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Evaluation of Oxygen Reduction System (ORS) in Large-scale Fire Tests

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ABSTRACT

An oxygen reduction system (ORS) is a fire prevention system that uses a low-oxygen environment to reduce, if not eliminate, the potential for ignition and fire propagation in a protected space. The key parameter for ORS design is the limiting oxygen concentration (LOC), defined as the lowest O_2 concentration that can support combustion for a given fuel. The present work examines LOCs of solid fuels at large scale in a configuration representative of a rack-storage and discusses the results in relation to the design concentration for ORS.

To simulate ORS applications in engineering practice, a two-tier fuel array of standard commodities in rack storage configuration was set up in an enclosure. A constant N_2/Air mixture flow was supplied to the enclosure at a desired oxygen concentration. The oxygen concentration was varied from 9% up to 17%. A premixed flame with a constant heat release rate was used as the ignition source to maintain repeatable test conditions. This premixed flame ignitor represents potential heat sources such as electric arc and hot work that are not sensitive to oxygen level. The tested materials included five standard commodities: Class 3, Cartoned Unexpanded Plastic (CUP), Cartoned Expanded Plastic (CEP), Uncartoned Unexpanded Plastic (UUP) and Uncartoned Expanded Plastic (UEP). This paper reports detailed test results at different oxygen levels only for Class 3. The impact of the test conditions on fire propagation was examined and the results showed that the oxygen concentration was the major parameter to control fire propagation. When successful flame spread is initiated by the igniter, the fire size tends to be larger as the igniter is sustained for a longer time. The results of fire propagation success were obtained for the five standard commodities under different oxygen concentrations with a sustained igniter (hard limits) and without a sustained igniter (soft limits). The LOC was defined as an oxygen concentration at 0.05 probability of flame spread by using statistical analysis. The resulting LOC values measured for different commodities in a two-tier rack storage are:

- Cartoned (Class 3, CUP and CEP) – hard limit 11.1%,
- Uncartoned (UUP and UEP) – hard limit 13.0%,
- Cartoned (Class 3, CUP and CEP) – soft limit 13.8%,
- Uncartoned (UUP and UEP) – soft limit 14.7%.

These LOCs are generally lower than the oxygen design concentrations recommended by existing standards including VdS 3527 and EN 16750 due to different test conditions. The hard limits resemble fundamental LOC for gases and vapors and do not depend significantly on the ignition duration and array size, while the soft limits vary significantly with the size and configuration of the fuel array and ignition duration. It is concluded that the hard limits are more suitable for ORS design purposes.

KEYWORDS: *oxygen reduction system; limiting oxygen concentration, rack-storage fire*

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INTRODUCTION

An oxygen reduction system (ORS) is a fire prevention system that uses a low-oxygen environment to reduce the likelihood of ignition and minimize fire propagation in a protected space. A typical ORS consists of an on-site nitrogen generator located outside the protected space, piping and pump network to provide an N_2/Air mixture of the desired oxygen concentration, and multiple sensors measuring oxygen concentrations within the protected space. A control unit located outside the protected space monitors the signals from the oxygen sensors to adjust the nitrogen production and supply.

The ORS uses the reduction of the oxidizer concentration as the protection strategy. If ignition and fire propagation can be greatly reduced, if not entirely prevented, the damage from heat, water and smoke becomes minimal, leading to favorable fire protection for high-value occupancies and other occupancies that are sensitive to water and smoke damage. However, when the O_2 level is too low, life safety becomes a concern even for a primarily unoccupied space. As a result, proper ORS design requires to know not only the key parameter, the limiting oxygen concentration (LOC), but also the fire behavior at oxygen concentrations close to the LOC.

The LOC is the lowest O_2 concentration that can support combustion for a given fuel. There have been extensive studies of LOC levels for premixed and non-premixed flames of gaseous fuel and vapors in various configurations including microgravity conditions [1-3]. It has been shown that the LOC depends on the competition between heat release and heat losses at the scale of the laminar flame thickness. The LOC decreases as the strain rate induced by turbulent or laminar flows decreases. It reaches a minimum at a low strain rate condition and then increases with even lower strain due to radiation losses becoming dominant. This minimum LOC for a given fuel, temperature, and diluent is a fundamental property that results in flame quenching at any flow condition [3, 4].

