples, Fig. 9a[147] shows the distillation gases from anthracite and Fig. 9b[47] from gas coal as a function of the distillation temperature. One sees that of the flammable gases the production of CO is with 5 - 10% more or less constant throughout the temperature range. The hydrocarbons, mainly CH_4 plus ethane and illuminants, forming at low temperatures the highest proportion of flammable gases, decrease with temperature. Hydrogen increases with temperature, especially for the higher ranking coals where it does not appear below 300°C.[147]

Distillation products of wood contain mainly CO_2 (up to 60%), CO (up to 35%), hydrocarbons (up to 10%) and much smaller quantities of CH_4 and H_2 than produced by coal.[23]

The composition of fire gases produced by combustion or distillation can be changed by secondary reactions. The producer gas reaction $C + CO_2 \rightarrow 2\ CO$ has already been mentioned (Fig. 7b). The water gas reaction, taking place when water or steam is brought into contact with incandescent carbon, comprises several reactions

$$C + H_2O \rightarrow CO + H_2; \quad C + 2\ H_2O \rightarrow CO_2 + 2\ H_2; \quad C + CO_2 \rightarrow 2\ CO;$$

$$CO_2 + H_2 \rightarrow CO + H_2O$$

and produces H_2, CO, and CO_2.

B. Practical Observations of Gas Compositions Behind Fire Zones

1. Timber Fires

Not too much knowledge exists about the properties of mine fires. Systematic studies have been conducted, mainly with timber as the combustible material.[59] According to Roberts and colleagues[141] mine fires can display two different modes of propagation: through localized heat feedback from the flames, and through all over heat feedback from the fire gases.

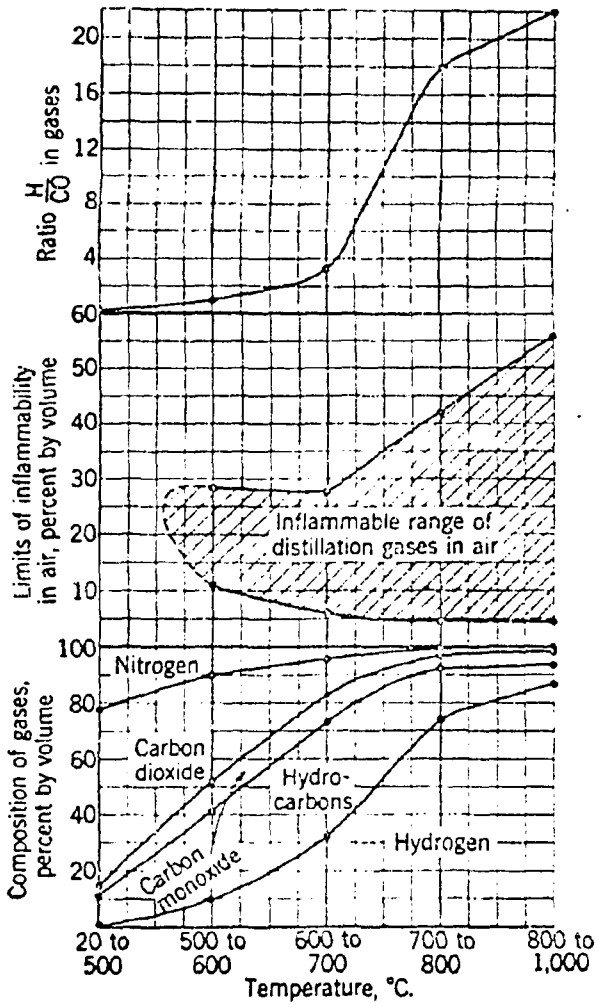


Fig. 9a : Composition, inflammability, and ratio H/CO of gaseous distillation products from anthracite.[147]

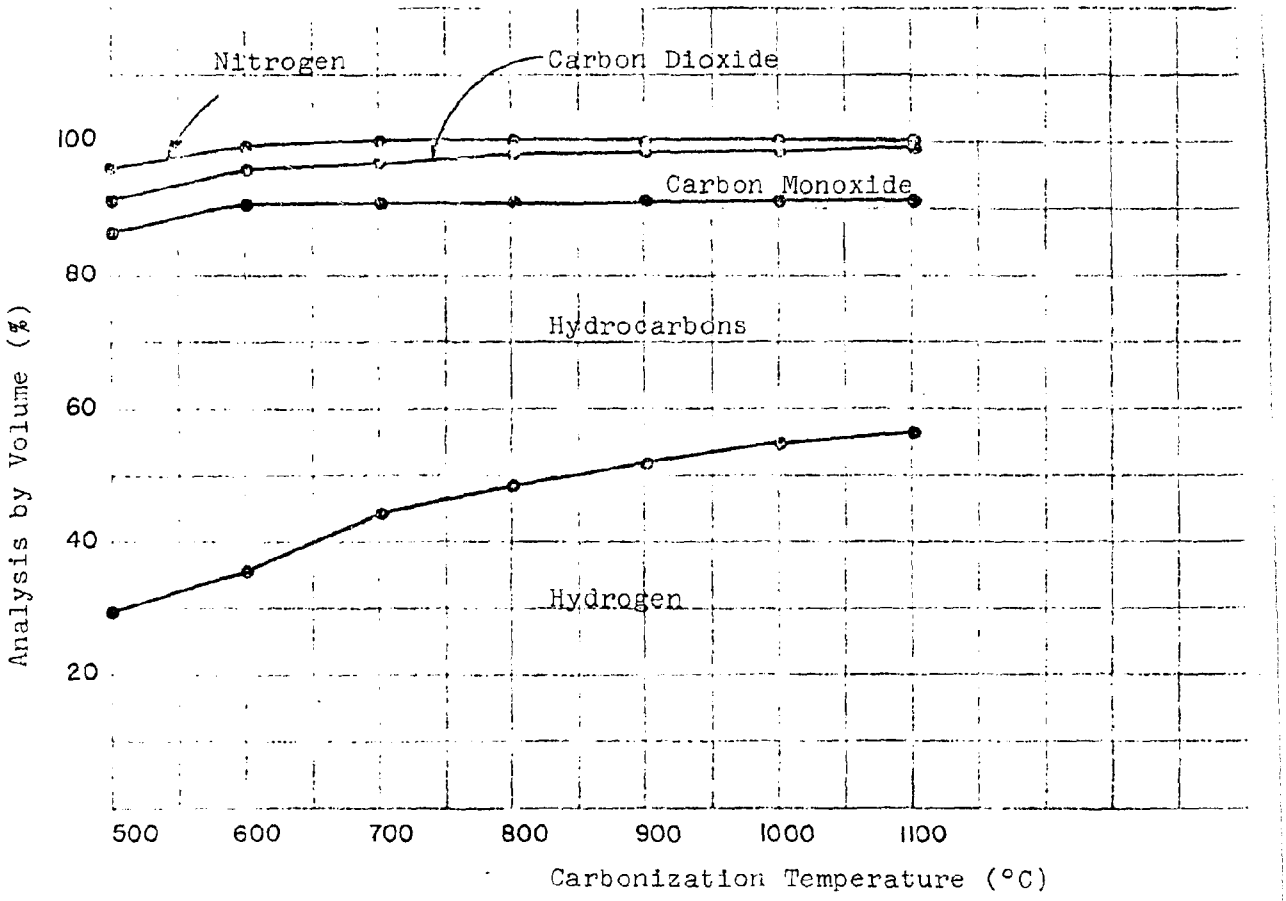


Fig. 9b : Distillation products from gas coal[100]

In fires of the first type (oxygen rich fires) the ventilating current is not heated to temperatures high enough to generate gaseous fuel from combustible material or to light it. Combustion takes place only where the combustible material is heated by the flames. The larger part of the oxygen from the ventilating air current passes through the fire zone without being consumed.

In fires of the second type (fuel rich fires) the ventilating air current has become hot enough to generate gaseous fuel from the combustible material along which it passes. The fire extends until all available oxygen is being consumed. The generation of gaseous fuel continues for some distance downstream.

Whether a fire of the first or second type develops, depends on the type of combustible material, its quantity, the mine roadway size, the ventilation and the intensity of the ignition source. Except for fires of some easily ignitable materials, like mineral oil, most accidental mine fires, being started by relative small ignition sources, develop into oxygen rich fires and stay oxygen rich. When enough timber is available, airway cross sectional areas and air velocities are small and the ignition source is powerful, timber fires can, however, burn fuel rich and oxygen rich timber fires can develop into fuel rich fires by reduction of the air velocity.

The fumes of fully developed oxygen rich timber fires have an oxygen deficiency of up to approximately 6 - 8%. The combustion product is mainly CO_2, mixed with up to 0.5% CO. The fumes of fully developed fuel rich timber fires are virtually depleted of oxygen. They contain up to 20% CO_2, mixed with up to 12% CO and 4% H_2.[59] Roberts and colleagues state as average values for oxygen rich timber fires[143]

3 - 5% CO_2, 0.1 - 0.5% CO, 16 - 18% O_2

and for fuel rich timber fires[142]

18 - 20% CO_2, 5 - 8% CO, 2 - 5% H_2, 0 - 1% O_2.

2. Coal Fires

No data could be found in the literature on stable fuel rich coal fires. If a coal fire by reduction of the ventilation becomes fuel rich, this is only a temporary phenomenon and the fire returns after a short time to the oxygen rich state. The reason may be that coal has a lower volatile content than timber and that substantial

generation of volatile fuel starts only at higher temperatures. When, as in producer gas generators, coal fires burn in a fuel rich mode, the ratio airway perimeter to cross sectional area has to be much higher than it is in coal mine airways.

The fumes of ventilated coal fires contain as combustion products mainly CO_2, CO, and H_2O, accompanied by unburned H_2 and hydrocarbons, mainly CH_4. Since few systematic studies on the composition of combustion products of coal mine fires exist, data from descriptions of several hundred fires, contained in the literature, were extracted. Additionally, several mine inspector reports were evaluated.

The results show that in ventilated coal mine fires more than half of the oxygen consumed is used to produce CO_2. The CO_2 concentrations are usually below 5%, but can rise to higher values. The highest concentration (15.3%) was observed in a timbered roadway in a lignite coal seam.[104]

The carbon monoxide production was in all cases much lower than the carbon dioxide production, the lowest ratio CO_2/CO reported being 2.44.[57] Both[15] states that more than 10,000 gas samples taken in the West German coal mines showed an average ratio of $CO_2/CO = 10$ and that this value was confirmed by most fire experiments. An estimate of the proportion of CO in the fire gases can be made from the carbon monoxide/oxygen deficiency ratio also. If the oxygen deficiency were caused by the combustion of carbon only, the relation between the CO_2/CO ratio and the CO/O_{2def} ratio is $CO_2/CO = 100/(CO/O_{2def}) - 2$. With carbon accounting approximately for 95% of the oxygen consumption in the combustion of anthracite and for 85% in the combustion of high volatile bituminous coal, this relation should indicate the approximate order of magnitude. Values of the CO/O_{2def} ratio calculated from reported gas samples were between <1 and 23.5%, the average being around 10%. It is accepted[189] that CO/O_{2def} ratios of 0.5 - 1% indicate with almost certainty the presence of a heating and that with increasing fire intensity ratios as high as 10 or more should be expected. Very high ratios usually indicate producer or water gas reactions. Neumann and colleagues[122] report that ratios of up to 60% have been observed.

Hydrogen was found in small concentrations below 0.5% only. When higher concentrations occurred, they could be explained as the result of coal distillation shortly after the sealing was completed (0.53%[27], 1.3%[178]); or in

unventilated cavings (6.36% H_2 airfree[147]); or of a water gas reaction caused by foam application (1.56%,[145] several minor explosions[41]); flooding (0.57%,[186] 0.6%,[48] explosion[8]); burning material falling into water (1.4%[48]); or a timber fire in a very wet lignite coal seam (7.9%[104]). The ratio H_2/CO_2 was in almost all cases lower than 0.1. It exceeded this value only in some cases of sealed areas or of larger water gas reactions, like in the instances just mentioned; but even here, the H_2/CO_2 ratio stayed below 0.3 or exceeded it only slightly. Only in the case of the timber fire in a wet lignite coal seam,[104] a value of 0.6 was observed.

Hydrocarbons found in fumes comprise mainly methane Other hydrocarbons are produced in larger quantities by distillation processes, but even there, they account for less than 20%, the rest being methane. In mine fires their concentrations are so low that they are usually not determined separately but are combined with CH_4 and expressed as such.

Methane plays a different role than the gases discussed so far. Only part of the CH_4 found in fumes is produced by the fire. All coalbeds contain CH_4, of which some is stored as free gas molecules in the fracture porosity, but the main portion of which is adsorbed to the coal in its micropore structure. The amount of gas stored in the coal depends on the gas pressure in the fractures. If the pressure is reduced, adsorbed gas will be released. Since the gas moves through the micropore structure by diffusion, this is a slow process, qualitatively described as "slow bleeding". The speed of the gas release depends mainly on the concentration gradient of the methane in the coal or on the size of the coal particles formed by the fracture system of the coalbed and the gas pressures in this system. Whereas powdered coal can release its gas in a few hours, the desorption process of particles of the size of 1/2 inches diameter lasts months or years.[28]

The gas pressure in an undisturbed coalbed can be of the order of several hundred psi. Since the pressure in mine workings is approximately equal to the atmospheric pressure, methane will flow from the coalbeds into mine workings. As the coal surrounding mine workings is gradually drained of gas, gas pressure and resulting gas flow decrease with time. Although this decrease may be accelerated by the fracturing which the coal experiences due to increased stresses,[85] it is still a very slow process and it is justified to consider the rate of methane release from coal faces, ribs, and pillars as roughly constant over short time periods.

When coal is mined, an increased methane emission results. This is due to the advance of the coal face into regions of high gas pressures and degradation of coal while being mined and transported away. How high the increase is depends on the mining method and the rate of face advance. In the face area the methane emission can be expected approximately to double.[28,84] When the mining operations stop, the increased methane emission will, within the next hours, only gradually taper off.

Additional methane can enter the mine workings from wastes or sealed off mine sections when atmospheric pressure changes or ventilating pressures provide a propelling pressure difference. The magnitude of the methane emission in U.S. bituminous coal mines has lately been statistically evaluated by Irani and colleagues.[69]

How much of the methane found in the fumes of a fire that originates from the fire itself is difficult to answer. Since methane, like hydrogen, is a distillation product and has a slightly higher ignition temperature than hydrogen and is produced below this temperature in larger quantities than hydrogen, the quantity of methane produced by the fire in the fumes would be higher than that of hydrogen - if the latter does not come from a water gas reaction. Since hydrogen is usually found in much smaller concentrations than methane, it can be assumed that the ordinary methane made in a coal mine is responsible for most of the CH_4 in fumes. This finds its expression in the British memorandum on sealing off fires underground[189] which states: "The permissible extent by which the ventilation can be reduced can only be determined by a sound knowledge of the make of gas within the district".

When a coal mine fire is sealed, the atmosphere in the sealed off area will experience a decrease in oxygen due to combustion and adsorption, and an increase in methane content due to continued emission from the coal. Both carbon dioxide and carbon monoxide, as products of combustion, will initially increase in concentration. After the fire has been reduced in its intensity or has been extinguished, the carbon dioxide concentration will be increased by oxidation and decreased by adsorption to the coal, solution in water, and by dilution with other gases. The overall result is a constant or slightly dropping carbon dioxide concentration. When the fire zone has cooled down, carbon monoxide is no longer formed and it disappears gradually by oxidation to CO_2, although not always.[107] Still, the carbon monoxide/oxygen deficiency ratio is generally accepted as a scale for the presence of a fire or heating. Hydrogen disappears by bacterial oxidation also.

The literature is replete with data on changes of the gas composition in sealed fire areas. As an example, Fig. 10[13] shows the composition of the atmosphere behind the seals of a coal mine fire. In timber fires in noncoal mines, CO_2 and N_2 become eventually the dominant constituents of the sealed atmosphere.

Except for methane, all the gases discussed so far are products of the fire. When a fire is fully developed and has reached an equilibrium state, the production of these gases is proportional to the flow rate of the ventilating air current and their concentration in the fumes is approximately constant, irrespective of the magnitude of the flow rate. Every change in the ventilation will mean a disturbance of the equilibrium state and the composition of the fumes will change, until a new equilibrium state has been reached. A reduction of air flow will make a larger amount of distillation products enter the fumes, until the reduced oxygen supply has reduced the heat supply for distillation processes also. This is one reason why, as all experts agree, unduly sharp reductions of ventilation should be avoided when sealing a fire until the seals can be closed. An increase in ventilation will dilute the combustion products to lower concentrations, until the increased oxygen supply has fanned the fire to a greater intensity.

C. Oxygen Adsorption of Coal

It has been mentioned that coal can oxidize at every temperature. Since at low temperatures a strong resemblance to physical adsorption exists,[148] the resulting oxygen consumption is frequently called adsorption, or less correctly, absorption. Due to its importance for predicting spontaneous heatings and for successful sealings, this process has found early and careful attention.[26,55,135] Burrell and Seibert[22] write in 1912 that the absorption of oxygen by coal "may be so rapid that the fire plays only a minor part in depleting the oxygen of the air in the burning section. This is particularly the case when the area on fire is very small in proportion to the area inclosed. That such absorption takes place is fortunate, because the removal of the oxygen in an inclosed section is hastened and the atmosphere more rapidly becomes incapable of supporting combustion". Rice, Paul and von Bennewitz in their study of 59 coal mine fires[139] state in 1927 that most of the oxygen in sealed off areas is consumed by absorption. Willett[188] comes, however, to the conclusion that wide variations in the extent and rate of oxygen content reductions exist and that high concentrations are not necessarily an indication that

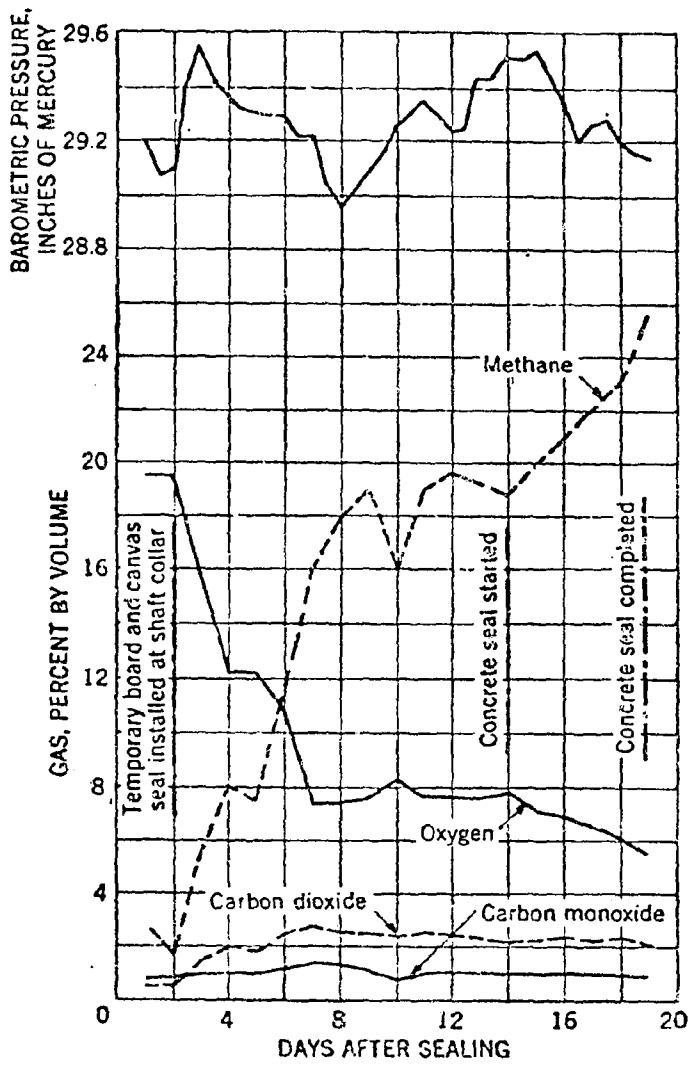


Fig. 10: Record of gas composition in sealed area after sealing an actual coal-mine fire at the shaft collar.[13]

leakage takes place. It has already been discussed that the solid coal-oxygen complex, produced by oxidation at low temperatures, has a retarding effect on the oxidation process.

Fig. 11[107] shows as an example the rapid oxygen decrease to 5% within one week in a sealed off coal mine section without a fire. Fig. 12[188] shows the slow decrease in the waste of a longwall face.

D. Explosibility of Fire Gases

1. General Discussion

It can be shown in different ways that the carbon monoxide content alone in the fumes of ventilated fires is in most cases too low to make the fumes explosive. If in the air entering the fire, 20.9% of oxygen is associated with 79% of nitrogen, every part of oxygen consumed by the fire sets 79/20.9 = 3.78 parts of nitrogen free. According to Table 4, one part of carbon monoxide can be inerted with 4.12 parts of nitrogen. All carbon monoxide will therefore be inerted by the nitrogen in the firegases, as long as the CO/O_{2def} ratio is equal or or smaller than 3.78/4.12 * 100 = 91.7%. This is a ratio which is rarely found, at least it has not been reported in the literature.

Carbon monoxide in the fire gases is always associated with carbon dioxide, which itself is inert and sets additional nitrogen free. Under the same assumptions as above for the air entering the fire zone and with 2.16 parts of carbon dioxide used to inert 1 part of carbon monoxide (Table 4), one obtains that all CO in the fire gases can be inerted with the available nitrogen and carbon dioxide when the CO_2/CO ratio is equal to 0.37. If the CO_2/CO ratio is higher, additional nitrogen and carbon dioxide is available. Fig. 13, which is based on Table 4, shows how much hydrogen or methane in the fire gases (expressed as H_2/CO_2 and CH_4/CO_2 or as H_2/CO and CH_4/CO ratios) can in this way, at different CO_2/CO ratios, be inerted. The lowest CO_2/CO ratio found in the evaluation of gas analyses for ventilated fires was 2.44, although most values were generally much higher. Fig. 13 shows that at CO_2/CO = 2.44 not only all the carbon monoxide but also a hydrogen content of up to H_2/CO_2 = 0.275 can be inerted with the carbon dioxide and the residual nitrogen resulting from the combustion process. For higher CO_2/CO ratios, the inerted hydrogen quantity is even larger. Since most of the H_2/CO_2 ratios found were lower than 0.1 and only some, for the described reasons, approached 0.3 or exceeded it,

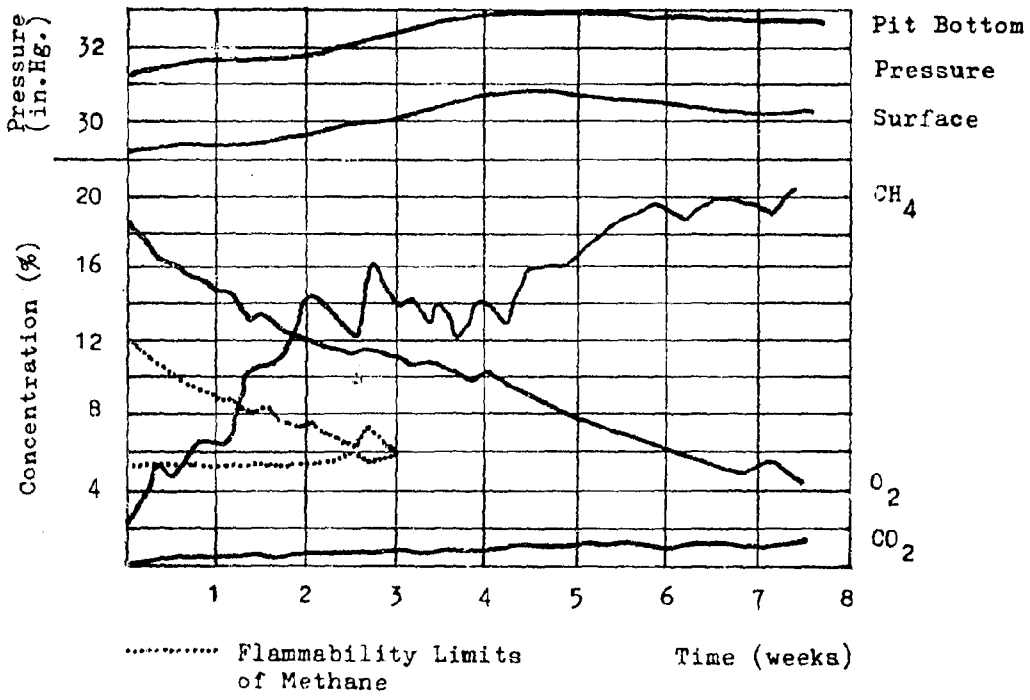


Fig. 11: Chart showing average analysis of all samples taken in sealed district.[107]

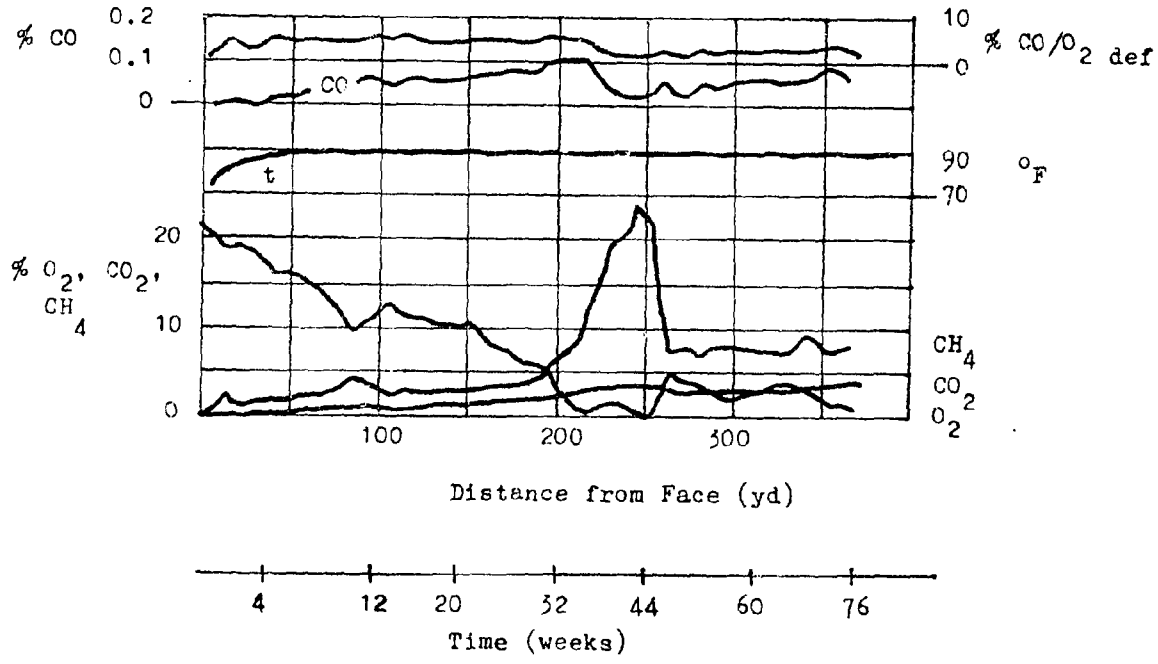


Fig. 12: Composition of the atmosphere in a waste under normal conditions. Dunsil Seam, Colliery B.[188]

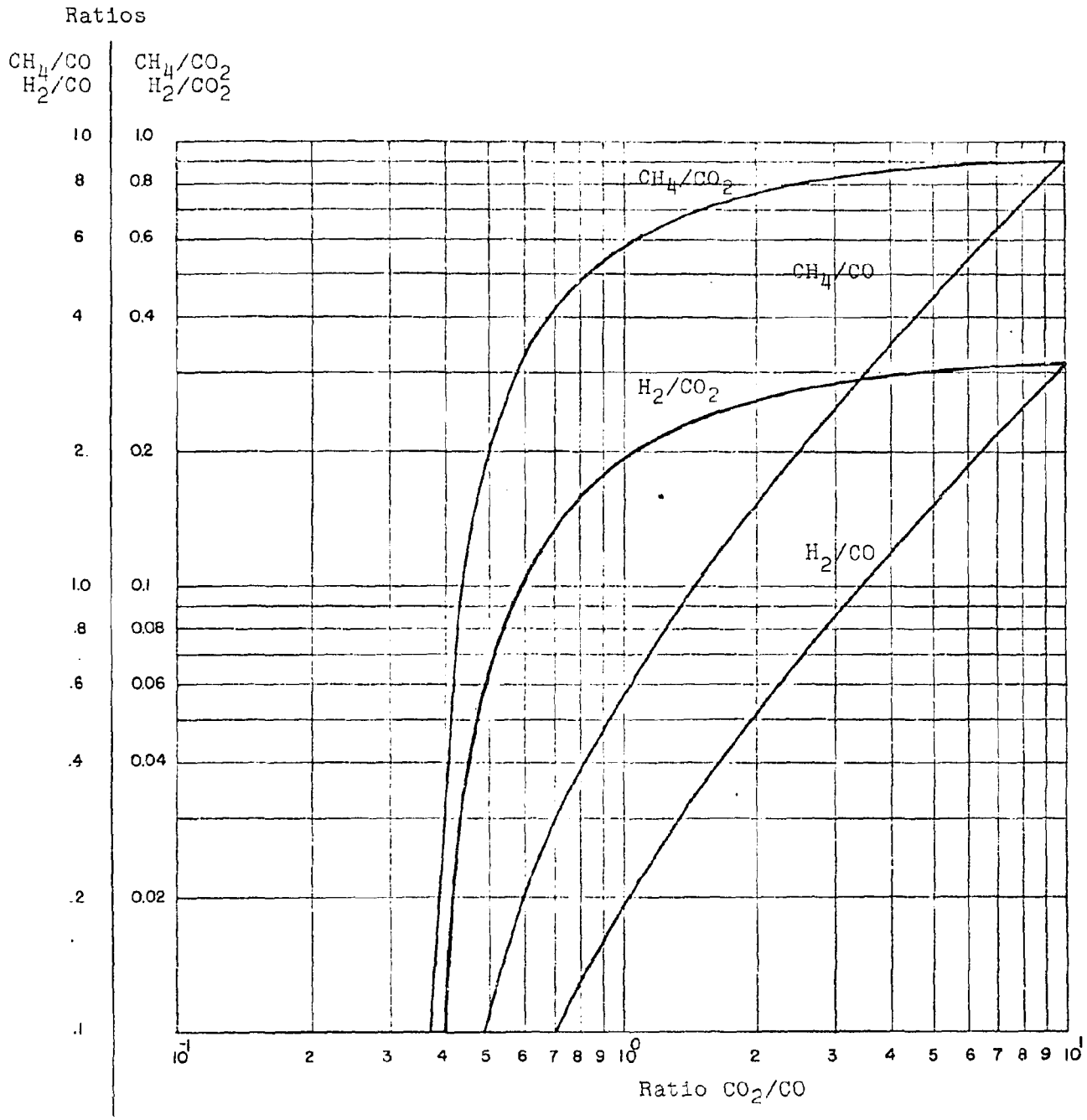


Fig. 13: Methane or Hydrogen (Besides Carbon Monoxide) Inerted by Carbon Dioxide and Residual Nitrogen Produced by a Fire

one can conclude that in almost all ventilated fires, the carbon monoxide and hydrogen produced by the fire can be inerted by the carbon dioxide and the residual nitrogen resulting also from the fire. When no other combustible gases are present, the fire gases of ventilated fires should generally be nonflammable. Exception from this statement are firegases with high carbon monoxide or hydrogen contents due to distillation, producer, and water gas processes. The fumes from fuel rich timber fires are on the borderline of being flammable or not.

One should bear in mind that in mixtures with other flammable gases, like methane, the carbon monoxide and hydrogen from a fire contribute to the flammability of the mixture. The carbon dioxide and residual nitrogen, which are capable to cope with the carbon monoxide and hydrogen in inerting them, are no longer available to inert any other flammable gases.

2. Opinions on the Explosibility of Combustion Products

The danger of explosions caused by fire gases has been discussed for a long time. Burrell and Seibert[22] state in 1912 that "the data thus far accumulated by the Bureau of Mines indicate that the danger from the formation of explosive mixtures of CO or of H_2 is subordinate to the danger from CH_4". Burrell and Oberfell[23] conclude, however, in 1915, from a study of one particular explosion, that it was caused by the CO and CH_4 generated by the fire, which after an airflow reversal had been forced back into the fire zone. Ryan[146] states in 1926 that "all mine fires are liable to generate some combustible gases, but the probability of an underground fire itself generating sufficient combustible gases to cause other than slight explosions is extremely slight. The great hazard, therefore, is the CH_4 liberated in the mine". Scott, in his comprehensive study on anthracite mine fires[148] seems to have a similar opinion, since he writes that "in a sealed fire area the safety depends on the hot coal removing the oxygen before normal CH_4 production can form an explosive mixture". Mason and Tideswell[103] comment that it was shown in their experiments "that a blazing fire in a restricted space is unlikely to create an explosive mixture by the distillation of inflammable gases from the coal, but that most of the gases evolved are burnt at the open fire". The British memorandum on sealing off fires underground[189] warns that, when a fire is well developed and there is much hot material, dangerous accumulations of flammable gases may be formed on the down-

wind side of the fire. Usually they are protected from ignition by nonflammable combustion products, but when blown back over the fire they can pose a serious hazard. The explosion hazard arising from mine fires is, however, mainly due to the accumulation of firedamp, after the ventilation has been stopped or seriously reduced. Baltajtis and Egorov[8] report that of 580 investigated fires, 50 were accompanied by explosions, one of these in a nongassy mine attributed to distillation products. Otasek and Bajer[132] comment that distillation products in well sealed fires do not pose an immediate threat. Dangerous conditions are rather caused in gassy mines by the CH_4, which together with the distillation products lets the sealed atmosphere become explosive after a certain time.

E. Changes in the Composition of Fire Gases After Inert Gas Injections

When mixtures of inert gases with air or inert gases alone are passed over a fire, the effect on the gas composition should be the same as a reduction or a stopping of the airflow. Scott[148] observed that in steady state conditions the oxygen concentration of the air passing over a fire appears to have little effect on the composition of the primary oxidation products, only on the rate at which they are formed. Since the inert gas flow cools the fire zone, distillation processes will be less pronounced than after an airflow reduction or stoppage.

Those practical observations about the composition of fire gases after a nitrogen injection into the fire zone, which have been reported in the literature, give no indication of significant changes in the ratio of CO_2, CO, H_2, and CH_4. Usually they are all diluted by the nitrogen in the same proportion. If changes occur after an injection into a sealed district, tney can be explained by the gas movement from the interior of the district towards the sampling points.[130]

Carbon dioxide, although in mining practice called an inert gas since it is incombustible and deprives fire of oxygen, is not truly inert but reacts chemically with carbon in the producer gas reaction: $C + CO_2 \rightarrow 2CO$. The ratios of CO and CO_2 which are at different temperatures in equilibrium have been shown in Fig. 7b. The high CO concentrations, which even at low temperatures are found in the equilibrium state, have led to warnings against the use of carbon dioxide. It is, however, frequently overlooked that the reaction velocity of the producer gas reaction is remarkably low. Its reaction rate constant is only 1/100 to 1/1000 of that for the combustion reaction

$C + O_2 \rightarrow CO_2$.[86] Although no generally accepted mechanism for the reduction of a stream of CO_2 by heated solid carbon exists, this fact can be explained with the hypothesis that the volume of CO flowing from the interface is double the volume of CO_2 approaching it and that the adverse CO flow causes an increased diffusional resistance.[50] With the reaction rate constant of the producer gas reaction so much lower, it can be expected that the concentration of CO behind a mine fire ventilated with 100% CO_2 will still be lower than the CO_2 concentration in a mine fire ventilated with air. Since the producer gas reaction is endothermic and cools the coal surface, the production of CO will, anyway, only be a short phenomenon.

Due to the technical importance of producer gas reactions, detailed measurements of reaction rate constants for this process in fuel beds as a function of temperature, size, volatile content, ash composition, moisture, catalysts, preheating, etc., exist.[29,82] No data could, however, be found for channels of sizes comparable to mine workings.

Observations and opinions about the practical importance of the producer gas reaction when using CO_2 for extinguishing fires vary accordingly. Wald[179] reports that CO_2 blown into a fire for a short time formed such an amount of CO that the fire gases contained concentrations of 5 - 6%. No particular mentioning of high CO concentrations is, however, made by most other users. Belik and colleagues[10] measured CO concentrations which were approximately proportional to the CO_2 values, but did not exceed 0.4% at CO_2 concentrations of 27%. Westfield and colleagues[186] found that after 135 minutes of CO_2 injection into a sealed coal fire the H_2 content reached peaks of 1.2% (CO_2 = 49.4%) and after 200 minutes, the CO and CH_4 contents peaked with 2.0 and 1.4% (CO_2 = 69.1%). The main disadvantage of CO_2 as a fire extinguishant is seen by Osipov and colleagues[128-9] in its high absorption rate by coal and its poor mixing with the fire gases due to a much higher density.

VII. INERT GAS REQUIREMENTS FOR FIGHTING MINE FIRES

Inert gases can be utilized for fighting mine fires in the following ways:

the prevention of gas explosions when fires are fought directly or seals are constructed or closed;

the extinction of fires by lowering the oxygen concentration of their atmosphere; and

the effective sealing of fire zones with pressure chambers.

In mines without explosive dangers from flammable gases, they can be used with advantage to move the fumes of fires towards the return airways and to keep the intake airways free of smoke, without fanning the fire unnecessarily.

There is, naturally, considerable overlap among these different ways of inert gas application and every method of using it will partially accomplish the aims of the other methods.

Injection lances and portable fire extinguishers shall not be considered at this place since they are suited for minor fires, either concealed or in their incipient stages only. The discussion shall furthermore be limited to nitrogen, carbon dioxide and mixtures of these two as the inert gases used.

A. Prevention of Gas Explosions During Direct Attack on Fire and Construction of Seals

The main concern while fighting fires directly or constructing seals is to prevent gas explosions. As has been described in chapter II B., it is for this reason general practice to reduce the ventilation of a fire site to such a minimum only, which is still large enough to prevent explosive mixtures from forming and to move the fumes of the fire in the desired direction. The continued, although diminished provision of the fire with oxygen, has to be tolerated.

It has likewise been described in chapter II B. that explosions after closing the seals are prevented, when the oxygen in the sealed area is faster consumed and inert gases are faster produced than flammable gases can accumulate. The methods to accomplish this aim, large sealed spaces and fires of a certain minimum intensity, have been discussed together with their shortcomings and the practical compromises. Due to the explosion danger, it is common practice in coal mines to close seals only after all men, except for those immediately involved, have left the mine and not to approach the seals again before waiting periods between 8 hours[125] and 72 hours[41] have passed. Much destruction of seals by explosions are reported in the literature. Willet and colleagues[189] state that owing to lack of data it is unknown how frequently ignitions of gas occur but that it

would be reasonable to assume that more have occurred than have been observed. A Russian figure[8] of 50 explosions in 580 investigated mine fires has already been mentioned in chapter VI D. 2.

Inert gas injections can be helpful in preventing or reducing gas explosion dangers without the shortcomings of the conventional methods. Osipov[127] mentions that the use of carbon dioxide has become mandatory in the Donbass and the use of nitrogen in Czechoslovakia during sealing operations for rendering methane-air mixtures nonexplosive. Gorb and Stalerov[53] conclude from their experiments that it is advantageous to create behind light temporary seals (plastic foil) an inexplosive atmosphere before erecting permanent seals or continuing the direct attack on the fire.

Due to the results obtained on the composition of fire gases and their explosibility in chapter VI, it seems permissible to base calculations of inert gas requirements in coal mines in a theoretical investigation on the normal methane evolution. As shown in chapter VI D., the carbon monoxide and hydrogen produced by ventilated fires is in almost all cases inerted by the carbon dioxide and residual nitrogen resulting from the fire. The methane emission can be considered to remain approximately constant, at least over a period of several days, when direct fire fighting measures and construction of seals can be carried out. An exception are face areas with coal production, where after a stop of the production, the methane emission during the next hours tapers off to approximately half its peak value.[28,84]

In the case of a practical application of inert gas in a real, existing mine fire one would, of course, base the inert gas requirements on the measured presence of flammable gases, determined with the help of volume flow measurements and gas analyses.

1. Phlegmatizing of Methane With Inert Gas

The volumes of carbon dioxide and nitrogen required to extinguish methane flames in air have been given in Table 4, and are 3.2 parts of carbon dioxide or 6 parts of nitrogen for 1 part of methane. For mixtures of nitrogen and carbon dioxide, as are produced by inert gas generators, the required volume parts of mixture per part of methane can be calculated from

$$L = \frac{100}{\frac{\%CO_2}{3.2} + \frac{\%N_2}{6}}$$

For the optimal product of inert gas generators with 21% CO_2 and 79% N_2, one obtains 5.07 volume parts. Values for other compositions of CO_2 and nitrogen mixtures are given in Fig. 14.

By adding these inert gas quantities, all methane will be fully phlegmatized. In explosibility diagrams of the type shown in Fig. 5, the composition of the resulting inert gas - methane - air mixture will be indicated by the inerting boundary, which separates the explosive and potentially explosive gas mixtures from the nonexplosive ones. When a gas mixture has reached this boundary, only an additional admixture of flammable gases can make the mixture explosive again, otherwise it remains always nonexplosive.

How much methane has to be inerted can be estimated from the normal methane evolution in the fire zone and pertinent intake airways. Most of the intake airways, in which the airflow after the outbreak of the fire is not substantially reduced, can for this purpose be neglected - since the major part of their methane evolution does not travel through the fire zone but is diverted to other airways.

The inert gas quantities obtained by multiplying the CH_4 emission by the factors 6 for nitrogen, 3.2 for carbon dioxide and the values from Fig. 14 for mixtures of both, should furthermore be multiplied by a safety factor. This moves the composition point of the gas mixture in Fig. 5 to the right, deeper into the nonexplosive region. For the safety factor, a value of 2 is suggested because experience shows that under continuous monitoring of ventilation conditions, such a factor is large enough. For active coalfaces, where the CH_4 evolution drops after the coal production stops, this factor can gradually be reduced and after a few hours be omitted.

Another way to estimate the inert gas requirements can be based on the fact that, when made nonexplosive by diluting with air, every part of CH_4 has to be "inerted" by 19 parts of air. If the same degree of safety is accepted as under ordinary ventilation conditions, 1 part of air can be replaced by 6/19 parts of nitrogen, 3.2/19 parts of carbon dioxide or 5.07/19 parts of a 21% CO_2 - 79% N_2 mixture of both. If a safety factor of 2 instead of the conventional factor of approximately 5, contained in the usual 1% CH_4 limit, is accepted, 1 part of air used under ordinary ventilation conditions can be replaced by 6/(19*2.5) = 0.126 parts of nitrogen, 3.2/(19*2.5) = 0.067 parts of carbon dioxide, or 5.07/(19*2.5) = 0.107 parts of a 21% CO_2 -

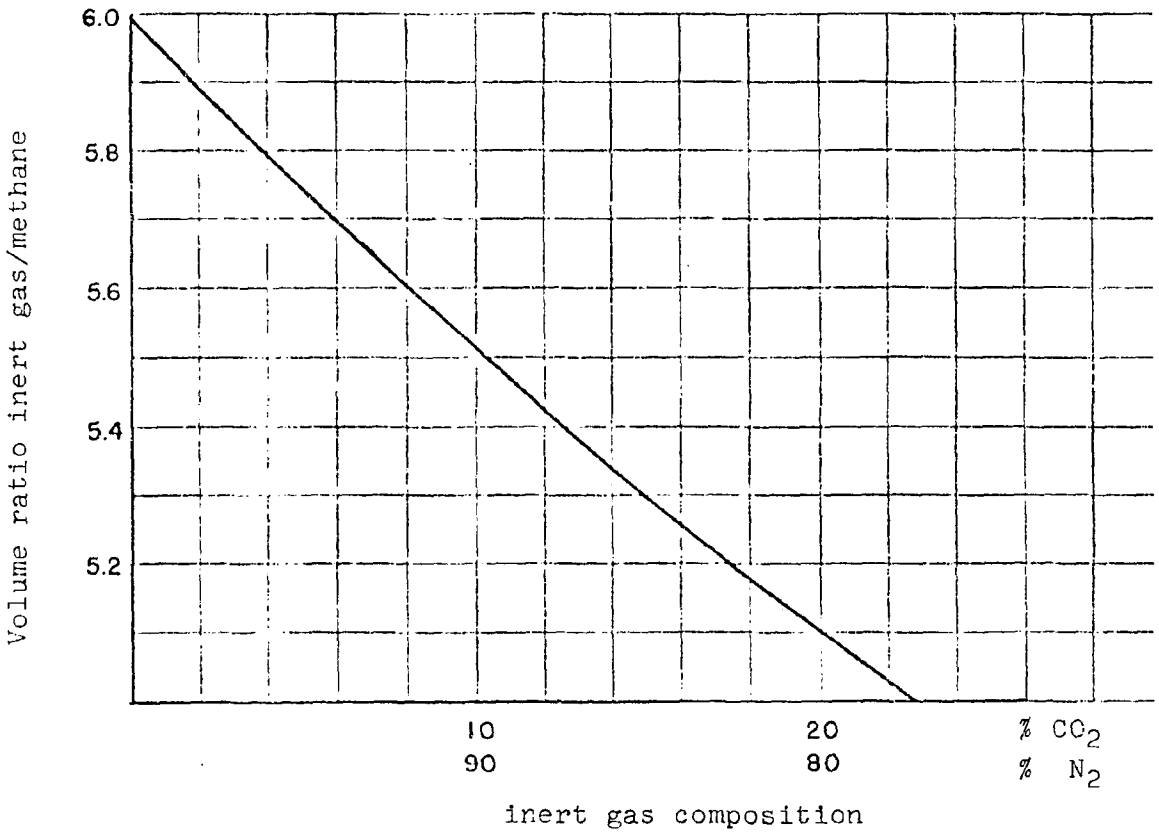


Fig. 14: Required inert gas quantities to fully phlegmatize methane

79% N_2 mixture. For active coal faces these values can gradually be reduced by about one half after the coal production has been stopped.

Methane evolution and airflow rates vary in wide limits with coal beds, their depth below the surface and coal production.[69] No statistical data for the different types of airways could be found, but methane emission variations between 40 and 400 ft^3/min have been reported for coal faces in West Virginia.[30] The inert gas quantities needed to fully phlegmatize the largest encountered methane evolutions can consequently be quite large.

If the flammable gases can be fully phlegmatized with inert gases, the ventilating air current through the fire zone can be completely interrupted without any danger of gas explosions. One has, however, to be careful not to reduce the ventilating air current before the inert gases have passed through the fire zone and filled the total length of those airways, where an airflow reduction might result in explosive gas concentrations.

In many cases, the available inert gas quantities alone will not be large enough to allow a controlled movement of the fumes, and the ventilation with air will have to be partially maintained. Naturally, the airflow rates should be kept as small as possible to prevent an unnecessary oxygen supply of the fire. If carbon dioxide or nitrogen= carbon dioxide mixtures and air are simultaneously used, one has to safeguard that perfect mixing takes place to prevent the formation of air layers floating on top of the heavier inert gas. In the presence of a methane emission from the roof, these layers could allow the formation of explosive gas mixtures. The problem of air layers will occur wherever air leakage takes place also. Chapter IX in this report discusses the minimum velocities required for the prevention of gas layers and the measures to break them up.

2. Dilution of Methane With Mixtures of Air and Inert Gas

If the available inert gas quantities are too small to fully inert the flammable gases, a continued dilution with air has to tkae place to keep the composition within the triangle D of the explosibility diagram shown in Fig. 5. If, with the use of the data published by Jones,[76]

the lower explosive limit in this diagram is approximated by a straight line, the methane concentration at the lower limit can be expressed for methane - nitrogen - air mixtures by

$$(\%CH_4) = 5.2 + \frac{0.3}{33} \quad (\%N_2)$$

for methane - carbon dioxide - air mixtures by

$$(\%CH_4) = 5.2 + \frac{0.86}{19.4} \quad (\%CO_2)$$

and for methane - 21% CO_2 - 79% N_2 inert gas - air mixtures by

$$(\%CH_4) = 5.2 + \frac{0.5}{28.8} \quad (\%\ \text{mixt.})$$

This means that along the lower explosive limit of methane, 1 part of air can be substituted by

1/1.175 parts of nitrogen
1/1.855 parts of carbon dioxide
1/1.325 parts of a 21% CO_2 - 79% N_2 inert gas mixture

Figure 15 shows by how much an air current can be reduced with the injection of inert gas, if methane shall be diluted to the lower explosive limit. As has been discussed in chapter III A., there already exists an excess of oxygen at the lower limit which acts like an inert gas. Replacing this oxygen with another inert gas has, therefore, only a minor influence. The possible reductions in airflow are, therefore, not too large; the total flow of air plus inert gas remains approximately constant.

Not overlooked, however, should be that the oxygen concentration of the atmosphere, with which the fire is ventilated, can be significantly reduced. As will be discussed in the following chapters, the timespan, during which a sealed atmosphere remains in the explosive range, can be considerably shortened also. Equally, the time which passes before a below the explosive limit diluted atmosphere becomes after sealing explosive, can be lengthened.

