RESEARCH TECHNICAL REPORT

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

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Executive Summary

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. However, at the low oxygen levels that are typically required, life safety concerns can be an important factor for the use of ORS.

Previous work using bench-scale testing has shown that the LOCs for common solid fuels are lower than those recommended in existing standards including VdS 3527 and EU prEn16750 (Draft). To further evaluate this technology, the present work focuses on large-scale fire tests to determine the effective O_2 design concentrations for ORS applications.

Large-scale fire tests were designed in this work to simulate current 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 nominally in 2% steps from 9% up to 17%. To maintain repeatable test conditions, a premixed flame with a constant heat release rate (HRR, 33 kW) was used as the ignition source in this work. This premixed flame ignitor represents potential heat sources such as electric arc and hot work that are not sensitive to oxygen level. The HRR of the ignition source is consistent with that of two half igniters used routinely in sprinkler fire tests under normal air conditions. 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).

The impact of the test conditions on fire propagation was examined for Class 3 in detail at different oxygen levels. The tests showed that the oxygen concentration was the only major parameter to control fire propagation. Other test conditions, such as the flow blockage under the fuel array, the N_2/Air mixture gas flow rate, and the initial gas temperature had minor effects on fire propagation.

The limiting oxygen concentration for fire propagation was obtained for five commodities with/without a sustained igniter. The LOC was defined as an oxygen concentration at 5% probability of flame spread. The resulting values measured for different commodities in a two-tier rack storage were:

- 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 pointed out that the LOCs obtained herein are generally lower than the O_2 design concentrations recommended by existing standards including VdS 3527 and EU prEn16750 (Draft).

FM Global recognizes that ORS is a relatively new fire protection system which aims to maintain a steady low oxygen concentration in an enclosed protection space to control fire ignition and/or fire spread. The most important factor for the ORS to be effective is to maintain an oxygen level (LOC), below which the fire spread beyond the ignition location can be excluded. The LOC can be determined through appropriate bench-scale and large-scale tests for a specific fuel. In addition, to ensure adequate protection, systematic reliability analysis should be performed to develop the inspection, testing and maintenance (ITM) programs to provide the required availability of the system.

The results in this report and prior work illustrate that, although not a replacement for the fire sprinkler protection in general, ORS with adequate availability may be used in well-sealed and unoccupied enclosures that can consistently maintain a uniform reduced oxygen concentration. The oxygen concentration in the enclosure needs to be designed based on robust LOC fire tests and the system availability needs to be analyzed to determine ITM cycles. It is expected that the ORS satisfying these conditions can provide adequate protection with relatively low level of fire damage under certain conditions.

Abstract

This work evaluated the oxygen reduction system (ORS) for fire prevention 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 nominally 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. The impact of the test conditions on fire propagation was examined for Class 3 in detail at different oxygen levels, with the finding that the oxygen concentration is the only major parameter controlling fire propagation. The results of fire propagation success (Yes or No) 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 are generally lower than the oxygen design concentrations recommended by existing standards including VdS 3527 and EU prEn16750 (Draft).

Acknowledgements

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1. 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. Figure 1-1 shows a schematic of an ORS with the key components. 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.

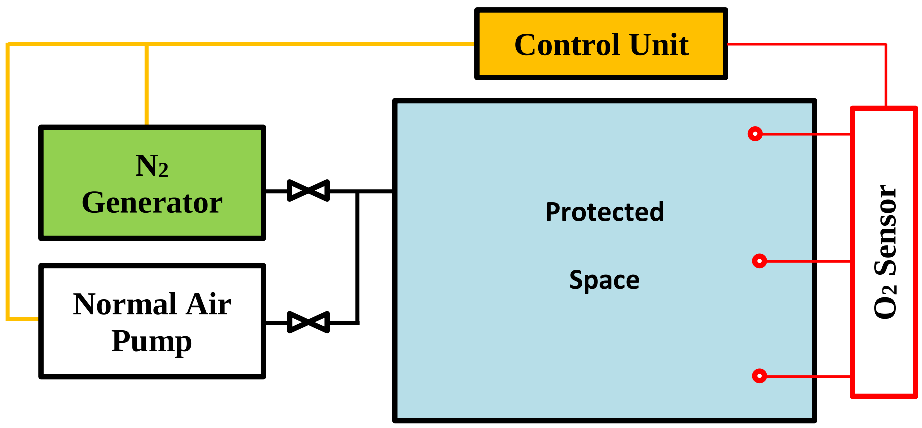


Figure 1-1: Schematic of an oxygen reduction system.

The basic operating principle of an ORS is explained by the fire triangle concept as shown in Figure 1-2. A fire event requires combustible materials (fuel), oxidizer (O_2) and energy (heat) to initiate and sustain the exothermic chemical reaction. The ORS uses the reduction of the oxidizer to minimize the potential for ignition and propagation of fire in the protected space. 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. For example, OSHA regulation [1915.12(a)(3)] states that “An employee may not enter a space where the oxygen content, by volume, is below 19.5 percent” [1]. As a result, proper ORS design requires to know not only the key parameter, the limiting oxygen concentration (LOC), but also the behavior of the fire at oxygen concentrations close to but above the LOC.

The LOC is the lowest O_2 concentration that can support combustion for a given fuel. The LOCs of many common fuels were studied using laboratory-scale experiments in a previous work [2]. The results showed that LOCs can be measured using a variable O_2 method in the Fire Propagation Apparatus (FPA) [2]. The measurements also showed that for common fuels such as corrugated cardboard, wood, polystyrene (PS) and polyethylene (PE) plastic, the LOCs are below 15%. This level of oxygen concentration generally requires personal protection measures in ORS applications.

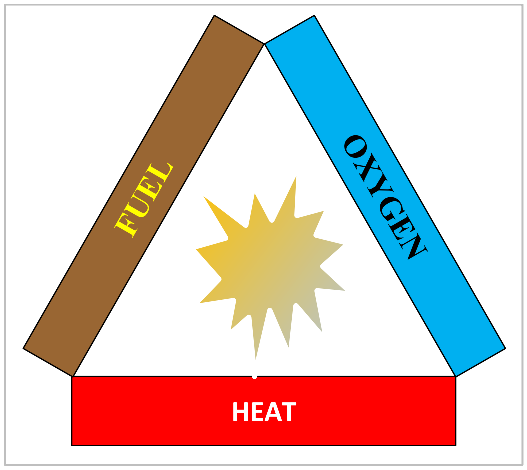


Figure 1-2: Fire triangle for fire prevention and protection.

To further evaluate this technology, the present work focuses on large-scale fire tests to determine the effective oxygen design concentrations for ORS in comparison to existing standards such as VdS 3527 [3] and EU prEn16750 (Draft) [4].

2. Experimental Setup

The large-scale fire test was designed to simulate ORS applications with sufficient low-oxygen air supplies. Figures 2-1 and 2-2 show the schematic of a simulated ORS environment with the fuel array placed in an enclosure. This work used a 2-tier fuel array of standard commodities in rack storage configuration. In each tier, half-pallet load [0.53 m × 1.07 m (21 in. × 42 in.)] commodities including the wood pallets [0.53 m × 1.07 m (21 in. × 42 in.)] were arranged in 1×2 matrix to reduce the total footprint of the fuel array. The flue space between the two half-pallet loads was 0.15 m (6 in.). The test commodities included Class 3, CUP, CEP, UUP and UEP as defined in Ref. [5]. For the corrugated board and PE plastic, the O_2 design concentrations recommended by VdS [3] and LOCs measured by FM Global in small scale experiments [2] are shown in Table 2-1.

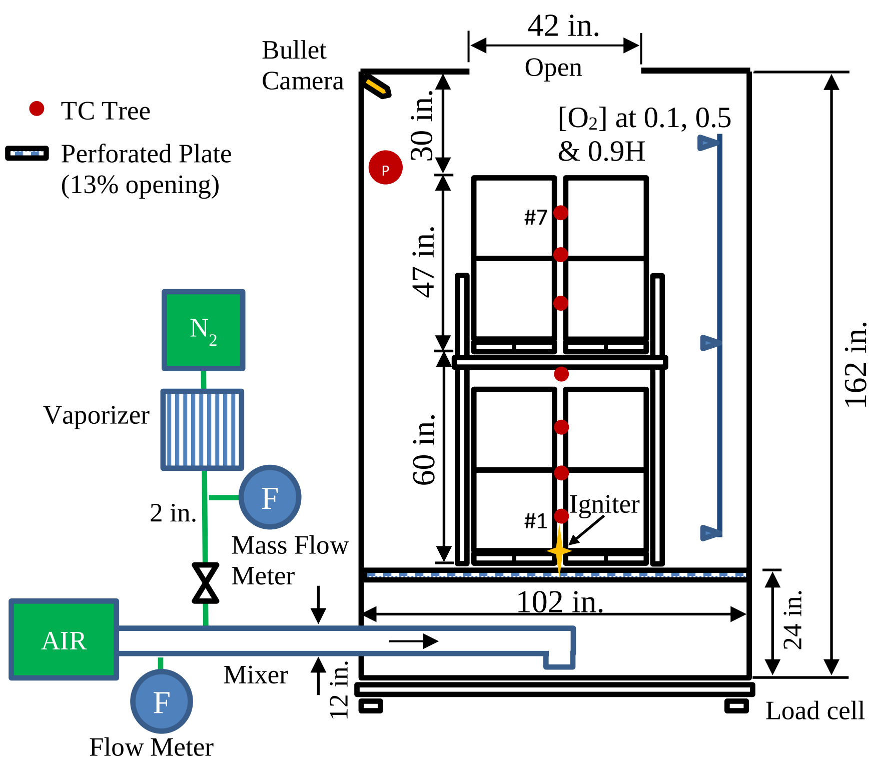


Figure 2-1: Schematic (elevation view) of the simulated ORS test design (English units).