For solid fuels such as plastics and packaging, the determination of LOC is more complicated. One way to tackle the problem is to refer to the LOC of the products of thermal decomposition of solid fuels, i.e., the pyrolysis gases. The composition of the pyrolysis gases depends on the nature of the fuel and on the thermal conditions experienced by the fuel, such as the heating rate, maximum temperature, etc. The fundamental LOCs of these fuels are expected to be in the range of 6-13% by volume [2].

Another way to consider the LOC problem for solid fuels is to assess the competition between heat release and heat losses at a macro level for the problems of heterogeneous ignition and flame spread. The rate of heat release in heterogeneous reaction depends on the heat flux to the fuel surface from an ignition source or spreading flame, and on the oxygen concentration. The rate of heat losses depends on the convective flow over the fuel surface and the radiative loss. The ignition source creates an ignition kernel, which generates energy roughly in proportion to its volume and loses heat roughly in proportion to its surface. The larger the size of an ignition source, the lower is the portion of heat lost by the ignition kernel. With a positive heat balance the ignition kernel expands due to flame spread and it may become sufficiently large that the removal of the ignition source doesn't change the positivity of that balance. Therefore, with a longer duration of the ignition source, the size of the ignition kernel becomes larger, making it less dependent on the continuation of the ignition source. Moreover, any configuration with fuel surfaces facing each other over a narrow gap traps radiation and reduces the radiation loss. The physical effects described above suggest that the macro-level LOC depends significantly on the overall scale, fuel configuration, the size and duration of the ignition source.

The LOCs of several solid fuels were studied using laboratory-scale experiments in the Fire Propagation Apparatus (FPA), where additional heating was provided to model large-scale fire test conditions [5]. It was found that, for common fuels such as corrugated cardboard, wood, polystyrene (PS) and polyethylene (PE), the LOCs are in the range of 10-13%. This level of oxygen concentration is lower than the 15-16% range given by the testing prescribed by standards such as VdS 3527 [6] and EN 16750:2017 [7]. This difference is expected considering the effects described above and the test conditions such as ignition and fuel configuration [8].

The present work examines LOCs of solid fuels at large scale in a configuration representative of rack-storage and discusses the results in relation to the design concentration for ORS.

EXPERIMENTAL SETUP

The large-scale fire test was designed to simulate ORS applications with sufficient low oxygen air supply. Figure 1 shows the schematic of a simulated ORS environment and a photo of the test enclosure under a 5 MW calorimeter. The test enclosure included two parts: a lower plenum space for the supply of the nitrogen/air mixture, and an upper controlled-atmosphere (CA) volume as test space. A steel perforated plate with 13% opening area was installed at the separation between the lower plenum and the upper CA room. The upper CA

room was enclosed using fire resistant gypsum board. The tested commodities including the wood pallets were placed on the perforated plate at the center of the enclosure in a 1×2 and 2-tier high rack-storage configuration. The flue space between the two commodities was 0.15 m. Five standard commodities of Class 3, Cartoned Unexpanded Plastic (CUP), Cartoned Expanded Plastic (CEP), Uncartoned Unexpanded Plastic (UUP) and Uncartoned Expanded Plastic (UEP) [9] were tested and only the results for the Class 3 commodity are reported in this paper. Below the commodity platform was the perforated floor that was designed to achieve a uniform co-flow boundary condition. The nitrogen-diluted air supply was provided through a 0.3-m duct discharging downward to the floor of the lower plenum to generate a uniform air/N_2 upward flow. A liquid nitrogen tank with vaporizer was used in this work to provide gaseous N_2.