The flow rate curves in Fig. 15 do not change when a safety factor is used since the factor applies as well to the original airflow without inert gas injection as to the mixture of air and inert gas. The oxygen concentration curve will change, although only slightly, since methane comprises only a small portion of the atmosphere, and air and inert gas maintain, with and without the use of

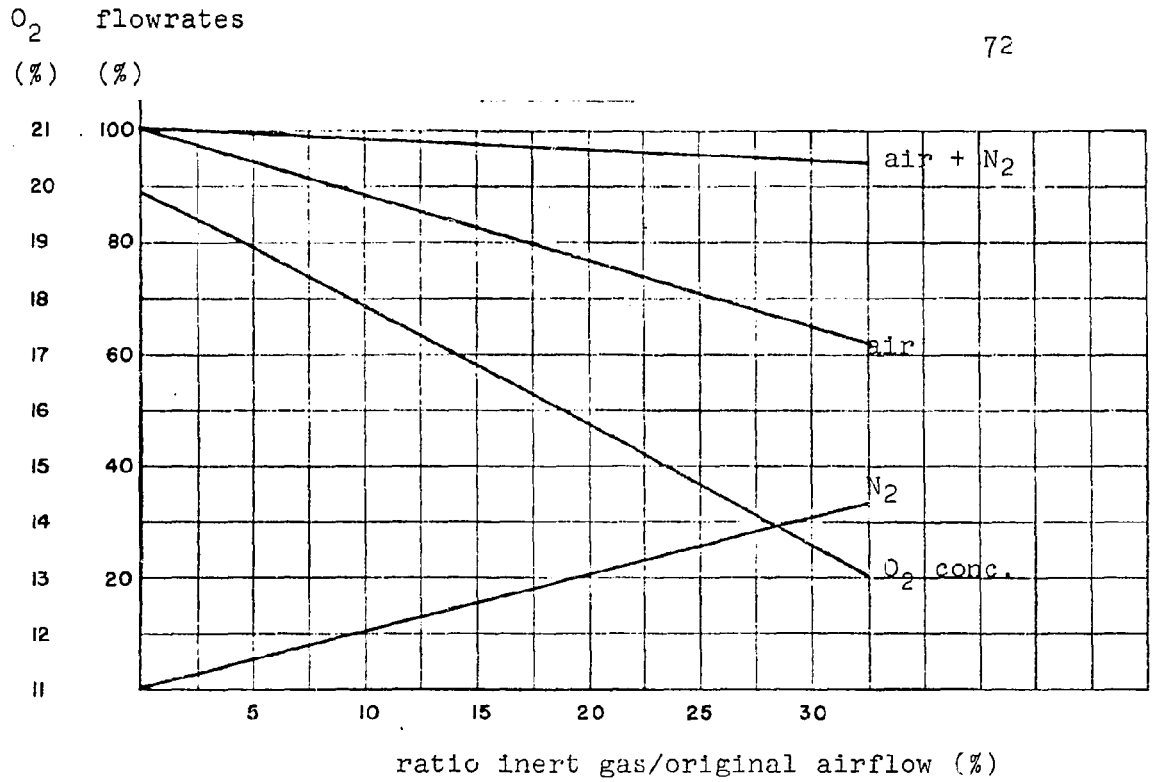


Fig. 15a : dilution with air and nitrogen

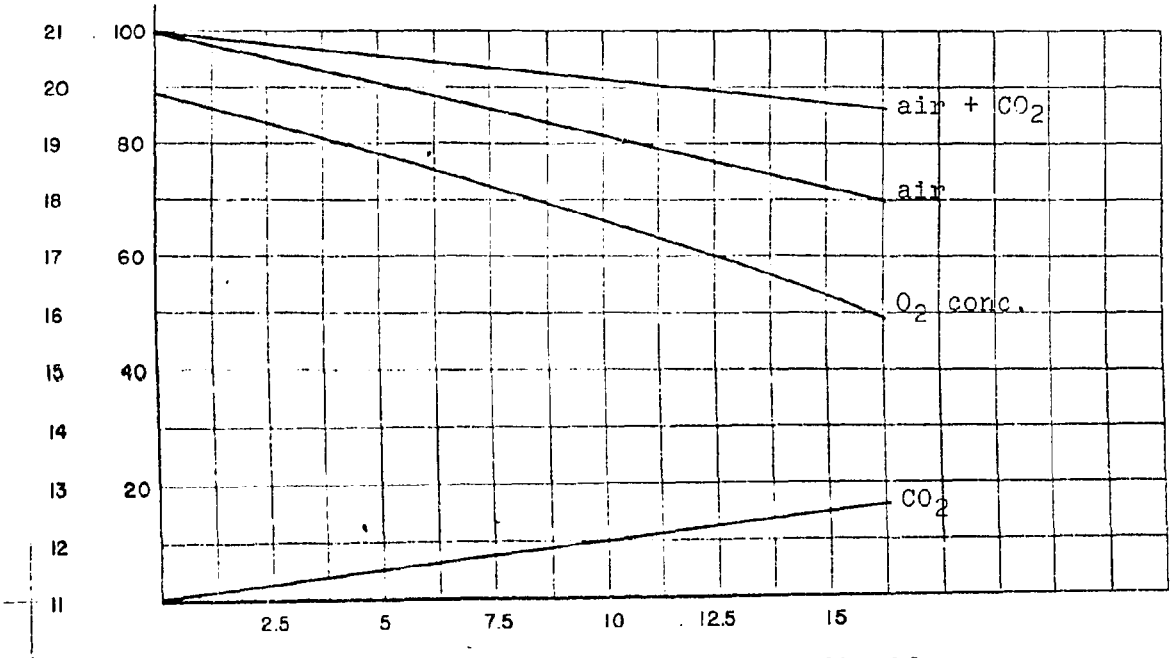
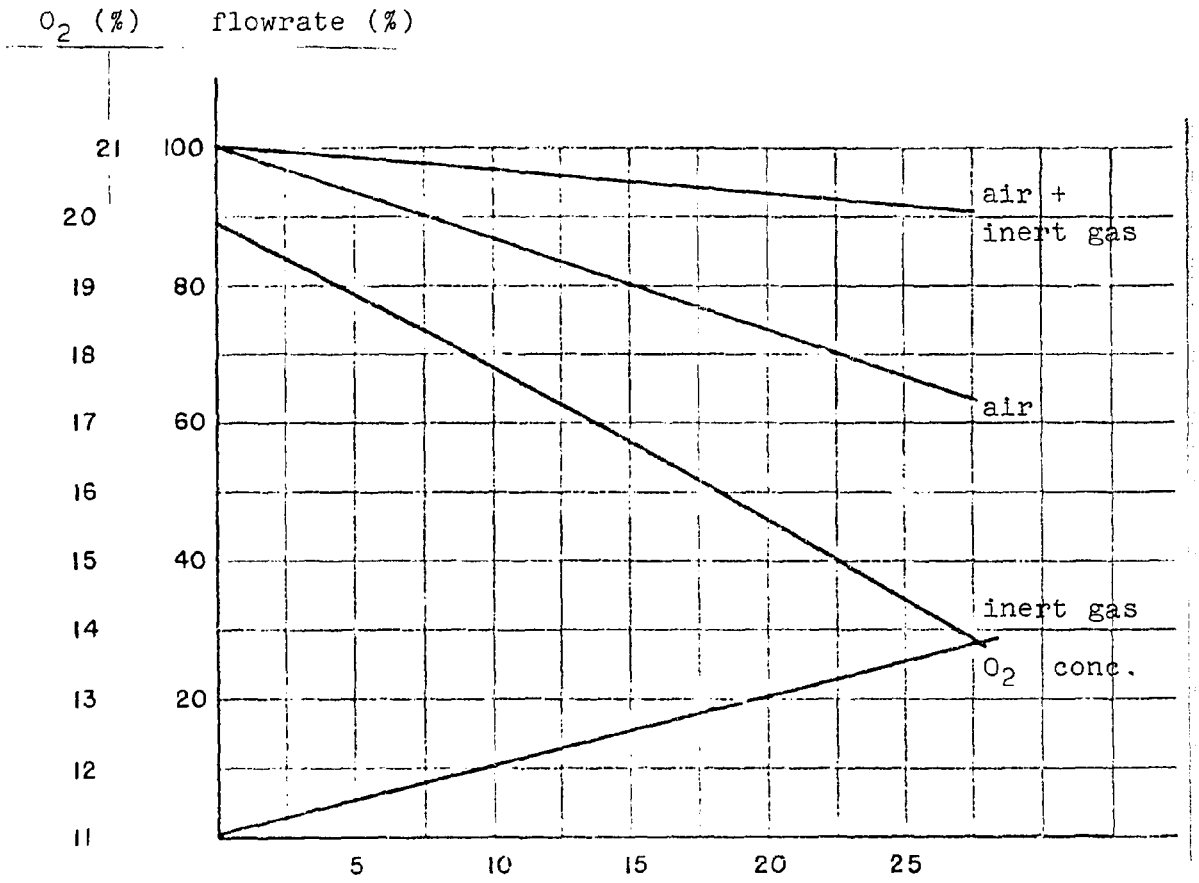


Fig. 15b : dilution with air and carbon dioxide



c : dilution with air and a 21% CO_2 - 79% N_2 inert gas mixture

Fig. 15: Required air and inert gas flow rates for dilution of methane to its lower explosive limit

a safety factor, the same ratio. To demonstrate this, Fig. 16 shows the lower permissible methane concentration of methane - air - nitrogen mixtures for a safety factor of 2 in an explosibility diagram with the oxygen concentration entered into this diagram also.

B. Prevention of Gas Explosions After Sealing of Fire Zone

Under the assumption that perfect mixing of the gases comprising the atmosphere in a sealed space takes place, and no gases disappear due to chemical reactions or sorption, the concentration change for every constituent of the atmosphere can be described by

$$dc = \frac{d\tau}{V} (\dot{q}_i - \dot{q}_e\, c)$$

where c = concentration of constituent in sealed space
τ = time
V = volume of sealed space
$\dot{q}_i$ = flow rate of constituent into sealed space
$\dot{q}_e$ = flow rate of gas mixture leaving sealed space

With the boundary conditions: $c = c_o$ for $\tau = 0$ one obtains

$$c = \frac{\dot{q}_i}{\dot{q}_e} - \left(\frac{\dot{q}_i}{\dot{q}_e} - c_o \right) \exp\left(- \frac{\dot{q}_e}{V} \tau\right)$$

$$\tau = \frac{V}{\dot{q}_e} \ln\left(\frac{\dot{q}_i - \dot{q}_e\, c_o}{\dot{q}_i - \dot{q}_e\, c}\right)$$

For $\tau = \infty$ the concentration becomes

$$c_\infty = \frac{\dot{q}_i}{\dot{q}_e}$$

In an explosibility diagram of the type shown in Fig. 5, the change of c is indicated by a straight line connecting the composition point c_o with the final concentration c_∞. This can be shown by considering two constituents 1 and 2. From

$$c_1 = \frac{\dot{q}_1}{\dot{q}_e} - \left(\frac{\dot{q}_1}{\dot{q}_e} - c_{o1}\right) \exp\left(- \frac{\dot{q}_e}{V} \tau \right)$$

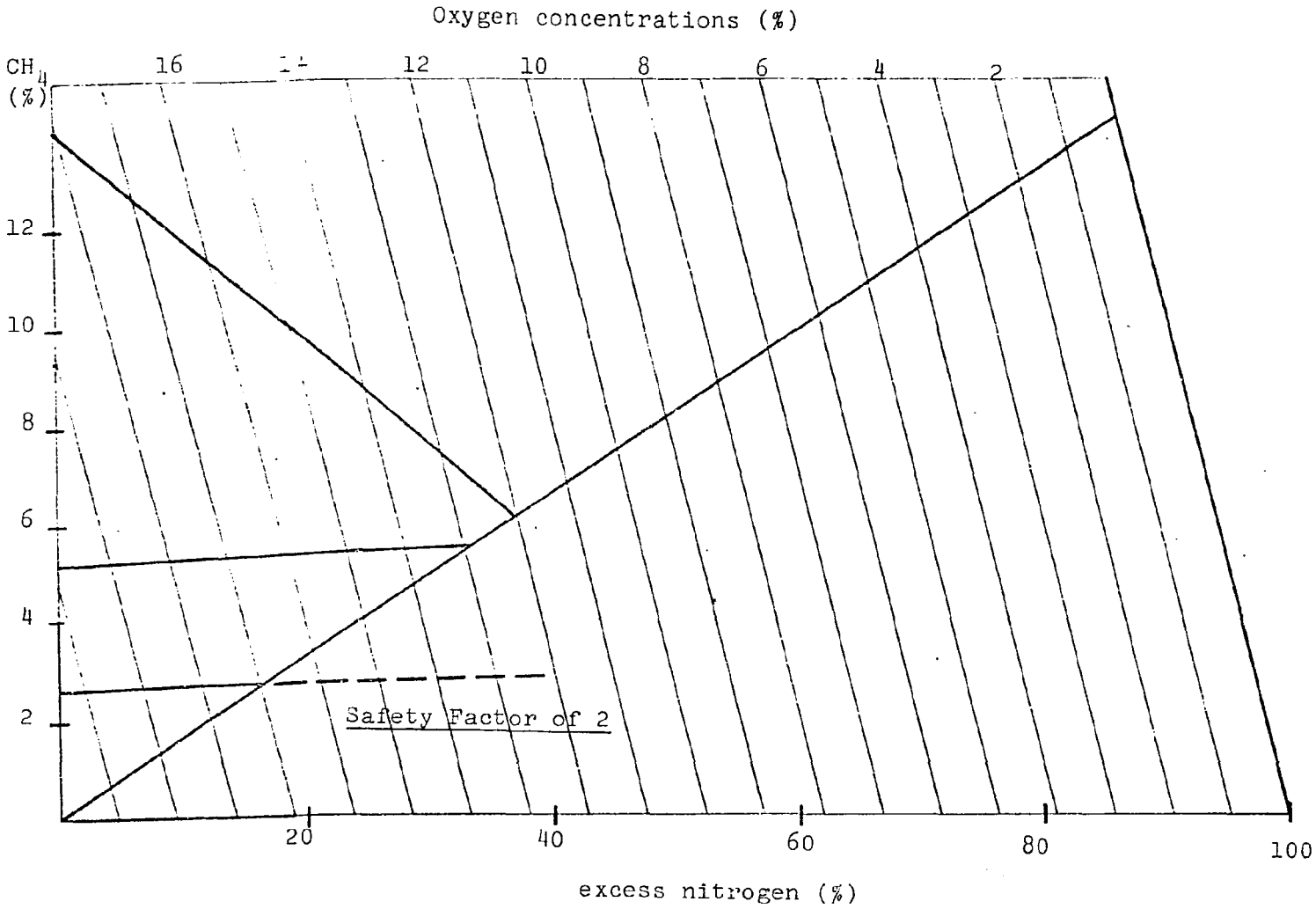


Fig. 16: Explosive range of methane-air-nitrogen mixtures; oxygen concentrations of mixtures

$$c_2 = \frac{\dot{q}_2}{\dot{q}_e} - \left(\frac{\dot{q}_2}{\dot{q}_e} - c_{o2}\right) \exp\left(-\frac{\dot{q}_e}{V}\tau\right)$$

one obtains

$$\frac{dc_1}{dc_2} = \frac{\dot{q}_1/\dot{q}_e - c_{o1}}{\dot{q}_2/\dot{q}_e - c_{o2}} = \text{constant}$$

The justification of the perfect mixing assumption and the conditions, which for this assumption have to be met, will be discussed in chapter IX. The assumption that no chemical reactions and no sorption occur means for the calculation of explosibilities an additional safety, since the consumption by these processes, is for oxygen and methane, larger than for the inert gases.

1. Sealing After Methane Has Been Fully Phlegmatized

When the seals of a fire zone containing fully phlegmatized flammable gases are closed, passing of the sealed atmosphere through the explosive range can be prevented in several ways. One possibility is to continue the injection of inert gas at such a rate that all flammable gases produced in the sealed space, or entering it after the seals have been closed, become fully phlegmatized also. Again it seems permissable, for the time period after the seals have been closed and the fire has decreased in intensity, to consider among the flammable gases, methane only. The result of this continued phlegmatizing will be that the composition of the sealed atmosphere is always nonexplosive and indicated in an explosibility diagram (Fig. 5) by the triangle below the inerting boundary. The final concentration can for every constituent be determined from

$$c_\infty = \frac{\dot{q}_i}{\dot{q}_e}$$

This method is very safe. The atmosphere in the sealed space- as well as leakage from it, undiluted and diluted with air- is always nonexplosive, but it is a costly method. Since the methane evolution of coal continues, even when no coal is mined, the inert gas injection has to continue also. However, once the concentration of the sealed atmosphere is above the upper explosive limit, the naturally evolving methane keeps it nonexplosive anyway. As far as the prevention of gas explosions is concerned, the injection of inert gas can, therefore, be stopped or reduced.

If a fully phlegmatized atmosphere shall, after

sealing, not pass through the explosive range, it has to have a certain minimum concentration of methane and inert gas. Figure 17 brings an example. Assumed are two different initial compositions,

point 1 with 6% CH_4, 54% air, 40% N_2,
point 2 with 3% CH_4, 67% air, 30% N_2,

and several different flow rate ratios of CH_4, air, N_2 with which these gases enter the sealed space. As one sees from the straight lines marking the composition changes, all of the flow rate ratios make the atmosphere of point 2 pass through the explosive range and of point 1 avoid it. Generally one can say that passing through the explosive range can be avoided for fully phlegmatized methane - air - inert gas mixtures after a cut off or reduction of inert gas flow when the inerted methane concentration is higher than that of the "nose point", the point where upper and lower explosibility limit curves meet, and when the methane/airflow rate ratio is larger than 14/86 = 1/6.14. The nose point concentration is for methane - air - mixtures with

nitrogen:	6.1 % CH_4
carbon dioxide:	7.3 % CH_4
21% CO_2 - 79% N_2 mixtures:	6.3 % CH_4

2. Sealing After Methane Has Been Diluted With Air and Inert Gas

If not enough inert gas can be delivered to fully phlegmatize the evolved methane, either air alone or air - inert gas mixtures have to be used to dilute the methane to nonexplosive concentrations. If a fire zone ventilated in this way is sealed, it can not be prevented that its atmosphere passes through the explosive range. It has, however, already been mentioned that the injection of inert gases lengthens the time until the atmosphere reaches the lower explosive limit and shortens the time the atmosphere stays in the explosive range. This shall be confirmed with several examples. All of them have been derived for methane - air - nitrogen mixtures only, since one obtains corresponding results for other inert gases also.

Assumed is an original ventilation in the fire zone with a CH_4 concentration of 1% and an inverse proportionality between CH_4 concentration and airflow rate. While the seals are constructed a methane concentration, which is one half as large as that of the lower explosive limit, shall not be exceeded (safety factor of 2). Figure 18a shows the state of the ventilation for different ratios of inert gas/airflow rates of the original ventilation.

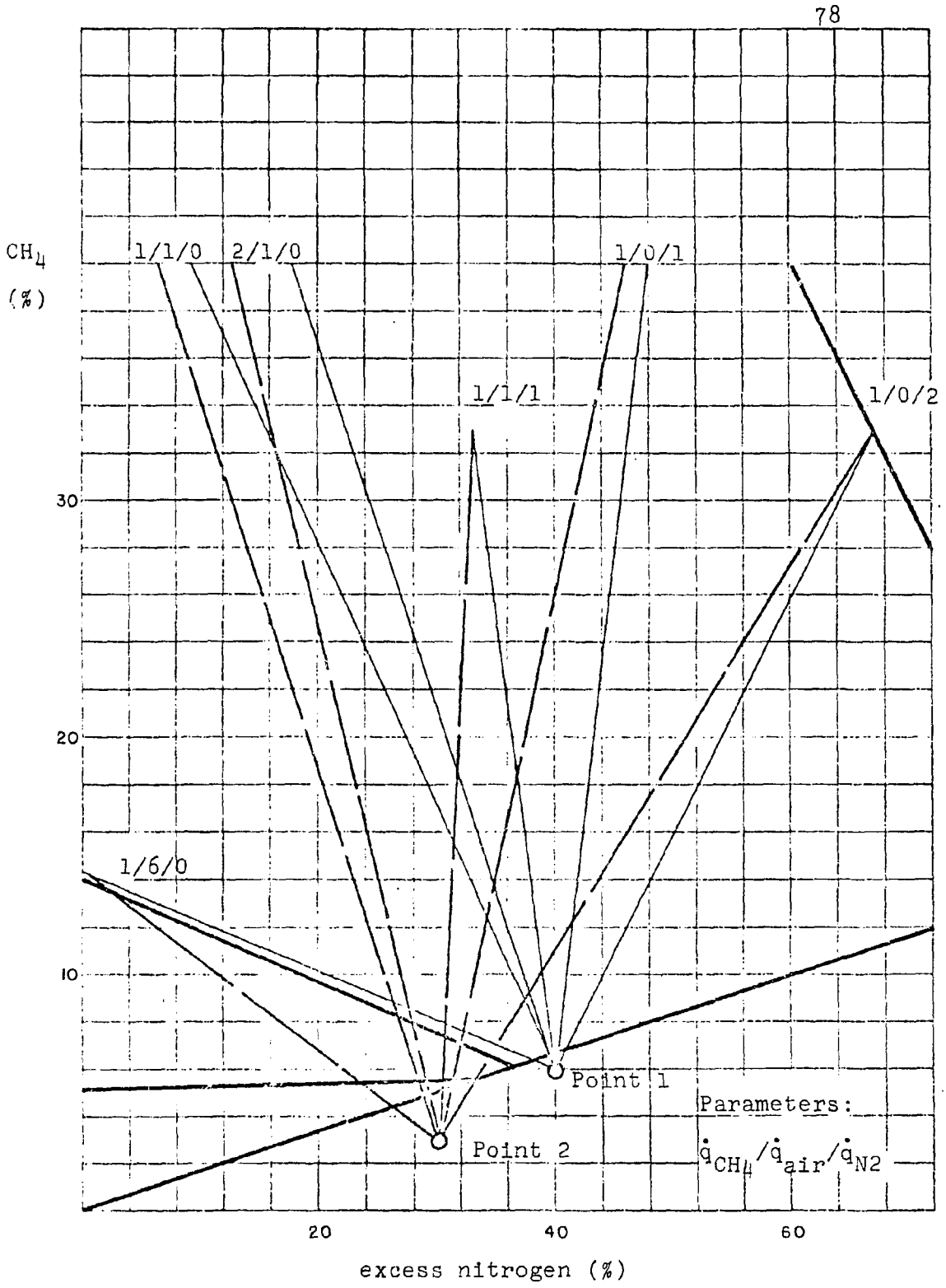


Fig. 17: Examples for composition changes with different methane-, air-, and nitrogen- flowrates

Figure 18b shows at which CH_4 concentrations the lower and upper explosive limits are reached by the atmosphere when after closing of the seals the airflow is completely interrupted, but CH_4 emission and inert gas injection continue at the previous rate. As can be expected, one sees that an increase in inert gas use narrows the explosive range until at full phlegmatization it disappears altogether.

Figure 18c contains the time periods after which under these conditions the explosive limits are reached. They are given relative to the time after which the sealed atmosphere of a fire zone, which has been ventilated with air only, reaches the lower explosive limit.

To indicate the order of magnitude for the time within which a sealed atmosphere increases its methane concentration from 2.6 to 5.2% when no air leakage takes place and no inert gas is injected, Fig. 18d shows this time as a function of sealed volume, airflow rate and methane emission.

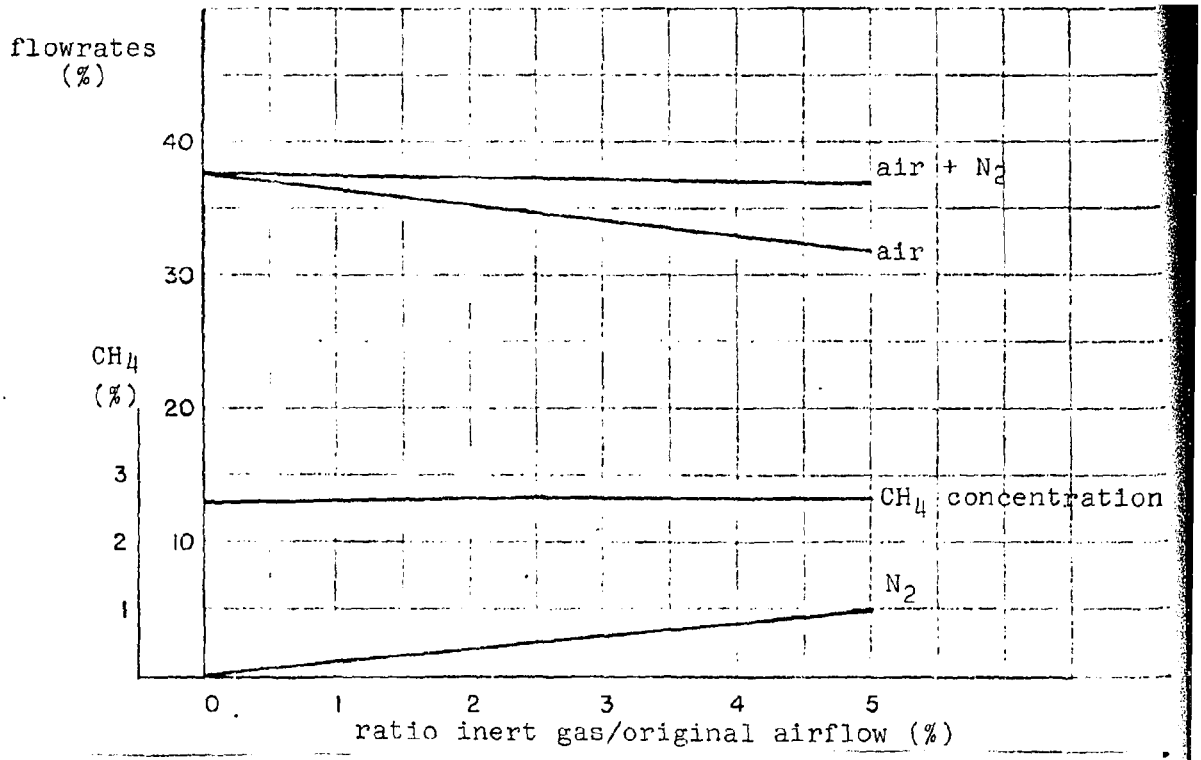
It is of interest to know which air leakage can maintain the sealed atmosphere in an explosive state. Figure 18e shows the air leakages which under the above assumptions make the final composition of the sealed atmosphere coincide with the upper and lower explosive limits. Leakages between these two curves would consequently provide for an explosive sealed atmosphere.

C. Extinction of Fires by Lowering Oxygen Concentration of their Atmosphere

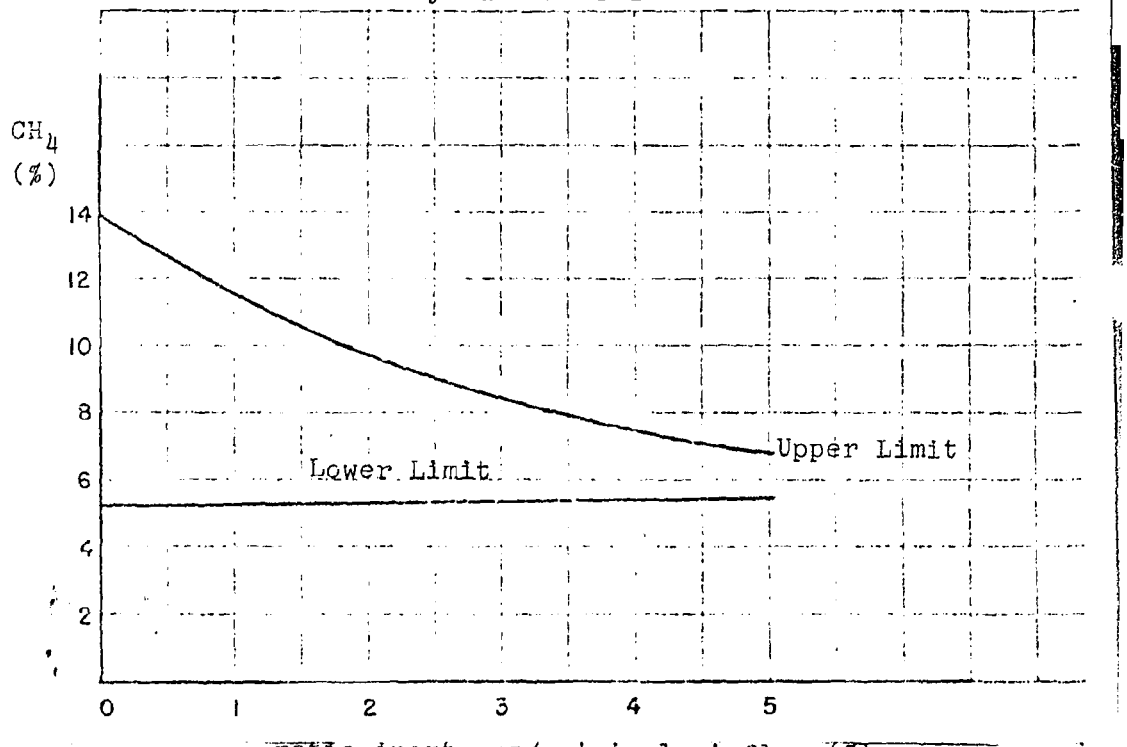
It has been discussed in chapter III that combustion processes in mine fires can be divided into two categories: the burning of gaseous combustibles or flaming combustion, and the burning of solid combustibles.

The minimum oxygen concentrations which are needed to support flaming combustion depend on nature and composition of flammable gases and their admixtures. For the mainly occurring flammable gases - methane, hydrogen, and carbon monoxide in mixture with air, nitrogen, and carbon dioxide - these minimum concentrations can be determined from Fig. 4. They are compiled in Table 11. Since, as has been discussed in chapter VI A. 2., the composition of the volatiles emitted by a heated fuel depends very much on the type of fuel and its temperature, the minimum oxygen concentrations to maintain flaming combustion can be expected to change in wide limits. For the composition of anthracite distillation

Fig. 18: Sealing after methane has been diluted with air and nitrogen

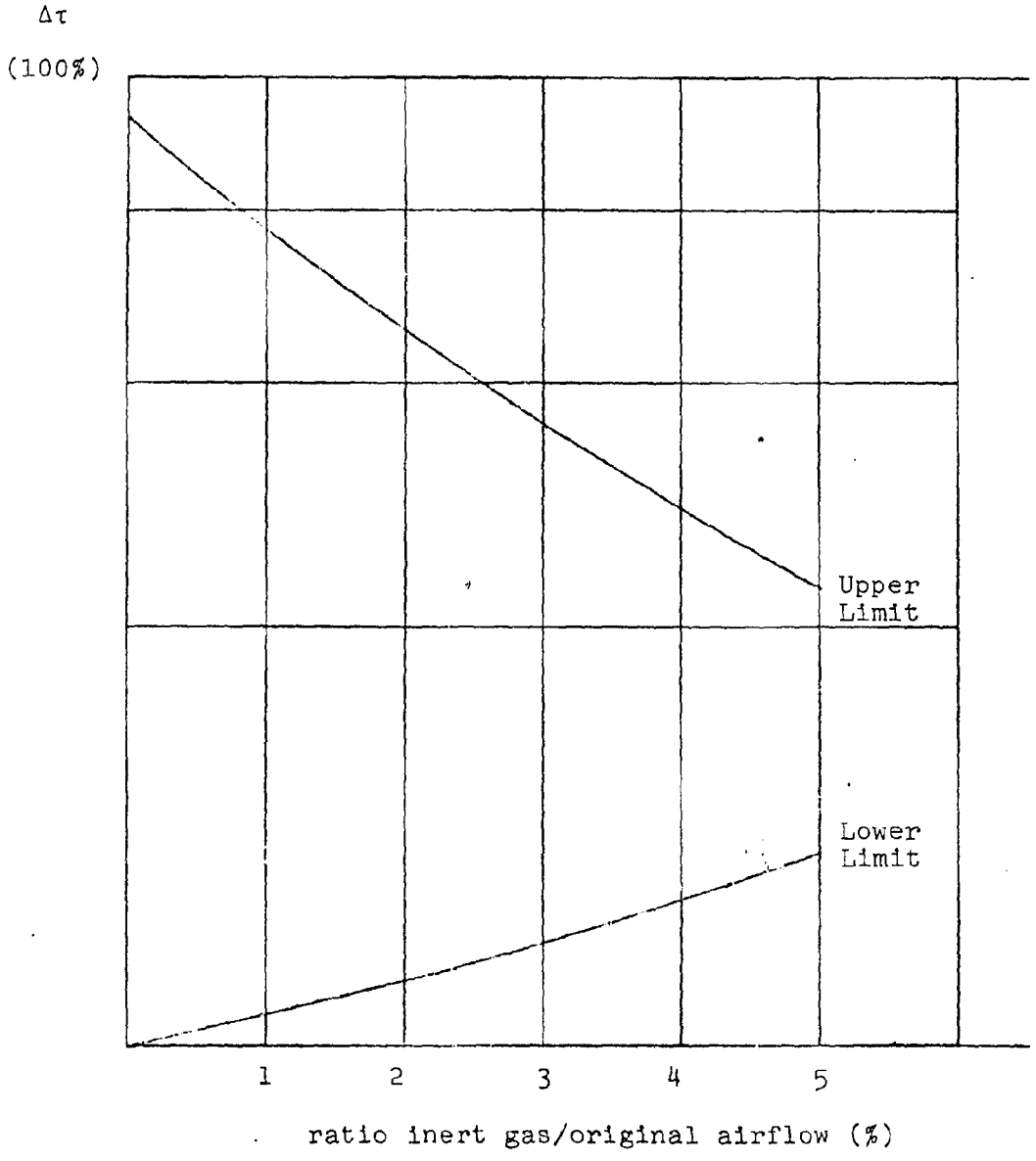


a : Required air and nitrogen flowrates during construction of seals for a safety factor of 2



b : Methane concentrations at which explosive limits are reached when airflow after closing of seals is cut off

Fig. 18c : Relative time periods after which the explosive limits are reached



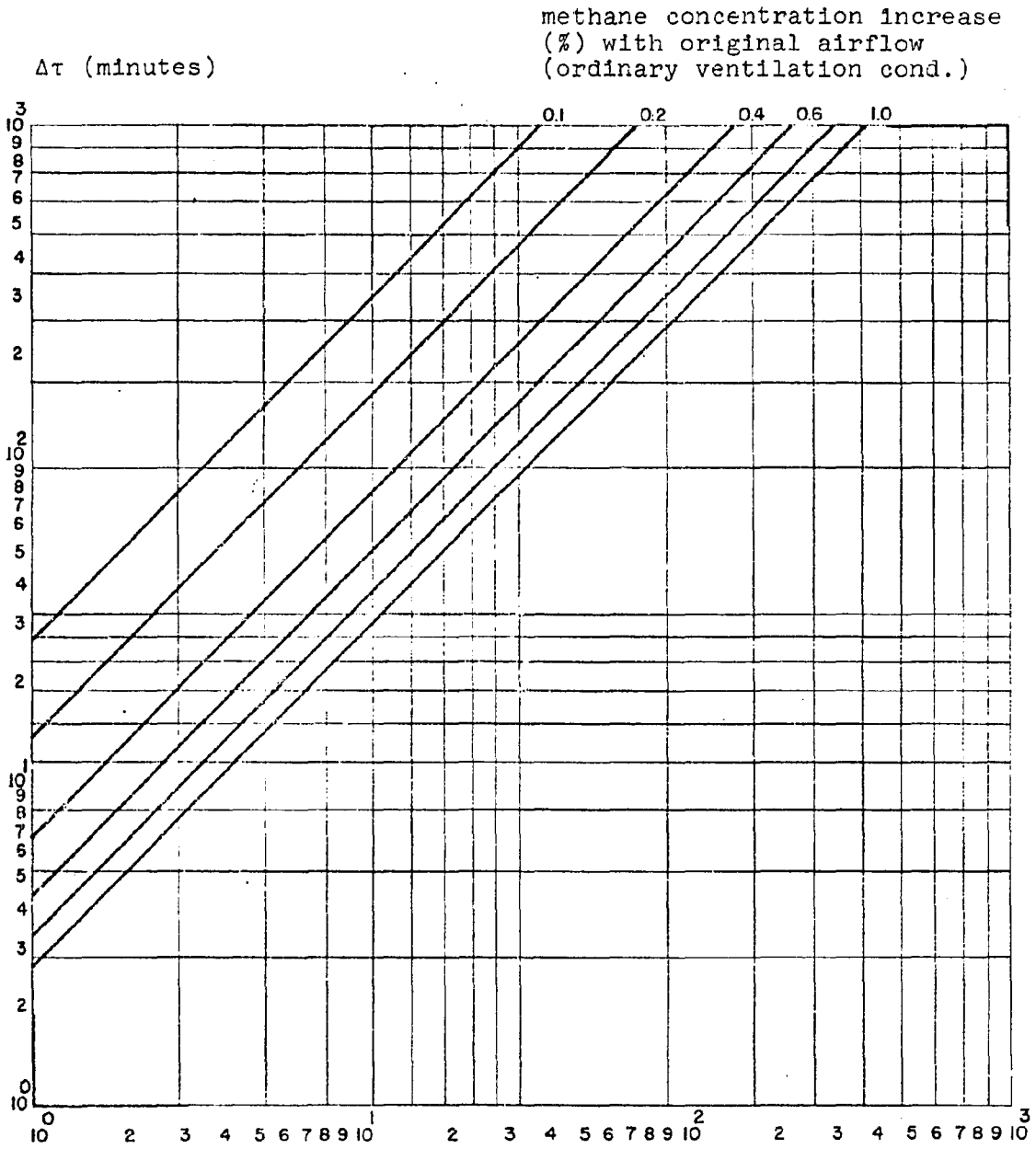


Fig. 18d : Time within which a sealed area increases its methane concentration from 2.6 to 5.2% (no airflow, no inert gas injection)

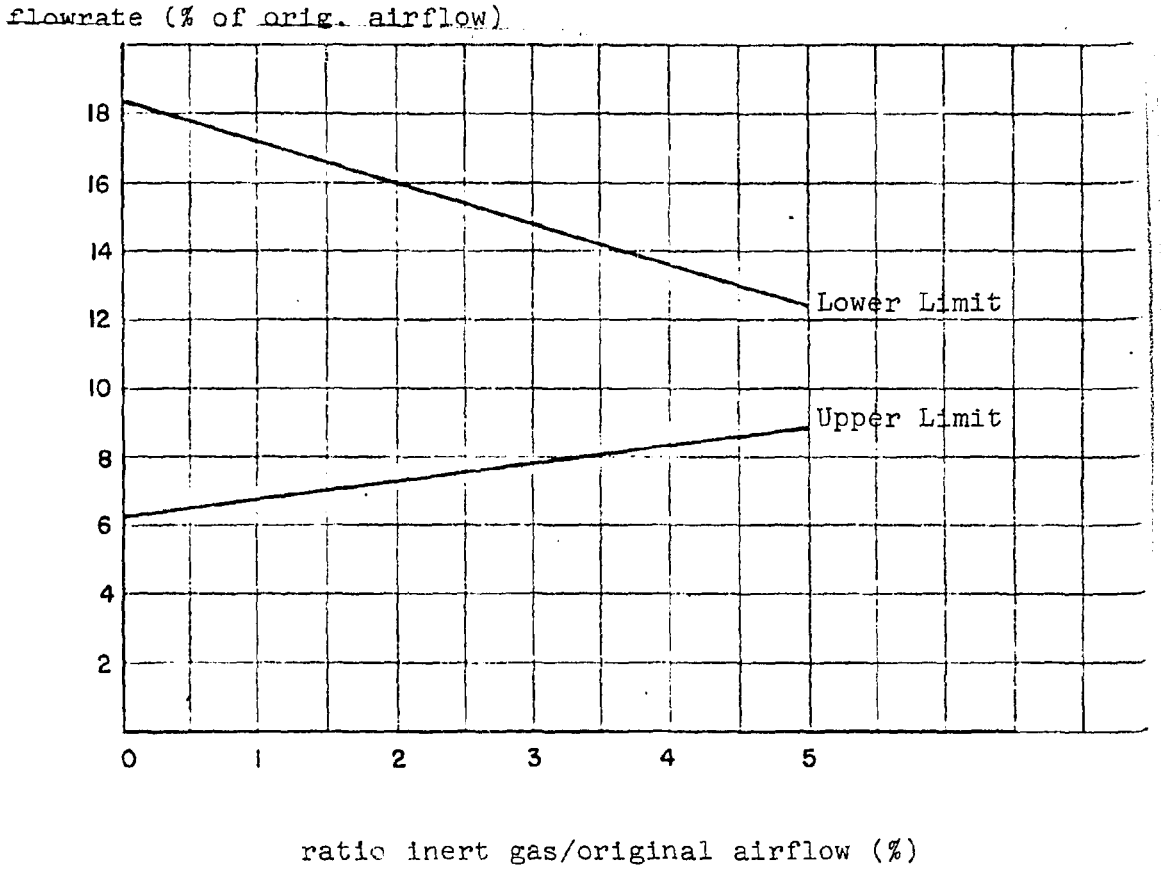


Fig. 18e : Air leakage rates which provide after sealing explosive atmospheres

Table 11: Minimum Oxygen Concentration to Maintain Combustion

Flammable Gas	Flammable Gas in Mixture with Air and Nitrogen	Flammable Gas in Mixture with Air and Carbon Dioxide
CH_4	12.1%	14.6%
H_2	4.9%	5.9%
CO	5.6%	5.9%

products shown in Fig. 9a, it changes from 15% for temperatures below 700°C to 9.2% for temperatures of 800 to 900°C. For volatiles evolving from wood with 55% CO_2, 30% CO, 10% CH_4, and 5% H_2 it is 11.1% O_2. It is, therefore, of little surprise that practical observations (chapter III B.) place the minimum oxygen concentration to support flaming combustion between 5 - 15% with 12% mentioned most frequently. As one sees from Table 11, 12% coincides approximately with the limits for the flammability of methane close to the nose point, so that one can assume that little probability of flaming combustion exists when methane-air mixtures have been fully inerted or pass close to the nose point through the explosive range.

Since it is necessary to lower the oxygen concentrations considerably below this level to extinguish the combustion of solids, not too much importance is attached to any particular concentration in this report. It will on several occasions, however, be indicated when the 12% O_2 concentration has been reached, since 12% seems to be considered as an average limit for the support of flaming combustion.

The minimum oxygen concentration needed for the combustion of solids is a function of oxidation rate and heat transfer from the burning surface. As discussed in chapter III B, theoretical derivations and systematic experiments have been performed for particles only, where the lowest obtained oxygen concentrations were 3%. Concentrations reported of mine fires vary between 1.3 and 3%. Concentrations observed in fire experiments were 2% for coal[102] and 2% for wood.[156] For the calculations performed in this chapter, it is therefore assumed that solid fire will no longer continue to burn when the oxygen concentration drops below 2%.

1. Dilution of Oxygen

The oxygen concentration in a fire zone can be changed by oxygen consumption through oxidation and sorption and by dilution. Which influence prevails depends on the type of mine, size of fire, extension of fire zone with reduced air supply, and on the flow rates of gases diluting the atmosphere in the fire zone. For small fires in non-coal mines, dilution will have a greater effect than consumption. For small fires in coal mines with small fire zones and large gas quantities passing through them, the same principle applies. As a comparison of the data which will be obtained in this chapter for dilution only, with

those which will be obtained in the next chapter for dilution and consumption, shows there is a rather wide range of small fire zones with large gas flow rates, where the oxygen consumption can be neglected.

If only the effect of dilution on the oxygen concentration c shall be considered, the concentration change dc can, as already mentioned in chapter VII B., be determined from

$$dc = \frac{d\tau}{V} (\dot{q}_a c_a - \dot{q}_e c)$$

where τ = time

V = volume of fire zone

$\dot{q}_a$ = flow rate of air entering fire zone

c_a = oxygen concentration of $\dot{q}_a$

$\dot{q}_e$ = flow rate of gas leaving fire zone

c = oxygen concentration of $\dot{q}_e$

With $c = c_{ao}$ for $\tau = 0$ one obtains

$$c = \frac{\dot{q}_a c_a}{\dot{q}_e} - (\frac{\dot{q}_a c_a}{\dot{q}_e} - c_{ao}) \exp(- \tau \frac{\dot{q}_e}{V})$$

$$\tau = \frac{V}{\dot{q}_e} \ln(\frac{\dot{q}_a c_a - \dot{q}_e c_{ao}}{\dot{q}_a c_a - \dot{q}_e c})$$

If no air enters the fire zone ($\dot{q}_a = 0$), the oxygen concentration is described by

$$c = c_{ao} \exp(- \tau \frac{\dot{q}_e}{V})$$

This function is shown in Fig. 19 for an initial oxygen concentration c_{ao} = 21% and parameters $V/\dot{q}_e = 50 - 50*10^3$ minutes. If no oxygen consumption takes place and the consumption of other gases is neglected, the flow rate of gases leaving the fire zone $\dot{q}_e$ is equal to the sum of the flow rates of gases entering the fire zone or, when inert gas is injected and CH_4 is emitted,

$$\dot{q}_e = \dot{q}_{CH_4} + \dot{q}_{inert}$$

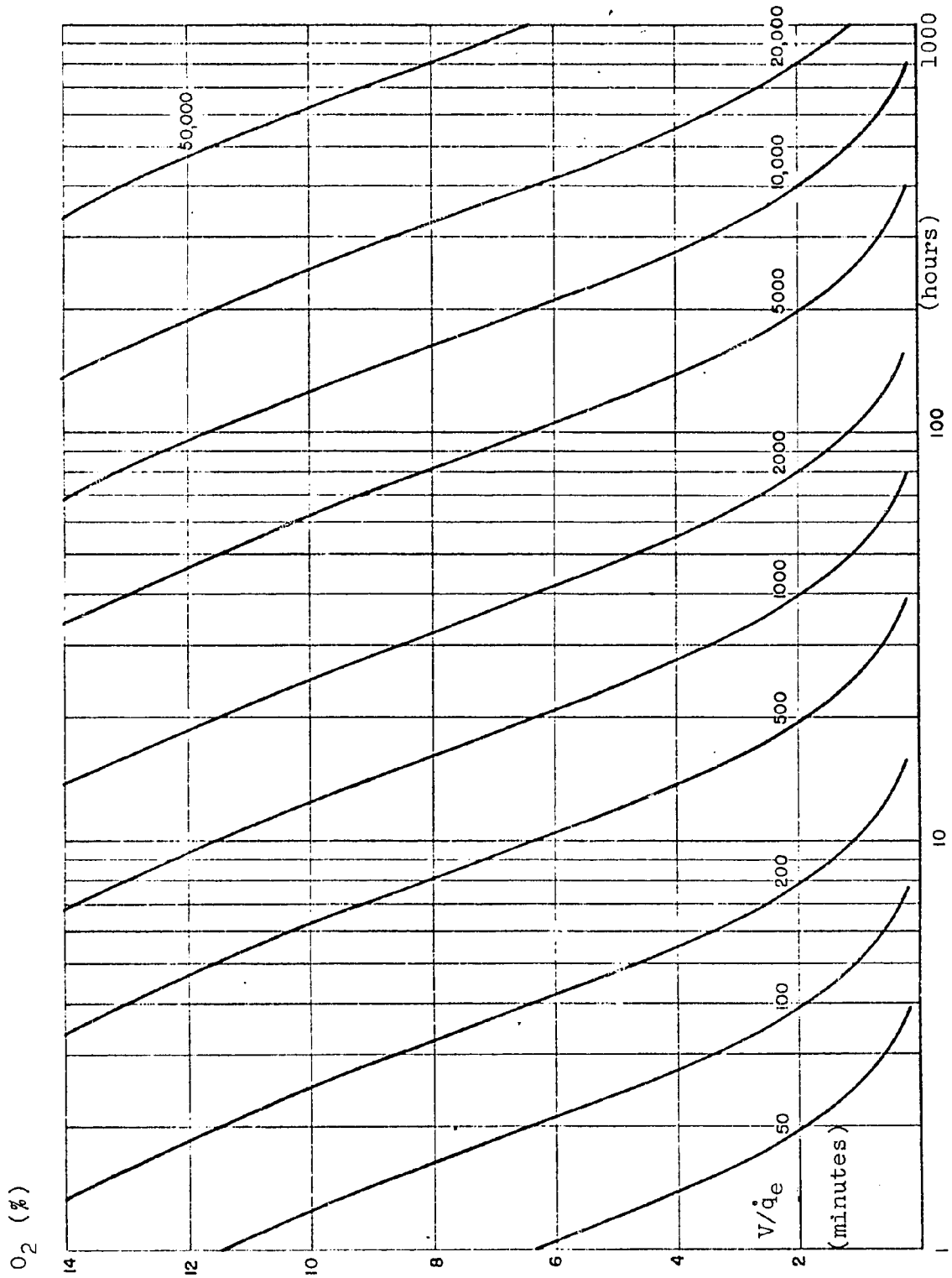


Fig. 19: Change of oxygen concentration caused by dilution (Parameters: $V/\dot{q}_e$ minutes)

The time after which a certain oxygen concentration c is reached is for

$$\dot{q}_a = 0$$

$$\tau = \frac{V}{\dot{q}_e} \ln \frac{c_{ao}}{c}$$

This function is shown in Fig. 20 for c = 12% and c = 2%. If air flows into the fire zone, the minimum flow rate ratios $(\dot{q}_{CH_4} + \dot{q}_{inert})/\dot{q}_a$ to reach a concentration c_∞ can be obtained with

$$\tau = \infty \quad \text{and} \quad \dot{q}_e = \dot{q}_a + \dot{q}_{CH_4} + \dot{q}_{inert} \quad \text{from}$$

$$c_\infty = \frac{\dot{q}_a c_a}{\dot{q}_e} = \frac{c_a}{1 + (\dot{q}_{CH_4} + \dot{q}_{inert})/\dot{q}_a}$$

For c_∞ = 2% and c_a = 21% one obtains

$$(\dot{q}_{CH_4} + \dot{q}_{inert})/\dot{q}_a = 9.5$$

for c_∞ = 12% and c_a = 21% one obtains

$$(\dot{q}_{CH_4} + \dot{q}_{inert})/\dot{q}_a = 0.75$$

The time until the concentration c is reached when air flows into the fire zone can be calculated as a function of $(\dot{q}_{CH_4} + \dot{q}_{inert})/\dot{q}_a$ from

$$\tau = \frac{V}{\dot{q}_e} \ln\left(\frac{\dot{q}_a c_a - \dot{q}_e c_{ao}}{\dot{q}_a c_a - \dot{q}_e c}\right)$$

$$= \frac{V}{\dot{q}_a} * \frac{1}{1 + (\dot{q}_{CH_4} + \dot{q}_{inert})/\dot{q}_a} \ln\left(\frac{c_a - c_{ao}(1 + (\dot{q}_{CH_4} + \dot{q}_{inert})/\dot{q}_a)}{c_a - c(1 + (\dot{q}_{CH_4} + \dot{q}_{inert})/\dot{q}_a)}\right)$$

This function has been plotted with $c_a = c_{ao}$ = 21% for c = 2% in Fig. 21a and for c = 12% in Fig. 21b.

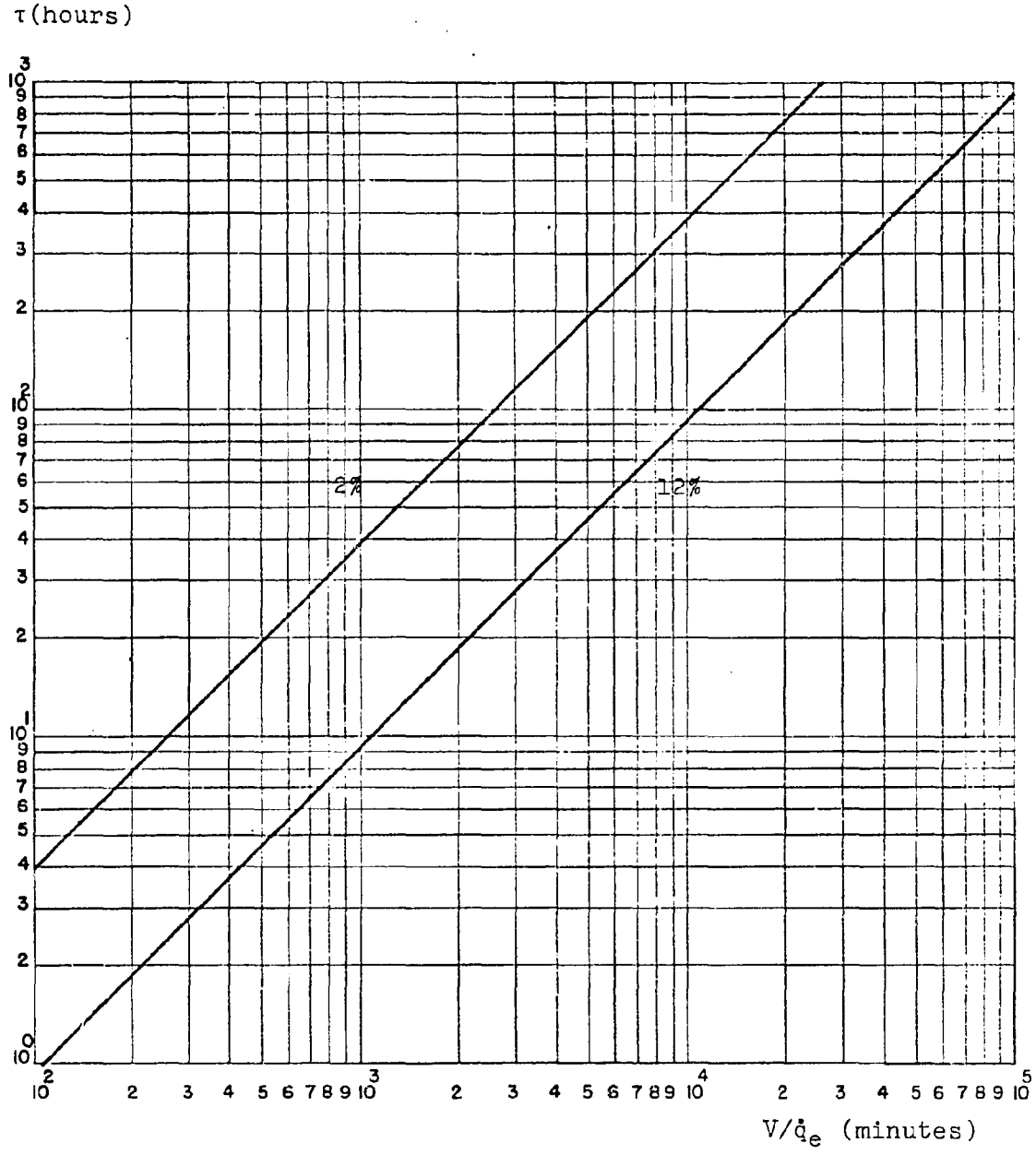


Fig. 20: Times after which oxygen concentrations have been lowered by dilution from 21% to 12% and 2%.

