Advantages and challenges with using hypoxic air venting as fire protection

Nilsson, Martin; Van Hees, Patrick

Published in:
Fire and Materials

DOI:
10.1002/fam.2197

2014

FIRE AND MATERIALS
Fire Mater. (2013)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/fam.2197

Advantages and challenges with using hypoxic air venting as fire protection

Martin Nilsson*,† and Patrick van Hees

Department of Fire Safety Engineering and Systems Safety, Lund University, P.O. Box 118, SE-221 00, Lund, Sweden

ABSTRACT

The use of hypoxic air venting system as fire protection is increasing and is sometimes used to replace traditional extinguishing systems. An oxygen level of 15% is generally used because a lower concentration could pose serious health risks. On the request of the Swedish Radiation Safety Authority, a literature review was conducted to determine advantages and challenges with the system and further research needs. The main advantages with a reduced oxygen environment are the reduced probability of ignition and lowered heat release rate. However, at 15% oxygen level, risk for fire still exists, and the system cannot be seen as an alternative to extinguishing systems. Reduced oxygen environment also results in higher production rates of soot and smoke, and there is limited knowledge regarding the effect of fuel configuration and fire behavior of products. In addition, a first evaluation of the test method specified in the hypoxic air venting standards was carried out through testing. The testing showed that the particleboard passed the test criteria at normal atmosphere even though it is commonly known that a particleboard burns in normal air. It is concluded that the test method has deficiencies, and there is clearly a need for development of the test method to guarantee safety levels. © 2013 The Authors. Fire and Materials published by John Wiley & Sons, Ltd.

Received 12 April 2013; Revised 19 June 2013; Accepted 26 June 2013

KEY WORDS: hypoxic air venting; reduced oxygen; burning behavior; ignition; heat release rate; limiting oxygen concentration

1. INTRODUCTION

Over the last years, the use of hypoxic air venting systems has increased and been proposed as an alternative to traditional extinguishment systems. Hypoxic air systems have been introduced, for example, in storage rooms of museums, computer rooms, and warehouses [1], where even a small fire could cause large damage before the fire is extinguished. The systems are now being considered in other industries as well, for example, the system is planned to be installed in electrical appliance rooms in one of the Swedish nuclear power plants. Further, in multifunctional buildings, electrical appliance rooms and computer rooms have been found to be essential to societal important functions [2,3]. These occupancies are very sensitive to fire and products of combustion, and the main purpose of hypoxic air venting is to prevent ignition by a permanent reduced oxygen environment, hence, potentially offering a suitable protection option. The level of protection, however, is dependent on the oxygen level, which in reality has to be balanced against the possible negative health effects of working or being present in a reduced oxygen atmosphere without personal

* Correspondence to: Martin Nilsson, Department of Fire Safety Engineering and Systems Safety, Lund University, P.O. Box 118, SE-221 00 Lund, Sweden.
†E-mail: martin.nilsson@brand.lth.se

protective equipment [4]. Usually, a design oxygen concentration level of around 15% is used [1,4,5]; hence, the achieved oxygen level is generally higher than the limiting oxygen concentration, for example, refer to Xin and Khan [6], and therefore, a potential for fire occurring and developing still exists.

2. PURPOSE, GOAL, AND METHOD

On request of the Swedish Radiation Safety Authority, a literature review was conducted. The purpose of the literature review was to determine the current state of the art regarding hypoxic air venting as fire protection and to increase the knowledge about using the system as fire protection in electrical appliance rooms. The goal was to present advantages and disadvantages with the system and to identify areas where further research is needed. A number of specific questions were formulated to achieve the purpose and goal of the literature review:

- How is the risk for fire affected by a reduction of the oxygen concentration to 15% ,and how is the potential for ignition affected by a reduction in oxygen concentration?
- How is the fire development (heat release rate (HRR), soot production, and flame speed) affected by a reduction in oxygen level?
- How does a reduced oxygen environment affect a smoldering fire?
- What are the advantages and disadvantages with different test methods, and how well do they account for different configurations of fuel?
- How is the information on reliability and effectiveness of a hypoxic air venting system? Especially considering uneven oxygen levels, experiences from fires, and the need for redundant systems.
- What are the health risks associated with a reduced oxygen environment?
- Are there any specific considerations (temperature, combustible material, functionality of equipment, etc.) needed with respect to the occupancy, that is, electrical appliance rooms?

For the literature review, two scientific databases were used, Web of Science and Google Scholar. Searches were made with the keywords ‘fire’, ‘burning behavior’ in combination with ‘hypoxic air’, ‘reduced oxygen’, ‘hypoxic’, and ‘hypoxia’. The searches in the two scientific databases yielded 27 articles considered to be relevant to obtain the purpose and goal of the literature review, that is, focusing on hypoxic air venting systems for fire protection. Many of the articles that came up in the searches discussed medical aspects of hypoxic air. Because of the limited amount of relevant peer-reviewed articles, the search engine ‘Google search’ was used to find more articles on the subject. Through these searches and through the reference lists in the articles, a base with relevant literature was established through which the questions could be answered. In addition, standardization web pages were used to find any standards for hypoxic air venting systems. The relevant literature has been cited in the reference list of this paper.

In addition to the literature review, the test method, specified in hypoxic air standards [5,7], to determine the required oxygen level in a protected space was evaluated through testing. This testing was performed in a normal atmosphere, and the material used was a regular particleboard. The purpose of the testing was to determine if the test method results in an adequate safety level based upon the known fact that regular particleboard burns in normal atmosphere.

3. RESULTS AND DISCUSSION

The results are presented and discussed in the succeeding texts; each subsection addresses the questions previously mentioned. The last question in the aforementioned bullet list is, however, discussed under Section 4.

3.1. The risk for fire at 15% oxygen concentration and the potential for ignition

According to PAS 95:2011 [7] and VdS 3527en [5], different oxygen concentrations should be used depending on the material subject to burning (refer to Section 3.4 for description of the tests). In

DOI: 10.1002/fam

Table I, different values of oxygen concentrations, below which burning cannot take place in the test application, is shown. It can be seen that the values differ quite widely; this is dependent upon the test procedure. The limiting oxygen concentration was obtained by Xin and Khan [8] in the Fire Propagation Apparatus (FPA) with an external heat flux of 30 kW/m^2 for solid fuels and with no external heat flux for the liquids. In the table, values for the oxygen index obtained according to ASTM 2863/ISO 4589-2, and values from NFPA 69 [9] are given. It should be noted that NFPA 69 covers explosion prevention systems; hence, values for solids are obtained for dusts resulting in low values, which are not appropriate for the hypoxic air application.

When staff occupies the protected area occasionally or normally, the used oxygen concentration is generally 15–16%, which is referred to as preventive mode [1]. The 15% oxygen concentration was also the preferred concentration in the electrical appliances rooms in the Swedish nuclear power plants. When comparing this concentration to the concentrations in Table I, it can be seen that according to the VdS standard, a 15% oxygen concentration can generally be used to protect an area with plastic materials as the combustible load, which is applicable to electrical appliances rooms. However, the values provided by Xin and Khan [8] shows significantly lower concentrations because of the applied external heat flux, which is not present in the test method in VdS 3527en. Xin and Khan [8] showed that the oxygen concentration needed to extinguish a fire is highly dependent upon the external radiation level; however, below a certain oxygen level, extinguishment will occur even with an infinite external radiation. Delichatsios [10] also showed that with an external heat flux plywood can be ignited at 15% oxygen concentration, at 13% ignition was not possible. An external heat flux could be obtained, for example, if an arson fire is expected where flammable liquids are used as an ignition source or if materials are reradiating towards each other as in the parallel panel test [8]. The test method, specific for hypoxic air venting systems, to determine the required oxygen concentration for protection with hypoxic air venting is described in VdS 3527en [5] and Pas 95:2011 [7]. This test method challenges the material more than the oxygen index according to ASTM 2863/ISO 4589-2, but there is still a risk for fire if the ignition source is more challenging than the one used in the test method. Stating that a 15% oxygen concentration fully protects against fire in plastic materials is therefore not completely true, it is only under those conditions used during the test where the 15% was obtained that fire is prevented. Polyvinyl chloride (PVC), for example, needs 44.9% oxygen to burn on the basis of the ASTM 2863/ISO 4589-2 test, and there are several examples where PVC has burnt in normal air. The oxygen index method is therefore questionable for purposes other than ranking materials, and the obtained result is, for example, dependent upon the material, sample type, and ignition procedure. Another example is the parallel panel test where PMMA is extinguished first at 14.7% oxygen concentration with no external radiation present [8].

