Fire Prevention and Health Assessment in Hypoxic Environment

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Abstract
The main objective is to investigate if hypoxic environment is a viable fire prevention method in occupied enclosures. Hypoxic environment is a technique where the oxygen concentration is constantly reduced inside an enclosure. The purpose with the technique is to prevent fires and in case of a fire reduce the risk for fire spreading. The risks are studied and different reduced oxygen concentrations have been analysed. Suitable objects and activities are discussed which illustrate the issues and complications. The conclusions made in this study are possible to use as help when designing a hypoxic environment.

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Summary

Hypoxic environment is a technique where the oxygen concentration is constantly reduced inside an enclosure. The purpose with the technique is to prevent fires and in case of a fire reduce the risk for fire spreading. Reduced oxygen concentration will result in less oxygen and more nitrogen for a fire but also less oxygen for respiration. There are many advantages with reduced oxygen concentration in an enclosure, but the risks of the technique need to be investigated, especially when people are occupied in the enclosure.

The main objective is to investigate if hypoxic environment is a viable fire prevention method in occupied enclosures. The objective is also to investigate the risks when using hypoxic environment as a fire prevention method and analyse what environments are best suited for its use.

Four important areas are studied; fire behaviour, health effects, safety management and safety risks. By reducing the oxygen concentration, the probability of ignition and combustion are reduced or even eliminated. Oxygen concentration is however not the only parameter that prevents a fire. Different materials, parameters and experiments are analysed and discussed to understand the fire behaviour in hypoxic environment. Reduced oxygen concentration will result in health risks for humans. The individual differences between humans are considerable and people will suffer from symptoms at different concentrations. The symptoms are both dependent on the oxygen concentration and on the exposure time. Probability relations studied in the report illustrate the probability of a fire and the probability of detrimental effects to health. This gives basic knowledge for the evaluation of the combined risk between them.

Safety management is very important in hypoxic environment and is therefore necessary to discuss. If fire prevention should work as optimal as possible it can be necessary to forbid entrance for certain fuels, minimise ignition sources etc. Safety risks are studied and analysed to understand the importance of a safe and reliable technique.

The creation of scenarios has made it possible to understand the issues and the possibilities with hypoxic environment. Suitable objects and activities have been treated to understand what type of enclosures and occupants the environment is suitable for. A model of the suitability is developed which will ease the decision and illustrate the complexity of the suitability.

Hypoxic environment is a unique method where the purpose is to prevent fires. The theory about hypoxic environment is simple but the application of the technique is connected with risks that should be minimised. Hypoxic environment is not suited for all applications, but appears to be a good fire prevention method for certain applications. The most difficult judgement is when humans are suffering from different symptoms. Hypoxic environment have possibilities for unoccupied enclosures. No considerations are required for health aspects and therefore any oxygen concentration could be chosen. The oxygen concentration should be chosen so that ignition is unlikely. A public enclosure is a space where the health status of the occupants is unknown. Because it is impossible to control people's health status in these spaces it is not feasible to reduce the oxygen concentration enough for prevention of fires. Hypoxic environment is also possible for non-public enclosures if certain restrictions are followed regarding the health aspects of the occupants.

One big problem with hypoxic environment is when a fire actually occurs inside the enclosure. A fire is still possible, even if the probability of a fire is reduced considerably. This highlights the need of a highly sensitive detection system, fire extinguishers and other fire safety equipment. The designed oxygen concentration should be chosen as a compromise between health risks and fire risks. A priority between the two risks must be made. The conclusions are summarised by saying that decreased fire risks can be bought at the expense of increased health risks.

Sammanfattning

Hypoxic environment är en teknik där syrekoncentrationen konstant är reducerad i ett utrymme. Syftet med tekniken är att förebygga bränder och om brand skulle uppstå reducera risken för brandspridning. Reducerad syrekoncentration innebär att mindre syre och mer kväve finns tillgängligt för en brand, men också mindre syre för att andas. Det finns många fördelar med reducerad syrekoncentration i ett utrymme, men riskerna med tekniken måste undersökas, speciellt när människor vistas i utrymmet.

Det huvudsakliga syftet är att undersöka om konstant reducerad syrekoncentration är en genomförbar brandförebyggande metod i utrymmen där människor vistas. Syftet är också att undersöka vilka risker som finns med tekniken och vilka utrymmen som är bäst lämpade för denna teknik.

Fyra viktiga områden studeras; brands beteende, hälsoeffekter, management och säkerhetsrisker. Genom att reducera syrekoncentrationen så kommer sannolikheten för antändning och förbränning att minskas eller till och med att elimineras. Syrekoncentrationen är dock inte den enda parameter som förebygger brands uppkomst. Olika material, parametrar och experiment analyseras och diskuteras för att öka förståelsen för brands beteende i reducerad syrekoncentration. En lägre syrekoncentration kommer att innebära hälsorisker för människor. Dom individuella skillnaderna är betydande och människor drabbas av symtom vid olika syrekoncentrationer. Symtomen är både beroende på syrekoncentrationen och på exponeringstiden. Sannolikhetssamband studeras i rapporten, vilket illustrerar sannolikheten för brands uppkomst och sannolikheten för negativa effekter på hälsan. Detta ger grundläggande kunskaper som kan användas när den sammanvägda risken mellan brand och hälsa ska bedömas.

Management är väldigt viktigt i ett utrymme med reducerad syrekoncentration och därför är det nödvändigt att detta diskuteras. Om reducerad syrekoncentration ska fungera så optimalt som möjligt så kan det vara nödvändigt att förbjuda inträde av vissa brännbara ämnen, minimera antändningskällor etc. Säkerhetsrisker studeras och analyseras för att förstå vikten av en säker och tillförlitlig teknik.

Scenarios har skapats och analyserats, vilket har gjort det möjligt att förstå problemen och möjligheterna med reducerad syrekoncentration i ett utrymme. Olika objekt och verksamheter behandlas för att förstå vilka utrymmen och populationer som kan är vara lämpliga för reducerad syrekoncentration. En lämplighetsmodell har utvecklats som ska underlätta beslutet och illustrera komplexiteten av lämpligheten hos olika objekt.

Reducerad syrekoncentration i ett utrymme är en unik metod, där syftet är att förebygga bränder. Teorin bakom reducerad syrekoncentration är enkel men användningen av tekniken är förknippad med risker, som bör minimeras. Reducerad syrekoncentration är inte lämpad för alla användningsområden, men verkar vara en bra brandförebyggande åtgärd för vissa tillämpningar. Den svåraste bedömningen är att veta när människor drabbas av olika symtom. Reducerad syrekoncentration är möjlig i obemannade utrymmen och där kan syrekoncentrationen väljas utan hänsyn till hälsan. Syrekoncentrationen bör dock väljas så att sannolikheten för antändning blir minimal. Ett publikt utrymme är en plats där hälsostatusen hos individerna är okänd. Eftersom det är omöjligt att kontrollera människors hälsa i dessa utrymmen, så är det inte möjligt att reducera syrekoncentrationen tillräckligt mycket för att förebygga bränder. Reducerad syrekoncentration är också möjlig för icke-publika utrymmen om vissa restriktioner följs med hänsyn till hälsoaspekterna.

Ett stort problem med reducerad syrekoncentration är när en brand faktiskt uppstår i utrymmet. En brand är fortfarande möjlig, även om sannolikheten för en brand är avsevärt reducerad. Detta framhäver behovet av ett detektionssystem med hög känslighet samt brandsläckare och annan brandsäkerhetsutrustning. Den designade syrekoncentrationen bör väljas som en kompromiss mellan brandrisk och hälsorisk. Slutsatserna kan sammanfattas genom att säga att minskade brandrisker kan köpas på bekostnad av ökade hälsorisker.

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1 Introduction

1.1 Background

Human casualties in fires are not acceptable and if they are prevented lives could be saved. The values of today's property are increasing and the complexity of buildings and the sensitive equipment they contain require higher levels of fire protection. Water, foam and dry chemical powder are effective in fire extinguishment but the damage from their use can be irreplaceable. Chemical manufactures and fire equipment suppliers try to develop gaseous agents that are effective, clean and of low toxicity. Halon and other competitive gaseous agents exist, but improvements are desired. Halon is effective, but is banned today because of its ozone depletion potential.

A clean gaseous agent that actually prevents fires is desirable. The risk to human occupants will decrease considerable if a fire never starts. One possible solution is hypoxic environment, where the oxygen concentration is constantly reduced in order to prevent fires. There are many advantages with reduced oxygen concentration in an enclosure, but the risks of the technique need to be investigated, especially when people are occupied in the enclosure.

1.2 Objective

The objective is to investigate the risks when using hypoxic environment as a fire prevention method and analyse what environments are best suited for its use. What risks regarding fire, health, safety and safety management exist and how could those be minimised? The main objective is to investigate if hypoxic environment is a viable fire prevention method in occupied enclosures. What are the issues? Which is the appropriate design concentration for different applications? Existing knowledge in this area are fundamental for our discussions, conclusions and evaluations. Conclusions are meant to be used as a basic structure for possible objects in future projects.

1.3 Method and disposition

The strategy of the report is presented in figure 1.1 and explained in the following text.

To reach the objective we need to identify, investigate and describe different aspects and issues that are important when using reduced oxygen concentration. First of all the subject is introduced and the theory about using reduced oxygen concentration is explained. Four important areas have been studied and these are the most important to reach the objective. There are connections between them which are illustrated with arrows. A literature review has been done to find the most relevant information in these areas.

- **Fire behaviour**. How is a fire developed at reduced oxygen concentration? External radiation, ignition, temperature and humidity are example of parameters that are discussed in the report. Different materials are important to discuss and research and experiments are necessary to study.

- **Health effects.** What kinds of health effects are related to reduced oxygen concentration and how are human behaviour and functions affected? Are there any differences between individuals? Many parameters affect the health, but which ones are the most significant? Are there any synergic effects?

- **Safety management**. From our point of view, a well working management is treated from policy, routines and instructions. How important is safety management and how should this be treated for a hypoxic environment? Maybe a well designed environment without safety management will be sufficient. A short outline of present regulations and standards that could affect the design of a hypoxic environment will be discussed.

- **Safety risks**. Which aspects are important when designing a reliable system? Is it for example necessary with a backup system?

The technical part of the environment is studied to understand the process to reduce the oxygen concentration. How is a reduced concentration generated, monitored and controlled? How important are integrity of enclosures and smoke detection system? A site visit of a present installation has provided additional input and solutions used in reality.

Probability relations from fire behaviour and health effects give basic knowledge for the evaluation of the combined risk between them. Different parameters are discussed and analysed.

Conclusions from probability relations and the four areas above will make it possible to study different scenarios. Moreover, it is very important to know when the hypoxic environment is possible to use. The creation of scenarios will make it possible to understand the issues and the possibilities with hypoxic environment.

Suitable objects and activities will be treated to understand what type of environments and occupants the environment is suitable for. Important issues will be discussed regarding the environment, for example technical and practical problems with the technique. A model of the suitability is developed which will ease the decision and illustrate the complexity of the suitability. Economic aspects will briefly be discussed.

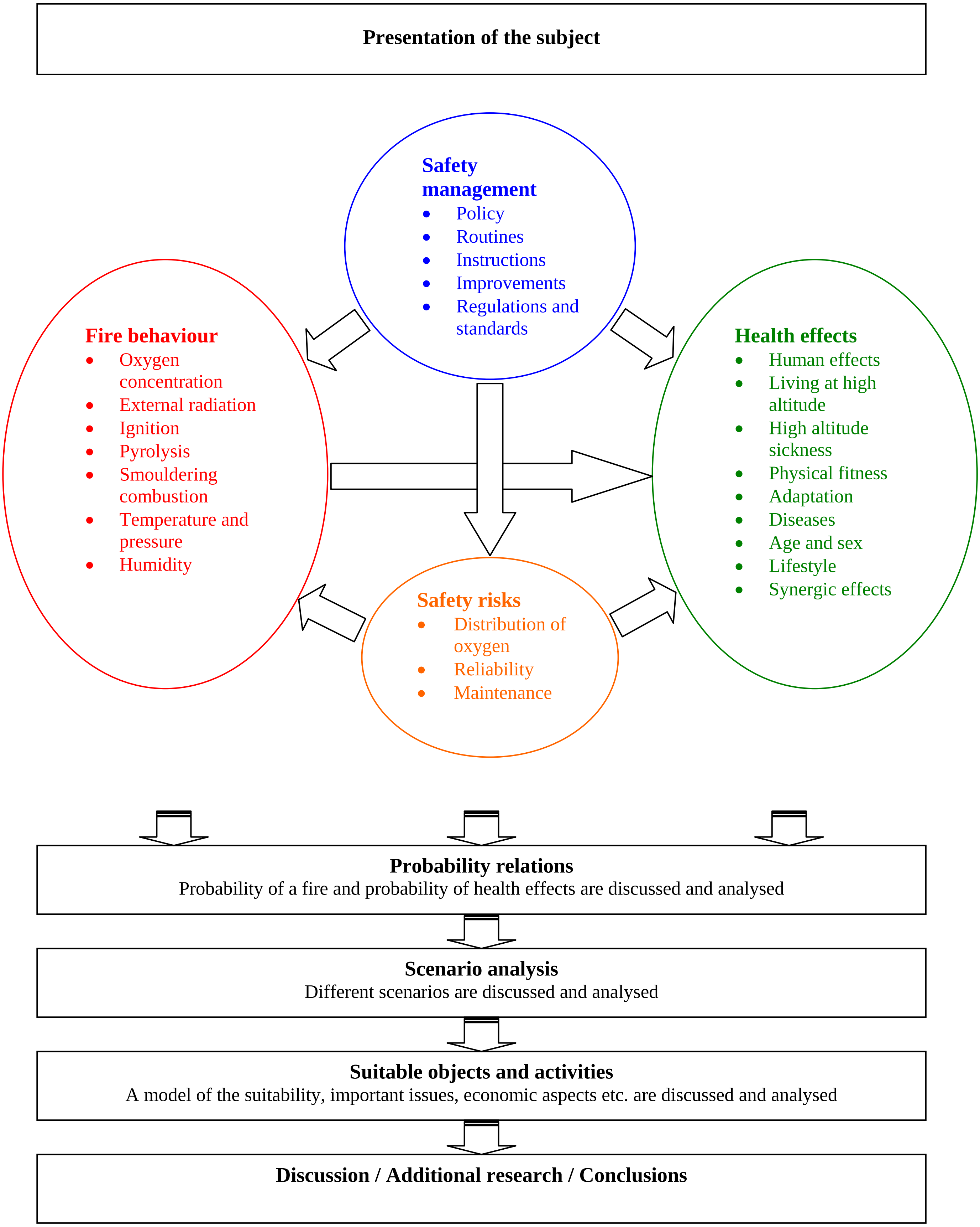

Figure 1.1. Strategy and approach to the subject.

1.4 Target group

This report is mainly written for people with academic education such as fire safety engineers. Our hope is that approving agencies, local councils and building owners also will get a brief understanding of the subject.

1.5 Limitations

This report only addresses the risk considerations of a completely installed hypoxic environment. This information would hopefully provide the designer with sufficient information to base the suitability of use of such an environment. It does not address the risk related to the individual components of a hypoxic environment. This information is highly case specific and an analysis should be undertaken.

This report only draws a general view of the subject and analyses are only performed briefly. Instead this report gives a comprehensive understanding of the subject. The analysis and the model made in this report shall be regarded as illustrations of complex issues. Changes in the parameter of the analysis and the model may give a different result.

2 Nomenclature

Adiabatic flame temperature	Theoretical temperature for a flame at the stoichiometric fuel limit. No exchange of heat with the surroundings is present.
Air sampling detection system	Highly sensitive smoke detection system
AIT (Auto ignition temperature)	The lowest temperature where a mixture of vapour or gas and air self ignites [26].
AMS (Acute mountain sickness)	Illness due to insufficient oxygen in tissues (normally caused by high altitude). See chapter 5.6.
Asphyxiant	An asphyxiant is a substance that can cause unconsciousness or death by suffocation.
Burning	Controlled combustion
Combustion	A chemical chain reaction, where an initial heat source contributes enough energy to warm up fuel and in combination with oxygen (ignites) continues to react.
Cup burner	Small scale method that measures extinguishing values, see appendix E.
Edema	Accumulation of considerable amount of water in cells, tissues or body cavities. If accumulated in lungs it seriously decreases gas exchange in lungs and can be fatal.
Equivalent oxygen concentration at sea level	The oxygen concentration (vol%) at sea level for which the partial pressure of oxygen matches the ambient partial pressure at a given altitude
Fire	Uncontrolled combustion
Fire prevention	Prevention of the origin of a fire.
Fire suppression	Extinguishment of a fire.
Haemoglobin	The protein that carries oxygen inside red blood cells.
Hyperventilation	Increased respiratory volume (RMV) in response to e.g. hypoxia, exercise, heat or increased CO_2.
Hypobaric	The air pressure is lower than at sea level.
Hypoxia	A reduction in the amount of oxygen available for tissue respiration.
Hypoxic	The partial pressure of oxygen is lower than at sea level.
Hypoxic environment	Constant reduced oxygen concentration in order to prevent fires in an enclosure where a stable atmosphere can be maintained.

Ignition	The onset or initiation of combustion.
Inerting concentration	Small scale method that measures extinguishing values, see appendix F.
LC50	The amount of a substance that causes a certain effect on 50 percent of the exposed population.
LFL (Lower flammability limit)	The lowest ratio of fuel in a fuel and oxidiser mixture that can be ignited and lead to propagation [26], see appendix F.
LOAEL (Lowest observable adverse affect level)	The highest concentration of a substance (lowest oxygen concentration) at which an adverse physiological or toxicological effect has been observed.
LOI (Limiting Oxygen Index)	Small scale method that measures extinguishing values, see appendix D.
MIE (Minimum ignition energy)	The energy required to ignite flammable mixtures or materials.
NOAEL (No observed adverse affect level)	The highest concentration of a substance (lowest oxygen concentration) at which no adverse toxicological or physiological or toxicological effect has been observed.
Normobaric	The air pressure corresponds to the pressure at sea level.
Normoxic	The partial pressure of oxygen corresponds to the pressure at sea level.
ODP (Ozone depletion potential)	Potential to damage the ozone layer in the atmosphere.
Oxygen saturation / Haemoglobin saturation	The capacity to carry oxygen in the blood.
Partial pressure	The pressure exerted by a single component. This pressure is equal to the pressure it would exert if it occupied the same volume alone at the same temperature.
Pilot flame	A form of ignition source existing of a small flame.
Psychomotor	Psychomotor skills are required to perform behavioural tasks involving a series of coordinated movements of the type required to escape from a fire in a compartment (such as a building).
Pulmonary edema	If the accumulated fluid exudes out of from blood vessels as a result of inflammation or insufficient circulatory. The lung tissues can be swollen and accumulated with water. *See also edema.*

Pyrolysis / Pyrolyzing	Chemical degradation due to heat. Some chemists define pyrolysis as degradation due to the action of heat in the absence of oxygen. However, in fire science the definition is used for degradation due to action of heat in any atmosphere (including the one with oxygen) [16].
Retina	The light-sensitive inner lining of the back of the eyeball.
Risk owner	Responsible person for the object or activity, where the risk is present.
RMV (Respiratory minute volume)	The volume of air breathed per minute (litres/minute).
Synergic	The interactions between different substances. The total effect of two substances could for example be more or less strong than the product from the individually effects.
Toxicity	The nature and extent of adverse effects of a substance upon a living organism.
Visual dark adaptation	The ability for the eyes to increase its sensitivity to light.

3 Presentation of the subject

Hypoxic environment is a technique where the oxygen concentration is constantly reduced inside an enclosure. The purpose with the technique is to prevent fires and in case of a fire reduce the risk for fire spreading. This technique is working day and night by changing the normal proportion of oxygen/nitrogen in the air. Reduced oxygen concentration will result in less oxygen and more nitrogen for a fire but also less oxygen for respiration.

3.1 Fire prevention and health effects

The theory about using hypoxic environment as fire prevention is simple. The hypoxic environment where the oxygen concentration is reduced is unlikely to support ignition and combustion, but may still be sufficient for human respiration. Hypoxic air is further explained in this chapter. The fire is influenced by the proportion of oxygen, when on the other hand a human is dependent on the partial pressure of oxygen. This will be discussed in more detail further on in the report.

The issues with this fire prevention method can be described in figure 3.1. The area where there is a probability for both fire and health effects is the one of interest. This area shows clearly that there is a risk that needs to be investigated. The interactions between fire and health are complex and the size and shape of the area is uncertain. There are of course big differences between materials and humans which are associated with uncertainties.

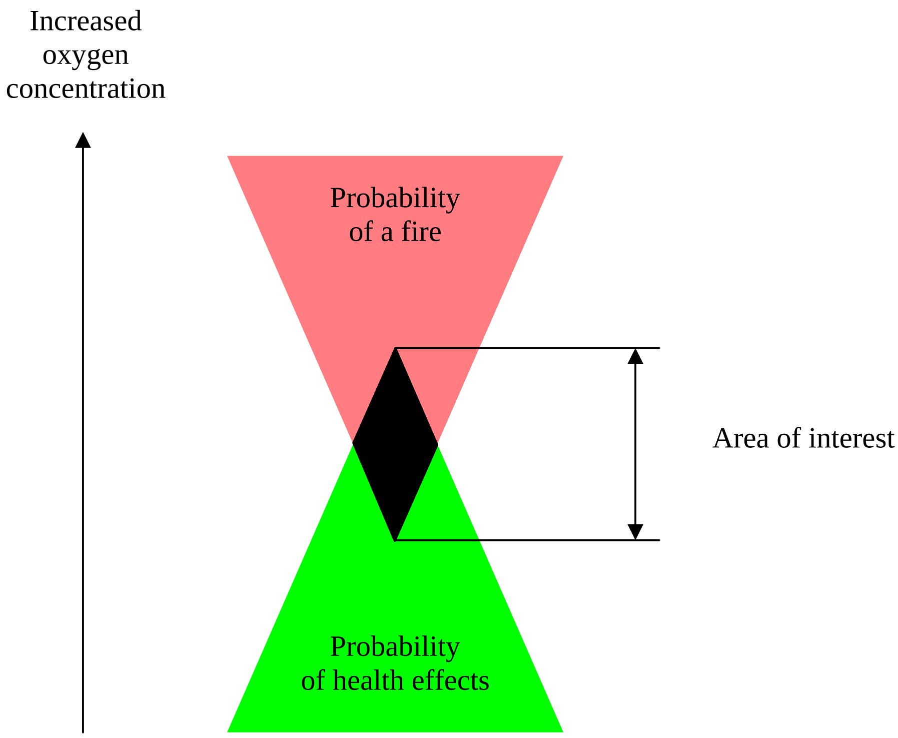

Figure 3.1 Description of the probability of a fire and the probability of health effects.

The processes of combustion and ignition in oxygen reduced air are far different from the processes that occur in the natural environment with 21 vol% oxygen. A candle for example, can easily burn at sea level or high altitudes, but will not burn in a hypoxic environment of 16 vol% oxygen. The method where the oxygen concentration is rapidly lowered in a room by introducing an inert gas has been used for a long time for fire suppression and has proven to be effective.

Reduced oxygen concentration can be used in enclosures for fire prevention purpose where a stable atmosphere can be maintained. Today the method is for example used in fuel tanks in aircraft to decrease the risk of explosions. Existing applications with occupants are for example submarines, computer rooms and warehouses.

3.2 Normobaric air

Normobaric means that the air pressure is normal.

Dry air in natural environment is made up of 20.9 vol% oxygen, 78.1 vol% nitrogen and 1.0 vol% other gases (mainly argon and carbon dioxide) [1], see figure 3.2. This is independent of the altitude, which means that the natural ratio is the same at sea level and at high altitude.

Normobaric air is present naturally at sea level, where the air pressure normally is 101.3 kPa. The partial pressure of oxygen is normally 21.2 kPa at sea level. The air pressure is lower at high altitude, which means that the amount of oxygen or the partial pressure of oxygen is less. The proportion of oxygen is however the same, 20.9 vol%.

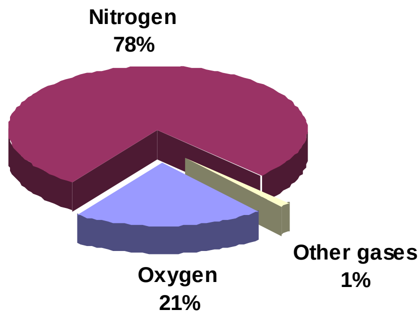

Figure 3.2 Dry air in natural environment. This is the case at sea level and at high altitude.

3.3 Hypobaric air

Hypobaric means that the air pressure is lower than normal.

Hypobaric air is present at high altitude. When you for example climb up to 4000 metres, the oxygen concentration is still 20.9 vol%, but the oxygen partial pressure is only 12.9 kPa, which is equivalent to an oxygen concentration of only 12.7 vol% at sea level. Figure 3.3 shows equivalent oxygen concentrations at sea level for different altitudes. When you fly a commercial aircraft the air pressure in the cabin is usually equivalent to 1520-2440 metres [2], which corresponds to 17.4-15.5 vol% oxygen at sea level.

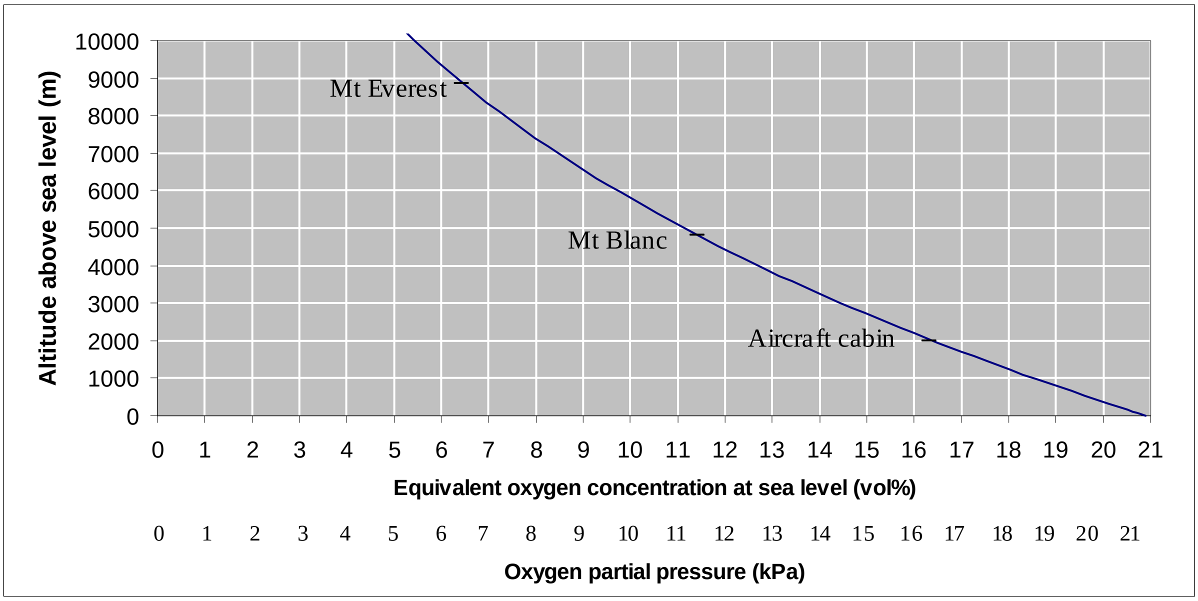

Figure 3.3 Equivalent oxygen concentrations at sea level for different altitudes [3].

3.4 Normoxic air

Normoxic means that partial pressure of oxygen is normal, 21.2 kPa. This is the case for the air at sea level, where the oxygen concentration for dry air is 20.9 vol%.

3.5 Hypoxic air and hypoxia

Hypoxic means that partial pressure of oxygen is lower than normal, <21.2 kPa.

Figure 3.4 shows the difference between normobaric, hypobaric, normoxic and hypoxic air. The process to go from 1-3 in figure 3.4 is described below. Note that the proportions in the figure are only valid for dry air.

(1) Normobaric normoxic air is present at sea level.
(2) Hypobaric hypoxic air has the same fraction of oxygen/nitrogen as in (1) but the pressure is reduced. The partial pressure of oxygen is therefore reduced.
(3) Normobaric hypoxic air has the same pressure as in (1), but the partial pressure of oxygen is the same as in (2). As shown in figure, the oxygen partial pressure is the same for hypobaric normoxic air at 2700 metres as for normobaric hypoxic air with 15 vol% oxygen.

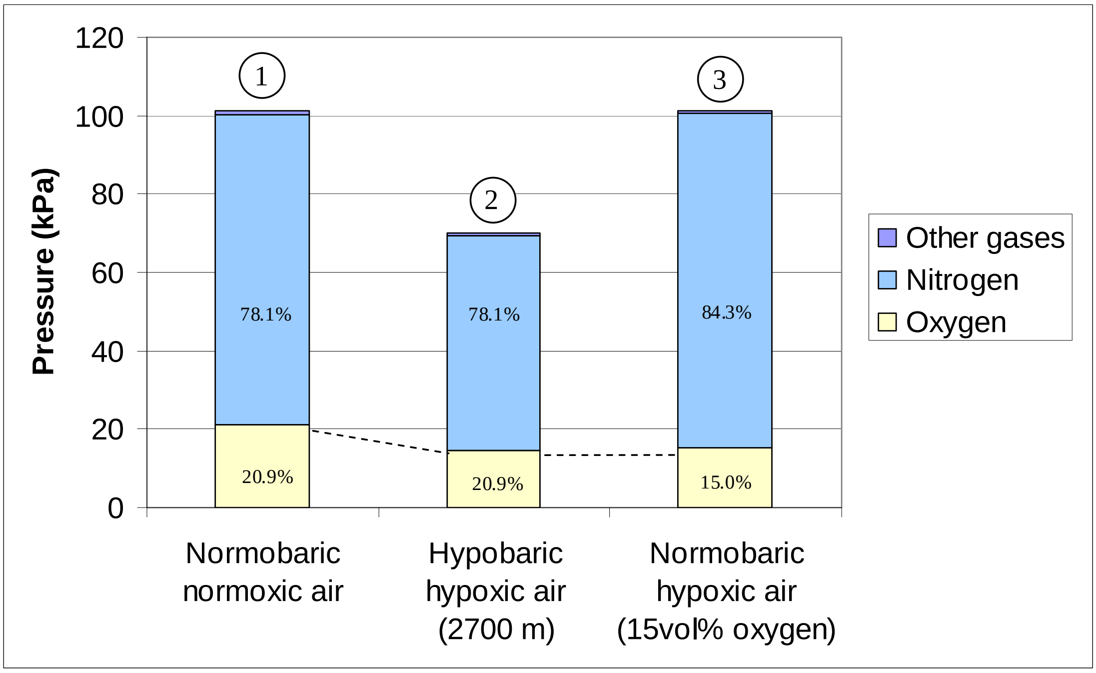

Figure 3.4 Comparison between normobaric normoxic air, hypobaric hypoxic air and normobaric hypoxic air.

When the human body is exposed to hypoxic air, less oxygen is carried in the human blood. This phenomenon is named hypoxia and limits the ability to transport oxygen. The effects of reduced oxygen concentration on health are discussed in chapter 5.

3.6 Humidity

Humidity is the water vapour present in the air. This is often expressed in relative humidity, which can be expressed as:

$$\text{Relative humidity} = \frac{\text{Vapour pressure of the air}}{\text{Saturation pressure of the air at the actual temperature}}$$

Water vapour will reduce the oxygen concentration in the air. This phenomenon could be explained by the partial pressure of water vapour. As showed in figure 3.5, dry air and humidified air have the same total pressure, but the partial pressure is reduced for oxygen and nitrogen when water vapour is present.