To determine the enclosure size and air-N_2 supply rate, the key is to consider sufficient supply of total amount of oxygen to support the fire growth. For a typical significant fire with size of 0.5 MW after ignition, the stoichiometric oxygen flow rate should be 37 g/s or a normal air (21% O_2) supply rate of 0.13 m^3/s (270 CFM). Generally, the total air entrainment rates for buoyant fires in an open space are roughly 10 times the stoichiometric value. Considering that the air-N_2 in this work was supplied directly from the bottom of the fuel with no entrainment from outside of the enclosure, the oxygen portion of the air-N_2 supply rate was selected in a range of five times the stoichiometric value to represent oxygen available for entrainment in a large enclosure.

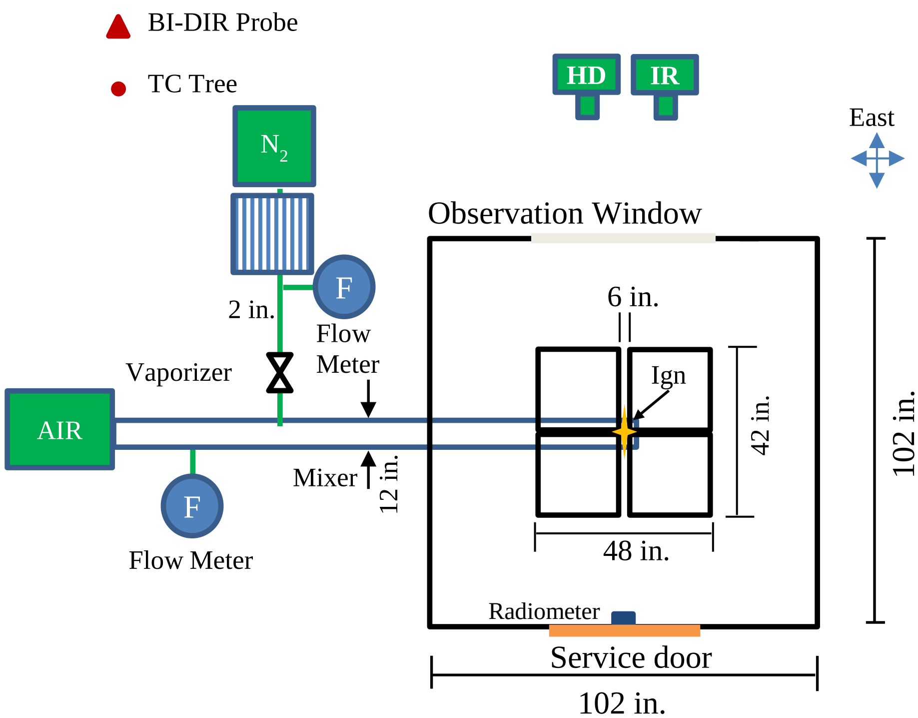


Figure 2-2: Schematic (plan view) of the simulated ORS test design (English units).

Table 2-1: ORS design concentrations for different fuels.

Fuel	VdS3527 [O_2] (% volume) [3]	FM Global [O_2] (% volume) [2]
Polyethylene (LD)	15.9	11.4
PMMA	15.9	10.5
Corrugated board	15.0	12.9
Methanol	11.0	11.6
Ethanol	12.8	12.4

The ORS tests were conducted under the 5-MW calorimeter in the Small Burn Lab (SBL) of the FM Global Research Campus in West Glocester, RI, USA. Figure 2-3 (a) and (b) shows the enclosure constructed based on the schematic shown in Figures 2-1 and 2-2. The test enclosure includes two parts: a lower plenum space for the supply of nitrogen/air mixture, and an upper controlled-atmosphere (CA) room for fire tests. The lower plenum was constructed using 0.1-m (4-in.) wide steel angle frame at the top and bottom and supported vertically by eight, 0.05-m (2-in.) diameter steel pipes. The steel angle frame was wrapped with sheet metal. A perforated floor 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 [0.013-m

(1/2-in.) thick] supported by wood frame made of lumber [0.04 m x 0.09 m (1.5 in. x 3.5 in.)]. The top opening was partially covered using gypsum board so that the opening size was 1.07 m by 1.07 m (42 in. by 42 in.) located 0.53 m (21 in.) above the top of the fuel array.

Figure 2-3: Photos of the test setup: (a) enclosure view from the west, (b) enclosure view from the east, (c) two-tier rack storage in the enclosure, and (d) liquid nitrogen tank.

Figure 2-3 (c) shows the tested commodities placed on a platform at the center of the enclosure in a 1×2 and 2-tier array to represent a rack storage configuration. Below the commodity platform was the perforated floor (steel perforated plate with 13% opening area), which was designed to achieve a uniform co-flow boundary condition. The nitrogen-diluted air supply was provided through a 0.3-m

(12-in.) duct discharging downward to the floor of the lower plenum (see Figure 2-1) to generate a uniform air-N_2 upward flow. Figure 2-3 (d) shows the liquid nitrogen tank with vaporizer used in this work to provide gaseous N_2.

The ignition location of all tests was selected at the center of the flue space [0.15 m (6 in.)] between the two half-pallet loads of the fuel array. To maintain repeatable test conditions, a premixed flame with a constant heat release rate (HRR) of 33 kW was used as the ignition source in this work. This premixed-flame ignitor represents potential heat sources such as electrical short or arc and hot work that are not sensitive to oxygen level. The HRR of the ignition source is consistent with that of two half igniters used routinely in sprinkler fire tests under normal air conditions. Figure 2-4 shows the U-shape tube igniter with propane/O_2 premixed flames. The propane supply rate was 22 lpm and an air supply rate of 380 lpm was used to maintain a stable flame.

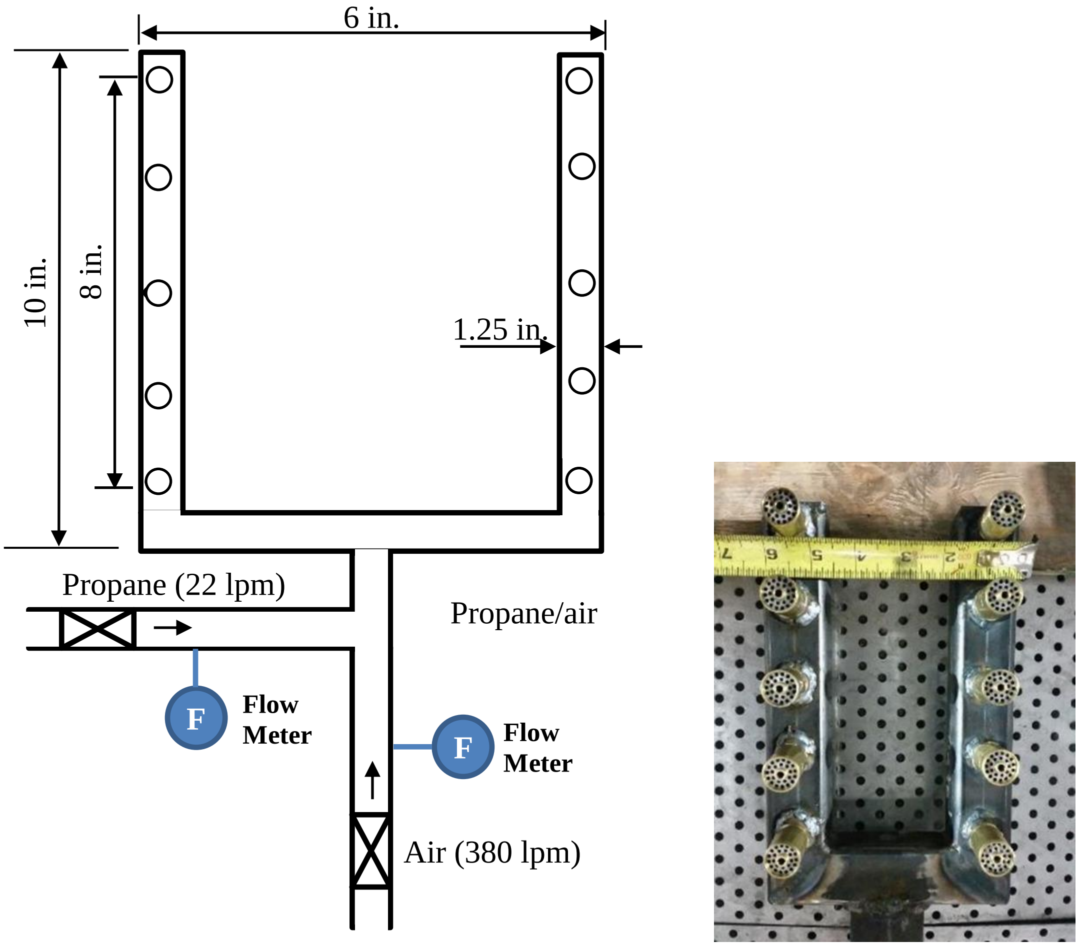


Figure 2-4: U-shape premixed igniter.

The O_2 concentration in the enclosure was measured by three gas sampling probes installed at different elevations: 0.1H [0.35 m (14 in.)], 0.5H [1.75 m (69 in.)] and 0.9H [3.15 m (124 in.)], where H = 3.51 m (138 in.) is the enclosure height above the perforated floor. The gas sampling probes were used to perform species concentration measurements. After initial checks that showed uniformity, the three gas sampling lines were merged into one and then connected to the gas analyzer cabinet. The differential pressure in the enclosure was measured at 0.9H (124 in.) above the perforated floor.