The ignition energy, needed to ignite dusts, as a function of oxygen concentration has been studied by, for example, Schwenzfeuer *et al.* [12] and Ackroyd *et al.* [13]. The results show that the ignition energy needed increases with a reduction in oxygen level; measurements have been made with oxygen concentrations as low as 6% [13]. A schematic is shown in Figure 1, which also shows two

Table I. Oxygen concentrations below which burning cannot occur in the test.

Substance	VdS ignition threshold (vol%) (design concentration vol%) [5]	Limiting oxygen concentration (vol%) [8]	Oxygen index ASTM 2863/ISO 4589-2 (vol%) [11]	NFPA 69 (vol%) [9]
Methanol	11.0 (10.0)	11.64	—	10
Ethanol	12.8 (11.8)	12.40	—	10.5
PMMA	15.9 (14.9)	10.48	17.8	
Polyethylene	HD: 16.0 (15.0)		HD: 16.9	h.p.: 10
	LD: 15.9 (14.9)	LD: 11.39		
Corrugated Board	15.0 (14.0)	12.86	—	—
Polyvinyl chloride	16.9 (15.9)	—	44.9	—

HD, high density; LD, low density

DOI: 10.1002/fam

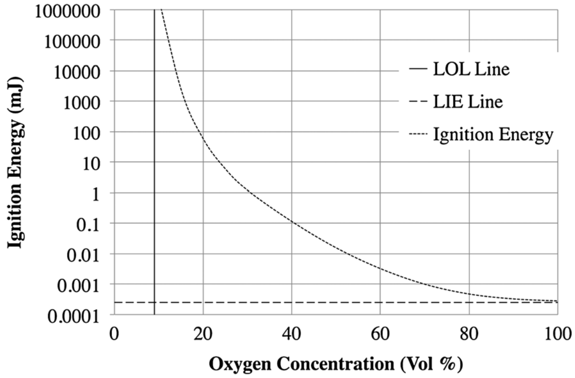

Figure 1. Schematic of relationship between oxygen concentration and MIE, reproduced from Schwenzfeuer *et al*. [12].

asymptotes [12]. One asymptote, lowest ignition energy (LIE) line, represents the energy below which no ignition is possible even in 100% oxygen. The other asymptote, lower oxygen limit (LOL) line, represents the oxygen concentration below which no ignition is possible even with an unrealistic high ignition source. The same trends have been shown for gases (see e.g., Blanc *et al*. [14] and Glor [15]). Because the ignition energy needed increases with a reduction in oxygen concentration, the probability for fire occurring is lowered with a reduction in oxygen concentration; it can be compared with removing some of the ignition sources. Little information has been found on the minimum ignition energy needed to ignite solid materials in reduced oxygen atmosphere, but the same trend is expected for solids; however, such values would be beneficial for risk assessment purposes.

Babrauskas [16] discussed the oxygen concentration's effect on ignition times. He stated that there are studies that show a dependence upon oxygen concentration where a decrease in oxygen concentration leads to an increased ignition time [16]. However, the reported tests were either performed with fuels where an oxidizer was mixed in the fuel or autoignition was tested [16]. Babrauskas also reported results from the tests in Mullholland *et al*. [17] (PMMA, ABS, PE, and Douglas Fir); with external radiant heat flux and piloted ignition, it is shown that the oxygen concentration had no bearing on the time to ignition down to a 14% oxygen level [16]. Delichatsios [10] in his experiments with wood concluded that a reduced oxygen atmosphere does not affect the time to ignition as long as the fuel mass flux is nearly independent of oxygen concentration and suggests that ignition times are weakly dependent upon reduced oxygen concentrations, that is, when the irradiance level is low (larger dependence upon oxygen concentration was shown for an irradiance of 50 kW/m^2 in Delichatsios tests) [10]. Hshieh and Beeson [18] also showed that for flame retardant epoxy composites and two out of three tested phenolic composites, the time to ignition is relatively constant between 30% and 18% oxygen concentration, but for phenolic graphite, the time to ignition increases with a decrease in oxygen. Chiti *et al*. [19] reported that the ignition times are increased with a decrease in oxygen concentration. This is consistent with Mikkola [20] who reported an increase in ignition time of about 25% for a variety of solid fuels. However, Mikkola [20] used an external radiation level of 50 kW/m^2, the same level at which Delichatsios [10] also saw a weak dependence. It appears that the time to ignition could be increased with a reduction in oxygen, and this seem to be dependent upon fuel and external radiation level; however, the results are not completely conclusive.

In electrical appliances rooms, there is a potential for higher temperature than ordinary temperature, especially in electrical cabinets. In addition, extremely high temperatures can arise if a high-energy electrical discharge because of an electrical fault occurs. The flammability limits are affected by temperature and is extended with an increase in temperature as shown in Figure 2 [21]. This means that the oxygen limit is reduced when the temperature increases [22]. Such a situation could move the fuel into the flammable limit even with a lower than normal oxygen concentration.

In conclusion, a reduction of the oxygen level to 15% does not achieve conditions where a fire cannot occur or is extinguished. However, it reduces the probability of a fire occurring by increasing

DOI: 10.1002/fam

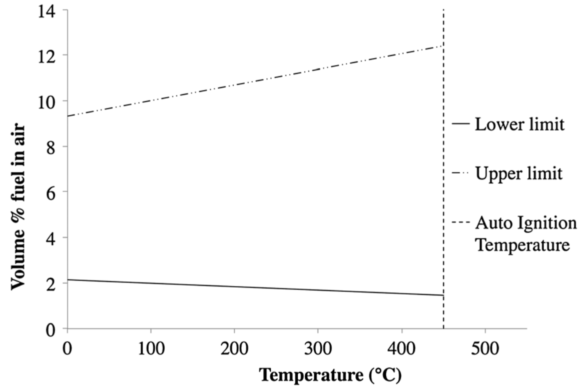

Figure 2. Effect of temperature on flammability limits for propane, reproduced from Drysdale [21].

the ignition energy needed, and there are also indications of increased ignition times. To fully protect against a fire, the oxygen level needs to be lowered even more, to the inerting point of the fuel also known as the limit line [22]. As a comparison, the FM Global Data Sheet on clean agent extinguishing systems recommends a 12–14% design concentration for typical electrical equipment where no ordinary combustibles are present [23]. In addition, different test methods provide different oxygen concentrations at which burning cannot take place for the same material, and these materials are only generic (PVC, PE, etc.) and not for specific components. The test method in hypoxic air venting standards [5,7] appear to obtain concentrations where burning is still possible under certain conditions. The effect of a rise in temperature on flammability limits also needs to be accounted for.

3.2. *The oxygen concentration's effect on fire development*

If the oxygen concentration is higher than the inerting point, a risk for fire still exists. If a fire occurs in a reduced oxygen atmosphere, the fire will become ventilation controlled or smolder. Under such conditions, for example, more soot, carbon monoxide, and other hydrocarbons will be produced [24]; the effect is illustrated in Figure 3. The increased production of these products could increase the damage to sensitive components, the need for clean up, and some products also have a negative effect on life safety. However, the knowledge on production of other gases such as corrosive and irritating is limited. Tewarson *et al*. [25], however, showed that there is an increase in other gases than soot, CO, CO_2, and hydrocarbons when the oxygen concentration decreases, examples are HCHO and HCN.