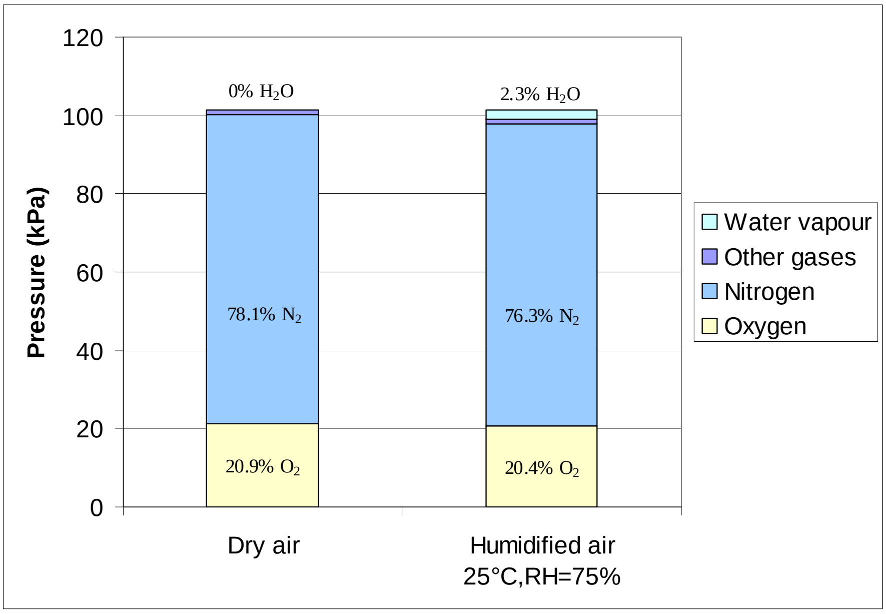

Figure 3.5 Difference between dry air and humidified air.

In figure 3.6 the oxygen concentration is estimated for different temperatures and relative humidity. The graphs are calculated for normal atmospheric pressure, normobaric conditions. The ability to store water in the air is increasing when the temperature is increasing.

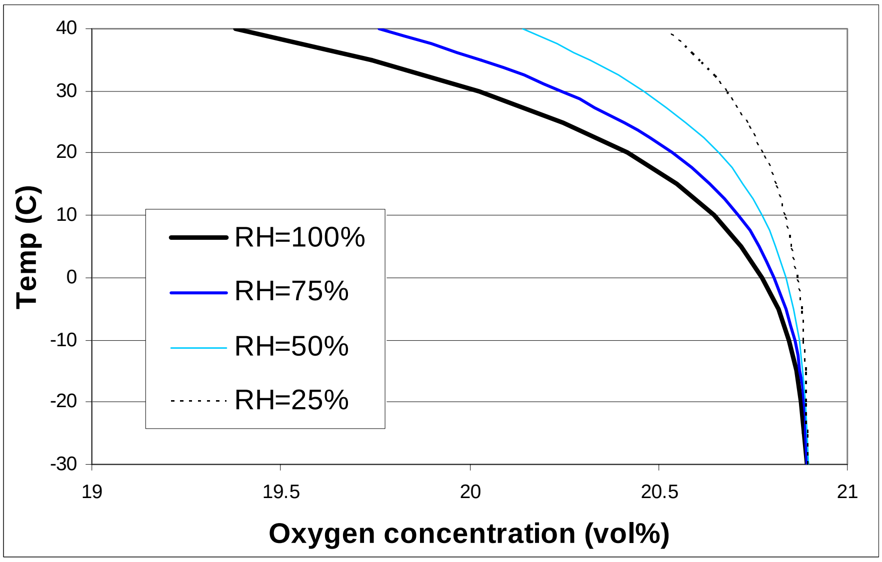

Figure 3.6 Humidity influence on normobaric normoxic air.

Normal levels for the relative humidity in Sweden are found in table 3.1. The oxygen concentration is reduced a few tenths compared to dry air. The temperature and relative humidity in tropical countries are higher and therefore the oxygen concentration will be reduced even more, as shown in figure 3.6.

Table 3.1 Typical humidity values in Sweden [4].

	Relative humidity	Oxygen concentration (vol%)
Winter 0°C	60-100	20.8
Summer 25°C	35-70	20.7-20.4

The influence of humidity on normobaric hypoxic air with 13, 15 and 17 vol% oxygen is estimated and found in appendix A. Water vapour affects the fire behaviour; see more in 4.7.

3.7 Materials

Materials can be divided into different classes depending on the state of aggregation. There are different classes in different countries, but in this report definitions from British standard have been used, see table 3.2. Note that NFPA standard [5] uses other definitions.

Table 3.2 Different material classes discussed in this report, definitions are from British Standard [6].

Class	Material
Class A	Combustible solids
Class B	Flammable liquids or liquefiable solids
Class C	Flammable gases

3.8 Probabilistic approach

It is very hard to quantify the risks related to hypoxic environment, mainly because of variations and uncertainties related to both fire behaviour and health effects. The risks are therefore discussed in a more philosophic point of view instead of being quantified.

In this report the combined risk between fire and health is explained with illustrative figures and models and the results should not be used quantitative. A general model for the whole population is irrelevant, because the population could be completely different for different activities.

There are two different ways to approach these risks:

- A deterministic approach, see figure 3.7. The probability is either 0 or 1 and variations are not considered. The designed oxygen concentration should be chosen in the gap between fire and health, if there is any gap.
- A probabilistic approach, see figure 3.8. The risks are described with probability functions that consider variations in population, materials etc. The curves in the figure are illustrated as normal distributed, but are not analysed further. The shape of the curves depends on e.g. individual differences and characteristics of materials, but is of course associated with uncertainties.

The deterministic approach is the easy way to look at the probability and is unfortunately a common approach. The probabilistic approach is more scientific approach and is used through out this report and shows that there is a distribution of the probabilities, which should agree with reality. The two curves are overlapping each other and this intersection is important. A priority between the risks must be made. The design concentration in figure 3.8 is chosen so that the combined risks between fire and health are minimised. However, in fire safety engineering, life and health are often of higher importance compared to property and therefore should life and health be prioritised.

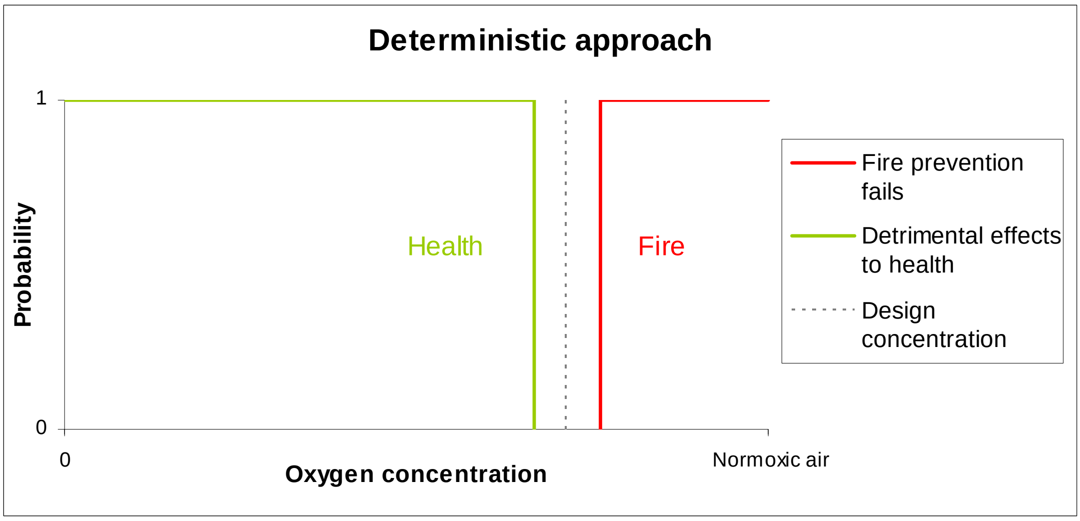

Figure 3.7 Deterministic approach.

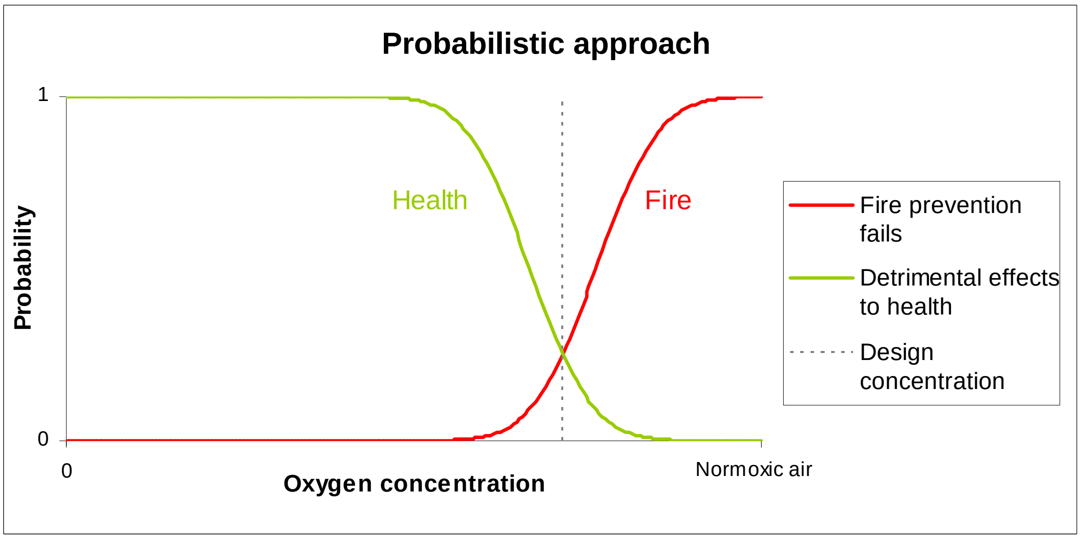

Figure 3.8 Probabilistic approach.

4 Fire behaviour

This chapter describes the fire behaviour at reduced oxygen concentration. To understand the fire, the process of extinguishing is described. Fire is a complex process and oxygen concentration is not the only parameter that prevents a fire and therefore an engineering approach is needed to understand the fire and the extinguishing process.

The parameters described in this report are:

- Oxygen concentration
- Pressure
- External radiation
- Humidity
- Temperature
- Ignition
- Geometry of fuel

Research and experiments for fires in hypoxic environment are studied and conclusions from them are important when the fire risks are evaluated. A study of fires in submarines has been the main source for this research. Occurrence of pyrolysis and smouldering combustion are discussed in more detail because they are critical and important when the oxygen concentration is reduced. The probability for a fire at different oxygen concentration has also been evaluated in this chapter.

4.1 Fire theory

Except for bonfires and fireplaces, fires are usually not welcomed and are preferably extinguished or at least controlled. The chemical reactions of a fire can be stopped in several ways. In order to understand the reactions in a fire the explanation of the theory should start at a basic level. From the fire triangle, to mostly known, is the best way to start exploring a fire and its way of prevention.

As shown in figure 4.1 the fire needs three fundamental elements to ignite and burn: heat, fuel and oxygen. If one of those three elements are eliminated or lowered under a certain level, the fire is extinguished. This is the traditional way to look at a fire; commonly known from the fire triangle. The fire triangle shows the different components necessary to maintain a flame but is not sufficient to explain why the flame is extinguished [7]. The extinguishment of a flame is explained in appendix B with the fire point theory.

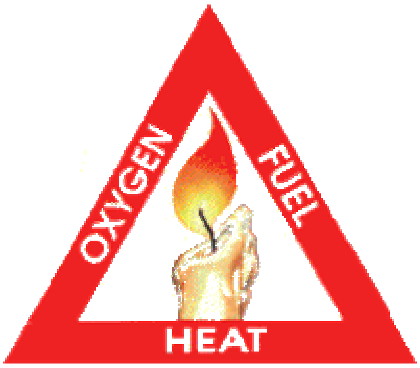

Figure 4.1 Oxygen, fuel and heat are the different elements necessary to maintain a fire.

It is difficult to completely eliminate one of the elements and sometimes an impossible solution. This solution is often excluded by practical reasons and therefore reduction of more than one element is of more interest. Fuel and heat are briefly investigated in appendix C where the chemical reaction also is explained.

4.2 Oxygen concentration

The fire behaviour is very sensitive to increased nitrogen concentration, when for example the air is inerted with nitrogen. The increase of nitrogen will decrease the oxygen concentration with approximately the same amount. The sensitivity of oxygen concentration is best showed with the burning rate of materials, which is the controlling factor for propagation, heat release and vitiated gas production etc. An experiment with paper burning in different oxygen/nitrogen mixtures (held horizontally) at atmospheric pressure is shown in figure 4.1. The result in figure 4.1 is only valid if the oxygen concentration is reduced with dilution of nitrogen. If other gases than nitrogen are used the curve will have another appearance due to different thermal heat capacity of the inerted gas. The fact is that nitrogen and oxygen molecular weights, heat capacities and heat conductivity etc. are very equal. The chemical contribution of oxygen concentration is important [8].

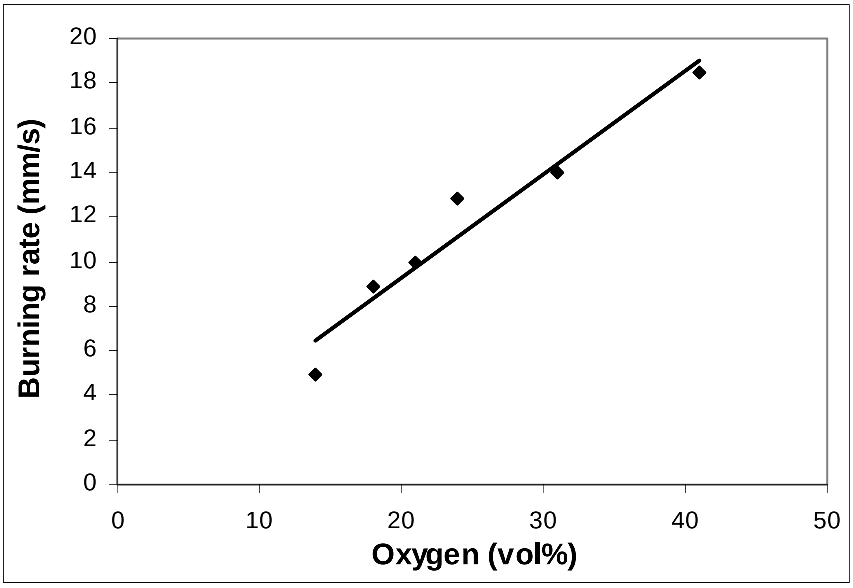

Figure 4.1 Burning rate of paper in different oxygen concentrations [8].

In figure 4.2 the burning rate of different class A and B materials are showed. The effect of reduced oxygen concentration on burning rate is clearer in class B materials compared to class A materials. However, the difference in burning rate for class A materials in reduced oxygen concentration are significant as well.

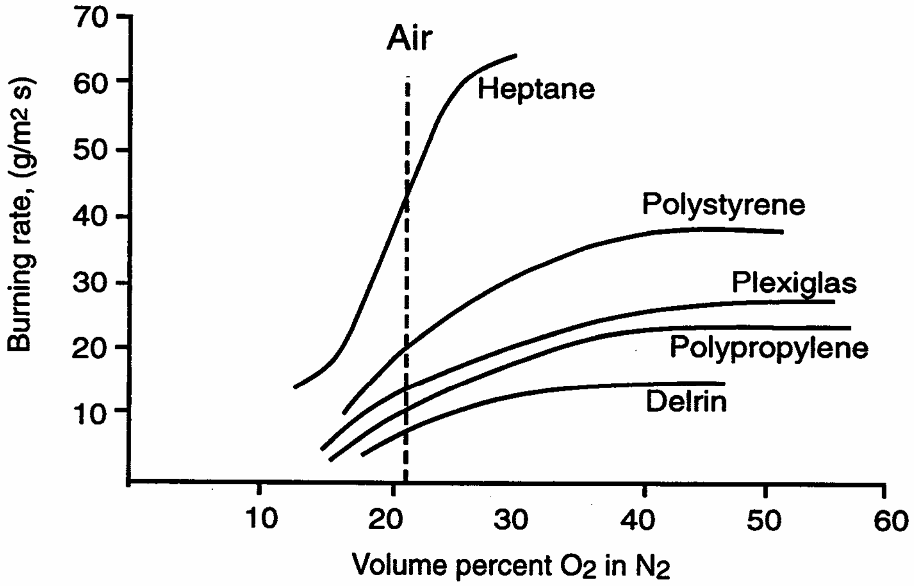

Figure 4.2 Burning rate of different class A and B materials in different oxygen concentrations [9].

When oxygen concentration is reduced a flame is extinguished in two ways [10]:

1. Dilution and lowering of temperature as a result of providence of inert gas. The inert gas could for example be N_2 or CO_2. The temperature decreases and the magnitude of it depend on the thermal heat capacity of the inerted gas.
2. Chemical effects on the fuel surface or in the flames which result in decreased combustion reaction and decreased re-radiation to fuel surface from flames.

4.3 Methods for measuring of extinguishing values

It is important to know how different materials behave during a fire at different oxygen concentrations and when a fire in them is extinguished. There are different methods how this could be measured in reality. In appendix D-F three different methods are presented and discussed

1. LOI (Limiting oxygen index)
2. Cup burner
3. Inerting concentration

Typical values are also presented in appendix D-F. Even if it exist many different small scale methods, full scale tests are probably the best way of measuring the extinguishing values. However, full scale tests are very expensive and difficult to carry out in reality and therefore it is hard to find data.

4.4 Pressure

The fire behaviour is sensitive to very small changes in oxygen/nitrogen concentration as shown in 4.2, but on the other hand very insensitive to changes in the oxygen partial pressure. Experiments conducted by Johnson et al. [11] show that if partial pressure of oxygen is increased, by increasing the total pressure of a gas mixture in a burning environment, this will only result in a small increase on burning rate. The fact that the total pressure of the gas mixtures is increased means that nitrogen partial pressure is increased as well as the oxygen partial pressure. This can partly explain why the burning rate is not increasing significantly with pressure since nitrogen acts as a heat sink and controls the flame spread by heat and mass transfer. Figure 4.3 shows a small increase in burning rate when pressure is increased and a big increase when oxygen concentration is increased. Figure 4.4 shows experiments where burning rate of liquids also are highly dependent of oxygen/nitrogen mixture.

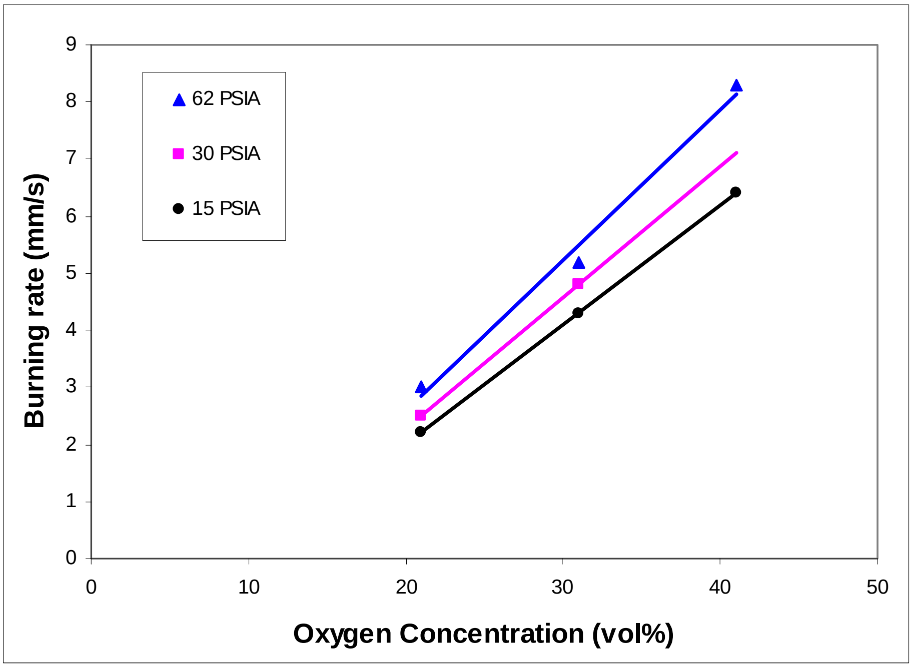

Figure 4.3 Experiments show the dependence of oxygen concentration and the small dependence of oxygen pressure on burning rate of class A material [8].

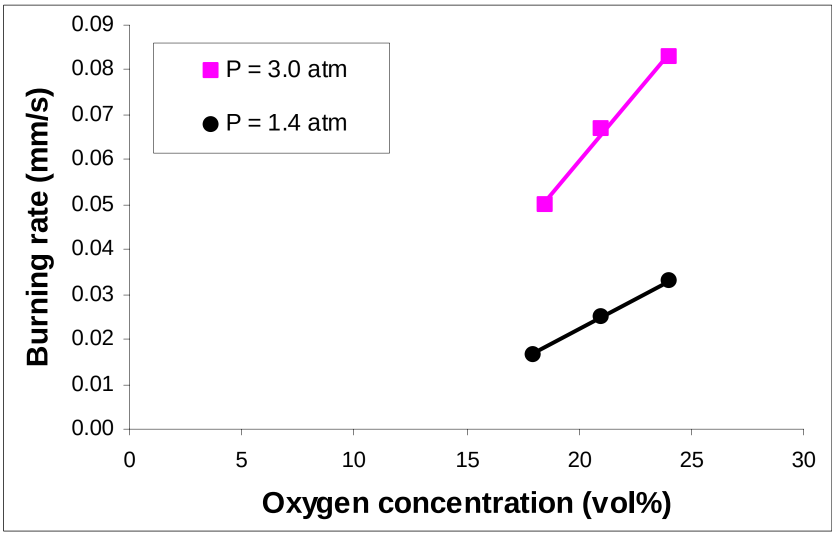

Figure 4.4 Experiments show the dependence of oxygen concentration on burning rate of class B material (Kerosene) [8].

Note that the experiments with class A and B materials shown in figure 4.3 and 4.4 burn with a lower oxygen concentration than possible according to the limiting oxygen index (LOI). This is possible due to the LOI test method used and is explained in appendix D.

Measurement of fire behaviour parameters such as heat release and ignition etc. is also dependent on oxygen concentration, but not as dramatically as for propagation [12].

Figure 4.5 shows how mass loss rate depends on oxygen/nitrogen mixture and pressure. The mass loss rate depends mainly on oxygen concentration and the pressure is of much less importance. The mass loss rate of materials is closely related to the burning rate. This experiment shows that a fire in methyl alcohol is prevented at approximately 13 vol% oxygen.

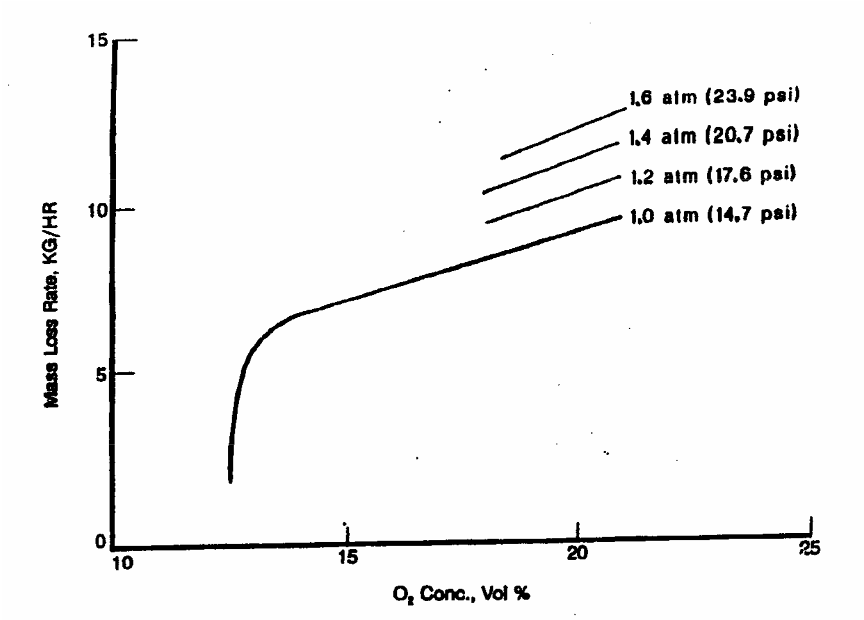

Figure 4.5 Experiments show the dependence of oxygen concentration and the small dependence of oxygen pressure on mass loss rate of a class B material (methyl alcohol) [8].

4.5 External radiation

External radiation is one of the most important parameters in the combustion process. When a material is exposed to external radiation the required concentration of extinguishing agent to obtain extinction will increase [13]. Explanation of the importance of the heat balance is explained in the fire point theory in appendix B. It is important to consider the difference in laminar and turbulent behaviour in flames and differences in heat balance when comparing small scale experiments with real fires. External radiation is the main reason why the results differ. Real fires usually contain of more than one burning material and external radiation is possible.

The oxygen concentration needed for extinguishing of heptane and PMMA is different depending on the radiation level, see figure 4.6. These graphs are calculated with the fire point theory and are supported by real experiments. Less oxygen concentration and more nitrogen are needed when the external radiation is increased. For heptane, the oxygen concentration is almost equal to the inerting concentration when the radiation level increases [14]. The importance of external radiation is clearly showed in the PMMA curve. The dotted part of the curves is theoretical values.

To get an understanding of the magnitude of external radiation, 1 kW/m^2 corresponds to the maximum value naked skin could endure without feeling pain. Human skin will get second-degree burn if exposed to 9 kW/m^2 during 20 seconds. Most materials made of wood will reach auto ignition temperature around 20-25 kW/m^2 [15] and a criterion of flashover inside an enclosure is 15-20 kW/m^2.

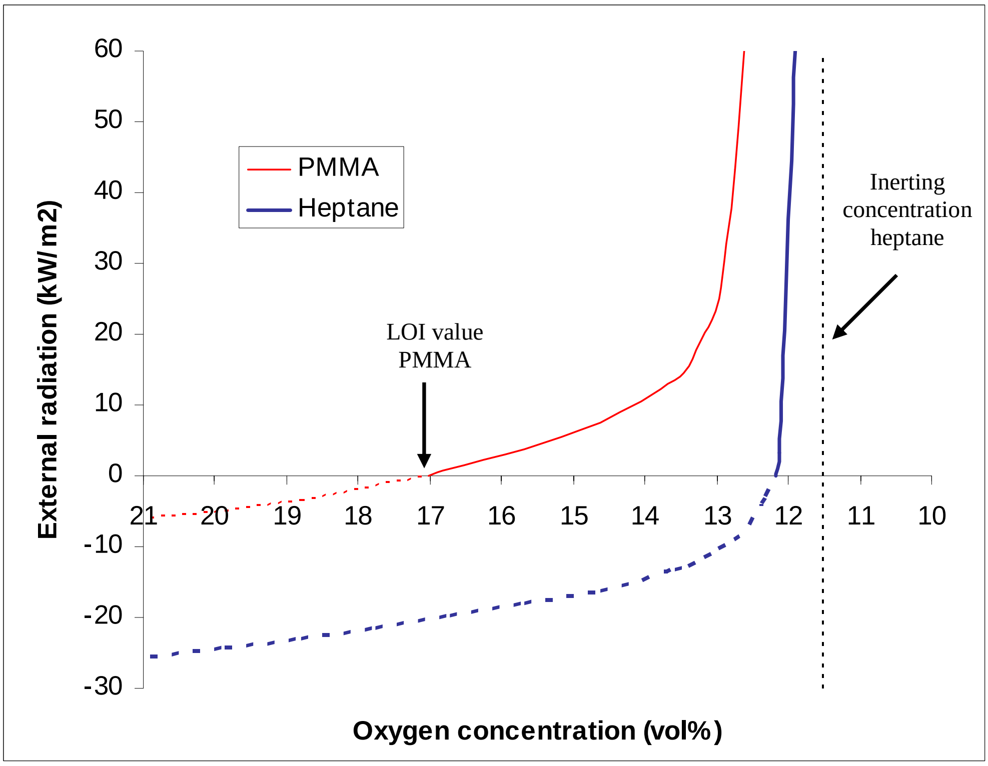

Figure 4.6 Oxygen concentration needed to extinguish a fire calculated by using the Fire point theory.

4.6 Ignition

There is no fire unless there is an ignition. To achieve optimum fire prevention, ignition sources must be minimised. Available data indicates that oxygen concentration affects the ignition time and the minimum ignition energy (MIE). The temperature when the fuel ignites is also an important parameter. The theory about ignition in solids, liquids and gases is described in appendix G.

4.6.1 Ignition of class A materials

Experiments conducted by Mikkola [16,17] show ignition time at different oxygen concentrations where materials are exposed for external radiation of 50 kW/m^2. The results show an average of 24% increased ignition time in 15 vol% oxygen compared to 21 vol% oxygen, see figure 4.7. When the oxygen concentration is decreased below 15 vol%, the ignition time will increase dramatically. Ignition time for two plastic materials is presented more detailed in figure 4.8 and this shows clearly the oxygen concentration influence on ignition of class A materials. Ignition is still possible at 12.5 vol% oxygen but external radiation is necessary for ignition.

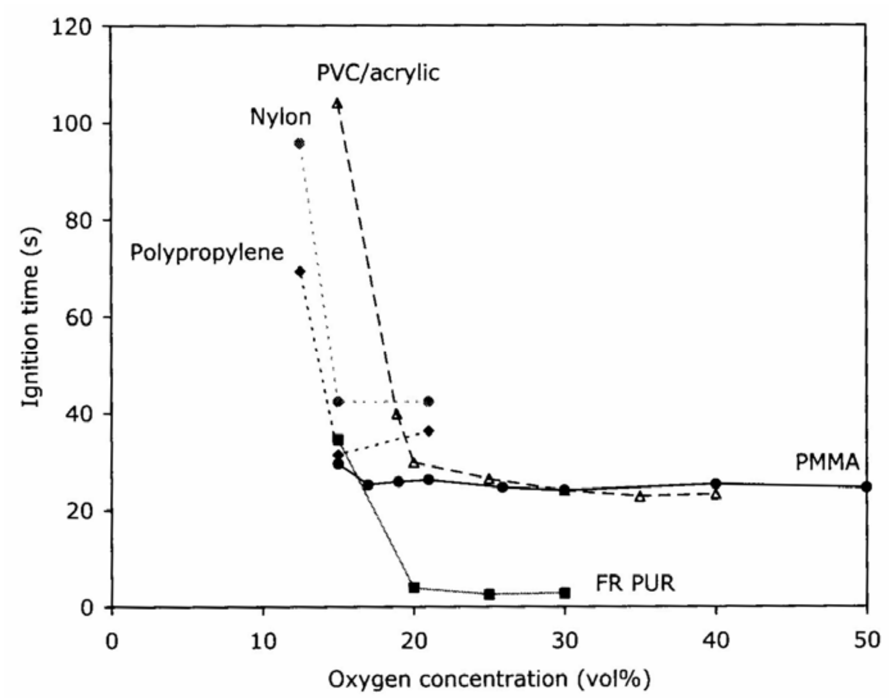

Figure 4.7 Ignition time (s) of different plastic materials in different oxygen concentrations (vol%). Heat flux is 50kW/m^2 [16].