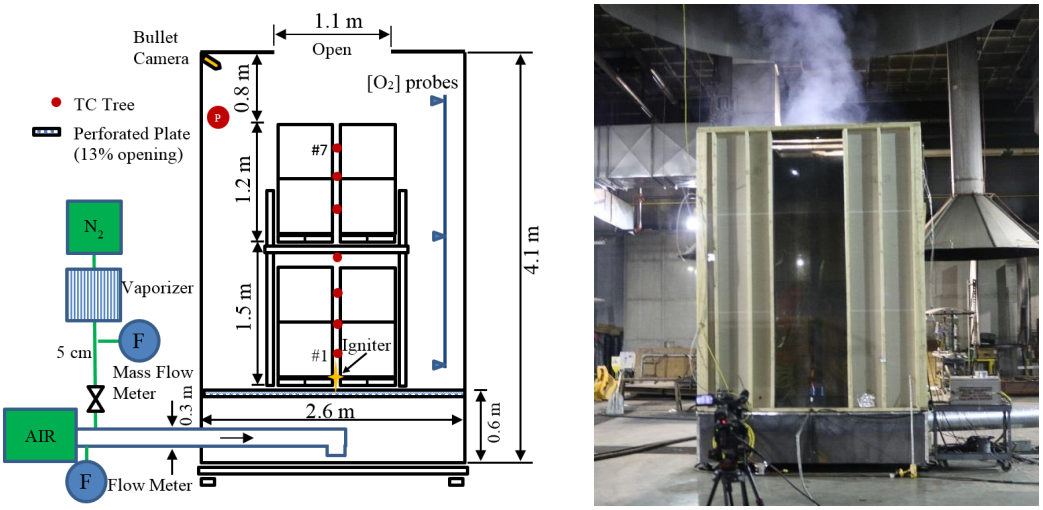


Fig. 1. Elevation view of the simulated ORS test design and a photo of the test enclosure.

The ignition location of all tests was selected at the center of the fuel array. To maintain repeatable initial conditions, a premixed flame (propane/air) with a constant heat release rate (HRR) of 33 kW was used, which is consistent with that of two half igniters used routinely in sprinkler fire tests under normal air conditions. This premixed-flame ignitor also represents potential heat sources such as electrical short or arc and hot work that are not sensitive to oxygen level. The O_2 concentration in the enclosure was measured by three gas sampling probes installed at different elevations. High-Definition cameras were positioned in front of the observation window to record the test. Seven thermocouples [TCs, Type K, gage 28 (0.33 mm), bare-bead] were installed vertically along the centerline of the fuel array to monitor flame propagation, as shown in Fig. 1. The enclosure air was purged by supplying the N_2/air mixture to achieve the specified O_2 design concentration before ignition for each test. The O_2 concentrations used in this work were between 9% and 17% by volume.

RESULTS AND DISCUSSIONS

To illustrate the fire development, Fig. 2 shows a series of flame images recorded at different times for Class 3 commodity with [O_2] at 11.4%. Prior to ignition, the O_2 concentration in the enclosure was maintained around the target value for at least one minute. The average gas supply rates were 0.32±0.01 m^3/s for N_2, and 0.430±0.001 m^3/s for air, which were adjusted toward the target O_2 concentration. Before ignition, the temperature of the air/N_2 mixture entering the enclosure was 17.3±0.1 °C monitored by TC #1 near the perforated floor. The average velocity of air/N_2 mixture in the enclosure was estimated to be 0.11 m/s based on the total gas flow rate and the enclosure cross-section area. As shown in Fig. 2, the time of 0 s denotes the ignition event when the premixed flame was pushed to the flue center of the fuel array. At 20 s after ignition, the flame spread upward along the external cardboard surface with exfoliation of several large pieces of paper. At 40 s, the flame propagated to the 2nd tier. At 70 s, the flame height exceeded the top of the fuel array and started to exit through the opening at the top of the enclosure. In the present work, successful fire propagation was indicated by the flame height exceeding the top of the fuel array.

Once the flame height exceeded the top of the fuel array, the igniter was shut off at 79 s by stopping the supply of propane/air. Figure 2 shows that the flame disappeared at 82 s, indicating that the fire was extinguished three seconds after the igniter was shut off. For this case, the test result is considered unsuccessful propagation after igniter shut-off. Following these flame images, Fig. 3(a) shows the gas temperatures measured in the flue center

by using seven TCs. Except for TC #1 near the igniter, the other TCs showed that gas temperature increased with time to 800°C or a higher value. Using the temperature of 400°C to denote flame arrival, the time required for fire propagation was 23 s from TC #2 to #4, and 9 s from TC #4 to #7. The flame propagation speed was initially slow in the 1st tier and then increased in the 2nd tier. After the igniter was shut off at 79 s, Fig. 3(a) shows that all the gas temperatures dropped rapidly with time, indicating a decaying fire.