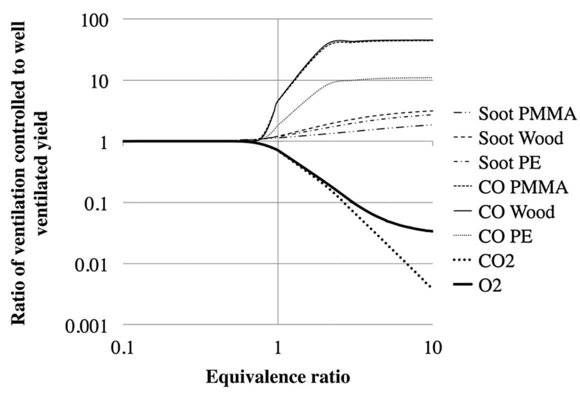

Figure 3. Effect of underventilation on yields for carbon monoxide, carbon dioxide, oxygen, and soot based on correlations by Tewarson [24].

DOI: 10.1002/fam

Xin and Khan [8] conducted one parallel panel test in the FPA using PMMA with 21% oxygen concentration until the HRR reached steady state (after that, the oxygen concentration was reduced to obtain extinction). Xin and Khan [8] also conducted one parallel panel test using PMMA and a constant oxygen concentration of 15%. When comparing the graphs, that is, the slope of the HRR curve, from the two tests, it can be concluded that the test with 15% oxygen concentration had a lower fire growth rate than the test with 21% oxygen concentration. This indicates that a decrease in oxygen concentration results in a decrease in fire growth rate for the two tested oxygen levels. Rasbash and Langford [26] showed the same trend where the flame speed for wood in a vertical configuration is reduced from 2.75 to 1.82 cm/s when the oxygen concentration is reduced from 21% to 13.7%. Loh [27] studied flame spread of PMMA and filter paper in concurrent flow and concluded that the flame spread was reduced with a decrease in oxygen concentration; oxygen concentrations from 100% to 18% were tested. From the graphs in Loh [27], it can be seen that the decrease in flame spread for PMMA is marginal when reducing the oxygen concentration from 21% to 18%; the thin filter paper was not tested below 21% oxygen concentration. Fernandez-Pello *et al.* [28] studied PMMA and thin paper sheets as well, but in opposed flow, he also concluded that the flame spread decreased with a decrease in oxygen concentration; oxygen concentrations from 100% down to 19% were used. Tewarson and Ogden [29] also showed a decrease in flame spread rate for PMMA with a decrease in oxygen; oxygen concentrations down to 16% were used. Carhart [30] provides a graph where he showed an increase in burning rate (m/s) with an increase in oxygen concentration for thin paper, but the study seems to be for elevated oxygen concentration only. Tewarson and Khan [31] showed an increase in flame propagation rate with an increase in oxygen concentrations; however, 21–45% oxygen concentration was used. Rasbash and Langford [26] also discussed that the effect on flame speed with oxygen reduction is greater for horizontal configurations. They attribute this to the mechanism of heat transfer, that is, for horizontal configurations, the radiation is dominant and where convective heat transfer is substantial, such as for vertical configurations, the effect of oxygen reduction is less prominent [26]. This is consistent with observations by Tewarson [32] that radiation to the fuel surface (horizontal configuration) decreases significantly with reduction in oxygen concentration.

A comparison of the results from the two parallel panel tests conducted by Xin and Khan [8] (also discussed previously) indicated that the peak HRR and the mass loss rate (MLR) decrease with reduced oxygen concentrations for the tested levels; Xin and Khan also pointed this out. In a horizontal test with PMMA with an external heat flux of 30 kW/m^2, Xin and Khan [8] showed a reduction in the HRR by 15–20% when the oxygen concentration is reduced from 21% to 15% compared at the same time into the test. However their horizontal experiment also showed that the peak chemical HRR remained the same but with a time delay [8]. Xin and Khan [8] also stated that the difference in fire growth rate is negligible for the horizontal test. Experiments with horizontal samples were also carried out by Marquis *et al.* [33] for PMMA with an external heat flux of 50 kW/m^2 in a modified cone calorimeter (CC) to examine the effect of the design of the controlled atmosphere CC (CACC). Marquis *et al.* [33] showed that there is approximately a 20% reduction in HRR per unit area, and also, the MLR is reduced when the oxygen concentration is decreased from 21% to 15%. They do not discuss fire growth, but by the slope of the HRR curve, it can be seen that the slope is about the same for oxygen concentrations of 21–12.5% [33]. Mikkola [20] showed a small decrease in HRR for horizontal samples for a variety of fuels with a 50 kW/m^2 external heat flux; the exception is PVC where the HRR was reduced by 60% when the oxygen concentration was reduced from 21% to 15%. Tewarson *et al.* [32] and Mullholland *et al.* [17] showed a decrease in MLR, Mullholland *et al.* [17] also showed a decrease in HRR (moderate for wood and greater for plastics) and that the effective heat of combustion was independent of oxygen concentration, that is, the HRR mirrored the MLR [16]. However, the experiments by Mullholland *et al.* [17] used a lowest oxygen concentration of between 13.7% and 12.4% (refer to Section 3.4 for further discussion). Yao *et al.* [34] conducted tests burning cardboard boxes with no external heat flux at high altitude (3650 m, corresponding to approximately 13.5% oxygen concentration (partial pressure) at sea level [35]) and at sea level (50 m). Similar to other references, Yao *et al.* [34] showed a decrease in HRR and MLR when the oxygen concentration is decreased (oxygen partial pressure). However, Yao *et al.* [34] showed that the heat of combustion is approximately 40% lower

DOI: 10.1002/fam

at the higher altitude, which contradict the results by Mullholland *et al*. [17]. From the tests by Xin and Khan [8] (the two parallel panel tests previously discussed), the graphs indicate that the heat of combustion is independent of the oxygen concentration. The reason for the deviating results could be because of the total static pressure is lower at high altitudes and that Yao *et al*. [34] did not use external heat flux to pyrolyze the material, whereas oxygen concentration has been shown to affect the pyrolysis [36] (also, see discussion under smoldering combustion). It could also be because of the way of calculating the total HRR. However, the reason for the deviating results cannot be fully determined, and the affecting mechanism of low oxygen concentration on solid pyrolysis is complex and needs further research [34]. Peatross and Beyler [37] put forward a correlation where the MLR is dependent upon the oxygen concentration; this correlation agrees well with the test results for PMMA from Tewarson [32], and the reduction in MLR will also result in a reduction in HRR at moderately low oxygen concentrations. The mechanisms of heat transfer to the fuel surface reducing the MLR, HRR, and flame speed in a reduced oxygen atmosphere in the aforementioned applications is thought to be mainly two parameters. First, the flame temperature is decreased as an effect of the decrease in oxygen but also as an effect of the increased thermal capacity by nitrogen [38]. Second, because the combustion takes place further away from the fuel surface to encounter oxygen, the view factor is reduced as well. This was also observed, for example, during the experiments conducted by Marquis *et al*. [33] where combustion was observed further away from the fuel surface, and no change on MLR was observed. This is also consistent with the observation made by Tewarson and Steciak [39] where they show an increase in flame height with a decrease in oxygen concentration. The results by Xin and Khan [8] where the peak chemical HRR does not change with oxygen concentration for the horizontal configuration is deviating from the other results. It would be beneficial to investigate the reason for this deviation.