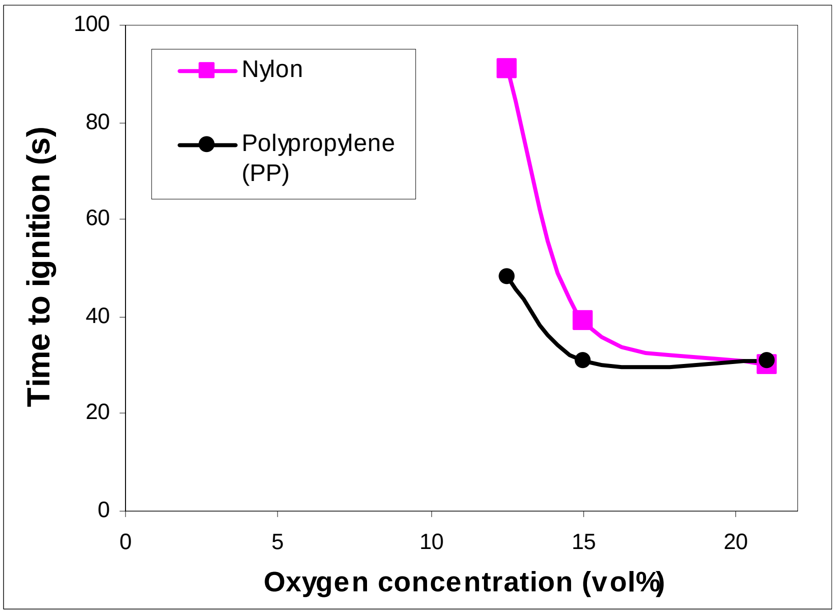

Figure 4.8 Ignition time (s) of nylon and polypropylene (PP) in different oxygen concentrations (vol%). Data is measured with a cone calorimeter with heat flux of 50kW/m^2 [17].

To start a fire in hypoxic environment there has to be a considerable amount of energy. The minimum ignition energy for two plastic materials is given in figure 4.9. The ignition energy is calculated by:

Equation 4.1

$$E = \int_0^{t_{ig}} \dot{q}_r dt$$

E = *Ignition energy*
t_{ig} = *Ignition time*
$\dot{q}_r$ = *External radiation*

If external radiation is assumed to be constant, the ignition energy is calculated by:

Equation 4.2

$$E = \dot{q}_r \cdot t_{ig}$$

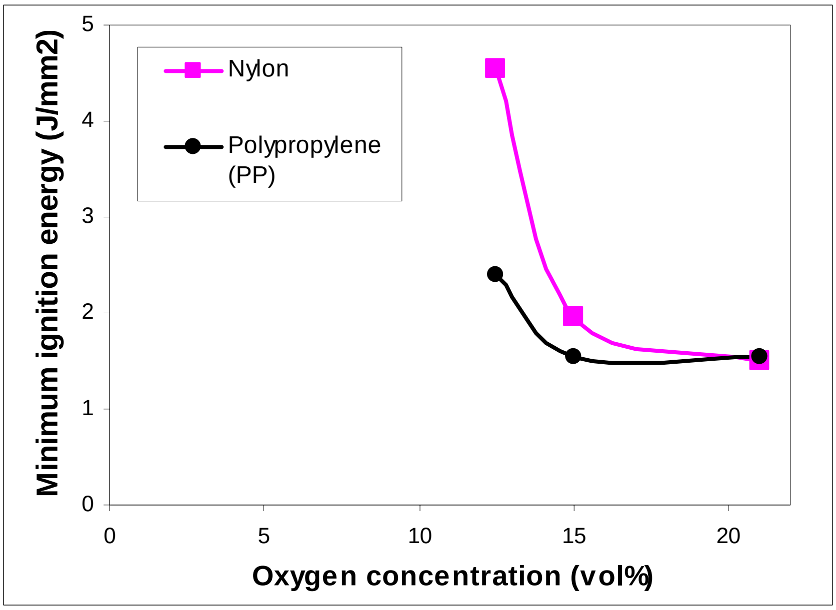

Figure 4.9 Minimum ignition energy (MIE) for class A materials in different oxygen concentrations [17].

4.6.2 Ignition of class B and C materials

The aspects of ignition of liquids are very similar to those of gases and are for that reason treated in the same chapter. If a material is present as a gas or a liquid depends on both pressure and temperature. Ignition of pure liquids are with a few unusually exception not feasible. Ignition of liquids usually occurs in the vapour of the liquid. The vapour mixes with the air in the atmosphere and when the vapour concentration has increased over the lower flammability limit (LFL) ignition is possible [16]. Gases can when ignited result in a diffusion flame or a premixed flame. A premixed gas mixture can result in a gas explosion, if ignited.

The minimum ignition energy (MIE) for gases will increase when the oxygen concentration is decreased [16]. This is shown for methane in figure 4.10.

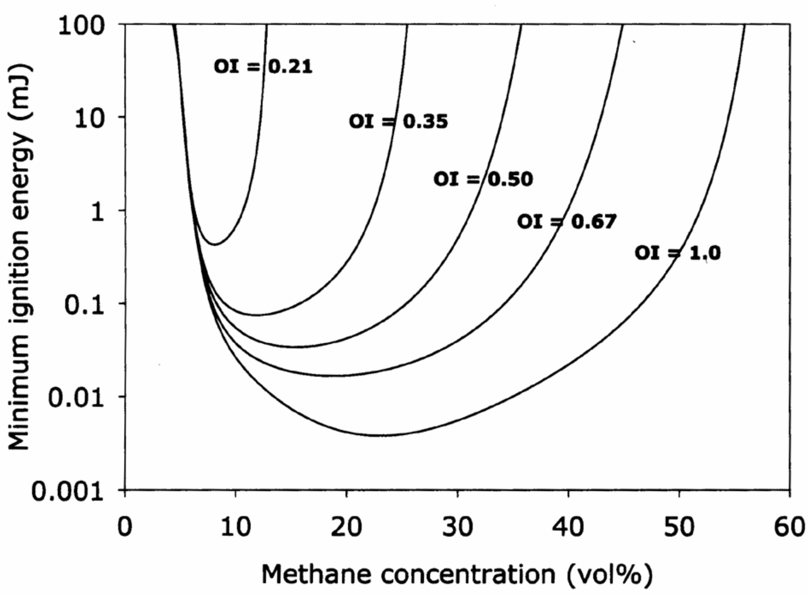

Figure 4.10 Minimum ignition energy (MIE) for methane in different oxygen concentrations [16]. OI is the oxygen concentration in volume fraction.

It is very hard to predict oxygen concentration effect on autoignition temperature (AIT) and experiments show a huge span of results. Although results show that the autoignition time generally increases with reduced oxygen concentration [16].

4.6.3 Experiments

Different levels of ignition in cargo compartments are discussed in a report from NASA [18]. Cargo compartments generally consist of class A materials. A hot surface ignition can be prevented with approximately 16 vol% oxygen and an ignition spark of 1.0 Joule with approximately 12 vol% oxygen. In military applications 9 vol% oxygen is required to prevent ignition by small arms fire up to 23 mm [18].

A report from FAA [19] shows inerting concentration with various ignition sources from 0.08-0.5 Joules and the result only showed a little variation, 12.0-12.8 vol% oxygen. A heated metal block, used for simulation of surface ignition, ignites fuel at 14 vol% oxygen.

4.7 Humidity

According to 3.6, humidity will reduce the oxygen concentration in the air. Water vapour is a suppressant in its own right and is actually more efficient than nitrogen [20]. Experiments that measure the effect of humidity has been carried out in a full scale cup burner with extinguishing agent FM 200 (HFC-227ea). This indicates that less agent is needed when the humidity is increasing. Extinguishing concentration of 6.4 vol% is needed for 100% relative humidity and 6.8 vol% for 0% relative humidity. The difference is obvious, but conservative for fire behaviour, and is of that reason necessarily not considered. Most cup burner methods use very dry air with a relative humidity less than 1% compared to real fires that burn with up to 40 % of relative humidity [20].

4.8 Temperature

Temperature is one parameter that affects the extinguishing process. When the temperature increases the inerting requirements increases [21]. Conclusion from above is that some margin of safety must be used, especially when the temperature is higher than normal room temperature. Temperature is not studied in detail, but the increased risk with increased temperature must be considered.

4.9 Fire behaviour in class A materials

4.9.1 Geometry of fuel

For class A materials, the time to ignition is strongly dependent on the geometry of a sample. The actual thickness of the material and the geometrical arrangement of the sample determines the time it takes for the sample to get uniformly hot.

As seen in figure 4.11 the ignition time of spruce panels clearly depends on the thickness of a material. However, when increasing the external radiation the time to ignition for different thicknesses approaches the same value and therefore the thickness of materials is of less importance if external radiation reaches high values.

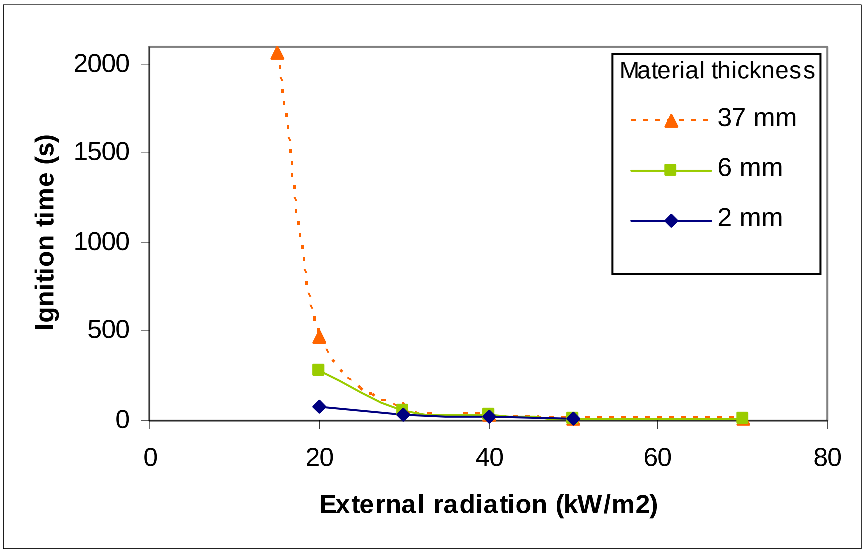

Figure 4.11 Ignition time in normoxic air for different thicknesses of spruce panels plotted as a function of external radiation [16].

The geometrical arrangement of the burning samples is of importance. Certain arrangement of materials can generate higher external radiation than other and thereby keep the flame burning in lower oxygen concentration.

4.9.2 Pyrolysis

A flame is a gas phase phenomenon and almost all solids and liquids must change to gas phase before a flame can be ignited [22]. Materials start pyrolyzing due to external heating and the pyrolysis process produces combustible gases above the material's surface and mixes with the air before ignited in the gas phase [10]. Liquids normally evaporate when boiling due to external heat. For almost all solids chemical decomposition or pyrolysis is necessary to produce enough pyrolysis gases from the material to sustain a flame after ignition. The surface temperature of a burning solid is rather high, typically 400°C [22]. Liquids with very high boiling point, for example cooking oil, can also undergo thermal decomposition [22].

Pyrolysis can still occur even if the oxygen concentration is low. This is because thermal decomposition can proceed without the involvement of oxygen. However, ignition of the pyrolysis gases can be difficult if the oxygen concentration is reduced.

4.9.3 Smouldering combustion

Smouldering combustion and deep seated fires are discussed in this chapter. These are two different expressions for non flaming fires. The fire behaviour is similar, but a deep seated fire has been developed during a longer time and the combustion takes place deeper inside the material.

Smouldering fires are insidious and flaming fires normally develop after a long time. In case of reduced oxygen concentration, flaming fires may never develop. Besides the previously mentioned classification in class A, B and C materials, class A can be further divided into those who do and do not develop smouldering combustion. Class A materials, such as organic products like textiles, paper and wood may still smoulder at reduced oxygen concentration where flaming fires are impossible. Rubber and polymers are other products that can develop into smouldering combustion. Smoke is still produced at smouldering combustion, which creates a toxic environment.

The process of smouldering is a flameless slow combustion with low temperature. When oxygen directly attacks the surface of a condensing fuel it produces heat as a result of the oxidizing process.

Char oxidizing is considered to be the most common source of heat in self-sustained smouldering. A cigarette is a good example of a smouldering combustion process. It is important to separate smouldering and pyrolysis. Forced pyrolysis, as when material is exposed for high radiation, is sometimes incorrect assumed as smouldering combustion [10]. Ignition of smouldering materials occur after the material has been heated by the exothermic reaction to a level where it overcomes the heat loss to the surrounding [23].

The developing time of deep seated fires for a material varies with the external radiation, exposure time or for the materials internal heat developing capability [24]. In a poorly ventilated room, the smouldering process can produce a lot of combustible smoke. If this smoke ignites it causes a smoke gas explosion with devastating consequences. Smoke gas explosions are fortunately not common [25]. Smouldering fires are considered to be both a fire and health hazard as it produces a higher fuel and toxic content than flaming fires [10].

Less oxygen is required for smouldering combustion than fire with flame propagation [23]. This conclusion makes it interesting to look at situations where a specific oxygen concentration prevents a flame fire but smouldering combustion is still possible. The oxygen concentration also affects the heat produced by smouldering materials. Experiments with less oxygen will reduce the produced heat [10]. If the oxygen concentration will be reduced to just a few percent, smouldering heat will be significantly reduced.

The process of smouldering is complex and has gone through less research than flame propagation. The most important subject for smouldering process is the oxygen supply rate. An important factor is also the relative movement of oxygen supply and smouldering propagation [26]. The chemical contents of the material are of secondary importance regarding the smoulder rate. Data that confirm this is limited, but data found show similar result.

Decomposition temperature in smouldering fires is about 400°C. A great variety of toxic products are formed under smouldering conditions, which causes hazardous conditions. The main danger is carbon oxide (CO), which is produced due to incomplete oxidation. A higher fraction of CO is produced during smouldering fires than during flaming fires. CO has the capability to cause serious injuries on human body and death at high concentration. See more about health effetcs in chapter 5. Reduced oxygen concentration due to smouldering fires may be dangerous if the room is small and the ventilation is poor. With smouldering fires, room temperature is relatively low and smoke is light. Therefore conditions are hazardous only after a long period of time, but can be dangerous if no detection system is working and occupants are sleeping or trapped inside the enclosure [26].

In figure 4.12 the development of major fire gases and the reduction of oxygen concentration are shown from a full scale experiment. The experiment is performed in an enclosure with a door in the end of a corridor as ventilation to the fire. The differences between this enclosure compared to a hypoxic environment are that no ventilation of fresh air is present and oxygen concentration will reduce faster in hypoxic environment.

Hypoxic environment will result in changes in fire behaviour:

- Fire growth will be slower.
- The fire gases will consist of more un-combusted contents and particles.
- Critical conditions will probably occur faster.

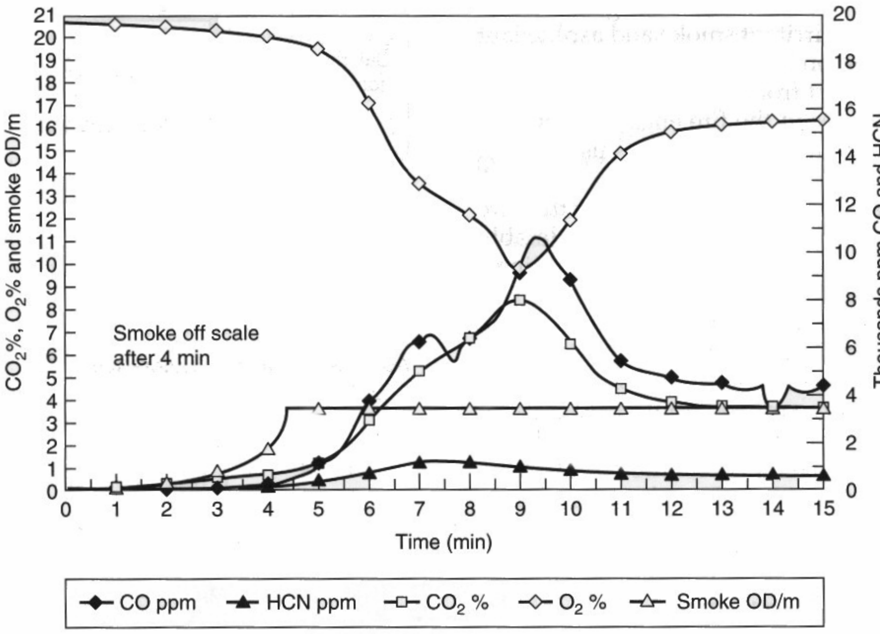

Figure 4.12 Gases and smoke analysis in full scale tests in an enclosure that starts with smouldering combustion [26].

Fire investigations from real fires where people have died after exposure to CO and reduced oxygen concentration in combination shows a reduced tolerance for fire gases during reduced oxygen concentration. Example in fig 4.12 is a reconstruction from reality. The fire starts with smouldering combustion in a confined enclosure. The smouldering fire develops eventually into a very small fire before it a few minutes later was discovered and extinguished with only a bucket of water. The door to the enclosure was closed until the fire were discovered and extinguished (after approximately 9 minutes). Unfortunately two persons died, an adult and a four year old child who where exposed to the fire gases, when they were sleeping in the enclosure. The two persons died due to CO poison in there blood, the CO level in blood were half the lethal concentration. According to calculation of the size of the enclosure it would have been enough to combust 0.5 kg of the fuel to reduce the oxygen concentration to 10 vol% and produce 1 vol% of CO, which could be enough to get incapacitation or death in minutes together with other toxic fire products [26].

The values in table 4.1 and 4.2 are for the extinguishing of class A material with Halon 1301. These values are indications by six different halon industry groups. The tables are presented only with meaning of comparing the extinguishing concentration between solid materials that are and are not developed into deep seated fires. These values are not applicable on nitrogen, but show the need of great amount of extinguishing agents for deep-seated fires compared with flaming fires.

Table 4.1 Extinguishing volume concentration of Halon 1301 of some class A materials, flammable solids, flaming fires [24].

Flaming fires	Factory Mutual	Fenwal	Ansul	DuPont	Safety First	Under-writers Labs
Polyvinyl chloride		2.00		2.6	3.8	
Stacked computer printout			5.1			
Crumbled paper	3	6			3.8	
Shredded paper loose on floor					3.8	
Polyester computer tape		5			3.8	
Wood crib 1A 50 pcs. 2”*2”*18”					3.8	3.88
Polyurethane foam				3	3.8	

Table 4.2 Extinguishing volume concentration of Halon 1301 of some class A materials, flammable solids, deep seated fires (smouldering fires) [24].

Deep seated fires (smouldering fires)	Factory Mutual	Fenwal	Ansul	DuPont	Safety First	Under-writers Labs
Shredded paper in wire basket					20	18
Polyester computer tape loose in wire basket		10				
Charcoal	13					
Parallel wood blocks	20					
Glazed fox fur					6.5	

4.9.4 Heat release rate

The effect of reduced oxygen on heat release rate (HRR) has been investigated. Figure 4.13 shows the HRR for 21, 17 and 15 vol% oxygen without external radiation [26]. The burning samples are empty boxes made of corrugated paper with sides of 50 mm in 2 x 2 x 2 arrangement. As seen in figure 4.13 flame extinction is close when the concentration is 15 vol% oxygen.

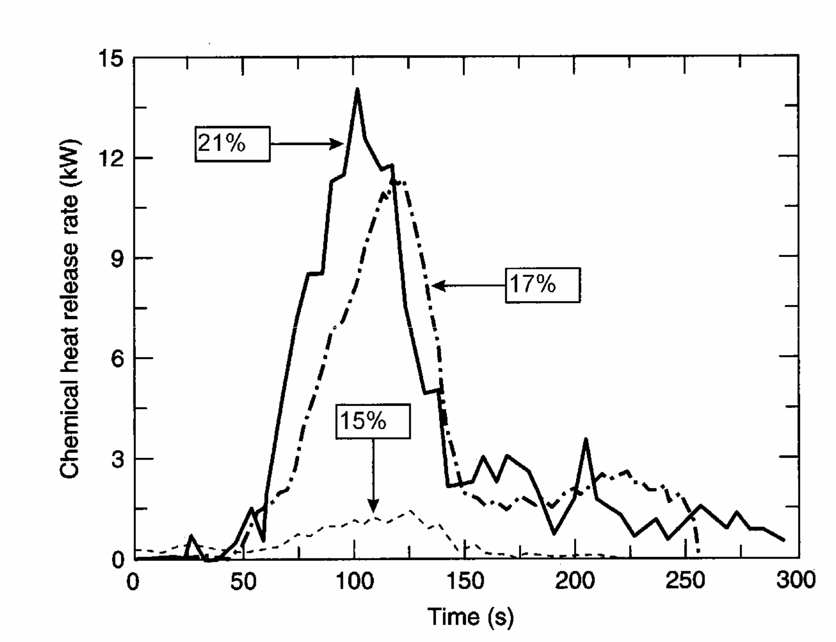

Figure 4.13 Heat release rate (kW) for burning paper boxes in 21, 17 and 15 vol% oxygen without external radiation [26].

Figure 4.14 shows the peak heat release rate for two plastic materials. The HRR is significantly reduced when the oxygen concentration is reduced to 12.5 vol% but samples are still burning.

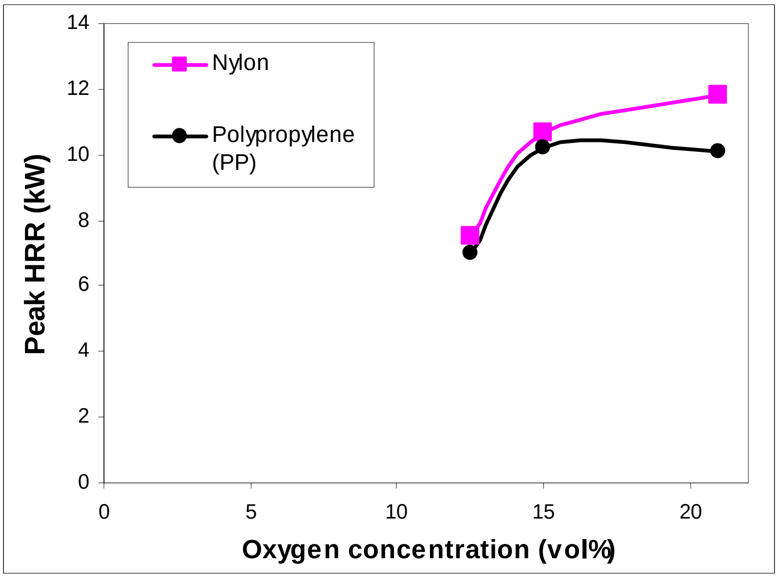

Figure 4.14 Peak HRR (kW) of nylon and polypropylene (PP) in different oxygen concentration (vol%). Data is measured with a cone calorimeter with external radiation of 50kW/m² and gas inflow of 180 l/min [17].

4.10 Experiments in hypoxic air

4.10.1 Jet fuel tank study

A report from Federal Aviation Administration (FAA) in USA shows necessary oxygen concentration for inerting of a jet fuel tank [21]. Experiments were performed using laboratory equipment and some full scale studies in aircraft fuel tanks. For inerting of JP-8 fuel, 12 vol% oxygen is considered suitable for fire prevention. More literature discussed in this report shows that minimum oxygen concentration required for flame propagation for common hydrocarbons (methane, ethane, propane etc), gasoline (octane) and jet fuel (JP-3) are between 11.0-12.5 vol% oxygen. These experiments were performed at sea level pressure and 25°C. Jet fuel is a mixture of more than 300 different hydrocarbons [27].

4.10.2 Submarine study

Werling and Onnermark [28] have performed experiments regarding combustion in hypoxic environment. The experiments were meant to be used as a basis for fire prevention in submarines. Submarines should be suitable for hypoxic environment due to its confined space without leakage (hopefully) and an atmosphere with same conditions during a longer time.

Conclusions from fire experiments are that ignition reduces with reduced oxygen concentration. Fire behaviour assumes to change; both burning rate and flame spreading is decreased when the oxygen concentration is decreased. The authors' results show a positive fire retardant effect due to oxygen reduction.

The experiments were performed from the assumption that ignitability is dependent on the radiation the material is exposed to. This may only be one way to measure ignitability. The authors have not carried out any comparison of which is the most significant way to ignite materials in reduced oxygen concentration.

Five materials are presented in the experiments and several tests of each material were performed. The experiments were performed at 21 and 15 vol% oxygen. Pressure was 100 kPa in both test series. Three of five materials showed an increased ignition time when reducing the oxygen concentration and two other materials showed no change at all. Tested materials were typical submarine materials but note that these materials may be present at other places too with some modifications. The plastic materials for example are placed on steel to imitate the steel hull of a submarine which could affect the fire behaviour due to its essential conductivity.

The tested materials were of class A and B:

- Cable
- Plastic foil (0.15mm) on steel
- Plastic foil (4mm) on steel, also known as Tarkett floor
- Diesel oil
- Hydraulic oil

The authors exposed the materials to different levels of external radiation and measured time to emit smoke and time to ignition. The full results from the experiment are presented in Appendix H. As seen in figure 4.15, an example of the experiment with the cable, longer time is needed to ignite the cable in 15 vol% oxygen than in 21 vol% oxygen condition. Note that the value of radiation level is of high importance for the time to ignition and is more important than the oxygen concentration.

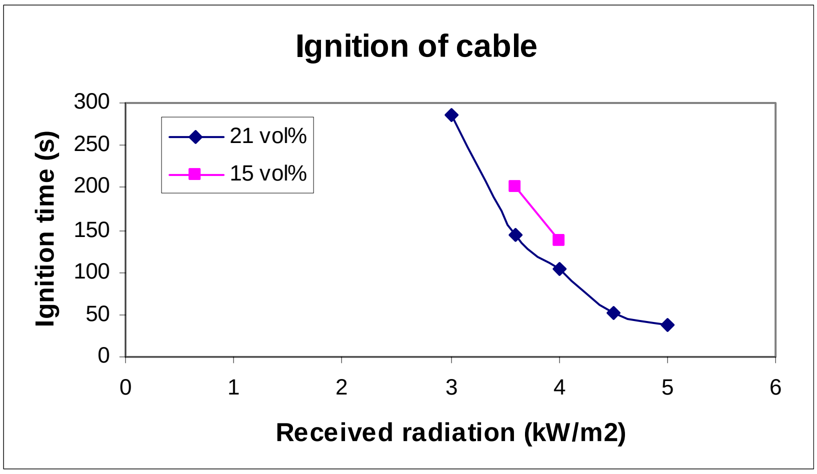

Figure 4.15 Time to ignition at different radiation levels and oxygen concentrations.

Figure 4.16 displays the relationship between radiation level and time to emit smoke, from the same cable as above. The figure shows that time to emit smoke is less in hypoxic air than in normoxic air. This result is not clear-cut, the time to emit smoke for diesel oil in figure 4.17 shows the opposite result.

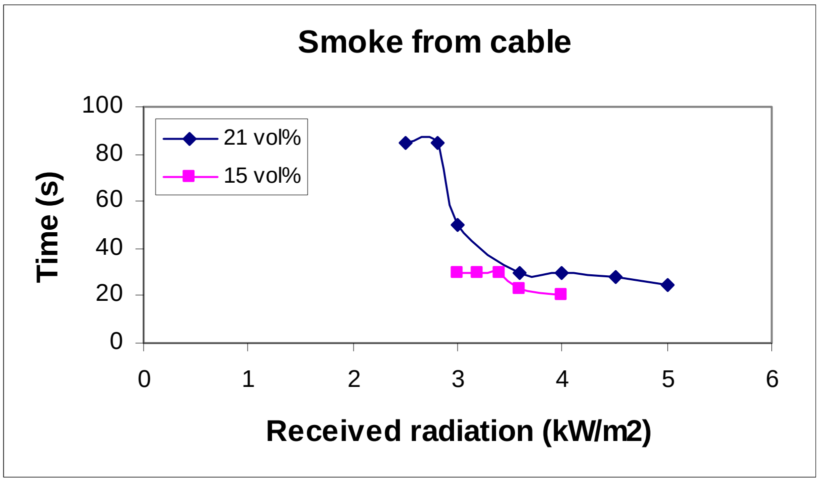

Figure 4.16 Time to emit smoke from cable at different radiation and oxygen concentration.

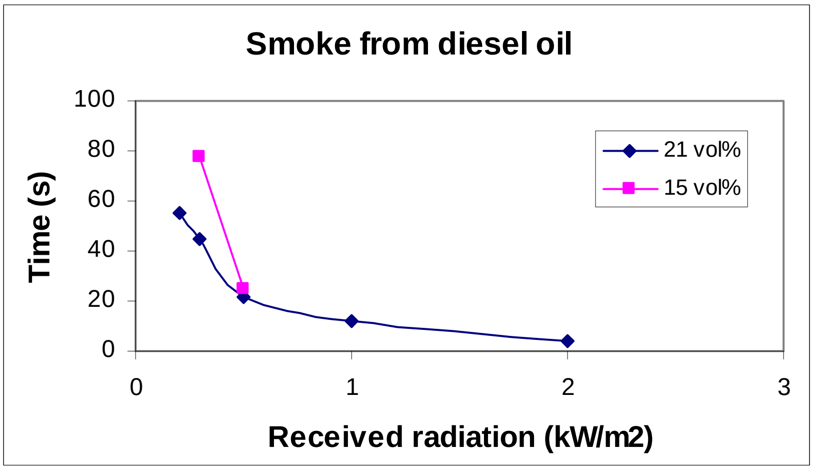

Figure 4.17 Time to emit smoke from diesel at different radiation levels and oxygen concentrations.

The above discussed difference in results between different materials could indicate an experimental fault. All materials emit smoke up to 40% earlier in hypoxic air with 15 vol% oxygen compared to normal atmosphere except diesel oil. Diesel oil emits smoke earlier in normoxic air.

4.11 Probability of a fire

The probability of a fire at different oxygen concentrations has been evaluated. The purpose of this probability relation is to be a valuable input for the scenario analysis in chapter 9. The fire behaviour is affected by many different parameters and oxygen concentration is not the only parameter that prevents a fire. The probability relation illustrates the probability that a fire is prevented in different classes of materials. The materials chosen are typical materials that are valid for other similar materials. There is a variation between the chosen materials, but the most extreme values are not included. A safety margin must be used if all fires should be prevented. Safety margin is more discussed in 9.1. However, the probability relation is evaluated in a conservative manner and some materials will have the probability to be prevented at higher oxygen concentration than showed.

The probability of a fire has been categorised in three different risk classes:

- Class A flaming fires
- Class A smouldering fires
- Class B and C fires

These risk classes have been chosen because they have significant differences in fire behaviour. Burning rate, heat release rate and oxygen concentration required for fire prevention are some areas where clear differences are found between these risk classes. The probability relation is based on these three risk classes.

When calculating the required oxygen concentration for fire prevention, different methods can be used. The oxygen concentration required to prevent a fire is similar to the oxygen concentration required to extinguishing a fire. Therefore the same designing method can be used for hypoxic environment as for gas suppression systems. Some differences between the prevention theory and extinguishing theory are however worth mention. Prevention of a fire must consider the process of ignition compared to a burning fire where ignition already has occurred. Another difference is the produced heat from an already burning material. As mentioned in 4.5, increased external heat increases the need of extinguishing agent. Gas suppression systems are designed to extinguish an already burning fire and therefore it may seem to be a conservative method if the same values are used for fire prevention as for fire extinguishing. However, the values used for gas suppression systems are not always sufficient.

