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Fire behaviour and occurrence of Fire in enclosures protected by oxygen reduction systems

Patrick van Hees and John Barton

Brandforsk

Keywords
Fire Behaviour, Ignition, Hypoxic air, Oxygen reduction Systems, risk analysis.

This report constitutes a final working manuscript for the headlined project.

The official project report, to which reference should be made, can be found on the LTH´s website.

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Abstract

Hypoxic air systems or ORS (oxygen reductions systems) are used to reduce the occurrence of ignition and possibly to reduce the fire growth by means of a lower oxygen level in the ambient air. purpose of this study is to increase the level of knowledge about fire behaviour and ignition properties of different materials in oxygen-reduced environments to assess / quantify the effects of introducing a reduced oxygen system. Both a literature study and experiments in the cone calorimeter and FPA apparatus were used in order to obtain this knowledge. The project confirmed that more studies are necessary to know the behaviour of materials, products and systems in an oxygen reduced atmosphere. The actual determination methods in the design standards for ORSs are not covering all possible scenarios and it is important to decide if the system is used for fire prevention (i.e. preventing ignition) or fire protection (reducing fire growth). Further research such as validations studies and full-scale tests are needed.

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Preface and Acknowledgments

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Lund, 27 December 2018.

Patrick van Hees

John Barton

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1 Introduction

1.1 Background

Recently, fire protection through permanent reduction of the oxygen concentration has been proposed as a fire protection system to replace traditional extinguishing systems or other passive fire protection systems such as fire compartmentation. The system which is called "hypoxic air-venting" means that the oxygen content in the room is lowered below normal atmospheric level. Another term for the system is often oxygen reduction system (ORS).
Recently, it was decided to install such system with oxygen-reduced environment at Forsmark's nuclear power plant [Fredholm 2014] and the system has had a great impact in libraries and museums [Jensen 2006] as well as in storage room. Another example is an installation which was completed at a hospital in Australia, Sydney Adventist Hospital, in critical rooms [Ara 2013]. Common to these spaces is that a fire could have major consequences and that is the reason why a protective method that prevents the appearance of fire is appealing.

The major consequences can be, for example, safety (for example, nuclear industry and hospital), economic (for example manufacturing losses in industry or large property damage), loss of cultural historical properties and buildings which in some cases are considered to be irreplaceable.

In practice, however, the level of protection obtained depends on the selected oxygen concentration. The lower the oxygen content, the higher the fire protection level [van Hees et al 2012]. This, in turn, must be weighed against the negative health effect that a reduction in oxygen content means for persons staying in the protected area [Nilsson et al 2013], see Figure 1. Usually a system with an oxygen content of about 15% is installed as a compromise between the level of fire protection achieved and health aspects, see for example [Chiti 2009, Jensen 2006, VdS 2007, EN 2017]. It was also 15% oxygen concentration selected in the current space of Forsmark's nuclear power plant [Fredholm 2012].

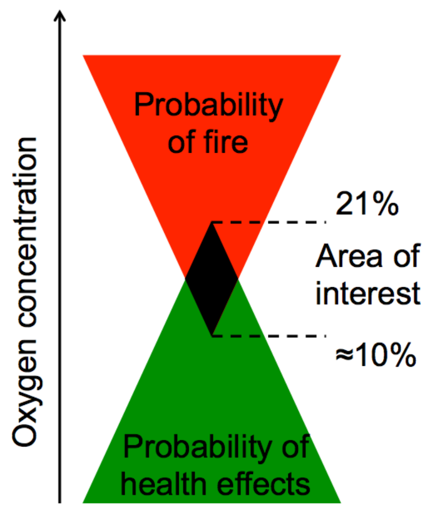


Figure 1 Schematic figure explaining the balancing between fire and health effects probabilities for ORSs

However, an oxygen content of 15% does not generally prevent the onset of fire. Usually, fire can still occur and further spread at these oxygen levels [Fredholm 2012, van Hees et al 2012, Nilsson et al 2013, Xin and Khan 2007, Xin and Khan 2007b, Mulholland et al 1991, Mikkola 1993, Marquis 2012, FM globla 2010, Delichatsios 2005, Rasback and Langford 1968]. However, there are many advantages of the system even at oxygen levels above the inerting level of the fuel in question.

A comprehensive literature study was conducted by Nilsson and van Hees [van Hees et al 2012, Nilsson et al 2013] where the advantages, disadvantages / challenges and further research needs in the field were identified on behalf of NBSG / SSM. In summary, it was found that at 15% oxygen content, the system cannot generally be seen as a substitute for a traditional extinguishing system, and fire can still occur and spread. However, it is noted that the risk of ignition decreases when higher ignition energy is required and that power output decreases and thus also the rate of fire spread. However, the information about how different types of materials behave in different oxygen concentrations are very limited, i.e. it is unclear how big the benefits really are for different types of materials, especially for combinations of materials and actual products on the market [van Hees et al 2012, Nilsson et al 2013]. It was also found that the configuration of the fuel is of great importance regarding the risk of ignition and the spread of fire, which is currently not considered when dimensioning according to existing standards such as PAS 95: 2011 [BSI 2011] and VdS 3527en [VdS 2007] and the area is largely unexplored. A fire in an oxygen-reduced environment means that a possible fire will also be ventilation controlled, resulting in increased production of smoke, soot, etc. that may adversely affect possible injuries and for the evacuating people. The magnitude of this is largely unknown, especially for less generic materials. Soot production is often the decisive parameter in sensitive environments and cause major damages. In addition to this, it was also found that the number of installed systems is few, which means that information regarding probabilities of malfunction and reliability of the systems is limited. This, together with the above-mentioned uncertainties regarding ignition and fire behavior, make assessments of the effects of an installed system difficult to perform, as well as possible risk analyses.