To monitor the fire development, a transparent, heat-resistant glass [1.22 m. x 2.74 m (48 in. x 108 in.)] was installed on the east wall of the enclosure as an observation window [Figure 2-3 (b)]. High-Definition (HD) and Infrared (IR) cameras were positioned in front of the observation window to record the test. Seven thermocouples (TCs, Type K, gage 28 bare-bead) were installed vertically along the centerline of the fuel array to monitor flame propagation, as shown in Figure 2-1. The elevations of the TCs were 0.38 m (15 in.), 0.66 m (26 in.), 0.94 m (37 in.), 1.42 m (56 in.), 1.91 m (75 in.), 2.18 m (86 in.), and 2.46 m (97 in.) above the perforated floor. To quantify flame radiation, a radiometer was positioned on the south wall to assess heat fluxes at the middle elevation of the fuel array 1.75 m (69 in.) above the perforated floor. In addition to the observation window, a service door was installed on the west wall to allow access to the enclosure.

The enclosure air was purged by supplying N_2/ air mixture to achieve the specified O_2 design concentration before ignition for each test. Table 2-2 shows the target O_2 concentrations used in this work for different commodities. These test conditions were selected based on the recommended oxygen concentration levels by VdS [3], which suggests that corrugated paper and PE plastic can be protected using 15.0% and 15.9% O_2 by volume. The VdS design also requires that the system O_2 level is 1% below the LOC test data. Therefore, the system should be designed to achieve 14% and 14.9%, respectively, for Class 3 and UUP commodities. In contrast, the LOC measurements in FM Global's previous work [2] suggest that these two materials should be protected using 12.9% and 11.4% O_2 by volume, respectively. Therefore, tests with lower O_2 concentrations were also conducted to evaluate the validity of the observed values in large-scale fires for Class 3 and CUP.

Table 2-2: Target O_2 concentrations used for fire tests of different commodities.

Commodity	O_2 concentration (% volume)
Class 3	9, 11, 13, 15, and 17
CUP	9, 11, 15, and 17
CEP	11, 13, and 15
UEP	11, 13, 15, and 17
UUP	11, 13, and 15

For life safety reasons, the liquid nitrogen source shown in Figure 2-3 (d) was placed outside the SBL. The N_2 supply rate was monitored using a mass flow meter. The air supply was monitored using an orifice plate [0.184 m (7.25 in.) in diameter] installed in the 0.3-m (12-in.) diameter duct. Two TCs (Type K, gage 28) were installed to monitor the gas temperatures of air and N_2 supply ducts. Since the SBL doors were kept open to the ambient during the test for safety, air and N_2 were at ambient temperature in each test. The primary controlled test condition is the O_2 concentration in the enclosure, which was compared and adjusted toward the target value by changing the supply rate of air and N_2.

To simulate a steady O_2 concentration available in a large enclosure, the air supply with nitrogen was originally designed to achieve a uniform upward flow in the enclosure through a perforated floor (see Figure 2-1). Since the rack storage fire is ignited on the floor, the upward gas velocity can affect the ignition and flame extinction by stretching the flame and potentially blowing it off. To examine the importance of this effect, a metal plate [1.4 m × 1.4 m (56 in. × 56 in.)] was placed on the perforated plate below the commodity to block the N_2-air mixture flow in the second phase of testing. The fuel array with the metal rack and the wood pallet were positioned on the metal plate. The blockage ratio introduced by the plate was 30% of the entire bottom area. In addition to the potential blow-off, the total gas flow rate may also affect ignition and flame spread. The total gas flow rate was thus varied to check its impact on flame spread. The role of the presence of a sustained igniter was also evaluated by changing the sustained time of the ignition source.

The impact of these test conditions on flame spread was examined in detail using one commodity (Class 3), i.e., different gas flow rates, with/without blockage plate and different sustained ignitor time. Each test started with ignition of the premixed flames. The igniter was then moved to the flue center of the fuel array. The maximum test duration was 10 minutes if the flame could not propagate to the top of the fuel array. If the flame propagated to the top of the fuel array, the premixed flame igniter was shut off. When safe operation was ensured, the test would continue for an additional 1-2 minutes before manual fire suppression.

3. **Results and Discussion**

The test operating conditions including air velocity and oxygen level are presented first in this section. Then, test results for Class 3 commodity are given and the impact of test conditions on fire propagation is examined. The test results of fire propagation for the five commodities at different oxygen concentrations are discussed next. Finally, statistical analysis is used to estimate generally applicable LOC values based on the results obtained.

3.1 Test Conditions: Air Velocity

The air velocity distribution in the enclosure was measured at different locations with the commodity in place. Figure 3.1 shows the air flow velocity measured at the middle level [1.4-m (54-in.) high] and 0.3-m (12-in.) away from the four side walls (East, South, West and North), for two air flow rates of 0.28 m^3/s (600 CFM) and 1.13 m^3/s (2400 CFM). Generally, the air velocity distribution is within ±10% from the average value of the four sides. At the center of the top opening [1.07 m by 1.07 m (42 in. by 42 in.)], the exit air velocity was measured as 0.24 m/s for the air flow rate of 0.28 m^3/s (600 CFM) and 1.02 m/s for the air flow rate of 1.13 m^3/s (2400 CFM). These two velocities are within 3% of those calculated from the air flow rate divided by the opening area.

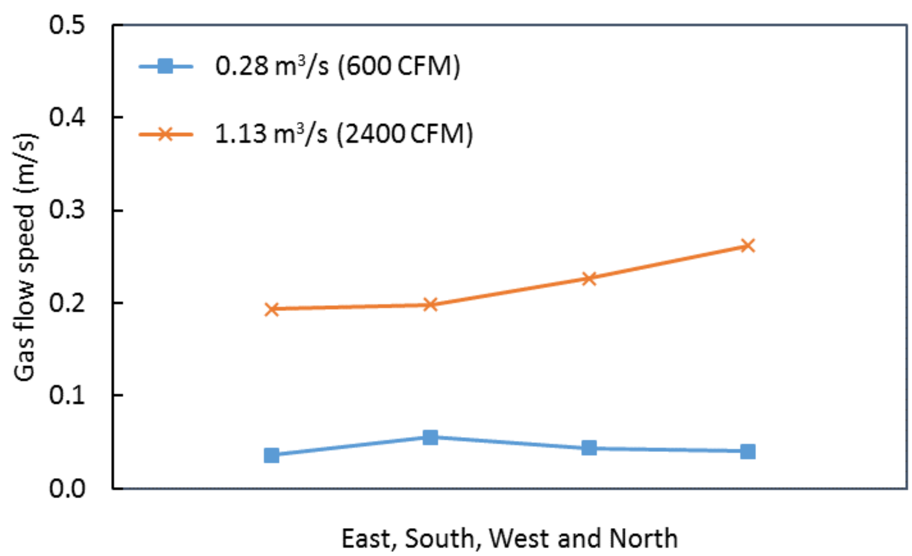


Figure 3-1: Air velocity distribution in the enclosure measured for two air flow rates at the same height of 1.4 m (54 in.) and 0.3-m (12-in.) from the wall (E, S, W and N).

3.2 Test Conditions: Oxygen Levels and Gas Flow Rates

Prior to ignition in each test, the O_2 concentration in the enclosure was maintained around the target value for at least one minute, which represents a large space with a certain O_2 concentration. The ignition is denoted as the time when the pre-ignited propane burner is moved to the ignition location in the fuel array (see Figure 2-2). To illustrate the initial test condition generated in the enclosure, Figure 3-2 shows the evolution of O_2 volume fraction, N_2 flow rate and air flow rate monitored in one of the tests for Class 3 targeting 11% O_2. Note that the ignition time and igniter shutoff time are labeled using arrows.

As shown in Figure 3-2, during the one minute before ignition, the average N_2 flow rate was 0.32 m^3/s (670 CFM) with a standard deviation of ±0.01 m^3/s (±25 CFM), air flow rate was 0.430±0.001 m^3/s (910±2 CFM), and the O_2 concentration was 11.4% with a standard concentration deviation of ±0.03%. Because of mixing in the enclosure (~37 sec for one volume change at the conditions of the test in the figure), Figure 3-2 shows that the O_2 concentration decreased slowly with the supply of N_2. The O_2 measurement was also not corrected for mixing and time delay by the sampling system and by the analyzer. Based on the volume flow rates of N_2 0.32 m^3/s (670 CFM) and air 0.43 m^3/s (910 CFM), the calculated O_2 concentration was 12.0%, which is 5% higher than that measured by the sampling system. The discrepancy possibly comes from the uncertainty of volume flow rate measurements, especially the N_2 volume flow rate which is calculated from the mass flow rate and gas density (related to N_2 temperature) measurements. Therefore, the oxygen concentration obtained from the sampling system was used to monitor the test condition and was maintained at a steady value before ignition.