When designing a gas suppression system, a cup burner value is used in combination with a scale factor of 1.2 or inerting concentration is used by multiplying the required extinguishing agent with 0.8 for diffusion flames and 1.0 for premixed. Generally it is very difficult to transfer result from small scale experiments to reality. Scale effects are for example due to differences in turbulent and laminar flames. As indicated in 4.5, a fire is highly dependent on external radiation, which often is neglected in small scale experiments. In lack of full scale data, cup burner and inerting concentration is found to be the most appropriate approach for the probability relation. Values from LOI (Limiting Oxygen Index) method are not used because the relationship between LOI and real fires is unclear and therefore it should not be used to describe the fire behaviour of materials in actual fire conditions.

Cup burner values and inerting concentrations for class A materials are gathered and found in appendix E and F. Extinguishing values for class A materials are very difficult to find. Research in this area is insufficient and therefore an accurate relation is impossible to develop. Class A materials are divided into flaming fires and smouldering fires. Values from four typical class A flaming materials are studied, see table 4.3. Lowest oxygen concentration that ignites PMMA and particleboard has been measured in a cone calorimeter by Mikkola [29]. Conclusion from table 4.3 is that 12.5-14.9 vol%

oxygen is required to prevent typical class A flaming fires. This interval represents the curve for class A flaming fires in figure 4.18, which is assumed to be normal distributed. The mean value in table 4.3 is 13.8 and the standard deviation is 0.9. Class A materials are highly dependent on the size and the geometry as discussed in 4.9.1. Some materials may not burn at concentration higher than 15 vol% oxygen and some may burn at even lower concentration than illustrated in figure 4.18.

Table 4.3 Added nitrogen (vol%) required to prevent flaming fires in typical class A materials. Maximum oxygen concentration (vol%) is found in brackets.

Fuel	Large Cup Burner no scale factor	Full scale room fire no scale factor	Cup Burner scale factor 1.2	Cone calorimeter
Polypropylene	34.7 **(13.6)**			
Wood crib		28.6 **(14.9)**		
PMMA (0 kW/m^2)			33-33.5 **(14.0-13.9)**	
PMMA				**12.5**
Particleboard				**14**

Class A smouldering fires are difficult or almost impossible to prevent. According to discussion in 4.9.3 only a few percent oxygen will support a smouldering fire. It is difficult to determine the quantity required to completely extinguish smouldering fires and values are hard to find. Smouldering combustion require a much higher extinguishing concentration than flaming fires. Although combustion is slow and the risk for fire spread during smouldering fires is small as long as the fire not develops into a flaming fire. The curve for class A smouldering fires in figure 4.18 is illustrated as normal distributed and should not be used quantitative. The interval that represents the curve is unknown but goes from a few percent and up to an unknown value below 21 vol% oxygen. The question mark points out the uncertainty in this area.

Cup burner values and inerting concentrations for class B and C materials are gathered and found in appendix E and F. Typical fuels are chosen and maximum oxygen concentration necessary to prevent fires in class B and C is calculated and given in table 4.4. Conclusion from table 4.4 is that 9.8-13.7 vol% oxygen is required to prevent a fire in class B and C materials. This interval represents the curve for class B and C fires in figure 4.18, which is assumed to be normal distributed. The mean value in table 4.4 is 11.7 and the standard deviation is 1.1.

Table 4.4 Oxygen concentration (vol%) required to prevent fires in typical class B and C materials. Required amount of added nitrogen (vol%) is found in brackets.

Fuel	Cup Burner Scale factor 1.2	Inerting conc. premixed	Inerting conc. Diffusion flame
Acetone	13.7 (34.2)	11.5	
Ethanol	12.9 (38.5)	10.7	11.9
Gasoline		11.6	
n-Heptane	13.1 (37.1)	11.5	
Methanol	11.2 (46.2)	9.8	10.0
Propane (g)	12.7 (39.0)	11.4	12.3

Figure 4.18 describes the probability that fire prevention fails for different classes of materials. The probability functions are assumed to be normal distributed but this has not been analysed further. Other distributions may be present in reality and the probability of a fire will in that case appear differently.

The figure is connected with uncertainties and is best used as an illustrative figure. The distributions in figure 4.18 are only valid for materials comparable with materials in table 4.3-4.4. Some materials behave different during fire than those represented in the curves and a safety margin must be used if this relation should be valid for all materials and conditions.

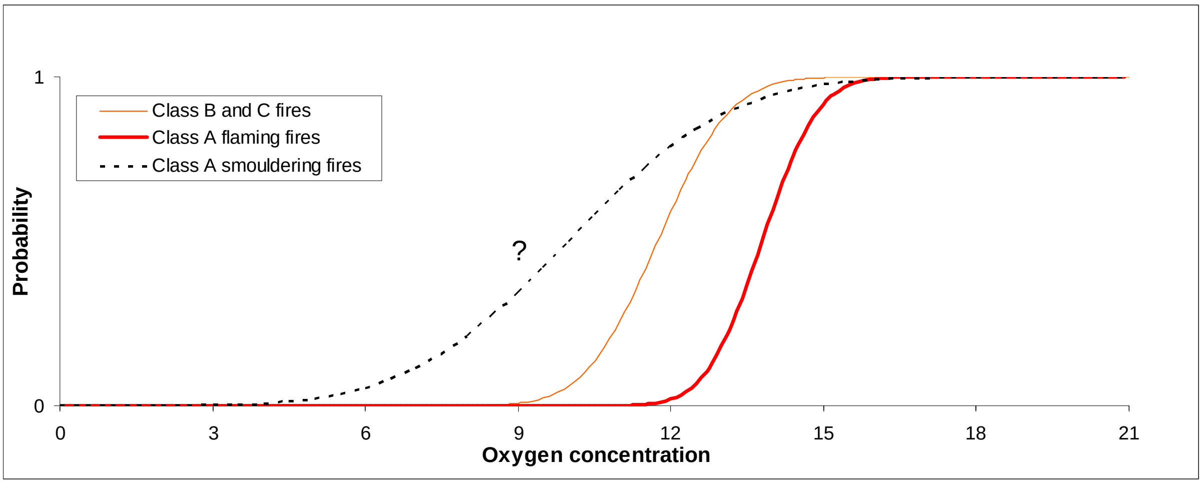

Figure 4.18 Probability that fire prevention fails in different oxygen concentrations. The probability of a fire is illustrated for different classes of materials.

The gradient of the curves for class B and C and for class A flaming fires is steep in figure 4.18. This means that a small change in oxygen concentration will change the probability of a fire considerably. A difference of a few percent could be the difference between a fire and no fire. The dotted line for class A smouldering fires is uncertain as discussed above. The curve illustrates that the probability for smouldering fires is obvious, but the oxygen concentration necessary to prevent smouldering fires is uncertain.

5 Health effects

This chapter describes health effects when humans are exposed to reduced oxygen concentration. Oxygen is vital for human breathing and is not toxic itself, but the environment will be non-breathable if the oxygen concentration is reduced to an insufficient concentration. Expected symptoms are described for different oxygen concentrations.

People have different sensitivities to reduced oxygen concentration and parameters the affects the sensitivity are for example:

- Diseases
- Age and sex
- Physical fitness

Exposure time and adaptation are discussed to understand the complexity of human effects. Interactions and synergic effects from toxic fire gases are discussed further on. Interactions between hypoxic environment and produced fire gases are essential for understanding of the additional risk connected to hypoxic environment in case of a fire. Synergic effects are presented on a discussion basis since it is hard to find relevant research in this area.

The area of human exposure to hypoxic environment has gone through rather little research. Human experiments are seldom found for normobaric hypoxic conditions and therefore advantages must be taken from exposure to high altitudes, hypobaric hypoxic conditions.

The probability for detrimental effects to health at different oxygen concentration has been evaluated and is based on the studied literature.

5.1 Transportation of oxygen in human body

Transportation of oxygen involves a great number of functions. The main functions are described below [30, 31].

1. The air passes through the airways and is humidified. Gas exchange occurs by diffusion and takes place between the alveoli in the lungs and the blood. It depends on the differences in partial pressure of oxygen.

2. Oxygen is bound and carried by haemoglobin in the blood. Circulation of haemoglobin in the blood transports the oxygen to the cells.

3. Gas exchange takes place in the cells and occurs by diffusion. Oxygen releases from haemoglobin if the partial pressure in the blood is higher than in the tissue.

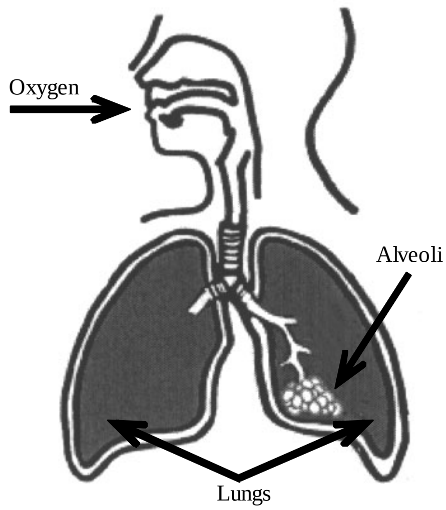

Figure 5.1 Respiration mechanisms.

Oxygen in the blood is limited by the functions described above. For healthy young persons, the oxygen partial pressures in the blood and in the alveoli are almost the same. Elderly and chronically ill persons will have a lower arterial oxygen partial pressure [30].

Haemoglobin saturation is the percent of haemoglobin molecules that carries oxygen. A normal value for young and healthy persons is 97%. This value decreases when a person is exposed to reduced oxygen concentration. An oxygen concentration corresponding to 15 and 13 vol% at sea level reduces this value to 92% and 89% respectively if exposed for 2 hours [32]. During rest, the body has a reserve of oxygen and only 20-25 % of haemoglobin molecules give up oxygen to the cells [31]. When exercising, the body needs more oxygen. More oxygen is released from the haemoglobin molecules and increased respiration makes a higher uptake possible.

Oxygen supply can be disturbed by many reasons and diseases that may affect oxygen supply are described and discussed in 5.9.

5.2 Difference between normobaric hypoxia and hypobaric hypoxia

The only difference in normobaric hypoxic air and hypobaric hypoxic air is the total pressure. Many effects are comparable, because the oxygen partial pressure is the main factor that affects the body. Results from experiments are often treated in the same way for normobaric hypoxia and hypobaric hypoxia. However, some experiments show that the risk for altitude mountain sickness (AMS) is lower in normobaric hypoxia [30], but it does not describe the physiological reasons for this. Historically, extensive human testing has been conducted for hypobaric hypoxic air but not for normobaric hypoxic air, which is the case for hypoxic environment.

Loeppky et al. [33] have investigated the effects of normobaric hypoxia compared to hypobaric hypoxia. The conclusion is that the difference in human effects is change in respiration. The respiration increases in average 26% for normobaric hypoxic compared to hypobaric hypoxic. But the first hour at hypobaric hypoxic the respiration is however higher than at normobaric hypoxic. One explanation to the fact that respiration is lower at hypobaric then at normobaric conditions can be that the partial pressure of carbon dioxide (CO_2) is higher at normobaric condition. Other suggested factors which can explain the difference, besides the difference in CO_2, can be physical activity, climate, test condition, anxiety, sleep disturbance and carbon monoxide (CO) [9]. However, the first hour at hypobaric condition shows a higher respiration. According to the investigation, this can depend on microbubbles in the pulmonary circulation, which temporally disturbs oxygen distribution [33].

5.3 Human effects

The most basic parameters to estimate the oxygen uptake are the concentration of oxygen in the air and the duration of exposure. The respiratory minute volume (RMV) is also important when estimation is done [26]. It is important to know that the oxygen concentration in the air is not the concentration that directly determines how the human is affected. If someone suddenly is given hypoxic air, the air in the lungs and the gases in the blood usually require a few minutes to equilibrate to the new conditions. This time to equilibrium is often neglected in literature. Concentration does not change noticeable with time once equilibrium is reached.

In tables 5.1-5.5 the result from different publications on the human effects of reduced oxygen concentration is presented. Note that these expected symptoms are only valid for people who are in good health and when no exercise is performed.

Table 5.1 Human effects of reduced oxygen concentration. Reference: Kimmerle [34].

Oxygen (vol%) at sea level	Symptoms	Exposure time
20	None	-
17	Respiration volume increases, muscular coordination diminishes, attention and clear thinking require more effort	-
12-15	Shortness of breath, headache, dizziness, quickened pulse, efforts fatigue quickly, muscular coordination for skilled movements lost	-
10-12	Nausea and vomiting, exertion impossible, paralysis of motion	-
6-8	Collapse and unconsciousness occurs	-
< 6	Death	6-8 min

Table 5.2 Human effects of reduced oxygen concentration. Reference: Arac [27].

Oxygen (vol%) at sea level	Symptoms	Exposure time
19.5-	None	-
14-19.5	Laboured breathing, particularly at higher workloads	-
12-14	Physical and intellectual performance impaired, increased heart rate	-
10-12	Rapid breathing, dizziness, disorientation, nausea, blue lips	10 min
8-10	Loss of control, gasping, white face, vomiting, collapse	50% will not survive 6 min 100% will not survive 8 min
4-8	Coma	40 sec
	Death	2 min
< 4	Death	Seconds

Table 5.3 Human effects of reduced oxygen concentration. Reviewed by Trconsulting [35], but accessible references are not cited.

Oxygen (vol%) at sea level	Symptoms	Exposure time
21	None	-
16-21	Increased breathing volume, accelerated heartbeat, impaired attention and thinking, impaired coordination.	-
10-14	Very faulty judgement, very poor muscular coordination, muscular exertion brings on rapid fatigue that may cause permanent heart damage, intermittent respiration.	-
6-10	Nausea, vomiting, inability to perform vigorous movement, or loss of all movement, unconsciousness followed by death.	-
< 6	Spasmodic breathing. Convulsive movements. Death	Minutes

Table 5.4 Human effects of reduced oxygen concentration. Human effects have been classified into four phases. Reference: SFPE 3rd edition [26]

Oxygen (vol%) at sea level	Symptoms
14.4-20.9	*Indifferent phase:* Minor effects on visual dark adaptation and beginnings of effects on exercise tolerance toward 15 vol% oxygen.
11.8-14.4	*Compensated phase:* Slightly increased ventilation and heart rate, slight loss of efficiency in performance of complex psychomotor tasks and short term memory, some effects on judgement. Maximal exercise work capacity is reduced.
9.6-11.8	*Manifest hypoxia:* Degradation of higher mental processes and neuromuscular control, loss of critical judgement and volition, with dulling of the senses. Emotional behaviour may vary from lethargy and indifference to excitation with euphoria and hallucinations. Marked increase in cardiovascular and respiratory activity. This is the region likely to be particularly dangerous, representing the catastrophe point as a victim passes from this stage into the fourth stage (critical hypoxia) at approximately 10 vol% oxygen.
7.8-9.6	*Critical hypoxia:* Rapid deterioration of judgement and comprehension leading to unconsciousness followed by cessation of respiration and finally of circulation at death.

Table 5.5 Human effects of reduced oxygen concentration. Reference: OSHA [36].

Oxygen (vol%) at sea level	Symptoms
17	Deterioration to night vision, increased breathing volume, accelerated heartbeat
14-16	Very poor muscular coordination, rapid fatigue, intermittent respiration
6-10	Nausea, vomiting, inability to perform, unconsciousness
< 6	Spasmatic breathing, convulsive movements, death in minutes

According to table 5.1-5.5 very low concentration or a complete lack of oxygen will lead to death within a few minutes. Reduced oxygen concentration for a short period of time will cause irreparable brain damage. Higher concentrations of oxygen, but still lower than normal, will affect the brain cells and change the human behaviour. These symptoms are reversible, but faulty judgements and problem with coordination may lead to mistakes that can cause serious accidents [34].

Reduced oxygen concentration is a normal physiological occurrence, for example during exercise and at high altitude. The body have natural compensative mechanisms that are able to compensate for a reasonable low concentration of oxygen. The respiration will increase and brain blood vessels will be slightly dilated [37]. Because of the compensate mechanisms, the physiological status and behaviour task performance will only be very little decreased at moderate low oxygen concentration or above approximately 12 vol% oxygen according to table 5.1-5.5. The body tries to maximize the oxygen concentration to the brain, but when the concentration is too low the mechanisms will not succeed. When oxygen concentration in the body reaches a certain point, referred as catastrophe point in table 5.4, there will be a sudden change from a condition of near normality to a condition with severe effects. The oxygen concentration in the tissues becomes critical and this will usually lead to unconsciousness. This very rapid change occurs approximately at 10 vol% oxygen [26].

Regarding to “NFPA 2001 Standard on Clean Agent Fire Extinguishing Systems” [5] the NOAEL-value (No observed adverse affect level) is 12 vol% oxygen and LOAEL-value (Lowest observable adverse affect level) is 10 vol%.

NAEG's report [38] presents the experts review and opinion about reduced oxygen concentrations. These criteria are based on short-term exposure (up to 20 minutes). It was concluded that people should not suffer from adverse effects if the criteria in table 5.6 are followed. The criteria are different if carbon dioxide (CO_2) is present, because of its effect on human breathing, see appendix I.

Table 5.6 Criteria if adverse effects should be avoided. Ref: NAEG [38].

Oxygen (vol%) at sea level	Exposure time CO_2 level is normal (0,03 vol%)	Exposure time CO_2 level is 2.5-5.0 vol%
12-15	10 min	20 min
10-12	1 min	2 min
< 10	No exposure	No exposure

The effects on human tissues are important for the understanding of why reduced oxygen concentration can be a health hazard. Different organs in the body react in different ways and some primary organs reactions and important aspects are explained in appendix J.

5.4 Cognitive and psychomotor performance

Mood and several cognitive and neurophysiological functions are impaired when the oxygen concentration is less than 13 vol% in normobaric hypoxic air. Evidence of this is has been shown in several experiments [30]. Acclimatization by continuous exposure to hypoxic air prevents or delays many of effects on brain functions. This is indicated by several studies [30]. The severity increases when oxygen concentration decreases.

Memory is impaired in some experiments but individual differences are large. Some reports conclude that learning a new task is one clear-cut effect of mild hypoxia (1500-4000 metres or 17.4-12.7 vol% oxygen) but more recent studies show no evidence that learning is impaired [30]. Experiments performed at the corresponding oxygen concentration of 13-15 vol% oxygen show no clear results. Some experiments demonstrate no effect while other show mild or temporary impairment of cognitive functions, but individual variations are large. Possible effects are increased reaction time and decreased accuracy. Performance of complex cognitive tasks and demanding memory functions may be impaired.

In a literature review done by Gustavsson et al. [9], the authors came to the conclusions that research results from 27 studied experiments were divided into two approximately equal sized groups. The first half state that reduced oxygen concentration impairs performance and the other half states that the performance is unchanged. This shows the major uncertainties in this area. However, learning a new task appears to be the most sensitive function in hypoxic air [9].

Physical, psychomotoric and mental performance are studied by Angerer et al. [32]. Persons are exposed to 2 hours work within a reduced oxygen environment corresponding to 15 and 13 vol% oxygen at sea level. No effects were found on performance in cognitive and psychomotoric tests. No medical complication was found, but potentially endangered persons have been excluded from the experiments. These results indicate that 2 hours is safe, but limitation of stay and health checks are recommended if a person enters hypoxic environment temporarily.

5.5 Living at high altitude

Many people live and work at altitudes higher than 3000 metres. They breathe hypobaric hypoxic air permanently, which corresponds to an oxygen concentration of less than 15 vol% at sea level. Some people in Himalaya live at some of the highest altitude in the world, up to 5000 meters. People at high altitude are exposed to hypoxic air 24 hours a day and the body will adapt to this chronic hypoxic stress, see more about adaptation in 5.8. Several studies have been done on people living at high altitude. Conclusions from one study show that people exposed to high altitude from birth to adolescence resulted in an efficient oxygen transport in blood and greater aerobic exercise performance [39].

One question to ask oneself is whether people living at high altitudes are healthier than those living at sea level. Many researches indicate that this is true, but the question is if the health status only relates to altitude. Other parameters may also affect the human health e.g. genes and less air pollution.

5.6 Acute mountain sickness

The development of illness due to travelling to high altitude has been known for many decades. First at present time researchers named the phenomena to acute mountain sickness (AMS). The first and most common symptom of AMS is headache and this is usually followed by more severe symptoms. The symptoms usually come within hours to three days [40]. The symptoms can be many and vary with initial altitude, rate of ascent and the physical exercise the next coming 24 hours [9]. Some typical AMS symptoms are shown in table 5.7 and these are necessary to be aware of when entering a hypoxic environment.

Table 5.7 AMS symptoms [9, 40]

Frequency	Occurrence	Symptoms
Very common	Usually from 1500-3000 metres to higher altitudes for unacclimatized travellers	Headache, anorexia, insomnia, nausea and vomiting
Common	Fast ascent in short time	Weakness, lassitude, general malaise, decreased coordination, dizziness or light-headedness and oliguria.
Unusual	Very high altitude or very high ascent in short time	Cerebral edema, tissue edema, fine motor control and balance, hostile behaviour changes with thoughts of paranoia, depression, anxiety and obsessive-compulsiveness predominating.

Certain groups of people are more likely to suffer of AMS, for example people with certain heart diseases, pulmonary diseases or haematological diseases. Some healthy people are also more likely to suffer from AMS by reasons like high physical activity when arriving at high altitude or people with previous problems with AMS [40]. It is worth mention that there is a great difference in individuals' experience of AMS and acclimatization to high altitude.

5.7 Physical fitness

People with low physical fitness are more sensitive to high altitude and will have an increased risk for AMS. This is indicated by different reports, but the relation between physical fitness and altitude is unclear and some report show the opposite result [41].

High altitude training or hypoxic training is described in appendix K. This section will give the reader an understanding for how hypoxic air can be used for other applications than fire prevention. This will also give a deeper understanding of how the human is affected by reduced oxygen concentration.

5.8 Adaptation

In this chapter different experiments have been studied of the human adaptation to hypoxic environment. The experiments are divided into different sections with respect to the exposure time. The following three sections start with short-term adaptation and continue with medium-term adaptation and long-term adaptation.

- Short-term adaptation corresponds to an exposure time of only a few minutes
- Medium-term adaptation corresponds to an exposure time of several hours
- Long-term adaptation corresponds to an exposure time of more than seven days in succession

5.8.1 Short-term adaptation

In tests where humans are exposed for short-term intermittent normobaric hypoxia results show that background CO_2 level in lungs increases after exposure. Tests also show some evidence of increased ventilatory sensitivity if being exposed repeatedly [42]. Increased heart rate is also to be expected both at rest and at high workload [9].

Short-term intermittent tests were performed with six repetitions of five minutes inhalation of hypoxic air consisting of 10 vol% oxygen alternating with 3 minutes inhalation of normoxic air. At the end of the tests the pulmonary ventilation increased with as much as 25%, a natural reaction from the body trying to compensate to the increase of CO_2 in the lungs.

After 60 minutes exposure to normobaric hypoxia, the pulmonary ventilation, gas exchange and saturation of blood are back to normal values, but CO_2 level is still 10% higher in the lungs.
Some individuals get the opposite result with lower value of CO_2 in the lungs after the exposure. This result is not further discussed in the referred article. Indication from the tests shows an increased tolerance for hypoxic air, but no difference in the effect of CO_2 [42].

5.8.2 Medium-term adaptation

This section is a review of experiments done for respiratory responses to normobaric hypoxic air [43]. The experiments are carried out with twelve males sleeping for 8-9 hours per night for five consecutive days at a simulated altitude of 4300 metres, corresponding to 12.2 vol% oxygen at sea level. The experiments tested the hypothesis that five consecutive nights of normobaric hypoxia would resemble the same changes in respiration control as for chronic altitude exposures. Ventilation increases further more than in the short time exposure and the amount of red blood cells increases. After acclimatization the heart rate will reduce to the normal value, same as normal at sea level [9].

The majority of the exposed individuals experienced symptoms of AMS as mild headache and insomnia during the first night of sleep. These AMS symptoms became very mild during the following four nights of sleep. The experiments show that the time for acclimatization and de-acclimatization was very similar. The experiments also show results that support the above mentioned hypothesis [43].

5.8.3 Long-term adaptation

During long-term exposure of a hypobaric hypoxic environment, red blood cells will increase even more than in short and medium-term adaptation and the plasma volume will slowly reduce to sea level volume due to acclimatization. The ventilation reduces and is stabilized just above the value at sea level. The heart rate is the same as in short-term adaptation and the vascular increase seen in medium-term adaptation decreases but not to the sea level value [9].

5.9 Diseases

Persons with certain diseases may be exposed to a situation where oxygen supply is decreased to the same level as for healthy persons at extremely high altitudes. Diseases are investigated in Angerer et al [30]. Other diseases than discussed below or pregnant women are not discussed in that report. Evidences are limited and therefore monitoring of individuals is necessary.

5.9.1 Heart diseases

Experimental studies show that people with heart diseases are expected to have a markedly increased risk when exposed to hypoxic air, but the risk is surprisingly low [30]. However, exposure time in experiments is often short and people with severe heart diseases are not studied in detail. Possible effects on people with heart diseases are acute coronary syndrome, life-threatening arrhythmia or cardiac decompensation. These effects are not supported by the studies but the risk should not be excluded. Examples of heart diseases are coronary artery disease (COD) and chronic heart failure.

The strain on people with heart diseases is greatest in the first hours. That is due to the fact that the body adapts to hypoxic conditions. Air travel is not recommended 2-3 weeks after a myocardial infarction. These recommendations are from The American Heart Association and American College of Physicians [30] and are applicable on hypoxic environment as well.

5.9.2 Pulmonary diseases

The general symptom for people with pulmonary diseases is reduced oxygen in the blood. This means that the oxygen partial pressure in the blood is lower compared to healthy persons. Living with a pulmonary disease at sea level is comparable to a healthy person living at high altitude. This means that the symptoms caused by hypoxia appear at higher oxygen concentrations. In conclusion, the safety margin will decrease for people with pulmonary disease. Examples of pulmonary diseases are chronic obstructive pulmonary disease (COPD) and cystic fibrosis.

5.9.3 Haematological diseases

A haematological disease affects the quality or quantity of haemoglobin. The amount of haemoglobin is critical since it carries oxygen to the tissues. If a subject suffers of sickle cell disease, hypoxic conditions may lead to sickle cell crisis, which means that haemoglobin changes its structure due to reduced oxygen [30].

5.10 Age and sex

The ageing process on humans has a negative effect on the capability to transport oxygen in the blood [44]. This means that the oxygen saturation decreases and the conclusion is that elderly people are more sensitive to reduced oxygen concentration.

Some researches found that there is a slight difference between male and female regarding oxygen transportation. Females have higher oxygen saturation than males during the female reproducing span (up to 50 years of age) [44]. Some research indicates that acute mountain sickness (AMS) is less common in females. This is perhaps because of the presence of higher levels of the ventilatory-stimulating hormone progesterone, but other reports and studies do not show any sex differences [41].

5.11 Lifestyle

Alcohol has many negative influences on altitude sickness like impaired judgement, depressed respiration and dehydration. The short-term effect of tobacco dominates by the carbon monoxide accumulation, which restrains the haemoglobin from transporting oxygen effectively to the cells [40].

Sleeping at high altitude has many disadvantages and travellers doing so often experience restless sleep of one or more causes. At intermediate altitude (around 1500-3000 meters) many experience periodic sleeping, frequent wakening and rapid eye movement. At very high altitude over 6300 metres, the majority experience periodic sleeping. Sleeping at very high altitude will be continuously disturbed but at intermediate altitude it will go back to normal due to adaptation, same as for other AMS symptoms [40].

5.12 Synergic effects from toxic fire gases

In this chapter, the most conspicuous substances from fire gases are discussed. The most important interactions are between CO_2, CO, HCN and hypoxia. Interactions between different smoke products produced by the fire are very hard to tell. Little research is performed about synergic effects, partly because hypoxic environment as fire prevention is rather new.

The materials of today's interior of buildings are highly complex. More and more synthetic materials are used when building and furnishing properties. These materials tend to produce more smoke than natural occurring materials, like wood. The effects of toxic gases on humans produced during fires are especially interesting to investigate, especially since the majority of fire fatalities result from smoke and not from burns. Plastic materials can for example produce more than 400 different combustion products.

The problem with synergic effects is to identify the component in the gas that is toxic or a combination of them that are toxic. It is hard to determine the interactions between them, sometimes the effects may be additive and other times equalize each other. The best approach to the problem with synergic effects is to study different gases and suggest likely degrees of interaction between them and combine them with data from experiments that exists [26]. The interaction of toxic fire gases from fires are hard to predict and are highly dependent on the fire scenario. For most cases, if considering the asphyxiant effect of fires, CO is the most important toxic product. CO_2 is the most important interaction due to the increased uptake of CO because of the hyperventilation caused by CO_2. The additional effects of HCN and hypoxia will further more contribute to the effects of CO. This may significantly reduce time to incapacitation in some situations [26].

The CO_2 is the most lethal gas in combination with other fire gases due to its respiratory effects. By adding CO_2 to the air, the respiration is increasing and the lungs are exposed to more oxygen due to the higher air intake, see more in appendix I. The effects of CO and HCN are that CO reduces oxygen carriage ability for the blood and HCN reduces the tissues ability to use the oxygen after delivered. These effects look like additive and especially because HCN has an increased respiration effect, they should be considered to be additive [26]. Hypoxic environment with following hypoxia and CO both reduces the oxygen concentration in the arterial blood and CO also decreases the ability for the blood to carry oxygen to the tissue. These facts point in the direction that CO and hypoxia would have some degree of addition [26].

An experiment performed on animals decides LC50 values on rats for CO, CO_2, HCN and with or without a combination of reduction in oxygen concentration. The effects measured 30 minutes exposure and post exposure if necessary. Fire gas toxicity was increased when test animals were exposed for hypoxic environment. The conclusion from this test shows that the less oxygen concentration in environment the higher toxicity of fire gases is produced. During experiments the majority of test animals died during the time they were exposed to toxic gases in hypoxic environment [45]. The threshold for deaths due to hypoxia was increased if 5% CO_2 were added to the environment at the same time as the LC50 value for HCN was decreased. The value of 5% carbon dioxide where chosen because it appeared to be the most toxic value when combined with carbon monoxide [45].

5.13 Probability of detrimental effects to health

The probability of detrimental effects to health at different oxygen concentrations has been evaluated. The purpose of this probability relation is to be a valuable input for the scenario analysis in chapter 9. This relation is general and illustrates the probability of human effects at different oxygen concentrations. People are different sensitive to reduced oxygen concentrations; some will endure lower concentration better than others. The model is only valid for healthy people and if other populations will be added to the model, a safety margin must be used. Safety margin is more discussed in 9.1.

In table 5.8 the effects on humans are summarised from table 5.1-5.5. Symptoms are grouped into oxygen concentration intervals where the effect is most likely to appear according to table 5.1-5.5. There are differences between the effects in tables 5.1-5.5, but there is a clear tendency of equality. Some of the intervals in table 5.8 are overlapping each other, which show a distribution. It exists uncertainties both for individuals and the data found in literature.

Table 5.8 describes the effects at different oxygen concentrations (dose-effect relation), but does not say anything about the fraction of people that are affected at different concentrations (dose-response relation). Data about dose-response is hard to find and therefore the probability relation is based on dose-effect relations. Table 5.8 is only valid for people with good health.

Table 5.8 Summary of human effects of reduced oxygen concentration according to table 5.1-5.5.