There appears to be a reduction in HRR when the oxygen concentration is reduced; however, it seems to be very dependent upon the fuel. The reduction in HRR would result in less radiation also between fuel packages, which would reduce fire spread between fuel packages. Further, there are indications that the flame spread decreases with a reduction in oxygen. Babrauskas [16] suggested that for lower oxygen concentrations, the dependence of flame spread rate becomes larger and approaches an asymptotic value upon which extinction occur. However, limited tests have been found at low oxygen concentrations, that is, ranging from 18% down to the point of extinction. All these effects would aid in limiting fire damage; however, there is an increased production of gases negative for smoke damage, and the information is limited for production of, for example, corrosive and irritating gases. Further, the underventilated fire could cause conditions where pyrolysis still occurs creating the risk for a backdraft or gas explosion; the probability for this event occurring is most likely low but has not been studied.

3.3. *Smoldering combustion and oxygen concentration*

Smoldering combustion may still occur even if flaming combustion is not possible, and materials might still smolder at reduced oxygen concentrations because less oxygen is required for a smoldering fire [35]. This process can produce combustible smoke, and if the smoke is ignited, a smoke gas explosion can occur. Berg and Lindgren [35] concluded that if the oxygen concentration is reduced to just a few percent smoldering heat will be significantly reduced. Chiti [4] concluded from his review of the literature that a reduction in oxygen concentration limits the smoldering spread and velocity, but the effect is not as relevant as in flaming fires. He also stated that hypoxic air would not be fire preventing under the circumstances where smoldering can still occur at very low oxygen concentrations [4]. Chaos *et al*. [36] studied pyrolysis of corrugated cardboard in inert and oxidative environments (under non-flaming conditions). They showed that under low incident heat flux (20 kW/m^2) an increase in oxygen concentration resulted in an increase in MLR, that is, pyrolysis rate, this was not evident for higher fluxes (60 and 100 kW/m^2) [36]. This indicates reaction of oxygen with char formed during pyrolysis [36]. The result is consistent with the conclusion made by Yao *et al*. [34] where they state that incomplete paper and cardboard pyrolysis is a result of the pyrolysis is suppressed by low oxygen concentration. Chaos *et al*. [36] also showed that the char oxidation HRR per unit area is reduced with a decrease in oxygen concentration, which is consistent

DOI: 10.1002/fam

with Berg and Lindgrens previous statement. However, Chaos *et al*. also showed that the heat released from the char oxidation process is always lower than 15 kW/m^2 in their tests; hence, the contribution is low when considering high heat fluxes, which explains why an increase in MLR was not evident for higher heat fluxes [36]. However, effects on smoldering combustion at reduced oxygen concentrations is fairly uninvestigated, but it is clear that even at low oxygen concentrations, smoldering combustion can still occur.

3.4. Test methods and configuration of fuel

As discussed previously, at 15% oxygen concentration, most materials can still burn under certain circumstances, and it is clear that the, for protection, obtained oxygen concentration is dependent upon test procedure. A generalized test method to determine the required oxygen concentration to prevent fire therefore needs to cover a range of different possible initiating events and scenarios following to be able to state that the obtained oxygen level will prevent fire.

Because a hypoxic air venting system is designed to keep the whole atmosphere at a constant oxygen concentration, it is important that the testing procedures reproduce this condition; hence, it is important that burning takes place within such an atmosphere. Marquis *et al*. [33] investigated the design of the CACC where they varied the way of enclosing the sample and space in which burning takes place. One variation had no enclosure (the same setup as used by Mikkola [20]), one with a quartz chimney (similar to what Xin and Khan [8] used in the FPA) and one with a metal chimney [33]. Marquis *et al*. [33] did not perform tests with a full enclosure to the exhaust hood as Mullholland *et al*. [17] did. The tests by Marquis *et al*. [33] used horizontal samples of PMMA with an external heat flux of 50 kW/m^2, and the oxygen concentrations used was 21%, 15%, 12.5%, and 10%. From the test results, it can be seen that the MLR is independent upon the design of the enclosure; however, the HRR varies depending on the design [33]. Just as Mullholland *et al*. [17] concluded, it can be seen from the tests performed by Marquis *et al*. [33] that the HRR mirrors the MLR with oxygen concentrations between 21% and 12.5% especially for the unenclosed configuration, when a chimney is used, the peak HRR is somewhat lower; however, given experimental uncertainties, this could not be proven. At 10% oxygen concentration, on the other hand, there is a statistical difference in measured effective heat of combustion and HRR. It is concluded that the design of CACC without direct connection to the exhaust hood and without a chimney seems to be inappropriate to study phenomena in the gas phase under low oxygen concentration [33]. In the tests for 10% oxygen concentration, a peak HRR of approximately 800 kW/m^2 is observed when the chimney is used. Without a chimney, the peak HRR is approximately 180 kW/m^2, which is explained by dilution to below the lower flammability limit when no chimney is used [33]. The previous texts illustrates the importance of the design of the test apparatus and what conditions are actually tested. The design with a full enclosure to the exhaust hood, as used by Mullholland *et al*. [17], is appealing because there intuitively would be less of a risk for dilution with normal air, and the matter of deciding the length of the chimney so that all burning takes place within the chimney, as pointed out by Marquis *et al*. [33], disappears.

The test procedures specified in VdS 3527en [5] and PAS 95:2011 [7] have the advantage that the test is conducted in a room with reduced oxygen concentration, which is realistic to the real application of hypoxic air venting systems. As ignition source, an acetylene–oxygen torch is used and placed to the test sample for 180 s (also refer to Figure 5 for the test setup), if the sample keeps burning independently for a period of 60 s after the ignition source has been removed the test has failed, and a lower oxygen concentration is needed [5,7]. Use of acetylene as fuel for the ignition source is maybe not so common because of its specific combustion/flammability characteristics. There are small differences in the test procedures, PAS 95:2011 specifies that both a vertical and a horizontal sample should be tested [7], and VdS 3527en specifies that materials shall be tested as unfavorable as possible in terms of orientation [5]. In these proposed tests, there is no external radiation applied as in the CC or FPA tests, that is, the flame need to supply sufficient heat to assist the pyrolysis after the torch has been removed. External radiation in a fire scenario can occur if something else is burning in the room and radiates towards another fuel package, for example, if flammable liquids are used as ignition source. Although both VdS 3527en [5] and PAS 95:2011 [7] point out the

DOI: 10.1002/fam

importance of testing both horizontal and vertical arrangements of the fuel, the standards do not consider the possible configuration between fuel packages. If the fuel packages are spaced close together but with flue spaces between them, such as in rack storage, the ignition at the bottom of such a flue with both surfaces burning would cause a radiation exchange between the surfaces. This can be compared with the parallel panel test performed by Xin and Khan [8] where no external radiation was applied, but sustained burning of PMMA was obtained at 14.7% oxygen concentration as compared to the ignition threshold according to VdS 3527en of 15.9% oxygen concentration [5]. Chiti [4] tested cribs made of wood with an acetylene–oxygen torch; however, he applied the torch only for 15 s on the wood cribs. The cribs were placed in a room similar to the one specified in hypoxic air standards [5,7] with a reduced oxygen concentration. At 16% oxygen concentration, there were small flames 2 min after the torch had been removed [4], and therefore, the test criteria in PAS 95:2011 or VdS 3527en would not have been fulfilled. As discussed previously, Rasbash and Langford [26] also showed sustained burning of wood at oxygen concentrations of 13.1%, without external radiation but with a configuration that favors radiation exchange between fuel packages. However, VdS 3527en specifies 17% oxygen concentration as ignition threshold for wood [5] on the basis of the test method in the standard. The reason for this discrepancy is probably because of the configuration of the fuel packages, which in the tests in VdS 3527en and PAS 95:2011 is not considered; hence, the potential for radiation exchange is ignored, and the obtained oxygen concentration in the standards appears to be nonconservative maybe overestimating the performance of the hypoxic air venting system. An even more common configuration might be that of a corner where also radiation exchange between surfaces can take place and more intensive air entrainment.