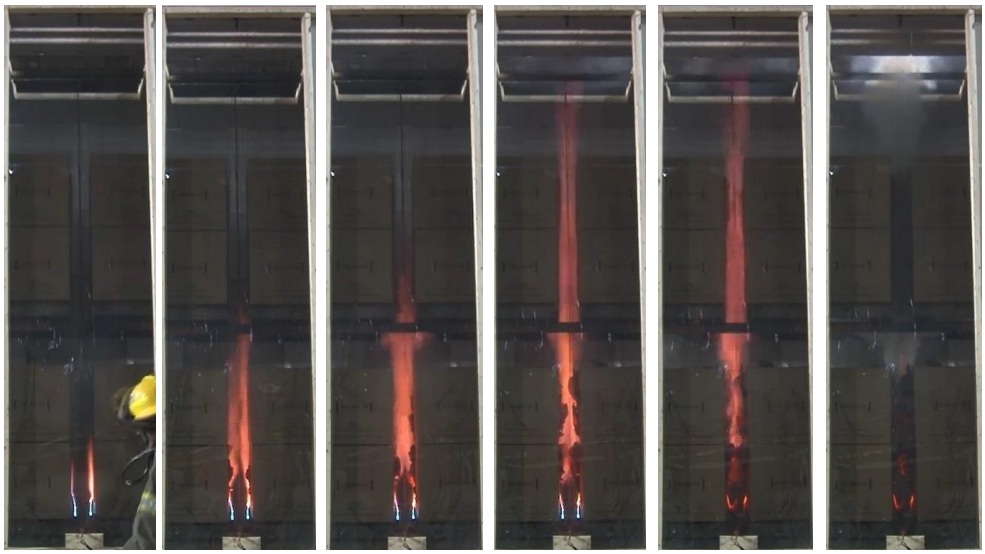
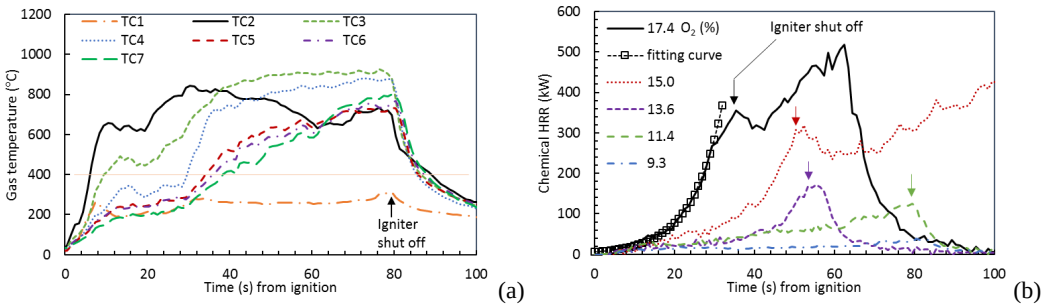


Fig. 2. Images of fire development for Class 3 commodity with 11.4% O_2.



(a) (b)

Fig. 3. (a) Gas temperatures measured in the flue center along the height for 11.4% O_2, and (b) chemical heat release rates (HRR) measured for Class 3 commodity under different O_2 concentrations.

Figure 3(b) shows the chemical HRRs measured for Class 3 under different O_2 concentrations, where the arrows mark the time when the flame propagated to the top of the fuel array and the igniter was shut off. For 17.4% O_2, Fig. 3(b) shows a fast HRR growth (10 kW/s) from ignition to the first peak of 360 kW when the igniter was shut off at 35 s. This is considered a propagating fire. After the igniter was shut off at 35 s, the HRR slightly reduced and then increased again to the second peak of 520 kW at 63 s. The fire was manually extinguished at 63 s. This fire at 17.4% O_2 was sustained without the igniter. For a lower oxygen level of 15.0%, Fig. 3(b) shows a similar HRR growth trend. The test results are that the flame propagated both with/without sustained igniter. It is noted that the peak value of HRR with 15.0% O_2 is slightly lower than that of 17.4% O_2. For the other two tests with 13.6% O_2 and 11.4% O_2, the HRRs increased with time and then decreased after the igniter was shut off. Both tests are marked as propagated for flame spread with igniter and non-propagated when the igniter was shut off. For 9.3% O_2, the Class 3 commodity could not be ignited, and Fig. 3(b) shows a flat HRR with time. The test results with 9.3% O_2 are non-propagated for both cases of flame spread with/without igniter.