Oxygen (vol%) at sea level	Symptoms
14-21	Effects on night vision
12-21	Increased breathing, increased heart rate
12-17	Physical and intellectual performance impaired, fatigue, headache
10-14	Disorientation, faulty judgement
6-12	Nausea, vomiting
6-10	Unconsciousness
< 10	Death

Exposure time is not included in table 5.8. Exposure time for survival is of high importance and these values are summarised in table 5.9. A few minutes are necessary before the air in the lungs and the gases in the blood reach equilibrium with the new oxygen concentration in the air. This time step is often neglected in the literature and it is uncertain if this is included in table 5.9.

Table 5.9 Summary of exposure time for survival according to table 5.1-5.5.

Oxygen (vol%) at sea level	Exposure time
8-10	8 min
4-8	2 min
< 6	Minutes

Figure 5.2 illustrates the probability of human effects according to table 5.8. The probability functions are assumed to be normal distributed but this has not been analysed further. The functions represent the 95% percentile according to the intervals in table 5.8. Moreover, 97.5% of the humans are assumed to be dead if exposed acute to reduced oxygen lower than 6 vol%. The functions are only assumed to be normal distributed, but other distributions may be present in reality. However, normal distribution is a common distribution for illustration of biological occurrence. The figure is connected with uncertainties and is best used as an illustrative figure of health effects. The distributions in figure 5.2 are only valid for healthy persons. Some individuals are more or less sensitive to oxygen concentration than represented in the curves and a safety margin must be added for other populations than healthy people.

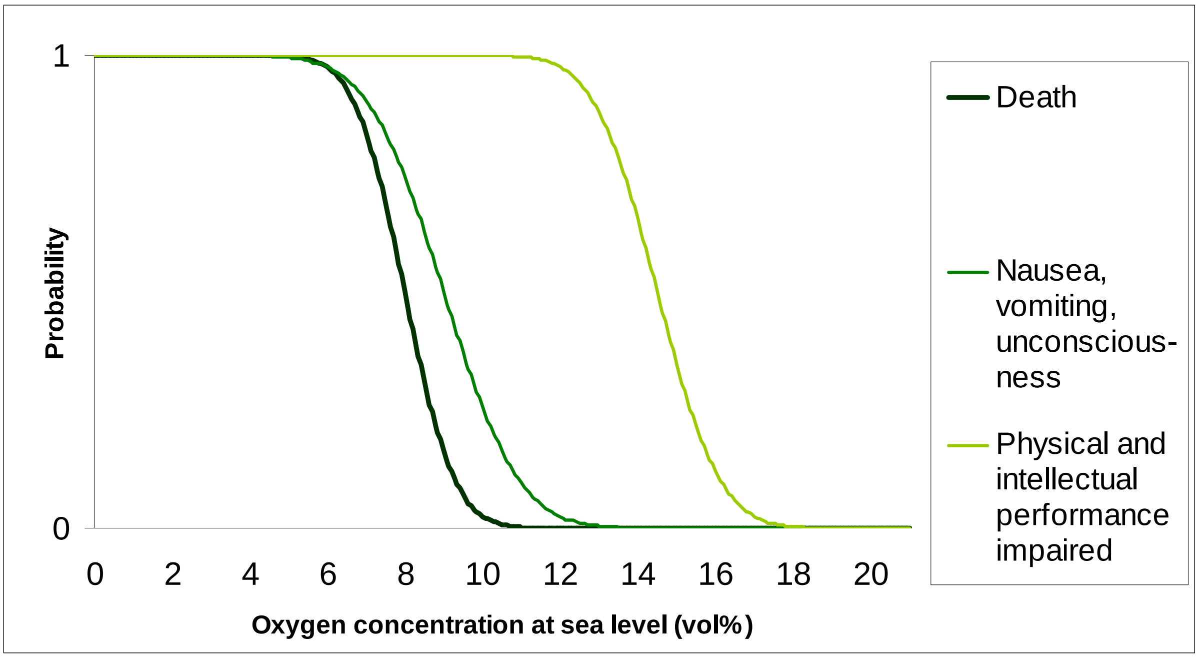

Figure 5.2 Probability of detrimental effects to health according to table 5.9.

The gradient of the curves in figure 5.2 is steep, which means that a small change in oxygen concentration at sea level will change the hazard for humans significantly. The effects will be obvious very rapidly if the concentration drops, equally to the “ketchup effect”, and the warning signs will be too late to alert the senses for hazardous conditions.

6 Safety management

Safety management is an important aspect to consider when designing technical systems. This must pursue in the whole width of a company's structure from the top leadership to the last employed worker. As seen in figure 6.1 safety management consists of policy, routines and instructions. These three blocks represent different levels of the organisation. Except policy, routines and instructions, the feedback is a crucial factor. The feedback should go both from top and bottom of the organisation to get a continuously improving organisation.

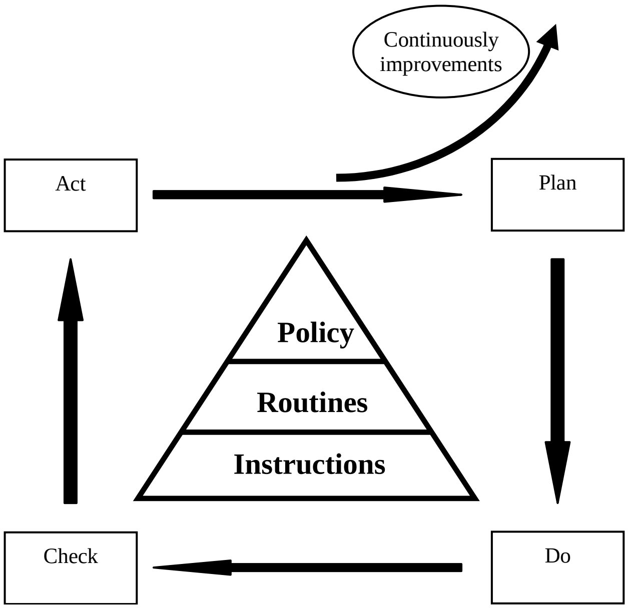

Figure 6.1 Structure and model for safety management [47].

To get a continuously improving organisation it is crucial that the blocks are closely linked with each other and that the feedback in both directions is working sufficiently. The management should work from a PDCA perspective. PDCA means; plan, do, check, act and this is a way to treat continuously improvements.

6.1 Policy

Companies that operate enclosures with hypoxic environment should have a policy regarding the hypoxic environment. The board of the company draws up global goals for the whole company and the policy must give general direction of the companies' overall goals.

It is of great importance that new findings in the area of hypoxic environment are continuously evaluated to keep the policy updated. Especially as the area of use is rather new and new experiments and findings are probable to come after the projection time of the installation. If the companies' management is not capable to gather new information to keep their policy updated, they have to get help from consultants with experience in the area.

6.2 Routines

The managers and directors of the business receive a policy from the board of the company and will have to plan how to fulfil the goals and how arising situations must be handled.

Example of areas that should be affected by routines:

- Education of employees. Employees should receive the right information and this is especially important for new employees.
- Health checks of new employed and continuously update employees health status regarding the special conditions with reduced oxygen concentration.
- Continuously practicing of emergency routines.
- Integrity checks of the enclosures so that air exchange is minimised.
- Control of fire safety equipment: fire extinguishers, fire hoses, emergency exits, smoke detection system etc.
- Minimise fuel and ignition sources, which will decrease the probability for ignition.
- Have routines for what kind of materials that can be entered in the protected enclosure. To make the fire prevention work as optimal as possible it can be necessary to forbid entrance for certain fuels in the enclosure. What material that will be prohibited depends on material characteristic and the design concentration in the protected enclosure.

6.3 Instructions

To actually fulfil the policy and the goals, the managers have to design detailed instructions of how the day to day work shall pursue. Instructions could be how maintenance and service must be performed and where and when oxygen measuring must be done.

Example:
A smoke detection system can act as a good example where safety management can be exploited. In this example the company's board have decided in the policy that the consequences of a fire should be minimised and that it should be less probable that people could get injured. This policy forces people at manager level to draw up routines to make this vision in the policy to come through. In this case a smoke detection system was installed. To get this system to operate correctly, managers also have to draw up instructions that employed can follow.

6.4 Improving organisation

Without feedback the safety management is unlikely to work properly. To gain a continuously improving organisation the feedback is to be used. The feedback should not only go from top management to the employed but the other way too. To be assured about effects of policy, routines and instructions the employees should have the ability to give feedback.

6.5 Revision

Revision is for many companies a yearly recurrent event but it should be a constant course of event. The company and the board of the company should constantly work to improve their safety management. Revision could include; safety management and organisation, regulations and licences, report, education and maintenance. It is of importance that the policy, routines and instructions are shaped for the kind of organisation it is supposed to act on. The safety management work ought to be proactive and be evaluated continuously of an external audit.

6.6 Regulations and standards

Hypoxic environment is a new technique and therefore it is hard to find standards and regulations valid for this technique. Regulations and standards are not written for hypoxic environment, but some are applicable in this area. Information about fire extinguishing systems is found, but conclusions are not directly transferable to fire prevention. This chapter briefly points out how a reduced oxygen concentration is treated for confined spaces in UK, USA and Sweden. This is not a complete study of today's paragraphs but gives a sample of typical regulations and standards that is present for abnormal oxygen concentrations. Hopefully regulations and standards valid for hypoxic environment will arise in the future.

UK

In the UK, Health and Safety Commission (HSC) describes the risk with reduced oxygen concentration in Confined Space Regulations 1997 (HSE Document L101) [48] as follows: *"There are substantial risks if the concentration of oxygen in the atmosphere varies significantly from normal (ie 20.8%). For example, oxygen enrichment will increase flammability of clothing and other combustible materials. Conversely a relatively small reduction in the oxygen percentage can lead to impaired mental ability. The effects are very rapid and generally there will be no warning to alert the senses. This can happen even in circumstances where only a person's head is inside a confined space. Very low oxygen concentrations (i.e. below l6%) can lead to unconsciousness and death. Any difference in oxygen content from normal should be investigated, the risk assessed, and appropriate measures taken in the light of the risk."*

In the UK any environments lower than 16 vol% oxygen would fall under the Confined Space Regulation. A risk assessment that investigates the risk should be performed to comply with the regulation. A risk assessment for hypoxic environment is suggested in this report as well. The risk assessment should be valid for investigation of both the fire risks and health risks.

USA

In the USA, Occupational Safety & Health Administration (OSHA) defines hazardous atmosphere as *"…an atmosphere that may expose employees to the risk of death, incapacitation, impairment of ability to self-rescue (that is, escape unaided from a permit space), injury, or acute illness from one or more of the following causes…"*. The standard then goes on to list five causes, one of which is *"...atmospheric oxygen concentration below 19.5 percent...."* [49].

Obviously, hypoxic environment is below 19.5 vol% oxygen and it is clearly mentioned in the OSHA standard that this environment could be dangerous if the oxygen concentration is below 19.5 vol%.

Sweden

In Sweden, Arbetarskyddsstyrelsen has written general advice about work in confined spaces (AFS 1993:3 [50]). *"The atmosphere in a confine space could, related with work, result in different risks. Unhealthy, explosive or flammable vapour or gases can occur in dangerous concentrations as too high or too low concentrations of oxygen…"* The general advice then goes on about reduced oxygen concentration *"An oxygen concentration of 15-17 vol% could result in symptoms as fatigue and increased heart rate. If the concentration decreases more, it could result in problems for the exposed to evacuate and risk for asphyxiating could exist. The cause of too low oxygen concentrations in a confined space could for example be: When the space is filled with other gases the oxygen concentration will decrease. This could have been done deliberately e.g. the space is filled with inert gas in order to reduce the risk for a fire and explosion. This could as well be due to leakage, mistake or similar."*

In Sweden this advice clearly describes the risk with reduced oxygen concentration in a confined space. It is not especially written for hypoxic environment but can however be used when conclusions are drawn.

7 Technical description

In this chapter the technical aspects are described for a typical system that protects an enclosure with hypoxic air. A schematic figure is presented in figure 7.1, which describes how hypoxic air is achieved and maintained. Information about a typical hypoxic environment is gathered from a site visit from an installation designed by Wagner UK Ltd [51]. The authors of this report have also been in contact with other manufactures that design similar systems e.g. Minimax GmhB and Lowndesconsult Ltd. The schematic view below is written for a general hypoxic environment.

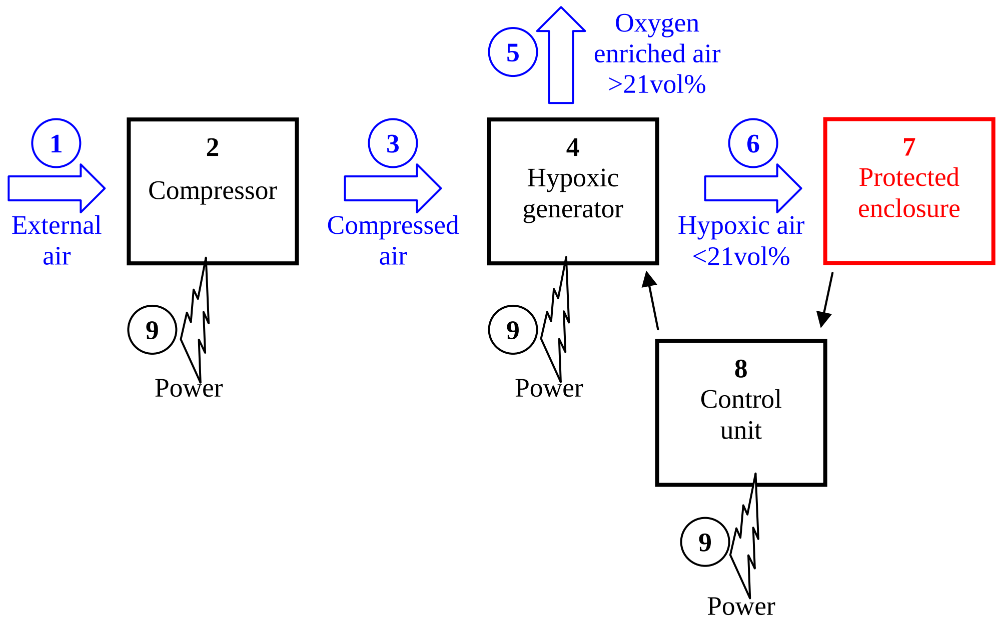

Figure 7.1 Typical concept of a hypoxic environment.

7.1 Process description

External normoxic air (1) is sucked into a compressor (2). The air is normally compressed to 10 bar or more. The compressed air (3) is dehumidified and significantly reduced from pollution before it enters the hypoxic generator (4). Hypoxic air is produced by a generator that filters out oxygen and results in two different streams, one stream contains of oxygen enriched air (5) and the other one contains of hypoxic air (6). The oxygen enriched air flows out to the atmosphere and hypoxic air supplies the protected enclosure (7).

The oxygen concentration of the hypoxic air that flows into the enclosure must be lower or of the same value compared to the oxygen design concentration. The generator supplies the enclosure with hypoxic air until the design concentration is reached. The hypoxic air is transported through pipes to the protected environment. For big enclosures multiple pipes and multiple inlets must be used to create a homogeneous mixture. Hypoxic inlets must be installed at different positions and different heights for appropriate performance. Monitors will measure the oxygen concentration both in the generator and inside the protected enclosure. A control unit (8) controls the concentration and will keep it to the design value. If the oxygen concentration rises due to external air supply, e.g. a door opens; more hypoxic air must be supplied through the inlets. If the value is lower than design concentration, the generators are simply turned off. The compressor, the hypoxic generator and the control unit consume electrical energy and power (9) is absolutely necessary for the process.

The space where the compressor, hypoxic generator and control unit is located is recommended to be protected by hypoxic environment in order to reduce the probability of a fire in these components.

7.2 Integrity and ventilation

To maintain a constant concentration of oxygen, leakage must be minimised. The actual rate of leakage within the enclosure must be incorporated into the design of the environment. Some leakage is though needed to release the overpressure created by the hypoxic air inflow. If the integrity is disrupted, for example when a door or a window is opened to the outside, normoxic air will be added to the enclosure. This will result in increased oxygen concentration, which will increase the probability of a fire in a short period of time. The time it takes depends on the opening geometry and the rate of air movement.

The design of the ventilation system is important, especially if the ventilation system distributes air both to rooms with hypoxic air and to rooms with normoxic air. Limited air movement and ventilation are necessary in a protected enclosure. It must be isolated from the ventilation system that supplies the room with normoxic air. Ideally, less than 1 complete air change per hour at 50 Pascal pressure is preferred [52].

7.3 Oxygen monitoring

Monitors that display oxygen concentration should be installed. These should alert personnel if oxygen concentration decreases below a preset value. As mentioned in 3.6 water vapour has an influence on the oxygen concentration. This is important to have in mind when an enclosure will be controlled with a certain concentration of oxygen. Monitoring of the actual oxygen concentration with consideration to humidity is important.

7.4 Smoke detection system

Even if the materials do not develop into flaming fires, there is still a potential problem with pyrolysis and smouldering combustion. Common products like textiles, paper, wood, rubber and polymers may still burn at a reduced rate with no flames. Smoke and particles are still produced under these conditions, which creates a toxic environment for humans and a destructive environment for sensitive equipment, e.g. computers.

The use of an air sampling detection system is recommended for hypoxic environments. Such a system is very sensitive and can detect different amounts of smoke well before flaming fires are present. This can be used to give different pre alarms or alarm signals depending on how much smoke is detected. It provides a great opportunity for management to start acting in a pre determined way when the pre alarm sounds. The time from pre alarm to alarm could be used to investigate and if necessary taking action against an eventual fire before evacuating the building. Safety management plays a central role and it is important that the staff is well educated in standard operating and emergency operating procedures.

A temperature difference between the smoke and the surrounding air is needed to raise the smoke upwards. This is required for early detection of a fire, but is not always the case, especially for smouldering fires.

8 Safety risks

This chapter briefly describes and discusses the hypoxic environment and the safety risks with the environment. A brief analysis is done, and this illustrates important aspects that need to be included in the design process. Distribution of oxygen is important to ensure the safety.

8.1 Initial risk analysis

An initial risk analysis is presented in table 8.1, and this describes critical components and possible consequences due to a possible failure. Recommended actions are presented to prevent these risks. Note that this analysis is brief and only illustrates possible safety risks with the environment. A more detailed and comprehensive analysis should be done to analyse the magnitude of the possibilities and the consequences.

Table 8.1 Initial risk analysis for safety risks.

Component	Failure	Oxygen concentration	Probability for health risks	Probability of a fire	Prevention action
Power supply	No power	Too high	Decrease	Increase	Reserve aggregate
Compressor	Not working	Too high	Decrease	Increase	Double compressors (One backup or two continuously operated)
Filter	Ineffective	Too high or too low	Decrease or increase	Decrease or increase	Spare filter. Change filter according to information from manufacture
Control unit	Not working	Too high or too low	Decrease or increase	Decrease or increase	Multiple control units, regular test
Oxygen monitors in air inlet	Not working	Too high or too low	Decrease or increase	Decrease or increase	Multiple oxygen monitors
Oxygen monitors in enclosure	Not working	Too high or too low	Decrease or increase	Decrease or increase	Multiple oxygen monitors
Pipe system	Leakage, blocked	Too high or too low, heterogeneous mixture	Increase	Increase	Regular pressurising test
Smoke detection system	Not working	Increased risk for undetected fire	Increase	Unchanged	Multiple detectors, regular test
Enclosure	Leakage, doors opened	Too high or too low, heterogeneous mixture	Increase	Increase	Regular integrity test and instructions to employees
Ventilation	Incorrect air exchange	Too high or too low, heterogeneous mixture	Increase or increase	Decrease or increase	Correct installation and maintenance of ventilation system

The consequence is worse when the oxygen concentration is too low. The human health will be affected instantaneously of this. Too high oxygen concentration will result in an increased probability of a fire but this does not mean that a fire will start at once.

Inspection and maintenance are important to ensure reliability. A testing procedure should be developed and done regularly. A user friendly system is desirably to ensure that mistakes in the operation procedure are minimised.

8.2 Distribution of oxygen

Homogenous mixture of hypoxic air (nitrogen/oxygen mixture) in a protected enclosure is important. In case of too high concentration the fire prevention may not work as intended and too low concentration may expose the occupants to unnecessary health risks. It is almost impossible to avoid fluctuations, but this should be minimised and controlled at the design concentration.

Figure 8.1 illustrates an assumed probability function for distribution of oxygen. The fluctuations are mainly due to the sensitivity of the system. Environmental factors e.g. the size of the enclosure and the distance between hypoxic inlets affects the desired homogenous mixture. Acceptable fluctuations must be analysed for different applications.

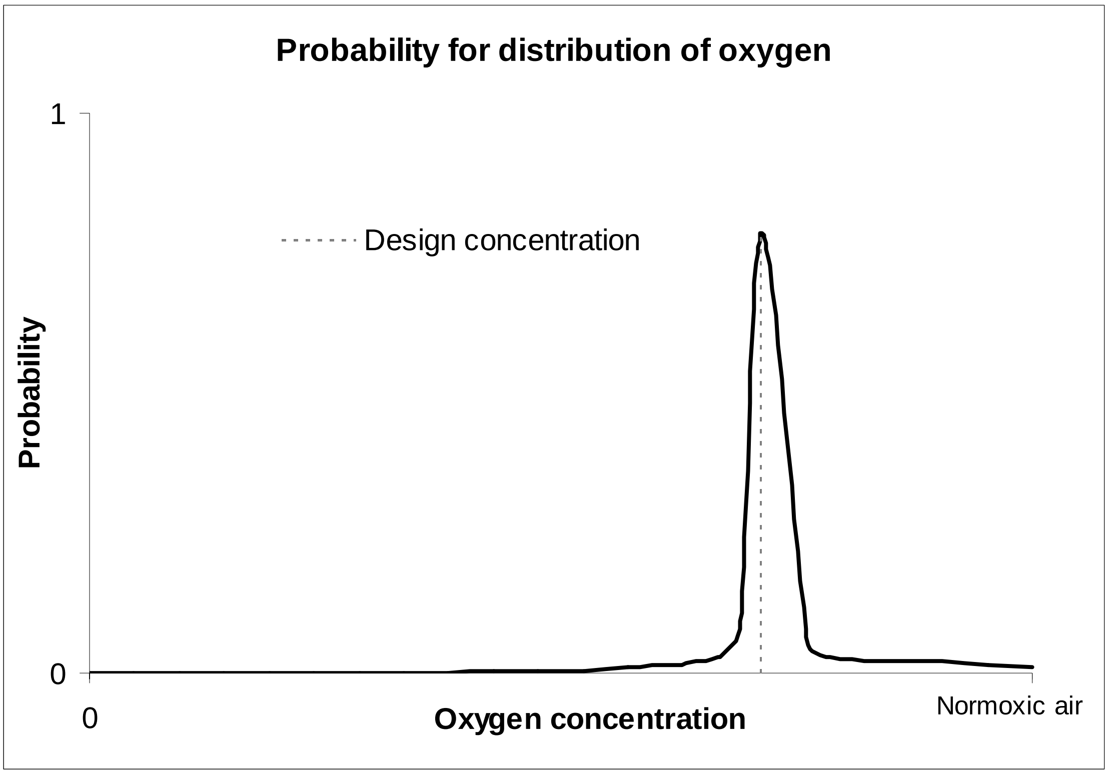

Figure 8.1 Probability for distribution of oxygen in the protected enclosure.

An enclosure may be unprotected to fires or be a health hazard due to incorrect or heterogeneous oxygen concentration. A value that differs significantly from the predetermined oxygen concentration could depend on many factors. These factors are analysed in table 8.1 and continuous maintenance of the system is one way to minimise the safety risks.

In case of a power failure the oxygen concentration will not rise to normal concentration immediately. The time it takes to rise to normal oxygen concentration depends on the integrity of the enclosure and it is important to calculate and consider this during the design process. If the enclosure has valuable content or poor integrity a backup power system is preferred.

If the oxygen concentration in the inflowing hypoxic air has a lower oxygen concentration than the predetermined design concentration there can be a gas mixture problem in the enclosure. Even if nitrogen is a natural occurring content in the air the added hypoxic air can not just diffuse into the hypoxic air in the enclosure. The mixing of the added hypoxic air has to be made with help of convection. The convection can be maintained with fans in the enclosure and by a high velocity of the inflowing hypoxic air. Monitoring of the oxygen concentration in the enclosure should be carried out on many different places and should be measured individually.

9 Scenario analysis

In this chapter the fire behaviour and health effects are linked together. Hypoxic environment is studied in four different scenarios, and these are studied to give a comprehensive description of the subject. What happens with the human and the fire in these scenarios? From previous knowledge studied in the report these cases cover the main area of interest, see figure 9.1. In this area there is a probability of both health effects and of a fire. The conclusions about health effects are only valid for short time occupation in hypoxic air, typically for a few hours.

Scenario 1: 17 vol% oxygen
Scenario 2: 15 vol% oxygen
Scenario 3: 13 vol% oxygen
Scenario 4: A fire occurs in hypoxic environment for scenario 1-3

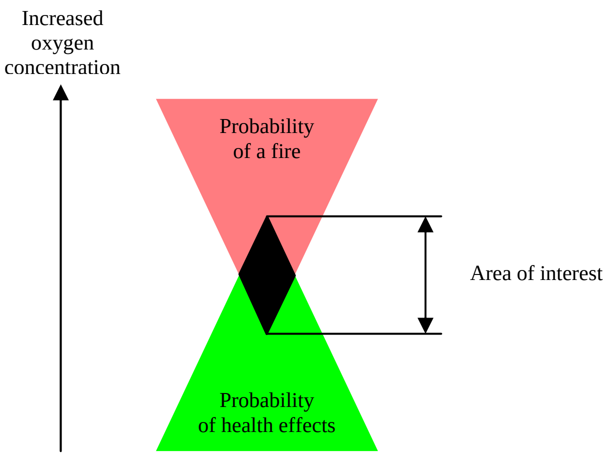

Figure 9.1 Description of the probability of a fire and the probability of health effects.

Scenario 4 shows what happens when a fire actually occurs in a hypoxic environment for scenarios 1-3. The probability of a fire will increase when the oxygen concentration is increased, but is still possible for all three scenarios.

9.1 Safety factor

When hypoxic air is used in a designed environment, it is important to use a margin of safety. Should the oxygen concentration be chosen safe for the main population or for the fire behaviour? There are uncertainties regarding hypoxic environment, especially because people have different sensitivities to reduced oxygen concentration.

Is a safety factor applicable for hypoxic environments? A safety factor of 2-5 is normally used for a health risk assessment, when the substance is relatively harmless and its effects are reversible and well established with epidemiological studies [53]. A safety factor of 100 is normally used when test results are used from animals. For hypoxic environment, a safety margin is preferred instead of a safety factor.

Referring to figure 9.2, a safety margin for both fire behaviour and health effects is impossible for this technique. If a safety margin is used for fire behaviour the probability of human effects will increase. In the same way, if a safety margin is used for health effects the probability of a fire will increase. A safety margin will not reduce the combined risk and therefore a priority between the risks must be made. In fire safety engineering life and health is often of higher importance compared to property and therefore should life and health be prioritised.

It is important to maintain a constant oxygen concentration and therefore a safety margin should be used on the individual items of equipment used to provide a hypoxic environment, e.g. multiple compressors, monitors etc.

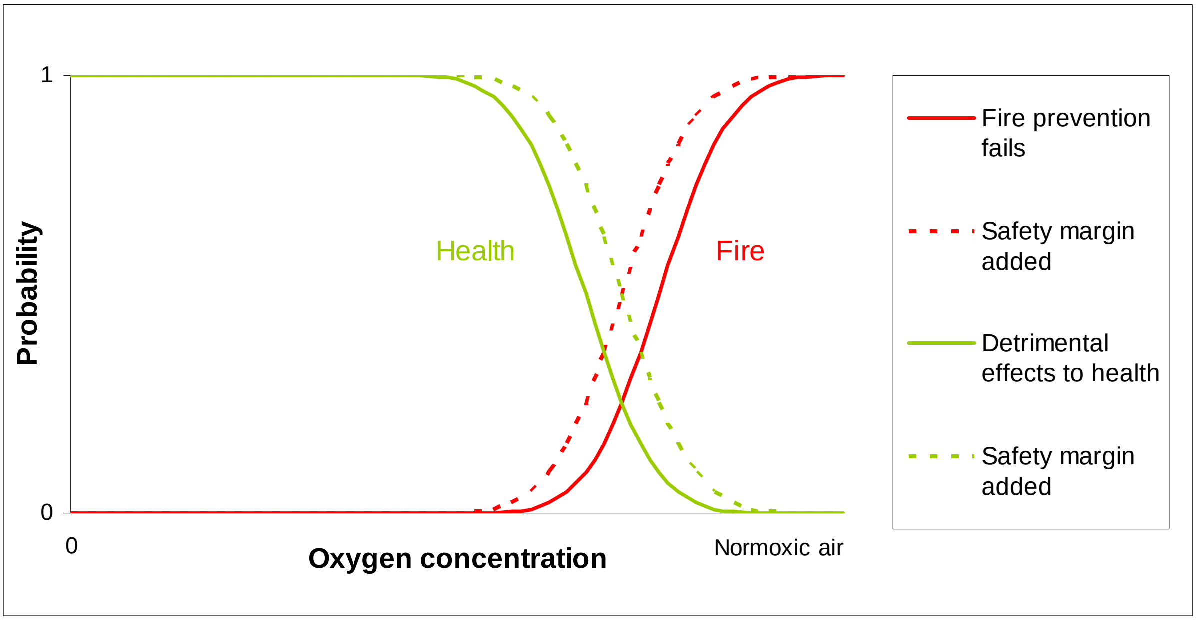

Figure 9.2 Adding a safety margin will increase the probability for either health or fire.

In normal atmospheric air at sea level, normobaric normoxic air, the safety margin to adverse health effects is wide. When using hypoxic air at moderate concentration, the condition may be safe but the safety margin is decreased. If a fire actually occurs in a hypoxic environment, the level of the safety margin is of high importance. A fire consumes oxygen due to combustion and the oxygen concentration drops, which means that the safety margin drops to zero faster than in normoxic air. This is discussed more in scenario 4.

9.2 Scenario 1

Scenario 1 represents a hypoxic environment with 17 vol% oxygen. The following will happen compared to a normoxic environment with 21 vol% oxygen:

Fire:

- The probability for a fire is unchanged according to the probability relation of fire. However, if the circumstances are favourable, some fires will actually be prevented in certain conditions, e.g. no external heat, high humidity, low temperature and compact geometry of fuel (class A materials).
- The fire behaviour will change: Heat release rate (HRR) will decrease, time to ignition will increase, burning rate will decrease etc.

Health:

- According to the probability relation of health the following symptoms could appear: effects on night vision, increased breathing, increased heart rate and headache. The visual dark adaptation is affected when the oxygen concentration is slightly reduced. This could be an issue during a possible evacuation. Therefore escape lightning and exit signage which illuminate the escape route are important equipment in the building.
- For sensitive individuals, during longer exposure and at higher workloads these symptoms are also probable: fatigue and physical and intellectual performance impaired.
- Worse effects could also occur for extremely sensitive persons.

9.3 Scenario 2

Scenario 2 represents a hypoxic environment with 15 vol% oxygen. The following will happen compared to a normoxic environment with 21 vol% oxygen:

Fire:

- The probability of a fire is slightly reduced according to the probability relation of fire. Some material where external heat is insignificant will not ignite in this scenario.
- The fire behaviour will change considerably. Heat release rate (HRR) will decrease, time to ignition will increase, burning rate will decrease etc. The geometry of the fuel is important for ignition of class A materials.