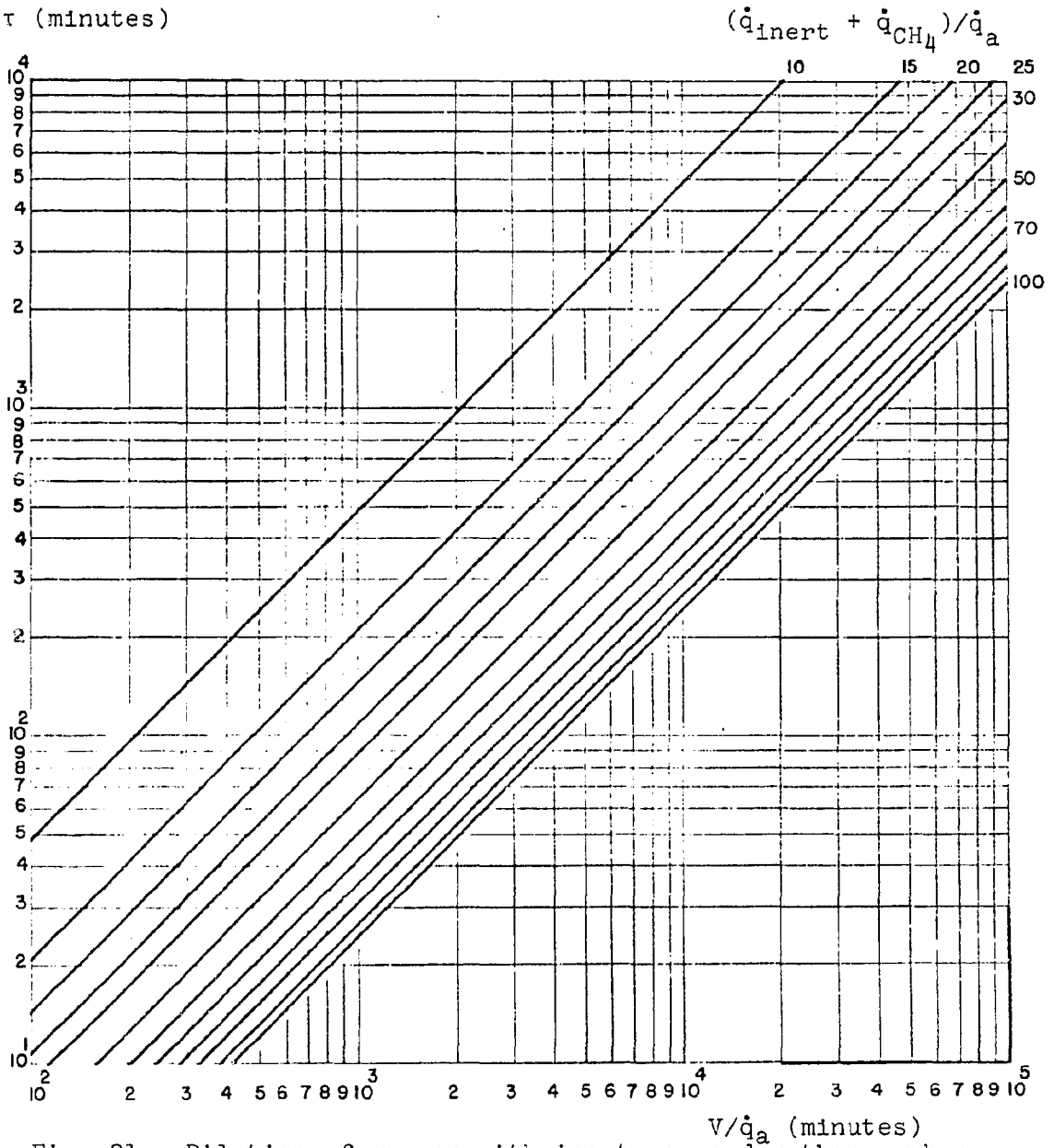


Fig. 21: Dilution of oxygen with inert gas and methane, when simultaneously air flows into sealed area

a : Time within which O_2 concentration has been lowered from 21 to 2%

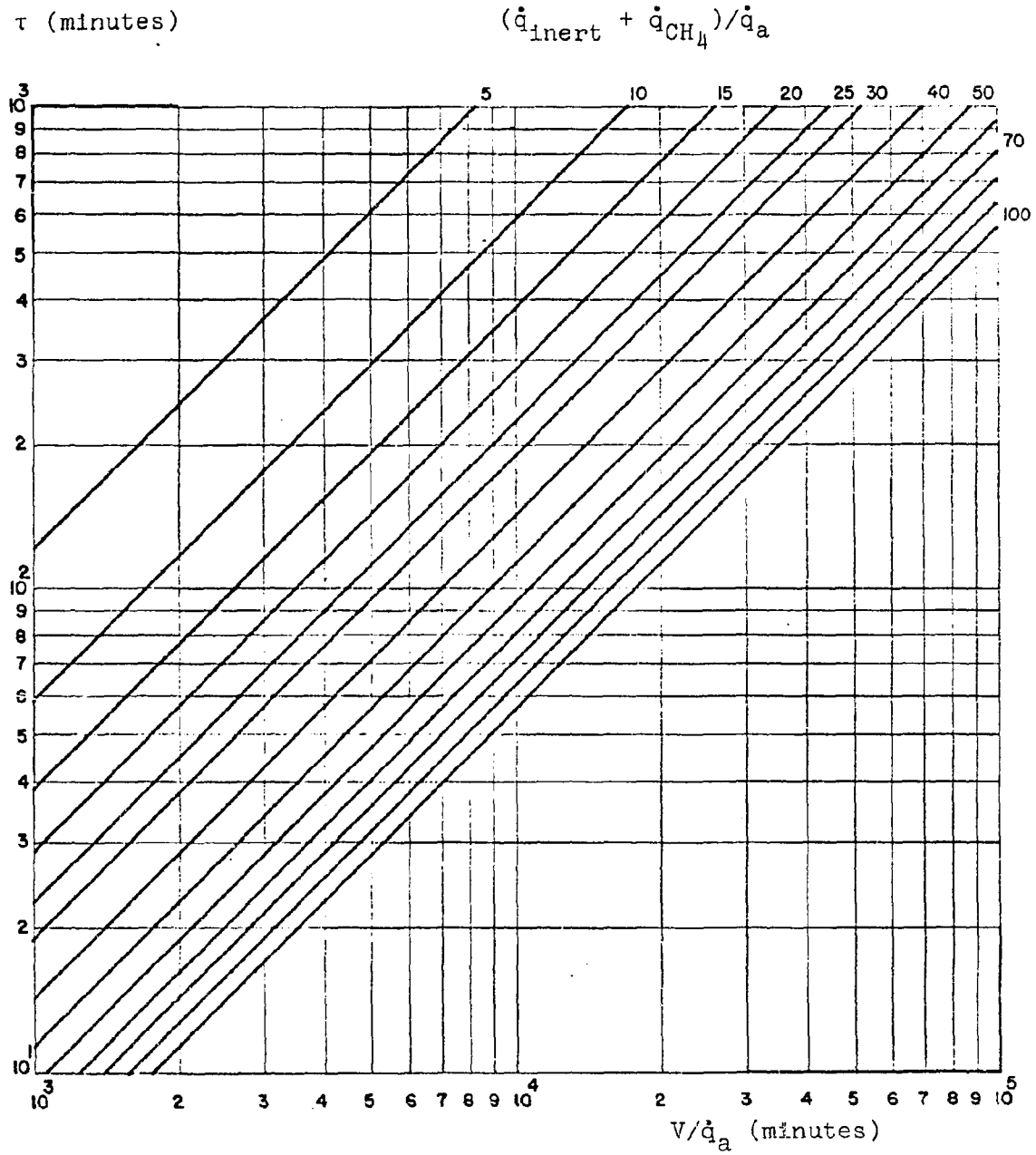


Fig. 21b : Time within which O_2 concentration has been lowered from 21 to 12%

Hajek[60] suggests to calculate the inert gas flow rate $\dot{q}_i$, which is necessary to lower the oxygen concentration to c_∞ from

$$\dot{q}_i = \frac{\dot{q}_a(c_a - c_\infty)}{c_\infty - c_i}$$

where c_i = oxygen concentration of entering inert gas

This formula can be derived from

$$dc = \frac{d\tau}{V} (\dot{q}_a c_a + \dot{q}_i c_i - \dot{q}_e c)$$

which becomes for $c_a = c_{ao}$ for $\tau = 0$

$$c = \frac{\dot{q}_a c_a}{\dot{q}_e} + \frac{\dot{q}_i c_i}{\dot{q}_e} - (\frac{\dot{q}_a c_a}{\dot{q}_e} + \frac{\dot{q}_i c_i}{\dot{q}_e} - c_{ao}) \exp(-\tau \frac{\dot{q}_e}{V})$$

and for the equilibrium state at $\tau = \infty$ with $\dot{q}_e = \dot{q}_a + \dot{q}_i$

$$c_\infty = \frac{\dot{q}_a c_a + \dot{q}_i c_i}{\dot{q}_a + \dot{q}_i}$$

2. Combined Dilution of Oxygen and Consumption by Combustion and Sorption

The amount of oxygen consumed by a fire depends on the extension and temperature of the fire and on ventilation conditions, and is, therefore, hard to predict. Although, as has been discussed in chapter VI, studies on the oxygen adsorption of coal exist, the prediction of the oxygen consumption by sorption is equally difficult, because type of coal, temperature, past[54,55] influence it in wide limits. Since it appeared impossible to find measured reaction rate constants of general validity for oxidation and adsorption, a different approach was chosen. From the literature and several mine inspector reports were 33 complete gas analyses from 33 well sealed fires, which could be extinguished by sealing, extracted. The reported oxygen concentrations $[O_2]$ have been plotted over the time after closing the seals in Fig. 22. The concentration change $[O2]_{cons}$ due to oxygen consumption was then calculated from the measured nitrogen concentration $[N_2]$ by using the formula

$$[O_2]_{cons} = 0.21 - [N_2] \frac{21}{79}$$

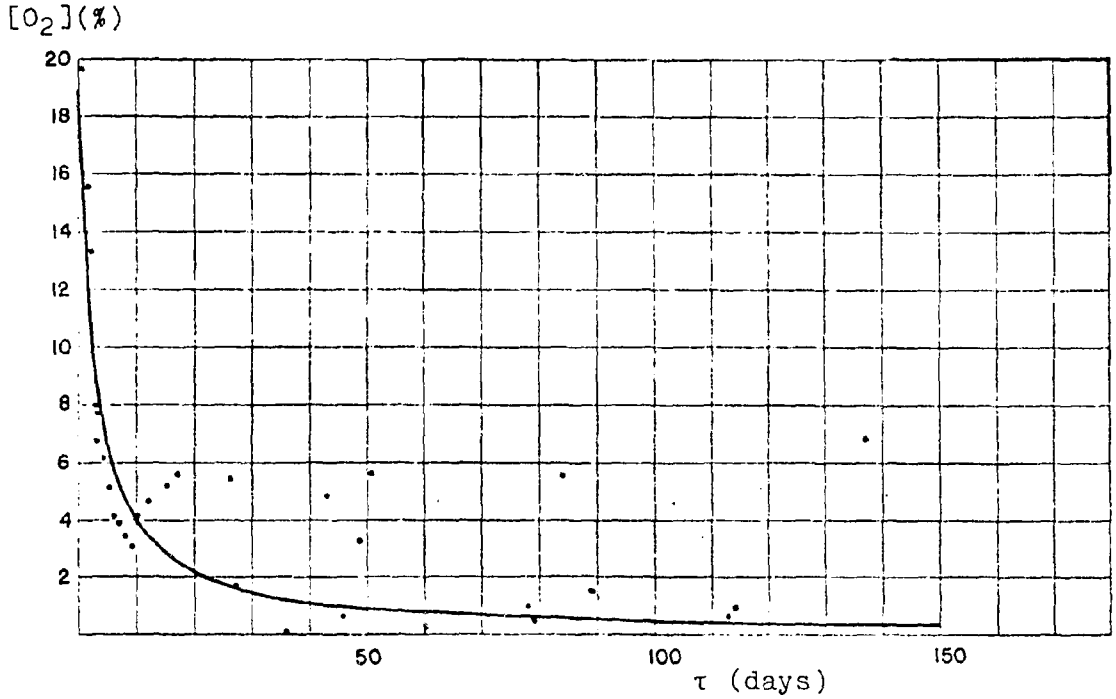


Fig. 22: Observed oxygen concentrations in sealed atmospheres

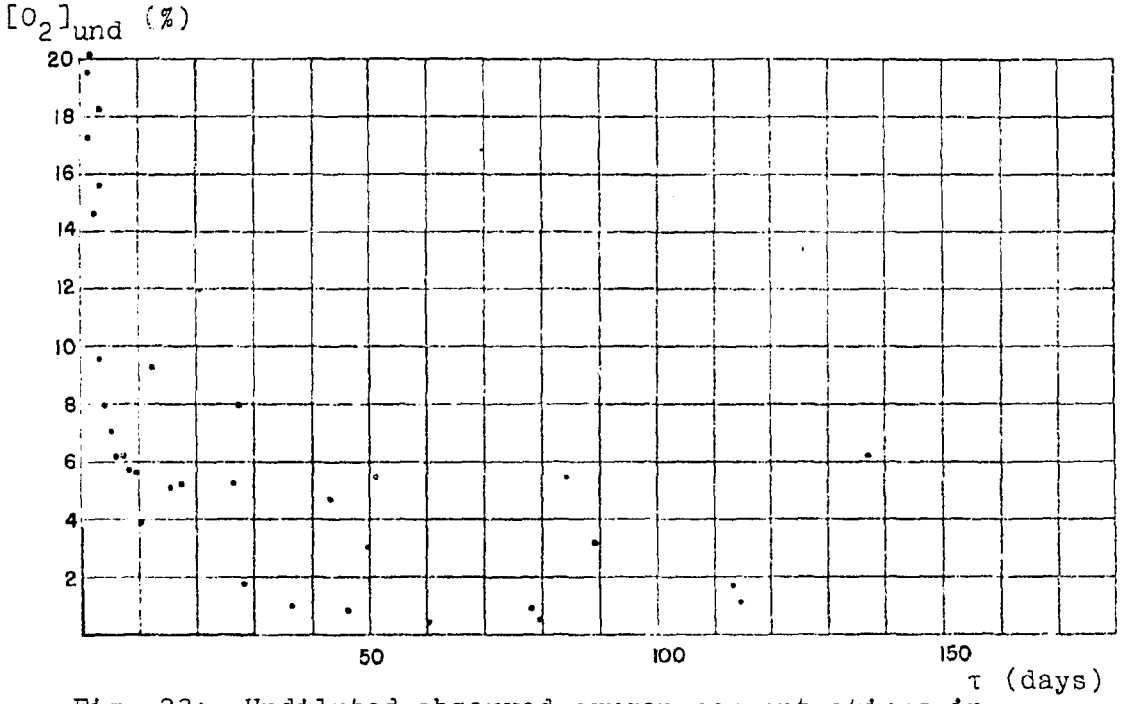


Fig. 23: Undiluted observed oxygen concentrations in sealed atmospheres

which is based on the assumption that the major part of the oxygen consumption precedes the dilution. This assumption seems to be justified since the undiluted oxygen concentrations $[O_2]_{und}$, determined from $[O_2]_{und} = [O_2] \frac{0.79}{[N_2]}$

and plotted in Fig. 23 show no great deviation from the values of $[O_2]$ shown in Fig. 22. This indicates that the dilution took place only after the oxygen concentrations were already low. Errors are caused by air leakage and this is the reason why only well sealed fires were considered.

Adsorption is a first order reaction with respect to $[O_2]$. Oxidation of solid coal and volatiles approach first order reactions when an excess of fuel is present. It seems, therefore, possible to define (o_c) an average reaction rate per unit volume, time and concentration by dividing $[O_2]_{cons}$ by the time of sealing and the average oxygen concentration in the sealed atmosphere, i.e.,

$$o_c = [O_2]_{cons}/(\tau\ [O_2]_{average})$$

Reaction rates for adsorption and the burning of solids should be based on units of surface area; but not enough accurate data could be found on sealed volumes and their interior surfaces. However in coal mines, the ratio of cross sectional areas and perimeters of mine workings does not vary too much. The assumption of a constant proportionality between volumes and surfaces seems, therefore, possible.

Since oxygen concentrations in sealed fire zones change rapidly, it is necessary to calculate the average oxygen concentration from

$$[O_2]_{average} = (\tfrac{1}{\tau}) \int [O_2]d\tau$$

A first approach to describe the change of oxygen concentration with time $[O_2]_\tau$ for every measured concentration $[O_2]$

$$[O_2]_\tau = 0.21 \exp(-x\tau),$$

and then to use the average concentrations obtained from these functions to calculate reaction rates o_c resulted in widely varying values of o_c. A better result was obtained by averaging the concentrations $[O_2]$ by a common function, which takes for the first 40 days of sealing all measured concentrations and for the following time only those below 2% into account. It can be suspected that the higher oxygen concentrations after 40 days of sealing have resulted from air leakage. The function obtained is

$$[O_2]_\tau = (0.21 - 0.4\tau\,[O_2]_\tau)\exp(-0.002\tau)$$

It has been entered into Fig. 22. The values o_c obtained with this function

$$o_c = [O_2]_{cons}/(\tau/[O_2]\,d\tau/\tau) = [O_2]_{cons}//[O_2]_\tau d\tau$$

have been plotted over the time in Fig. 24. One sees that they are all in the same order of magnitude, the values for long sealing periods having a tendency to decrease due to the underestimated oxygen consumption because of air leakage, the values for short sealing periods varying due to different intensities of the sealed fires. The arithmetic mean of all values is

$$o_c = 0.132\ (\text{days})^{-1}$$

and this value will be used in the following calculations of this chapter.

If the combined effect of dilution and sorption on the oxygen concentration c shall be considered, the concentration change can be calculated from

$$dc = \frac{d\tau}{V}\,(\dot{q}_a c_a - (o_c V + \dot{q}_e)\,c)$$

from which one obtains with $c = c_{ao}$ for $\tau = 0$

$$c = \frac{\dot{q}_a c_a}{o_c V + \dot{q}_e} - \left(\frac{\dot{q}_a c_a}{o_c V + \dot{q}_e} - c_{ao}\right)\exp\left(-(o_c V + \dot{q}_e)/V\right)$$

$$\tau = \frac{V}{o_c V + \dot{q}_e}\,\ln\left(\frac{\dot{q}_a c_a - (o_c V + \dot{q}_e)\,c_{ao}}{\dot{q}_a c_a - (o_c V + \dot{q}_e)\,c}\right)$$

The quantity of gases leaving the fire zone is approximately equal to the quantity of gases entering minus the oxygen consumed plus the combustion products generated. Gases entering comprise mainly of air, methane and injected inert gas. Among the combustion products leaving, the carbon dioxide mainly needs consideration. As discussed in chapter VI B., the CO_2 concentration of fire gases is usually around or below 5%. For the 33 extracted analyses the CO_2 concentration has been plotted over the time in Fig. 25 and is approximately 5%. Consequently one can substitute for the flowrate of gases leaving the fire zone

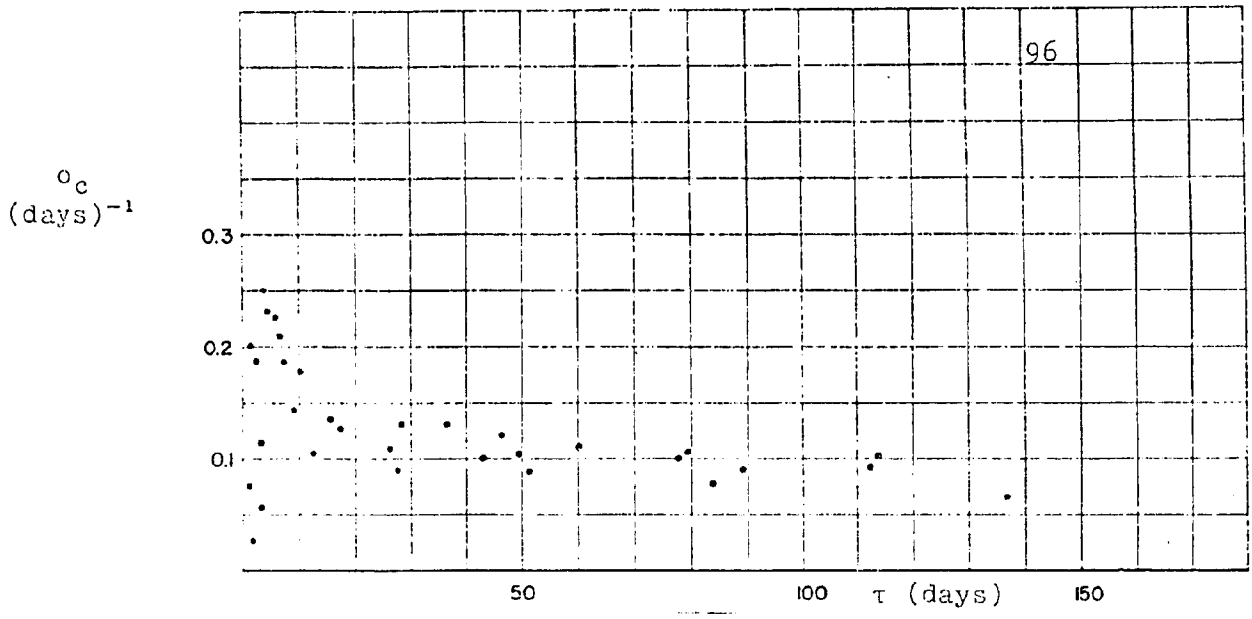


Fig. 24: Reaction rate constants o_c for the oxygen consumption in sealed atmosphere

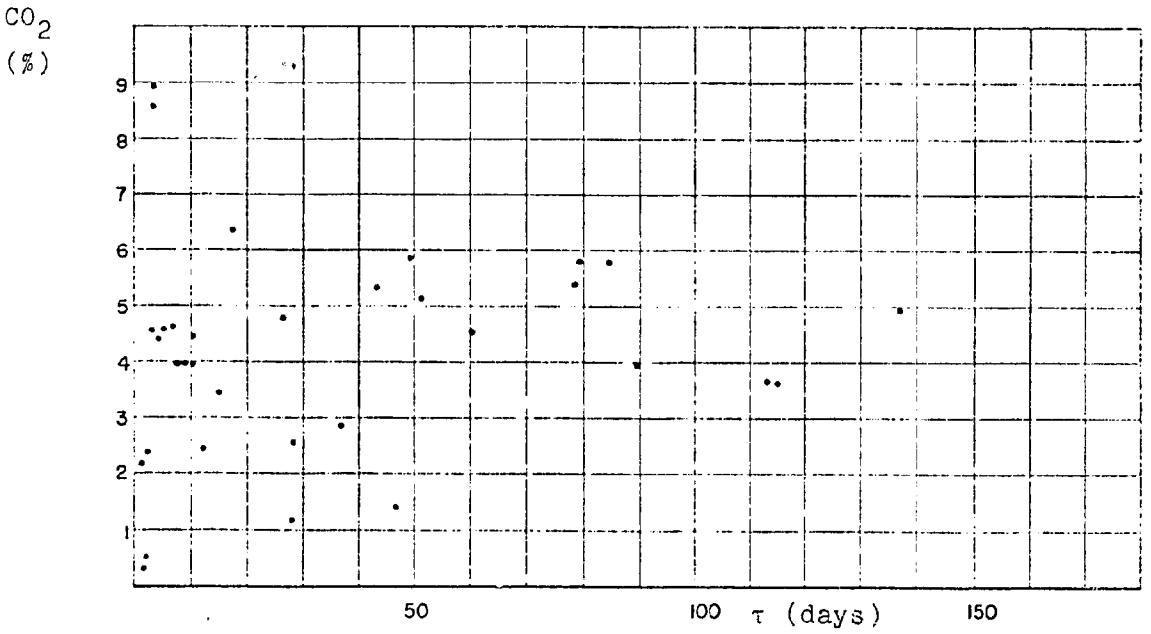


Fig. 25: Observed carbon dioxide concentrations in sealed atmospheres

$$\dot{q}_e = \dot{q}_a + \dot{q}_{CH_4} + \dot{q}_{inert} - o_c V c + 0.05 \dot{q}_e$$

If a fire zone is sealed, no air enters and no gases leave ($\dot{q}_a = 0$, $\dot{q}_e = 0$) the oxygen concentration changes according to

$$c = c_{ao} \exp(- \tau o_c)$$

This function is shown for $c_{ao} = 21\%$ and $oc = 0.132(\text{days})^{-1}$ in Fig. 26.

The equilibrium concentration c_{equ} ($\tau = \infty$), when the oxygen adsorption balances the oxygen supply brought into the fire zone with an inward leaking air flow rate $\dot{q}_a$, and when the inflow of methane makes up for the volume change caused by the oxygen adsorption ($\dot{q}_a = \dot{q}_e$) can be calculated from

$$c_{equ} = \frac{\dot{q}_a c_a}{o_c V + \dot{q}_e} = \frac{c_a}{o_c V/\dot{q}_a + 1}$$

This function has been plotted for $c_a = 21\%$, $o_c = 0.132/1440 = 91.5*10^{-6}(\text{min})^{-1}$ and values of $V/\dot{q}_a = 10^2 - 10^5$ minutes in Fig. 27.

The minimum ratios (inert gas injection plus methane evolution)/air leakage which are necessary to lower the oxygen concentration to 2% or 12% ($\tau = \infty$) can be calculated from

$$c = \frac{\dot{q}_a c_a}{o_c V + \dot{q}_e}$$

With $c = 0.02$, $\dot{q}_e = \dot{q}_a + \dot{q}_{CH_4} + \dot{q}_{inert} - 0.02\, o_c\, V + 0.05\, \dot{q}_e$ (ft^3/min), and with V in ft^3 one obtains

$$(\dot{q}_{CH_4} + \dot{q}_{inert})/\dot{q}_a = 8.975 - 85.1*10^{-6} \frac{V}{\dot{q}_a}$$

and with $c = 0.12$

$$(\dot{q}_{CH_4} + \dot{q}_{inert})/\dot{q}_a = 0.662 - 75.95*10^{-6} \frac{V}{\dot{q}_a}$$

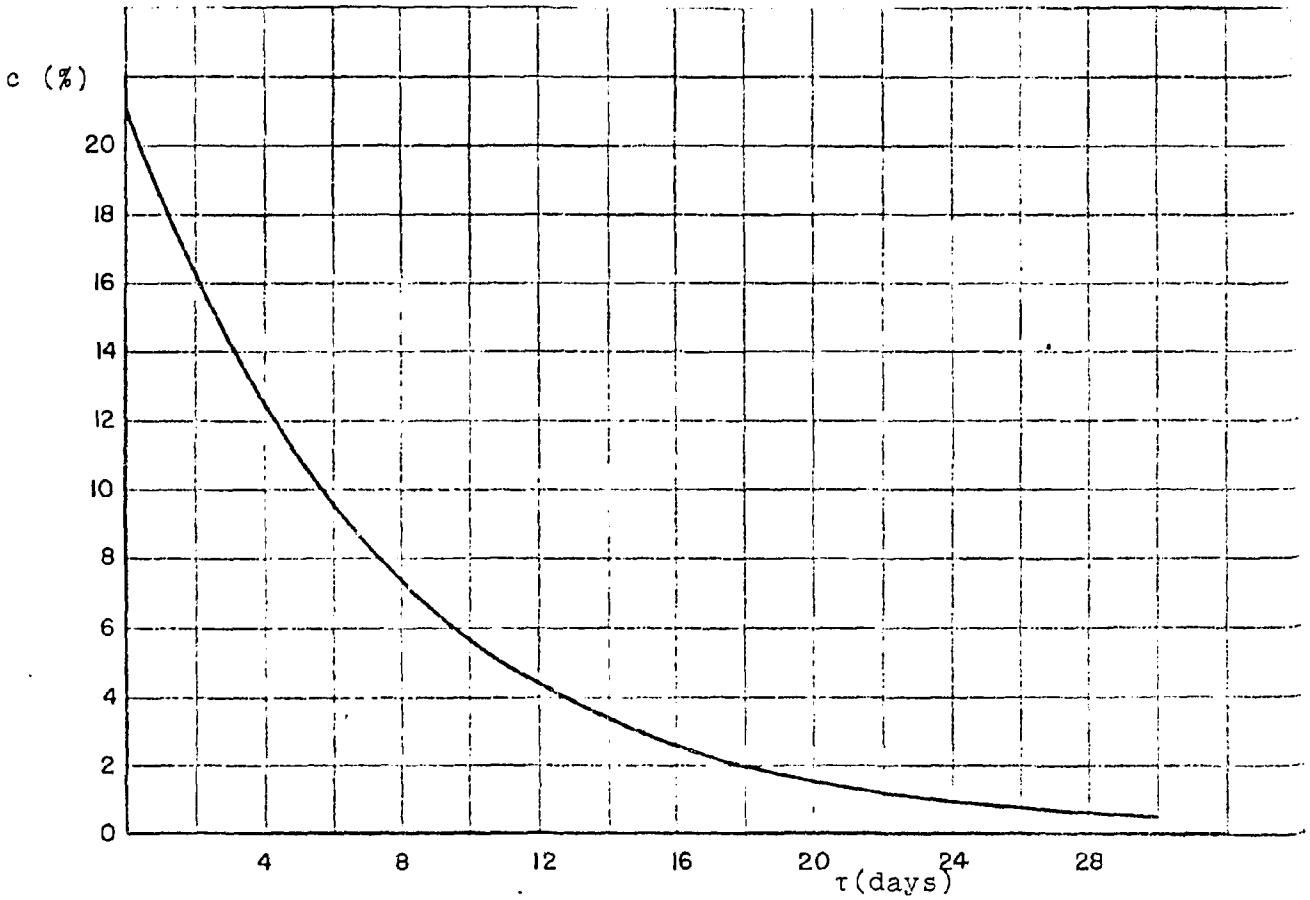


Fig. 26: Change of oxygen concentration caused by consumption only

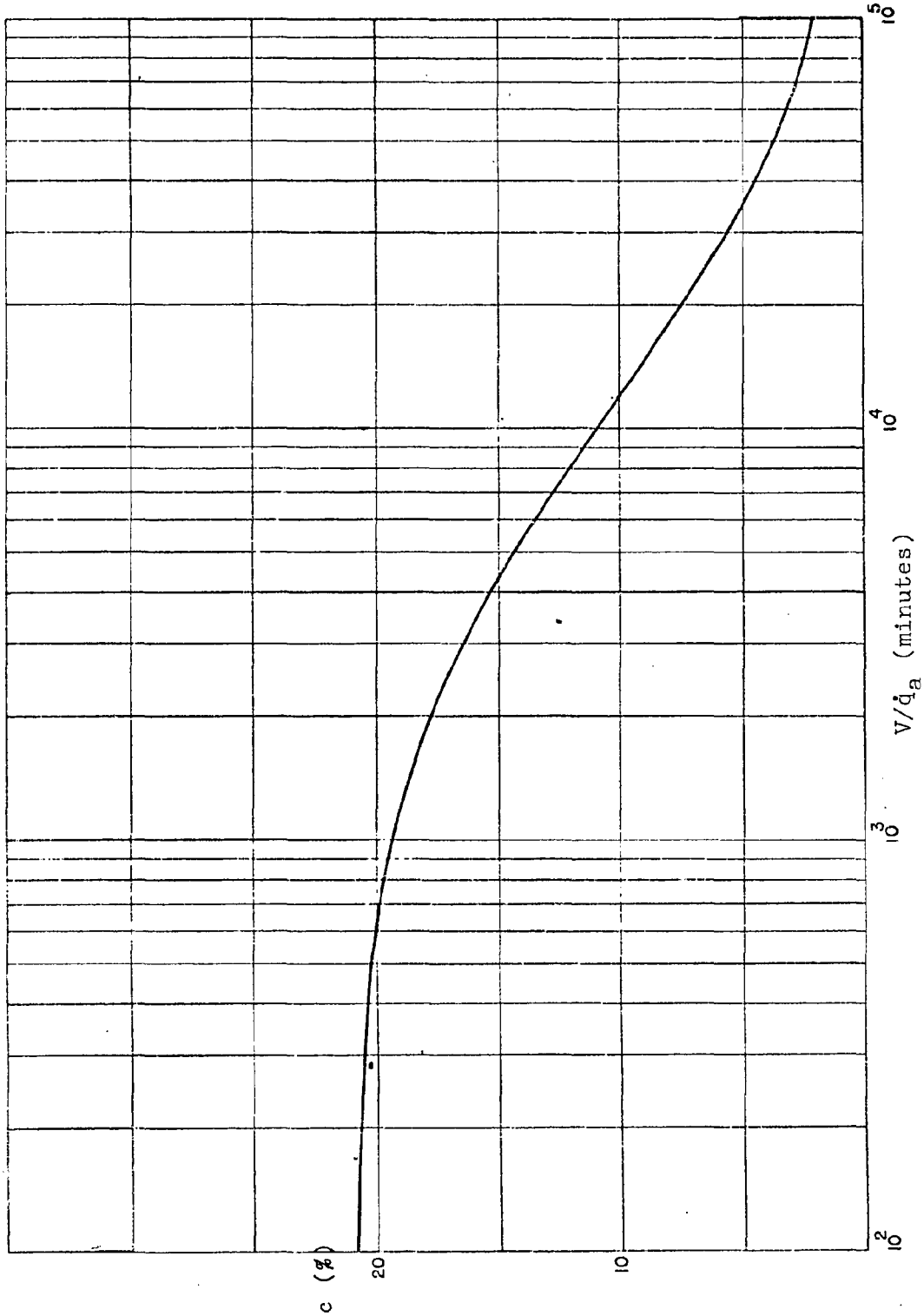


Fig. 27: Equilibrium concentration when oxygen consumption balances oxygen supply

Both functions are shown in Fig. 28. Absolute minimum values of ($\dot{q}_{CH_4} + \dot{q}_{inert}$) ($ft^3/min$), which are necessary to lower the oxygen concentration to 2% when the inflow of air is $\dot{q}_a$ (ft^3/min) and the sealed volume is V (ft^3), can be obtained from

$$\dot{q}_{CH_4} + \dot{q}_{inert} = 8.975\ \dot{q}_a - 85.1*10^{-6}\ V$$

and are shown in Fig. 29. One sees from Fig. 28 and Fig. 29 that the oxygen consumption helps to lower the oxygen concentration to 2% only when air leakages are small and sealed spaces large. As long as the ratio $V/\dot{q}_a$ is smaller than 10,000 (minutes), the lowering of the oxygen concentration must be mainly accomplished by dilution with oxygen free gases.

This is demonstrated in Fig. 30 where the change of oxygen concentration in a sealed space has been plotted over the time for $(\dot{q}_{CH_4} + \dot{q}_{inert})/\dot{q}_a = 10$ with and without consideration of the oxygen consumption.

Figure 30 a. applies to values $V/\dot{q}_a = 10^2$, and one sees that the concentration is only slightly influenced by the oxygen consumptiom. Fig. 30 b. applies to values $V/\dot{q}_a = 10^5$ and one sees that the oxygen consumption lowers the time until a certain concentration is reached to about one half of what dilution alone would require.

The time τ which is needed until the oxygen concentration c in a sealed fire zone has by an injection of inert gas and evolution of methane been lowered to 2% when air with 21% O_2 leaks in and the original oxygen concentration was 21%, has been plotted in Fig. 31 as a function of $V/\dot{q}_a$ with parameters $(\dot{q}_{CH_4} + \dot{q}_{inert})/\dot{q}_a$ = 10, 15, 20, 25, 30.
One sees that the time curves are for small values of $V/\dot{q}_a$ straight lines and all have the same slope, which again indicates the dominating influence of dilution.

For the case that no air enters the sealed fire zone but that inert gas is injected and methane is evolved, the time after which the oxygen concentration has dropped to a level c can be calculated from

$$\tau = \frac{V}{o_c V + q_e} \ln \left(\frac{c_{ao}}{c}\right)$$

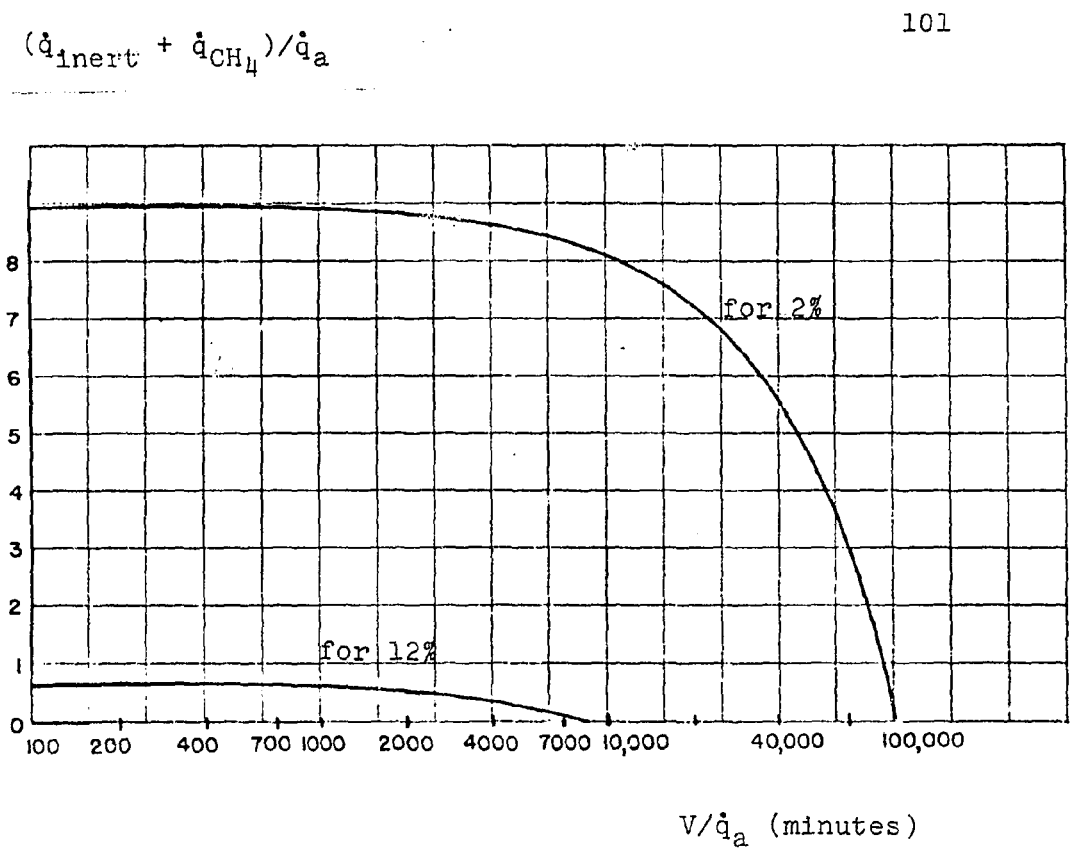


Fig. 28: Minimum flow rate ratios $(\dot{q}_{inert} + \dot{q}_{CH_4})/\dot{q}_a$ to reach 2 and 12% oxygen concentrations

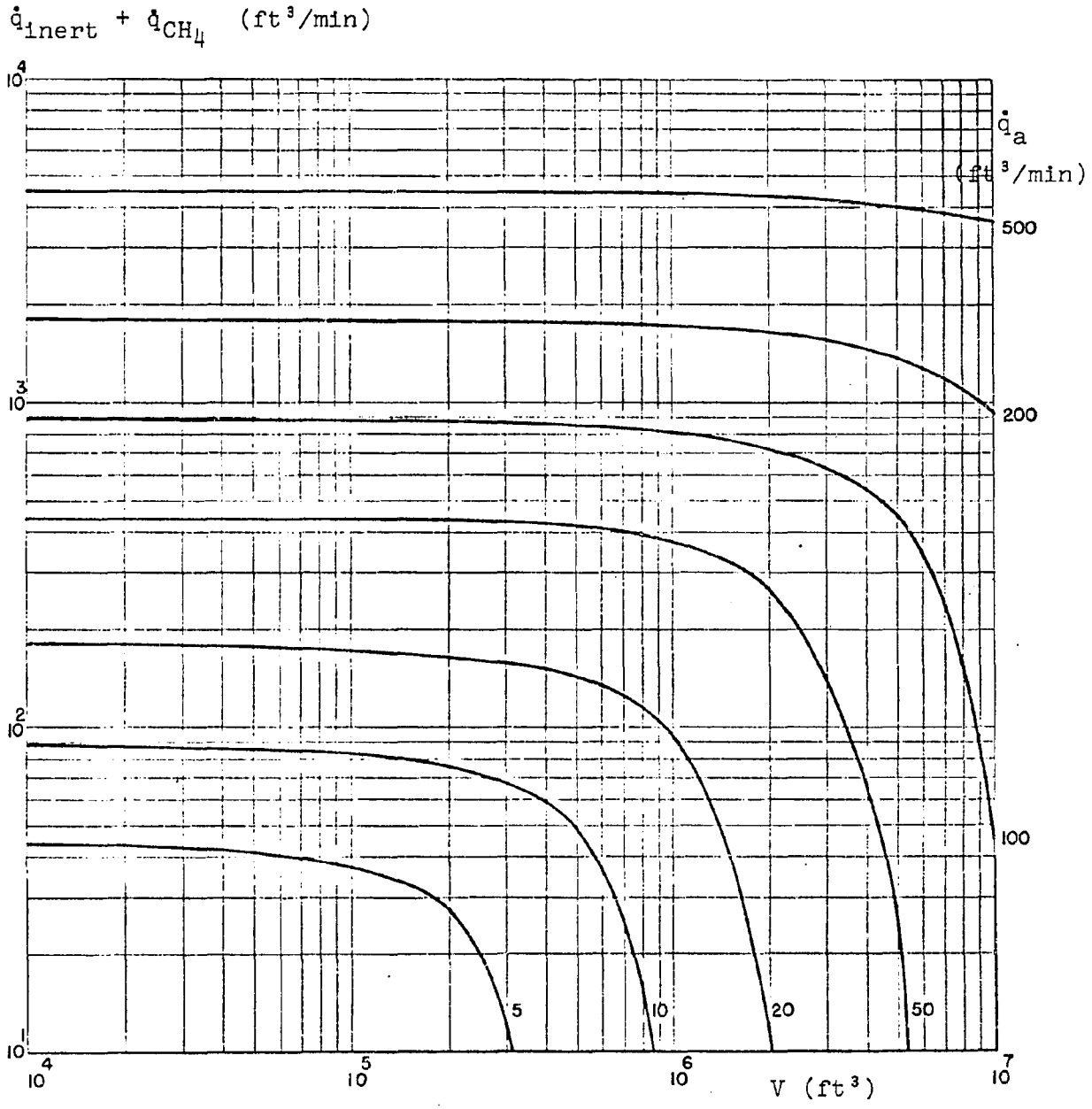


Fig. 29: Minimum flow rates ($\dot{q}_{inert} + \dot{q}_{CH_4}$) to reach an oxygen concentration of 2% for different air leakage rates $\dot{q}_a$

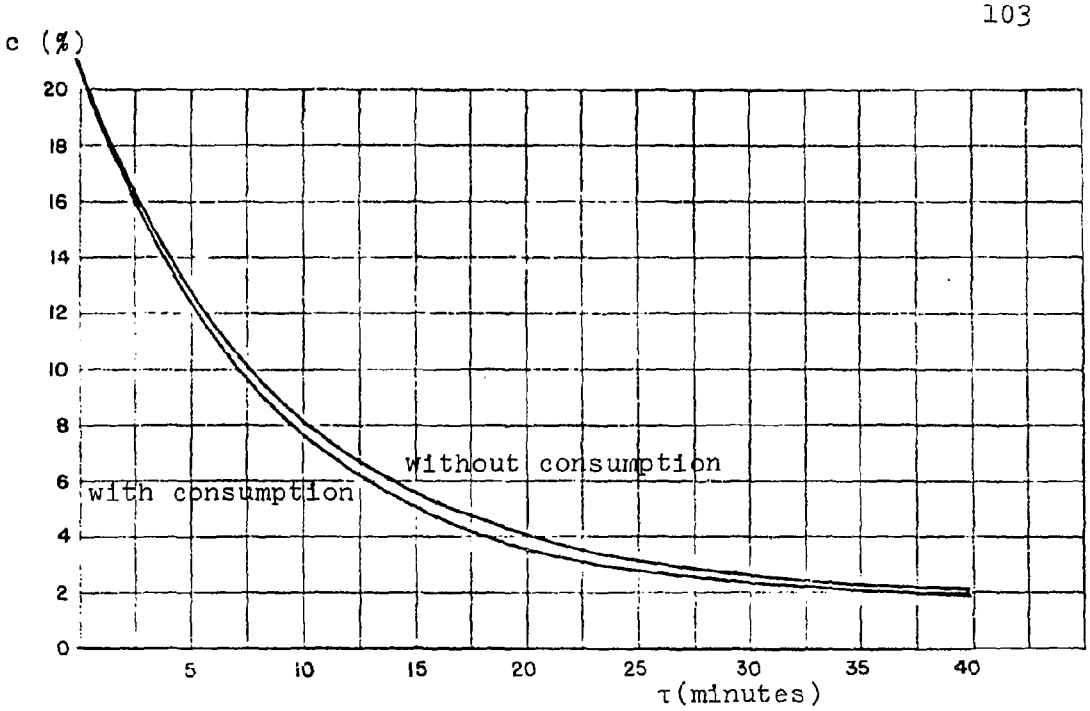
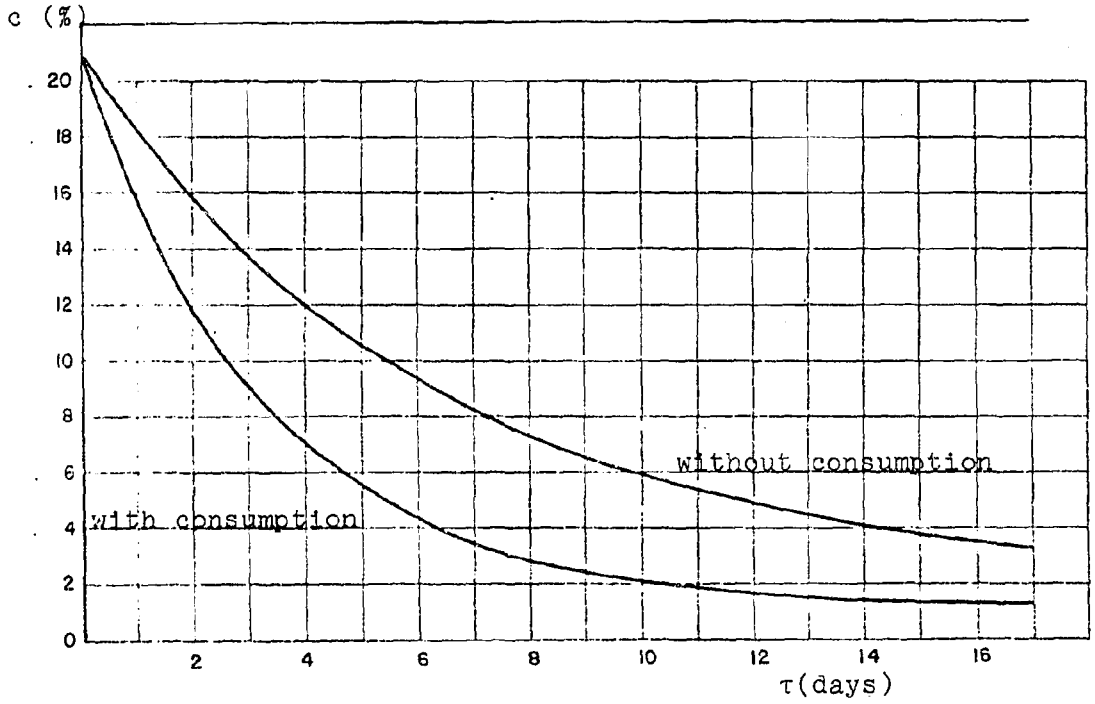


Fig. 30: Change of oxygen concentration calculated with and without consideration of the oxygen consumption

a : for values $V/\dot{q}_a = 100$ minutes and $(\dot{q}_{inert} + \dot{q}_{CH_4})/\dot{q}_a = 10$



b : for values $V/\dot{q}_a = 10^5$ minutes and $(\dot{q}_{inert} + \dot{q}_{CH_4})/\dot{q}_a = 10$

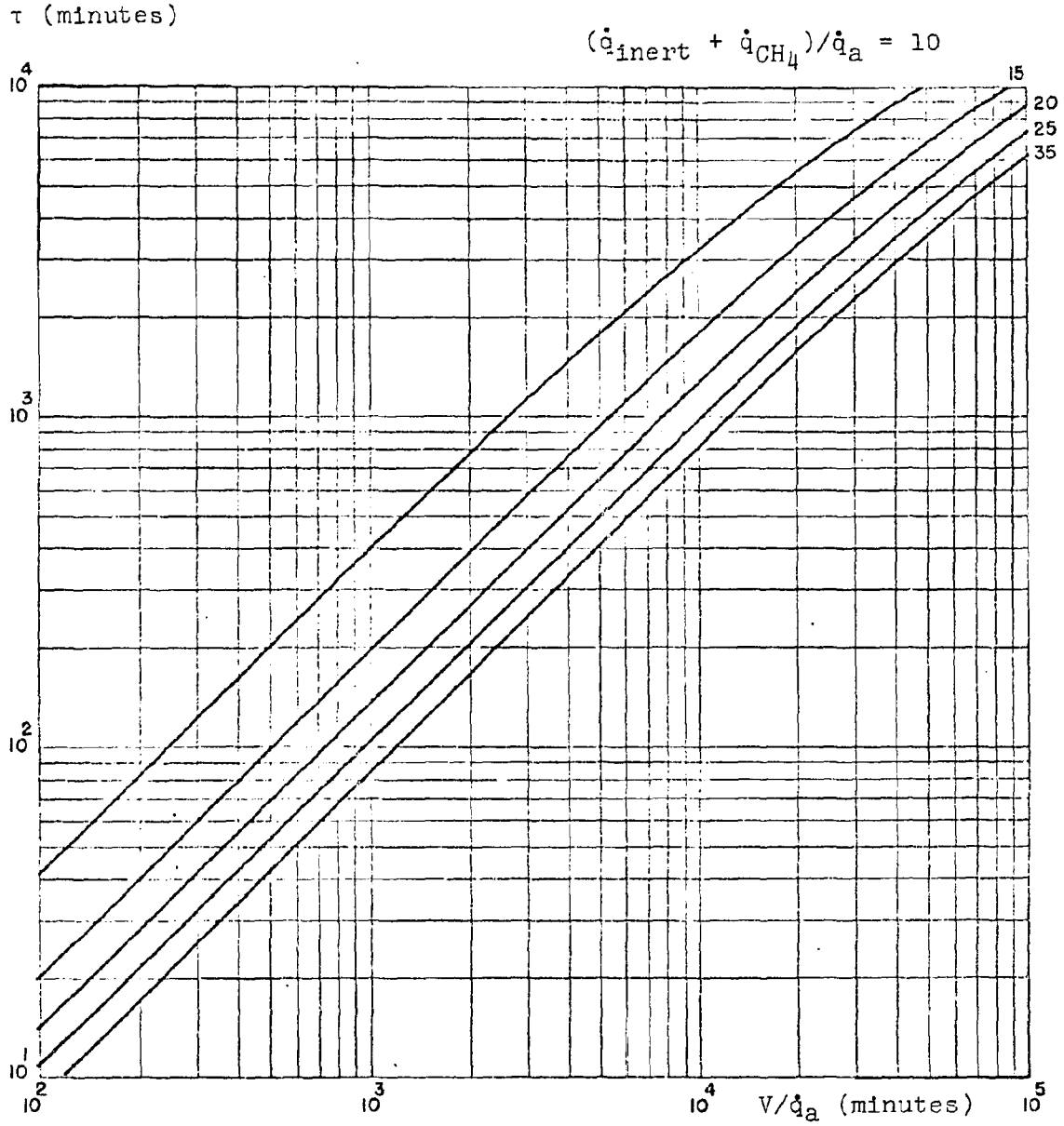


Fig. 31: Time within which the oxygen concentration in a sealed area can be lowered from 21% to 2%

with $\dot{q}_e = \dot{q}_{CH_4} + \dot{q}_{inert} - o_c \, V \, c + 0.05 \, \dot{q}_e$

It has been plotted in Fig. 32 a. for c = 12% and in Fig. 32b for c = 2% and c_{ao} = 21% as a function of V with parameters $(\dot{q}_{CH_4} + \dot{q}_{inert})$ = 10, 50, 100, 200, 400, 700, and 1000 ft^3/min.[4] If the oxygen consumption is neglected one obtains again

$$\tau = \frac{V}{\dot{q}_e} \ln \left(\frac{c_{ao}}{c}\right)$$

which was already shown in Fig. 20.