In addition, the thickness of the sample for testing is specified not to exceed 25 mm in VdS 3527en [5]. The thickness of the material has an impact on the time to ignition where an increased thickness increases the time to ignition. However, when increasing the external radiation, the time to ignition for different thicknesses approaches the same value, and the importance of the thickness of the material reduces when external radiation is applied [35]. Because the application of the torch for ignition in both PAS 95:2011 and VdS 3527en is of limited time, it cannot with certainty be stated that a thickness of 25 mm will not affect the result. If the material used in the real application is thinner than the one tested, the oxygen concentration might not prevent ignition. Application of external radiation will reduce the risk.

It need to be recognized that if a scenario was to occur that presents a larger initiating event, both in terms of energy in the ignition source or exposure time, than was used in the test to obtain the oxygen concentration, there is a clear possibility that ignition followed by sustained burning could occur. Further, the tested configuration of the fuel packages and orientation of the fuel plays an important role; there are several examples of more challenging scenarios than the ones covered in both PAS 95:2011 and VdS 3527en. External radiation is excluded in the test methods proposed by the standards for hypoxic air venting; external radiation might be one way of challenging the test to cover different configurations of fuel and larger ignition sources. However, it needs to be pointed out that hypoxic air venting systems are not designed to extinguish fires, as is recognized in the standards [5,7], and therefore, the need for applying external radiation might not be entirely relevant. If external radiation is not applied, the configuration of the fuel becomes more important, and there appears to be a need for further development of the test methods for hypoxic air venting systems to cover this aspect and how large an initiating event needs to be.

3.5. Description and results from evaluation of the test method in PAS 95:2011 and VdS 3527en

Testing was performed according to the testing procedure in PAS 95:2011 [7] and VdS 3527en [5]. All tests were performed at normal atmosphere (21% oxygen concentration) to investigate the test conditions.

The flame length in all tests was approximately 0.3 m; it should be noted that it is hard to be exact when adjusting the flame length and the mixture between oxygen and acetylene, and there is no firm description of this in the test method (e.g., equivalence ratio to be used, gas flows, etc.). Mainly, a vertical orientation of the samples was used. All the tests specified in Table II had the sample in a vertical position. All sample sizes measured 0.2 m × 0.2 m, the thickness of the standard

DOI: 10.1002/fam

Table II. Vertical tests performed.

Test	Flame (length is 0.3 m)	Distance from outlet to sample (m)	Material	Test criteria (P, passed; F, failed)	Comment
P1	Transition from orange to blue, slightly on orange side	0.2	Standard particleboard	P	No burn through, self-extinguish 13 s after flame removal
V2	Transition from orange to blue, slightly on orange side	0.1	Standard particleboard	P	No burn through, self-extinguish 20 s after flame removal
V4b	Transition from orange to blue, slightly on blue side	0.2	Standard particleboard	F	135 s burn through, no self-extinguishment
V4c	Transition from orange to blue, slightly on blue side	0.2	Standard particleboard	P	140 s burn through, self-extinguish 5 s after flame removal
V5	Transition from orange to blue, slightly on blue side	0.1	Standard particleboard	P	75 s burn through, self-extinguish 5 s after flame removal
V6	Transition from orange to blue, slightly on blue side	0.2	Low density particleboard	F	45 s burn through, no self-extinguishment
V9	Transition from orange to blue, slightly on blue side	0.2	Medium-density fibreboard	P	No burn through, self-extinguish 9 s after flame removal

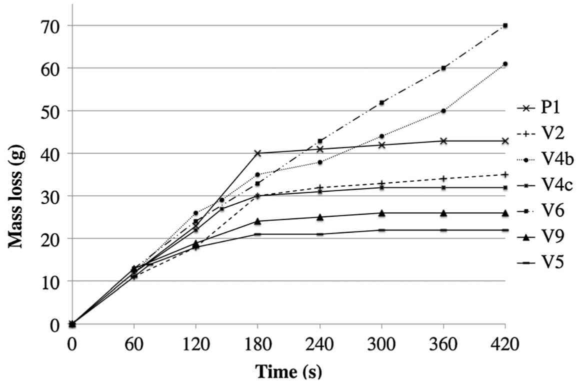

Figure 4. Total mass loss during the different tests.

particleboard was 10.5 mm with a density of 610 kg/m^3, the low density particleboard 13.5 mm and 240 kg/m^3, and the medium-density fibreboard board 18 mm and 600 kg/m^3.

From the tests (refer to Table II), it can be seen that regular particleboard passes the test in many cases at normal atmosphere (21% oxygen concentration) (refer also to Figure 5 in the succeeding texts). This is remarkable because it is common knowledge that this type of material burns and contributes to fire spread in common applications and scenarios at normal atmosphere. Hence, it seems that the test method in PAS 95:2011 and VdS 3527en results in a protection level that might be on the unsafe side, and the test method does not differentiate protection performance sufficiently.

In test V4b, the test did not meet the test criterion, that is, sustained burning was still observed 60 s after the ignition source was removed; this was due to the position of the flame on the test sample. The position was so far down in the corner of the sample that once the flame burned through the sample the edges of the sample caught fire and continued burning during the test. However, the test standards are not clear on exactly where to position the flame, and the results illustrates the importance of flame position. Further, the description of the test procedures and criteria is on approximately one page in VdS 3527en [5] and on approximately two pages in PAS 95:2011 [7]; hence, it is fairly unspecified, and there is limited guidance given presenting the potential for varying interpretations and test procedures between labs. The lack of guidance on gas flows, equivalence ratio, imprecise, etc. can be given as examples.

In test V4c and V5 where burn through occurs and the sample passes the test criteria, it can be seen that the mass loss in principle stops shortly after burn through has occurred see Figure 4. This was observed in the tests as well where the material was virtually not burning after burn through. Oxy-fuel flames in an impinging jet-like configuration are designed to apply heat very locally [40] and at the same time with a very high heat transfer rate [41]. The main heat transfer mechanism for these flame jets is

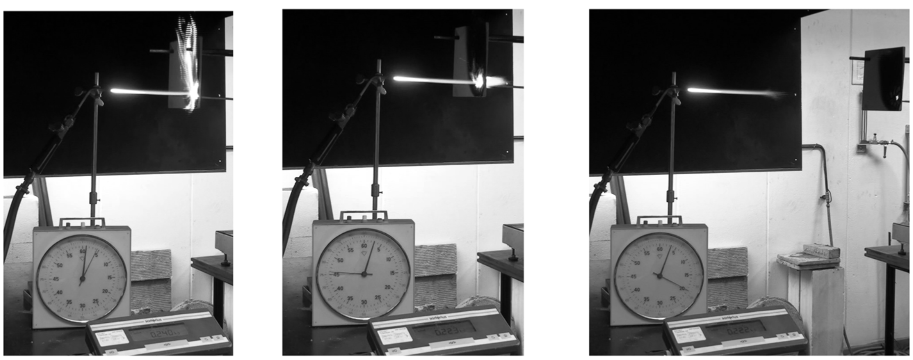

Figure 5. Particleboard tested according to the test method specified in PAS 95:2011 and VdS 3527en at normal atmosphere (21% oxygen).