Health:

- According to the probability relation of health the following symptoms could appear apart from the symptoms mentioned in scenario 1: fatigue and physical and intellectual performance impaired.
- For sensitive individuals, during longer exposure and at higher workloads these symptoms are also probable: disorientation and faulty judgement.
- Worse effects could also occur for extremely sensitive persons.

One additional effect with hypoxic air is that it will be almost impossible to light a cigarette when the concentration is 15 vol% oxygen. This will both reduce the health risk from cigarette smoking and reduce the number of fires caused by cigarettes. It is however unclear if the smouldering combustion in a cigarette still can propagate in hypoxic environment.

9.4 Scenario 3

Scenario 3 represents a hypoxic environment with 13 vol% oxygen. The following will happen compared to a normoxic environment with 21 vol% oxygen:

Fire:

- The probability for a fire is reduced according to the probability relation of fire. Some class B and C materials will still ignite, especially if external heat is present. Smouldering fire is still possible in some class A materials.
- The fire behaviour will change considerably. Heat release rate (HRR) will decrease, time to ignition will increase, burning rate will decrease etc. The consequences from smouldering fires are small and these can be managed by an air sampling detection system.

Health:

- According to the probability relation of health the following symptoms could appear apart from the symptoms mentioned in scenario 1 and 2: disorientation and faulty judgement.
- For sensitive individuals, during longer exposure and at higher workloads these symptoms are also probable: nausea, vomiting, collaps and AMS symptoms (headache, insomnia, nausea, vomiting etc). The risk for AMS symptoms is great at 13 vol% oxygen and if the exposure time is not limited up to 50% of the persons will presumable suffer from AMS symptoms [30].
- Worse effects could also occur for extremely sensitive persons.

9.5 Scenario 4

Scenario 4 represents a hypoxic environment (13-17 vol% oxygen) where a fire occurs. This scenario is probably a worst case scenario but still possible. If a fire actually occurs in a hypoxic environment the safety margin is small and critical conditions for human probably occur faster than in normoxic conditions. The burning rate is decreased and the fire growth is slower under hypoxic conditions, but a fire still consumes oxygen due to combustion. A fire produces a lot of toxic products and oxygen is essential for survival. The proportion of toxic products will be higher when oxygen is reduced.

Fire:

- Fires in class B and C materials are the most probable fires in hypoxic environment with 15 vol% oxygen or less. However, a class A material could ignite after receiving sufficient radiant heat from a burning class B or C material. Smouldering fires are also probable, but will have a lower burning rate and therefore does not consume oxygen as much as flaming fires.

- Another case is when a fire starts outside a hypoxic environment. If a fire starts outside the protected enclosure and spreads to this area, the environment will be ineffective. A fire that is supported by external normoxic air could destroy the integrity of the protected environment from the outside. Therefore the hypoxic environment is likely to lose its fire protection. This can be a problem when using a fire protection system inside an enclosure e.g. gas extinguishing system and water sprinkler system. Therefore it is important to separate hypoxic environment and its surroundings with suitable levels of fire resistance.

Health:

- The health risks from a hypoxic environment will increase if a smouldering fire occurs. The already reduced concentration will decrease due to oxygen consumption from the fire. However, the smouldering process will be slower due to the reduced oxygen concentration but may on the other hand produce even more incomplete combusted products.

- The results from experiments with reduced oxygen concentration only treat the physiological effects under non-fire situations. Psychological effects like stress and anxiety are hard to measure but are very important during a fire situation. A fire is inconvenient and an irritant to eyes, nose and the throat because of toxic gases and particles which gives a negative and stressful feeling. The health effects studied in this report are only valid for a non-fire situation. What happens in a fire situation? It is very hard to know what will happen, but the conditions will probably deteriorate and the health hazards worsen. It is hard to predict if the health hazards will worsen more quickly than in a normal environment with 21 vol% oxygen.

10 Suitable objects and activities

This chapter describes and discusses different suitable objects and also for what type of occupants this environment can be used for. The primary objective with this chapter is to understand issues and complications that can develop during implementation of hypoxic environment. Issues and possibilities will be highlighted in the chapter. This chapter is a way to use the knowledge and conclusions from the literature review and the analyses made in this report. Conclusions from this chapter are possible to use as a help when designing a hypoxic environment.

When designing a hypoxic environment a detailed analysis is needed. Every enclosure where hypoxic environment is suitable should have a specific solution that suits the application. When is hypoxic environment suitable?

A model in figure 10.1 has been developed to give a comprehensive view of the issue and make the decision easier if an object is suitable for hypoxic environment. The model is illustrated with a decision tree, which shows the complexity and interactions of the issue from four different aspects. These four are the most significant parameters according to this report. The order of them is chosen qualitative so that the first aspect is the most important one, the second is the second important one, and so on. The model shows how the different combinations of the aspects are suitable or not. This model is a qualitative and can not be treated quantitative.

The four different aspects in figure 10.1 are:

1. Type of occupation
2. Safety management
3. Fire hazard
4. Mixture of hypoxic air

Type of occupation is the most crucial factor regarding the health aspect. Occupation is divided in three categorises: unoccupied, non public and public.

Safety management is a very significant parameter for a safe operation of the environment and is divided in three levels: poor, good and excellent. Good means that policy, routines, instructions and feedback are well working. Excellent means that safety management is working excellent and continuously improved. Poor safety management is not accepted for hypoxic environment and good safety management is only accepted for unoccupied enclosures. More explanation about safety management is given in chapter 6.

Fire hazard include ignition sources, properties and amount of flammable materials, geometry of class A material etc. and is divided in three categorises: low, moderate and high. Low and moderate mean that no class B and C materials are present. Ignition sources must be insignificant and geometry must be carefully organised for compliance with low fire hazard. High fire hazard is only accepted in unoccupied enclosures since the oxygen concentration required for this case will result in unacceptable health effects. High fire hazard is therefore excluded from public and non public enclosures in the decision tree. More explanation about fire behaviour is given in chapter 4.

Mixture of hypoxic air is an important parameter because leakage could destroy the predetermined oxygen concentration. This parameter is divided in two categorises: good and poor. Good mixture of hypoxic air means that openings are mainly closed, leakage is insignificant and convection of hypoxic air is excellent. Poor mixture of hypoxic air will result in a heterogeneous mixture of nitrogen/oxygen. Hypoxic air must also be generated in great amounts if integrity is poor and this could be very costly. More explanation about integrity and distribution of oxygen is given in chapters 7 and 8.

The design concentration given in figure 10.1 is a recommended oxygen concentration related to the health effects. The three arrows are connected with the three type of occupations showed in the figure. This gives an indication of suitable design concentration depending on the type of occupation. These values are used when the consequences in the model are estimated. Other values are also possible, but these are used when estimation is done in this model. If other values however will be used, a higher oxygen concentration is recommended since health aspects generally are of higher importance.

In an unoccupied enclosure the oxygen concentration could be chosen with no respect to health, but should be chosen so that ignition is unlikely. In a non-public enclosure the exposure time is of high importance. If the exposure time is short a lower oxygen concentration could be chosen. For public buildings, it is impossible to know the occupants and the exposure time and therefore the design concentration should be chosen safe for the health.

The outputs from the model (the two branches to the right) in figure 10.1 give a qualitative estimation of the consequences for health effects and fire behaviour. The estimation is based on the literature review and the analyses made in this report. The outputs give information about the suitability of hypoxic environment for different combinations of aspects.

The consequences are divided in three levels: small, moderate and severe consequences. These are marked with the colours green, yellow and red respectively. Explanations to the qualitative estimation of the consequences for health effects and fire behaviour are described below.

The consequences for health effects are worse for public enclosures because sensitive persons can enter the space and the exposure time may not be limited. If the fire hazard increases the consequences to health effects will increase. This is due to the increased consequences when a fire occurs. The consequences will also get worse for health if the mixture of hypoxic air is poor. This is due to the homogenous mixture of nitrogen/oxygen which could cause severe effects to health. If a door for example is opened, more hypoxic air is generated. If the inflowing hypoxic air is lower than the designed oxygen concentration, this could result in health hazards for some areas in the enclosure.

The consequences for fire behaviour are worse for public enclosures because the design concentration is only lowered a few percent in this model. The fire behaviour and the probability for a fire are therefore almost unchanged. Excellent safety management will result in education of employees, control of fire equipment, control of flammable materials etc. which will result in less consequence for fire behaviour. A lower fire hazard will also result in less consequence for fire behaviour because ignition sources are few, amount of flammable materials are less etc. The consequences will get worse for fire behaviour if mixture of hypoxic air is poorer, because a higher oxygen concentration in some areas will be favourable for the fire behaviour.

It is important to have in mind that the decision tree is only a figure that gives a comprehensive view when deciding whether the object is suited or not for hypoxic environment. This is only a qualitative model that illustrates the suitability and the result must be used with precaution. The aspects studied in this model are complex and if other aspects are studied, the outputs could be different. This is only one way to look at the complexity and the result from the model is only aimed to be used as an illustration.

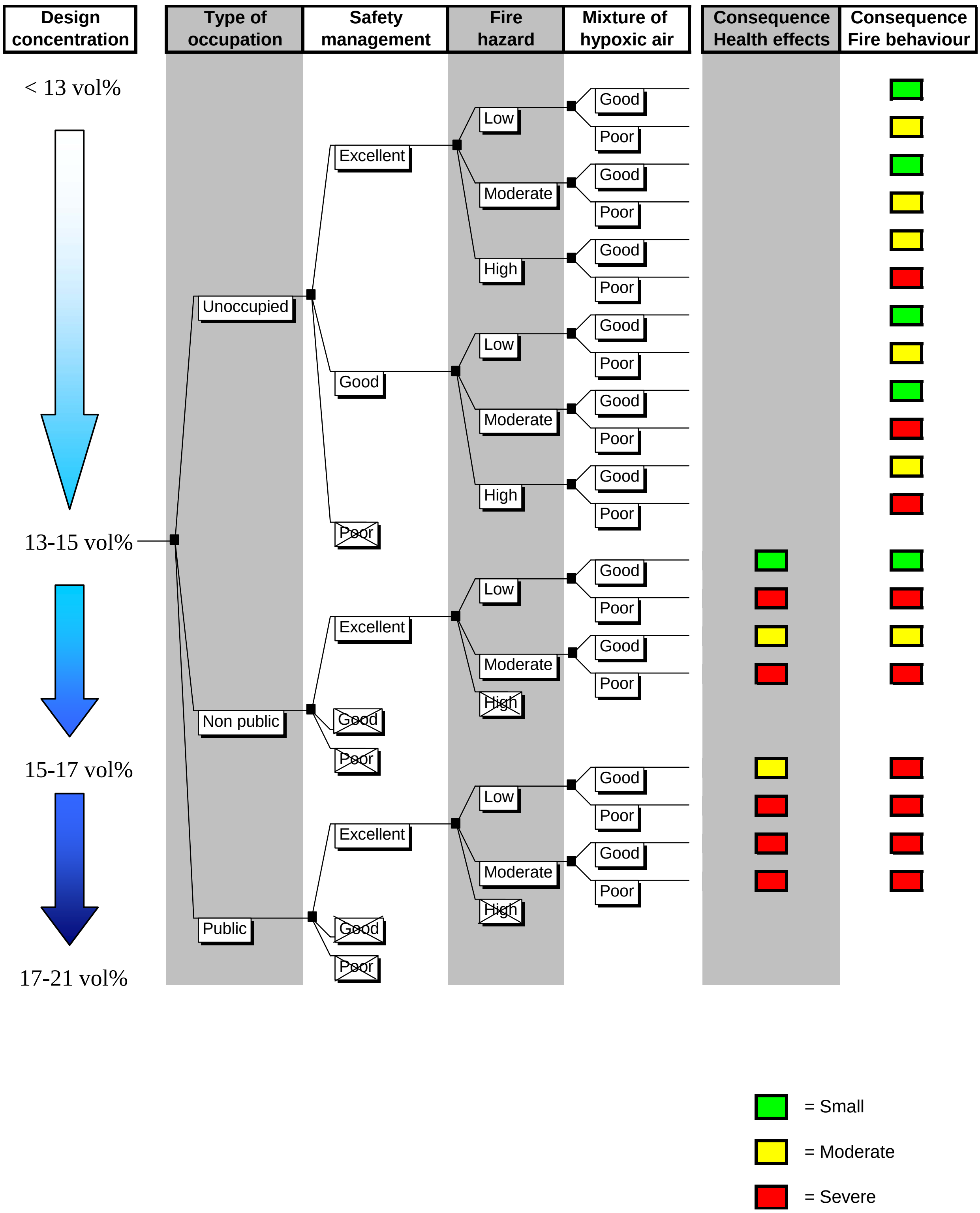

Figure 10.1 Suitability for thinkable objects and realistic design concentration.

10.1 Unoccupied enclosures

An unoccupied enclosure is a space where no humans are present at anytime. According to figure 10.1 hypoxic environment is possible in this category. No considerations are required for health aspects and therefore any oxygen concentration could be chosen. The oxygen concentration should be chosen so that ignition is unlikely. Entering a hypoxic environment with less than 13 vol% oxygen will result in severe health effects and therefore safety management is very important. If the environment must be entered by humans the use of breathing equipment may need to be considered. The oxygen concentration could also be increased when entering the enclosure, but this method needs a well working safety management.

Typical examples in this category are:

- Unmanned warehouses
- Fully automatic industry
- Cargo compartments in aircraft and ships
- Automatic parking systems

10.2 Non public enclosures

A non public enclosure is a space where it is possible to control the occupants. Regular health checks of the occupants are important. The exposure time inside the enclosure must be controlled and preferably minimised. According to figure 10.1 hypoxic environment have some possibilities in this category. Decreased fire risks could be bought at the expense of increased health risks. However, the effect on health is insignificant if certain restrictions are followed. The occupants must be aware of symptoms of hypoxia and the exposure time should be kept at a minimum. The symptoms can still occur too late for respond and the persons entering the enclosures should be strictly controlled.

The design concentration should be chosen as a compromise between health risks and fire risks. A priority between the two risks must be made because they are both dependent on the oxygen concentration. The risk owner needs to decide which parameter is the most important and from this decision choose the design concentration. The risk that is not preferred needs extra attention and control e.g. if health risks is preferred there have to be more focus on the fire risks. Ignition sources should be reduced, combustible materials limited and highly flammable material prohibited. And vice verse, if fire risks are preferred the persons need to have breathing equipment when entering the enclosure or extensive restriction in exposure time in the enclosure. The level of human performance also affects the possible choice of the design concentration if health risks are preferred. Tasks that need high brain activity require higher ability to concentrate and therefore a higher concentration of oxygen is required. High fire risks will require a too low concentration of oxygen for the occupants and is by that reason excluded from the decision tree.

Enclosures that have excellent working safety management can manage the type of people entering. Therefore the most sensitive population are not necessarily included when designing a hypoxic environment for non public enclosures. Excellent safety management is required for environments with occupants and good and poor safety management is for that reason excluded from the decision tree when people are present.

In enclosures with sensitive contents, water sprinkler systems are presumably not welcomed because of sensitive and valuable objects. Hypoxic environment could be one possible solution for these objects. Preservation of valuable artefacts can be one additional effect of reduced oxygen concentration and it could be worth to check these beneficial effects before designing.

Typical examples in this category are:
- Submarines
- Computer rooms, electrical switch rooms and telecommunication rooms
- Archives
- Warehouses
- Cold stores (Additional fire behaviour benefits due to low temperature)

10.3 Public enclosures

A public enclosure is a space where it is impossible to control the occupants. The biggest issue with these enclosures are the occupants. Because it is a public area, it is impossible to know the characteristic of the occupants. All types of people could be potentially; elderly people, children, people with diseases and Olympic athletes. Physical status of people is unknown and regular health checks of the occupants are not feasible. According to figure 10.1 hypoxic environment is less suitable for this category. This is due to that the consequences to health are unacceptable. The most sensitive population must be included when designing a hypoxic environment for public enclosures. Most of the occupants will manage hypoxic conditions but the most sensitive people will suffer and may get severe symptoms and this is unacceptable.

According to figure 10.1 the most significant parameter is the safety management and this will give negative effects on the integrity of enclosures. It is almost impossible to give instructions to the occupants and to avoid that doors being opened. Many shopping centres, libraries and museums have opened designs with few fire compartments. Ceiling height is often high, which results in problem to keep a constant concentration of reduced oxygen, both because of the volume and the integrity.

Because it is impossible to control people’s health status it is not feasible to reduce the oxygen concentration enough for prevention of fires. The consequences of a fire will be reduced due to lower burning rate, HRR etc. and this will result in less fire spreading. This may seem like an expensive measure, but in some cases it can be enough to motivate the investment. High fire hazard will require a too low concentration of oxygen for the occupants and is by that reason excluded from the decision tree.

The design concentration must be chosen with priority to the health risks. A reduction of the oxygen concentration by a few percent could be a realistic approach for public enclosures. This is equivalent to the oxygen pressure in aircraft’s cabin. Note that some people are not allowed to fly commercial aircraft due to certain heart diseases or pregnancy [30]. This is recommended to be transferred directly to a hypoxic environment.

Typical examples in this category are:
- Shopping centres
- Museums
- Libraries
- Offices
- Archive
- Hotels

10.4 Non suitable enclosures

A non suitable enclosure is a space where hypoxic environment is impossible or doubtful to use.

Typical examples are enclosures where:

1. Health status is already impaired. In certain environments health status is already an issue at normoxic conditions. The most sensitive population are sometimes gathered at one location e.g. hospitals, home for old people, care centre etc.

2. The fire risks are extremely high. Some highly flammable, pyrotechnic or explosives materials and dusts require extremely reduced oxygen concentration for fire prevention. This is specially an issue if people are present in the enclosure. Note that some materials are a fire risk without oxygen in air.

3. The process requires normoxic air. Hypoxic environment will not work where a flame is part of the normal process in the enclosure. There are good possibilities for fire prevention in kitchens but have in mind that gas stoves will not work.

   There are also big issues regarding combustion engines when using hypoxic environment. The engines are optimised for 21 vol% oxygen and will not work properly in hypoxic environments. Combustion engines also require air exchange to remove fumes and air exchange is preferable minimised in hypoxic environment for homogenous mixture of hypoxic air. Electrical motors are not affected by reduced oxygen concentration.

4. The air pressure is obviously lower than pressure at sea level. A hypoxic environment is best suited for sea level applications due to the reduced atmospheric pressure at high altitudes. At high altitude the oxygen partial pressure is lowered, which is a health risk even if the oxygen fraction is 21 vol%. A slightly less percent of nitrogen is needed to extinguish a fire at high altitude, but the health risks are increasing fast when ascending to high altitudes. Therefore hypoxic environment is not recommended at altitudes above sea level.

   Reduced oxygen concentration onboard an aircraft is theoretically possible, but there is one important issue about this application. The cabin is pressurized at 1520-2440 metres [2], which means that the oxygen partial pressure is lowered to 15.6-16.6 kPa. This corresponds to an equivalent oxygen concentration of 17.4-15.5 vol% oxygen. If hypoxic air is used inside the airplane for fire prevention the oxygen concentration must be lowered even more which creates hazardous levels for the humans. To prevent fires in airplanes the cabin pressure should be pressurised already at sea level. Pressurising of airplanes is fuel consuming which makes this solution not cost effective.

5. Safety management is insufficient. A well working management is required if hypoxic environments shall be used.

6. Mixture of hypoxic air is insufficient. Air exchange, doors, ventilation, convection of hypoxic air etc. must be controlled if hypoxic will be used.

11 Economic aspects

Economic aspects are studied briefly to get an overview and understanding of the investments costs and the maintenance costs of a hypoxic environment. The total cost over the expected life time is not studied in detail. When a hypoxic environment is installed in a building it requires a site specific design which includes a number of different activities:

- Fire risk assessments – ignition sources, materials etc
- Health risk assessment – health status of population, exposure time, type of work etc
- Smoke detection system
- Safety management – policy, routines, instructions etc
- Separate ventilation system
- Integrity of building – minimise leakage, airtight doors etc

The maintenance costs for hypoxic environment are mainly due to electricity consumption. Other maintenance costs are for example service of hypoxic generator (filter, gauges etc). A hypoxic generator uses electricity and operates nearly twenty-four hours a day depending on the following factors:

- Design concentration
- Oxygen concentration of inflowing hypoxic air
- Leakage of building – doors, windows etc
- Required air exchange – number of people in enclosure, comfort aspects etc

It is interesting to compare the economic aspects for hypoxic environments with gas suppression systems or water sprinkler systems. This is unfortunately hard to estimate because the technique for prevention and suppression are different. A hypoxic environment is continuously activated and therefore the maintenance costs are running nearly twenty-four hours a day. On the other hand, a technique that actually prevents fires will hopefully remove the cost due to fire. The maintenance cost for gas suppression systems or water sprinkler systems are mainly running when the system is activated due to fire. It may also be activated even if the situation does not need it (false alarm). Refilling of the system and cleaning may be costly. Hypoxic environment seems to be cost effective if the probability for a fire is high and the environment prevents all fires.

Wagner UK Ltd has estimated that a hypoxic environment for IT applications is apparently cost effective compared with a fixed gas suppression system if enclosures are larger than 1000 m^3 [52]. They also indicate that hypoxic environments generally are cost effective compared with water sprinkler installations.

Current manufactures of hypoxic environments uses high pressure membranes for production of hypoxic air. These high pressure membranes consume a considerable amount of energy and have in mind that the generator installed operates nearly twenty-four hours a day. New generation of hypoxic membranes that consume less energy due to operation with lower pressure are expected in the future [54].

12 Discussion

Hypoxic environment is a unique method. Today it is more and more common to work in a preventive way but a method that actually prevents fires is unique. If a fire is prevented, life and money can be saved. The theory about hypoxic environment is simple but the application of the method is connected with risks.

The method does not suit every kind of environment but can be a viable fire prevention method for certain applications. If any occupants will reside in the enclosure they affect the fire prevention attained by the method. A risk assessment and a site specific solution must be performed to achieve a minimised risk.

12.1 Fire

A fire is a complex process and is affected by many parameters. When trying to prevent fires in hypoxic environment it is important not only to look at the oxygen concentration. External radiation and ignition is considered to be the most significant parameters that affect fire prevention. The impact from external radiation is largest on class A materials (combustible solids).

By reducing the oxygen concentration, the probability of ignition and combustion is reduced or even eliminated. Materials behave differently during fire when reducing the oxygen concentration. Even if a fire is not prevented the oxygen concentration is decisive for ignition, fire spread, heat release rate etc.

There exist different methods for measuring of materials behaviour during fire in hypoxic environment. It is very important that experiments not shall be compared with real fire conditions. Small scale experiments can be misleading and therefore only be used as relative comparison between different materials. Some experiments can be applicable on real fires if an engineering approach and a scale factor are used.

Without ignition there will be no fire and therefore is this parameter crucial for fire prevention. Hypoxic environment will result in increased ignition time and increased minimum ignition energy. Even if a fire is not prevented, ignition would be more difficult in hypoxic environment. A valuable method is to minimise ignition sources or even eliminate them. Materials with high resistance against ignition are preferred.

Class A materials have properties during fire that separates them from other materials. Some of them can develop into smouldering fires and these fires can still be present in a hypoxic environment even when flaming fires are impossible. The oxygen concentration required to prevent smouldering fires is difficult to determine but much lower concentrations are needed compared to flaming fires. The risk of fire spreading during smouldering fires is small as long as a fire does not develop into a flaming fire. Smouldering fires have a low burning rate and does not consume oxygen as much as flaming fires. Time to critical conditions for flaming fires are less and smouldering fires give more time for response and evacuation. A highly sensitive smoke detection system is necessary to detect a smouldering fire. Hypoxic environment could result in decreased time for material to emit smoke and therefore an air sampling detection system is recommended.

Fire prevention of class B materials (flammable liquids) requires lower oxygen concentration compared to class A materials. Arson is often connected to liquid fires, which can act as a fire starter for class A materials due to the added external radiation. Arson is unfortunately well represented in fire statistics and can spoil the purpose with hypoxic environment.

12.2 Health

Reduced oxygen concentration can result in health risks for humans. The individual differences between humans are considerable and people will suffer from symptoms at different concentrations. The symptoms are both dependent on the oxygen concentration and the exposure time. Most of the symptoms are harmless and reversible (intellectual performance impaired, fatigue, nausea etc) but some of the severe symptoms can result in irreversible symptoms and even death. Monitoring of symptoms is necessary and people suffering from symptoms must leave the environment before the symptoms worsen. If the oxygen concentration drops there will be a sudden change from a condition of near normality to a condition with severe effects. It is very important to be aware of this rapid change. The first most common symptom that is easy to recognise is headache and is usually followed by more severe symptoms.

The area of hypoxic environment has gone through rather little research and therefore advantages must be taken from other research areas where the oxygen partial pressure is reduced. Experiences from high altitude are similar but some differences are found. Human reactions when entering a hypoxic environment is similar to acute exposure to high altitude. Human reactions when living constantly in hypoxic environment is similar to live at high altitudes. There are some issues regarding human studies. Most of the studies involve young healthy persons, no exercise and they normally do not investigate real life stress. In a real life fire situation psychological stress is important.

Symptoms are dependent on the exposure time and more symptoms will be present if a person is exposed during a longer time. On the other hand, if exposed for hypoxic environment continuously for many days in succession, the body is able to adapt to hypoxic environment and therefore manage hypoxic air better. Adaptation is important and it takes many days for the body to get used to hypoxic environment. This is the case for certain applications e.g. submarines. For most of the suitable applications adaptation is not the case e.g. computer rooms, warehouses. Working inside an enclosure with reduced oxygen concentration is not the same as living at high altitude with the equivalent partial oxygen pressure. It is also worth to mention that there is a great difference in individuals' experience of adaptation.

It is very difficult to perform a proper health risk assessment if you only study an average population. A population could be very different depending on activity. The people in an office workplace are for example not similar to the people in a public space where people are a mix between all type of ages and physical conditions; newborn, old, people with diseases etc. Precautions must be done on persons with known or suspected heart disease, pulmonary disease or haematological disease. These persons must undergo special medical check before entering hypoxic environment.

If high brain activity or exercise is performed in the enclosure, special considerations need to be done. Performance skills will be affected when reducing the oxygen concentration. Therefore work that requires high brain activity and exercise should be avoided to minimise errors and accidents.

Synergic effects from reduced oxygen concentration and toxic gases are important in case of a fire in hypoxic environment. Literature about exposure to both hypoxic air and other toxic substances are hard to find. Results from animal experiments show that reduced oxygen concentration will result in higher proportion of toxic fire gases. Conclusion from this is that a fire gases is likely to be more hazardous during a fire in hypoxic conditions compared to a fire in normoxic conditions.

12.3 Safety management

Already at an early point during this project the conclusion was drawn that public buildings are not ideal for hypoxic environment. Safety management in hypoxic environment is very important. In public enclosures it is not feasible to inform the people about safety instructions and health risks regarding the environment.

To make the fire prevention work as optimal as possible it can be necessary to forbid entrance for certain fuels and minimise ignition sources in the enclosure. Which materials that should be prohibited depend on material characteristic and the design concentration in the protected enclosure. The cause of a fire could be a result of entering forbidden fuel in the enclosure or keeping a too high oxygen concentration. If this should work properly safety management must be implemented. Instructions and routines are an important part of the day to day business. Routines about what kind of materials that can be entered in the protected enclosure is necessary.

At present time, few regulations and standards for hypoxic environment exist. Some are applicable in this area but hopefully more and improved regulations and standards will arise in the future.

12.4 Safety risks

Different factors may cause a failure to the system. This means that the enclosure may be unprotected due to incorrect or heterogeneous oxygen concentration. The fire risks are increasing when ignition and combustion are more likely. If the oxygen concentration is reduced under a safe level this could cause adverse effects on human health. Hypoxic environment is a sensitive technique and this indicates that maintenance, inspection and management are necessary to avoid unnecessary risks.

If the oxygen concentration in the inflowing hypoxic air (nitrogen/oxygen mixture) has a lower oxygen concentration than the predetermined design concentration there can be a gas mixture problem in the enclosure. The convection of the hypoxic air in the enclosure can be maintained with fans and with help of high velocity of the inflowing hypoxic air. Monitoring of the oxygen concentration should be carried out on many different places in the enclosure and should be measured individually.

A safety margin should be applied to the individual items of equipment used to provide a hypoxic environment. In case of a prolonged failure, where hypoxic air is not generated, it is possible to forbid people from entering the building, but the probability of a fire in the enclosure will increase. The enclosure and its contents will therefore be unprotected during the time the failure is present.

12.5 General

Four important areas have been studied: fire behaviour, health effects, safety management and safety risks. There is a connection between them which is interesting to discuss, se figure 12.1. The aim with reduced oxygen concentration is to reduce the fire risks and this will result in increased health risks. The fire behaviour can be controlled and minimised with safety management and if safety risks are reduced. Safety risks are on its part influenced by safety management. Health effects are influenced by many aspects. A poor safety management and safety risks will increase the health effects. Another aspect that affects the health effects is a possible fire in hypoxic environment.

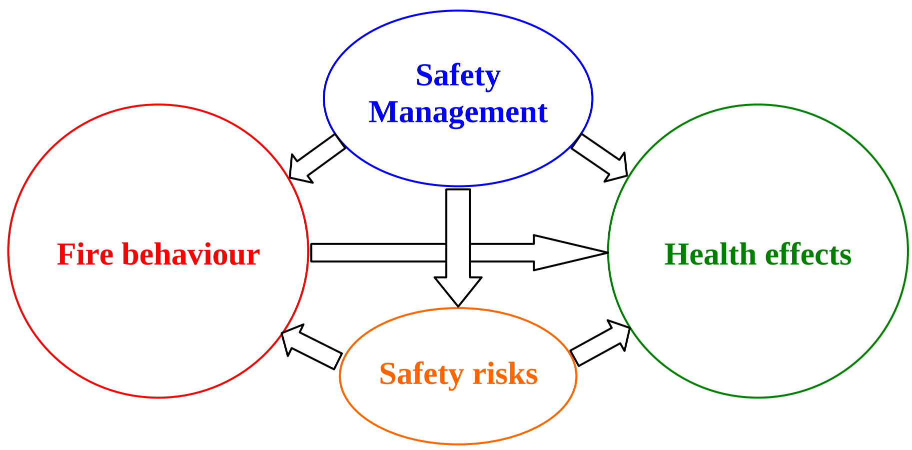

Figure 12.1 Connection between studied areas.

The probability relations that have been carried out for health and fire in this report are purposed to explain the complexity of the risks. The probabilities are only assumptions because statistical data are hard to find and the consequences are studied qualitative. The relations should not be analysed literally but gives an insight into the complexity of the risks.

The most difficult judgement is when the humans are suffering from different symptoms. Although the amount of information about health effects in hypoxic air is enormous compared to the information that is to be found in the area of fire behaviour in hypoxic air. Individual differences are the main issue when drawing conclusions.

Hypoxic environment is a sensitive technique. One big problem with hypoxic environment is when a fire actually occurs inside the enclosure. A fire is still possible, even if the probability of a fire is reduced considerably. The literature about health effects in hypoxic environment during fire is almost non-existent. The consequences of being exposed to fire gases while at the same time staying within a hypoxic environment are probably severe. According to the scenario analysis the safety margin for human health decreases when staying in hypoxic environment. This rapid change in environmental condition requires fast response from the occupants if a fire occurs. Even a small and slowly growing fire in hypoxic environment could be a potential death-trap, especially in small enclosures. This highlights the need of a highly sensitive detection system. Hypoxic environment will result in changes in fire behaviour such as slower fire growth, more un-combusted gases and particles and critical conditions for humans will probably occur faster.