3. Comparison of Calculated Data With Reported Inert Gas Consumptions

The cases of inert gas application described in chapter V, which contain sufficient data for this purpose, were compared with the formulas developed in the previous paragraphs.

If air leakage, oxygen consumption and methane evolution are neglected, the total volume of inert gas Q to reduce the oxygen concentration from 21% to 2% by dilution is obtained from

$$Q = \dot{q}_{inert} \, \tau = V \ln\left(\frac{21}{2}\right) = 2.3 \, V$$

In the cases of successful inert gas use, where these conditions applied, the ratio Q/V was 2.19 reported by Wang-Tie Sin,[183] 2.86 reported by Westfield, Brumbaugh, and Whittaker,[186] 5.1 reported by Haller and Michels.[61]

In the last case, an interest in the fast and reliable extinction of the fire in a small sealed space (18,000 - 20,000 ft^3) led to the planned oversupply of inert gas.

A general observation by Osipov[127] is that a ratio of 2 - 3 should be expected.

Wang-Tie Sin[183] reports that a well sealed fire could be extinguished by lowering the oxygen concentration to 5.1 - 6.7% with a ratio Q/V = 1. The formula Q/V = ln(21/c) would deliver c = 7.7%.

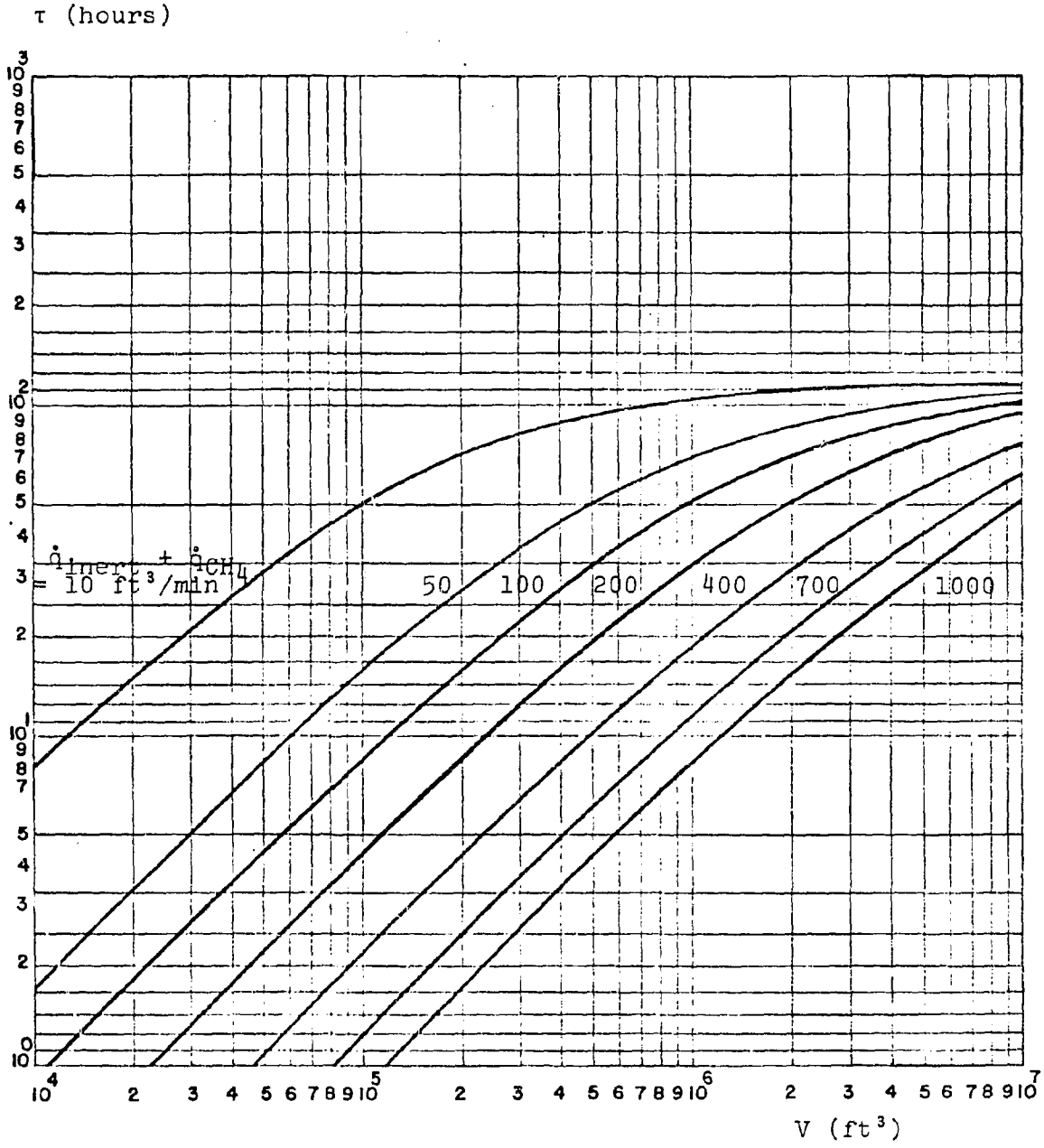


Fig. 32: Minimum time requirement (no air leakage) for lowering oxygen concentration in sealed areas

a : from 21% to 12%

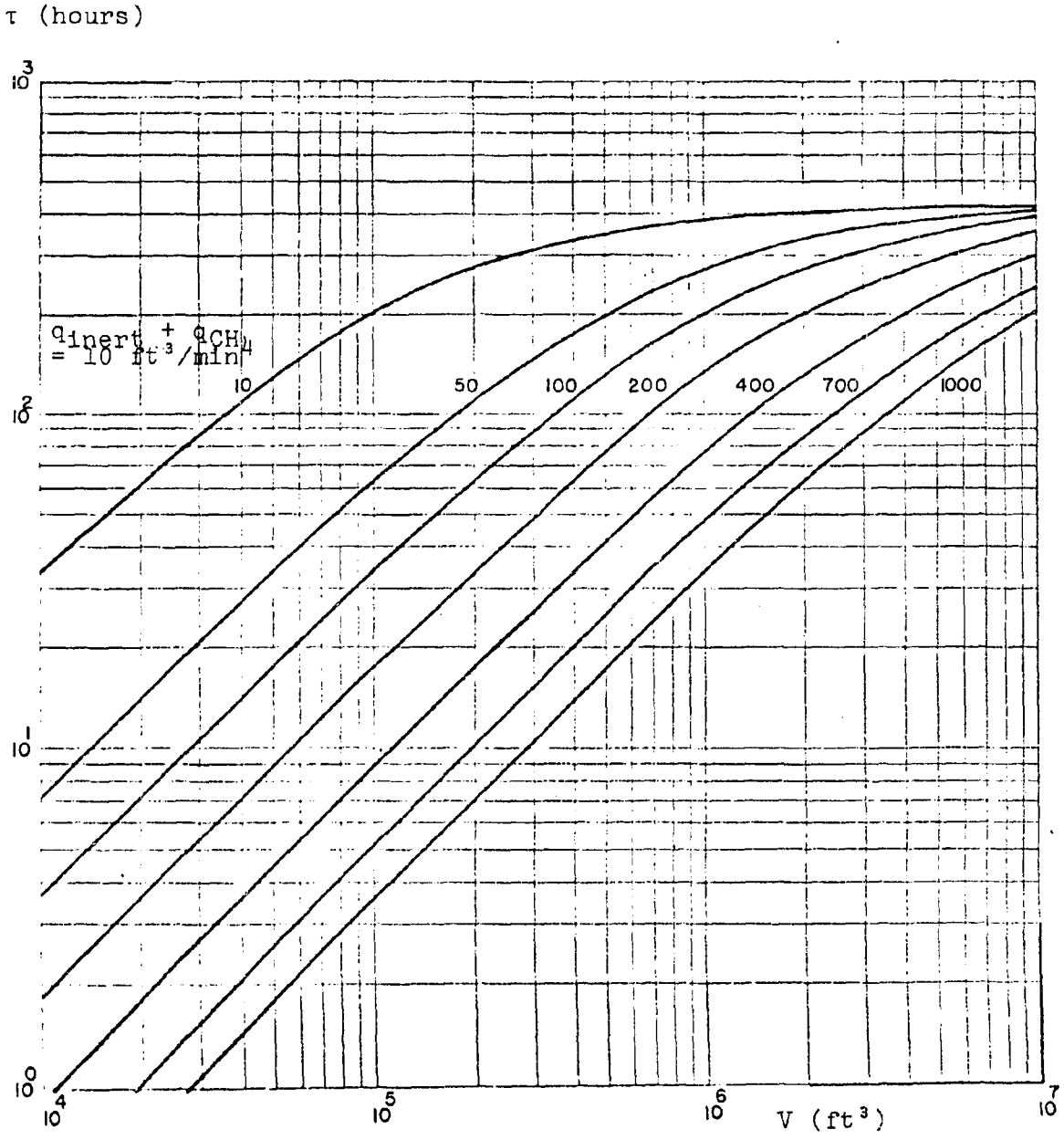


Fig. 32b : from 21% to 2%

The ratio Q/V = 1.24 reported by Sobolev[159] can be explained by the fact that the inert gas injection only started after the O_2 concentration had already dropped to 6.5%. The approximately constant CH_4 concentration indicates additionally a large CH_4 evolution.

In Table 10, only the first and the last listed mine fires give values of Q/V < 2.3. In both cases, the inert gas had to replace the atmosphere of a gob area, where the initial oxygen concentration must already have been low. For all the other mine fires of Table 10, the ratio Q/V is considerably higher than 2.3 since the ventilation of the fire zone with air continued during part of the inert gas release.

If the sealed volume is large and the air leakage negligible, the oxygen consumption becomes an influential factor and the oxygen concentration can be calculated from

$$c = c_{ao} \exp(- \tau \ (o_c \ V + \dot{q}_e)/V)$$

Osipov and Orlov report[130] that in a sealed space of $V = 3.32*10^6$ ft^3 with a total inert gas injection of $Q = 6.3*10^6$ ft^3 over 163 hours, the oxygen concentration could be lowered to 1% (Q/V = 1.9). The above formula delivers with c_{ao} = 21% and $o_c = 91.5*10^{-6}$ (min)$^{-1}$ a value of c = 1.3%.

In two reported cases the inert gas was mainly used to keep air leakage out of the sealed area. In the first fire (Jones[75]), no volume of the sealed area is reported but it is stated that the rate of inert gas injection $\dot{q}_{inert}$ was with 45 ft^3/min in the same order of magnitude as the ordinary air leakage $\dot{q}_{ao}$. In the second fire (Heers and Dennison[64]), the sealing period of 7 months (Fig. 26) alone should have been long enough to reduce the oxygen concentration to the finally reached 3%. A total volume of $23.5*10^6$ ft^3 inert gas injected into a sealed volume of $28*10^6$ ft^3 (Q/V = 0.84) helped, however, to reduce air leakage through surface cracks.

In one reported case (Vaughan-Thomas[178]) the air leakage was too large to lower the oxygen concentration sufficiently. With an ordinary air leakage of $\dot{q}_{ao}$ = 900 ft^3/min and with the air entering through cracks in the rock and leaving through a very tight seal, one can expect during the inert gas injection at the rate $\dot{q}_{inert}$ an air leakage of $\dot{q}_a = \dot{q}_{ao} - \dot{q}_{inert}$. The sealed space had a volume of 400,000 ft^3, injected were 590,000 ft^3 of inert gas during

the first 24 hours (Q/V = 1.475) and $1.87*10^6$ ft^3 during the first 60 hours (Q/V = 4.67). From

$$c = \frac{\dot{q}_a c_a}{\dot{q}_e} - \left(\frac{\dot{q}_a c_a}{\dot{q}_e} - c_{ao}\right) \exp\left(-\tau \frac{\dot{q}_e}{V}\right)$$

one obtains with $c_a = c_{ao} = 21\%$ and $\dot{q}_e = \dot{q}_{inert} + \dot{q}_a$

c = 11.6% after 24 hours and c = 8.9% after 60 hours. Observed were 10% and 7.37%.

D. Use of Pressure Chambers

It has been discussed that inert gas requirements are, to a great extent, determined by air leakage rates, and it is obvious that one should try to keep the latter as small as possible. Their magnitude depends, among other factors, on the differences in pressure inside and outside the sealed area, which are caused by: pressure losses in the adjoining ventilated mine workings (mine ventilating pressure differences); buoyancy pressures or natural drafts developed by density differences between sealed and unsealed mine atmosphere; and, absolute air pressure changes caused by barometric pressure variations at the surface of the mine.

Pressure differences from the first two sources have a tendency to pass air through the sealed area. They can be reduced by equalizing the pressures in the adjoining mine workings, adjusted for possible buoyancy pressures. This is a common practice, and has been described in the literature.[74,189] Barometric pressure variations cause approximately equal pressure changes in all adjoining ventilated mine working and create a pressure difference between the atmosphere within and outside the sealed area. They have a tendency to let the sealed area "breathe". These pressure differences can not be reduced by equalizing ventilating pressures in adjoining mine workings but by equalizing pressures across the seals. This requires the use of pressure balancing chambers which are formed by building a second stopping in a short distance from the seal, and which contain means for adjusting the pressure in the chamber to the pressure on the inside of the seal. Pressure balancing chambers are not only used in connection with sealed fire zones,[25,74,189] but to prevent air leakage into sealed old workings utilized for methane drainage.[19,39,191] Equipment for an automatic pressure control is available.[19,160]

1. Leakage Rates Caused by Pressure Variations of Surface Atmosphere

Although the literature is replete with observations on the breathing of sealed off mine workings, no data of general validity for the flow rates of gases leaving and entering could be found. It is, however, not too difficult to calculate these flow rates. If laminar flow through the seals is assumed and a flow direction into the sealed area, one obtains

$$\dot{q} = \frac{1}{R} (p_a - p_s)$$

where p_a = air pressure outside the sealed space
p_s = pressure of sealed atmosphere
R = total flow resistance of seals and leakage paths

The pressure of the sealed atmosphere changes from its original value p_{so} by

$$dp_s = \frac{\dot{q}\, d\tau}{V} p_{so} = (p_a - p_s) \frac{p_{so}}{V R} d\tau$$

For a constant p_a one obtains with $p_s = p_{so}$ for $\tau = 0$

$$p_s = p_a - (p_a - p_{so}) \exp\left(- \frac{p_{so}}{V R} \tau \right)$$

$$\dot{q} = \frac{1}{R} (p_a - p_{so}) \exp\left(- \frac{p_{so}}{R V} \tau \right)$$

The maximal flow rate $\dot{q}_{max}$ is obtained at $\tau = 0$.

Usually the air pressure does not suddenly jump to a value p_a but changes with time. If a linear change according to

$$p_a = p_{ao} + k\tau$$

is assumed, one obtains

$$d\dot{q} = \frac{1}{R} \left(k - \frac{\dot{q}\, p_{so}}{V}\right) d\tau$$

and, with $\dot{q} = 0$ for $\tau = 0$

$$\dot{q} = \frac{k\,V}{p_{so}}\left(1 - \exp\left(-\frac{p_{so}}{R\,V}\,\tau\right)\right) = \frac{\Delta p_a}{p_{so}}\,\frac{V}{\Delta\tau}\left(1 - \exp\left(-\frac{p_{so}}{R\,V}\,\tau\right)\right)$$

where Δp_a is the total increase of the pressure outside the sealed space within the time $\Delta\tau$. The maximal flow rate $\dot{q}_{max}$ is obtained at the end of the pressure change ($\tau = \Delta\tau$). The total flow is

$$Q = V\Delta p_a / p_{so}$$

If the pressure outside the sealed space varies according to

$$p_a = p_{ao} - \Delta p_a \cos\left(2\pi\,\frac{\tau}{\Delta\tau}\right)$$

where p_{ao} = average pressure

Δp_a = amplitude of variation

$\Delta\tau$ = cycle time

one obtains

$$d\dot{q} = \frac{1}{R}\left(\Delta p_a\,\frac{2\pi}{\Delta\tau}\sin\left(2\pi\frac{\tau}{\Delta\tau}\right) - \frac{\dot{q}\,p_{so}}{V}\right)d\tau$$

and with $\dot{q} = \dot{q}_o$ for $\tau = 0$ and $a = \frac{p_{so}}{R\,V}$, $b = \frac{\Delta p_a}{R} * \frac{2\pi}{\Delta\tau}$,

$c = \frac{2\pi}{\Delta\tau}$

$$\dot{q} = \exp(-a\tau)\left(\dot{q}_o + \frac{b*c}{a^2 + c^2}\right) + \frac{b}{(a^2 + c^2)^{1/2}}\sin(c\tau - \tan^{-1}(c/a))$$

When the transition period is over ($\tau \to \infty$), this becomes

$$\dot{q} = \frac{b}{(a^2 + c^2)^{1/2}}\sin(c\tau - \tan^{-1}(c/a))$$

The factor $\frac{b}{(a^2 + c^2)^{1/2}}$ is the amplitude of $\dot{q}$ and the

quantity $\tan^{-1}(c/a)$, the phase difference between $\dot{q}$ and p_a. The maximal flow rate is consequently

$$\dot{q}_{max} = \frac{b}{(a^2 + c^2)^{1/2}} = \frac{\frac{\Delta p_a}{R}\,\frac{2\pi}{\Delta\tau}}{\left(\left(\frac{p_{so}}{R\,V}\right)^2 + \left(\frac{2\pi}{\Delta\tau}\right)^2\right)^{1/2}}$$

The total flow, entering or leaving, is

$$Q = \dot{q}_{max}\Delta\tau/\pi$$

The ratio $q_{max}/\Delta p_a$, or the maximal flow rate per unit external pressure change has been plotted in Fig. 33 for linear and sinoidal pressure variations as a function of the ratio $V/\Delta\tau$. As parameters were resistance factors of R = 0.1, 0.05, 0.025, 0.0143, and 0.01 in. WG./cfm used. These resistance factors would correspond approximately to 1, 2, 4, 7 and 10 parallel seals of 100 ft^2 area each, built from foam or latex coated hollow core cinder-, slag-, or concrete-block dry-walls, or to latex coated brattice cloth stoppings.[80] The pressure p_{so} has been assumed to be 400 in. WG.

If leakage takes place through permeable rock and coal, the resistance of the leakage paths is difficult to estimate. In such cases, it may be possible to determine R from observations on pressure changes inside and outside the sealed area. For sinoidal barometric pressure variations, the phase difference τ_p between the variations of airway pressures p_a and the pressure differences of airways and sealed area $(p_a - p_s)$ may, for example, be used. With the above derived expressions for the phase difference one obtains

$$\frac{2\pi}{\Delta\tau}\,\tau_p = \tan^{-1}\left(\frac{2\pi}{\Delta\tau}\,\frac{R\,V}{p_{so}}\right) \text{ or}$$

$$R = \frac{\Delta\tau}{2\pi}\,\frac{p_{so}}{V}\,\tan\left(\frac{2\pi}{\Delta\tau}\,\tau_p\right)$$

Up to values $\frac{\tau p}{\Delta\tau} = 0.07$ one can without larger error substitute $\frac{2\pi}{\Delta\tau}\,\tau_p$ for $\tan\left(\frac{2\pi}{\Delta\tau}\,\tau_p\right)$ and obtain R from

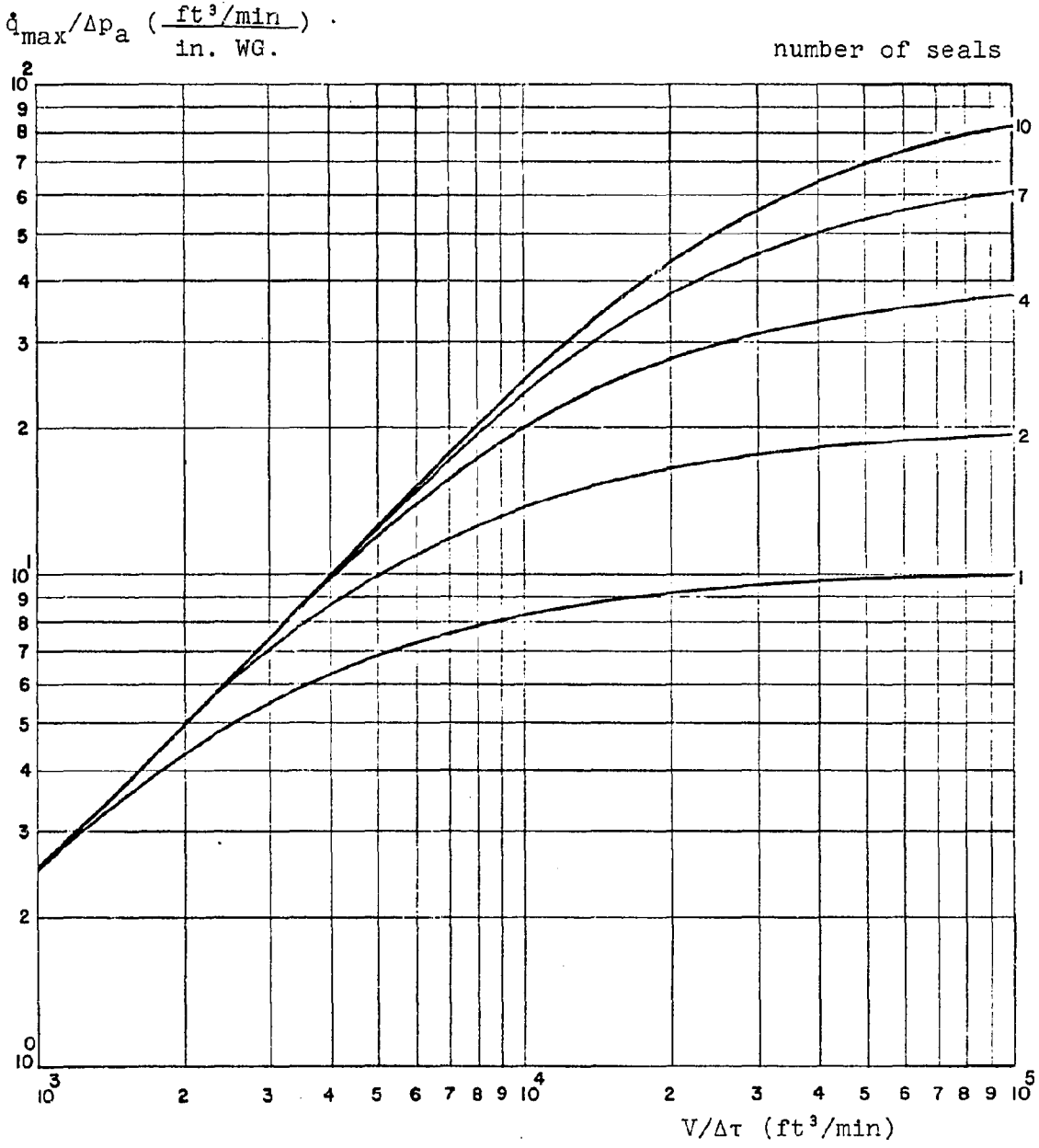


Fig. 33: Minimal air leakage rates caused by "breathing" of sealed areas

a : linear barometric pressure increases

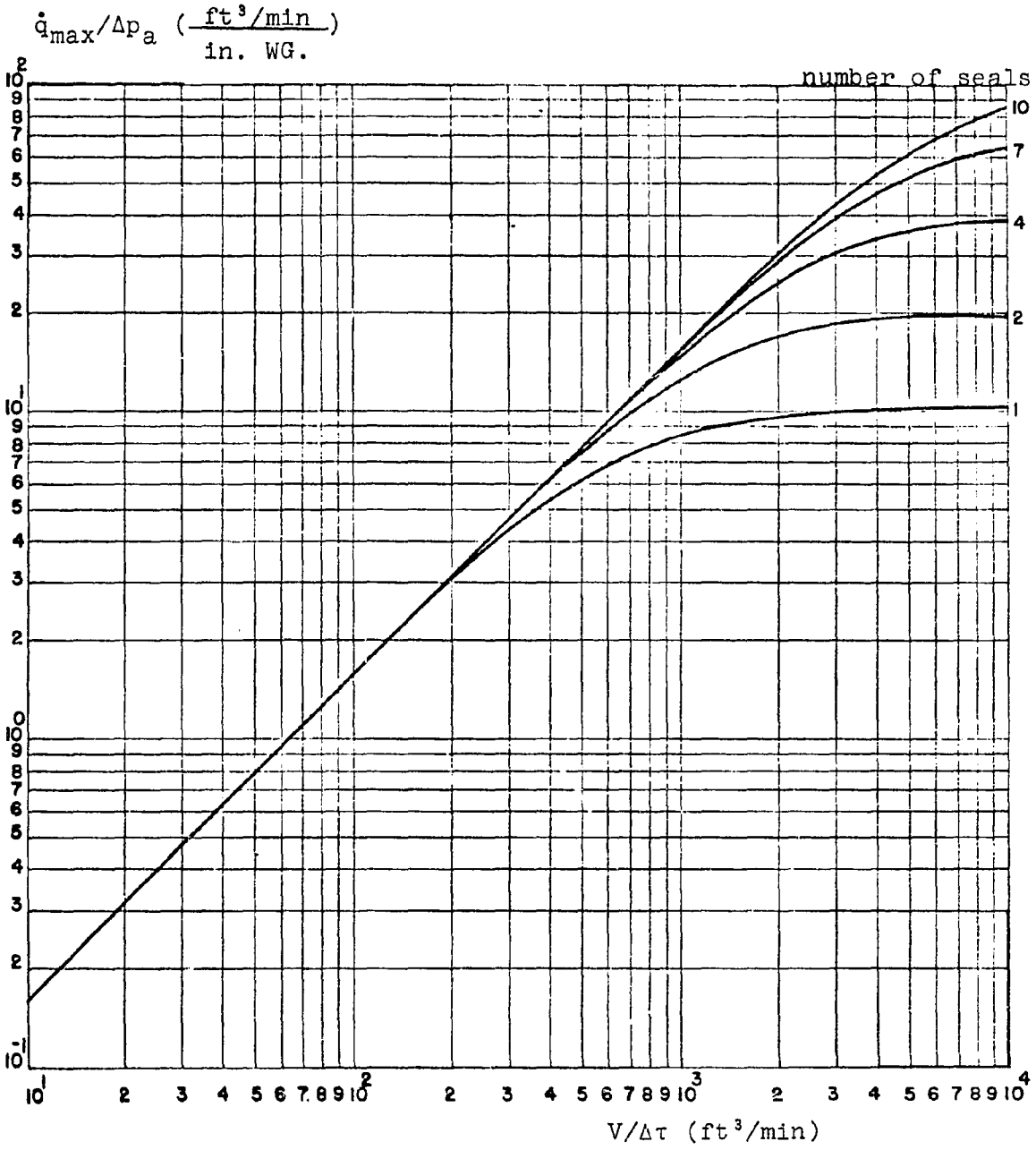


Fig. 33b : sinoidal barometric pressure changes

$$R = \frac{p_{so}}{V} \tau_p$$

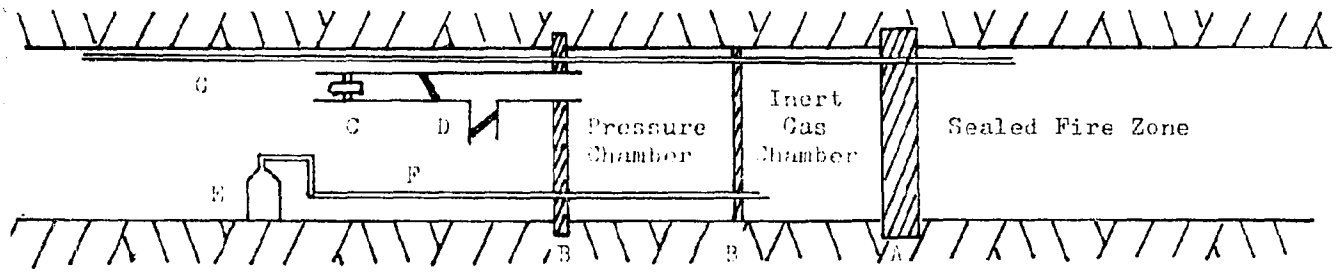
There have been suggestions to make whole mines independent of barometric pressure variations by providing regulating devices in all shafts and adits.[24] For example, a sealed fire zone of 690,000 ft^3 volume has been connected with an expansion container made from flexible ventilation duct of 6 ft. diameter and 800 ft. length.[92] The fire could be extinguished within 30 days.

2. Inert Gas Requirements in Combined Use of Inert Gas and Pressure Chambers

Inert gas filled pressure chambers of the gas lock type, as used in Poland and Czechoslovakia (chapter V), have to be kept at a pressure slightly higher than that of the mine atmosphere. They do not, therefore, reduce the gas leakage through the seals but provide that this leakage comprised inert gas only, not air. The order of magnitude of the gas leakage or the necessary rate of inert gas supply to refill the pressure chambers will be the same as the air leakage, which would occur without these chambers (Fig. 33).

Pressure balancing chambers can effectively prevent leakage through seals, when their pressure is always properly adjusted. As an additional safety, inert gas filled buffer zones (Fig. 34) can guarantee that possible leakage into the sealed area comprises inert gas only. How large this leakage is, depends on the pressure difference between chamber and sealed area. Automatic equipment can control the pressure differences to within 0.01 in. WG.[19] If the inert gas buffer zones are kept at a pressure which is 0.01 in. WG. above the pressure of pressure chambers and fire zones, approximately 0.1 to 0.2 ft^3/min or 150 to 300 ft^3/day are needed, wnen seals and stoppings are mortar-, foam-, or latex-coated and have an area of approximately 100 ft^2.[80]

Pressure balancing chambers cannot, however, control leakage through permeable rock and coal to adjoining ventilated mine workings. If this leakage is caused by mine ventilating pressure differences or buoyancy pressures, it can be fought by pressure equalizing along the boundary of the sealed area and by inert gas injections, to prevent air from entering. Figure 43 shows the needed inert gas flow rates as a function of resistances of intake and return leakage paths. For a resistance ratio of 1 the inert gas flow rate has, under the assumption of laminar flow,



A Main Stopping
B Pressure Chamber Stoppings
C Auxiliary Fan
D Airflow Regulating Valves
E Inert Gas Supply
F Inert Gas Line
G Spill-Over Line to Reduce Pressure in Sealed Fire Zone

Fig. 54: Pressure Balancing Chamber with an Inert Gas Filled Buffer Zone

to be twice as high as the flow rate of the air, which would without the inert gas pass through the sealed area. Under the assumption of turbulent flow, it has to be $\sqrt{2}$ times as high.

Air leakage through permeable rock and coal caused by "breathing" can only be prevented by maintaining in the sealed area with inert gas injections a pressure equal to that of the adjoining mine workings. For a linear pressure change according to $p_a = p_{ao} + k\tau$, the necessary inert gas flow rate is

$$\dot{q}_{inert} = \frac{k\ V}{p_{so}}$$

for a sinoidal pressure change according to $p_a = p_{ao} - \Delta p_a \cos(2\pi \frac{\tau}{\Delta\tau})$, it is

$$\dot{q}_{inert} = \frac{\Delta p_a V}{p_{so}} \quad \frac{2\pi}{\Delta\tau} \sin(\frac{2\pi}{\Delta\tau} \tau)$$

The maximal inert gas flow rate is

$$\dot{q}_{max} = \frac{\Delta p_a V \quad 2\pi}{p_{so} \quad \Delta\tau}$$

and the injection during the half-cycle with rising pressures is

$$Q = \dot{q}_{max} \Delta\tau/\pi \quad = 2\frac{\Delta p_a\ V}{p_{so}}$$

The required inert gas quantities are not small. If for Δp_a and $\Delta\tau$ average values of 10 in. WG. and 6000 minutes are assumed, one obtains

$$\dot{q}_{max} = \frac{10*2\pi}{400*6000} V = 0.0262*V*10^{-3}\ ft^3/min \text{ and}$$

$$Q = \frac{2*10}{400} V = 50*V*10^{-3}\ ft^3$$

or an average injection rate of

$$\dot{q}_{inert} = \frac{Q}{\Delta\tau} = 8.33*V*10^{-6}\ ft^3/min = 500*V*10^{-6}\ ft^3/hour$$

VIII. COOLING OF FIRE ZONES BY VENTILATING THEM WITH INERT GAS

A. Cooling Periods for Sealed Fire Zone Atmospheres

If fires are fought by reducing the oxygen content of their atmosphere, it is necessary to maintain the oxygen deficient state until the combustible material has been cooled sufficiently to prevent its reignition when the ventilation of the fire zone with air is resumed. Cooling takes place by heat transfer to the atmosphere and by heat flow into the strata. Which one has the greater effect depends very much on local conditions,[189] but it can be expected that the heat transfer to the atmosphere is generally more effective, at least when some movement of the atmosphere - like natural draft currents in sealed spaces -[106] exists. Cooling of fire zones is a slow process and at least 100 days are usually allowed before a sealed fire zone is reopened.[41]

No systematic observations on the temperature changes in a fire zone during its cooling exist. The temperature distribution in the rock surrounding an airway at fire has, however, been derived as a function of time, wall distance, gas temperatures, original rock temperature, convection coefficient and thermal rock properties by Kleshunov and Grin.[87] Based on their work, Baltajtis, Kleshunov, and Grin[9] calculate the temperature changes in the rock under the assumption of heat flow into the strata only and no heat transfer to the atmosphere. Under this assumption, the highest rock temperature can be expected at the airway wall and can be obtained from

$$\frac{\tau_c}{\tau_f} = \tan^2\left(\frac{\pi}{2} \frac{t_f - t_w}{t_f - t_{VR}}\right)$$

where τ_c = cooling off period
τ_f = active fire period
t_f = temperature of airway walls during active fire
t_w = temperature of airway walls at time τ_c.
t_{VR} = original rock temperature of strata

Figure 35 shows the dimensionless wall temperature

$$\frac{t_w - t_{VR}}{t_f - t_{VR}} = 1 - \frac{t_f - t_w}{t_f - t_{VR}}$$

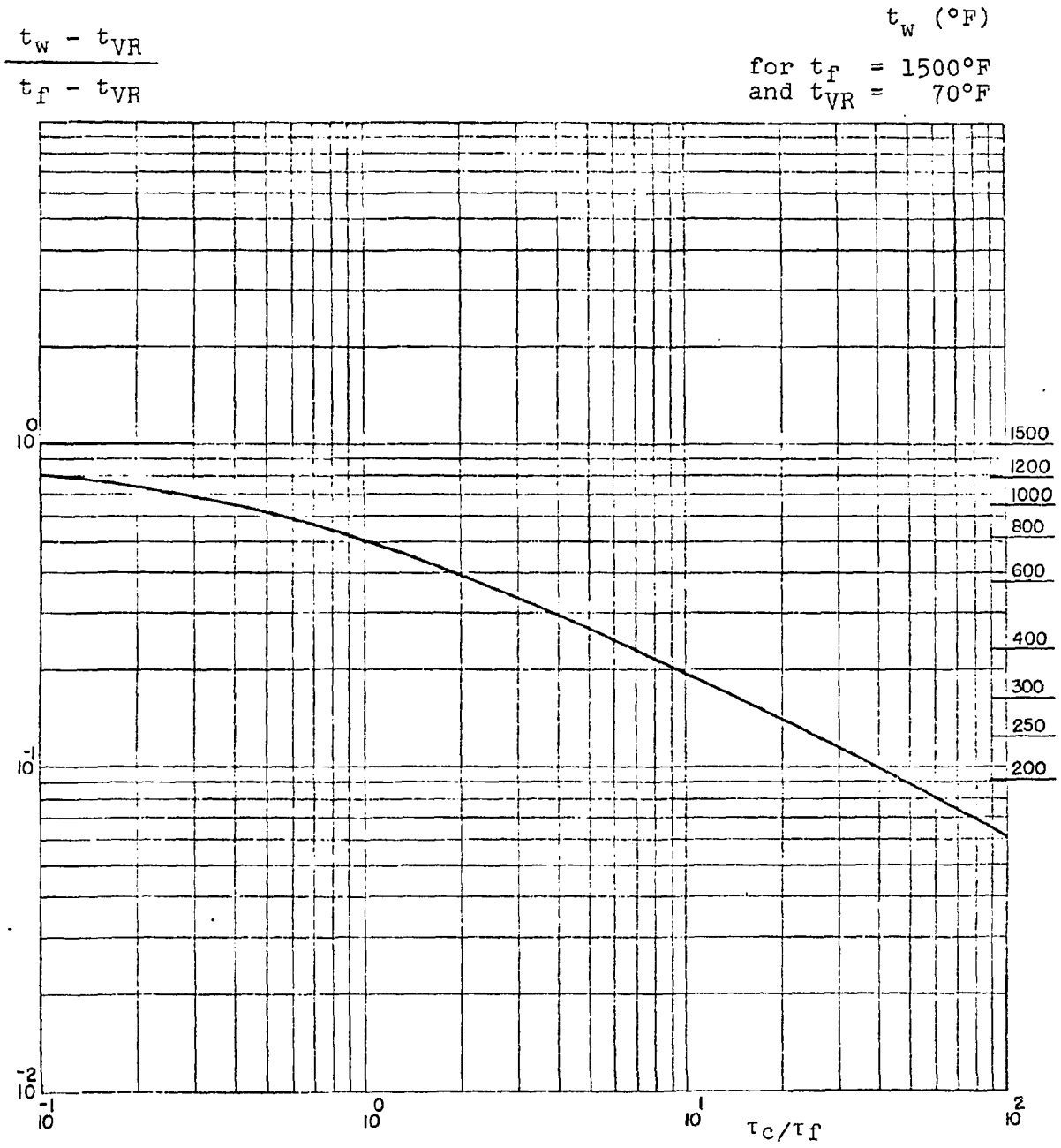


Fig. 35: Rock temperatures for different ratios of cooling off periods τ_c to fire periods τ_f

as a function of the ratio τ_c/τ_f. It shows, furthermore, absolute values of t_w for t_f = 1500°F and t_{VR} = 70°F. 1500°F were chosen because this value had been obtained as an average temperature in coal fire experiments.[162-3] One sees that for a cooling to 300°F, the lowest ignition temperature of coal dust,[164] a ratio τ_c/τ_f = 17 is necessary.

B. Cooling Periods of Fire Zones With Inert Gas Ventilation

It can be expected that the cooling of fire zones can be considerably accelerated if the fire zone is ventilated with inert gases, which carry heat away without fanning the fire. Rothwell[144] pointed out in 1875 that a mass of coal in full combustion requires a long time to cool and that, to hasten the cooling, the injection of inert gas has been practiced. McElroy[106] discussed in 1938 the recirculation of the fire gases in a sealed area in order to promote the cooling of burning masses together with a limited injection of inert gas to eliminate leakage of air into the fire zone. Kukuczka[91] suggested in 1964 the recirculation of inerted and cooled fire gases. A case of recirculation with intermediate cooling by dry ice[64] has been described in chapter V.A.

1. Calculation of Rock Temperatures as Function of Ventilating Time

Since no observations on the cooling effect of recirculated inert gases exist, this effect was calculated. No attempt was made to set up a complete model of the heat flow processes during the initial inert gas application to extinguish the fire plus the later recirculation, because the mathematical difficulties are disproportionately large, especially in view of the many idealizing assumptions which have to be made. Instead, it was assumed that during the fire period τ_f the airway walls were kept at the constant temperature t_f, and that during the subsequent ventilation of the fire zone with inert gases, the airway walls were kept at a temperature equal to the original rock temperature t_{VR}. This last assumption will be discussed later.

If the heat flow inside the rock is caused by conduction only, the temperature distribution inside the rock can be described by Fourier's equation

$$\frac{\partial t_g}{\partial \tau} = a\nabla^2 t_g + \frac{1}{c\,\gamma}\,W$$

where t_g = rock temperature
τ = time
$a = k/c\gamma$ = thermal diffusivity of rock
k = heat conductivity of rock
c = specific heat of rock
γ = specific weight of rock
W = rate of heat generation per unit volume inside rock

Under the assumption of: homogeneous and isotropical rock, uniform temperature in the rock at the beginning of the heat flow process, negligible heat flow parallel to the airway, no heat sources or sinks in the rock, and circular cross section of the airway, Fourier's equation can be written in cylinder coordinates as

$$\frac{\partial t_g}{\partial \tau} = a \left(\frac{\partial^2 t_g}{\partial r^2} + \frac{1}{r} \frac{\partial t_g}{\partial r} \right)$$

The error caused by the assumption of a circular cross section with the hydraulic radius $r_o = 2A/P$ (A = cross sectional area, P = perimeter of airway) has been theoretically and experimentally investigated. For the calculation of the heat exchange between rock and atmosphere, this error is for rectangular cross sections between 8 and 11% - for side ratios of the rectangles, between 1 (square) and 0.3.[88]

A larger number of general and numerical solutions of the above version of Fourier's equation for an infinite rock body, which is internally bounded by a cylindrical airway, exist, but most of them have been derived for the determination of the heat exchange between rock and atmosphere.[59] Several general solutions for the temperature distribution inside the rock have been published, but numerical solutions were only recently provided by Nottrot and Sadée.[124] These solutions are based on the boundary conditions

$t_g = t_{VR}$ for $\tau = 0$ and $t_g = t_{VR}$ for $r = \infty$ at all times

and are of the type

$$t_g = t_a + (t_{VR} - t_a) F(r/r_o, Fo, Bi)$$

where $F(r/r_o, Fo, Bi)$ = function of r/r_o, Fo, Bi
r = distance from airway center
r_o = hydraulic radius of airway
$Fo = a\,\tau/r_o^2$ = Fourier number
$Bi = \alpha_c r_o/k$ = Biot number
α_c = convection coefficient

For Bi = ∞, which corresponds to an infinite convection coefficient α_c and a wall temperature equal to the air temperature, $F(r/r_o, Fo, Bi = \infty) = (t_g - t_a)/(t_{VR} - t_a)$ is shown in Table 12.

If the airway walls are kept by a fire over the time τ_f at the temperature t_f and the rock had the original temperature t_{VR}, the temperature distribution inside the rock is given by

$$t_g = t_f - (t_f - t_{VR}) \quad F(r/r_o, Fo(\tau_f), Bi = \infty)$$

If the temperature of the walls is for an additional time τ_c kept by cooling through inert gas ventilation at the temperature t_c, it is

$$t_g = t_c - (t_f - t_{VR}) \quad F(r/r_o, Fo(\tau_f + \tau_c), Bi = \infty)$$

$$+ (t_f - t_c) \quad F(r/r_o, Fo(\tau_c), Bi = \infty)$$

since the addition of two solutions of a linear differential equation is again a solution. Under the condition that the inert gas on its way to the fire zone assumes the original rock temperature ($t_c = t_{VR}$), this can be reduced to

$$t_g = t_{VR} + (t_f - t_{VR}) \quad [F(r/r_o, Fo(\tau_c), Bi = \infty) - F(r/r_o, Fo(\tau_f + \tau_c), Bi = \infty)]$$

Based on this equation dimensionless rock temperatures $(t_g - t_{VR})/(t_f - t_{VR})$ have been plotted in Fig. 36, a - e for fire periods of 50, 30, 20, 10, and 5 days and for cooling periods of different lengths as a function of the dimensionless wall distance $(r/r_o - 1)$. The temperatures are based on coal with a thermal diffusivity of a = 0.01 ft²/hr and a hydraulic airway radius of r_o = 4 ft (12 x 6 ft² entry. If Fig. 36 shall be applied to other materials or hydraulic radii, the time changes inversely proportional to the diffusivity ratios and proportional to the square of the ratio of the hydraulic radii. If Fig. 36 is, for instance, used for sandstone rock with a thermal diffusivity four times as large as that of coal, all times would have to be reduced to 1/4 of the indicated values. The application to an airway with r_o = 5 ft. would effect an expansion of all times by a factor $(5/4)^2$.

Where the values of $F(r/r_o, Fo, Bi = \infty)$, provided by Nottrot and Sadée[124] did not suffice, interpolations with polynomial approximations were performed.