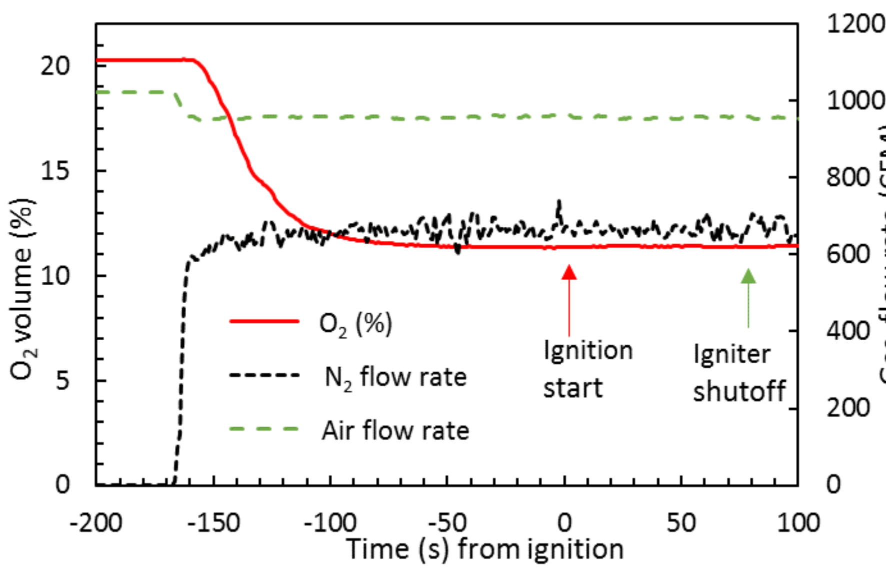


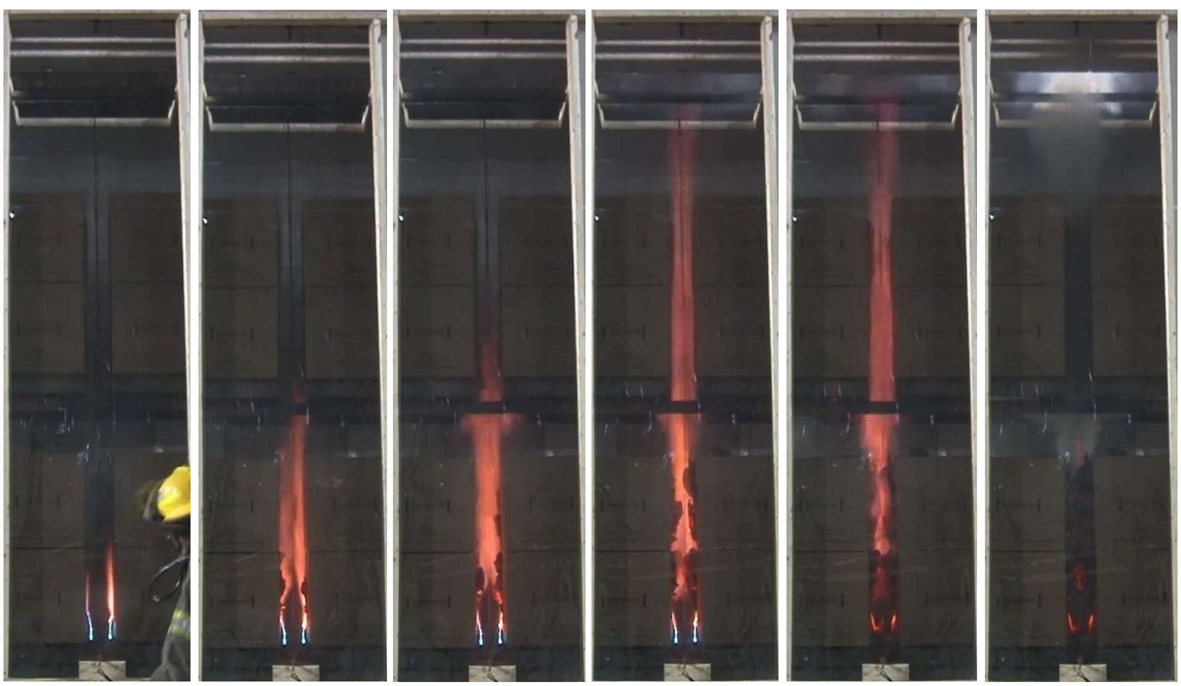
Figure 3-2: The test condition of O_2 concentration, air and N_2 flow rate monitored in a test for Class 3 with 11% O_2 as target.

The temperature of N_2 in the supply pipe was 15.1±0.1°C (59.1±0.2°F), and the air temperature was 18.3±0.2°C (65.0±0.3°F). The temperature of the air-N_2 mixture entering the enclosure was monitored by the TC near the perforated floor. Before ignition, the recorded temperature was 17.3±0.1°C (63.2±0.2°F). The average velocity of air-N_2 mixture in the enclosure was estimated to be 0.11 m/s (0.37 ft/s), based on the total gas flow rate and the enclosure section area. Considering that a portion of the section was occupied by the fuel array, the average velocity of the air-N_2 mixture was estimated as 0.14 m/s (0.45 ft/s) after accounting for the area reduction. The initial test conditions of the other tests were controlled at the same level as those shown in Figure 3-2.

3.3 Results for Class 3 Commodity

In this work, Class 3 commodity was tested extensively to examine fire propagation under various conditions. To illustrate the fire development, Figure 3-3 shows a series of flame images recorded at different times for Class 3 commodity with [O_2] at 11.4%. 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, it was deemed that the fire had propagated beyond the ignition location when the flame height exceeded the top of the fuel array. Accordingly, the test result is denoted as successful fire propagation [‘Yes’ later in Table 3-1 or 3-2]. Otherwise, the test result would have been denoted as unsuccessful fire propagation [‘No’ in Table 3-1 or 3-2].

Once the flame height exceeded the top of the fuel array, the igniter was shut off at 79 s by stopping the fuel supply. Figure 3-3 shows that the flame disappeared, indicating that the fire was extinguished 3 seconds after the igniter was shut off. Under this situation, the test result is considered unsuccessful propagation with igniter shut off, or denoted as ‘No’ in Table 3-3 or 3-4. Otherwise, the test result would have been denoted as ‘Yes’ or a sustained fire without igniter.



Ignition start 0 s 20 s 40 s 70 s Igniter shut off 79 s 82 s

Figure 3-3: Images of fire development for Class 3 with 11.4% O_2.

Following the flame images in Figure 3-3, Figure 3-4 shows the gas temperatures measured in the flue center by using seven TCs (see Figure 2-1). Except for TC #1 near the igniter, the other TCs showed that gas temperature increased with time to 800°C (1470°F) or a higher value. Using the temperature of

400°C (750°F) to denote flame arrival, the time required for fire propagation from TC #2 to #3 was 3 s, 21 s from TC #3 to #4, 4 s from TC #4 to #5, 2 s from TC #5 to #6, and 2 s from TC #6 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, Figure 3-4 shows that all the gas temperatures dropped rapidly with time, indicating a decaying fire.

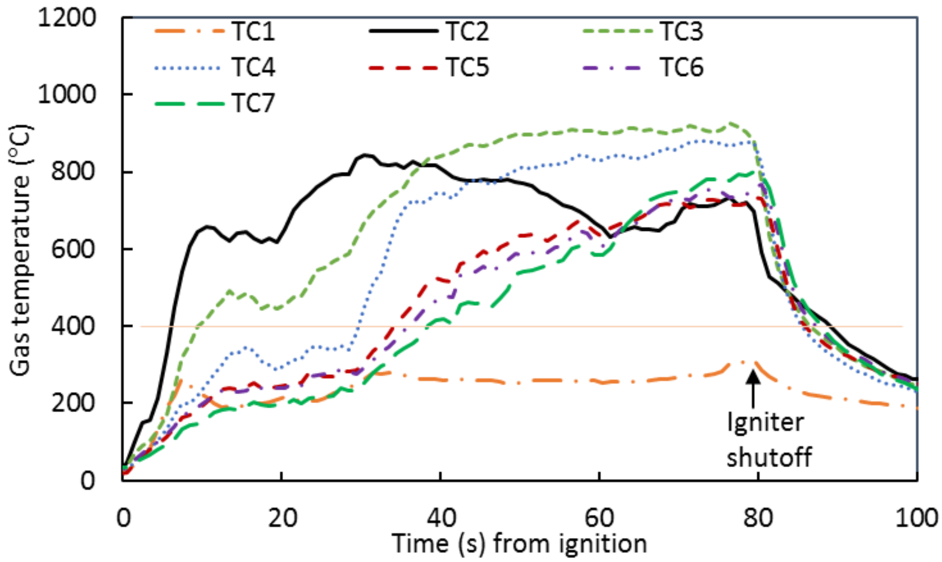


Figure 3-4: Gas temperature measured in the flue center along the height for Class 3 with 11.4% O_2.

Figure 3-5 shows the chemical HRRs measured for Class 3 under different O_2 concentrations. The chemical HRRs were calculated based on CO_2/CO calorimeter measurements. 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, Figure 3-5 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 positive for flame spread and the test result is denoted as 'Yes'. 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, therefore, the test result is denoted as 'Yes' also for this condition. For a lower oxygen level of 15.0%, Figure 3-5 shows a similar HRR growth trend. The test results are also denoted as 'Yes' for both cases 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 'Yes' for flame spread with igniter and 'No' when the igniter was shut off. For 9.3% O_2, the Class 3 commodity could not be ignited and Figure 3-5 shows a flat HRR with time. The test results with 9.3% O_2 are denoted as 'No' for both cases of flame spread with/without igniter.

The arrows shown in Figure 3-5 also denote the times required for the flame to propagate to the top of the fuel array. Following these arrows, it can be seen that the fire size (HRR) and the fire propagation speed decrease with the oxygen level. The combustion theory discussed in previous work [2] has shown that the chemical reaction rate and the flame temperature will reduce with the oxygen level. Therefore, as shown in Figure 3-5, the fire propagation was delayed due to lower flame temperature and thus flame heat fluxes to the solid fuel at lower oxygen levels. To quantify the fire growth rate, as shown in Figure 3-5 for 17.4% O_2, the exponential function of $HRR(t) = a_0 e^{bt}$ 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 Figure 3-5, 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, 0.08 s^{-1} for 13.6% O_2, 0.03 s^{-1} for 11.4% O_2, and near zero for 9.3% O_2.