DOI: 10.1002/fam

forced convection, and when the flames are operated with an increased amount of oxygen, a higher flame temperature and burning velocity are achieved, hence, increasing the convective heat transfer [41]. The maximum laminar burning velocity at stoichiometric conditions for an acetylene-air flame is 175 cm/s and for an acetylene-oxygen flame is 1120 cm/s [42]. This velocity can be compared with, for example, methane air at stoichiometric conditions, which has a maximum laminar burning velocity of 40 cm/s, or propane air with 41 cm/s or propane oxygen with 360 cm/s [42]. Wang *et al.* [43] measured the convective heat flux of the Bunsen flame used in the UL94 test concluding that the initial convective heat flux approached 100 kW/m^2 with a convective heat transfer coefficient of around 54.3 W/m^2/K. The UL94 test uses a premixed methane flame [43]; hence, the heat transfer from the oxygen acetylene torch used in tests showed in Table II has the potential to be even larger because of the higher burning velocity of acetylene oxygen. The high local heat transfer rate to the sample causes pyrolysis of the sample in the tests at a high rate, at the same time the flame has a high speed and momentum; this is thought to be the main reason for the burn through occurring. In addition, the high speed causes other pyrolysis gases to be transported away from the sample causing stretching and blowout of the flames. This is thought to be the reason why burning almost stops after burn through has occurred. An observation that enforces this is that in some test, continued burning was observed on the backside of the sample where the velocity of the acetylene-oxygen flame has a limited impact. On the basis of the previous statements, it is believed that an oxygen acetylene torch is unsuitable as an ignition source in this application because of its high burning velocity (compared with any regular ignition source) causing blowout of flames that could otherwise occur on the sample and causing burn through. Further, the flame presents almost no radiation further enforcing that heat is applied only very locally resulting in an optimistic evaluation of the safety level. It appears that a flame with a lower burning velocity, not as local application, and a sootier flame causing more radiation would be a more appropriate and realistic ignition source.

3.6. *Operational functionality and reliability*

In general, hypoxic air can be created either by supplying nitrogen to a protected space (e.g., nitrogen generator) or by removing oxygen by an air splitting unit with distribution through the regular ventilation system [1,4]. According to Chiti [4], around 500 installations are known today. Because the number of installations are few, there is limited knowledge regarding the reliability of the system, and no incident has been found where the effectiveness of the system has been challenged. There is a need for more information regarding the reliability and effectiveness of the system, that is, how often is the system unavailable because of impairment, and how well does it work in actual applications if put to the test. If a high protection level is warranted, as in the nuclear industry, it might be necessary to provide redundancy, both for the hypoxic air venting system itself and/or a back-up extinguishing system should a fire occur. Both VdS 3527en [5] and PAS 95:2011 [7] put forward the possible need for redundancy. Berg and Lindgren [35] concluded that because there still is a possibility of a fire occurring if the oxygen level is not reduced to the inerting point there is in general a need for a highly sensitive detection system, manual fire fighting equipment and emergency management procedures.

Jensen *et al.* [1] put forward the challenge of ensuring an even oxygen level, especially if a nitrogen feed system is used for complex geometries. A special case of this could be where there are a lot of concealed spaces present or, for example, enclosed electrical cabinets. Both VdS 3527en [5] and PAS 95:2011 [7] state that the oxygen level should be monitored, but there is little guidance on placement of where measuring points to ensure even oxygen levels and states that it needs to be determined on a case-by-case basis. Another aspect regarding the obtained oxygen level is leakage areas. The leakage area affects the required size of the nitrogen feed [4]; hence, if leakages increases over time, the size might not be sufficient anymore.

However, a hypoxic air system benefits from always being in place and does not need to activate like a regular extinguishing system, reducing the risk of failure to activate. When the system is impaired because of, for example, maintenance measures to limit the risks are needed, as with any other fire protection system.

3.7. Health aspects

Health aspects with respect to a reduction in oxygen in the atmosphere are not the expertise of the authors, and the subject is just discussed briefly in terms of findings in the literature. Further information on the topic can be found in the literature [7,35,44–47].

Table III summarizes different symptoms at different oxygen concentrations; it should be mentioned that depending on the reference, the symptoms at different oxygen concentrations varies a little. However, the most important parameters are the oxygen concentration and duration of exposure but also disease, physical fitness, age, and sex are important parameters [35]. Küpper *et al*. [46] stated that an acute but limited exposure down to 13% oxygen concentration does not cause a health risk if the persons are healthy; hence, this could be interpreted as a limit. Further, they pointed out that employees in a reduced oxygen atmosphere for fire prevention purposes can leave the room immediately if they do not feel well [46]. Burtscher *et al*. [45] stated that people without severe illnesses, a health risk is unlikely at greater than 14.5% oxygen concentration. However, they pointed out that there are large interindividual variations of response to hypoxia to be expected, especially in persons with preexisting diseases and that physical activity may increase the risk to get sick [45]. Angerer and Nowak [44] stated that oxygen reduced to 15% and 13% in normobaric atmospheres is equivalent to 2 700 and 3 850 m altitude, respectively. At these altitudes, persons respond within minutes to hours with increased ventilation rates, increased heart rate, etc. [44]. However, acute mountain sickness occurs frequently at these oxygen partial pressures, but the full syndrome is rare if the exposure is limited to 6 h [44]. Further, they state that at these concentrations mood, cognitive and psychomotor functions may be mildly impaired and that persons suffering from cardiac, pulmonary, or hematological diseases should consult a specialist [44]. Their conclusion is that working in environments with oxygen concentrations down to 13% does not impose a health hazard provided that precautions are observed, comprising medical exams and limited exposure time [44]. Angerer *et al*. [44], however, also pointed out that the evidence is limited particularly with respect to workers performing strenuous tasks or having various diseases.

Berg and Lindgren [35] suggested some possible consequences if fire occurs, for example, they discuss synergic effects, for example, the additional production of CO and low oxygen concentration; however, the effect is hard to determine. PAS 95:2011 [7] points out work environment considerations such as signage and low oxygen alarm. In conclusion, there need to be procedures to ensure people working in reduced oxygen atmospheres are healthy, that a risk assessment is conducted and that, the possibility of human errors because of work in reduced oxygen atmosphere with reduced cognitive performance as a result is considered among other aspects.

4. FURTHER DISCUSSION AND CONCLUSIONS

In general, a reduction of the oxygen concentration to 15% does not eliminate the possibility of a fire occurring, and at this oxygen level, a hypoxic air venting system cannot be seen as a substitute for an extinguishing system. If it should be seen as a substitute, the oxygen concentration needs to be lowered

Table III. Symptoms and exposure times at different oxygen concentrations, reproduced from Chiti [4].

Oxygen at sea level (vol%)	Symptoms	Maximum exposure time
20.9–17	No observed effects	—
17–15	Effects on night vision	—
15–13	Increased breathing and heart rate	—
13–11	Physical and intellectual performance impaired, fatigue, and headache	1 h
11–10	Giddiness and disorientation	20 min
10–8	Unconsciousness and torpor	2 min
5–0	Convulsion, apnea, cardiac standstill, and death	No exposure

DOI: 10.1002/fam

even further, and if this is feasible, the system would present a good protection option for electrical appliances rooms and sensitive equipment rooms in multifunctional buildings. Those low oxygen concentrations are often not possible because of health aspects; however, there are benefits with the system even at a 15% oxygen concentration, but there are also challenges and disadvantages; these are summarized in the succeeding texts.

The test method specified in PAS 95:2011 [7] and VdS 3527en [5] seem to be inappropriate, and the oxygen levels obtained through this test method appears to result in an insufficient protection level. This is particularly enforced by the fact that regular particleboard passes the test criteria in normal air.

4.1. Advantages

- Lowered probability for ignition and possible increased ignition times. Mikkola [20], for example showed an increase in ignition time of roughly 25% when the oxygen concentration was decreased from 21% to 15% oxygen; however, it differs between materials, and there are other references showing other results. Also, see discussion in the section regarding risk for fire at 15% oxygen concentration.
- Heat release rate is decreased (magnitudes of around 15% decrease in HRR have been shown when reducing the oxygen concentration from 21% to 15%; however, it is also shown to be very material dependent). There are also indications of reduced flame spread/speed; this will also reduce the fire spread between fuel packages. The reduction in flame spread is also supported by the indications of increased ignition times; increased ignition times correlates to a decrease in flame spread.
- The reduced oxygen atmosphere is always operational and activation because of fire is not needed.