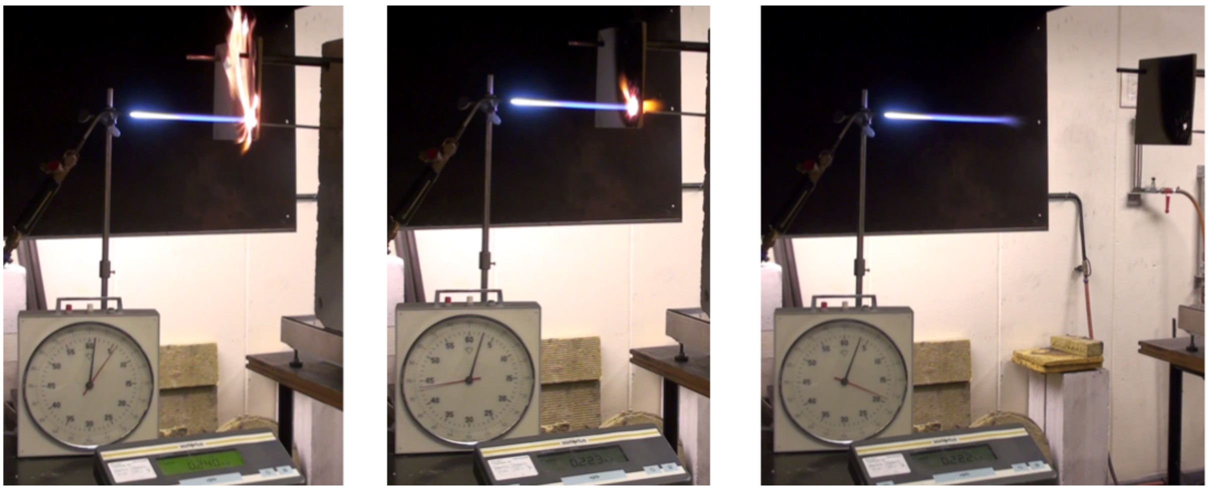


Figure 2 Particle board tested with the methods described in PAS 95:2011 and VdS 3527en at 21% oxygen.

Figure 2 shows a test conducted at Lund University, where the test method specified in PAS 95: 2011 [BSI 2011] and VdS 3527en [2007] standards for oxygen-reduced environments were evaluated. It was found that today's test methods in these standards do not consider a number of important parameters such as the configuration of the fuel especially when there is a risk of re-radiation and the ignition source used. The ignition source is inappropriate as it has low radiation intensity and a high velocity that burns straight through the material. The effect of this is that the scenario considered in the test method is not sufficiently challenging for a large majority of real cases. Figure 2 above shows that a typical particle board meets the test criteria at 21% oxygen content, although it is well known that this type of material contributes to fire spread in common applications and scenarios.

Fire behavior in oxygen-reduced environments is not only interesting from an ownership perspective. Such studies also provide information on how underventilated fires behave. For example, a local flashover in a room within a building may contribute to the production of a larger amount of gases that are dangerous to humans, which may affect the safety of persons in the event of evacuation. There is also a tendency to build more energy efficient buildings, which means more tighter and thermally insulated buildings where a fire is more quickly underventilated. One example is the fire in Farsta 2009 [DN 2013], where three people died. The fire was self-extinguished due to lack of oxygen because the building was kept tight. The victims died from the consequences of an under-ventilated fire due to oxygen deficiency and poisoning of hazardous gases such as carbon monoxide. Five people died also under similar conditions in a fire in Staffanstorp [DN 2013b].