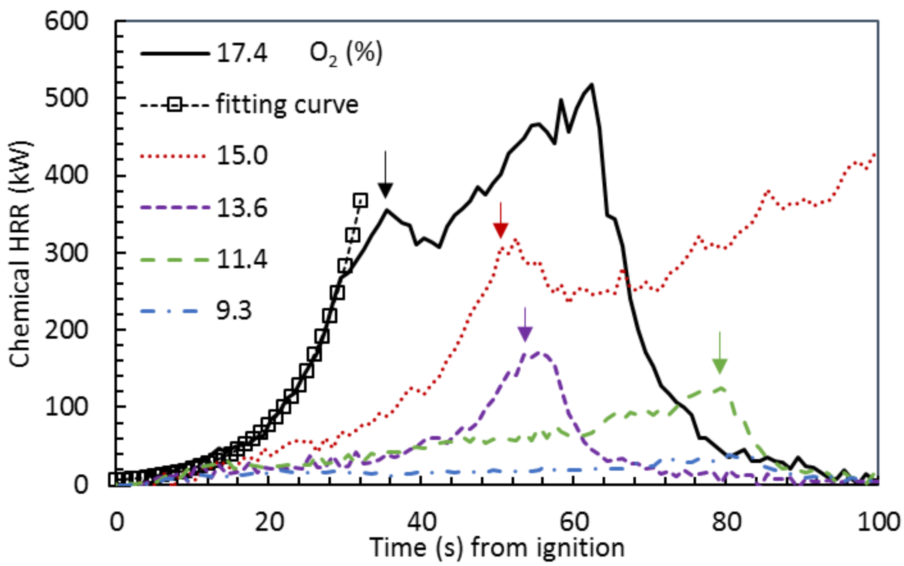


Figure 3-5: Chemical heat release rates (HRR) measured for Class 3 under different O_2 concentrations, in which the arrowheads denote the time of igniter shutoff.

When the oxygen level is reduced to a limit, such as 9.3% O_2 in Figure 3-5, 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 Figure 3-5, the fire can only sustain at a high oxygen level (15.0% and 17.4%), but not at a low oxygen level (13.6% and 11.4%), after the igniter is shut off.

It should be pointed out that the fire propagation outcome discussed above needs to be assessed in terms of a number of factors, including the gas supply flow rate, the sustained time of the igniter, and the blockage of the gas supply on the floor. The impact of these factors will be examined in the following sections using the Class 3 commodity as an example.

3.3.1 Impact of Blockage Plate and Gas Flow Rate

Figures 3-6 - 3-9 show the impact of the blockage plate and gas flow rate on the chemical HRR for Class 3 commodity at different oxygen levels. For a target oxygen concentration of 17%, Figure 3-6 shows the

HRRs measured for three tests at different flow conditions. At similar flow rates of 0.66 m^3/s (1400 CFM) and 0.57 m^3/s (1200 CFM), Figure 3-6 shows that the HRR growth without the blockage plate is essentially the same as that with the blockage. For the two cases with blockage plate, Figure 3-6 shows that the HRR growth at 0.57 m^3/s (1200 CFM) is the same as that at a much lower flow rate of 0.35 m^3/s (740 CFM).

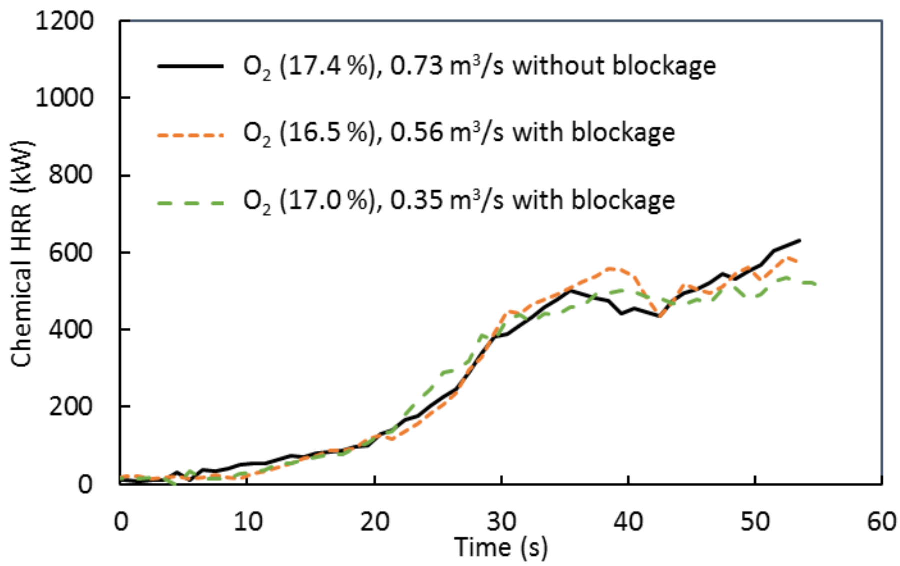


Figure 3-6: Chemical HRRs measured for Class 3 at a target 17% O_2 for different gas flow rates with/without the blockage plate.

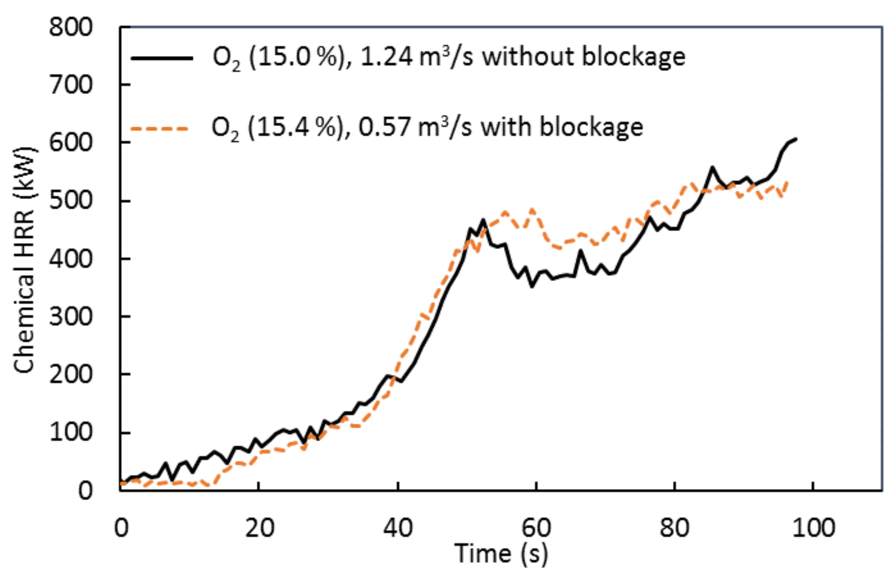


Figure 3-7: Chemical HRRs measured for Class 3 at a target 15% O_2 for different gas flow rates with/without the blockage plate.

When the target oxygen level was reduced to 15% and 13%, Figures 3-7 and 3-8 show, respectively, the same results for fire growth at different blockage conditions. These results suggest that the impact of the blockage plate and gas flow rate for flame spread is insignificant. However, at the target oxygen of

11%, Figure 3-9 shows a successful flame spread for 11.4% O_2 at 0.77 m^3/s (1630 CFM) without the blockage and two unsuccessful cases with the blockage and a lower flow rate. Note that the 11% O_2 concentration is very close to the LOC and the previous work [2] had showed that the flame was not stable at such critical condition. Hence, minor changes of the test conditions may generate either a successful or an unsuccessful flame spread when the oxygen level is close to the LOC.

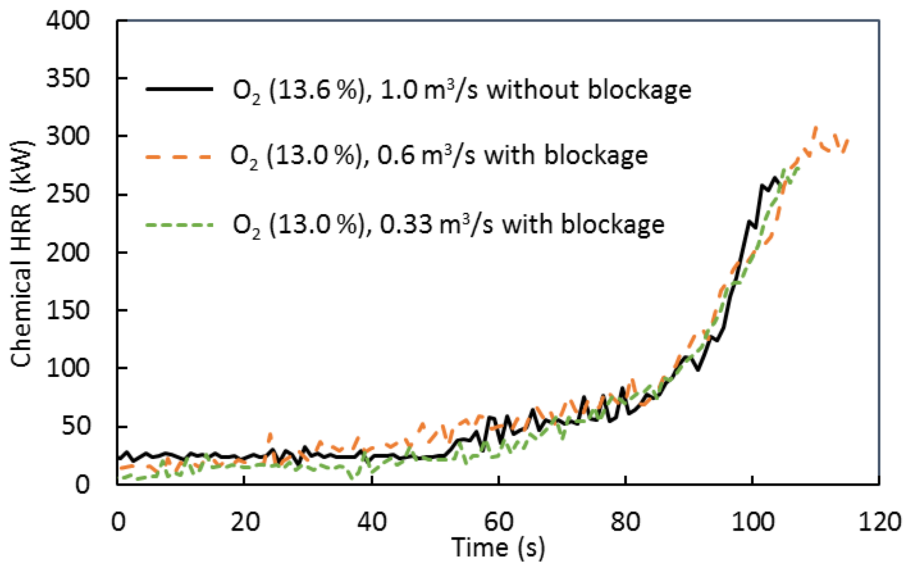


Figure 3-8: Chemical HRRs measured for Class 3 at a target 13% O_2 for different gas flow rates with/without the blockage plate.