4.2. Challenges/disadvantages

- The magnitude of the aforementioned advantages seem to be very dependent upon the material present, and the information available is mainly for generic materials; it might be necessary to conduct tests of the specific materials supposed to be present within a protected area. It is not uncommon that components consist of composite materials, and not all materials show the same beneficial effects.
- The configuration of the fuel is of great importance, orientation and distance to other fuel packages presenting the possibility of radiation could increase the risk for ignition and fire spread.
- The production of soot, smoke, and corrosive gases increases, if a fire was to occur creating a potential for larger damage to sensitive equipment. However, this needs to be balanced against the possible decrease in MLR.
- The information on reliability is uncertain, and there might still be a need for redundant systems (to create the reduced oxygen atmosphere, detection, and extinguishing system).
- Better guidance on how to ascertain even oxygen levels, especially with complex geometries.
- Health risks need to be managed considering exposure times, medical exams, strenuous work, increased risk for human error, technical provisions, and information among others.

4.3. Special considerations for electrical appliances rooms

In electrical appliances rooms, the primary default could heat the environment; further, there is a possibility for high energetic discharges because of an electrical fault causing high temperatures locally. Elevated temperatures widen the flammability limits, and this needs to be considered when installing a hypoxic air venting system in an electrical appliances room because it will affect the required oxygen level. Further, special attention is needed both for electrical rooms and for computer rooms with respect to the possibility of an increase in production of smoke and corrosive gases if fire occurs. In addition, where a high reliability and redundancy is warranted, such as in the nuclear industry, a reduction of the oxygen concentration to 15% has been shown to be a borderline case where a risk for fire still exists, and there is a possibility that additional fire protection systems are needed to limit the risks. Further, the effects of a reduction in oxygen concentrations are material dependent, and the introduction of a new material in such rooms or transient fire load needs to be controlled.

DOI: 10.1002/fam

4.4. Main concerns regarding the testing method in PAS 95:2011 and VdS 3527en

One of the main concerns regarding the testing method in PAS 95:2011 and VdS 3527en is that the ignition source is unsuitable. The oxygen acetylene torch has too high burning velocity and results in a very local heat transfer causing burn through of the material and blowout of any diffusion flames on the sample. Further, the flame presents virtually no radiation, and it appears that a sootier flame with a lower burning velocity and not as locally applied would be a more challenging, appropriate, and realistic ignition source. Also, the ignition source is poorly defined, and in general, the test procedure and criteria are imprecise and poorly specified. This could result in a large variety of testing results between individual tests and between test labs.

In addition to the previous statements, the test method does not take fuel configuration and reradiation between fuel packages into account resulting in optimistic oxygen concentrations overestimating the performance of a hypoxic air venting system. There is no external radiation applied; hence, the robustness in the test method is questionable. Applying external radiation would result in less uncertainty regarding the achieved oxygen concentrations because it would account for scenarios such as arson and radiation exchange between fuel packages.

The aforementioned issues are believed to contribute to the result raising the highest concern: regular particleboard, known to burn and contribute to fire spread, passes the test criteria in normal air (21% oxygen concentration). This indicates that the test procedure is inappropriate.

5. FURTHER RESEARCH

On the basis of the literature review, at least four research areas have been identified. These consist of burning behavior, information needed to support risk analysis, burning behavior of more complex materials, and testing methods.

Concerning burning behavior, information is limited on the effect of configuration and orientation of fuel on HRR, fire spread, and ignition thresholds in reduced oxygen atmospheres. Especially most test results found in the review have been for horizontal samples, and there is a special need to determine the effect on HRR for vertical fuel configurations at reduced oxygen concentrations. Furthermore, the production rates of corrosive, irritating, and other gases at reduced oxygen concentrations and choice of the most effective test method to determine this needs to be investigated. There is also little information on the oxygen concentration's effect on smoldering combustion and the affecting mechanism of low oxygen concentration on solid pyrolysis. Finally, flame spread at oxygen concentrations less than 18% (most test results found in the performed literature review were for oxygen concentrations between 100% and 18%), also considering different orientation of the fuel and the impact of external heat flux, needs more attention.

Because hypoxic air venting systems are used in the nuclear power industry, there is a clear need to be able to perform risk analysis. To be able to perform such analyses, information on reliability and monitoring is essential. Therefore, the probability of different failure modes for the system to support risk assessment and studies of effectiveness of the system in a real scale is needed. To be able to compare the ignition energy available in a protected room with the ignition energy required to start a fire in a reduced oxygen atmosphere, studies of ignition energy needed for different materials at different oxygen concentrations is necessary. A research area related to ignition energies is also the effect on ignition time with a reduction in oxygen concentration. Ignition time studies to cover both piloted and spontaneous ignition would be useful. Last, to improve the reliability of hypoxic air venting systems, critical points for monitoring of oxygen levels to ascertain an even concentration and how these measuring points could be determined needs to be investigated.

Information on ignition properties for generic materials (such as PVC and PMMA) is available. However, ignition properties for less generic materials and products, such as composite materials and products consisting of different materials, for example, cables and electrical components, needs further investigation at different oxygen concentrations, temperatures and selection of the most effective test method to determine this is needed. HRR for less generic materials and products at

DOI: 10.1002/fam

different oxygen concentrations, temperatures and selection of the most effective test method to determine this is also needed.

The concerns raised previously regarding the test method in PAS 95:2011 and VdS 3527en calls for validation and further development of this test method. Possibly, changes are needed of the fuel and ignition source and modifications to account for fuel configurations, material thickness and possible radiation are needed.

ACKNOWLEDGEMENTS

This project was funded by the National Fire Safety Group (NBSG) and the Swedish Civil Contingencies Agency (MSB).