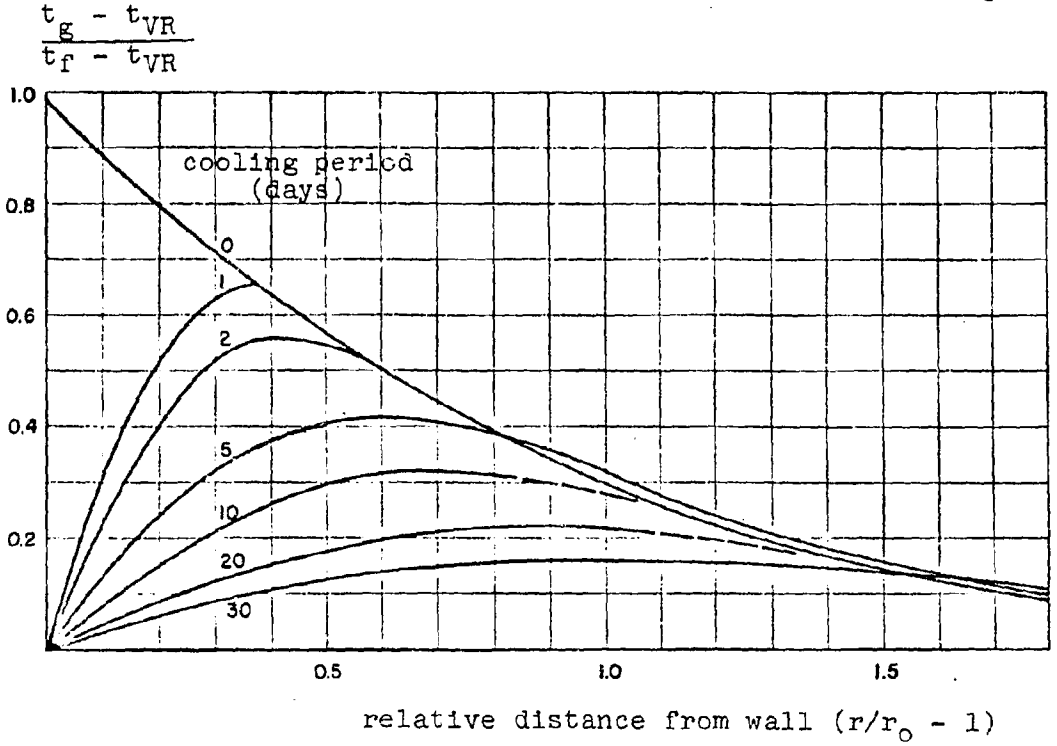


Fig. 36a : fire period of 50 days

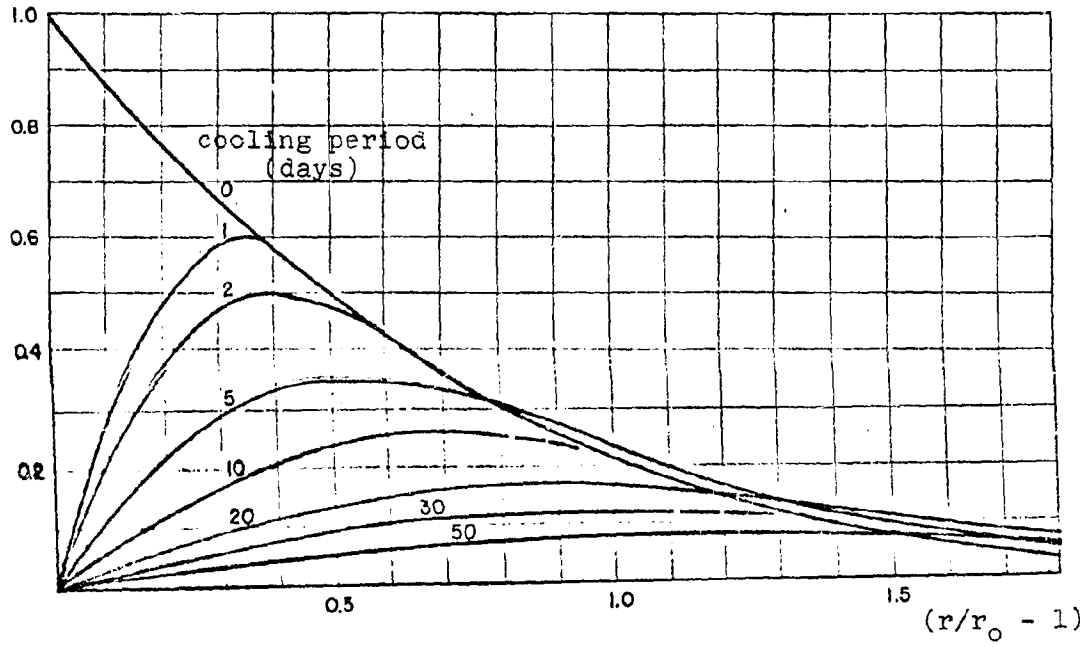


Fig. 36b : fire period of 30 days

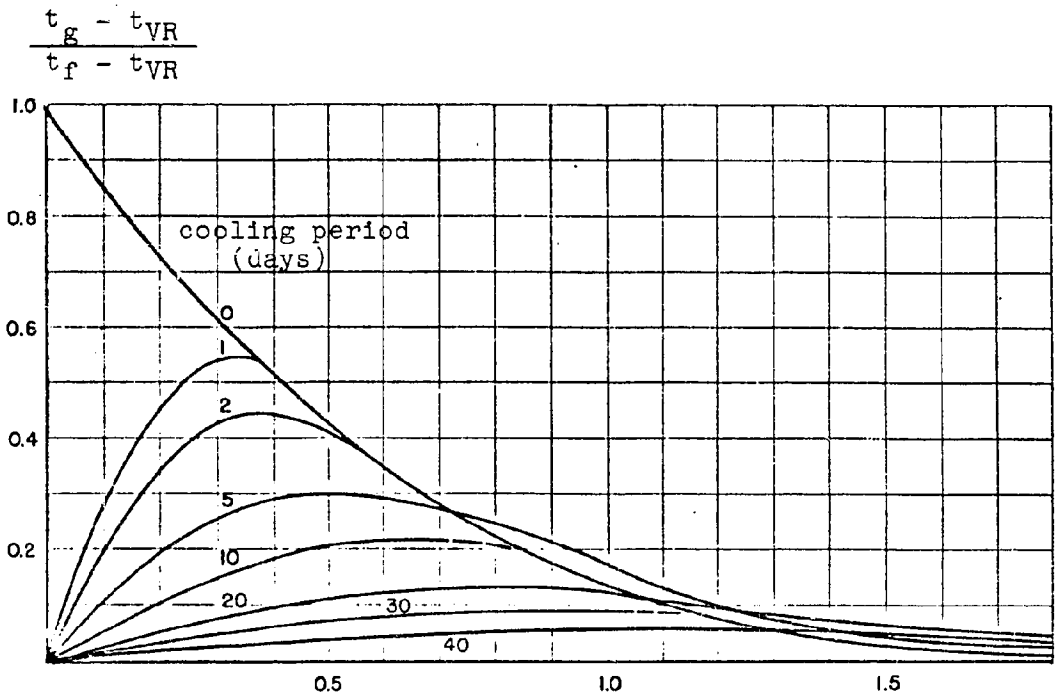


Fig. 36c : fire period of 20 days

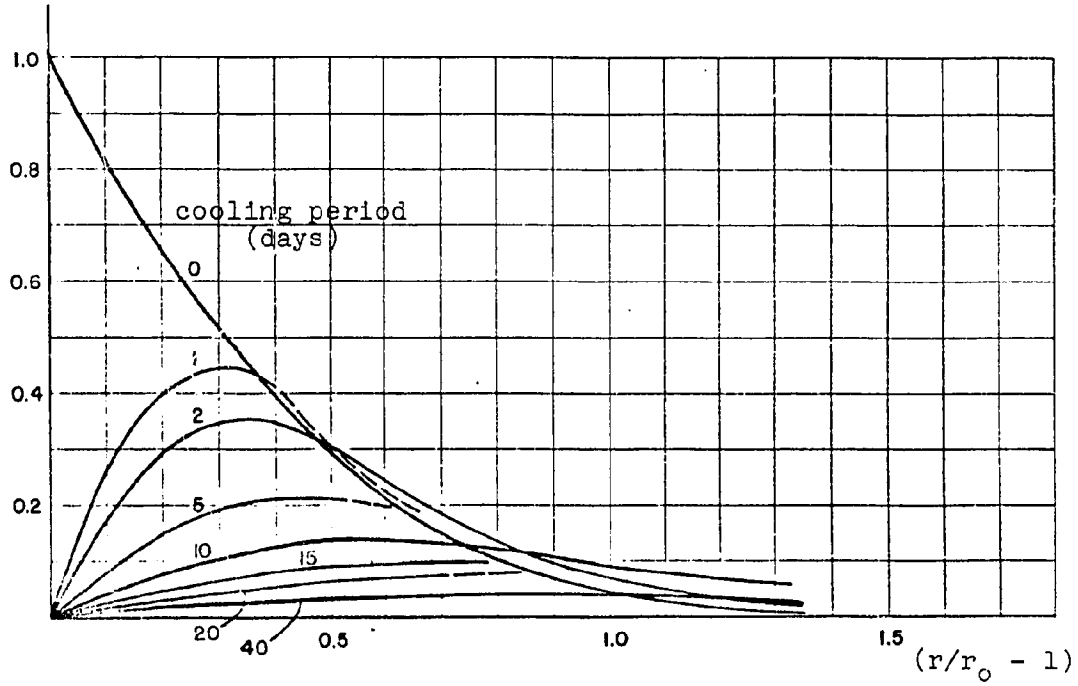
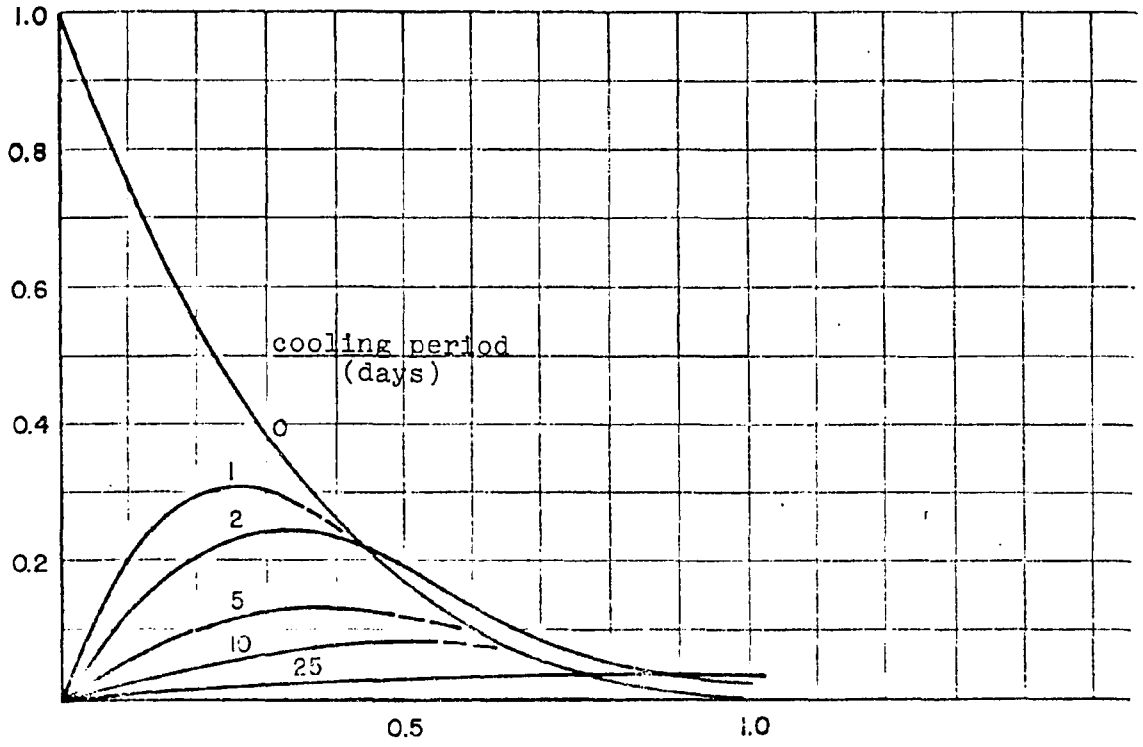


Fig. 36d : fire period of 10 days

$$\frac{t_g - t_{VR}}{t_f - t_{VR}}$$



relative distance from wall ($r/r_o - 1$)

e : fire period of 5 days

Fig. 36: Rock Temperatures for Different Fire and Cooling Periods When Airway Walls During Cooling Period are Kept at Virgin Rock Temperature

Fo \ r/r$_0$	1,00	1,33	1,67	2,00	3,33	5,00	6,67	8,33	10,00	13,33
0,008	0,000	0,994	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,014	0,000	0,961	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,02	0,000	0,919	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
0,08	0,000	0,650	0,928	0,992	1,000	1,000	1,000	1,000	1,000	1,000
0,14	0,000	0,540	0,840	0,960	1,000	1,000	1,000	1,000	1,000	1,000
0,20	0,000	0,479	0,778	0,921	1,000	1,000	1,000	1,000	1,000	1,000
0,80	0,000	0,303	0,526	0,689	0,965	1,000	1,000	1,000	1,000	1,000
1,40	0,000	0,255	0,448	0,597	0,908	0,993	1,000	1,000	1,000	1,000
2,00	0,000	0,230	0,406	0,544	0,860	0,979	0,998	1,000	1,000	1,000
8,00	0,000	0,162	0,287	0,388	0,660	0,842	0,933	0,975	0,992	1,000
14,00	0,000	0,143	0,254	0,344	0,591	0,769	0,874	0,935	0,969	0,995
20,00	0,000	0,133	0,236	0,320	0,551	0,724	0,832	0,900	0,944	0,985
80,00	0,000	0,103	0,183	0,249	0,431	0,575	0,673	0,747	0,803	0,883

Table 12 : Dimensionless rock temperatures $(t_E - t_a)/(t_{VR} - t_a)$ for an infinite Biot number Bi = ∞ [1 2 4]

Fo \ Bi	0,1	0.3	0,5	1,0	2,5	5,0	10,0	25,0	∞
0,0004	0,100	0,298	0,495	0,980	2,368	4,490	8,114	15,482	
0,008	0,099	0,292	0,477	0,912	1,997	3,277	4,723	6,104	
0,014	0,099	0,289	0,471	0,887	1,874	2,941	4,003	4,865	
0,02	0,098	0,287	0,465	0,868	1,788	2,717	3,569	4,197	4,472
0,08	0,097	0,276	0,437	0,772	1,400	1,873	2,188	2,375	2,463
0,14	0,097	0,270	0,422	0,724	1,239	1,578	1,786	1,887	1,967
0,20	0,096	0,265	0,411	0,691	1,138	1,412	1,573	1,667	1,715
0,80	0,093	0,244	0,361	0,557	0,803	0,924	0,995	1,033	1,056
1,40	0,092	0,235	0,340	0,506	0,698	0,788	0,839	0,870	0,888
2,00	0,091	0,228	0,326	0,475	0,640	0,716	0,759	0,785	0,800
8,00	0,087	0,203	0,276	0,375	0,472	0,515	0,540	0,553	0,562
14,00	0,085	0,193	0,258	0,343	0,424	0,459	0,477	0,489	0,496
20,00	0,084	0,187	0,248	0,325	0,397	0,427	0,444	0,455	0,461
80,00	0,079	0,167	0,218	0,269	0,317	0,336	0,348	0,355	0,358
120,00			0,205	0,256		0,316	0,326		0,336
1000,00									0,251

Table 13: Coefficients of age K(α) as a function of Fourier and Biot numbers [1 2 4]

If, similar to Fig. 35, the highest temperatures inside the rock are plotted over ratios τ_c/τ_f one obtains Fig. 37. A comparison between Fig. 35 and 37 shows clearly the large reduction in cooling time which an inert gas ventilation can accomplish. If the walls during the fire and cooling periods have assumed temperatures of 1500 and 300°F resp., cooling of the rock to 300°F requires a cooling period slightly shorter than the fire period has been.

2. Discussion of Assumptions For This Calculation

The assumption that the wall temperature of the fire zone during the ventilation with inert gas is kept at a constant level, has been made to avoid an excessive amount of mathematical work. In reality, the inert gas will have, on its way through the fire zone, been heated with the extent of heating decreasing with time. To judge the usefulness of the constant wall temperature assumption, the temperature change of the inert gas on its way through the fire zone is calculated next.

This requires the knowledge of the fire zone length, which is to be cooled by the inert gas ventilation. Although sufficient information for timbered roadways exists,[59] no systematic observations on fire zone lengths could be found for coal fires. To estimate the order of magnitude, the relations derived in chapter III. B. for channel burning were used. As described there, the oxygen concentration change along a channel can be expressed by

$$c = c_o \exp\left(- \frac{P}{A\,\bar{V}} \frac{1}{\frac{1}{\alpha} + \frac{1}{\alpha_{dif}}} L \right)$$

which for high temperatures ($\frac{1}{\alpha} << \frac{1}{dif}$, diffusion range) can be reduced to

$$c = c_o \exp\left(- \frac{P}{A\,\bar{V}} \alpha_{dif}\, L \right)$$

For turbulent flow, the approximation

$$\alpha_{dif} \approx \bar{V}\, 18 * 10^{-3}\, N_R^{-0.16}$$

has been suggested.[86]

In oxygen rich fires (chapter VI. B.), where fire propagation takes place by local heat transfer from

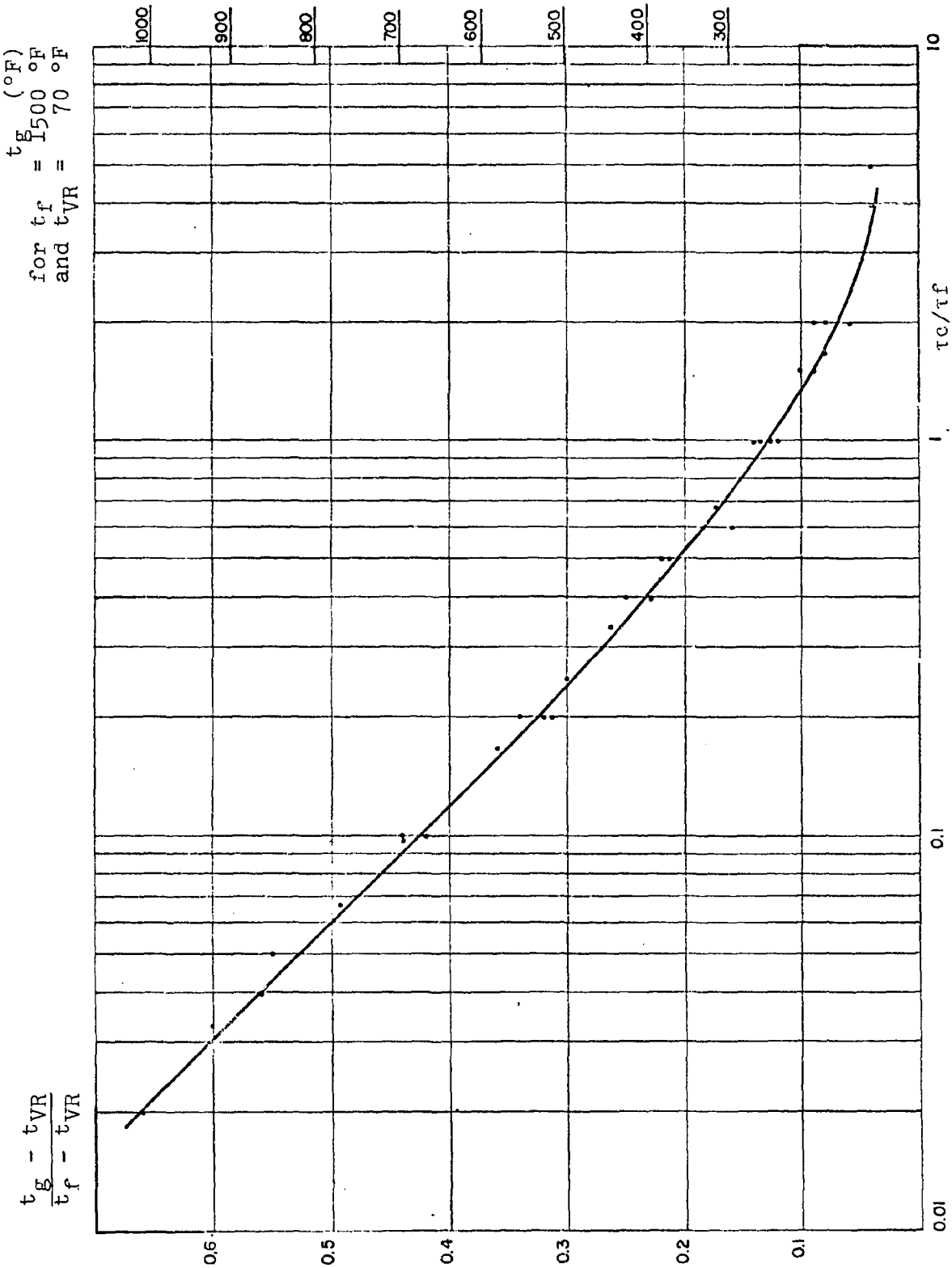


Fig. 37: Maximal rock temperatures for different ratios $\tau c/\tau f$

the flames, the end of the fire zone can be expected to be where flaming combustion is no longer possible. That is approximately the case at oxygen concentrations of 12% (chapter VI. C.). Under this assumption one obtains for the length of the fire zone

$$L = \frac{10^3}{18} \frac{A}{P} N_R^{0.16} \ln\left(\frac{21}{12}\right)$$

The results are shown in Fig. 38 for different air velocities and airway dimensions.

If the rock in a fire zone has assumed the temperature t_f, inert gas entering the fire zone at the mass flow rate $\dot{G}$ with the temperature t_{io} is after a length of travel L heated to[59]

$$t_i = t_f - (t_f - t_{io}) \exp\left(-\frac{P\ k\ K(\alpha)}{\dot{G}\ c_p\ r_o} L\right)$$

$K(\alpha)$ is usually called the "coefficient of age" and is a solution of the Fourier equation. Values for $K(\alpha)$ have been provided by several authors. Table 13 shows the values determined by Nottrot and Sadée[124] as a function of the dimensionless Fo and Bi numbers.

Figure 39 shows the relative temperature increase of the inert gas

$$\frac{t_i - t_{io}}{t_f - t_{io}} = 1 - \exp\left(\frac{P\ k\ K(\alpha)}{\dot{G}\ c_p\ r} L\right)$$

for two airways in coal with hydraulic radii of 4 and 6 ft. It has been assumed that the velocity of the ventilating air before the seals were closed or inert gas was introduced was 1 ft/sec and that fire zones of approximately 350 and 550 ft. length were developed (Fig. 38). The convection coefficient was determined from

$$\alpha_c = 0.4\ \bar{V}^{0.8}\ (\text{Btu/ft}^2\ ^\circ\text{F hr}),^{59}$$

for the thermal conductivity of coal, a value of k = 0.23 Btu/ft °F hr was used.

One sees from Fig. 39 that even under the assumption that all of the rock surrounding the fire zone has been heated to the temperature t_f, the cooling of the rock in the immediate vicinity of the fire zone is a fast process. After a few days of inert gas ventilation with

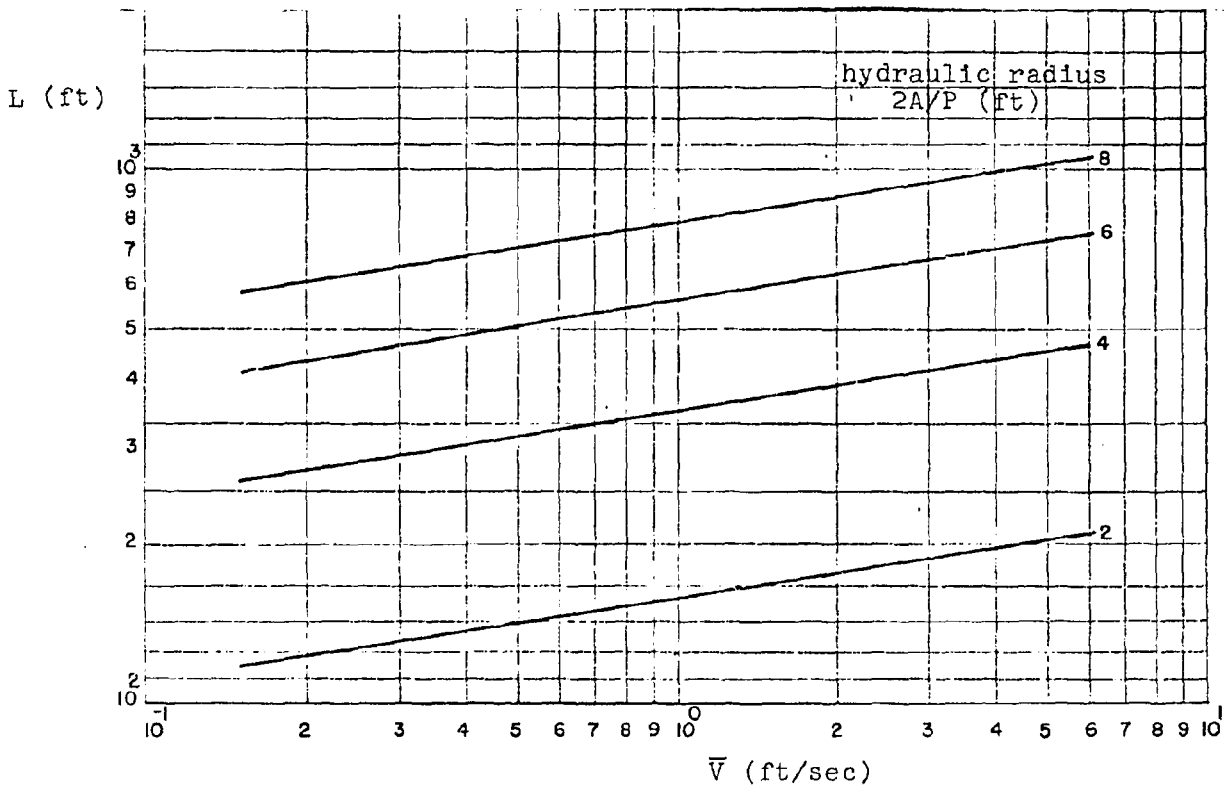


Fig. 38: Length of fire zone L which reduces the oxygen concentration from 21 to 12%

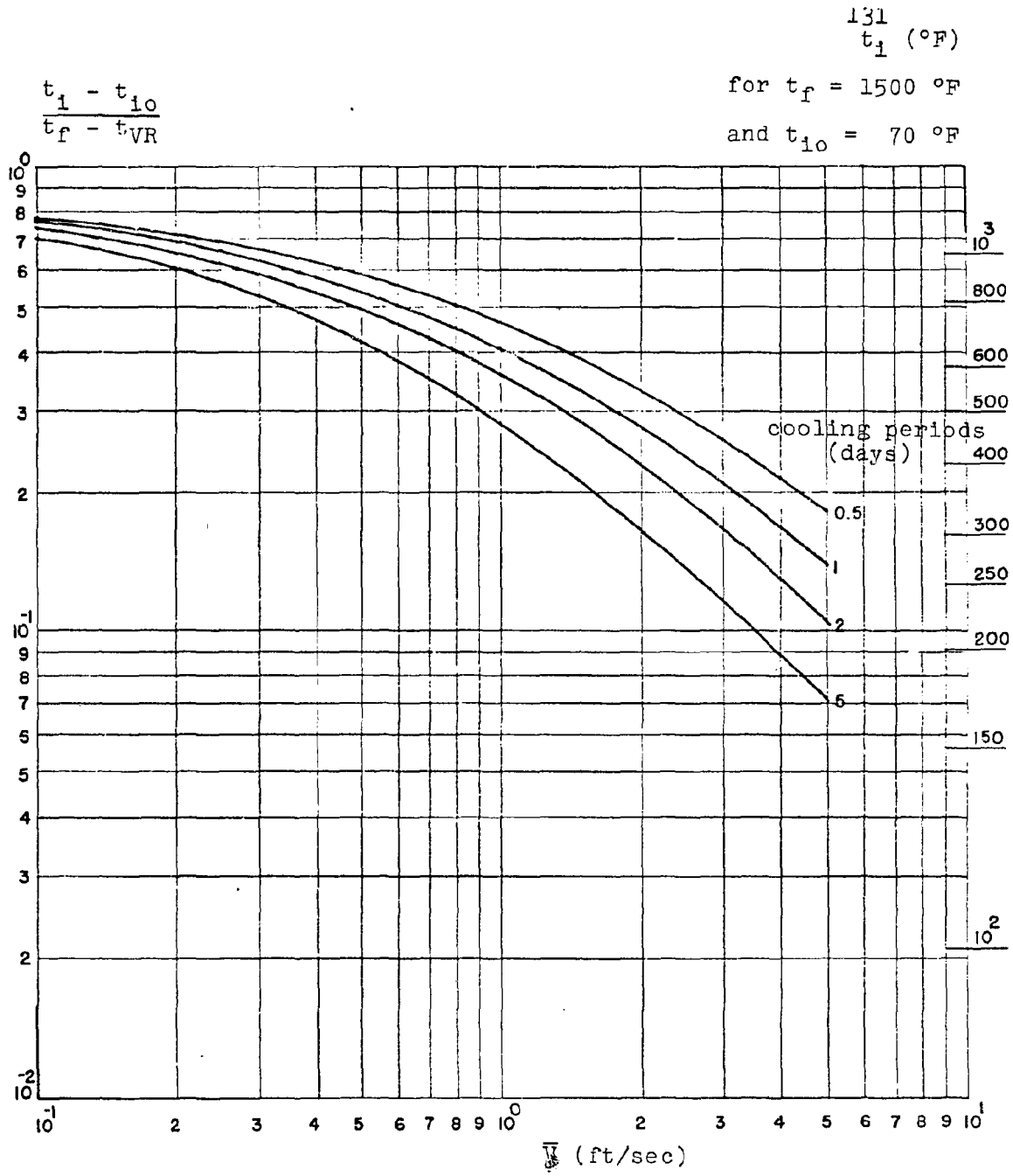
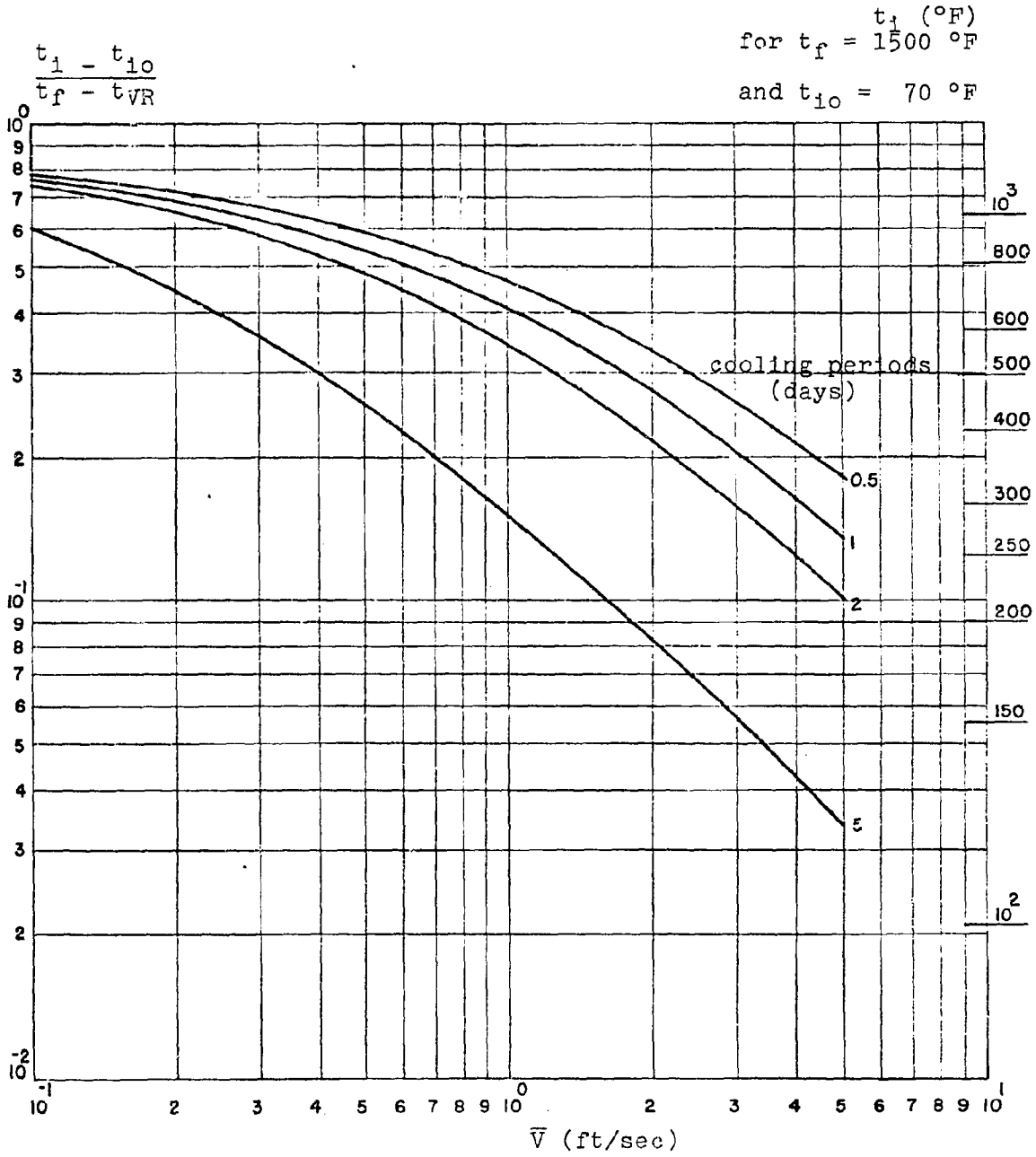


Fig. 39a : length of fire zone L = 550 ft, hydraulic radius of airway 2A/P = 6 ft



b : length of fire zone L = 350 ft, hydraulic radius of airway 2A/P = 4 ft

Fig. 39: Temperature increase of recirculated inert gas while passing through a fire zone at the end of different cooling periods and for different flow velocities

flow velocities larger than 1 ft/sec, the temperature increase of the inert gas in the fire zone is moderate. Since in reality not all of the rock but only the part immediately enveloping the airway has been heated to t_f (Fig. 36), the real temperature increase of the inert gas will be considerably lower than shown in Fig. 39.

Not all of the heat collected in a fire zone by the inert gas has, in recirculation set-ups, to be extracted in heat exchangers. A considerable portion can be transferred to the rock in other parts of the mine. Figure 40 shows the relative temperature $(t_i - t_{VR})/(t_{io} - t_{VR})$ for a gas, which leaves the fire zone with a temperature t_{io} and passes through airways with the rock temperature t_{VR} after 5 days (Fig. 40 a.), and 1/2 days (Fig. 40 b.) of recirculation. Figure 40 has been calculated for airways in coal with a hydraulic radius of 6 ft, otherwise the same assumptions, as in the determination of the inert gas heating, have been made.

IX. INTERACTION OF MINE VENTILATION SYSTEMS AND INERT GASES

Several ways in which inert gases can interact with mine ventilation systems have not yet been fully discussed.

Every inert gas release into a ventilation system will change the air flow distribution in this system. It will, in particular, reduce the air leakage through sealed areas when released into these areas.

The calculations on inert gas requirements in chapter VII were based on the assumption that perfect mixing of the released inert gas with the surrounding atmosphere takes place. Released inert gas will, however, have a tendency to push the original atmosphere away and let it move in front of the inert gas body. It has to be investigated how much mixing in flow direction can be expected to take place. It is, furthermore, known that gases with different densities can resist instanteous mixing and form extensive layers. If such layering can occur with inert gases or air leakage, it should be investigated also.

The propelling force for the movement of inert gases will generally be provided by the mine ventilating pressure, which acts at the airway to be filled with gas. Mine ventilating pressures depend on the ventilation system and have a limited maximal magnitude. It should, therefore, be determined which inert gas quantities they are able to move.

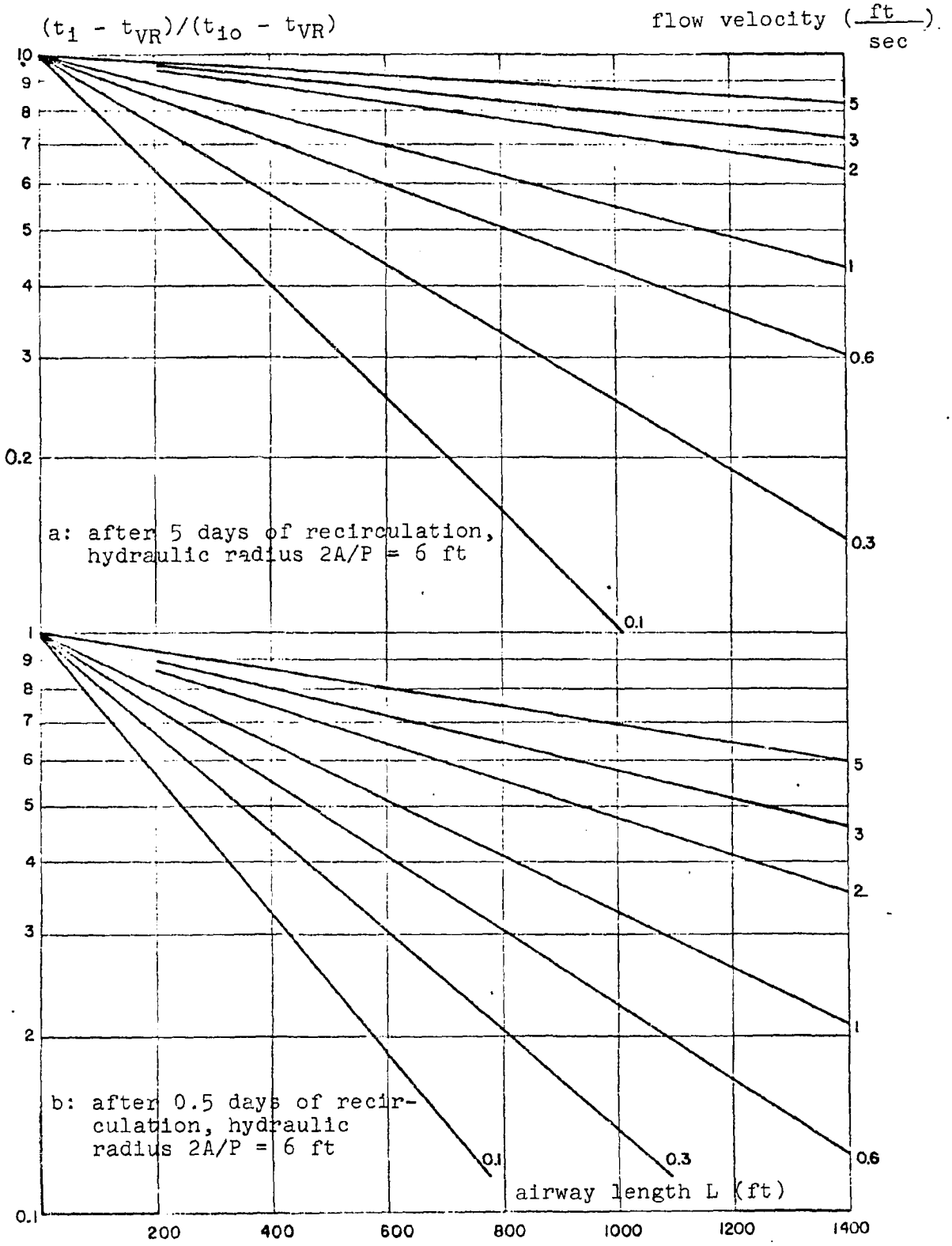


Fig. 40: Temperature drop of recirculated inert gas after leaving fire zone

If inert gas is forced into a sealed area, it will exert an increased pressure on seals and will have a tendency to leak out until an equilibrium with the mine ventilating pressure is reached again. The order of magnitude of pressure increases and leakage rates should be known.

It should, finally, be investigated if the presence of inert gases in a mine can create any additional risks for the mine ventilating system.

A. Reduction of Air Leakage Through a Sealed Area by Inert Gas Injection

The change of air flow rate through a sealed area is mainly determined by the ratio of flow resistances of inbye and outbye seals, by the flow rate of air normally entering the sealed fire zone, by the flow rate of injected inert gas, and by the mode of gas flow through the seals, laminar or turbulent. Which mode prevails, depends on the dimensions of the airpasses through the seals. Large holes, as in dry walls of rock, hollow core concrete-, slag-, cinder-blocks, or board stoppings will allow turbulent flow, small holes, like in mortar or foam coated dry or wet walls laminar flow. If large and small holes are simultaneously present, part of the flow will be laminar and part of it turbulent. This finds its expression in the varying exponents n of the resistance equation

$$p = R\,\dot{q}^n$$

relating the pressure p across a seal with the rate of gas flow $\dot{q}$ through it. Measured values of n vary between 1 (laminar flow) for the tighter walls and 2 (turbulent flow) for the less tight walls with a wide array of intermediate values.[80,153] The following calculations will be based on the two extremes, pure laminar and pure turbulent flow.

If the air flow rates before and after the injection of inert gas are $\dot{q}_{ao}$ and $\dot{q}_a$, the inert gas flow rate is $\dot{q}_{inert}$, the resistance factors of inbye and outbye seals are R_i and R_o, the justifiable assumption is made that the ventilating pressure acting at the sealed area is not changed by the inert gas injection, the following equation holds for laminar flow:

$$\dot{q}_{ao}(R_i + R_o) = \dot{q}_a R_i + (\dot{q}_a + \dot{q}_{inert}) R_o$$

and the following equation for turbulent flow:

$$\dot{q}_{ao}^2(R_i + R_o) = \dot{q}_a^2 R_i + (\dot{q}_a + \dot{q}_{inert})^2 R_o$$

The flow rate ratio of inert gas to air is changed from $\dot{q}_{inert}/\dot{q}_{ao}$ for laminar flow to

$$\frac{\dot{q}_{inert}}{\dot{q}_a} = \left(\frac{\dot{q}_{ao}}{\dot{q}_{inert}} - \frac{R_o}{R_i + R_o}\right)^{-1}$$

for turbulent flow to

$$\frac{\dot{q}_{inert}}{\dot{q}_a} = \left(-\frac{R_o}{R_i + R_o} + \sqrt{\left(\frac{R_o}{R_i + R_o}\right)^2 - \frac{R_o}{R_i + R_o} + \left(\frac{\dot{q}_{ao}}{\dot{q}_{inert}}\right)^2}\right)^{-1}$$

For the case that both seals are of the same quality ($R_i = R_o$), these functions are reduced to

$$\frac{\dot{q}_{inert}}{\dot{q}_a} = \left(\frac{\dot{q}_{ao}}{\dot{q}_{inert}} - \frac{1}{2}\right)^{-1} \text{ and}$$

$$\frac{\dot{q}_{inert}}{\dot{q}_a} = \left(-\frac{1}{2} + \sqrt{-\frac{1}{4} + \frac{\dot{q}_{ao}}{\dot{q}_{inert}}}\right)^{-1}$$

These functions $\dot{q}_{inert}/\dot{q}_a$ are shown in Fig. 41 and Fig. 42.

The air flow is stopped ($\dot{q}_a = 0$) at

$$\frac{\dot{q}_{inert}}{\dot{q}_{ao}} = \frac{R_i}{R_o} + 1 \text{ for laminar flow and at}$$

$$\frac{\dot{q}_{inert}}{\dot{q}_{ao}} = \sqrt{\frac{R_i}{R_o} + 1} \quad \text{for turbulent flow}$$

shown in Fig. 43.

If not only one inbye and outbye seal, but several seals on each side of the fire zone are used, similar relations can be derived which give qualitatively the same answers.

One sees from Fig. 41 and pertinent formulas that the air flow $\dot{q}_a$ is not changed by an inert gas injection $\dot{q}_{inert}$ when the resistance of the outbye seal R_o is negligible

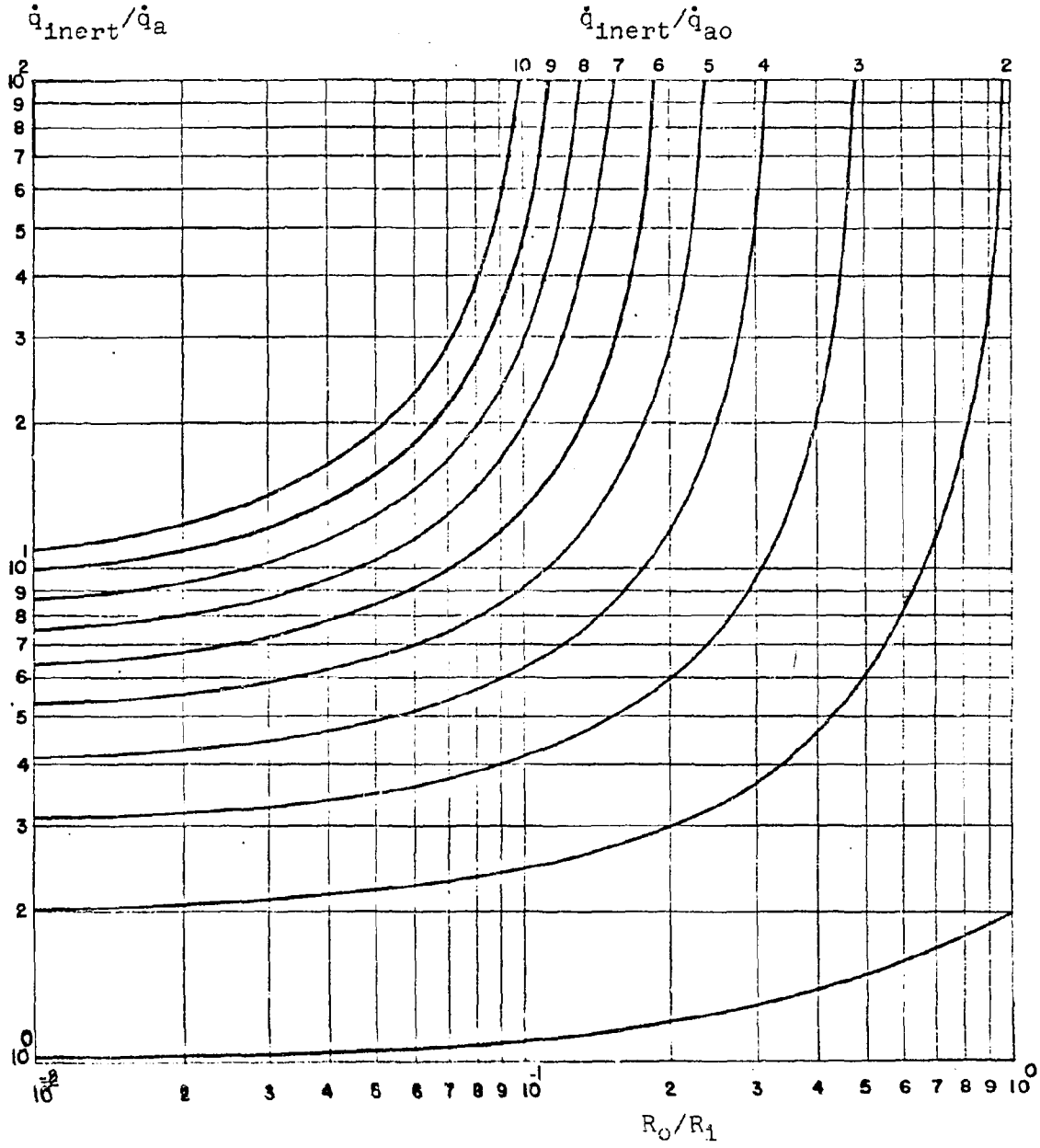


Fig. 41: Increase of flow rate ratio $\dot{q}_{inert}/\dot{q}_a$ caused by airflow reductions due to inert gas injections.

a :- laminar flow through seals

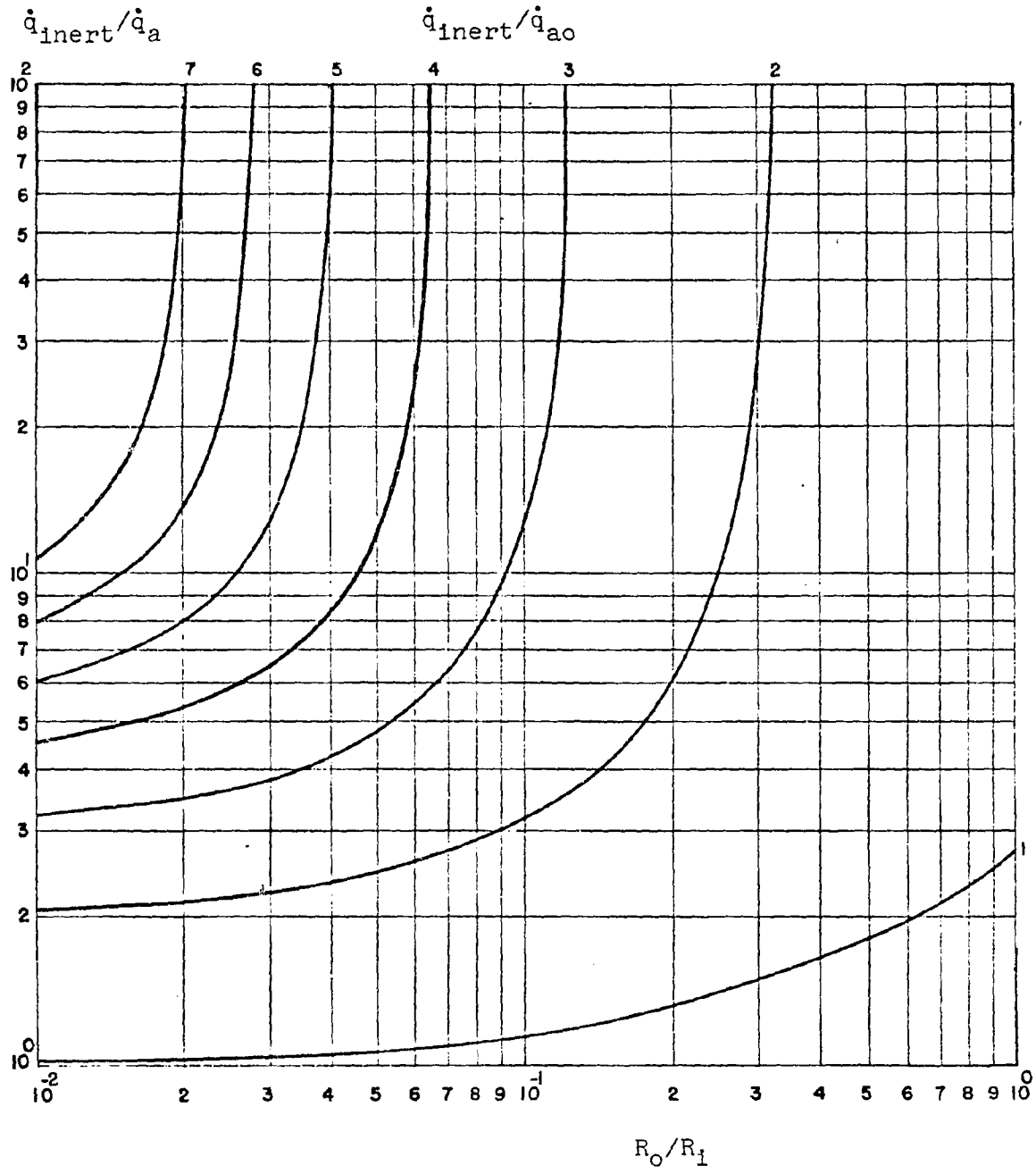


Fig. 41b : turbulent flow through seals

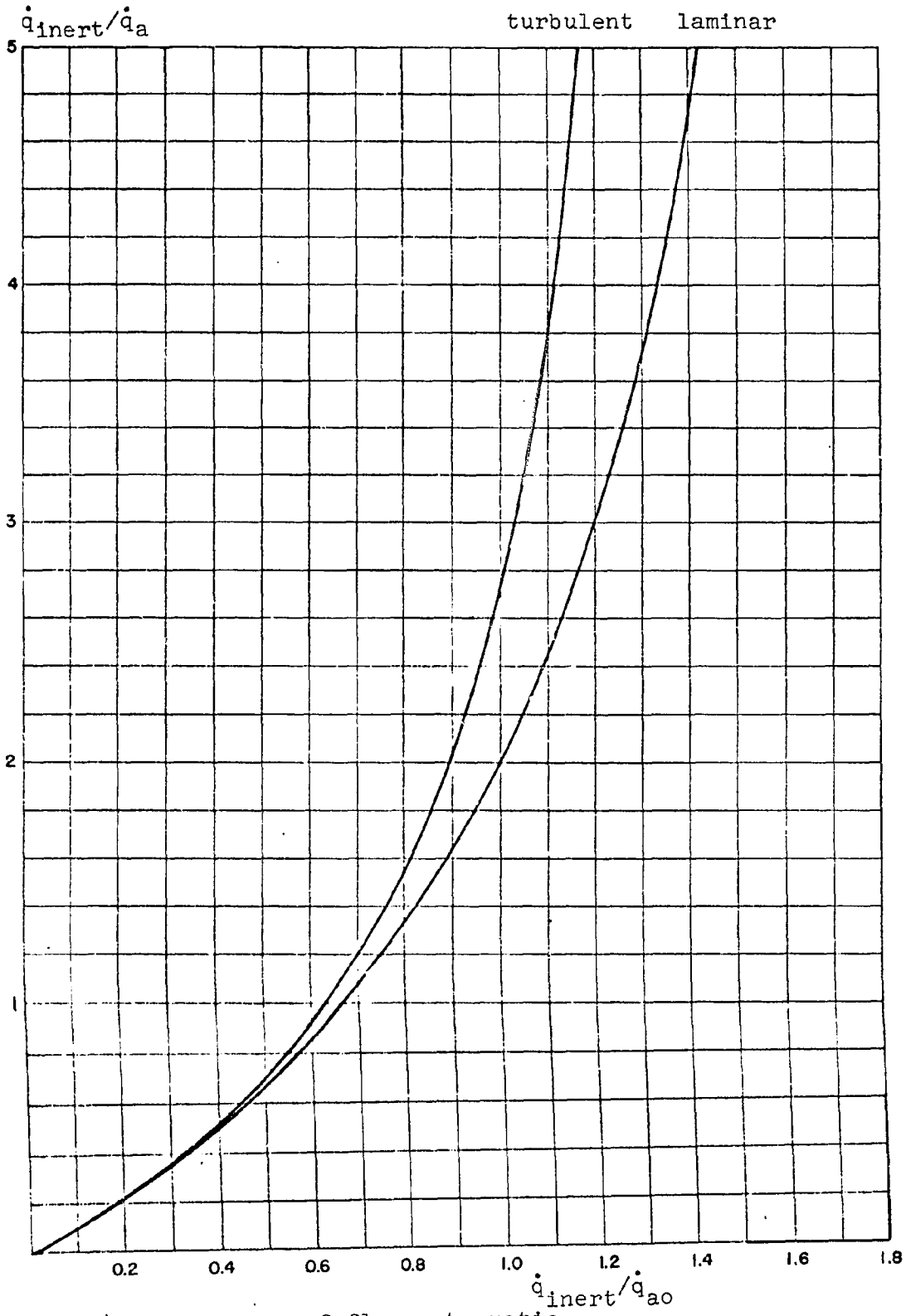


Fig. 42: Increase of flow rate ratio $\dot{q}_{inert}/\dot{q}_a$ caused by airflow reductions when inbye and outbye seals have the same resistance

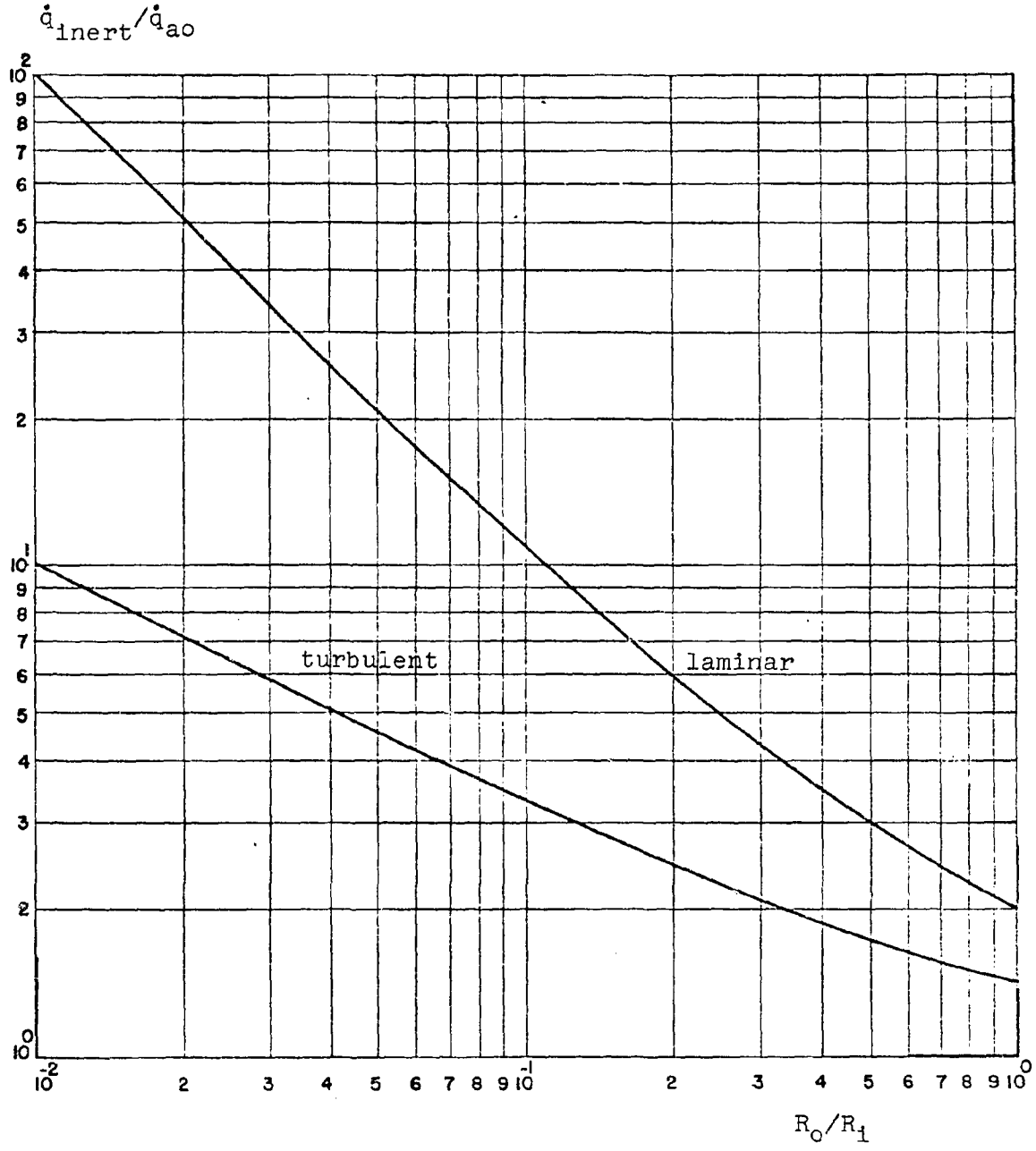


Fig. 43: Conditions for preventing air leakage with inert gas injections

compared with the resistance of the intake seal R_i, and that the changes are small as long as the ratio R_o/R_i is small. As R_o increases, $\dot{q}_a$ decreases, and the ratio $\dot{q}_{inert}/\dot{q}_a$ grows rapidly. The beneficial effects of this reduction in air leakage for producing an extinctive atmosphere can clearly be seen from Figs. 21, 27, 28, 29, and 31. As mentioned in chapter V, this effect is considered by some experts[75 139 181] as the main advantage of inert gas use. Figure 43 shows that for $R_o/R_i = 1$ inert gas injections $\dot{q}_{inert}$, which are 30 - 100% larger than the ordinary air flow $\dot{q}_{ao}$, stop the air leakage $\dot{q}_a$ altogether; and that the ratio $\dot{q}_{inert}/\dot{q}_{ao}$ for $\dot{q}_a = 0$ increases with decreasing ratios R_o/R_i. This emphasizes the necessity of matching the inert gas injections with the resistance of the seals to avoid spill over of the sealed atmosphere through the intake seals, which might contaminate intake air currents. If large inert gas injections are wanted to shorten the time for the build up of the extinctive atmosphere, it might be necessary to reduce the resistance of the outbye seals and to plan for spill over points in them.