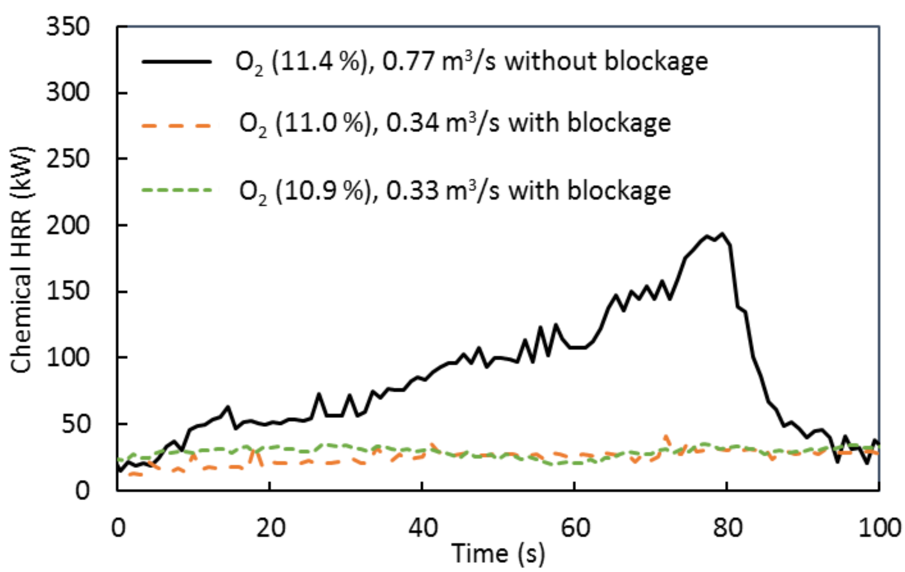


Figure 3-9: Chemical HRRs measured for Class 3 at a target 11% O_2 for different gas flow rates with/without the blockage plate.

3.3.2 Impact of Igniter Operation Time

To maintain repeatable test conditions, a premixed flame with a constant heat release rate was used as the ignition source in this work. Generally, the igniter was shut off during the test when the flame propagated to the top of the fuel array. For the fire images in Figure 3-3, the igniter operation time from ignition was 79 s, and the fire extinguished after the igniter was shut off. Since the duration of the ignition source may vary significantly in real fire events, its impact on fire growth deserves further investigation. For Class 3 commodity at a target oxygen concentration of 13%, Figure 3-10 shows the chemical HRR measured in five tests with different igniter shutoff times. The arrows in Figure 3-10 indicate the time of igniter shutoff. Clearly, the fire continued to grow before the igniter was shut off. All fires started to decrease in intensity after the igniter was shut off. Finally, all the fires were extinguished manually upon test termination.

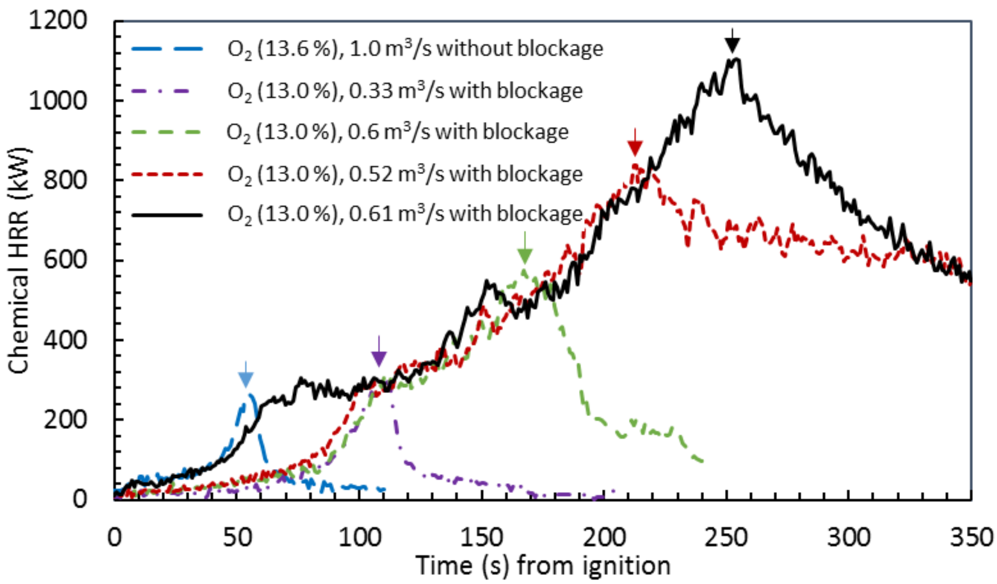
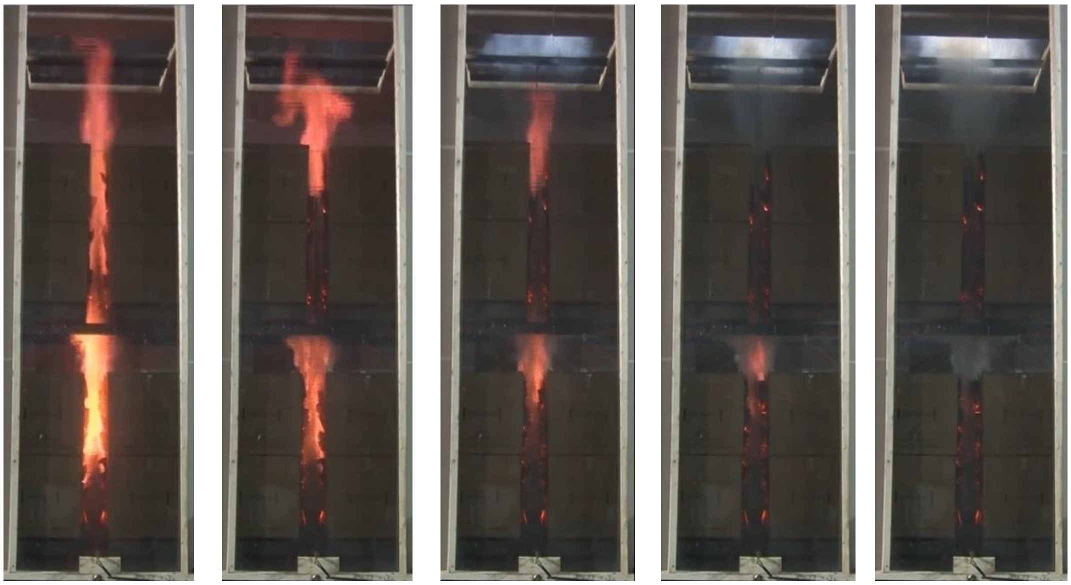


Figure 3-10: Chemical HRRs measured for Class 3 at a target 13% O_2 with different igniter operation times. The arrows denote the time of igniter shutoff.

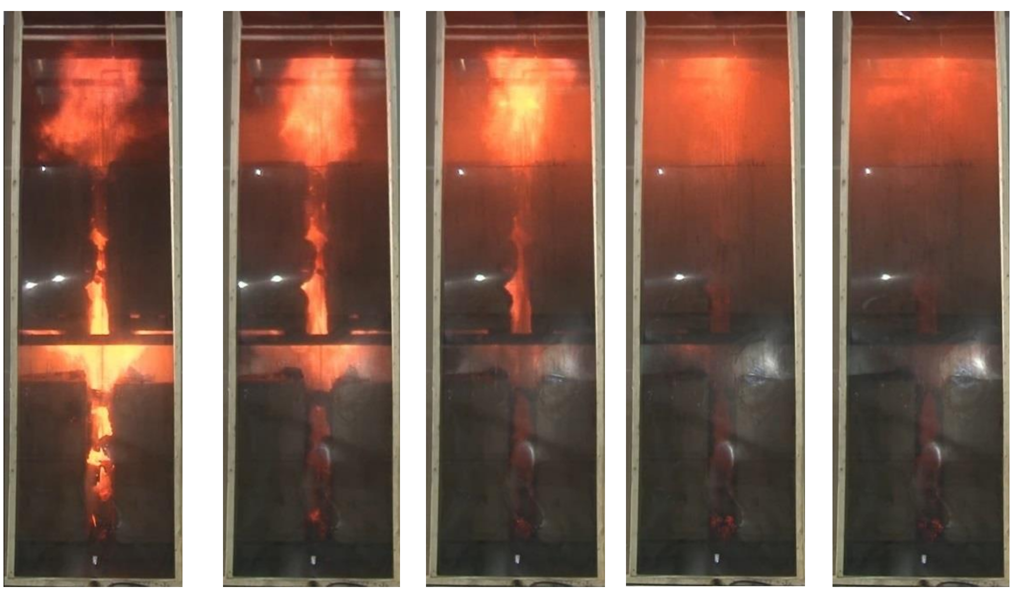
Figure 3-10 shows that the duration of the sustained ignition did not change the outcome in terms of continuous flame spread once the igniter was no longer active for the case of 13% O_2 concentration. However, it is conceivable that ignition duration may have an impact on the value of threshold O_2 level for continuing flame spread after removal of the ignition source. In the case considered in Figure 3-10, the HRR decay rates after the igniter is shut off become slower with a longer duration of sustained ignition. For the earliest shut off at 55 s with an HRR of 250 kW, Figure 3-10 shows that the HRR dropped in only 7 s to 1/10 of its maximum. When the igniter was shut off at 210 s with an HRR of 840 kW, the HRR remained above 600 kW for more than two minutes.

To illustrate the impact of the duration of the sustained ignition, Figure 3-11 shows a series of snapshots of flame images recorded at different times after the igniter was shut off at 55 s from ignition, and Figure 3-12 shows flame images after the igniter was shut off at 210 s. In the first case, the fire was no longer visible in a short time (4 s) after the igniter was shut off. However, Figure 3-12 shows that the fire size was still quite large two minutes after the igniter was shut off. Generally, after the igniter was shut off, the fire extinguishment started from the bottom (1st tier) of the fuel array. Figure 3-12 also shows that most of the flames persisted in the 2nd tier at a later time after the igniter was shut off as compared to Figure 3-11.