REFERENCES

1. Jensen G, Holmberg JG, Gussiås A. *Hypoxic air venting for protection of heritage*. Report within COST Action C17 project, ISBN 82-7574-037-1, Riksantikvaren, Directorate for Cultural Heritage and Crown; 2006.
2. Nilsson M, van Hees P, Frantzich H, Andersson B. Analysis of fire scenarios in order to ascertain an acceptable safety level in multi-functional buildings. *Proceedings of the 9th International Conference on Performance-Based Codes and Fire Safety Design Methods*. Society of Fire Protection Engineers: USA, 2012.
3. Nilsson M, van Hees P. *Subreport SAFE MULTIBYGG WP 1–4* (*in Swedish*), report From Department Of Fire Safety Engineering And Systems Safety, Report no 3165, Lund: Lund University; 2012.
4. Chiti S. *Test methods for hypoxic air fire prevention systems and overall environmental impact of applications*, MSc thesis, Modena: University of Modena; 2009.
5. VdS. *VdS 3527en - VdS-Guidelines for Inerting and Oxygen Reduction Systems*. VdS Schadenverhütung GmbH: Köln, 2007.
6. Xin Y, Khan MM. Flammability of combustible materials in reduced oxygen environment. *Proceedings Fire and Materials Conference 2007*. Interscience Communications Ltd: London, 2007.
7. BSI. *PAS 95:2011 - Hypoxic air Fire Prevention Systems: Specification*. British Standards Institution (BSI): London, UK, 2011, ISBN 978 0 580 67920.
8. Xin Y, Khan MM. Flammability of combustible materials in reduced oxygen environment. *Fire Safety Journal* 2007; **42**(8): 536–547, DOI: 10.1016/j.firesaf.2007.04.003.
9. NFPA. *NFPA 69, Standard on Explosion Prevention Systems* (2008 edn). National Fire Protection Association (NFPA): Quincy, MA, 2008.
10. Delichatsios MA. Piloted ignition times, critical heat fluxes and mass loss rates at reduced oxygen atmospheres. *Fire Safety Journal* 2005; **40**(3): 197–212, DOI: 10.1016/j.firesaf.2004.11.005.
11. Charsley EL, Schulz RA. An apparatus for the measurement of critical oxygen index incorporating a paramagnetic oxygen analyser. *Journal of Physics E: Scientific Instruments* 1975; **8**(2): 147–149.
12. Schwenzfeuer K, Glor M, Gitzi A. Relation between ignition energy and limiting oxygen concentrations for powders. *Proceedings of the 10th International Symposium Loss Prevention and Safety Promotion in the Process Industries*. 2001. 909–916.
13. Ackroyd G, Bailey M, Mullins R. The effect of reduced oxygen levels on the electrostatic ignition sensitivity of dusts. *Journal of Physics Conference Series* 2011; **301** 012034, DOI: 10.1088/1742-6596/301/1/012034.
14. Blanc V, Guest G, von Elbe G, Lewis B. Ignition of explosive gas mixtures by electric sparks. I. Minimum ignition energies and quenching distances of mixtures of methane, oxygen, and inert gases. *The Journal of Chemical Physics*. 1947; **15**(11): 798–802, DOI: 10.1063/1.1746337.
15. Glor M. Ignition of gas/air mixtures by discharges between electrostatically charged plastic surfaces and metallic electrodes. *Journal of Electrostatics* 1981;**10**: 327–332.
16. Babrauskas V Effect of environmental variables. In *Heat Release in Fires*, Babrauskas V, Grayson SJ (eds). Elsevier Applied Science: London, 1992; 307–325.
17. Mullholland G, Janssens M, Yusa S, Babrauskas V. The effect of oxygen concentration on CO and smoke produced by flames. *Fire Safety Science Proceedings, 3rd International Symposium*. Elsivier Applied Science: New York, 1991; 585–594.
18. Hshieh FY, Beeson HD. Flammability testing of flame-retarded epoxy composites and phenolic composites. *Fire and materials* 1997; **21**(1): 41–49.
19. Chiti S. A pilot study on hypoxic air performance at the interface of fire prevention and fire suppression. *FireSeat*, *5th Symposium*. 2011.
20. Mikkola E. Effects of oxygen concentration on cone calorimeter results. *Interflam 1993, 6th International Fire Conference*. Interscience communications: London, 1993; 49–56.
21. Drysdale D. *An Introduction to Fire Dynamics*. Wiley: Chichester, West Sussex, 2011.
22. Beyler CL. Flammability limits of premixed and diffusion flames. In *SFPE Handbook of Fire Protection Engineering*, DiNenno PJ, Drysdale D, Beyler CL, Walton WD, Custer RLP, Hall JR, Watts JM (eds). National Fire Protection Association: Quincy, MA, 2008; 2-194–2-210.
23. FM Global. *FM global property loss prevention data sheet 4–9 - clean agent extinguishing systems*, Factory Mutual Insurance Company; 2010.

24. Tewarson A. Ventilation effects on combustion products. *Toxicology* 1996; **115**(1): 145–156.
25. Tewarson A, Jiang FH, Morikawa T. Ventilation-controlled combustion of polymers. *Combustion and flame* 1993; **95**(1): 151–169.
26. Rasbash DJ, Langford B. Burning of wood in atmospheres of reduced oxygen concentration. *Combustion and Flame* 1968; **12**(1): 33–40.
27. Loh H. *Concurrent Flow Flame Spread Study NIST-GCR-92-603*. National Institute of Standards and Technology (NIST): Gaithersburg, MD, 1992.
28. Fernandez-Pello AC, Ray SR, Glassman I. Flame spread in an opposed forced flow: the effect of ambient oxygen concentration. *Symposium* (*International*) *on Combustion*. 1981: 579–589.
29. Tewarson A, Ogden SD. Fire behavior of polymethylmethacrylate. *Combustion and flame* 1992; **89**(3): 237–259.
30. Carhart W. Impact of low O_2 on fires. *Journal of Hazardous Materials* 1994; **36**(2): 133–141.
31. Tewarson A, Khan MM. Flame propagation for polymers in cylindrical configuration and vertical orientation. *Twenty-Second Symposium* (*International*) *on Combustion*. The Combustion Institute; 1988: 1231–1240.
32. Tewarson A, Lee JL, Pion RF. The influence of oxygen concentration on fuel parameters for fire modeling. *Symposium* (*International*) *on Combustion*. 1981: 563–570.
33. Marquis DM, Guillaume E, Lesenechal D. Accuracy (trueness and precision) of cone calorimeter tests with and without a vitiated air enclosure. *The 9th Asia-Oceiania Symposium on Fire Science and Technology*. Elsevier: Amsterdam, 2012.
34. Yao W, Hu X, Rong J, Wang J, Zhang H. Experimental study of large-scale fire behavior under low pressure at high altitude. *Journal of Fire Sciences* 2013; DOI: 10.1177/0734904113481326
35. Berg P, Lindgren A. *Fire prevention and health assessment in hypoxic environment*. Report from Department of Fire Safety Engineering and Systems Safety, Report no 5144, MSc thesis, Lund: Lund University; 2004.
36. Chaos M, Khan MM, Dorofeev SB. Pyrolysis of corrugated cardboard in inert and oxidative environments. *Proceedings of the Combustion Institute* 2013; **34**(2): 2583–2590, DOI: 10.1016/j.proci.2012.06.031.
37. Peatross MJ, Beyler CL. Ventilation effects on compartment fire characterization. *Fifth International Symposium on Fire Safety Science*. International Association for Fire Safety Science: Melbourne, 1997; 403–414.
38. Nasr A, Suard S, El-Rabii H, Gay L, Garo JP. Experimental study on pyrolysis of a heptane pool fire in a reduced-scale compartment. *7th Mediterranean Combustion Symposium*. 2011.
39. Tewarson A, Steciak J. Fire ventilation. *Combustion and flame* 1983; **53**(1): 123–134.
40. Cremers FG, Remie J, Schreel K, de Goey PH. Heat transfer mechanisms of laminar flames of hydrogen + oxygen. *Combustion and Flame* 2004; **139**(1-2): 39–51, DOI: 10.1016/j.combustflame.2004.08.004.
41. Remie J, Cremers FG, Schreel K, de Goey PH. Flame jet properties of Bunsen-type flames. *Combustion and Flame* 2006; **147**(3): 163–170, DOI: 10.1016/j.combustflame.2006.09.003.
42. Simmons RF. Premixed burning. In *SFPE Handbook of Fire Protection Engineering*, DiNenno PJ, Drysdale D, Beyler CL, Walton WD, Custer RLP, Hall JR, Watts JM (eds). National Fire Protection Association: Quincy, MA, 2008; 1-156–1-165.
43. Wang Y, Zhang F, Jlao C, Jin Y, Zhang J. Convective heat transfer of the Bunsen flame in the UL94 vertical burning test for polymers. *Journal of Fire Sciences* 2010; **28**(4): 337–356, DOI: 10.1177/0734904109351484.
44. Angerer P, Nowak D. Working in permanent hypoxia for fire protection-impact on health. *International Archives of Occupational and Environmental Health* 2003; **76**(2): 87–102, DOI: 10.1007/s00420-002-0394-5.
45. Burtscher M, Mairer K, Wille M, Gatterer H, Ruedl G, Faulhaber M, Sumann G. Short-term exposure to hypoxia for work and leisure activities in health and disease: which level of hypoxia is safe? *Sleep & Breathing* 2012; **16**(2): 435–442, DOI: 10.1007/s11325-011-0521-1.
46. Küpper T, Milledge JS, Hillebrandt D, Kubalová J, Hefti U, Basnyat B, *et al*. Work in hypoxic conditions-consensus statement of the Medical Commission Of The Union Internationale Des Associations D'alpinisme (UIAA MedCom). *The Annals of Occupational Hygiene* 2011; **55**(4): 369–386, DOI: 10.1093/annhyg/meq102.
47. Linde L, Gustafsson C, Ornhagen H. Effects of reduced oxygen partial pressure on cognitive performance in confined spaces. *Military psychology: the official journal of the Division of Military Psychology, American Psychological Association* 1997; **9**(2): 151–168, DOI: 10.1207/s15327876mp0902_3.

DOI: 10.1002/fam