Since the case of no air leakage is a desirable one, Figs. 19, 20, 26, and 32 were drafted for this state.

B. Mixing in Flow Direction of Released Inert Gas with Surrounding Atmosphere

The extent to which released inert gas mixes in flow direction with the surrounding atmosphere, depends mainly on the type of flow - laminar or turbulent. In laminar flow, mixing takes place only by molecular diffusion, which is a very slow process. One can, therefore, expect something like a "piston action" of the inert gas. In turbulent flow, transversal mixing (perpendicular to the flow direction) is accomplished within a very short distance, if not impeded by density differences (see chapter IX C.). Longitudinal mixing (in flow direction) takes place also, but due to the large longitudinal extension of mine airways, something like a blend of "piston action" and perfect mixing takes place.

Laminar flow can be expected for Reynolds' Numbers N_R smaller than 2700, turbulent flow for N_R larger than 2700. If inert gas flows at the rate $\dot{q}_{inert}$ (ft^3/min) in an airway with the cross sectional area A (ft^2) and the perimeter P (ft), one obtains from the definition of N_R

$$N_R = \frac{\bar{V}\, d}{\nu} = \frac{\dot{q}_{inert} * 4\, A}{A * 60 * P * \nu} = \frac{\dot{q}_{inert}}{15 * P * \nu}$$

where $\bar{V}$ = flow velocity (ft/sec)
d = hydraulic diameter of airway (ft) = 4 A/P
A = cross sectional area of airway (ft^2)
P = perimeter of airway (ft)
ν = kinematic viscosity (ft^2/sec)

with $\nu = 1.6*10^{-4} ft^2/sec$ for nitrogen or air
$\nu = 0.86*10^{-4} ft^2/sec$ for carbon dioxide
$\nu = 1.38*10^{-4} ft^2/sec$ for mixtures of 21% CO_2 and 79% N_2

one obtains as condition for turbulent flow

$$\frac{\dot{q}_{inert}}{P} > 6.5 \quad \text{for nitrogen or air}$$
$$> 3.5 \quad \text{for carbon dioxide}$$
$$> 5.6 \quad \text{for mixtures of 21\% } CO_2 \text{ and 79\% } N_2$$

In most reported cases of successful inert gas use, the injected quantities were large enough to assure turbulent flow.

If due to laminar flow very little mixing between the sealed atmosphere with the concentration c_s and the injected inert gas takes place during the injection and no other gases enter the sealed space ($\dot{q}_{inert} = \dot{q}_e$), the final concentration of the sealed atmosphere will change according to

$$V\, dc = -\dot{q}_e\, c_s\, d\tau$$

With $c = c_s$ for $\tau = 0$ one obtains

$$c = c_s \left(1 - \frac{\dot{q}_e \tau}{V}\right)$$

This compares with

$$c = c_s \exp\left(-\frac{\dot{q}_e \tau}{V}\right)$$

for perfect mixing. Both functions have been plotted for $c_s = 21\%$ in Fig. 44. Since $\exp(x) = 1 + x + x^2/2 + \ldots$ no great difference exists for small values $\dot{q}_e\tau/V$, but at concentrations below 10% the two functions diverge. In using $c = c_s\,(1 - \dot{q}_e\tau/V)$ one has, however, to bear in mind that the inert gas will usually enter the fire zone as a turbulent jet and that even in laminar flow, therefore, a zone of mixed composition is formed. This zone can be of considerable length and when it reaches the return seal, the above equation is no longer applicable.

The change of concentration by longitudinal turbulent diffusion has been calculated by Hull and Kent,[68] Taylor,[164-5]

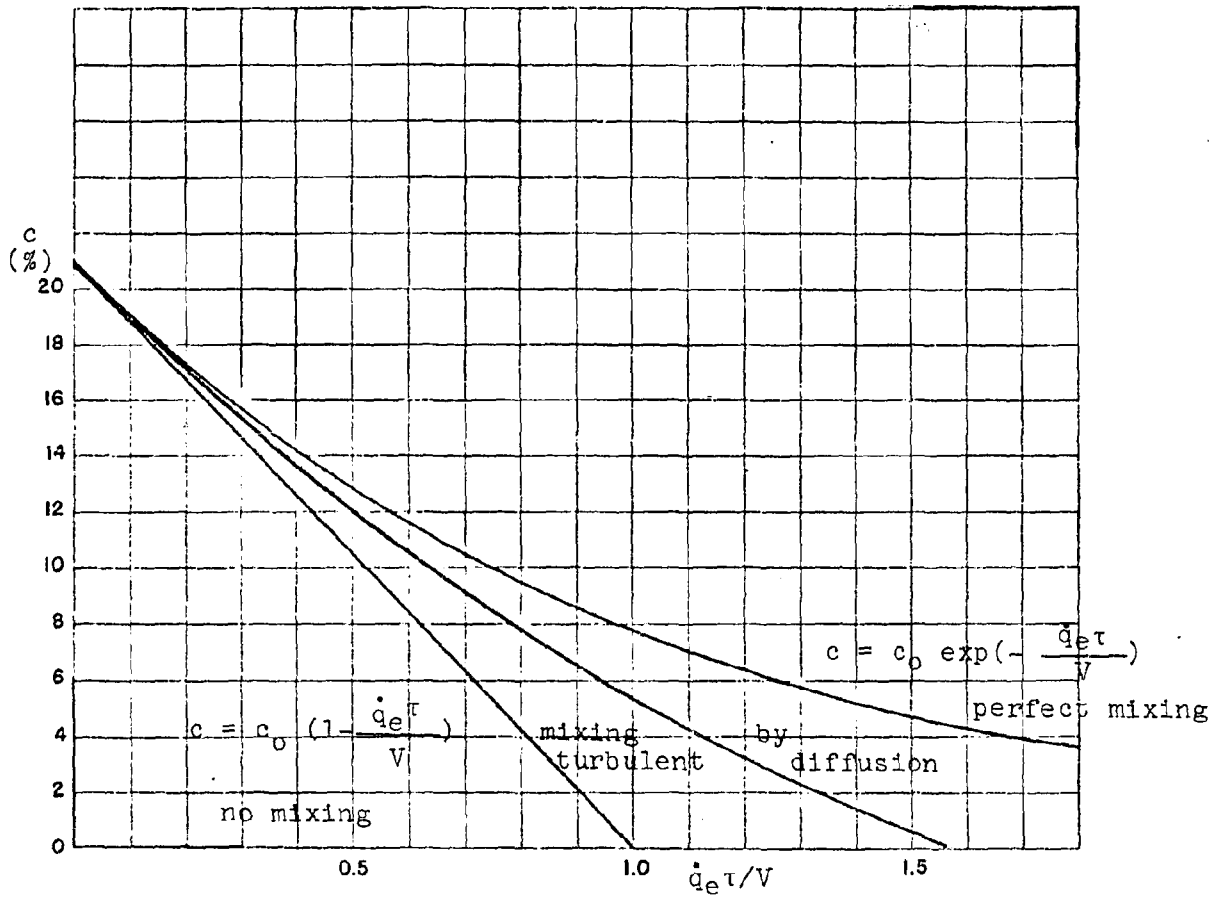


Fig. 44: Change of oxygen concentration in sealed areas with different assumptions for degree of mixing

Krasnostejn and Medvedev[89] and measured underground by Maas and Slootboom.[99] Krasnostejn and Medvedev come to the conclusion, and verify it with model tests, that the complicated functions describing the concentration c_L of the gas leaving the sealed space can for small N_R be approximated by a formula, which can be converted to

$$c_L = c_s \exp(-0.62\ \dot{q}_e\tau/V)$$

Using this equation, one can calculate the concentration c of the sealed atmosphere from

$$c = c_s - \frac{\dot{q}_e}{V} \int c_L\, d\tau = c_s \left(1 - \frac{\dot{q}_e}{V} \int \exp\left(-0.62\ \frac{\dot{q}_e\tau}{V}\right) d\tau\right)$$

$$= c_s \left(1 + \frac{1}{0.62} \left(\exp\left(-0.62\ \frac{\dot{q}_e\tau}{V}\right) - 1\right)\right) \quad \text{with } c = c_s \text{ for}$$

$\tau = 0$

This function has been plotted in Fig. 44 also. One sees that the agreement with $c = c_s \exp(-\dot{q}_e\tau/V)$ is quite good down to concentrations of c = 8%. At lower concentrations the two functions give increasingly different results. At these lower concentrations, mixing of the inert gas diluted atmosphere with remaining pockets of the original sealed atmosphere, which has remained undiluted in dead ends, will have a tendency to narrow the difference. The mixing caused by the jet of the entering inert gas will act in the same direction.

It seems, therefore, justified to use the simple formulas based on perfect mixing, when calculating the dilution of sealed atmospheres with inert gases.

C. Formation of Gas Layers

In laminar flow, mixing of gases is governed by molecular diffusion, in turbulent flow by the eddying motion of the turbulent particles. Due to the fact that the path along which the latter move (Prandtl's mixing length) is considerably longer than the mean free path of molecules, turbulent mixing occurs much faster than molecular diffusion. If a gas is introduced into the turbulent flow of another gas, mixing will be completed after 10 - 20 duct diameters, when no density difference between the two gases exists.

Although the airflow in ventilated mine workings is generally turbulent, layers of methane floating over long distances on top of the air are, nevertheless, frequently observed. The explanation for this phenomenon was given in 1920 by Richardson[140] who pointed out that turbulence may be weakened or damped out completely if a density difference between mixing gases gives rise to buoyancy effects. With light methane on top of heavier air, the turbulence will tend to cause the methane to disperse into the air. The buoyancy of the firedamp will oppose the mixing by tending to cause the methane to stay on top of the air. If the kinetic energy of the turbulence is insufficient to provide the necessary work against gravity, the mixing will decay and the turbulence may be damped out. Mixing takes place then by molecular diffusion only. As a scale for the probability that turbulence may be damped out, Richardson suggested the ratio of work to be done against gravity to kinetic energy

$$- \frac{g}{\rho} \frac{\partial \rho}{\partial y} \Big/ \left(\frac{\partial u}{\partial y} \right)^2$$

g = gravitational acceleration
ρ = density
u = velocity
y = vertical distance

which subsequently became known as the Richardson number. The results of the extensive research on gas layers, most of it performed between 1959 and 1964 in Great Britain, are usually presented as functions of Richardson numbers or modifications of it.

1. Length of Laminar Gas Layers

To demonstrate how slowly laminar gas layers are dispersed by molecular diffusion, the results of calculations by Bakke[5] can be used. He obtained for the maximum gas concentration c_{max} in a layer, formed by the emission of gas from a point source into the ventilation flow

$$c_{max} = \left(0.92 \frac{K\, W^{2/3}\, f^{1/2}\, \bar{V}\, L}{\nu^{1/2}\, \dot{q}^{3/2}} + 1 \right)^{-2/3}$$

where K = coefficient of molecular diffusion
W = airway width
$\bar{V}$ = ventilating velocity
f = coefficient of friction

L = length of layer
ν = kinematic viscosity of gas
$\dot{q}$ = volumetric rate of gas flow into layer

for the layer thickness

$$\delta = \delta_o/(c_o)^{1/2}$$

and for the initial layer thickness

$$\delta_o = 7.3 \frac{\dot{q}^{1/2}\ \nu^{1/2}}{W^{1/2}\ f^{1/2}\ \bar{V}}$$

Figures 45a and b show how long laminar air layers, floating on top of carbon dioxide currents, become before their maximum oxygen concentration has dropped to 2% or 12%, rsp. The difference of the diffusion coefficients of O_2 and N_2 has been neglected in the calculations, a coefficient of $K = 1.72*10^{-4}$ ft^2/sec for the diffusion of air into CO_2 was used. An airway width of W = 10 ft, a coefficient of friction of f = 0.1 and a kinematic viscosity of $\nu = 1.08*10^{-4}$ ft^2/sec was assumed. The layer lengths, which one would obtain for air underneath nitrogen, are in the same order of magnitude as those shown in Fig. 45.

Figure 45a shows that laminar air layers with oxygen concentrations larger than 2% can reach considerable lengths and can enable fires to continue to burn even when the average oxygen concentration in the sealed area would seem to exclude this. Figure 45b shows, however, that a dilution to 12% oxygen takes place comparatively fast. Laminar air layers should, therefore, pose no explosion danger.

Such layers can form in sealed fire zones whose atmosphere, under the influence of ventilating pressures or atmospheric pressure variations, is in a slow motion. The best possibility to disperse them is to erect hurdles to deflect carbon dioxide against the roof or nitrogen against the floor. The effectiveness of such hurdles, callled "mixing baffles", has been proven by Leach and Barbero.[94]

2. Gas Layers in Turbulent Flow

As recognized by Richardson, the formation of slow dispersing laminar layers on top or underneath a turbulent flow of heavier or lighter gas can be prevented, when the kinetic energy of the turbulent particles is large enough to provide the necessary work against buoyancy forces.

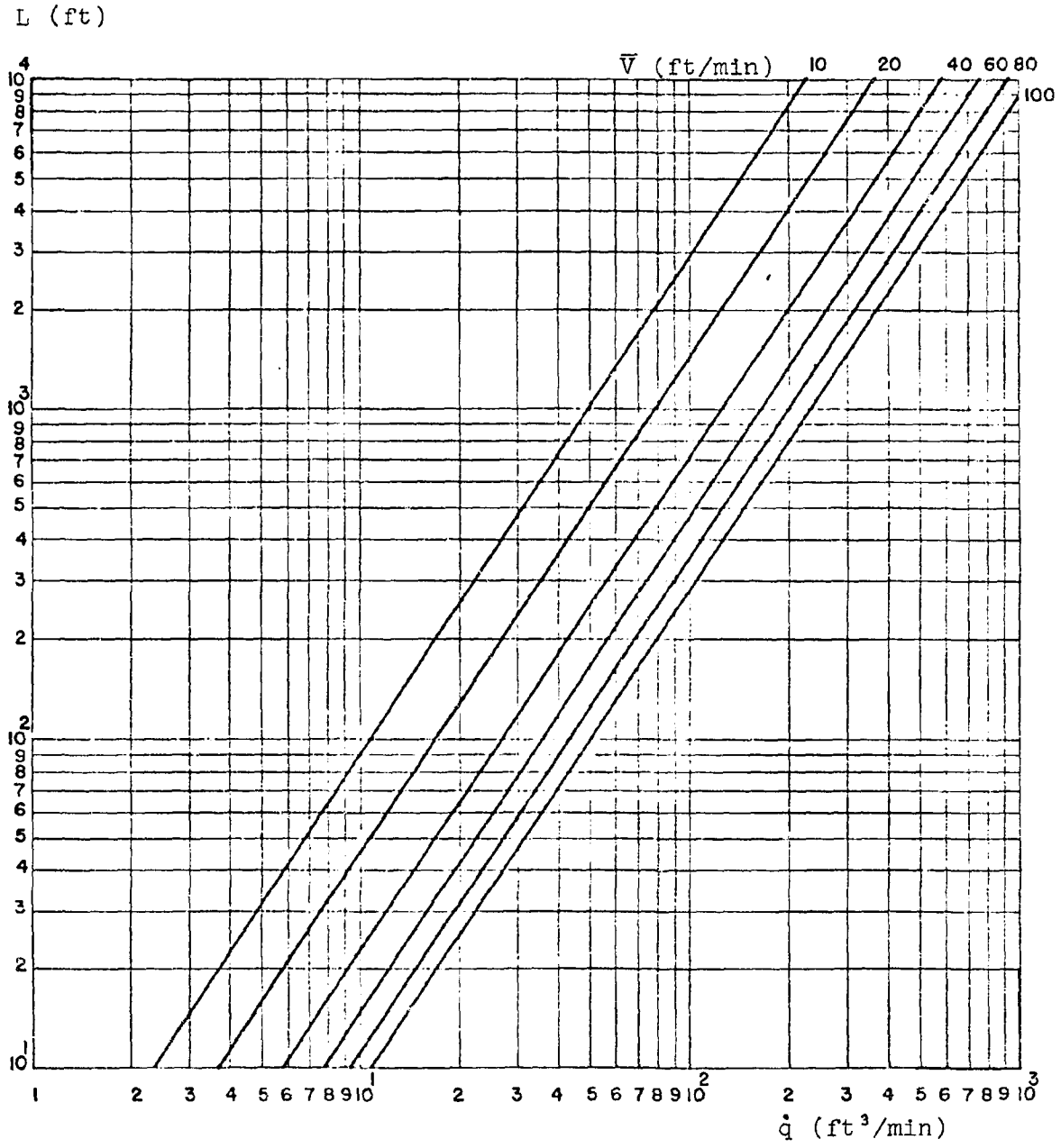


Fig. 45: Length of Laminar Air Layers on Top of Carbon Dioxide

a : Oxygen Concentration at End of Layer 2%

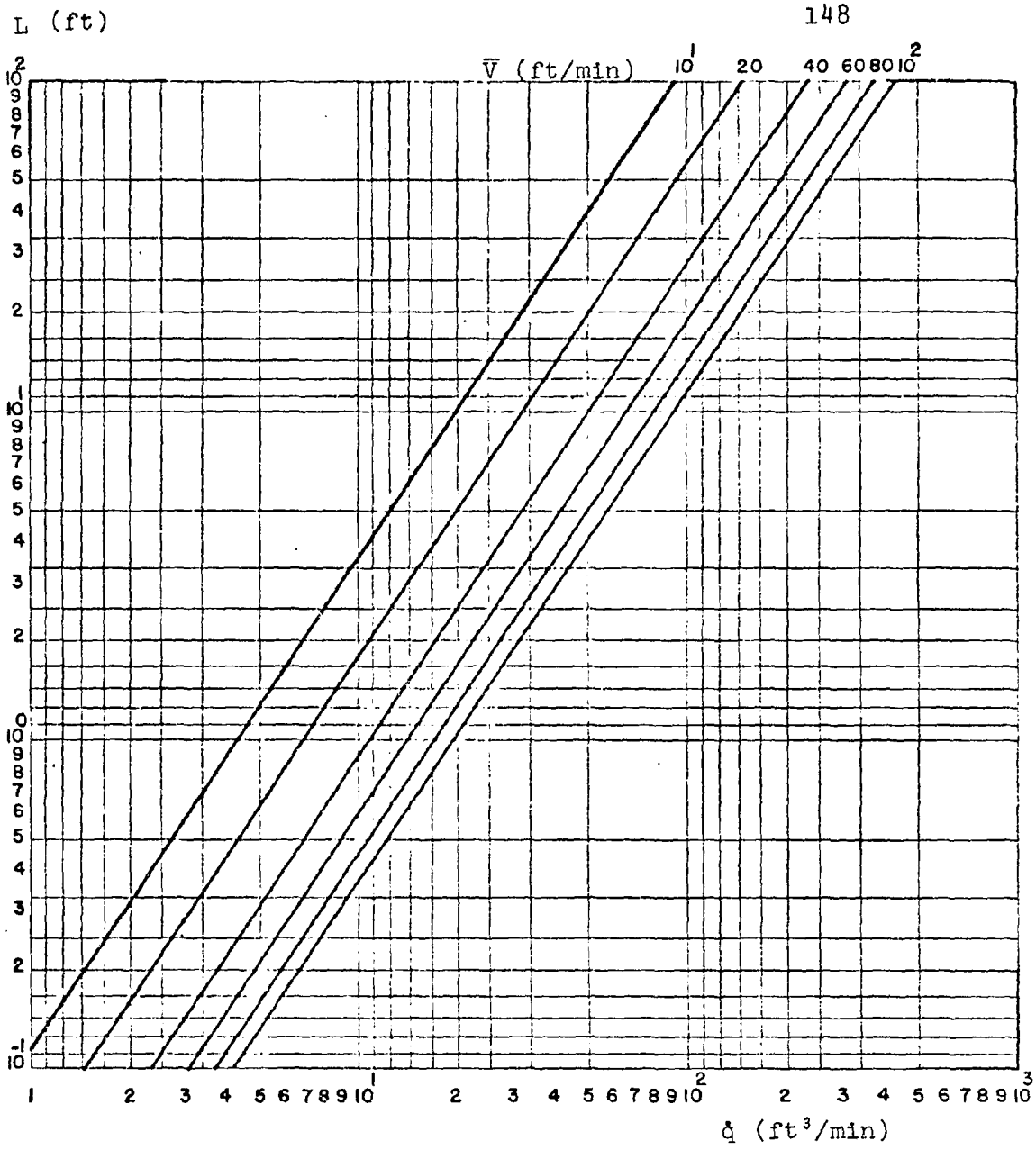


Fig. 45b : Oxygen Concentration at End of Layer 12%

Since the kinetic energy of turbulent particles is proportional to the square of the flow velocity, the usual remedy against gas layers in mine ventilation systems are sufficiently high ventilating velocities. Mining regulations in several countries specify, therefore, minimum ventilating velocities to safeguard against the occurrence of methane layers.

The details of the formation of layers in turbulent flow are very complex and extensive studies have been performed on this subject, which were summarized by Leach and Barbero.[95] It has become customary to present the results as functions of the airway slope, wall roughness, and the dimensionless, so called "layering number", N_L. The latter is derived from the Richardson number, and is obtained by substituting average ventilation properties for velocity and density gradients. With

$$\frac{\Delta\rho}{\delta} = -\frac{\partial\rho}{\partial y} \qquad \text{where } \delta = \text{thickness of layer}$$

$$\frac{\bar{V}}{\delta} = -\frac{\partial u}{\partial y}$$

$$\delta = \frac{\dot{q}}{\bar{V}\,W}$$

the Richardson number can be modified to

$$N_{Ri} = g\,\frac{\Delta\rho}{\rho}\,\frac{\dot{q}}{W} / \bar{V}^3$$

which can, without changing the nature of the number be converted to

$$N_L = \bar{V}/\left(g\,\frac{\Delta\rho}{\rho}\,\frac{\dot{q}}{W}\right)^{1/3}$$

If the influence of the slope on buoyance forces is not separately taken into account, the Richardson number can be multiplied by the co-sine of the slope angle.

Ellison and Turner[44] found empirically that turbulent mixing rapidly decreases as

$$N_{Ri} = g\,\frac{\Delta\rho}{\rho}\,\frac{\dot{q}}{W}\cos\alpha/\bar{V}^3$$

increases and is negligible when N_{Ri} is larger than approximately 0.83. Bakke and Leach[7] in an account of all previous work on gas layers for the practical ventilation engineer make recommendations on the minimum layering numbers which, for the prevention of gas layers, should be observed. They state that in horizontal airways no mixing by turbulence takes place when N_L is less than 2. If N_L is 5 or more, the length of the methane layer will not decrease much further with an increase in ventilation velocity.

Ascensionally moving layers on top of a heavier gas or descensionally moving layers underneath a lighter gas, exhibit special features. With small ventilation velocities the layer will move faster than the ventilation. Increasing the ventilation speed will reduce the velocity difference between ventilation and layer and decrease the mixing rate, which reaches a minimum when both have the same velocity. A further speed increase will increase the mixing rate again until, as in horizontal airways, a speed is reached beyond which the the length of the methane layer shows very little additional decrease. Suggested layering numbers in literature[7] are based only on this speed and are shown in Fig. 46, upper curve. Since they are based on optimal layer lengths, or air velocities, whose further increase for the dispersion of gas layers is not worthwhile, they are quite high.

The order of magnitude of critical ventilation speeds, where the mixing rate is at a minimum, and above or below which ventilation speeds should be kept, can be estimated in the following way. From Ellison's and Turner's work[44] it can be derived that the velocity of free streaming layers in a ventilation at rest with negligible mixing is

$$\bar{V} = g \frac{\Delta\rho}{\rho} \frac{\dot{q}}{W} \frac{\sin\alpha}{c_w}$$

where c_w = skin friction coefficient

The layering numbers, corresponding to these velocities are

$$N_L = (\sin\alpha/c_w)^{1/3}$$

With $c_w = 0.01$ as an average value for mine roadways, one obtains for N_L as a function of the slope angle α the values shown in the lower curve of Fig. 46. Ventilation speeds should be lower than these layering numbers indicate.

Since the ventilation propels the layer, the layering numbers at which ventilation and layer have the same velocity and where mixing is therefore poorest, are

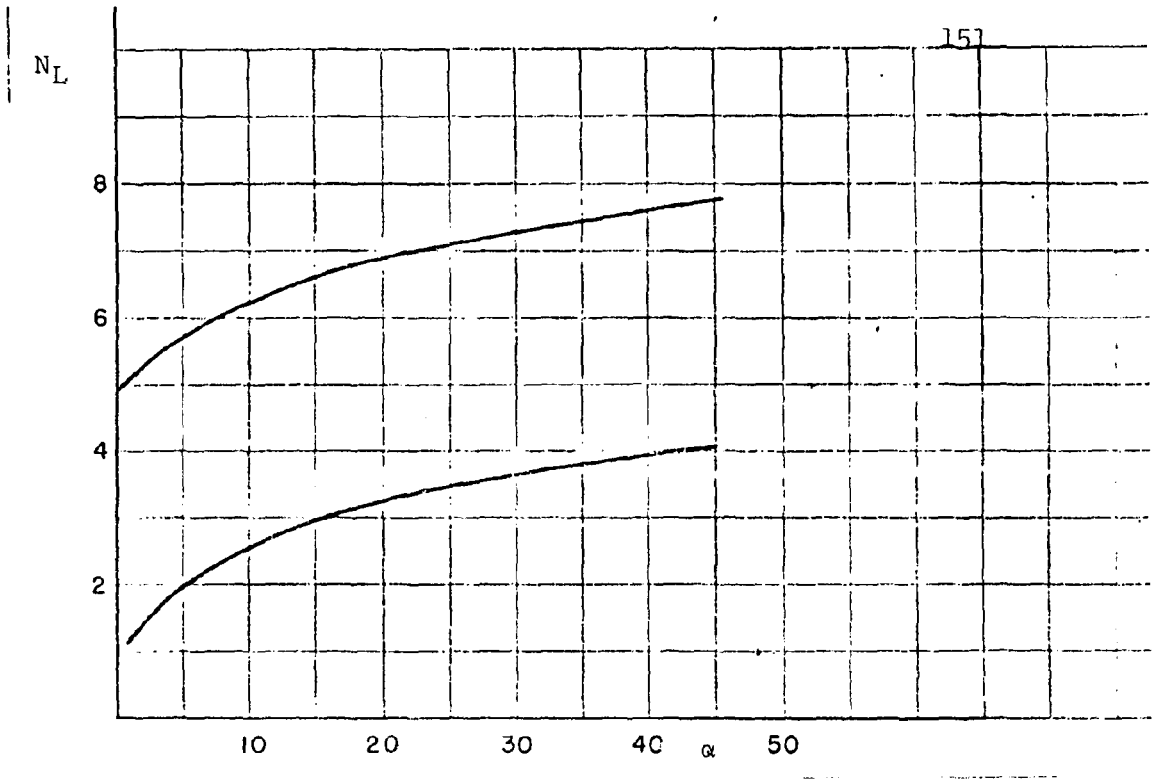


Fig. 46: Suggested (7) Optimal and Estimated Critical Layering Numbers for Ascensional Ventilation

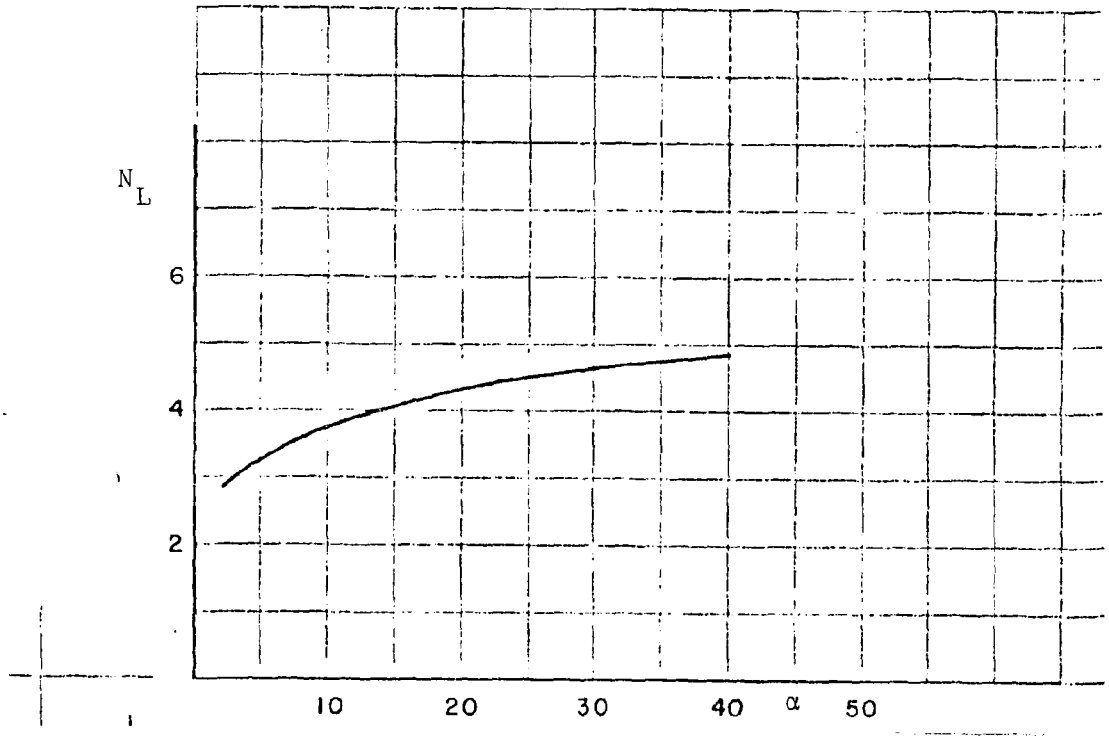


Fig. 47: Suggested Layering Numbers (7) to Prevent Backing of Layers in Descensional Ventilation

higher than these figures. From experimental observations[6] it can be estimated that to assure substantial mixing the ventilation speeds should at least be as high as those required for the prevention of layer backing (Fig. 47).

Descensionally moving layers on top of a heavier gas and ascensionally moving layers underneath a lighter gas have a tendency to back against the ventilation flow. Figure 47 shows suggested layering numbers to prevent such backing.[7]

Application of Theory tc Inert Gas Release

Turbulent flow in fire zones will mainly be experienced before the seals are closed. While the inert gas is released, an adequate ventilation has initially to be maintained to prevent the formation of explosive mixtures until the area prepared for sealing has been filled with a sufficiently high concentration of inert gas. This will usually require a simultaneous ventilation with air and inert gas. To prevent a continuing supply of oxygen to the fire from air flowing in layers on top of a heavier or underneath a lighter inert gas, and to prevent only a partial filling of the sealed fire zone with the gas, a fast mixing of air and inert gas should be achieved.

Mixing of air and inert gas at the place where the inert gas is released can be supported when the heavy inert gas is released at the roof and the light inert gas at the floor. In such a case, layering will be minimal.[7] If this is not possible, the Richardson number of the inert gas current should be smaller than 0.83. If the inert gas is released over the total width of the airway, this means that the release velocity $\bar{V}$ should be larger than

$$\left(\frac{\Delta\rho}{\rho}\, g\, \frac{\dot{q}}{W} \cos\alpha/0.83\right)^{1/3},$$

which for nitrogen in air means

$$\bar{V} > 16.6 \left(\frac{\dot{q}}{W} \cos\alpha\right)^{1/3}$$

and for carbon dioxide in air

$$\bar{V} > 41.7 \left(\frac{\dot{q}}{W} \cos\alpha\right)^{1/3}$$

where $\bar{V}$ is measured in ft/min, $\dot{q}$ in ft^3/min and W in ft. These conditions are met when the initial thickness of the inert gas current is smaller than $0.72\ (\frac{\dot{q}}{W})^{2/3}$ inches for nitrogen in air and $0.29\ (\frac{\dot{q}}{W})^{2/3}$ inches for carbon dioxide in air.

The above figures indicate that, if inert gases are released in gaseous form through pipes, their velocities will generally be high enough to provide turbulent mixing with the ambient air. If this is not the case, the speed of the ambient air, expressed by the layering number N_L, will decide the extent to which mixing takes place.

Whether or not layers of air entering the fire zone through uncompleted or poor seals form on top or underneath a turbulent inert gas flow also, depends on their layering numbers. How large the latter have to be to provide a fast dispersal of layers has been discussed. To help in determining layering numbers for air on top of a turbulent carbon dioxide flow and underneath of a turbulent nitrogen flow, Fig. 48a and b have been plotted. Figure 48a can also be used for explosive air-methane layers on top of carbon dioxide, since an air-methane-mixture of 15% has a density which is only 7% lower than that of pure air.

Since there is little difference in the term $(\frac{\Delta\rho}{\rho})^{1/3}$ with a value of 0.7 for air-carbon dioxide and with 0.75 for methane-air, the extensive literature on methane layers in coal mines can be used to estimate the probability of air layers on top of carbon dioxide. With the small density difference between air and nitrogen, which quite frequently may even disappear due to temperature differences or the admixture of other gases, the probability of air layers underneath nitrogen does not seem to be too high.

3. Turbulent Layers in a Stagnant Ventilation

When a gas, which is lighter or heavier than its surrounding, is released at the top or the floor of a sloping airway with a stagnant ventilation, it will flow as a relatively thin turbulent layer upwards along the roof or downwards along the floor. The flow is induced by buoyancy forces and opposed by wall friction and the turbulent momentum transfer into the surrounding stagnant atmosphere. The rate of mixing caused by the momentum transfer has been investigated by Ellison and Turner.[44] They find that in

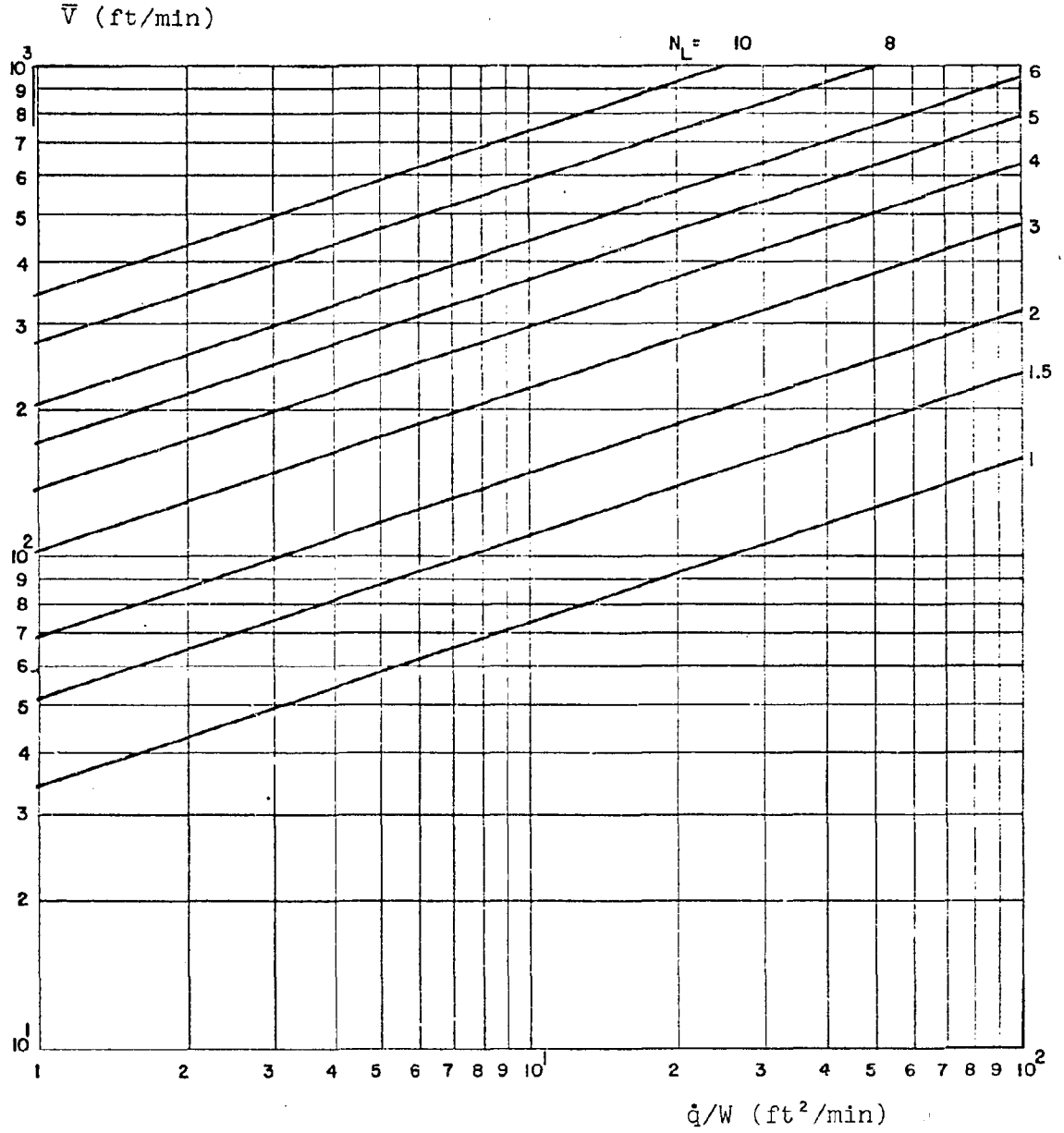


Fig. 48a : Layering Numbers for Air on Top of Carbon Dioxide

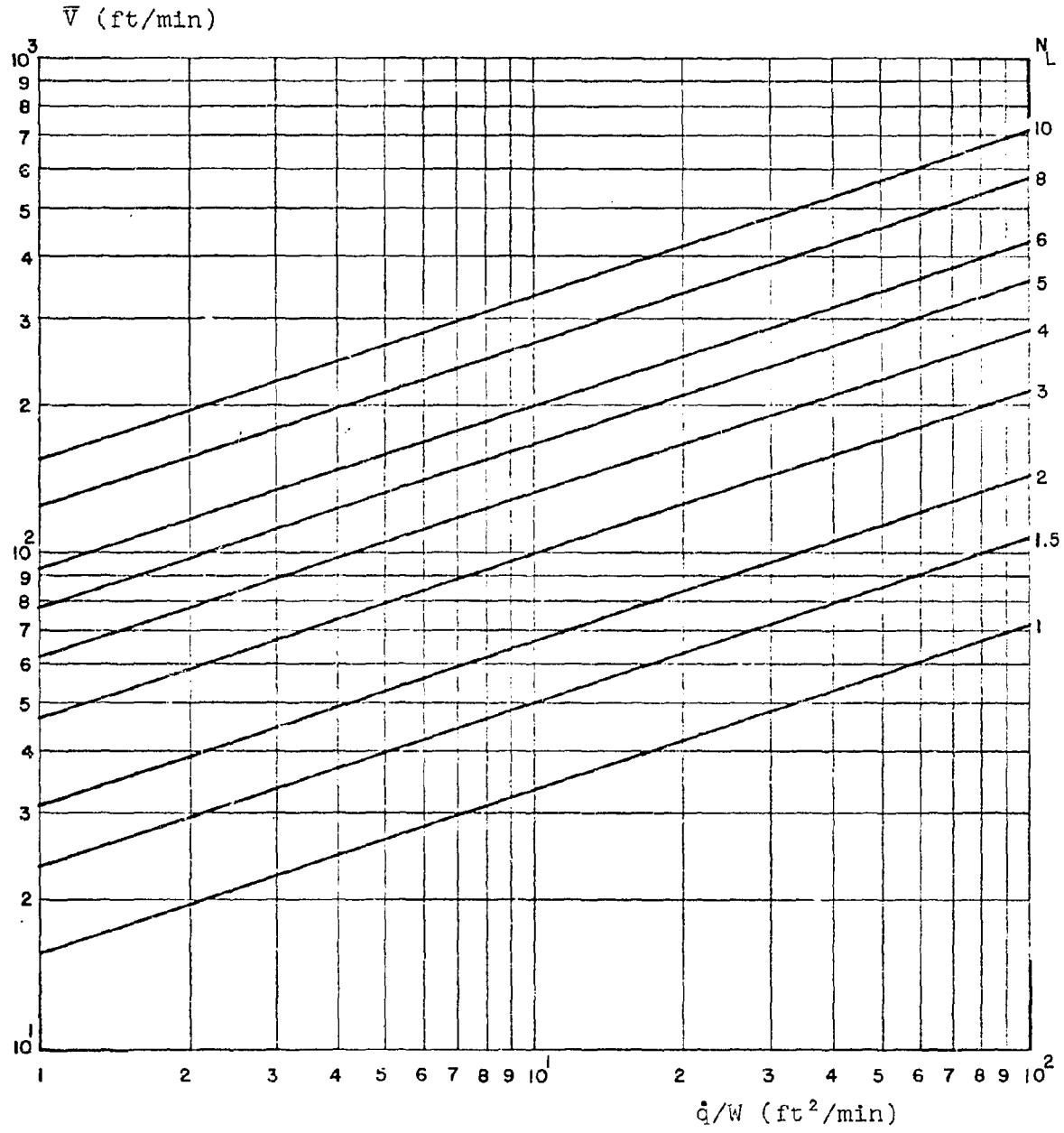


Fig. 48b : Layering Numbers for Air Underneath Nitrogen

most practical cases the layer will rapidly attain an equilibrium state in which the increase of layer thickness h with layer length L becomes constant and can be expressed by an empirical entrainment function $E(N_{Ri})$ of the overall Richardson number of the layer:

$$\frac{dh}{dL} = E(N_{Ri})$$

$$N_{Ri} = \left(\frac{\Delta\rho}{\rho} g \frac{\dot{q}}{W} \cos\alpha\right)/\bar{V}^3$$

This implies that the Richardson number and, due to $\Delta\rho\,\dot{q}$ = constant, the mean velocity $\bar{V}$ of the layer do not vary with distance downstream. Since it can be derived form Ellison's and Turner's calculations that this velocity is

$$V = \left(\frac{\Delta\rho}{\rho} g \frac{\dot{q}}{W} \frac{\sin\alpha}{c_w}\right)^{1/3}$$

it follows that the entrainment function E can be considered as function of the slope α and skin friction coefficient c_w only.

The values of E as function of N_{Ri} and α found experimentally by Ellison and Turner are shown in Fig. 49a and b. In experiments with free streaming methane layers in tunnels of 2° and 5 1/2° slope, Leach and Barbero[93] confirmed the validity of the above formula for the layer velocity and of the entrainment function shown in Fig. 49.

Turbulent layers in a stagnant atmosphere can, with respect to inert gas filled sealed fire zones, be of importance in several respects. Air leakage can travel on top of a heavier or underneath a lighter inert gas with very little mixing. As Fig. 50a for air-carbon dioxide and Fig. 50b for air-nitrogen show, the layer velocities can even at small slopes be considerable. The remedy against such layers would again be baffle plates, which enforce a dispersal of the layer into the ambient atmosphere.