Igniter shut off 0 s 1 s 2 s 3 s 4 s

Figure 3-11: Flame images recorded at different times (0 s, 1 s, 2 s, 3 s and 4s) after the igniter was shut off at 55 s from ignition for Class 3 with 13.6% O_2.



Igniter shut off 0 s 30 s 60 s 90 s 120 s

Figure 3-12: Flame images recorded at different times (0 s, 30 s, 60 s, 90 s and 120 s) after the igniter was shut off at 210 s from ignition for Class 3 with 13.0% O_2.

For higher storage (> 3 tiers) in a real warehouse, the 3rd tier fuel will not be ignited if the ignition source is deactivated when the flame has propagated only to the top of the 2nd tier (like in the case shown in Figure 3-11). On the other hand, Figure 3-12 shows that the 3rd tier or higher storage will likely be ignited if the ignition source remains active for a longer time. When the fuel cannot be ignited at a very low oxygen level (9.3% O_2 in Figure 3-5), the ignition duration time has no impact on flame spread. When the oxygen level is adequately high, e.g., 15.0% O_2 and 17.4% O_2 as shown in Figure 3-5, for the fire to be sustained without the igniter, there is no need to consider the impact of the ignition time either. Only for the oxygen level near the LOC is flame spread affected significantly by the duration of sustained ignition, i.e., a longer duration results in a larger fire size.

Table 3-1: Test results (Yes or No) of fire propagation with sustained igniter and initial test conditions for cartoned commodities of Class 3, CUP and CEP.

Fire propagated (1=Yes, 0=No) with igniter	O_2 volume fraction (%)	Gas flow rate (m^3/s)	Gas inflow temp (°C)	Blockage plate (Yes=1, No=0)	Cartoned Commodity
0	9.0	0.59	10.8	1	Class 3
0	9.0	0.63	9.0	0	CUP
0	9.3	0.63	16.0	0	Class 3
0	9.4	0.64	10.0	0	CUP
0	9.6	0.62	12.0	0	CUP
0	10.9	0.33	7.0	1	Class 3
0	11.0	0.34	13.0	1	Class 3
0	11.1	0.73	11.0	0	CEP
0	11.5	0.78	11.0	0	CEP
1	11.4	0.77	17.0	0	Class 3
1	11.4	0.79	12.0	0	CUP
1	13.0	0.33	12.5	1	Class 3
1	13.0	0.43	16.0	1	Class 3
1	13.0	0.60	10.5	1	Class 3
1	13.0	0.64	21.9	1	Class 3
1	13.4	1.02	12.0	0	CEP
1	13.5	1.02	12.0	0	CUP
1	13.6	1.00	16.0	0	Class 3
1	14.7	1.24	9.0	0	CEP
1	14.8	1.24	15.0	0	CUP
1	15.0	1.24	18.0	0	Class 3
1	15.4	0.57	13.0	1	Class 3
1	16.5	0.56	16.6	1	Class 3
1	17.0	0.35	18.3	1	Class 3
1	17.4	0.73	14.0	0	Class 3

3.4 Results for Other Commodities

All the test results obtained for five commodities at different oxygen levels are presented in this section. Table 3-1 lists the test results (Yes or No) of fire propagation with the sustained igniter and the initial test conditions applied for cartoned commodities (Class 3, CUP and CEP). These commodities are placed in the same group because the initial fire propagation all takes place on the external corrugated cardboard. The initial test conditions of O_2 volume fraction, gas flow rate, gas inflow temperature and with/without blockage plate are listed in the table. Clearly, there is no fire propagation with $[O_2] < 11\%$, while the fire can spread with $[O_2] > 13\%$. The limiting oxygen concentration appears to be around 11.5% by volume for this group of fuels. The two commodities of UUP and UEP are put in another group of uncartoned commodities. Table 3-2 presents the test results (Yes or No) of fire propagation with the sustained igniter and the initial test conditions applied for these two commodities. In this case, the critical condition (i.e., LOC) appears to be around 13.3% O_2 by volume.

Table 3-2: Test results (Yes or No) of fire propagation with sustained igniter and initial test conditions for uncartoned commodities of UUP and UEP.

Fire propagated (1=Yes, 0=No) with igniter	O_2 volume fraction (%)	Gas flow rate (m^3/s)	Gas inflow temp (°C)	Blockage plate (Yes=1, No=0)	Uncartoned Commodity
0	11.1	0.76	9.0	0	UEP
0	11.5	0.73	6.0	0	UUP
0	13.0	1.08	14.0	0	UUP
0	13.3	0.98	6.0	0	UEP
1	13.3	0.58	27.7	1	UUP
1	14.6	1.25	11.0	0	UEP
1	14.7	1.27	10.0	0	UUP
1	14.9	0.73	27.0	1	UUP
1	15.0	1.27	7.0	0	UEP
1	17.2	1.08	7.0	0	UEP

Once the igniter was shut off, the fire could either be self-sustaining or not. Table 3-3 presents the test results (Yes or No) of fire to self-sustain after igniter shutoff for cartoned commodities. It can be seen that the fire for cartoned commodities can be self-sustained for $[O_2] > 14.7\%$. Table 3-4 provides similar test results (Yes or No) for the ability to self-sustain after igniter shutoff for uncartoned commodities, where the fire can be self-sustained for $[O_2] > 15.0\%$.

3.5 Statistical Analysis of Test Results

As discussed earlier, the oxygen concentration was changed in this work with a nominal 2% interval (see Table 2-2). Since the oxygen level was not adjusted continuously to more precisely identify the flame extinction condition, and given the natural variability in the results, statistical analysis will be used to estimate the LOC value based on the results given in the previous section. Exact logistic regression is used to model binary outcome variables [6]. For the test results listed in Table 3-1, Figure 3-13 shows the fire propagation probability curve with respect to the oxygen volume fraction, where the black circles are the test results denoted as zeros (non-propagation) and ones (propagation). It can be seen from Figure 3-13 that the independent test results were well modeled by the probability curve, given that the oxygen level was the dominant variable to control fire propagation. The other test results listed in Tables 3-2 - 3-4 are shown in Figure 3-14 through Figure 3-16.

Table 3-3: Test results (Yes or No) of fire sustain with igniter shutoff and initial test conditions for cartoned commodities of Class 3, CUP and CEP.

Fire sustain (1=Yes, 0=No) after igniter shutoff	O_2 volume fraction (%)	Gas flow rate (m^3/s)	Gas inflow temp (°C)	Blockage plate (Yes=1, No=0)	Cartoned Commodity
0	9.0	0.59	10.8	1	Class 3
0	9.0	0.63	9.0	0	CUP
0	9.3	0.63	16.0	0	Class 3
0	9.4	0.64	10.0	0	CUP
0	9.6	0.62	12.0	0	CUP
0	10.9	0.33	7.0	1	Class 3
0	11.0	0.34	13.0	1	Class 3
0	11.1	0.73	11.0	0	CEP
0	11.5	0.78	11.0	0	CEP
0	11.4	0.77	17.0	0	Class 3
0	11.4	0.79	12.0	0	CUP
0	13.0	0.33	12.5	1	Class 3
0	13.0	0.43	16.0	1	Class 3
0	13.0	0.60	10.5	1	Class 3
0	13.0	0.64	21.9	1	Class 3
0	13.4	1.02	12.0	0	CEP
0	13.5	1.02	12.0	0	CUP
0	13.6	1.00	16.0	0	Class 3
1	14.7	1.24	9.0	0	CEP
1	14.8	1.24	15.0	0	CUP
1	15.0	1.24	18.0	0	Class 3
1	15.4	0.57	13.0	1	Class 3
1	16.5	0.56	16.6	1	Class 3
1	17.0	0.35	18.3	1	Class 3
1	17.4	0.73	14.0	0	Class 3

Table 3-4: Test results (Yes or No) of fire sustain with igniter shutoff and initial test conditions for uncartoned commodities of UUP and UEP.

Fire sustain (1=Yes, 0=No) after igniter shutoff	O_2 volume fraction (%)	Gas flow rate (m^3/s)	Gas inflow temp (°C)	Blockage plate (Yes=1, No=0)	Uncartoned Commodity
0	11.1	0.76	9.0	0	UEP
0	11.5	0.73	6.0	0	UUP
0	13.0	1.08	14.0	0	UUP
0	13.3	0.58	27.7	1	UUP
0	13.3	0.98	6.0	0	UEP
0	14.6	1.25	11.0	0	UEP
0	14.7	1.27	10.0	0	UUP
0	15.0	1.27	7.0	0	UEP
1	14.9	0.73	27.0	1	UUP
1	17.2	1.08	7.0	0	UEP

Figures 3-13 - 3-16 also show the cutoff points of the probability curve at the 5%, 50% and 95% probabilities of fire propagation, which are deemed as lower, mean and upper range of the LOC for the given test condition. For the four test conditions considered in this work (Tables 3-1 - 3-4), Table 3-5 lists the oxygen volume fractions corresponding to the cutoff points. The 5% probability column of Table 3-5 indicates that any oxygen level below the value will have a probability of fire propagation less than 5%. The last column indicates the oxygen level that has a probability of fire propagation of 95%. To apply a very small margin of safety, the LOC is estimated here as the oxygen volume fraction corresponding to the 5% probability column of Table 3-5 for four different conditions. This value hence provides a 95% confidence level in the LOC results.