According to the scenario analysis there is no clear design concentration that is ideal for hypoxic environment. Fire prevention can be bought at the expense of increased health risks. A lower oxygen concentration will result in increased health risks. There is no clear oxygen concentration where it is absolutely fire proof and there is no clear oxygen concentration where detrimental effects on health are non existent. The conclusion is that a priority must be made between the two risks.

Hypoxic environment is not suited for all applications, but appears to be a good prevention method for certain objects. Hypoxic environment is suited for unoccupied enclosures with good safety management and good mixture of hypoxic air in the enclosure. Hypoxic environment will also be a possible solution for non public enclosures where safety management is excellent. For optimal function of the environment, the fire hazards must be minimised and the mixture of hypoxic air must be good. Hypoxic environments are not recommended for public enclosures, because the oxygen concentration could not be reduced due to the unknown health status of the occupants. Existing installations are today used in non public and unoccupied enclosures and this agrees with the research and discussions in this report.

The main costs for hypoxic environment are the operation and maintenance costs. A hypoxic generator uses electricity and operates nearly twenty-four hours a day. The design concentration and the integrity of the building affect the electricity consumption to a great degree. The initial costs (installation, risk assessment, safety management etc.) are also considerable. To compare the economic aspects with a gas suppression system or water sprinkler system is unfortunately hard to do because the technique for prevention and suppression are different. The initial cost is probably less for hypoxic environment, but the operation costs are higher, but this is of course dependent on the application.

A fire in hypoxic environment can occur, even if the probability is reduced. Therefore fire safety equipment should not be excluded from the enclosure. Smoke detection system, fire extinguishers, fire hoses etc. must exist in the enclosure.

12.6 Additional research

It is our hope that this report will generate further research interest. The authors of this report recommend further research in the following areas:

Fire:

- Material's fire behaviour under reduced oxygen concentration, especially for class A materials (combustible solids): ignitability, geometry of fuel, heat release rate etc. The fire research is today focused on fires in normoxic air.
- An adequate method that measures required reduction in oxygen concentration for fire prevention. Methods used today are mainly suited for extinguishing of fires.
- Smouldering combustion in hypoxic environment.
- Changes in the produced toxic fire gases during fire in hypoxic environment.

Health:

- Which parameters are the most significant to affect the human health in hypoxic environment
- Exposure time before detrimental effects occur in hypoxic environment. Present research mainly shows exposure time for hypobaric conditions and when severe effects occur.
- Synergic health effects between hypoxic air and fire gases.
- Differences in human effects, and the causes to these, between hypobaric hypoxic air (high altitude) and normobaric hypoxic air.

Until more research is performed for hypoxic environment many questions regarding health effects and fire behaviour will remain unanswered. It is important to limit the use of hypoxic environments to areas where research shows no health hazards and sufficient fire prevention.

13 Conclusions

Hypoxic environment is a unique method. Today it is more and more common to work in a preventive way but a method that actually prevents fires is unique. When preventing a fire it is important not only to study the oxygen concentration. The fire is a complex process and is affected by many parameters. External radiation and ignition are considered to be the most significant parameters when preventing a fire.

Hypoxic environment is suited for unoccupied enclosures with good safety management and good mixture of hypoxic air in the enclosure. Hypoxic environment will also be a possible solution for non public enclosures where safety management is excellent. For optimal function of the environment, the fire hazards must be minimised and the mixture of hypoxic air must be good. Hypoxic environments are not recommended for public enclosures, because the oxygen concentration could not be reduced due to the unknown health status of occupants. Existing installations are today used in non public and unoccupied enclosures and this agrees with research and discussion in this report.

Hypoxic environment does not prevent all fires. A fire is still possible, even if the probability of a fire is reduced considerably. This highlights the need of a highly sensitive detection system, fire extinguishers and other fire safety equipment. Even if hypoxic environment is not a totally fire preventive atmosphere, it will have other possibilities. It will have a fire retardant effect and is decisive for ignition, fire spread, heat release rate etc. On the other hand, hypoxic environment is a sensitive technique and the safety margin for humans is decreased. A big problem is when a fire actually occurs inside the enclosure. A fire consumes oxygen and this can be an issue in occupied enclosures.

Hypoxic environment is associated with many different risks. The most considerable risks studied in this report are: fire, health, safety and safety management. The risks can be minimised as follows:

> **Fire**. Minimise ignition sources, prohibit certain fuels, install air sampling detection system etc.
>
> **Health.** Regular health checks, monitoring of symptoms, minimise the exposure time, avoid work with high brain activity and exercise etc.
>
> **Safety Management.** Policy, routines, instructions, feedback must be well working.
>
> **Safety.** Monitoring of oxygen concentration and air quality, regular inspections and maintenance etc.

Safety management in hypoxic environment is very important. To make the fire prevention work as optimal as possible it can be necessary to forbid entrance for certain fuels and minimize ignition sources in the enclosure. Policy, routines and instructions are an important part of the day to day business.

The occupants are the main issues when using hypoxic environment. If no human are present, then fire risks will determine the sufficient design concentration of oxygen. Hypoxic environment have the possibilities to be a viable fire prevention method in certain non public enclosures. Until more research is performed in the area of fire and health it is important to limit the use of hypoxic environments. The designed oxygen concentration should be chosen as a compromise between health risks and fire risks. A priority between the two risks must be made. Conclusions are summarised by saying that decreased fire risks can be bought at the expense of increased health risks.

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Appendix

Appendix A	-	Humidity influence on the oxygen concentration
Appendix B	-	Fire point theory
Appendix C	-	Fire theory
Appendix D	-	LOI (Limiting Oxygen Index)
Appendix E	-	Cup burner
Appendix F	-	Inerting concentration
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Appendix H	-	Submarine study
Appendix I	-	Interactions between carbon dioxide and hypoxic air
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Appendix K	-	Hypoxic training

Appendix A – Humidity influence on the oxygen concentration

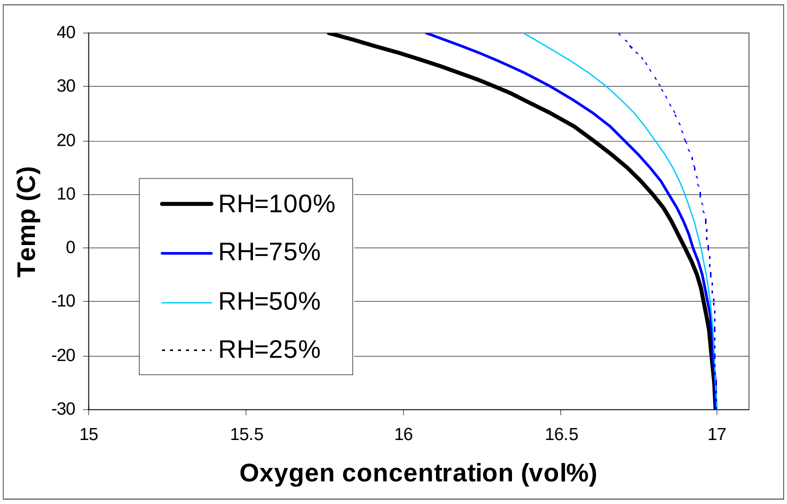

Figure A.1 Humidity influence on normobaric hypoxic air, 17 vol% oxygen.

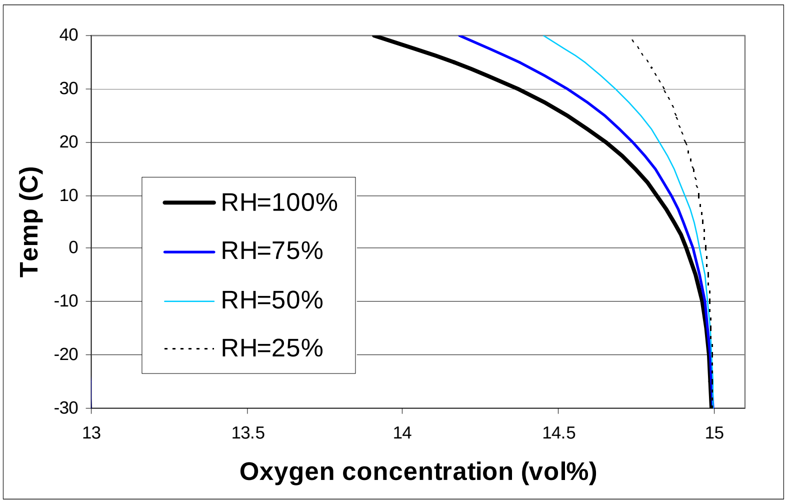

Figure A.2 Humidity influence on normobaric hypoxic air, 15 vol% oxygen.

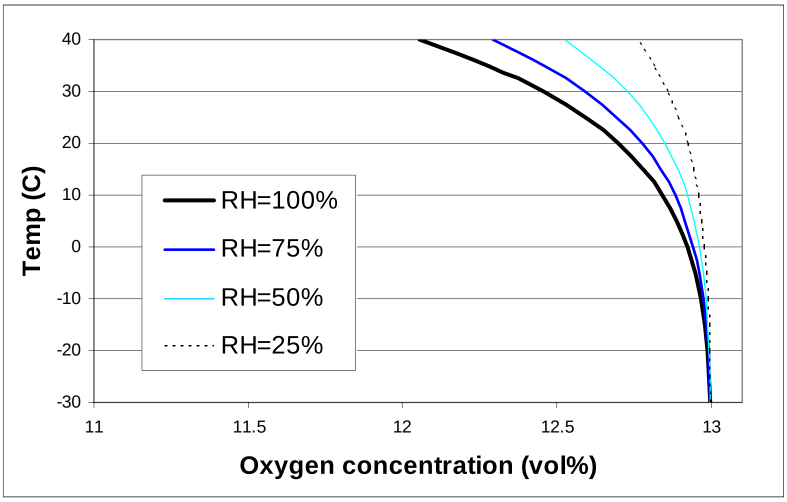

Figure A.3 Humidity influence on normobaric hypoxic air, 13 vol% oxygen.

Appendix B – Fire point theory

Rasbash fire point theory was developed during early 1980's and was further developed by Craig Beyler to a unified model of fire suppression. The unified fire suppression theory is able to handle both solids and gas phase effects including surface cooling, gas phase dilution, chemical dilution of flame reactions and endothermic agent decomposition [14]. The model is useful when the suppressibility of different extinguishing agents is evaluated for a defined material.

The model is able to predict the thermal mass consumed by an added suppression agent. Different suppression agents work in different ways. The interaction of water works primarily by extracting heat from the surface of solid burning materials. Other extinguishing agents often work in the flame region by extracting heat to quench and retard the combustion reactions. The extraction of heat works by adding additional thermal mass to the flame by adding the agent. Some gaseous agents also stop chain reactions besides the reaction in the flame gas phase region [14]. Examples of these gaseous agents are the now banned halon and the halon replacement gases containing of flour carbonate.

Extinguishment by water acts on the surface of burning materials and gas agents primarily work in the flame region and these extinguishing effects are very different. However, the fire point equation can be explained as a formula so general that it is suitable to describe different agent's interactions to extinguish a diffusion flame.

$$(\Phi \Delta H_C - L_v) \cdot \frac{h}{c_p} \cdot \ln\left(1 + \frac{Y_0 \Delta H_{R,O}}{\Phi \Delta H_C}\right) + Q''_E + Q''_L + Q''_W = 0$$

Equation B.1 The fire point equation.

Φ	The amount of produced heat, which must be taken from a flame to reach extinguishment.
ΔH_C	Heat of combustion of the fuel
ΔL_V	Heat of gasification of the fuel
h	Convective heat transfer coefficient
Y_0	Oxygen mass fraction
$\Delta H_{R,O}$	Developed heat per consumed mass fraction of oxygen
$\dot{Q}''_E$	External applied heat flux
$\dot{Q}''_L$	Heat loss from the surface
$\dot{Q}''_W$	Heat loss due to water evaporation

Appendix C – Fire theory

In this appendix the elements in the fire triangle are discussed briefly. This is the traditional way to look at a fire, commonly known from the fire triangle, but over time has been replaced by the fire tetrahedron, see figure C.1. Fuel, heat and chemical reaction are investigated briefly in this appendix. Oxygen is discussed more in 4.2. The fire tetrahedron was developed when the understanding of the halon extinguishing method became clearer as the halon resulted in a fourth extinguishing method, the chemical reaction.

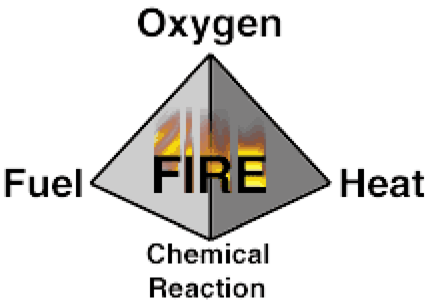

Figure C.1 Oxygen, fuel, heat and chemical reaction are the different elements necessary to maintain a fire.

C.1 Heat

A flame is often extinguished due to that there is too little energy released to maintain the heat of a flame [7]. For both premixed and diffusion flames it exists a temperature under which a flame can not propagate [67]. This temperature is called the critical adiabatic flame temperature and if the adiabatic flame temperature is lowered under this critical value, the flame will be extinguished. For most fuels the critical adiabatic flame temperature is 1500-1600K. This is only a theoretical value and the real flame temperature is about 200-300K lower [7]. Diffusion flames are often extinguished when more than 10-40% of the developed heat is cooled by an extinguishing agent or removed in another way. For premixed flames the same figure is approximately 45% [7].

C.2 Fuel

Removing of the burning material is a defensive way to tackle the fire, but may sometimes be the only reasonably way. If you for example have a gas flow from a broken pipe that has ignited it may be hazardous just to extinguish the burning gas since the streaming gas can collect in pockets and explode if ignited. If the gas stream instead is turned off and then wait for the flame to be extinguished is a better way and a form of separation. Separation of class A materials in smaller piles can of that reason be a easier way of extinguishing when a fire occurs in them. For smouldering fires, separating may be the only way to stop further fire spreading [7].

C.3 Chemical reaction

One of the most effective ways to stop an ignited fire, as known in modern time, should be by using halon. Unfortunately this gas has high ozone depletion potential (ODP) and was therefore banned. Halon works as thermal ballast to the fire reactants. The bromide product from the halon reactants works as a thermal ballast in several reactions and is not limited to one. Today it exist halon replacement gases that also work by interrupting chain reactions in the same way as the now banned halon. Unfortunately they are not as effective as halon.

Appendix D – LOI (Limiting Oxygen Index)

LOI (Limiting Oxygen Index) is widely used as a tool to investigate the flammability of polymers. LOI is defined according to the ISO4589 as the minimum oxygen concentration where the material will burn for three minutes or keep a sample burning over a distance of 50mm [55]. The higher the LOI, the less likely the material will burn. An apparatus for class A material is shown in figure D.1. The sample is placed vertically in a heat resistant glass chimney and is burnt within a controlled environment. The standard procedure is to ignite the top of the sample. The lowest concentration of oxygen that sustains combustion is calculated for a mixture of nitrogen and oxygen. LOI could also be used for class B and C materials, but the apparatus is different. The Limiting Oxygen Index (LOI) is also known as Oxygen Index (OI) and Critical Oxygen Index (COI). In table D.1 some typical LOI values are presented.

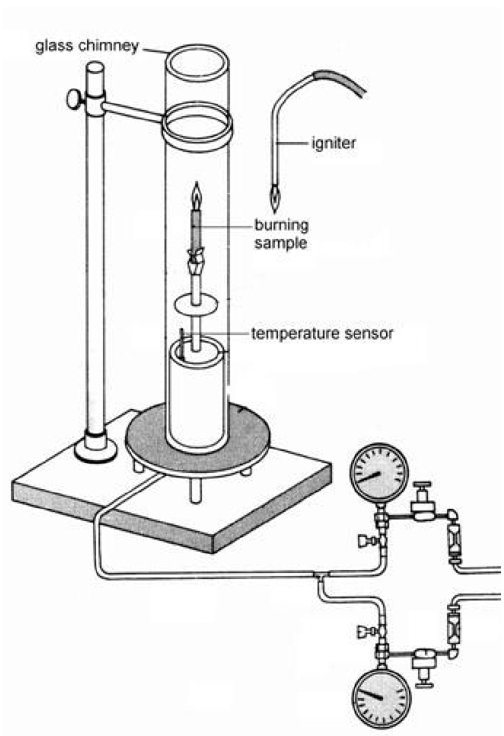

Figure D.1 An apparatus for LOI suited for class A material [35].

Table D.1 Typical LOI values for class A and class B materials.

Material	LOI	Ref
Methanol	11.0-12.0	61
Polyacetal	15.7	57
Acetone	16.0	61
Mineral oil	16.1	61
PMMA (Perspex)	17.3	35,57
Polyethylene (LDPE, HDPE)	17.4	35,57
Polypropylene	17.4	35,57
Polystyrene	17.8	35,57
Filter paper	18.2	40
Paper, cellulose filter	18.2	61
Cotton	16.0-19.9	61,57
Rayon	18.9	40
Polyester fibres	20.6	61
Sugar	22.0	40
Red oak	22.7	40
Wool	23.8	61
Nylon-6	24-29	35,57
Wool	23.8-25.2	40,57
Plywood	24.3-29.2	40
Nomex	28.5	35
Poly vinyl chloride (PVC)	45-49	35,57
PTFE (Teflon)	95	35,57

The advantages of the method are convenience, low cost and it only requires a small sample size. LOI has unfortunately many disadvantages. LOI is not an appropriate way of predicting real fire performance. A standard LOI test creates a downward burning which is far different from the normal upward burning in real fires. There are significantly differences in the results if the sample is ignited at bottom or at the top due to gravity effects. The energy feedback from the flame is low and the powerful effect of dripping affect the LOI observed with thermoplastics [56]. It does not measure the ease of ignition and external radiation is not included in the method. It is best used to give a relative index rating for different materials and is not a specific quantifiable value of flammability. Result from different LOI methods should not be compared with another LOI if the apparatus and conditions are not exactly the same.

Appendix E – Cup burner

The cup burner apparatus is developed by Hirst and Booth in the late 1970's and is today a widely spread method to study the effectiveness of different extinguishing agents on a diffusion flame. An example of a cup burner apparatus is presented in figure E.1. This one is suited for class B materials, but there are cup burner methods for A and C materials as well. The extinguish agent is mixed with the air and flows past a burner. The amount of oxygen is decreased until the flame is extinguished and concentration of the extinguishing agent is calculated.

Today cup burner method is internationally approved as a method for designing fire suppression system using gaseous extinguishing agents. Cup burner standards have been established which serves as the basis for determining design concentrations. Both the NFPA 2001 [5] and the ISO 14520 is widely used.

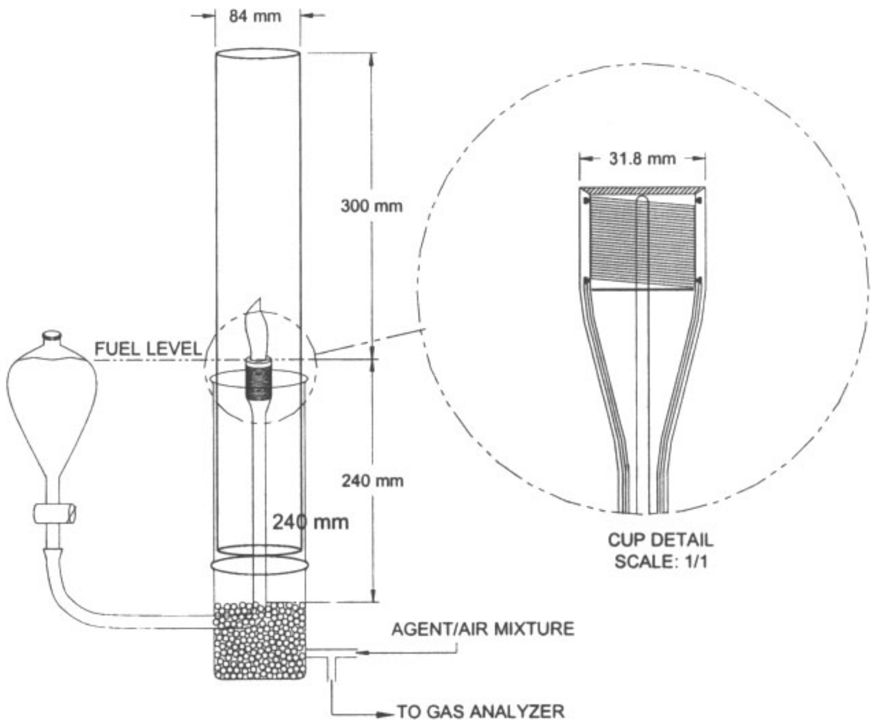

Figure E.1 Apparatus for cup burner suited for class B materials [57].

The advantages of cup burner are simplicity, low cost and it does not need much extinguishing agent. There are many disadvantages with this method. Several different techniques, apparatus and investigators exist and the results from them are partly different. Cup burner values differ up to 50% in international standards for certain fuels [7]. Standard cup burner values are presented in table E.1

The VdS Schadenverhutung in Germany has investigated the scale effect using a large cup burner and full scale tests [26]. In case of n-Heptane, 1.2 vol% less oxygen concentration was needed for full scale compared to a standard cup burner (14.4 vol% v. 13.3 vol%), see tables E.1 and E.2. With the large cup burner, a scale-up of 4.7, the difference was only 0.2 vol% oxygen. A standard cup burner flame is obviously not the most challenging fire and not appropriate for establish of design concentration for inert gases.

When designing a gas suppression system, cup burner value is used in combination with a safety factor [13]. A safety factor of 1.2 is normally used, but to guarantee extinguishing for certain fuels due to external heat a safety factor of 1.3-2.4 must be used [15].

In table E.3 cup burner values are found for PMMA with added external radiation. When external radiation is increased a lower oxygen concentration is required. This relation is obvious and agrees with discussion in 4.5.

Table E.1 Cup Burner values.

Fuel	Cup burner	ISO Cup burner (Unheated/ heated fuel)	Oxygen conc.[1] (vol%)	Reference
20% n-heptane in water	29		14.8	[58]
Acetone		28.5/29.9	14.9/14.7	[58]
Benzene	31		14.4	[58]
Diethyl ether	34		13.8	[58]
Diethyl ether		-/33.8	13.8	[59]
Ethanol	32.3-37.7 (3) [2]		13-14.1	[58]
Ethanol		32.1/34.5	14.2/13.7	[59]
Hydraulic fluid	22-26		15.5-16.3	[10]
JP-5	27		15.3	[10]
Kerosene	30		14.6	[58]
Methanol	37.5-44.5 (2) [2]		12.1-13.7	[58]
Methanol		38.5/41.2	12.9/12.3	[59]
n-Decane	34		13.8	[59]
n-Dodecane	33		14	[58]
n-Heptane	31.4-34.6 (3) [2]		13.7-14.3	[58]
n-Heptane	30-34		15.3-14.5	[60]
n-Heptane	32		14.2	[10]
n-Heptane		30.9/32.3	14.4/14.1	[58]
n-Hexane	31		14.4	[58]
n-Hexane		30.6/32.6	14.5/14.1	[59]
n-Octane	34		14.5	[58]
n-Pentane	30		14.6	[58] Non standard value
n-Pentane		-/32.4	14.1	[59]
n-Undecane	33		14	[58]
Propane (g)	32.5		14.1	[58]
Toluene	23-27 (3) [2]		16.1-15.3	[58]
Toluol		22.2/28	16.3/15	[59]
Transformer oil	27		15.3	[58]

Table E.2 Large cup burner values and full scale room fires.

Fuel	VdS large Cup burner	Room fire Extinguished	Oxygen conc.[1] (vol%)	Reference
Acetone	33.2		14.0	[59]
Methanol	44.8		11.5	[59]
n-Heptane	35.6	36.6	13.5, 13.3	[59]
Polyethylene (g)	30.8		14.5	[59]
Polypropylene (s)	34.7		13.6	[59]
Wood crib (s)		28.6	14.9	[59]

Table E.3 Cup Burner values at different external radiation.

Fuel	Radiation (kW/m^2)	Cup burner	Oxygen conc.[1] (vol%)	Reference
PMMA (s)	0	27.5-27.9	15.2-15.1	[15]
	5	36.0	13.4	[15]
	10	39.9-40.6	12.6-12.4	[15]
	15	41.6-44.0	12.2-11.7	[15]

[1] Oxygen concentration is calculated by: 0.209 x (100-Cup Burner value)
[2] Number in parentheses is the number of different values within the interval provided.

Appendix F – Inerting concentration

For every mixture of fuel, air and extinguish agent there is a minimum concentration of oxygen where the mixture is impossible to burn. This concentration is named the inerting concentration, LOC (Limiting Oxygen Concentration) or MOC (Minimum Oxygen Concentration). If the oxygen concentration is kept below LOC/MOC, premixed burning is prevented. This could be measured by experiments, but it is dependent on the experimental arrangement. Values valid for premixed gases are presented in table F.1. The inerting concentration is approximately 10-12 vol% oxygen except a few highly flammable fuels like hydrogen and carbon disulfide, where the inerting concentration must drop down to 5 vol% oxygen. For diffusion flames the inerting concentration values are about 1% higher than for premixed gases, see table F.2. LOC values for combustible dust are presented in table F.3 and oxygen concentrations below 5 vol% oxygen are needed for certain dusts. However, dust explosions are not studied in this report but the values give a description about risk with dust explosions.

Definition of inerting concentration for premixed gases is given in figure F.1. The region of flammability is delimited by lower flammability limit (LFL), upper flammability limit (UFL) and inerting concentration. Examples of hydrogen, propane and gasoline vapour is given in figures F.2 and F.3. Required oxygen concentration for a fire in these gases is 5, 12 and 12 vol% oxygen respectively.

When designing a gas suppression system, inerting concentration is used by multiplying the required extinguishing agent with 0.8 [15]. The inerting concentration is in reality too conservative for diffusion flames and a factor of 0.8 is used to get a more realistic design value for diffusion flames.

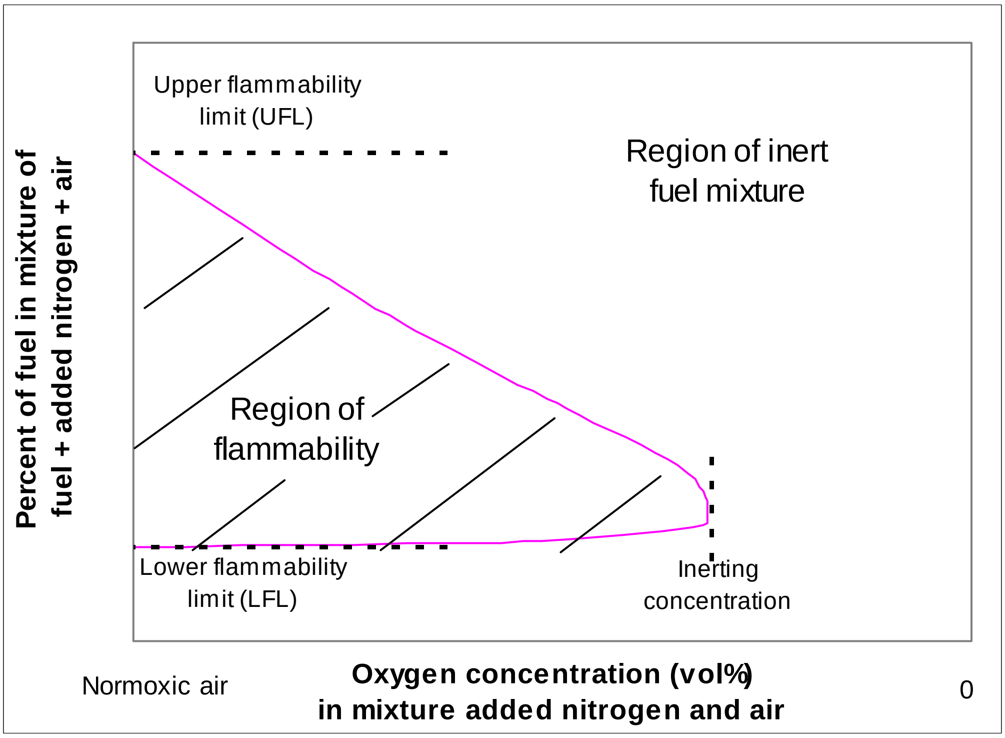

Figure F.1 Definition of inerting concentration.

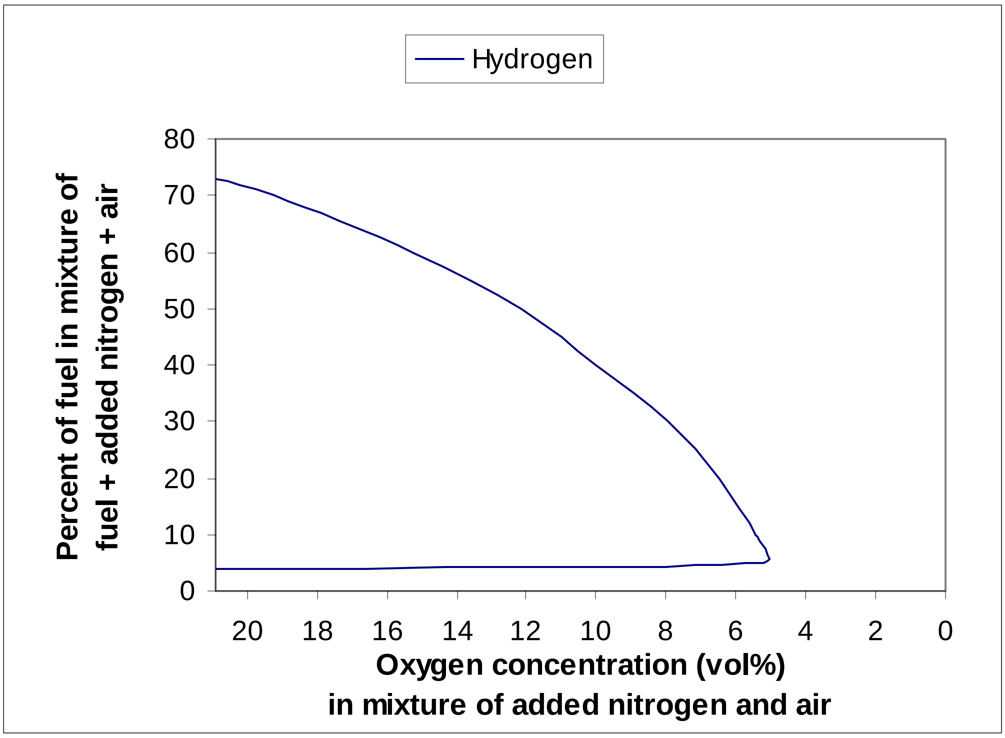

Figure F.2 Flammability limits and inerting concentration for hydrogen.