If a sealed fire zone is so slowly filled with inert gas that its atmosphere can be considered as stagnant, inert gas can flow in layers without filling the whole cross sectional area of an airway. This can even happen after the inert gas has already filled an airway, when the following airway has a slope and the layer velocity is higher than the ventilation velocity. Figure 50c shows the velocity of a carbon dioxide layer underneath of air. If the airway is sealed or again followed by a horizontal airway, the original atmosphere can be forced back by the inert gas,

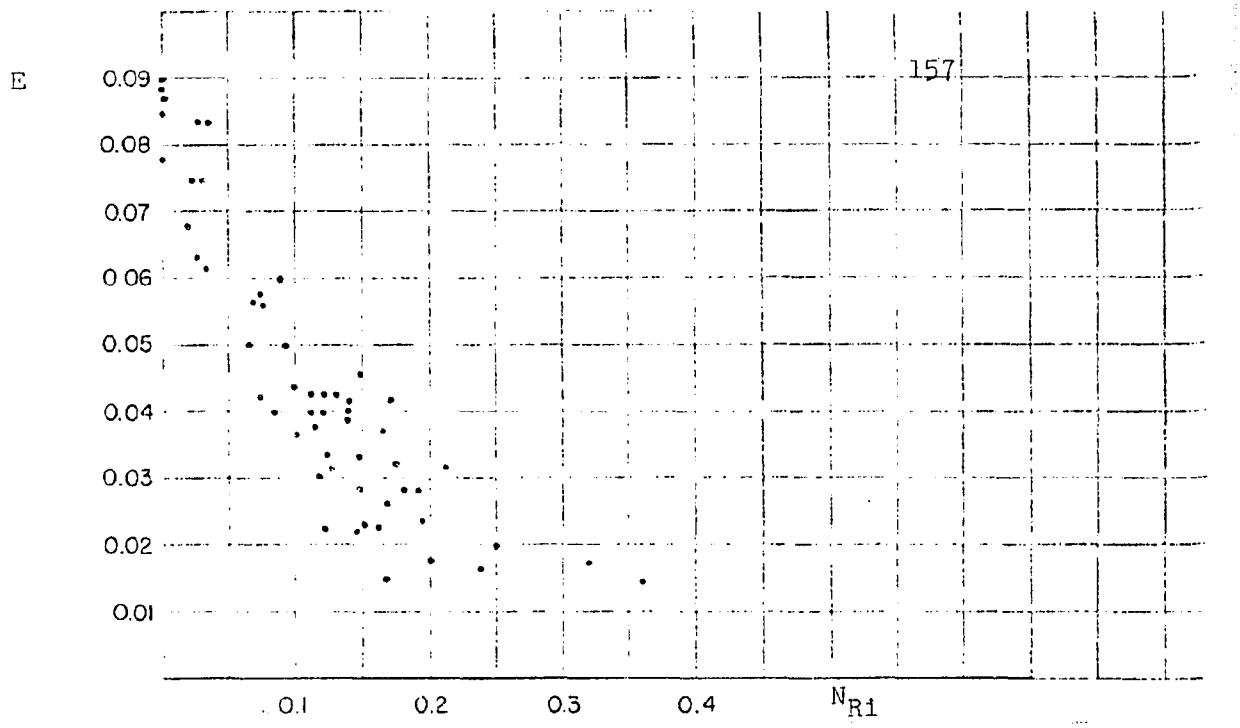


Fig. 49a : Entrainment E as a Function of Richardson Number N_{Ri} [49]

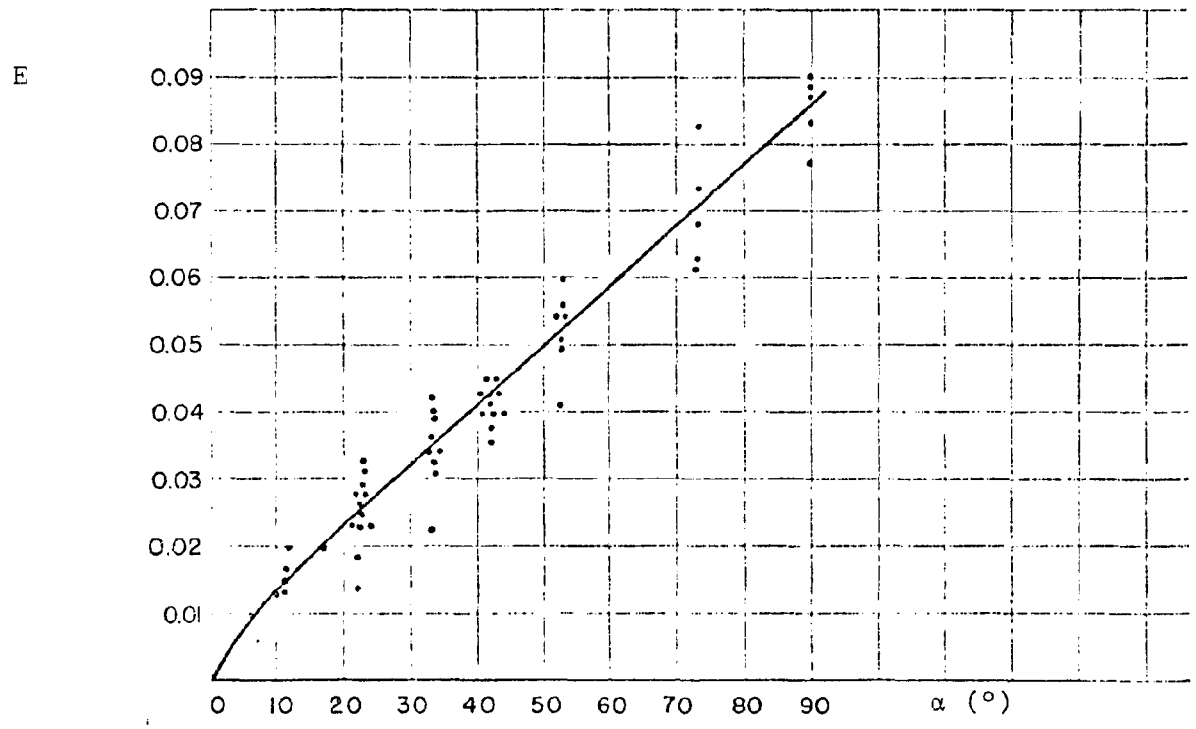


Fig. 49b : Entrainment E as a Function of Slope Angle[49]

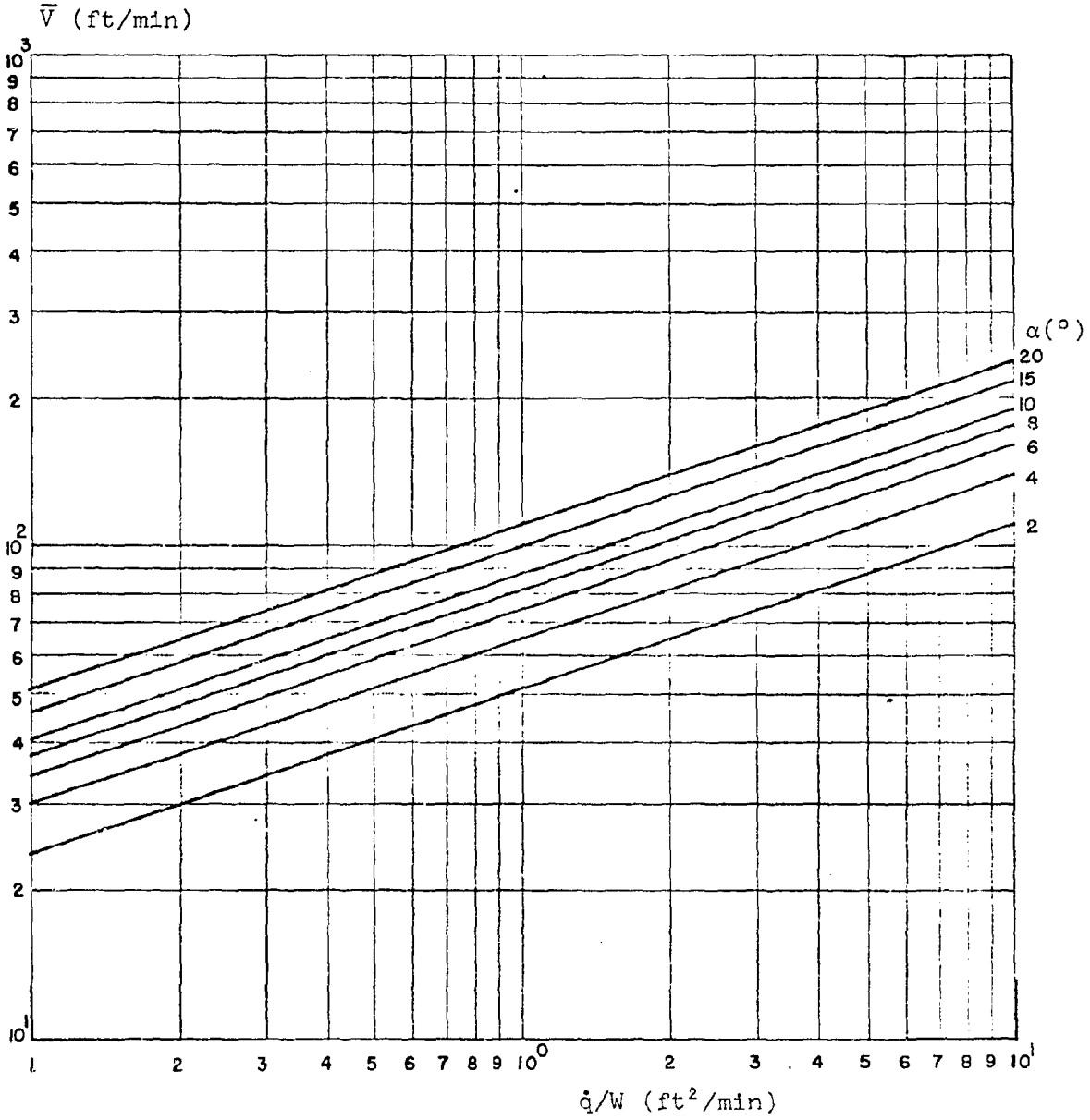


Fig. 50: Velocity of Free Streaming Gas Layers in a Stagnant Atmosphere

a : Air on Top of Carbon Dioxide

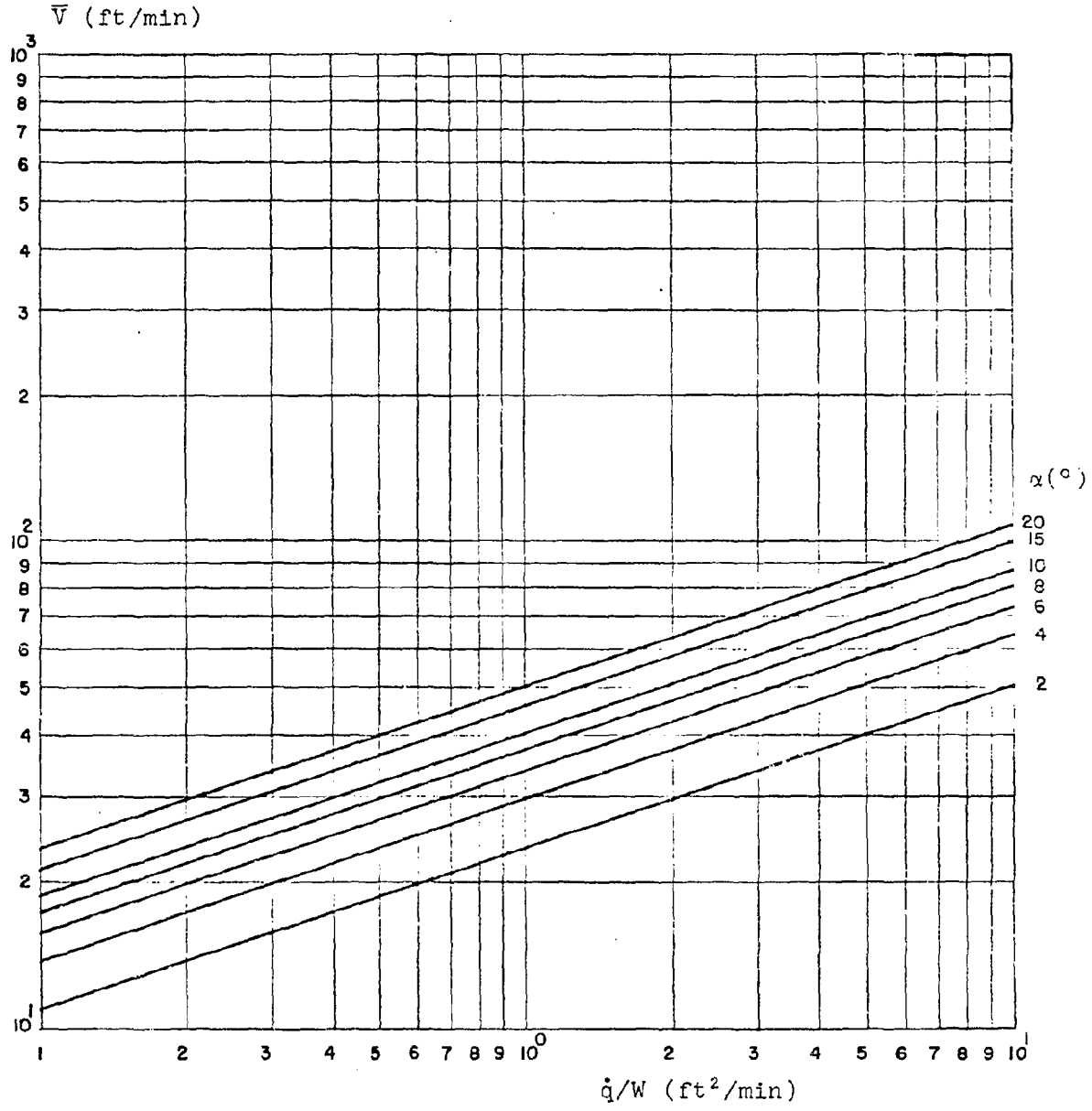


Fig. 50b : Air Underneath Nitrogen

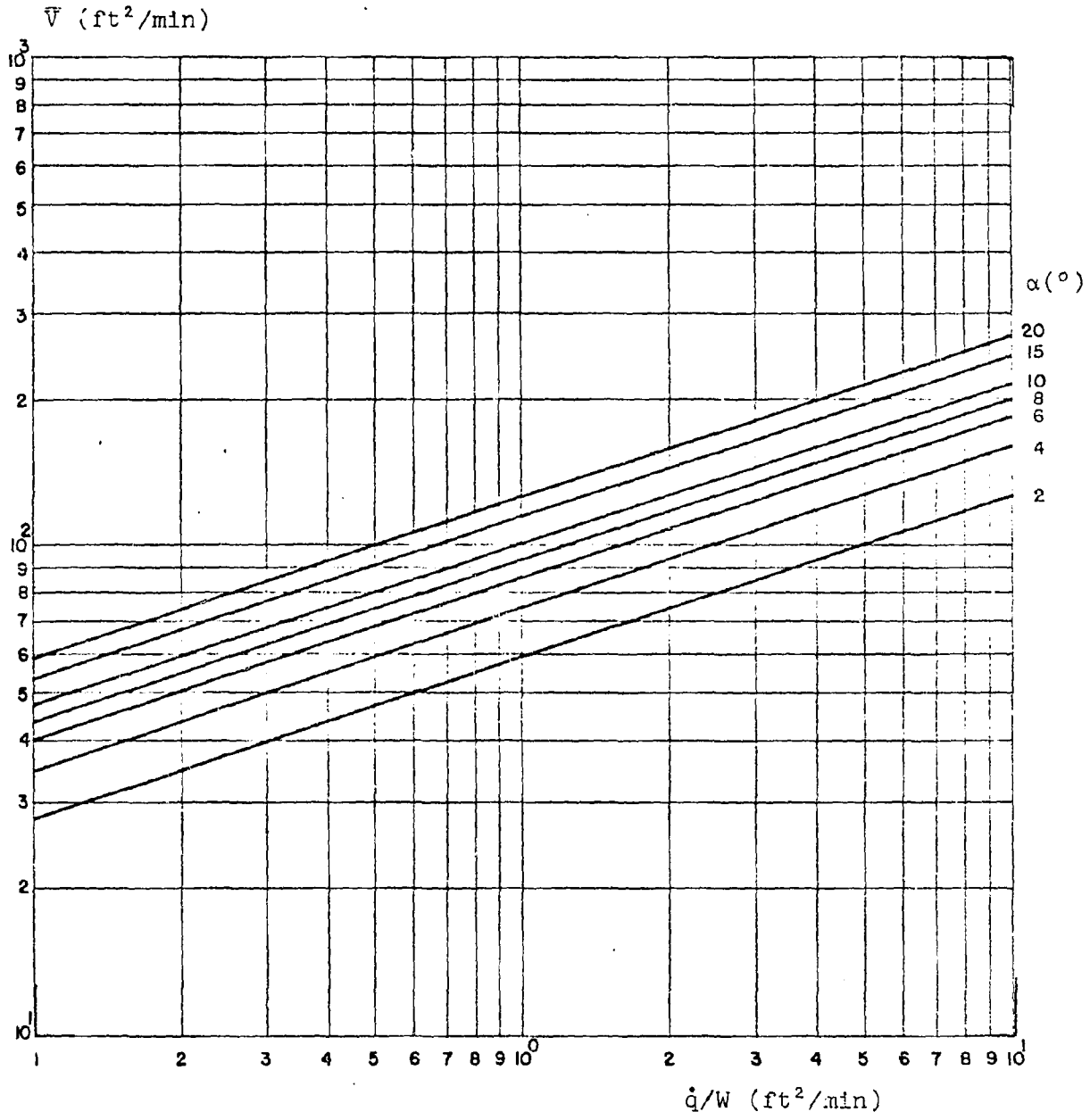


Fig. 50c : Air Underneath of Carbon Dioxide

which accumulates at the end of the hill. Leach and Barbero[93] describe such backflows of air caused by ascending methane layers.

D. Ventilating Pressures Required for Inert Gas Transport

When an airway is filled with inert gas, the pressure loss of the gas flow Δp_L is, according to Darcy's equation, proportional to the gas density:

$$\Delta p_L = f \frac{L}{A} \frac{P}{8} \frac{\rho}{} \bar{V}^2 = f \frac{L}{A^3} \frac{P}{8} \frac{\rho}{} \dot{q}^2$$

If the pressure difference between the beginning and the end of the airway is $p_1 - p_2$, the ratio of the inert gas flowrate $\dot{q}_i$ to the airflow rate $\dot{q}_a$ is

$$\frac{\dot{q}_i}{\dot{q}_a} = \left(\frac{\rho a}{\rho i}\right)^{1/2}$$

since in horizontal airways $\Delta p_L = p_1 - p_2$.

In nonhorizontal airways:

$$p_1 - p_2 = \Delta p_{La} + \rho_a g \Delta Z = \Delta p_{Li} + \rho_i g \Delta Z$$

where ΔZ = elevation change in airway

One sees that $\Delta p_{La} > \Delta p_{Li}$ applies in ascensional ventilation ($\Delta Z > 0$) for $\rho_i > \rho_a$ and in descensional ventilation ($\Delta Z < 0$) for $\rho_i < \rho_a$ and that, consequently, for an inert gas heavier than air flowing uphill and for an inert gas lighter than air flowing downhill: $\dot{q}_i < \dot{q}_a$. A standstill of the inert gas flow results in $\Delta p_{Li} = 0$, which is the case for $\Delta Z = \Delta p_{La}/g(\rho_i - \rho_a)$.

This is the height up to which the mine ventilating pressure p_{MV} acting on this airway and ordinarily balancing the air pressure loss Δp_{La} can lift a heavier inert gas or down to which it can depress a light inert gas against the buoyancy forces. With $g\rho_a = 0.075$ lb/ft^3 and $\Delta p_{La} = p_{MV}$ (expressed in inches water gage) this becomes

$\Delta Z = 133\ p_{MV}$ (ft) for pure carbon dioxide and

$\Delta Z = -2{,}061\ p_{MV}$ (ft) for pure nitrogen.

Since nitrogen is only 3% lighter than air, its buoyancy forces are so small that they shall not be discussed in this chapter.

Figure 51 shows values of maximal heights ΔZ for mixtures of CO_2 and air of different concentrations and temperatures. Since methane admixtures make the inert gas lighter also, Fig. 52 shows for CO_2 - CH_4 - air mixtures the equivalent CO_2 concentrations of CO_2 - air mixtures, which have the same density. Figure 52 can be used in conjunction with Fig. 51.

E. Inert Gas Forced Into a Sealed Area

If more carbon dioxide is injected into an ordinarily ascensionally ventilated airway than can be kept in suspension by the mine ventilating pressure, the CO_2 will exert a pressure on the lower seal. If the upper seal is open to allow for the spill over of air, the atmosphere in the fire zone is stagnant ($\Delta p_{Li} = 0$), and the pressure across the lower seal, or the pressure with which the CO_2 would have to be injected through the seal is p_s, it follows from

$$p_1 - p_2 = \Delta p_{La} + \rho_a \, g\Delta Z + \Delta p_{Li} = \rho_i \, g\Delta Z - p_s$$

$$p_s = g\Delta Z \, (\rho_i - \rho_a) - p_{MV}$$

Figure 53 shows values for the sum $p_s + p_{MV}$ for CO_2 - air mixtures of different concentrations and temperatures per 100 ft elevation difference. Negative pressures indicate a thermal draft caused by densities lower than that of air. One sees that these pressures exerted on the seals are not very large and will, in most practical cases, be smaller than those which stoppings between main intakes and return have to withstand.

Belik[12] suggests to use the pressure across the lower seal p_s as a scale for the mean CO_2 concentration in the sealed area and gives a formula, which follows from the above relationship between p_s and ρ_i. Figure 53 could be used for the same purpose also.

The leakage rate through the lower seal $\dot{q}_e$ depends on the magnitude of p_s. If laminar flow is assumed,[80] it is determined by

$$\dot{q}_e = p_s/R \qquad \text{where R = resistance factor of seal}$$

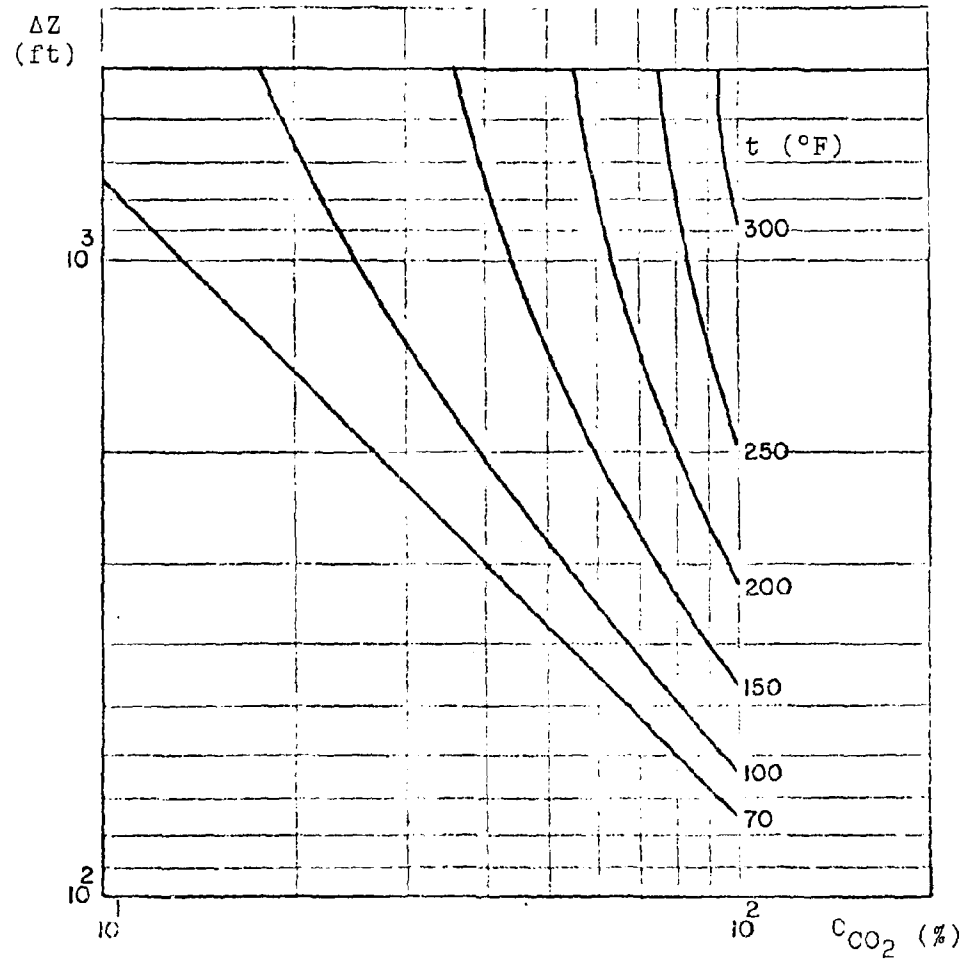


Fig. 51: Heights ΔZ Corresponding to Buoyancy Pressures of 1 In. WG. for CO_2 - Air Mixtures of Different Temperatures

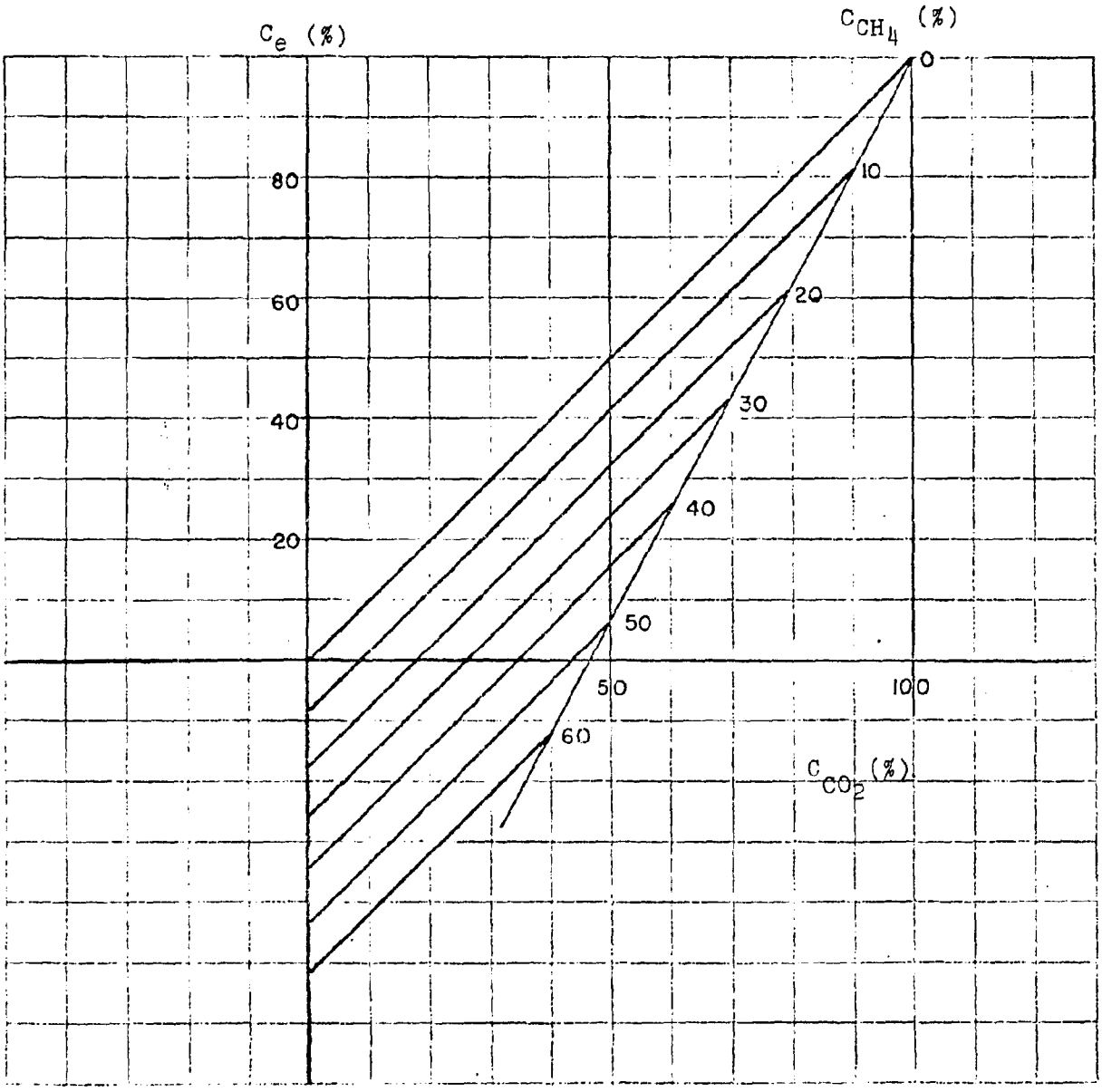


Fig. 52: Equivalent CO_2 - Air Concentrations C_e for CO_2 - CH_4 - Air Mixtures

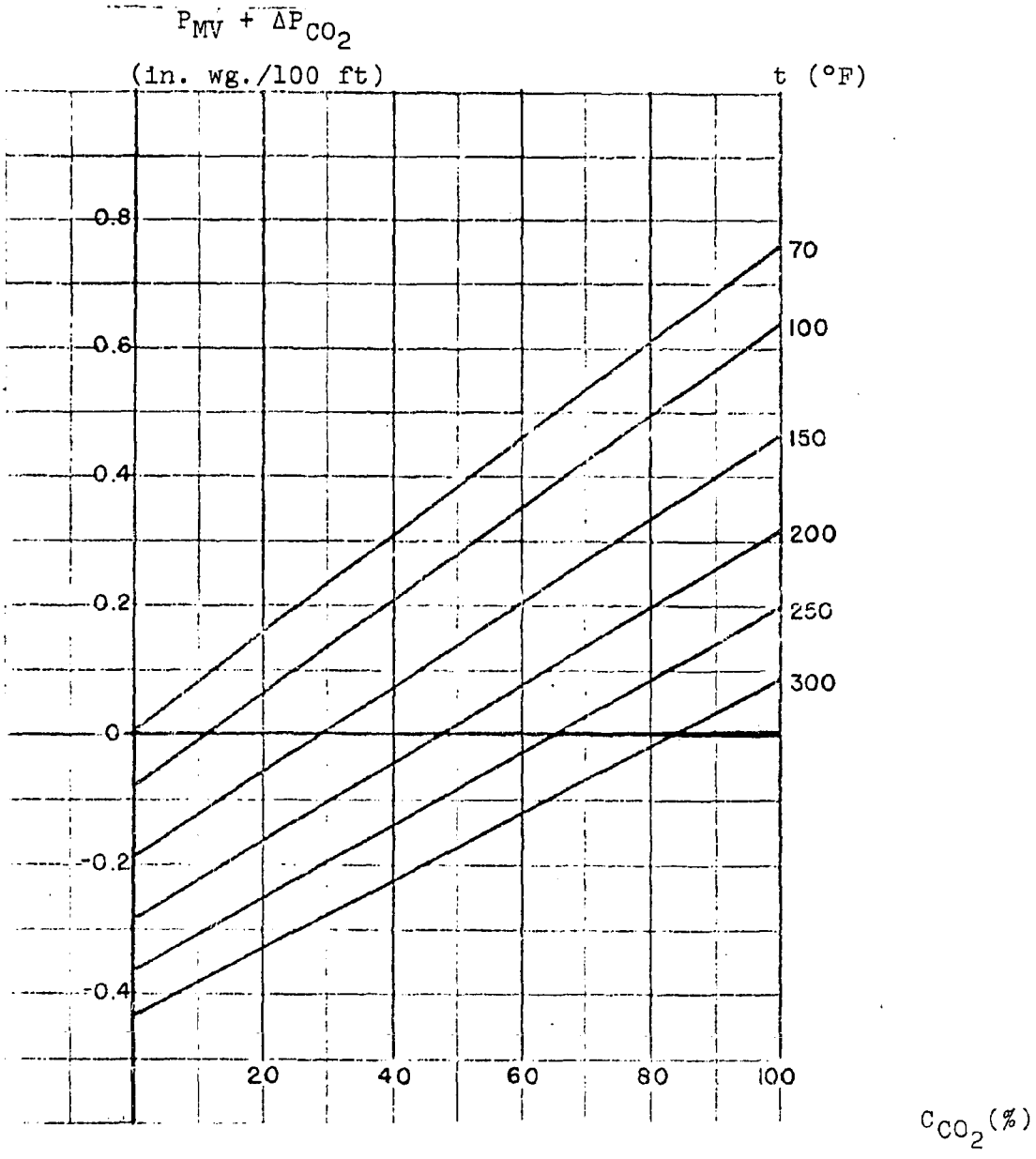


Fig. 53: Buoyancy Pressures for CO_2 - Air Mixtures of Different Temperatures per 100 ft Gas Column

The height of the CO_2 column Z changes in the time τ proportional to the difference of input rate $\dot{q}_i$ and leakage rate $\dot{q}_e$ and inversely proportional to the cross sectional area of the airway A

$$dZ = (\dot{q}_i - \dot{q}_e)\, d\tau/A$$

The resultant change in pressure is

$$dp_s = \Delta\rho \frac{g}{A} (\dot{q}_i - \dot{q}_e)\, d\tau = \Delta\rho \frac{g}{A} (\dot{q}_i - p_s/R)\, d\tau$$

where $\Delta\rho$ = density difference between inert gas column and atmosphere replaced by it

The general solution of this equation is

$$p_s = \dot{q}_i R + C \exp\left(- \Delta\rho \frac{g}{A R} \tau\right)$$

Leakage of air through the seal stops and of CO_2 starts when $p_s = 0$. If the time τ is counted from this moment, one obtains from $p_s = 0$ for $\tau = 0$ $C = - \dot{q}_i R$ and

$$p_s = \dot{q}_i R \left(1 - \exp\left(- \Delta\rho \frac{g}{A R} \tau\right)\right)$$

The final equilibrium pressure is reached ($\tau = \infty$) when $p_s = \dot{q}_i R$ or when leakage $\dot{q}_e$ and input $\dot{q}_i$ are equal. The height of the CO_2 column is

$$\Delta Z = \frac{PMV}{g\Delta\rho} + \frac{p_s}{g\Delta\rho}$$

where the second term on the right side of the equation indicates how much the gas can additionally be lifted by the pressure injection. Figure 54 shows this height $p_s/g\Delta\rho$ as a function of injection rate $\dot{q}_i$ and time τ. A cross sectional area of A = 100 ft^2 and a resistance factor of R = 0.1 in. wg./cfm, which would correspond to a foam or latex coated dry wall[80] was assumed for this figure.

F. Practical Experiences

Osipov and colleagues[128] mention that despite the fact of a long time and comparatively wide use of inert gases, no investigations of the movement of these gases within the fire zones exist. To start closing this gap they released CO_2 at a rate of 2,100 ft^3/min into the intake airway of an ascensionally ventilated longwall face of 365 ft length and 23° dip. Sealing of the intake airway reduced the airflow from 32,000 to 6,300 ft^3/min, the CO_2 release

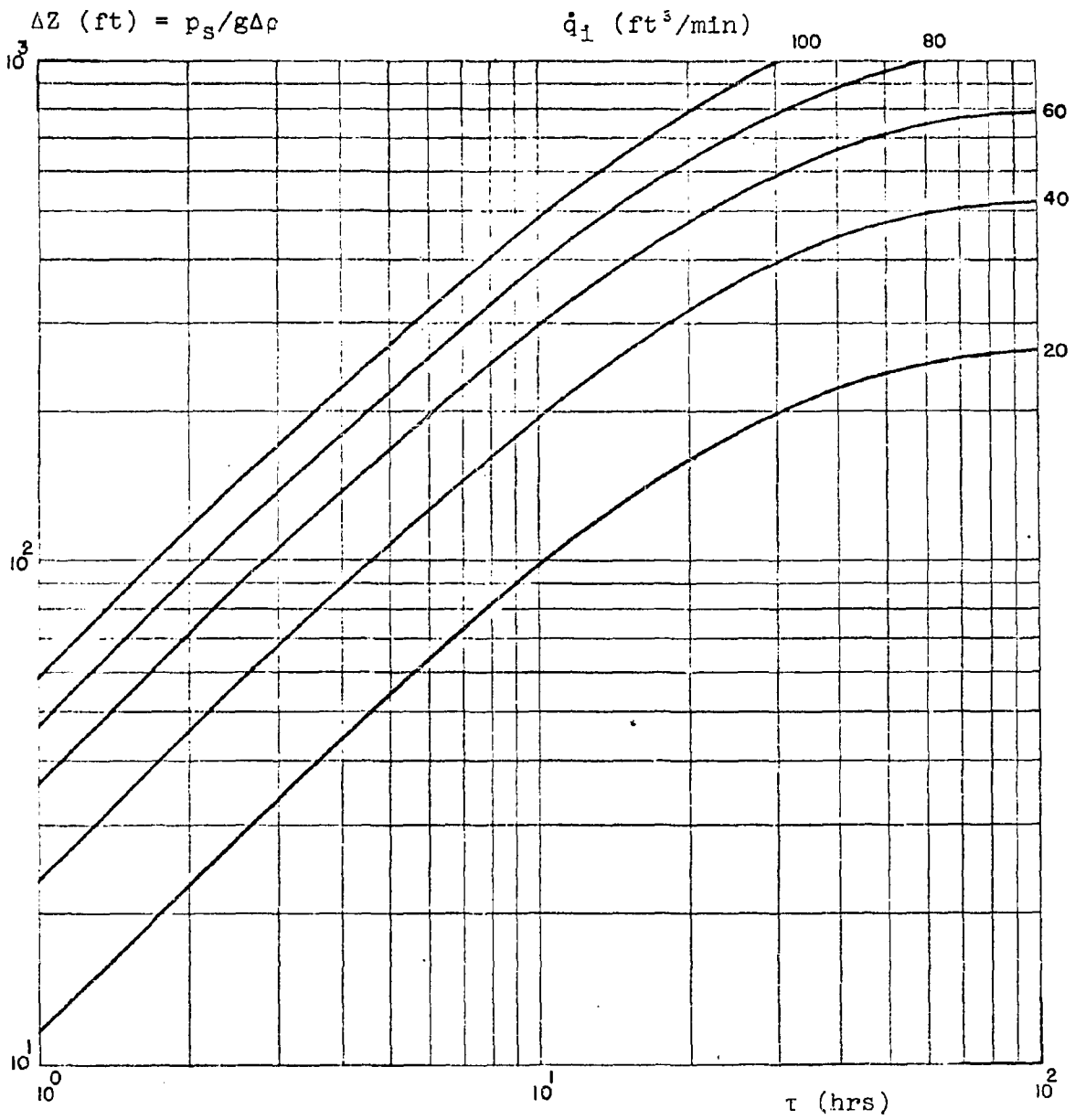


Fig. 54: Height Over Which a CO_2 Column Can be Lifted by CO_2 Released Under Pressure

and a further decrease in ventilating pressure by closing a ventilation door reduced it to 170 ft^3/min. Concentration measurements showed that the CO_2 filled only the intake airway and was unable to rise more than 100 ft (39 ft vertically) along the face. No CO_2 could be detected in the upper return airway and, due to the diminished ventilation, CH_4 concentrations reached 14%. Only after the ventilation was resumed with an airflow rate of 3,800 ft^3/min by opening the seals, an air - CO_2 mixture with a maximum CO_2 concentration of 12% reached the return airway. At the same time the CO_2 concentration in the intake airway was equal to 35 - 45%. This indicates that part of the air must have flown in a layer on top of the CO_2. The authors recommend that Reynolds' numbers of more than 50,000 should be provided to assure sufficient mixing of air and carbon dioxide.

No difficulties were experienced by Belik and colleagues[10] in filling a steep longwall face of 60° dip and 400 ft length with CO^2 from the top. The rate of gas discharge was 600 ft^3/min.

Equally, no difficulties in filling all sealed spaces with nitrogen from the bottom are reported by Osipov and Orlov[130] and Gorb and Stalerov.[53] The first two authors observed that the nitrogen acted like a piston with the dilution front clearly noticeable. The discharge rate was 1,120 ft^3/min. Gorb and Stalerov noticed considerable CH_4 layering at a combined flow velocity of nitrogen and air leakage of 55 ft/min.

Belik[12] quotes a recommendation by the National Institute for Scientific Research in Mines (VNIIGD) that CO_2 applications should be limited to lengths of 1300 - 1600 ft and elevation changes of 65 ft.

G. Risks of Inert Gas Use Underground

Inert gases in themselves are generally not toxic but asphyxiating. An exception is CO_2 which at 30,000 ppm is weakly narcotic, decreasing acuity of hearing and increasing blood pressure and pulse. A thirty minute exposure may at 50,000 ppm be intoxicating and at 70,000 - 100,000 ppm produce unconsciousness in a few minutes.[126] Industrial inert gases produced in combustion processes can contain CO in concentrations, which are deadly after several hours of exposure (at 500 ppm), or deadly after only a few inhalations (at 1%).

The changes which in the composition of fumes after an injection of inert gases into the fire zone can be expected, have been discussed in chapter VI E. Most inert gases should have the same effect as a reduction of airflow, that means a temporary increase in distillation products, which for coal contains approximately 5% CO and for timber up to 35% CO.

CO_2 can in a producer gas reaction generate additional CO, but opinions on the amount of CO produced are divided. Only in one case has a CO concentration of 5 - 6% been reported, otherwise it always stayed below 2%.

The asphyxiating properties of inert gases and the possible increase in the toxity of the fumes make it advisable not to use any inert gas as long as miners without self-contained breathing apparatus are underground. One has in particular to bear in mind that density differences between inert gases and mine atmosphere can cause ventilation disturbances, which can let the mixture of inert gases and fumes enter other airways than the return of airways of the fire zone.

Several ways can be imagined in which such ventilation disturbances can occur. The discussion shall be limited to CO_2 since it has the greatest density difference to air.

If a fire zone is ventilated with CO_2 before the seals are closed, some gas might flow from the return airways in layers along the floor into adjoining inclined airways. Figure 50c shows the considerable velocities this flow can acquire in a stagnant atmosphere, Fig. 47 the layering numbers which are required for the ventilation of these mine workings to prevent CO_2 from entering. Safeguards against such layers can be provided with increased air velocities caused by mixing baffles at the floor or by the collection of CO_2 in sumps and their subsequent dispersal by air blowers.[7]

The mine ventilating pressures which are necessary to lift a gas with a density ρ_i over a height ΔZ can be calculated from $p_{MV} = \Delta Z g(\rho_i - \rho_a)$. Values for $\Delta Z\ g\ (\rho_i - \rho_a)$ are shown for CO_2 - air mixtures of different concentrations and temperatures in Fig. 53. If larger elevation differences, than can be overcome by the mine ventilating pressure exist in the return airways, ventilation standstills will occur. This can lead to the formation of explosive mixtures when the CO_2 concentration is not high enough to fully inert evolving methane and it can lead to the backing of CO_2 if the CO_2 release is continued.

Such a backing can even occur without a continued CO_2 discharge. As Fig. 53 shows, CO_2 - air mixtures with high temperatures can by a given mine ventilating pressure be lifted to higher elevations than mixtures of low temperatures. If a ventilation standstill occurs and the CO_2 - air mixture in a nonhorizontal airway cools down, the mine ventilating pressure will only be able to hold a lower gas column in suspension. Although the shrinking volume of the gas balances this partly, a certain amount of the gas in the ascensional airway will flow back. The remedy in all these cases is a sufficient dilution of the CO_2 in the return airways with air.

The same difficulties which might occur during an inert gas ventilation of a fire zone before the seals are closed can happen after the seals are opened and the fire zone is ventilated again. The remedy is the same also, a sufficient dilution.

Leakage from sealed CO_2 filled areas might be another source of danger. Even at very small flow rates it can flow along a dipping floor in layers and form in depressions, pools of sufficient depths for people to suffocate. Such accumulations of CO_2 from other sources are a not infrequent cause for fatal accidents in some mining areas. This can be prevented with good ventilation, local air velocity increases by blowers and mixing baffles, or by draining the leakage into collection sumps.

X. INERT GAS GENERATORS

A. Limitations in the Use of Stored Inert Gases

In most of the cases of inert gas use for fighting mine fires, which have been described in chapter V, the inert gas source has been liquefied CO_2 or liquefied or highly compressed gaseous N_2, shipped in cylinders or tanks from a nitrogen or carbon dioxide plant to the mine site. The same applies to the few cases where large quantities of inert gases have been used to extinguish surface fires.[157] The Standards on CO_2 Extinguishing Systems of the National Fire Protection Association[121] are equally based on gaseous or liquid stored CO_2 supplies. Where inert gas is routinely used for fighting mine fires, the inert gas source is still mainly liquefied N_2 (USSR) or compressed gaseous N_2 (CSR).

The use of stored inert gas has several disadvantages. If it is transported in a gaseous state, large volume tanks are needed. The capacity of the Czechoslovakian N_2 trailers

is, for instance, only 21,000 - 25,000 ft^3 per unit. Liquefied inert gas has either to be transported in its liquid state to the fire site (CO_2), which limits the release rate to 1250 - 1400 ft^3/min,[175] or it has to be evaporated at the surface and to be piped into the fire zone. The USSR built evaporator AGU-2m has a capacity of 2800 - 3500 ft^3/min,[175] but due to the dimensions of the existing pipelines from the surface to the fire zone the practical output is usually considerably smaller (1240 ft^3/min,[159] 1400 ft^3/min [130]). The two evaporators used at the Fernhill fire[178] had a combined capacity of 1260 ft^3/min. Availability of the liquefied gas and transport from the N_2 or CO_2 plant to the mine presents in many cases a problem also.

Another disadvantage are the relatively high prices of liquefied N_2 and CO_2. They are lowest for N_2, when it can be purchased from large oxygen plants, like those supplying steelworks, where the nitrogen is a byproduct, and are in the range of 0.15-0.30¢/ft^3.[14] At the Fernhill colliery,[178] located 25 miles from the British Oxygen Company Ltd., Cardiff, the cost was 0.25 ¢/ft^3. Average prices will be considerably higher than these figures and they are higher for CO_2 than for N_2.

In view of these prices it has become attractive for inert gas consumers in other industries to produce their own inert gas and a greater number of different inert gas plants are on the market. They are relatively inexpensive to purchase and to maintain. Fuel costs can for mixtures of nitrogen and carbon dioxide be estimated from Table 14, a - c, where the ft^3 inert gas per ft^3 or gallon of fuel has been listed. They are at present in the order of magnitude of 0.05 ¢/ft^3.

With the large volumes and flow rates needed to fight mine fires it may be advantageous also to produce the inert gas at the fire site. Examples, either with commercially available surface plants or especially designed appliances have been described in chapter V. It seems, therefore, useful to review which inert gas generators are presently available and which properties they have.

B. Industrial Process Inert Gas Generators

1. Basic Operating Principles

Protective gases are used in many industrial processes to prevent oxidation and the formation of explosive atmospheres. Examples are the corrosion protection of tanks and boilers, the heat treatment of metals, the protection of flammable materials during process, as in pulverizing, drying, transporting, mixing, cooling operations, and the purging of

tanks and pipelines. The use of protective gases has in the last years steadily increased. Reasons are higher safety and quality demands as well as the greater availability of these gases due to the development of relatively inexpensive and simple protective gas generating systems.

If the process does not demand a pure gas, industrial protective gases are usually mixtures of N_2, CO_2, CO, H_2, and H_2O. They result from the combustion of a hydrocarbon fuel and can be roughly divided into endothermic-, rich-ratio-exothermic-, lean-ratio-exothermic-, and inert gases. The composition is a function of the air-fuel ratio and is shown for natural gas in Fig. 55.[43] For use in mine fires, only inert gases are of interest. Since all plants for producing protective gases except for those producing endothermic gases, which need the supply of external heat, are very similar and can be modified to produce inert gas, exothermic gas generators have been included in the following survey also.

The fuel used for these generators is gaseous or liquid, like natural or manufactured gas, propane, butane, gasified oil, liquid kerosene, light fuel oil, etc. Heavy fuel oil is less popular because of its high sulfur content and viscosity.

The gas generators consist primarily of a refractory lined combustion chamber fitted with burners. Gaseous fuels are usually mixed with air before entering the burner, liquid fuels in the burner. Controls maintain the selected mixing ratio. If the composition of the fuel can change or only small variations in the inert gas composition are permitted, the mixing ratio controls can be governed by a gas analysis regulator, usually based on the O_2 content. After leaving the combustion chamber the high temperature combustion products are cooled, either directly in spray coolers or indirectly in heat exchangers. Frequently compression to a higher delivery pressure follows. If necessary, several cleaning steps follow in which undesired constituents are removed. Figure 56[194] shows an example for a mixed (N_2 - CO_2) inert gas generator with combustion chamber and spray tower. Figure 57[133] shows a generator working with submerged combustion, where these two components are combined in one unit.

Composition and quantity of inert gases as well as heat development are not difficult to determine, since the working principles of the above generators is the stoichometric combustion of the used fuel. Composition and

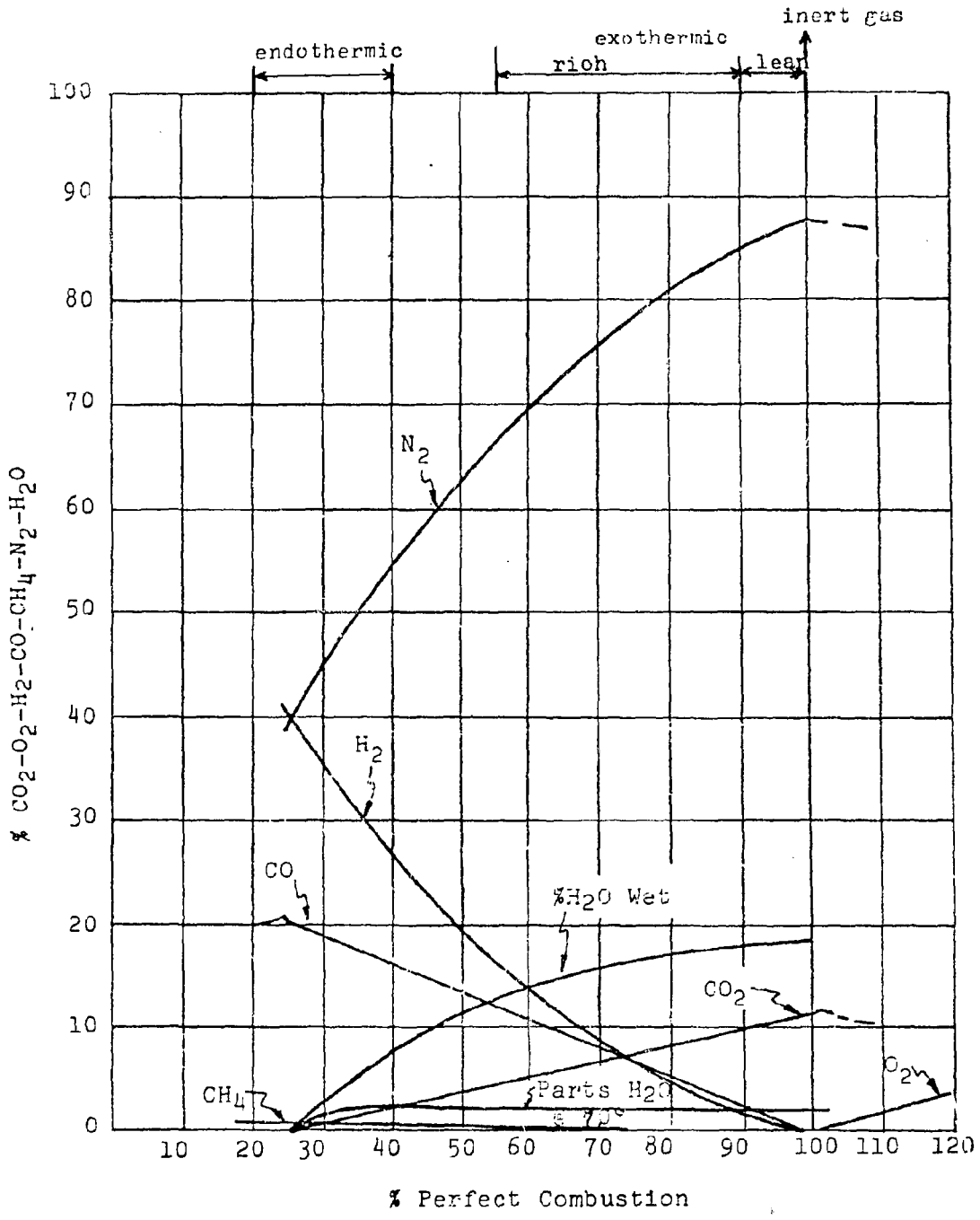


Fig. 55: Exothermic and Endothermic Atmospheres.[43]

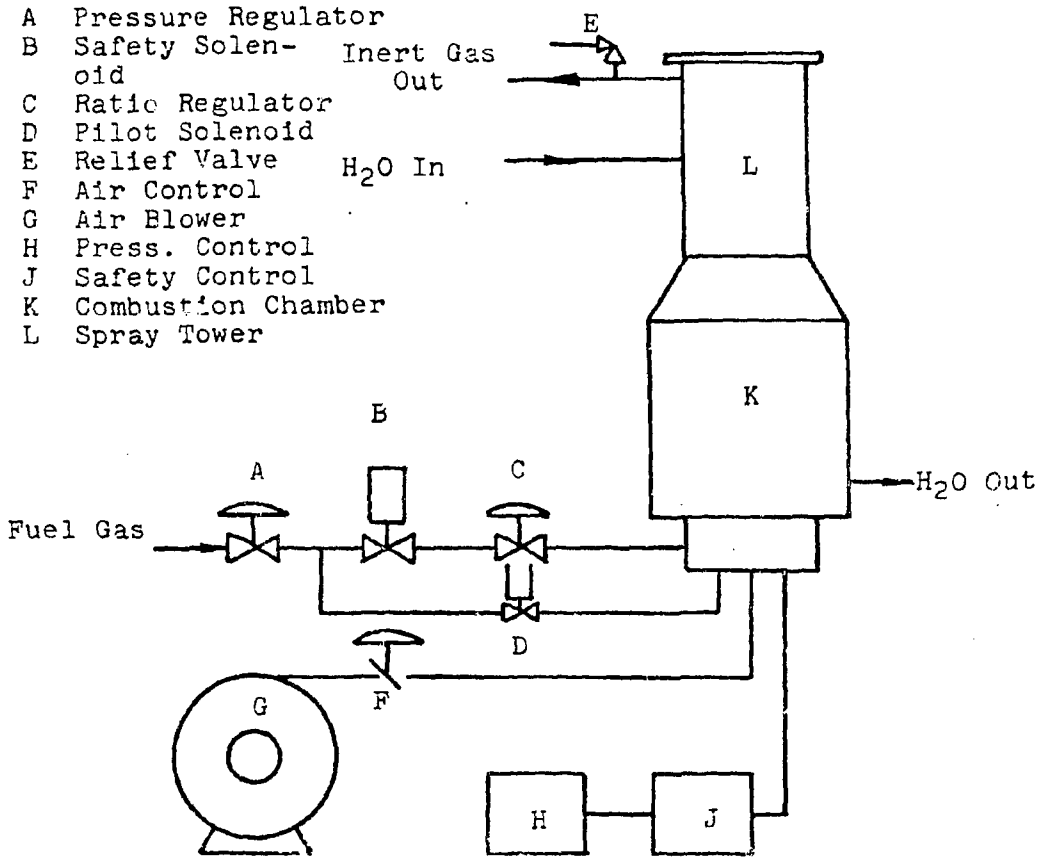


Fig. 56 Mixed Inert Gas Generator.[194]

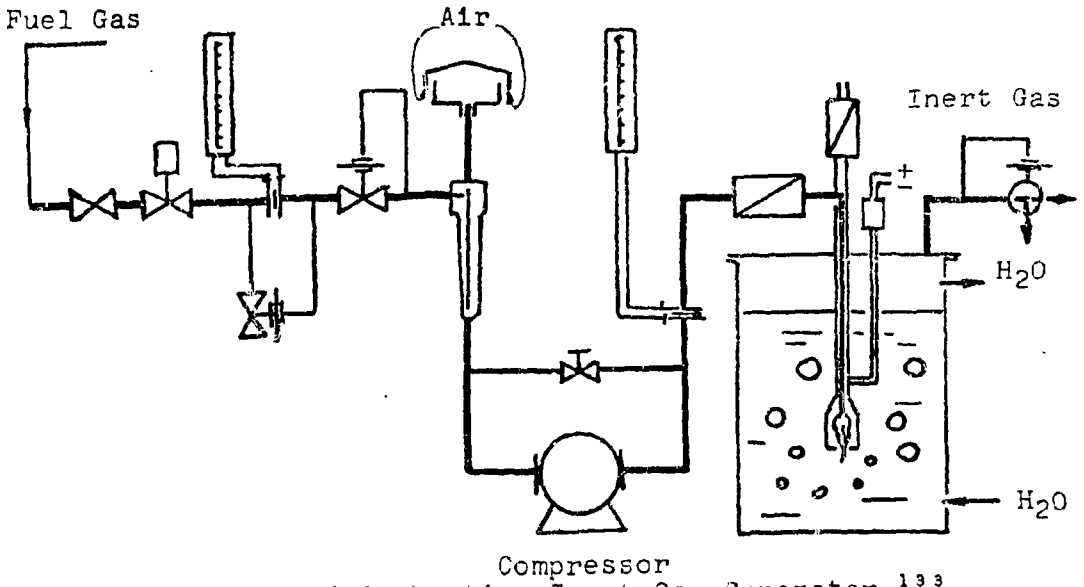


Fig. 57 Submerged Combustion Inert Gas Generator.[193]

quantities can be calculated from the combustion equation, but since the produced inert gas is identical with the dry flue products at zero excess air, existing charts and tables may be used for many commercial fuels.[66] The heat development is approximately equal to the gross heating value, which is usually known or easy to determine also.