The arrows in Fig. 3(b) also denote the times required for the flame to propagate to the top of the fuel array. Following these arrows, Fig. 3(b) shows that the fire size (HRR) and the fire propagation speed decrease with

the oxygen level. The combustion theory discussed in previous work [5] has shown that the chemical reaction rate and the flame temperature will reduce with the oxygen level. Therefore, as shown in Fig. 3(b), the fire propagation was delayed due to lower flame temperature and thus reduced flame heat fluxes to the solid fuel at lower oxygen levels. To quantify the fire growth rate, as shown in Fig. 3(b) for 17.4% O_2, the exponential function of $HRR(t) = a_0e^{bt}$ was used to fit the initial HRR growth during 0 – 30 s, in which b (s^{-1}) denotes the growth rate parameter and a_0 is a fitting coefficient. For the oxygen level of 17.4% shown in Fig. 3(b), the obtained growth rate parameter is b = 0.13 (s^{-1}). Using the same fitting function for the other oxygen levels, the growth rate parameters are 0.09 s^{-1} for 15.0% O_2, 0.056 s^{-1} for 13.6% O_2, 0.03 s^{-1} for 11.4% O_2, and near zero for 9.3% O_2.

When the oxygen level is reduced to a limit, such as 9.3% O_2 in Fig. 3(b), the chemical heat release of both the ignition source and reactions between pyrolysis gas and oxygen cannot overcome the heat losses from the combustion zone to sustain continuous ignition along fuel surfaces. When the igniter is shut off, the heat release rate from the reaction between the pyrolysis gases and oxygen needs to be sufficiently high to exceed the heat loss and sustain burning. As shown in Fig. 3(b), the fire can only sustain at higher oxygen levels (15.0% and 17.4%), but not at low oxygen levels (13.6% and 11.4%), after the igniter is shut off. This observation is specific to the size of the fuel array and the duration of the ignition (of the order of 1 min) as noted in the introduction.

Since the duration of the ignition source may vary significantly in real fire events, its impact on fire growth deserves further investigation. For a target oxygen concentration of 13%, Fig. 4 shows the chemical HRRs measured in five tests with different igniter shut-off times. The arrows in Fig. 4 indicate the time of igniter shut-off. Clearly, the fire continued to grow while the igniter was on. All fires started to decrease in intensity after the igniter was shut off. For the earliest shut-off at 55 s, Fig. 4 shows that the HRR dropped in only 7 s to 1/10 of its maximum. When the igniter was shut off at 210 s, the HRR remained above 600 kW for more than two minutes and the HRR decay rate became slower. Finally, all the fires extinguished with time. This behavior, however, may be due to the limited array size impacting the outcome of the tests, denoted by the red and black curves in Fig. 4. It is seen in Fig. 4 that, when successful flame spread is initiated by the igniter, the fire size tends to be larger as the igniter is sustained for a longer time.

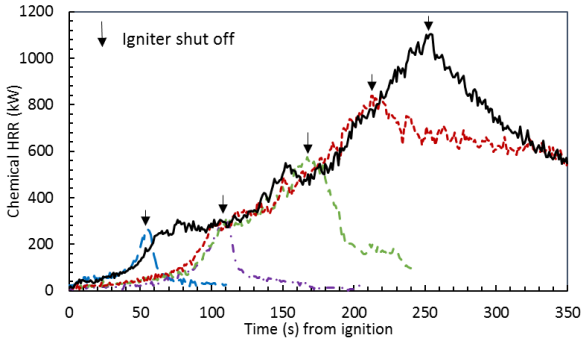


Fig. 4. Chemical HRRs measured for Class 3 commodity at 13% O_2 with different igniter shut-off times.