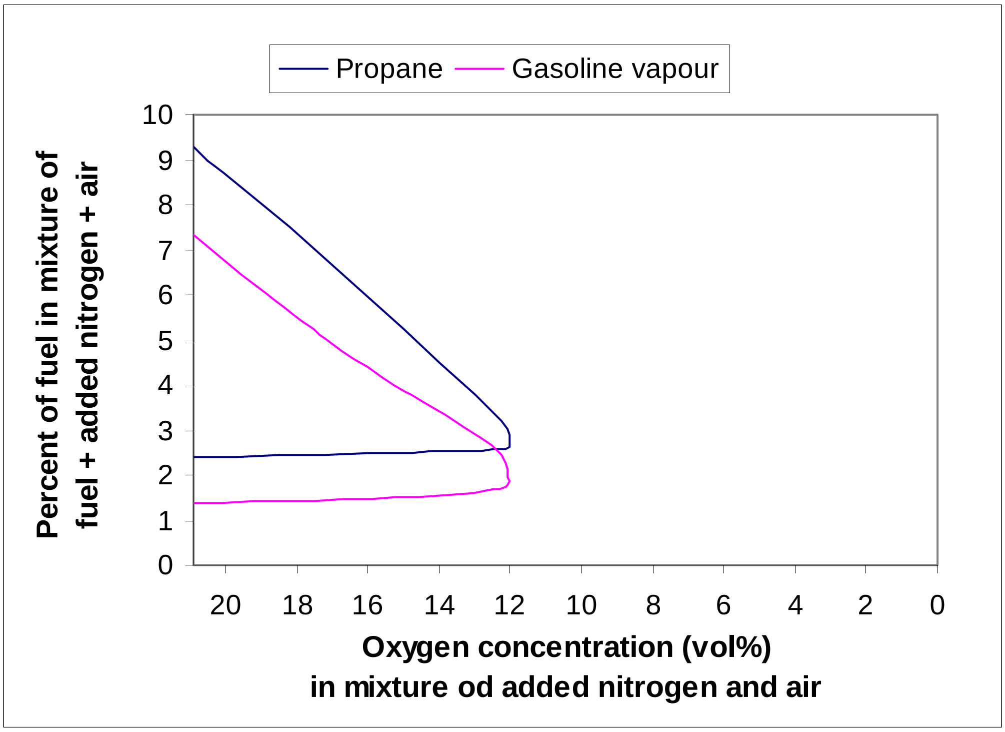

Figure F.3 Flammability limits and inerting concentration for propane and gasoline vapour.

Table F1. Limiting Oxygen Concentration (LOC) and MOC (Minimum Oxygen Concentration) for class B and class C materials at normal temperature and pressure [16,26].

Fuel	LOC (vol%)	MOC (vol%)
Acetone	11.5	11.5
Benzene	11.4	11.2
Butadiene	10.5	10.4
1-Butene	11.5	11.5
n-Butane	12	12.1
n-Butyl chloride	14 12 (100°C)	
Carbon disulfide	5	5
Carbon monoxide	5.5	5.6
n-cyclopropane		11.7
Diethyl ether		10.5
Ethane	11	11.0
Ethanol	10.5	10.5
Ethylbenzene		9.0
2-Ethyl butanol	9.5 (150°C)	
Ethyl ether	10.5	
Ethylene	10	10.0
Ethylene dichloride	13 11.5 (100°C)	13
Gasoline		11.6
Gasoline (70/100)		12
Gasoline (73/100)	12	
Gasoline (100/130)	12	
Gasoline (115/145)	12	12
n-Heptane	11.5	11.5
n-Hexane	12	11.9
Hydrogen	5	5.0
Hydrogen sulfide	7.5	7.5
Isobutyl formate	12.5	12.5
Isobutane	12	12.0
Isobutylene	12	12
Isopentane	12	12
JP-1 jet fuel	10.5 (150°C)	
JP-3 jet fuel	12	12
JP-4 jet fuel	11.5	11.5
Kerosene	10 (150°C)	
Methane		12.1
Methanol	10	10
3-Methyl-1-butene	11.5	11.5
Methyl acetate	11	11
Methyl ether	10.5	
Methyl ethyl ketone	11	11
Methyl formate	10	10
Methylene chloride	19 (30°C) 17 (100°C)	
Natural gas (Pittsburgh)	12	12
n-Pentane	12	12.1
Propane	11.5	11.4
Propylene	11.5	11.5
Propylene oxide		7.8
Styrene		9.0
Toluene		9.5
1,1,1-Trichloroethane	14	14

Trichloroethylene	9 (100°C)	
UDMH		7
Vinyl chloride		13.4
Vinylidene chloride		15
Vinyl toluene		9.0

Table F.2 MOC (Minimum Oxygen Concentration) for premixed versus diffusion flames [6].

Fuel	MOC (vol%) Premixed	MOC (vol%) Diffusion flame	Difference (vol%)
Decane	11.9	13.2	1.3
Ethanol	10.7	11.9	1.2
Hexane	11.7	13.1	1.4
Methanol	9.8	10.0	1.2
Octane	11.9	13.1	1.2
Pentane	12.0	13.0	1.0
Propane	11.4	12.3	0.9

Table F.3 Limiting Oxygen Concentration (LOC) for combustible dusts at normal temperature and pressure [26].

Combustible dust	LOC (vol%)
Aluminium	5
Cellulose Acetate	9
Coal, Bituminous	14
Corn Starch (17µm)	9
Silicon	11
Stearic Acid and Metal Stearates	10.6
Zinc	9
Zirconium	0

Appendix G – Ignition

These things must be satisfied before solids and liquids develop into flaming fires [16]:

1. The substance must be heated to a point were the concentration of pyrolysate is considerable some distance from the surface of the material.
2. There must be an oxidizer present and it must mix with the pyrolysate to form a flammable gas mixture some distance above the surface of the material. The most common oxidizer is the air.
3. There has to be an external energy source such as a pilot flame or a spark big enough for pilot ignition to occur.
4. If the temperature of pyrolysate and air mixture above surface is high enough autoignition may occur.

G.1 Ignition of solids

There are four basic ways of solids to ignite [16]:

1. Pyrolysis ignition; the most common ignition type is the one where fuel vapours are driven out of solids and ignited. This will turn into a flaming fire. Most solids produce flammable gases due to pyrolyzing. A few low molecular-mass solids liquefy and vaporize without pyrolyzing. This means that the vapours of the solid have the same chemical form as the solid of the material.
2. Smouldering ignition; when a porous of granular substance undergoes self heating the smouldering is commonly a first stage of the ignition. Smouldering ignition can also be caused by external heating or of applying of an external smouldering source.
3. Direct ignition; material is ignited by oxidation direct on the surface of the material since no flammable vapour is released that can ignite. Many metals and some other materials are acting this way. Note that wood can ignite this way, which is called glowing.
4. Ignition by chemical reaction; direct on the material's surface e.g. thermal decomposition. This is the case for reactive substances like explosives and pyrotechnics.

Piloted ignition of solids can expect to occur when the lower flammability limit (LFL) of a pyrolysate/air mixture is first reached. Autoignition of solids occur when the flammable gases due to pyrolyzing are autoignited. The effect of pyrolysis rate in different oxygen concentrations is small on most materials [16].

G.2 Ignition of liquids and gases

The flashpoint of a liquid fuel is its temperature at which the mixture of vapour/air is capable of supporting a flame when supported by a small pilot flame [26]. If the temperature of the liquid is lower than the flashpoint it may still be ignited in some case, for example when wicking or spraying the liquid. Auto ignition temperature (AIT) of a mixture of vapour/air is the minimum temperature at which the mixture is self ignited [26]. There is no correlation between flashpoint and AIT as they are describing different things. AIT corresponds to the fuels reactivity and flashpoint to its volatility [16]. Minimum ignition energy (MIE) is the energy required to ignite flammable mixtures or materials.

Appendix H – Submarine study

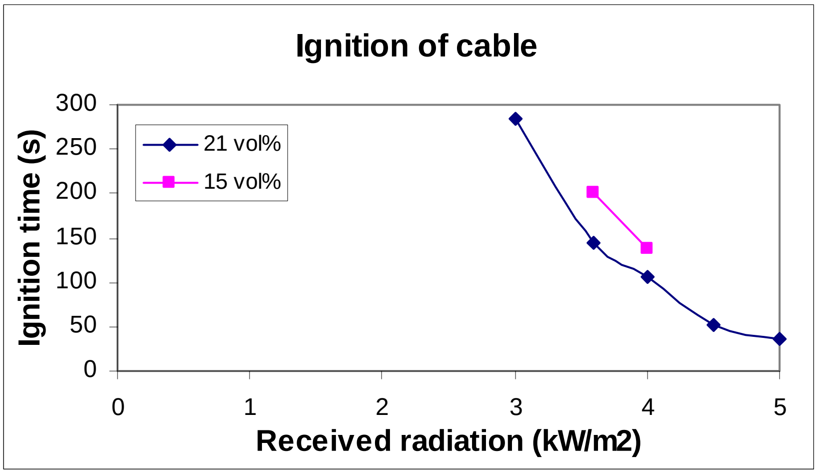

Figure H.1 Time to ignition at different radiation levels and oxygen concentrations.

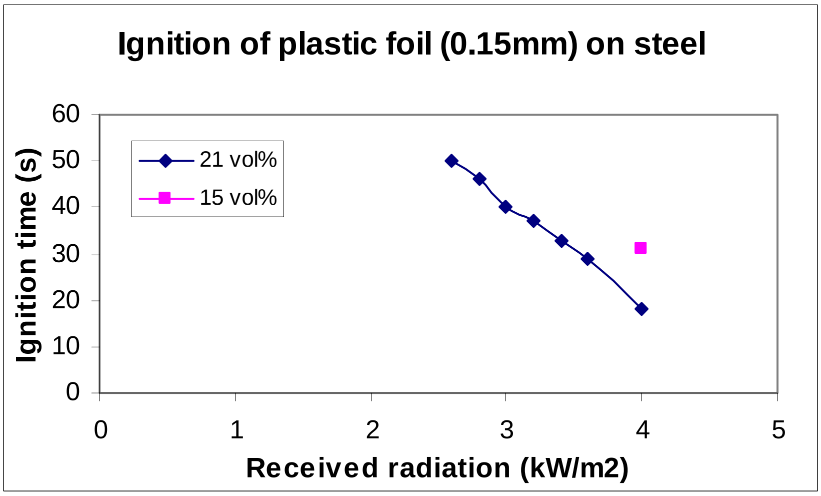

Figure H.2 Time to ignition at different radiation and oxygen concentrations.

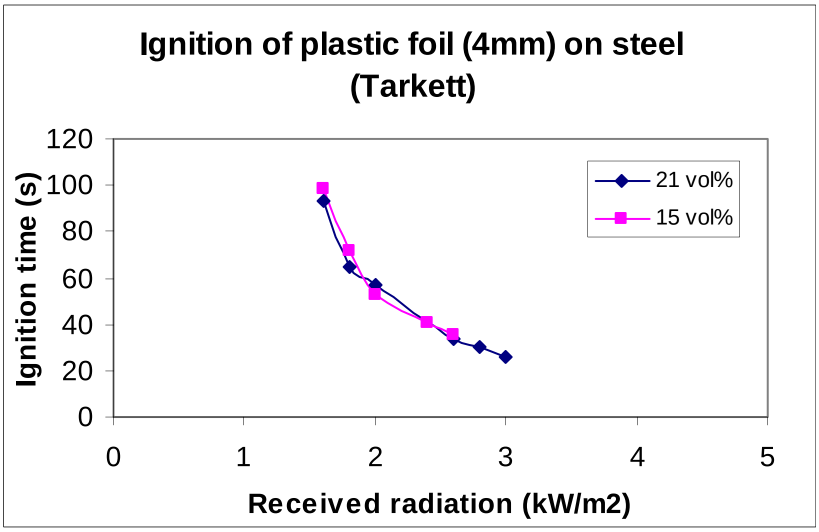

Figure H.3 Time to ignition at different radiation levels and oxygen concentrations.

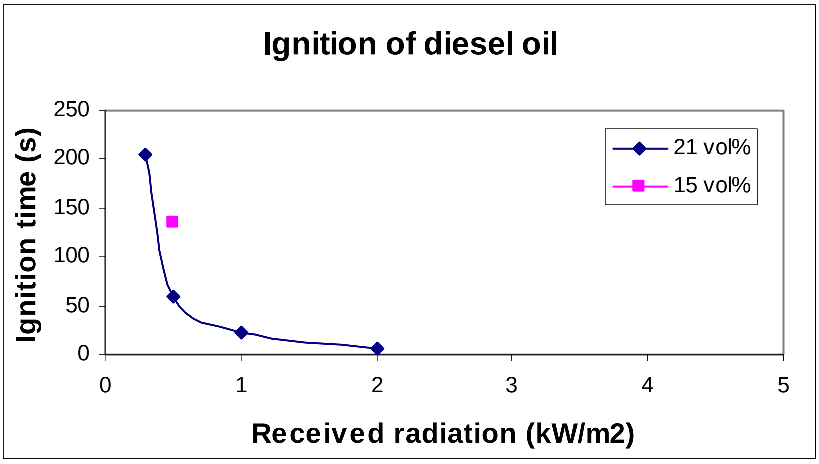

Figure H.4 Time to ignition at different radiation levels and oxygen concentrations.

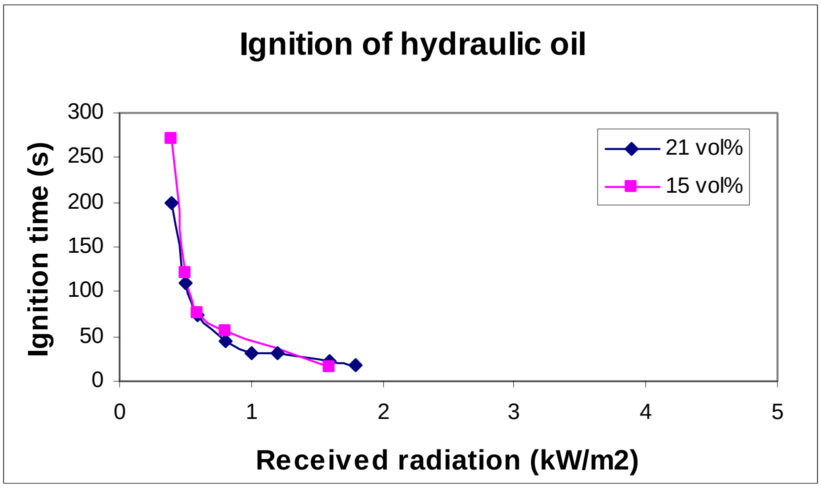

Figure H.5 Time to ignition at different radiation levels and oxygen concentrations.

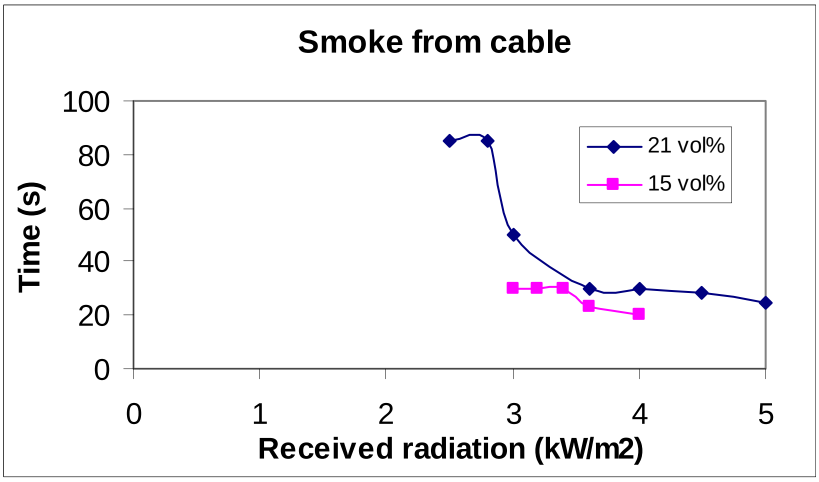

Figure H.6 Time to emit smoke at different radiation levels and oxygen concentrations.

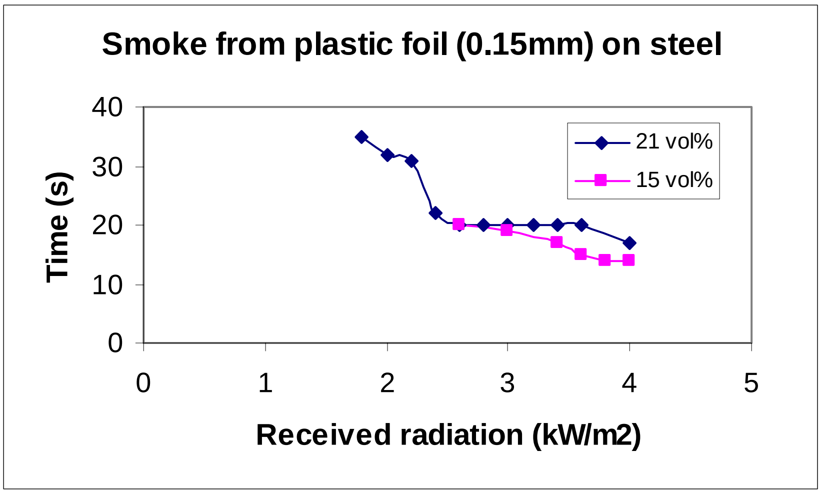

Figure H.7 Time to emit smoke at different radiation levels and oxygen concentrations.

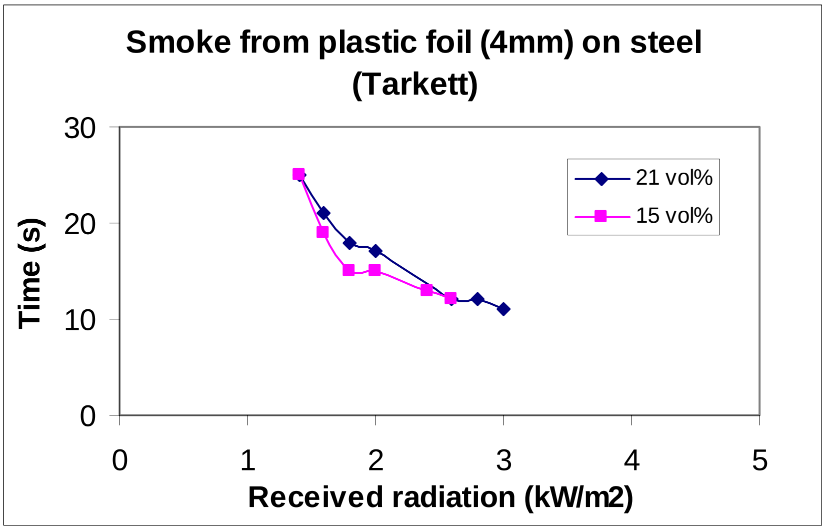

Figure H.8 Time to emit smoke at different radiation levels and oxygen concentrations.

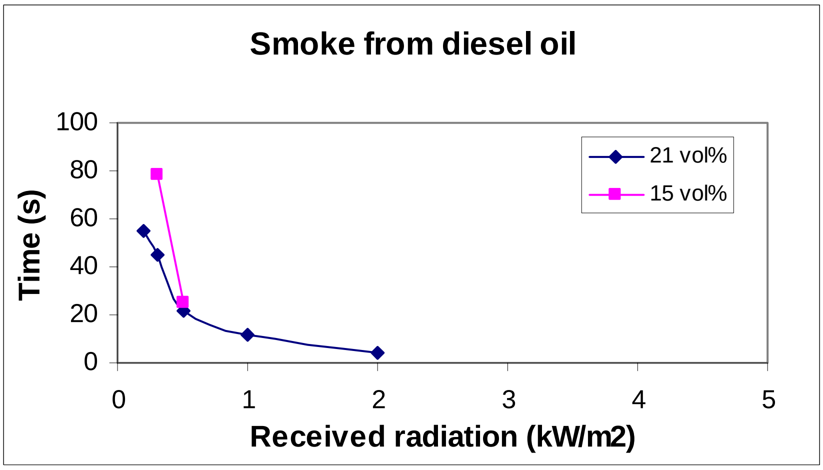

Figure H.9 Time to emit smoke at different radiation levels and oxygen concentrations.

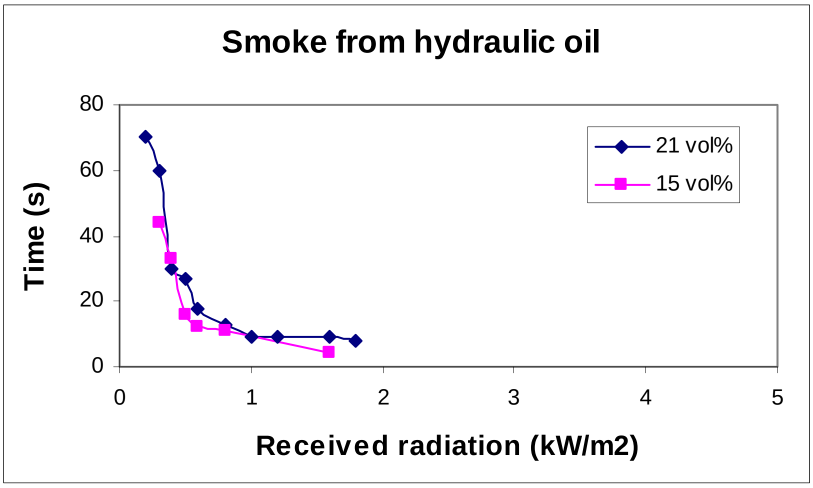

Figure H.10 Time to emit smoke at different radiation levels and oxygen concentrations.

Appendix I – Interactions between carbon dioxide and hypoxic air

Presence of carbon dioxide (CO_2) will increase respiration and brain blood vessels will be slightly dilated. These effects will increase the amount of oxygen in the blood, the blood flow to the brain and improve the delivery of oxygen to the tissues. As long as the CO_2 concentration is lower than 5 vol% in air, the effects will not be toxic [26]. The effect of increased respiration minute volume (RMV) is named hyperventilation. This effect would be little below 3 vol% CO_2, but the RMV will be doubled at 3 vol% and tripled at 5 vol%, see figure I.1 [26]. Human effects of increased CO_2 are showed in table I.1. These effects seem to worsen during exposure due to the gradual equilibrium process in the body. Note that these effects are valid in normoxic air, 21 vol% oxygen.

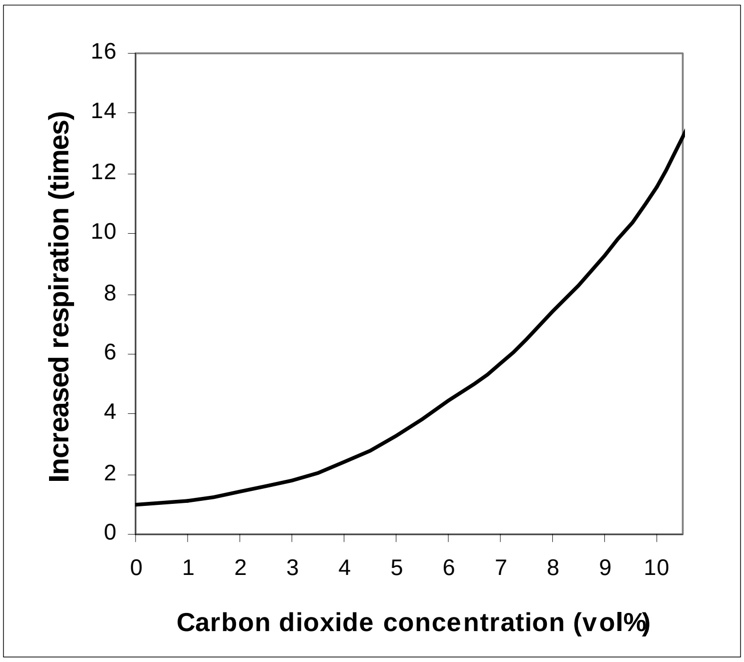

Figure I.1 Respiration response to carbon dioxide [26].

Table I.1 Human effects of increased carbon dioxide concentration [26].

Carbon dioxide (vol%)	Symptoms
< 5	No toxic effects
> 5	Severe breathing, discomfort, headache, vomiting
> 7	Dizziness, drowsiness, unconsciousness

Human experiments have been performed in normobaric hypoxic air, both with and without CO_2 [37]. There are significant differences in respiration and oxygen saturation when 4 vol% of carbon dioxide is added to hypoxic air with 10 vol% oxygen. No adverse effects are found in the study when CO_2 was added, but without added CO_2 severe effects were indicated both on physiological and cognitive tests.

The CO_2 effect is good due to the increased air exchange. Increased RMV will increase the uptake of oxygen, which is an advantage in a non-fire situation. Because of this the body will be able to endure lower concentrations of oxygen under a short period of time. However, a few percent increase of CO_2 will increase RMV and is a disadvantage when toxic and hot gases like CO are present in the air. The increased respiration effect also makes more substances that act irritating gather in the lungs. New evidence supports the thesis that these substances give post exposure toxic effects and even cause death at sub lethal concentrations [26].

Appendix J – Human effects

J.1 Heart

A fall in oxygen increases the heart rate and the cardiac output. This will return to normal when the body adapts to the reduced oxygen conditions [30]. Laboratory studies in hypobaric chambers shows that between altitudes of 4000-8000 metres, corresponding to 12.7-7.3 vol% oxygen at sea level, the cardiac output at maximum exercise is less than under normal conditions. These results are not clear-cut then other studies show the opposite result or no change in cardiac output. Uncertainties in these results can partly depend on the counteracting effects of blood volume of plasma being less and therefore the cardiac pressure also being less [40]. Experiments where humans are exposed to normobaric hypoxic air with 10 vol% oxygen show a 50% increase in heart rate when resting during 11 minutes and a 35% increase of heart rate during 50 watts exercise and 5 minutes [37].

J.2 Lungs

The instantaneously effect of high altitude to human lungs is an increase in ventilation volume due to increased breathing rate. Ventilation increases within the first minutes of reduced oxygen concentration and increases further during the first days. If the oxygen concentration is reduced for several days the ventilatory response becomes even stronger [30].The increase of ventilation differs between people and is less increased among people with a history of acute mountain sickness (AMS). At a level of 3900 metres, corresponding to 12.9 vol% oxygen at sea level, an unacclimatized human consumes more oxygen with increasing work than gained by increase in respiratory [40]. Experiment where humans are exposed to normobaric hypoxic air with 10 vol% oxygen shows a 50% increase in respiration minute volume (RMV) both when resting during 11 minutes and during 50 watts exercise and 5 minutes [37].

J.3 Blood

Clear positive effects of training at intermediate altitude (around 1500-3000 meters) are found and this phenomena is further more discussed in appendix K. Oxygen consumption decreases with up to 20 % and the performance is therefore increased. The ability to carry oxygen by haemoglobin is increased due to the increased number of red blood cells [40]. An excessive amount of red blood cells increases the risk of blood clotting or heart attack, which may cause a sudden death. This unsafe amount of red blood cells is only achieved if using EPO (erythropoietin), blood doping or hypoxic air with extremely reduced oxygen concentration during a long time [61]. Experiment where humans are exposed to normobaric hypoxic air with 10 vol% oxygen shows a 25% decrease in haemoglobin saturation when resting during 11 minutes and 45% decrease during 50 watts exercise [37]. The blood flow velocity increases 45% during 50 watts exercise and 5 minutes [37].

J.4 Muscles

Fitness training at intermediate altitude (around 1500-3000 meters) is found to be positive for muscles with bigger capillary and increased bloodstreams as a result. The anaerobic capacity of body is usually unchanged up to an altitude of 5500 metres, corresponding to 10.4 vol% oxygen at sea level [40].

J.5 Neurologic

The central nervous system and retina are the primary organs that are most sensitive to hypoxia [9]. Headache is the first warning of reduced oxygen and is showed both at intermediate and at high altitude but in different intensity and usually worse in the morning and increases with exercise. Headache may be caused by a benign expansion of the blood vessels in the brain in response to hypoxia. The headache should decrease due to acclimatization but can before that be reduced with the medicine ibuprofen or aspirin in combination with rest and fluids [40].

At very high altitudes headache could be the first sign of cerebral edema, often in combination with reduction in fine motor control and balance, which could be fatal. These symptoms are unusual at intermediate altitude (around 1500-3000 meters). Cerebral edema may lead to death within hours if not treated with oxygen supply or by rapid descend to lower altitudes [30,40].

Monkeys were exposed to hypoxic air containing 15 vol% oxygen. A slightly increased heart rate was observed, but no effects on brain. When the oxygen concentration was decreased to approximately 10 vol% cerebral depression was observed, conditions that are typical for unconsciousness [62]. Experiments where humans are exposed to normobaric hypoxic air with 10 vol% oxygen shows a 20% decrease in brain oxygen flow both when resting during 11 minutes and during 50 watts exercise and 5 minutes [37].

Appendix K – Hypoxic training

Athletes have for many years known about the benefits of altitude training. This method is practiced in a wide range of sports, especially where the sport is high-intensive and aerobic and is therefore limited by the ability to consume oxygen, for example cycling, swimming, cross country skiing and running.

If you stay at high altitude for several weeks, your body will adapt to reduced oxygen. The most important effect is increased amounts of red blood cells, which increases the oxygen-carrying capacity. More red blood cells are produced at high altitude when a greater amount of the hormone EPO (erythropoietin) naturally is released from the kidneys. This is the same effect as if the athlete takes the banned drug EPO.

The higher the altitude, the greater amount of red blood cells is produced. If the altitude is too high, symptoms like altitude sickness and overtraining may interfere with training. The average best altitude recommended by experts is 2200 metres [63]. An altitude of 1740 metres will only give a small effect on highly trained athletes [64], and therefore higher altitude is needed to stimulate red blood cells production. Short-term effects like altitude sickness can last for a few days at around 3000 metres [65], and symptoms can be severe higher up and interfere with training. The best duration time at high altitude is 4 weeks, after that the concentration of red blood cells doesn't rise anymore [66]. The effect is estimated as optimal after 2-3 weeks at sea level [63].

Athletes may improve the performance when exposed to high altitudes, because the body adapts to reduced oxygen. There is a large variation in the outcome from different studies [61]. The increased performance is not significant and a small group of athletes shows no improvement or even reduced performance.

There are two different strategies for altitude training suited for sea level competition:
- Live high, train high
- Live high, train low

K.1 Live high, train high

The most traditional method is when you both live and train at high altitudes. There are some problems with this method. Before the body is adapted to high altitudes, shortages of air will reduce the training intensity. One possible drawback is detraining or loss of muscle mass.

K.2 Live high, train low

Living at high altitude and training at low altitude is today common for many athletes. Training will be more intense at low altitudes and athletes can expect improvements of a few percent in performance [61]. This is an average value and some may get greater improvements and some will get no benefit at all. There are different strategies to achieve the right conditions.

The possible strategies are as follows:
- Live high on a mountain and train in a valley
- Live high and train high with oxygen-enriched air through a face mask
- Live in an enclosure at sea level with hypoxic air and train normally at sea level
- Breathe through a face mask with hypoxic air several times a day and train normally at sea level
- Live inside a chamber with hypobaric normoxic air. Vacuum is used to reduce the air pressure to simulated high altitude. Training will be exercised at sea level.

There are two more ways to achieve altitude exposure, but they are discussed among athletes and banned by the International Olympic Committee:

- Injection of EPO (erythropoietin)
- Intravenous infusion of extra red blood cells (blood doping)

There are of course individual differences in response to hypoxic training. Well trained athletes respond less, because they can’t improve the performance as much as others, simple because the interval for improvements is less [61]. Individual differences in studies may be uncertain due to placebo effect, which means that athletes physiologically are more motivated to perform better when they know that they are under treatment. Other parameters that are associated with individual differences may be altitude sickness and variation in training intensity before, under and after the study. Differences are often hard to predict and performance is likely associated with many unknown parameters.