Some examples for inert gas yield, composition, and heat development are given in Tables 14 a - c. Table 14a deals with pure combustible materials and has been extracted from the Gas Engineers Handbook.[176] Table 14b has been calculated from examples for commercial gases, given in Marks' Engineering Handbook.[101] Table 14c deals with liquid fuels based on petroleum oils. Since commercial fuels are complex and varying mixtures of hydrocarbons, Table 14c is based on the specific gravity of petroleum oils, expressed in degrees API. Diesel and fuel oil range approximately from 10 to 45 degree API, kerosene from 35 to 50, and gasoline from 55 to 75. Densities and heat values have been extracted from Marks' Engineering Handbook. It has furthermore, been assumed that the fuel comprises pure hydrocarbons only and that the weight percentage of hydrogen h can be obtained from

$h = 26 - 15\ d$ where $d = 141.5/(131.5 + \text{deg. API}) =$ specific gravity of oil compared to water

All tables are based on 60°F and 30 in. HG. Since the produced inert gases are mainly mixtures of nitrogen and carbon dioxide, only the CO_2 content has been listed in the tables, the rest being nitrogen.

If no other information exists, the yield of inert gas can be calculated for most gaseous fuels from

$$Q_{inert}/Q_{fuel} = 4.76\ C + 1.88\ H_2 + 2.88\ CO + Inert - 3.76\ O_2$$

where C, H_2, CO, Inert, O_2 are the volume concentrations of these constituents in the fuel.

For liquid and solid fuels it can be calculated from

$$Q_{inert}/lb_{fuel} = 1.5\ c + 0.56\ s + 3.55\ h + 0.14\ inert - 0.44\ o$$

where c, s, h, inert, o are the weight percentages of carbon, sulfur, hydrogen, inert matter, and oxygen in the ultimate analysis.

Table 14: Inert Gas Yield, Process Heat, and Dry Inert Gas Composition

a. Pure Combustible Substances

Substance	Inert Gas Yield $\frac{ft^3_{inert}}{ft^3_{fuel}}$	Inert Gas Yield $\frac{ft^3_{inert}}{gal_{fuel}}$	Process Heat $\frac{Btu}{ft^3_{fuel}}$	Process Heat $\frac{Btu}{ft^3_{inert}}$	CO_2 Content %
Carbon Monoxide	2.88		321.37	111.6	34.72
Hydrogen	1.88		325.02	172.9	0
Methane	8.52	503	1012.32	118.8	11.74
Ethane	15.16	626	1773.42	117.0	13.19
Propane	21.80	783	2523.82	115.8	13.76
n-Butane	28.44	875	3270.69	115.0	14.06
Octane	55.00	977	6260.00	113.8	14.55

b. Examples of Commercial Gases

Constituent	Natural Gas % by weight	Natural Gas % by weight	Water Gas % by weight	Producer Gas % by weight
CH_4	94.3	72.3	1.2	3.0
C_2H_6	2.1	5.9		
C_3H_8	0.4	2.7		
C_4H_{10}	0.2	0.3		
CO			38.0	27.0
H_2		0.1	48.0	14.0
O_2			0.6	0.6
CO_2	2.8	0.1	5.0	4.5
N_2	0.2	18.2	7.2	50.9
He		0.4		
ft^3_{inert}/ft^3_{fuel}	8.53	7.91	2.20	1.39
Btu/ft^3_{fuel}	1010	934	290	162.9
Btu/ft^3_{inert}	118.5	118.0	131.9	86.3
% CO_2	11.87	11.8	17.9	15.9

c. Petroleum Oils

degree API	Fuel Properties: specific gravity	density lb/gal	Composition H_2 (%)	C (%)	Inert Gas Yield ft^3/lb	ft^3/gal	Process Heat Btu/lb	Btu/ft^3_{inert}	CO_2 Content %
10	1.0000	8.328	11.00	89.00	172.66	1438	18,540	107.4	16.24
20	0.9340	7.778	11.99	88.01	174.70	1359	19,020	108.87	15.87
30	0.8762	7.296	12.86	87.14	176.49	1288	19,420	110.03	15.55
40	0.8251	6.870	13.62	86.38	178.06	1223	19,750	110.92	15.28
50	0.7796	6.490	14.31	85.69	179.48	1165	20,020	111.54	15.04
60	0.7389	6.151	14.92	85.08	180.74	1112	20,260	112.09	14.83
70	0.7022	5.845	15.47	84.53	181.87	1063	20,460	112.50	14.64
80	0.6690	5.568	15.97	84.03	182.90	1018	20,630	112.80	14.47

Table 15: Typical Composition of Inert Gases (14)

Constituent	Fuel: Cokeoven Gas	Methane	Gas Oil
N_2	90 %	88 %	84 %
H_2 + CO	1 %	1 %	1 %
CO_2	9 %	11 %	15 %
O_2	10 ppm	10 ppm	10 ppm

Since the weight ratio of hydrogen and carbon does not, for most hydrocarbon fuels, vary too much, it is not surprising that the heat produced per unit dry flue products, or, in our case, the Btu/ft^3_{inert} does not vary too much either. The variations range between 118.8 Btu/ft^3_{inert} for CH_4 and 107.4 Btu/ft^3_{inert} for 10 degrees API petroleum oil. Estimates of the inert gas production can therefore be based on the gross heating value of the fuel consumed in the generator.

2. Available Generators

Examples for the capacities with which stationary series built inert gas generators are available in the U.S. are the following:

17 - 333 ft^3/min,[40] 17 - 2,500 ft^3/min,[51] 21 - 417 ft^3/min,[133]
33 - 417 ft^3/min,[65] 33 - 1000 ft^3/min,[166] 33 - 1,167 ft^3/min,[162]
50 - 500 ft^3/min,[194] 100 - 3,330 ft^3/min.[54]

The order of magnitude of selling prices for these generators can be obtained for sizes up to 700 ft^3/min from a formula given for 1974 by Hirt Combustion Engineers:[65]

Selling Price = \$ 9,045 + \$ 421.4/(1000 ft^3/hr)

Prices quoted by other manufacturers are in the same range for small units, but vary for large custom built generators.

Examples for the specific weight in lbs per ft^3/min capacity are shown in Fig. 58. Generators working on the submerged combustion principle are the lightest; basic units of conventional combustion chambers are about twice as heavy, and accessories, like compressors, dryers and tanks can double the specific weight once again.

Designed as stationary plants, the dimensions of these generators are not small. For 50 ft^3/min plants they are in the order of magnitude of 5' x 5' x 10' for the basic unit, and 5' x 10' x 10' complete with accessories. 500 ft^3/min plants would measure 10' x 20' x 20', 1000 ft^3/min plants would be mounted on three skids with 10' x 10' x 30' each. Assembly of the plant at the users site takes 10 - 20 man-days.

Most makers of industrial process inert gas generators quote for the fuel consumption figures around 0.115 ft^3 natural gas per ft^3 inert gas, which is close to the theoretical value for CH_4. The same proximity applies to other gases or oil, when quoted.

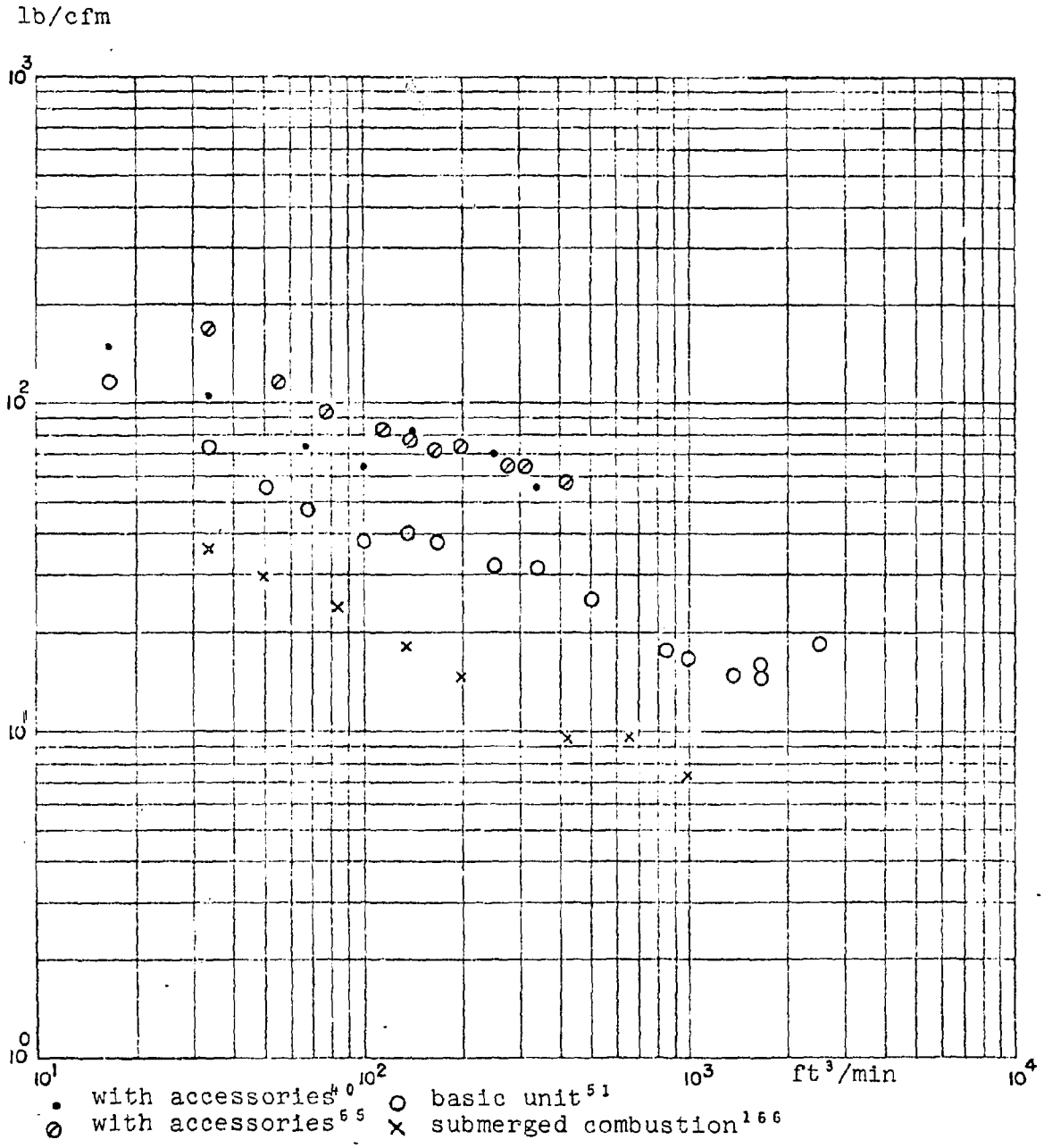


Fig. 58: Specific Weight of Inert Gas Generators

The composition of the inert gases depends on the fuel used. Borrmann[14] of J. F. Mahler Apparate und Ofenbau quotes as typical compositions the values given in Table 15. Other manufacturers quote for natural gas

12% CO_2, 87% N_2, 0.5% reducing and oxidizing residuals[194]
11.5% CO_2, 88% N_2, 0.3% H_2, 0.3% CO, 10 ppm O_2[65]
11.5% CO_2, 0.25% H_2, 0.25% CO, 0% CH_4 and O_2, balance N_2.[51]

The gas exit temperature is usually 5 - 10°F above the cooling water temperature. The quoted water consumption is around 0.4 gal/ft^3 inert gas which corresponds to a temperature increase of the cooling water by approximately 35°F.

Power is needed mainly to force air into the combustion chamber. The average power requirements are 0.04 HP for 1 ft^3/min inert gas when the gas is delivered with a pressure of 0.3 - 0.5 psig.

Few mobile generators are available. The truck mounted make, used by the Polish Coal Mines, has already been mentioned in chapter V.[90] Its data are: 118 ft^3/min inert gas with 85% N_2, 13% CO_2, max. 2% O_2, 1.5 psig discharge pressure, 392°F discharge temperature, 44 lb/hr fuel oil consumption, 3 - 4 kW energy consumption, 8.5' x 6.5' x 8' external dimensions, selling price (1966) $7,500. The largest mobile generator, built by the same manufacturer[100] has a capacity of 600 ft^3/min and a selling price (1967) of $20,000. A onetime use in a West German coal mine has been reported (chapter V, bibl. 16).

Nitrogen plants, like the one designed by the Czechoslovakian Coal Mines (chapter V) and based on liquid ammonia, are commercially available also. Since the cost of produced nitrogen is approximately 3 - 6 times higher than that of a CO_2 - N_2 mixture from hydrocarbon fuels,[14] they shall not be discussed in this report.

3. Experimental Fire Fighting Generators of Similar Design

The design of experimental inert gas generators for fighting purposes, which are similar to the above described appliances, has been reported from the USSR and Canada. The VostNII developed generator, mentioned in chapter V,[138] comprises basically a combustion chamber with burner, spray coolers, pumps and blowers. Its gas delivery rate is 295 ft^3/min with 1.5 - 2.5% O_2, 12.5 - 14% CO_2, traces of CO, its fuel consumption is 1.47 lb/min of fuel oil.

For easy transport it is mounted on a platform.

The National Research Council of Canada developed an experimental mobile inert gas generator for fighting building fires, based on the stoichometric combustion of gaseous propane.[108] It comprises essentially a combustion chamber fitted with a burner, an electrically driven blower for the air supply, and an array of spray nozzles through which water is injected into the combustion products. With a vortex type burner the combustion chamber can be held comparatively small. The generator produces approximately 3,800 ft^3/min inert gas at 212°F and 4 in. wg. with a composition of 68% (by volume) H_2O, 28% N_2, and 4% CO_2. It is light enough to be mounted on a one axle trailer and was successfully tested in experimental fires. One sees as advantages of this type of generator its simple design and the complete combustion of a stoichometric fuel - air mixture, which in a gas turbine can be achieved only with an afterburner. A disadvantage is the use of gaseous fuel, a requirement which to modify should not be too difficult.

C. Gas Turbines

1. Design for Building Fires

In fighting building fires, smoke is a major obstacle. Ventilating the fire with inert gas to remove the smoke and at the same time to reduce the burning rate could be a remedy. It seems to have been suggested first in 1954 in Great Britain that the required quantities of inert gases for these purposes, which are in the order of magnitude of 10,000 - 50,000 ft^3/min, could be obtained by the use of an aircraft jet engine.[136] The National Gas Turbine Establishment was requested to build a prototype unit for 50,000 ft^3/min, which was delivered in 1960.

The working principle of this unit is shown in Fig. 59.[136] Combustion of fuel in the main jet burners of the engine reduces the oxygen content of the air entering the engine and provides the power for the compressor. A further reduction of the oxygen content takes place in the after burner or reheat section. The combustion products are subsequently cooled by vaporizing water in a humidification section, where water is introduced as a fine spray.

The rate of airflow through the engine is proportional to the turbine speed, which in itself is controlled by the fuel feed to the main jet burners. The composition of the final gas is, to a large part, determined by the fuel supply to the after burner. This allows control of the oxygen

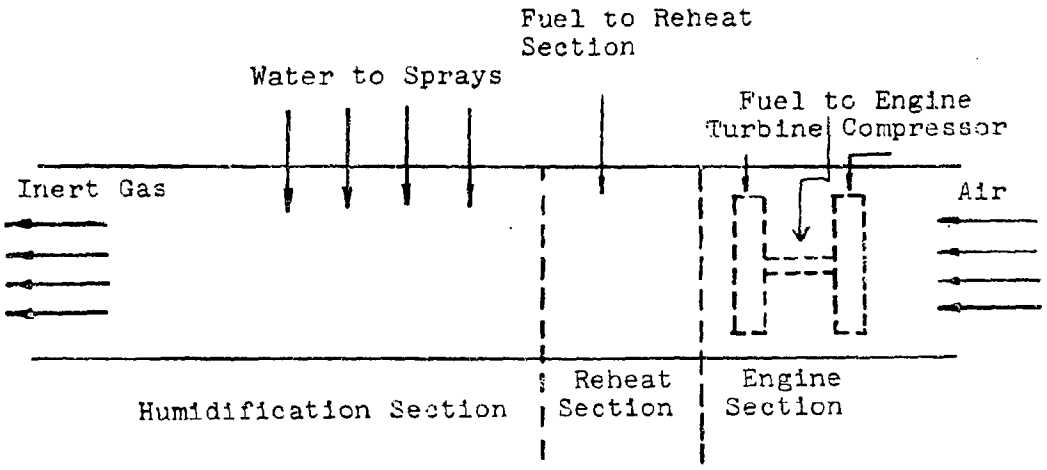


Fig. 59 Basical Principles of a Turbo-Jet Inert Gas Generator.[156]

concentration of the final gas, and of the delivery rate within a comparatively wide range, by varying the amount of fuel burned in engine and afterburner. Figure 60 shows the theoretical composition of the inert gas produced and Fig. 61 its volume and density as a function of the fuel - air ratio under the assumption, that the fuel is completely burned, that the cooling water is introduced at 59°F, completely vaporized, and that the exit temperature is 248°F.[136] The fuel is aviation kerosene. An additional change of delivery rate and gas composition is possible by varying the amount of water spray and entraining air into the outlet gas.

Because combustion is not complete and because of heat losses, the inert gas actually produced with this generator had a composition slightly different from the theoretical values shown in Fig. 60. At a peak delivery rate of 45,000 ft^3/min with a fuel - air ratio of 0.033, a composition corresponding to 0.030 was observed.[136] The composition was: 46% N_2, 3% CO_2, 44% H_2O, and 7% O_2. In producing this gas 6.5 gallons of kerosene and 70 gallons of water were used.[137] By varying the fuel feed to the afterburner, the air entrainment, and the water injection, the delivery rates and compositions listed in Table 16 could be achieved.[156]

A prototype unit uses a Bristol-Siddeley "Viper" engine with a water jacketed afterburner.[45] It is mounted on a 5 ton truck. To reduce its length it has been built in U-shape with one leg containing engine and afterburner and the other one the vaporization section. It has undergone extensive testing alone and in combination with high expansion foam generators,[96,137,156,185] and suggestions for improved designs were worked out.

Since the prototype unit had been designed to clear buildings from smoke and to suppress flaming combustion, the oxygen concentrations of the produced inert gases are relatively high, too high to extinguish smouldering fires. It is, of course, possible to design a generator operating with a greater fuel - air ratio and producing a gas with a lower oxygen concentration. The literature[156] reported in 1965 that Austin Motor Co. was developing a smaller unit with an output of 12,000 ft^3/min of hot inert gas with 2% O_2, and Gibbons Bros. Ltd. a unit with 2,000 ft^3/min of cool inert gas with 2% O_2.

A feasibility study for a gas turbine to generate inert gases of low oxygen concentrations without an afterburner was conducted by Macaulay.[198] Its size shall be

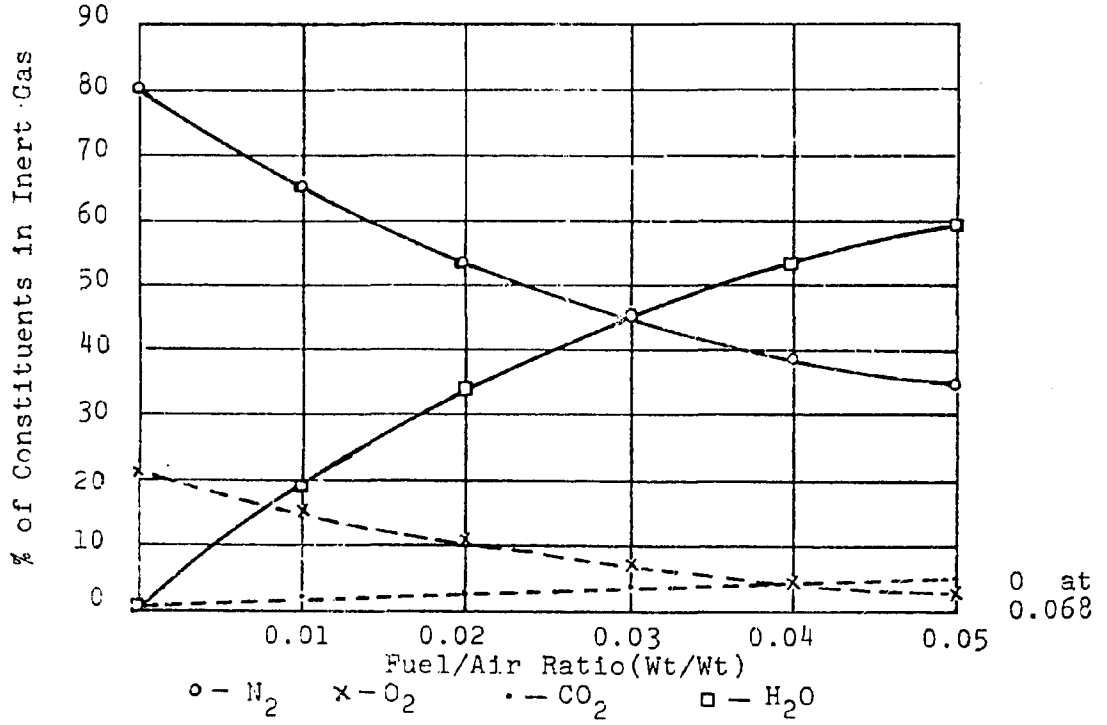


Fig. 60 Composition of Inert Gas from Jet Engine Cutlet Temperature 120°C.[136]

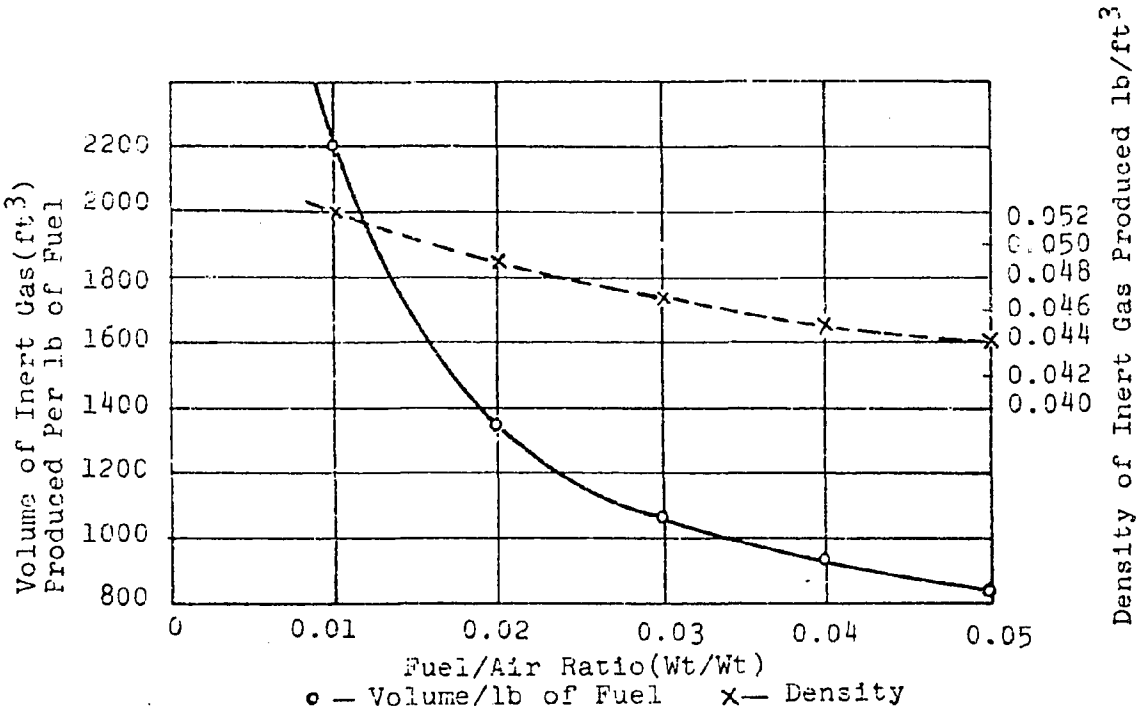


Fig. 61 Volume and Density of Inert Gases.[136]

Table 16: Some Fire Controlling Media That the Operational Inert Gas & Foam Generator is Designed to Produce[156]

Medium	Appliance Operation	Temperature °C.	Per cent. Oxygen	Rate of flow $ft^3/min.$	Visibility
Hot, flame extinguishing gas	Reheat. No. additional cooling	120	7	50,000	Clear, but may become misty
Warm, flame extinguishing gas	Reheat. Additional Cooling	65	9	33,000	Misty
Warm, flame extinguishing smoke clearing gas	Reheat. Air entrainment.	75	12	70,000	Clear
Cool smoke clearing gas. Respirable in an emergency	No. reheat. Air entrainment. Additional Cooling.	30-40	18	35,000-40,000	Probably clear
High expansion foam	No reheat. Air entrainment	35	18	25,000-30,000	Opaque

kept down by carrying out all the combustion and water evaporation at compressor delivery pressure. Such a generator would perform the following functions: air compression to a pressure sufficiently high to permit use of a reasonably small combustion chamber; near stoichometric combustion; water spray to cool the gases to the lowest possible turbine inlet temperature; and expansion in a work turbine to drive the compressor. Cycle calculations for some 70 sets of conditions were performed.

2. Designs for Underground Use

Gasturbine based inert gas generators for underground use have been developed in the USSR. The first design by the Mine Rescue Institute in Donetsk[60] had a basically cylindrical shape with a diameter of approximately 3 ft and a length of 36 ft. It comprised the gas turbine, a water jacketed expansion section, a water spray cooling section, and ancillaries. To facilitate underground transport it could be dissembled into components of 100 - 200 lbs weight except for the gas turbine section, which weighed 600 lbs. The total estimated weight, varying with the length of expansion and cooling sections was 1500 - 2100 lbs. The delivery rate reached approximately 9,000 ft^3/min at a temperature of 176 - 212°F, the dry composition of the inert gas was 82 - 86% N_2, 10 - 12% CO_2, 4 - 5% O_2, 0.0 - 0.7% CO, and 0 - 0.3% H_2. A consumption of 9 - 29 lb/min kerosene and 75 - 132 gal/min of water has been quoted.[60]

In an improved design, the inert gas generator GIG-2, an afterburner was added, which reduces the oxygen concentration of the combustion products to approximately 1%. The use of this generator in mine fires has been described in chapter V. In the cases listed in Table 10 the average delivery rate was 11,6000 ft^3/min at a temperature of 175°F. Since it can be assumed that the exhaust gas-water-vapor mixture leaving the generator at this temperature is fully saturated, the water vapor content would at an atmospheric pressure of 14.7 lb/in^2 and a saturation pressure of 6.715 lb/in^2 be 6.715/14.7 = 45.7%. With the reported average fuel consumption of approximately 30 lb/min of kerosene one obtains a dry inert gas production of 210 ft^3/lb, corresponding to 172 ft^3/lb at 60°F, which falls into the expected range. The reported average water consumption is 120 gal/min. This figure is hard to explain. Cooling of the combustion products to 175°F by water vaporization requires theoretically only about half this water flow rate. But then the water vapor content of the generated inert gas is again considerably lower than would

correspond theoretically to this flowrate. Part of the combustion heat must therefore be transferred by water vaporization to the air, part of it carried away with heated water.

The latest design is the inert gas generator GIG-4, which has a performance similar to the model GIG-2. It is equipped with the turbine AI-8P and has a delivery rate of 12,000 ft^3/min of an inert gas comprising approximately 51% N_2, 8% CO_2, 1% O_2, 500 ppm CO and 40% H_2O. The discharge temperature is 176°F, the gage pressure 40 in. wg. Its total weight is approximately 2,000 lb, its main unit can be dissembled into three parts for underground transportation.[175] An approximate fuel consumption of 3.5 gal/min kerosene, external dimensions of 2.5 ft diameter and 20 ft length and a price of 22,000 Rubles have been reported by a visitor to the Donetsk district.[17] Four of these generators were in use in 1974. Series production is under discussion also. A smaller gas turbine based generator with a delivery rate of 1,750 ft^3/min is under construction.

D. Use of Flue Gases from Other Plants

Inert gas plants, processing the flue gases of other fuel consumers like power plants, are quite frequently used when the produced inert gas is permitted to have oxygen concentrations as high as 2 - 4% and purity requirements are low. This is, for instance, the case on oil-tankers where the inert gas is used to prevent possible explosions in tanks and pipelines. Capacities of 10,000 - 20,000 ft^3/min are not uncommon.[14] Since these plants comprise only washcoolers and occasionally heat exchangers for further cooling and drying, installation and operating costs are low. Of disadvantage is the dependence on the performance of the main plant and the lacking mobility. They seem useful, therefore, only in exceptional circumstances for mine fire fighting purposes, like for the prevention of spontaneous ignitions in abandoned mine areas.

No applications of flue gases from other plants for fighting mine fires have been reported in the literature. As described in chapter V, it has been suggested to use flue gases from conventional coal furnaces to fight fires, and delivery rates of 57 ft^3/min flue gases per ft^2 of fire grate have been calculated.[181,182] Two fires were actually extinguished with flue gases from coal furnaces, which had been installed for this purpose as inert gas generators.[183]

XI. ADVANTAGES AND DISADVANTAGES OF INERT GAS USE

Advantages and disadvantages of inert gas applications compared with conventional fire fighting methods have been stated at several places in this report, especially in connection with the description of actual inert gas uses. The reasons for the choice of the inert gas method and its success or failure make some of its advantages and disadvantages quite obvious.

Unfortunately, only very few applications took place in U. S. coal mines. To allow a comparison but not to base it completely on speculation, the reports of five coal mine fires, obtained at random from Consolidation Coal Company, shall be utilized.[170-4] It shall be investigated if and how these fires could have been fought with inert gases and how the inert gas method would compare with the actual course the fire fighting operations took.

A. Description of Actual Fires and Likely Course of Inert Gas Application

1. Fire No. 1[172]

A damaged trailing cable or a splice short-circuited a cable reel and ignited combustible materials on a shuttle car at about 12:10 a.m., May 29, 1965. The shuttle car was loaded with spillage in the right, outside and return air entry of a section of 6 active entries, close to the last cross cut. Due to malfunctioning of the available fire extinguishers, the fire could not be extinguished in its incipient stage. Use of water and rock dust were equally unsuccessful. Check curtains were erected to adjust the ventilation and temporary stoppings set up to prepare for the use of a foam generator. The generator was installed 100 ft from the origin of the fire and was started at 8:15 a.m. but began to operate, due to lack of water, only at 12:22 p.m. At 1:45 p.m., May 30, it was discovered that the fire had advanced 500 ft outby the face. The ventilation of the fire zone was reversed and a second foam generator installed, which prevented further spread of the fire.

About 8:00 a.m., June 2, it was decided to seal the fire because the direct attack did not cool the fire sufficiently to permit loading out of the hot material. The whole section with a volume of approximately 350,000 ft^3 was sealed off with permanent seals across all six entries. Sealing was completed at 4:55 p.m. the same day. On June 6

air samples showed that the oxygen concentration had decreased to approximately 6% and work in the mine was resumed. Recovery operations started September 11, 1965. No rekindling occurred.

Although the fire could not be extinguished by direct attack, the foam generators helped to keep it under control. 6,520 gallons of foam concentrate were used.

Likely Course of Fire if Inert Gas Had Been Used

If this fire had been fought with inert gas, its history till completion of the stoppings at 7:05 a.m., May 19, would have been the same since the necessary ventilation adjustments for foam and inert gas applications are very similar. Additionally, it would have been advisable to install a sprinkler system and prepare a stopping in the return air entry at a distance of approximately 700 ft outby the fire. Since the highest CH_4 concentration measured in the section had been 0.41% with a ventilation of 30,420 ft^3/min, the CH_4 liberation in the section can be estimated to be not higher than 125 ft^3/min, or 62 ft^3/min in the air split passing through the fire zone. To dilute the CH_4 to 2.5%, an airflow rate of approximately 2,500 ft^5/min is needed. If the CH_4 shall be fully inerted, 62*6 = 372 ft^3/min of N_2, 62*3.2 = 198 ft^3/min of CO_2, or 62*5.07 = 314 ft^3/min of a 79/21 N_2/CO_2 mixture is needed. With a safety factor of 2 the flow rates double to approximately 700 ft^3/min N_2, 400 ft^3/min CO_2, or 600 ft^3/min mixture.

These quantities are small enough to be supplied by bottled gas and CO_2, of which the smallest quantity is needed, would probably be the best choice. A discharge rate of 400 ft^3/min corresponds to 1 cylinder with 50 lb content per minute.

While the CO_2 is released, the ventilation should be maintained at approximately the original flowrate of 2,500 ft^3/min until the whole area prepared for sealing is filled with the air - CO_2 mixture. With a cross sectional area of 80 ft^2 for the return entry and a length of 720 ft, this will take approximately 23 minutes. The average oxygen concentration will drop to approximately 17.4%. Actual mixing of the CO_2 and air should be secured.

To avoid the formation of explosive mixtures after closing the seals by the continued methane evolution, the initial oxygen concentration of the sealed atmosphere should be sufficiently low (chapter VII B. 2.), which is for CH_4 - CO_2-air mixtures 14.6% O_2 at 7.3% CH_4 (Table 4)

and 15.8% O_2 at 0% CH_4. For this purpose the ventilation of the fire zone with air is stopped and only the CO_2 release is continued at the previous rate. Since one cannot with certainty expect that sufficient fast mixing of the sealed atmosphere and the injected CO_2 occurs, it is advisable to release at least a CO_2 quantity equal to the volume of the mine workings prepared for sealing. This volume is approximately 60,000 ft^3, which means that the CO_2 release has to continue for 60,000/400 = 150 minutes. Under the assumption of no mixing (chapter IX B. 4.) between released CO_2 and atmosphere in the fire zone, the oxygen concentration will have dropped to zero, if no air leakage takes place. If perfect mixing of the released CO_2 and the atmosphere has occurred, the oxygen concentration will be

$$c = c_s \exp\left(-\frac{\dot{q}e^{\tau}}{V}\right) = 17.4 \exp\left(-\frac{462*150}{60,000}\right) = 5.5\%$$

To reach a concentration of 2% the CO_2 release has to be continued for another 130 minutes. A concentration of 12% is comparatively fast reached within 48 minutes after the airflow has been stopped.

No mixing and perfect mixing are idealization, the reality will be in between. Using an approximation formula introduced in chapter IX B. one obtains for 150 minutes CO_2 discharge an oxygen concentration of 3%. A concentration of 2% will be reached within 167 minutes and a concentration of 12% within 45 minutes after the airflow has been stopped.

Flaming combustion ceases at approximately 12% O_2, smouldering combustion at 2% O_2, the explosibility at 14.6 - 15.8% O_2, concentrations which are comparatively fast reached. If the CO_2 discharge is continued once the atmosphere can no longer become explosive or if the seals are closed and a further oxygen decrease and extinction of the fire is expected in the conventional way, is a question of economics. It has been described in chapter VIII that the time period needed to cool off a fire zone has been estimated to be 15 - 20 times the time period over which the fire burns. If the combustion can be stopped after 4 hours of CO_2 injection or 11 hours after the fire started, reopening of the seals might be possible after only 10 days.

During this time the oxygen concentration has to be maintained at below 2%. Leakage caused by ventilating pressures can in this particular case be avoided by pressure

balancing of the seals; leakage caused by barometric effects cannot be avoided. In chapter VII D.1., formulas for the maximal and average leakage rates were derived. With a total of 11 seals, each with a resistance factor of 0.1 in. wg./cfm, sinoidal barometric pressure variations with 10 in. wg. amplitude and 6,000 minutes cycle time, one obtains for the maximal leakage rate from Fig. 33b, a value of 1.57 ft^3/min and for the average flowrate, 0.5 ft^3/min. This means that approximately 7,200 ft^3 or 900 lb CO_2 injection are required over the sealing period of 10 days to replace the leakage.

Summarized: with an input of between 10,000 and 16,000 lb CO_2, it can be expected that any explosive danger could have been prevented, the sealed area could have been reduced from a volume of 350,000 to 60,000 ft^3, and that the reopening of the sealed area would have been possible after a much shorter time than the actually allowed for 3 months. Another possibility to reduce the sealing time would be the entering of the sealed area and direct attack of the fire behind a curtain of CO_2.

2. Fire No. 2[171]

This fire was started by the ignition of methane at the face of an entry 95 ft inby the last open cross cut, and was immediately noticed by the continuous miner and loading machine operators. Water and the contents of a 150 lb dry chemical extinguisher were applied without success. Several other fire extinguishers and a playpipe, which could be procured from the neighborhood, did not operate effectively or had little effect on the fire. Forty-five minutes after the fire had started, attempts to fight it directly had to be abandoned and a short time later management decided to seal the whole main section with 8 temporary seals across the main entries in a distance of approximately 2000 ft from the fire. The seals were completed 7 hours, 20 minutes after the fire had started. Gas samples taken three days later showed a non-explosive atmosphere with an average oxygen concentration of 7.3%.

Likely Course of Fire if Inert Gas Had Been Used

The section where the fire occurred consisted of 5 entries driven approximately 1000 ft off the main entries. It was ventilated by two splits with a total of 62,400 ft^3/min. The average CH_4 concentration was 0.5%, which indicates a methane liberation of 156 ft^3/min. To fully inert this quantity, with an additional safety factor of 2 being applied, approximately 1900 ft^3/min N_2, or

1000 ft^3/min CO_2, or 1600 ft^3/min of a 79/21 N_2/CO_2 mixture would be needed. Although it is technically feasible to provide these flow rates from gas cylinders (chapter V), bulk liquid nitrogen, evaporated at the surface and piped to the fire site, would probably be the better choice. If a portable inert gas generator for underground use would be available, its use would even be a better solution.

Piping 1900 ft^3/min without excessive pressure losses requires pipe diameters, which are usually provided by compressed air lines but not by all water lines. The pressure loss in an isothermal flow is given by

$$p_1 - p_2 = f \frac{L}{D} \frac{\rho 2}{2} \overline{V}_2^2 \frac{2 p_2}{p_1 + p_2}$$

where p_1; p_2 = pressures at beginning and end of pipeline
f = coefficient of friction
L = pipe line length
D = pipe line diameter
ρ_2 = density of gas at end of pipe line
$\overline{V}_2$ = flow velocity at end of pipe line

With a pressure of 80 psig, and under the assumption of a coefficient of friction of 0.04, one could transport 1,900 ft^3/min over a length of 2,200 ft in a 4 inch diameter pipeline and over 16,800 ft in a 6 inch pipeline.

If the available pipelines turn out to be too small, one can use ventilation ducting, which can be installed in a very short time since for the small flow rates no great care in the installation is required.

If it is possible to keep the atmosphere in the fire zone non-explosive at all times, the seals can be erected closer to the fire. In the case under consideration, a good site could be approximately 600 ft from the face, which reduces the number of seals to 5 and the sealed volume to 180,000 ft^3. The necessary air quantity to dilute the liberated methane to 2.5% is 6,100 ft^3/min. Once the nitrogen injection has started at the rate of 1,900 ft^3/min, the air flow can be reduced to 4,200 ft^3/min. With cross-sectional areas of 91 ft^2 and 2 parallel airways, it takes the air - nitrogen mixture 36 minutes to travel through the area prepared for sealing, after which time the average oxygen concentration in the area is approximately 14.3%.

This is still too high for closing the seals, so the nitrogen injection alone has to be continued. A quantity equal to the volume prepared for sealing should be injected, which at a rate of 1,900 ft^3/min would take another 95 minutes. This would lower the oxygen concentration to 0% if no mixing occurred, to 4.8% if perfect mixing took place, but the probable oxygen concentration will be around 3%.

With the comparatively low cost of nitrogen, one would most probably go on injecting it until 2% O_2 is reached, which would be the case after an additional 77 minutes. Then, 2 1/2 to 3 1/2 hours after the inert gas injection began and 10 - 11 hours after the start of the fire, the seals can be closed and a cooling period of 7 to 10 days has to be allowed for.

In this particular case, again pressure balancing of the seals to avoid leakage is possible. Leakage caused by barometric pressure changes with amplitudes of 10 in. wg. and cycle times of 6000 minutes will occur with maximal flow rates of 4.7 ft^3/min and average flow rates of 1.5 ft^3/min. To replace this leakage an additional 21,600 ft^3 nitrogen is necessary during a sealing time of 10 days. The total nitrogen consumption in the course of fighting the fire will therefore be 295,000 - 417,000 ft^3, or approximately 21,100 - 29,800 lbs.

3. Fire No. 3[173]

The fire occurred in a rectifier room located between Nos. 3 and 4 entries in a set of 8 entries. Entries Nos. 4 - 6 serve as intake airways, the other entries as return airways. After attempts to extinguish the fire with dry chemicals and water, a foam generator was installed, the necessary foam control stoppings were erected and ventilation adjustments were made to work, which was completed 4 1/2 hours after the detection of the fire. Operation of the foam generator was however, impeded during the next 8 hours and 20 minutes by the efforts to rescue two miners trapped inby the fire. When full scale operation of the foam generator had been started, the electrical power of the mine failed 5 hours later and fire fighting was interrupted for another 17 1/2 hours. A second foam generator was installed and foaming was continued; but after several days of foaming and trying to gain entry to the fire, and in view of the great bulk of burning material to be loaded, the direct approach was abandoned.

While foaming was continued, seals were erected and closed 5 days and 19 hours after the fire had been detected. This first sealed area was approximately 550 ft long and 250 ft wide, required 21 seals and had a volume of 290,000 ft^3. Four days later the oxygen content of the sealed atmosphere had dropped to approximately 4% and coal production was resumed.

42 hours later the oxygen content had, however, again increased to dangerous levels and the mine had to be evacuated. A much larger area was then selected for sealing and 34 new seals were completed 2 days later. Since the gas samples obtained through these seals were too erratic to judge the state of the sealed atmosphere, due to the large area sealed, a 3 inch borehole was drilled from the surface into the fire area. It was completed 32 days after the start of the fire and with the oxygen concentration down to 1.6%, work in the mine was permitted two days later.

Likely Course of Fire if Inert Gas Had Been Used

If the use of inert gas had been decided upon, it is highly probable that it would not have been applied before the power failure occurred because the seals would not have been ready. Using inert gas while men are trapped in a fire is out of the question due to its own CO content or the increased CO production of the fire. It is hard to predict how much sooner the seals could have been completed if all efforts had been concentrated on their erection, but 2 shifts after the power failure or a total of 50 hours after the start of the fire should have been a sufficient time span.

No observations on the CH_4 liberation of the area prepared for sealing have been reported. Since this area is older, a figure of 100 ft^3/min seems to be on the safe side. To fully inert this quantity, with the additional use of a safety factor of 2, an inert gas flow rate of 1,200 ft^3/min N_2, or 640 ft^3/min CO_2, or 1,014 ft^3/min of a 79/21 N_2/CO_2 mixture is needed. These flow rates are still small enough for the use of bottled gas but the size of the volume to be filled with inert gas to extinguish the fire makes bottled gas a rather expensive solution.

To dilute 100 ft^3/min CH_4 with air to a concentration of 2.5% requires an airflow of approximately 4,000 ft^3/min. When 640 ft^3/min of CO_2 or 1,200 ft^3/min N_2 are mixed with the air, the total flow rate should remain approximately the same. Since there are 3 parallel entries with a cross-sectional area of 100 ft^2 each and a sealed length of 550 ft, it will take approximately 14 minutes

until the area is filled with the mixture. This should lower the average oxygen concentration to 17.4% for the CO_2 and 14.5% for the N_2 injection. After the airflow has been cut off and an inert gas volume of 290,000 ft^3, equal to the volume of the area prepared for sealing, has been injected (453 minutes for CO_2, 242 minutes for N_2) the oxygen concentration will have dropped to a probable value of 3.0%. The seals can then be closed without the possibility of an explosive atmosphere forming.

The reason for sealing a second larger area was that the air leakage through the first sealed area was too large to maintain a sufficiently low oxygen concentration. This leakage was explained by poor seals caused by heaving ground but the calculation of air leakage and Fig. 28 show that even with good seals (R = 0.1 in. wg./cfm) it would have been impossible to maintain an oxygen concentration of 2%, if the ventilating pressures between the intake and return entries, between which the sealed area is located, exceeds 0.5 in. wg. Pressure balancing of the seals would most probably have reduced the leakage considerably.

In using inert gas one would have run into the same difficulties with the air leakage. To prevent this leakage would have required to continue the inert gas injection during the whole sealing time of 30 to 40 days at a rate equal to the flow rate of the leakage. This task could perhaps have been made more economical by using a borehole from the surface, which in the case of the actual fire was later drilled also to take reliable samples. A mobile inert gas generator could then have provided the gas.

Summarized: in the case of this fire the probable advantages of using inert gas are not as conspicuous as in the preceding two cases, described above. They may lie in the fact that sealing of a second larger area could have been avoided. Poor seals due to heaving floors because of extended foam application would perhaps not have occurred, air leakage could have been kept out of the sealed area by inert gas injection.

4. Fire No. 4[170]

This fire started at the bottom of a power borehole in an intake entry of a main heading at 6:15 p.m., April 27, 1965. Due to the power failure it caused, it was immediately

detected and fought with water and rock dust. From 8:00 p.m. on, additional water at the rate of 600 gal/min was pumped from the surface into the borehole, which helped to keep the fire confined, while ventilation adjustments were made, foam control stoppings were erected and a foam generator was installed. By 10:20 p.m. the generator was started. On April 29 the fire was considered to be sufficiently cooled and preparations for loading out the hot material were made, which started April 30. Application of foam and water continued. During transport the hot material was covered with rock dust. The recovery operations were concluded May 5, nine days after the fire started and the Withdrawal Order for the mine was annulled on May 6.

In the case of this fire, the use of inert gases would not have offered any special advantages since direct fighting of the fire was possible, which is always the fastest way to extinguish a fire.

5. Fire No. 5[174]

A continuous miner, while being trammed along a trolley track in main heading, short-circuited the trolley power and started a fire at 10:50 p.m., October 16, 1965. To prevent smoke from entering the inby sections, where 7 men were working, the main ventilating fan was stopped, and the fire fought directly with fire extinguishers and rock dust. No attempt was made to short-circuit the contaminated air to the return. About 1 a.m., October 17, the fan was restarted since backing of smoke impeded the fire fighting. Subsequently an explosion of the combustion products, travelling back over the fire occurred which destroyed several stoppings and overcasts. It took until 6:30 a.m., October 18, to reestablish the ventilation of the main heading and find the bodies of the entrapped miners. The fire was then fought directly with water and loading out of the hot material started about 7:10 p.m., October 21. It was completed on November 13, 27 days after the fire had started.

In this case the use of inert gases would not have offered any special advantages also. As long as men are entrapped, it increases the danger of poisoning them and when direct fire fighting is possible, it is to be preferred.

B. Summary of Advantages and Disadvantages

Inert gas methods will not be able to match direct fire fighting methods in effectiveness and economy. Their

ability to cool fires is limited and the needed gas quantities to lower the oxygen concentrations of the atmosphere sufficiently over the required cooling periods are prohibitively large, unless the fire is sealed or the inert gas is recirculated. Inert gas methods will therefore find their main application when a direct attack of the fire is no longer possible. They can permit the fast and close sealing of fire zones without danger of explosions, the fast buildup and maintenance of fire extinguishing atmospheres in the sealed area and the possible reduction of cooling times with a recirculated, cooled inert atmosphere. Inert gases can support the direct attack on the fire also by providing a nonexplosive atmosphere and clearing the fire site of smoke without fanning the fire.

Inert gases will, in many cases, be able to fulfill similar functions as high expansion foams. It has been discussed in chapter II that of the conventional fire fighting methods only large quantities of water, large quantities of high expansion (air) foam or sealing can extinguish mine fires once they are beyond their incipient stages. High expansion foam has become the "all important back up fire fighter"[72] when the fire has spread beyond the limited range of water hoses or can't be approached due to bad roof conditions or smoke. Like inert gases, it prevents air from reaching the fire and reduces the oxygen content of the atmosphere with the produced steam. It can be generated in considerable distances from the fire and still be effective, and can be used to support the direct attack on the fire. A description of advantages and disadvantages of the inert gas method will to a large extent, therefore, be a comparison with the high expansion foam method.

The basic advantage, which the use of inert gases can offer, is the prevention of explosive atmospheres at any stage of the fire fighting operations, when the available inert gas quantities are large enough. Although dangers from foam produced water gas or insufficiently diluted methane or distillation products can be prevented by proper operation of the foam generator and adequate ventilation measures,[73] the fire fighting skills to avoid this hazard when using high expansion foam are more demanding than with the comparatively simple inert gas method.

The same applies to the driving of inert gases or foam over the fire. Except for economics, there is no distance limitation for inert gases. Blocking of their flow by roof fall will be negligible. Except for the initial adsorption of carbon dioxide to coal, nothing similar to the disintegration of foam will occur.

If sealing cannot be avoided, inert gases can make it considerably more effective. The reasons have been stated at the beginning of this chapter. There will, however, be many cases where high expansion foam, due to its considerably higher cooling effect, allows the extinction of fires without sealing, whereas the inert gas method depends for success on it.

Another advantage of inert gases can be the cleanliness of their application and the avoiding of weakened roof and soft floors due to water or foam application.

The main handicap of the inert gas methods has in the past always been the limited availability of large inert gas quantities. This handicap can, however, be overcome by the use of bulk liquefied nitrogen, which may be delivered by tankers from strategically located depots, or by the use of large capacity mobile or portable inert gas generators. Both methods are routinely used in the USSR, where delivery rates of 2,800 - 3,500 ft^3/min with tankers and 12,000 ft^3/min with inert gas generators are reached.

Bulk supplies of liquefied nitrogen, tankers, and evaporators are commercially available. Mobile inert gas generators are either commercially available or prototypes have been built by research institutes (see chapter X). The disadvantage of bulk liquefied nitrogen is, apart from its price, that it has to be evaporated at the surface and piped from there into the fire zone. Equally the existing mobile inert gas generators have been developed for surface use and the produced gas would have to be piped underground also. The portable generator GIG 4, which has been developed in the USSR for underground use, weighs 2,000 lbs and costs approximately $30,000.[17] Due to the nature of inert gas and foam producing processes, inert gas generators will always be considerably bulkier, heavier, and costlier than foam generators.

There is no justification to expect the inert gas methods to become the standard methods for fighting mine fires. There is however reason to expect their wider use when sealing operations can cause explosion dangers.

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