The test results of fire propagation with/without the sustained igniter were also obtained for the other commodities at different oxygen levels [10]. Since the oxygen level was not adjusted continuously to precisely identify the flame extinction condition, and given the natural variability in the results, statistical analysis was used to estimate the LOC value from the data. Exact logistic regression is used to model binary outcome variables. Figure 5 shows the fire propagation probability curve with respect to the oxygen volume fraction with continuous igniter and after igniter shut-off, where the black circles are the test results denoted as zeros (non-propagation) and ones (propagation). The cartoned commodities (Class 3, CUP and CEP) are placed in the same group because the initial fire propagation takes place on the external corrugated cardboard. The statistical analysis showed that the oxygen level was the dominant variable to control fire propagation.

Figure 5 also shows the cutoff points of the probability curve at the 0.05, 0.5 and 0.95 probabilities of fire propagation. To apply a small margin of safety, the LOC is estimated here to the cutoff points as the oxygen volume fraction corresponding to the 0.05 probability. This value hence provides a 95% confidence level in the LOC results. The resulting LOC values measured for different commodities in a two-tier rack storage are:

- Cartoned (Class 3, CUP and CEP) with a sustained ignitor 11.1%,
- Uncartoned (UUP and UEP) with a sustained ignitor 13.0%,

- Cartoned (Class 3, CUP and CEP) with ignitor shut-off after ignition 13.8%,
- Uncartoned (UUP and UEP) with ignitor shut-off after ignition 14.7%.

It should be noted that the limits with a sustained ignitor approach the fundamental LOC values for gaseous fuels such as 11.1% - 12.0% for methane [2] as described in the introduction. These limits are thus the hard limits that do not depend significantly on the fuel configuration, size and ignitor duration. The limits with ignitor shut-off after ignition are the soft limits. They are obtained for relatively short (~1 min) ignition duration and are significantly dependent on the ignition duration and the size of the fuel array. It would, therefore, appear that the hard limits should be used for ORS design purposes.

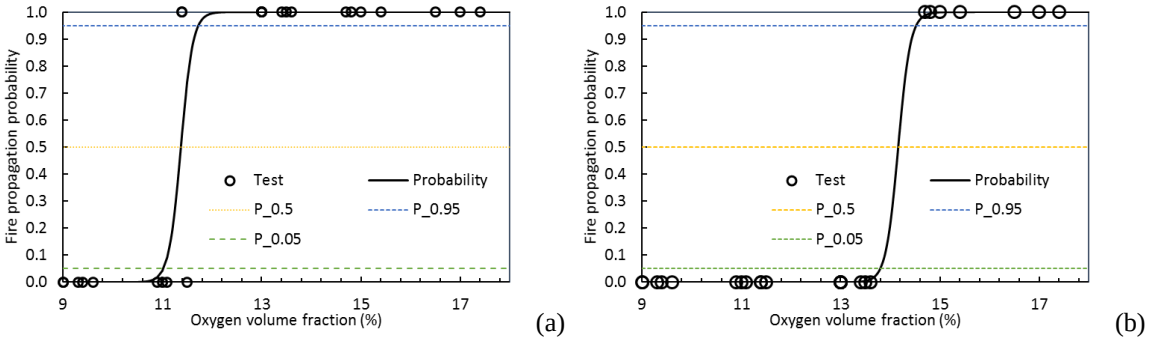


Fig. 5. Fire propagation probability by oxygen level estimated for cartoned commodities (Class 3, CUP and CEP): (a) with continuous igniter, and (b) after igniter shut-off.

SUMMARY

This work has evaluated the LOC limits for oxygen reduction system (ORS) in large-scale fire tests. A two-tier fuel array of standard commodities was set up in a rack-storage configuration within an enclosure. A constant nitrogen/air mixture flow was supplied to the enclosure at a desired oxygen concentration. The oxygen concentration was varied from 9% to 17%. A premixed propane ignitor was used as ignition source. The tested materials included five standard commodities of Class 3, CUP, CEP, UUP and UEP. Results for fire propagation success were obtained for the tested commodities under different oxygen concentrations with/without a sustained igniter to determine the limiting oxygen concentration (LOC) to support fire. These LOCs have been found to be generally lower than the oxygen design concentrations recommended by existing standards including VdS 3527 and EN 16750:2017 due to different test conditions. The difference between the hard and soft limits have been discussed, with the conclusion that the lower hard limit should be used for ORS design.

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