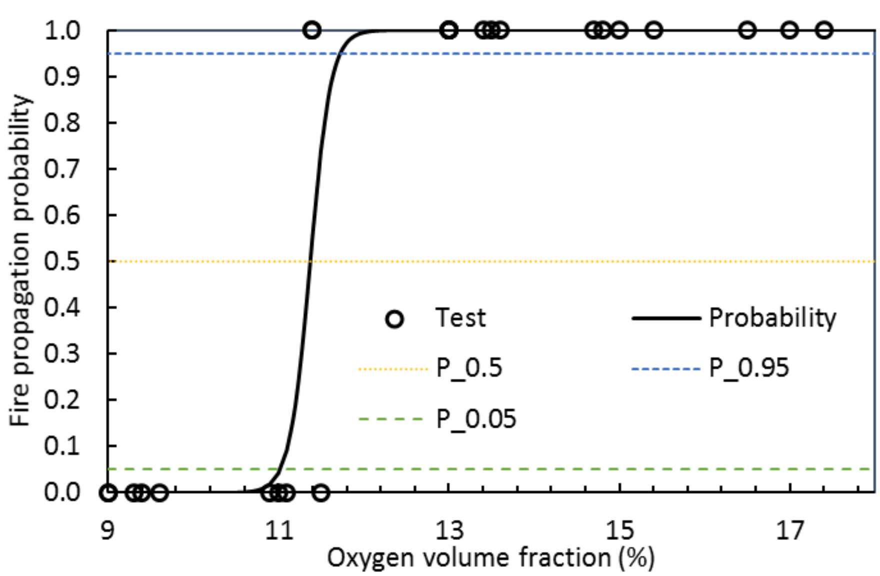


Figure 3-13: Fire propagation probability by oxygen level estimated for cartoned commodities (Class 3, CUP and CEP) with continuous igniter.

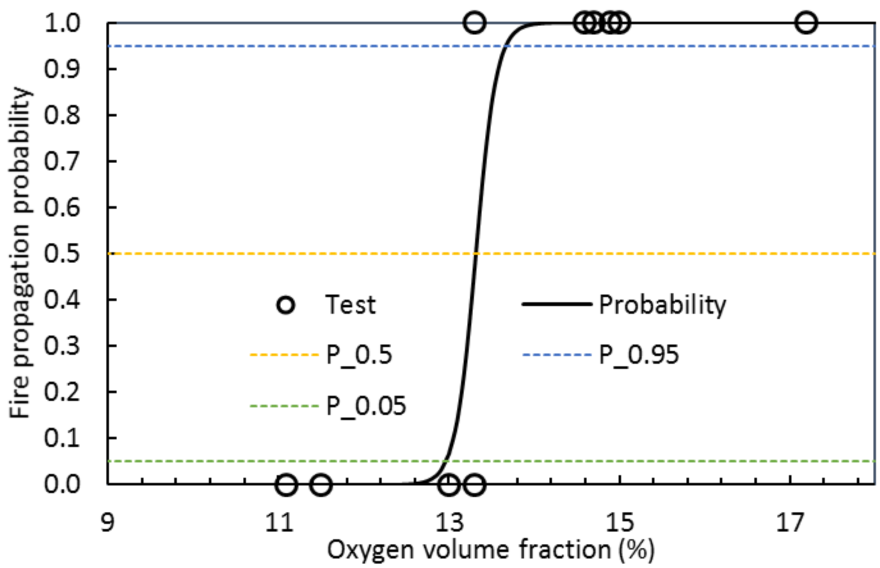


Figure 3-14: Fire propagation probability by oxygen level estimated for uncartoned commodities (UUP and UEP) with continuous igniter.

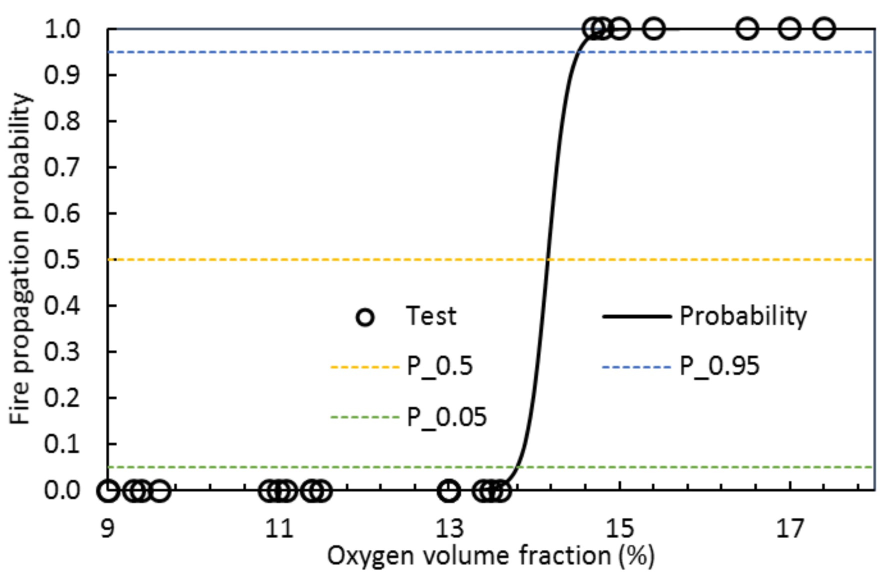


Figure 3-15: Fire sustaining probability by oxygen level estimated for cartoned commodities (Class 3, CUP and CEP) after igniter shutoff.

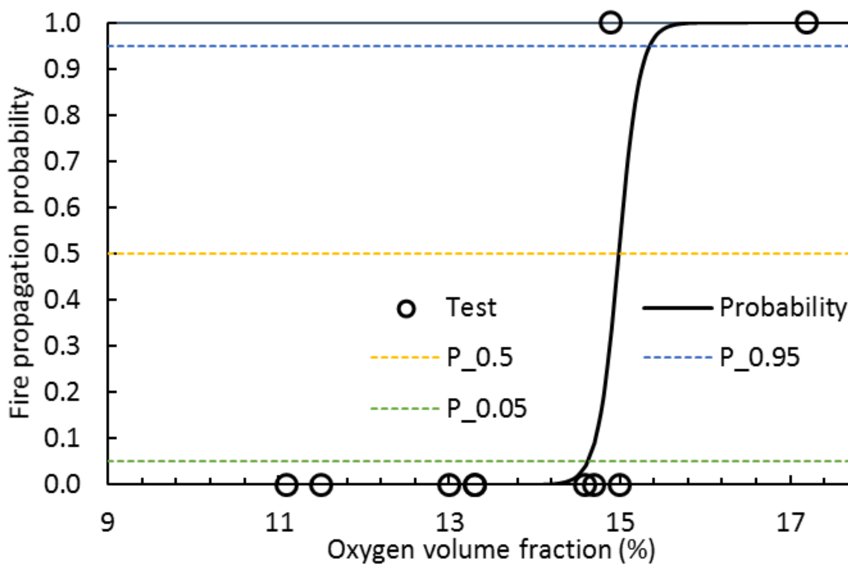


Figure 3-16: Fire sustaining probability by oxygen level estimated for uncartoned commodities (UUP and UEP) after igniter shutoff.

Table 3-5: Oxygen volume fraction corresponding to the cut-off points of the probability curve at the 5%, 50% and 95% probabilities of fire propagation.

Design Conditions	**Probability of fire propagation**		
	5%	50%	95%
Cartoned (Class 3, CUP and CEP) with sustained igniter	11.1	11.4	11.8
Uncartoned (UUP and UEP) with sustained igniter	13.0	13.4	13.7
Cartoned (Class 3, CUP and CEP) after igniter shutoff	13.8	14.2	14.6
Uncartoned (UUP and UEP) after igniter shutoff	14.7	15.0	15.4

4. **Summary and Conclusions**

Large-scale fire tests were conducted to evaluate the LOCs that can support fire propagation. The testing commodities included five standard commodities of Class 3, CUP, CEP, UUP and UEP. Two-tier fuel arrays of standard commodities were set up in rack storage configuration in an enclosure. To represent a large space at uniform concentration, a constant N_2/Air mixture flow was supplied into the enclosure at a desired oxygen concentration. The target oxygen concentration was varied in a 2% interval from 9% up to 17%. A premixed propane ignitor with a constant HRR was used as the ignition source.

The impact of the test conditions on fire propagation was examined in detail for Class 3 commodity at different oxygen levels. The results showed that the oxygen concentration is the dominant parameter controlling the fire propagation. The flow blockage installed under the fuel array, the N_2/Air mixture gas flow rate, and the initial gas temperature were shown to have insignificant impacts on fire growth. 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 limiting oxygen concentrations that can support flame propagation were determined with/without a sustained ignition source using statistical analysis of the large-scale data. The LOC was defined as the oxygen concentration for 5% probability of flame spread results for different commodities in a two-tier rack storage as:

- 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%.

FM Global recognizes that ORS is a relatively new fire protection system which aims to permanently maintain a low oxygen concentration in an enclosed protection space to control fire ignition and/or fire spread. The most important factor for the ORS to be effective is to maintain an oxygen level (LOC), below which the fire spread beyond the ignition location can be excluded. The LOC can be determined through appropriate bench-scale and large-scale tests for a specific fuel. In addition, to ensure adequate protection, systematic reliability analysis should be performed to develop the inspection, testing and maintenance (ITM) programs to provide the required availability of the system.

The results in this report and prior work illustrate that, although not a replacement for the fire sprinkler protection in general, ORS with adequate availability may be used in well-sealed and unoccupied enclosures that can consistently maintain a uniform reduced oxygen concentration. The oxygen concentration in the enclosure needs to be designed based on robust LOC fire tests and the system availability needs to be analyzed to determine ITM cycles. It is expected that the ORS satisfying these conditions can provide adequate protection with relatively low level of fire damage under certain conditions.

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