In summary, there is currently information about fire behavior (heat release rate, flame spread rate, etc.), ignition properties and the influence of fuel configuration in fire in oxygen-reduced environments. In addition, in today's installation, a test method is used to determine the oxygen content (see above). This method results in oxygen concentrations which do not to prevent fire when a variety of ignition scenarios occurs. This can result in an overestimation of the capability of the system. As these systems begin to be used more widely in industry as well as in buildings with cultural historical values, museums, libraries, hospitals etc., it is important for both the user and society as well as for the insurer and authorities to be able to quantify the fire protection that a permanent oxygen reduction system entails depending on the selected oxygen concentration. With today's limited knowledge, it is extremely difficult to determine the effects of the ORS, which means that the resulting fire safety level in many respects becomes unknown. Most studies conducted have been made with the involvement of system manufacturers, see for example, [Chiti 2009, Jensen et al 2006, BSI 2011] and present a strong positive image of the system's effect that has been shown to ignore a number of important parameters, see [Nilsson van Van Hees 2013, Xin and Khan 2007]. A structured independent scientific study is therefore necessary. One such needs to include how different materials behave in fire (heat release rate, gas production, flame spread rate, fuel configuration) in oxygen-reduced environments at different oxygen concentrations as well as the amount of critical ignition energy required for different materials at different oxygen levels. This information provides the necessary input to be able to assess and quantify the effects of the system. This information is necessary partly in conducting risk analysis (e.g. probabilistic safety analysis in the nuclear industry), fire engineering design and in assessing potential losses for underwriting in the insurance industry. Furthermore, the information contributes to increasing the knowledge about what factors should be considered in developing more sophisticated and standardized testing methods for the systems, providing the conditions for a consistent and safe application including validation of these methods. The primary benefit of the above-described studies is that the information will result in qualified assessment and quantification of how fire safety is affected by the installation of an ORS, which is not possible today, as knowledge is far too limited despite the existence of standards. The information will therefore be of importance to potential users because they are unable to determine which fire protection level they receive during an installation without that information. In the worst-case scenario, this could result in the risk of fire being greater than feared and that the damage will be greater than thought in the event of fire, which is serious when the system is used for critical functions such as nuclear power plants and hospitals. Furthermore, the information is also necessary for authorities such as SSM who have the requirement to perform probabilistic safety analysis (PSA) and without reliable information regarding fire behavior, likelihood of ignition, etc., a credible PSA will not be possible. Information on the production of hazardous gases at lower oxygen concentrations (underventilated fires) is also important for the development of Boverket's building rules [Boverket 2011] and the Boverket's general advice for analytical dimensioning of the fire protection in buildings [Boverket 2011b], which specifies the production of soot, carbon monoxide and carbon dioxide.

The research needs regarding methods for determining fire behavior of products at lower oxygen levels are high. Specifically, for the hypoxic air technique, a detailed preliminary study of LTH [Van Hees et al 2012] was conducted which resulted in an international publication [Nilsson and Van Hees 2013]. In this study, the Cone Calorimeter, ISO 5660 [ISO 2002, ISO 2015] and Fire Propagation Apparatus (FPA), ISO 12136 [ISO 2011] were identified as suitable methods for investigating fire behavior in oxygen-reduced environments. In addition, a number of studies has shown that both methods have a great potential for carrying out studies on fire behavior of products (and not just single materials) at different oxygen levels but they also conclude that more knowledge is necessary [Marquis et al 2012, Guillaume et al 2011, Werrel 2011, Werrel 2012]. It is important that we in Sweden can provide input to this international discussion and provide input on how different products behave. Another advantage of the Cone calorimeter and FPA methods is that they are standardized, which enables comparison between test results and ensures credible results with known repeatability and reproducibility. This is a big difference to the relatively unspecified test methods in today's proposal for hypoxic air venting standards [VdS 2007, EN 2017, BSI 2011] which proved to produce rather optimistic and unrealistic results, see above in connection with Figure 2and [Nilsson and Van Hees 2013]. Although hypoxic air venting intends to prevent the occurrence of fire, oxygen levels are chosen where fire can still occur due to that fact that staff must be able to stay in the enclosure. Due to this, it is of utmost importance to study fire behavior of different products / materials at different oxygen levels. In addition to the small-scale methods (Cone calorimeter and FPA), it is investigated if larger scale tests are possible or available.

1.2 Purpose and Aim

The purpose of the project is to increase the level of knowledge about fire behaviour and ignition properties of different materials in oxygen-reduced environments to assess / quantify the effects of introducing a reduced oxygen system. This is of utmost importance for potential users, authorities, insurance companies and others. because without this information it cannot be determined how the system affects fire safety and what the fire protection level is. Fire safety and fire protection levels will either be underestimated and result in non-cost-effective investments or, at worst, overestimated and represent a higher risk of fire and greater fire damage than expected. Furthermore, the aim is to get a better understanding of how under ventilated fires increase the production of gases dangerous to humans.

The project has the following objectives:

1. The overall objective of the project is to obtain such information (see item 2-6), which allows the effects of installing a system of reduced oxygen content to be assessed and quantified, which, with today's knowledge mode, is not possible. This means that the system's effect on fire safety and fire protection in a protected area can be determined and quantified, ensuring that the correct level of protection against fire is obtained.

2. Quantify the effect of an oxygen-reduced environment on fire for a set of materials, focusing primarily on heat release rate, fire spread, smoke production, soot production and this at different fuel configurations. Both generic materials and actual products will be studied if possible. This in order to assess and quantify how fire safety is affected when installing the system.

3. Quantify required critical heat flux levels for different materials at different oxygen levels and different fuel configurations. This in order to assess and quantify how fire safety is affected when installing the system.

4. Connect the quantified effects and ignition energy (critical flux levels) to physical material properties so that assessments can be made for unexamined materials. This will support the assessment of the risk of fire as well as the potential damage in the event of fire as support for underwriting and provide the user with information about the current fire protection level. Furthermore, the information is required to carry out risk analysis and to quantify the risk in the case of fire and to quantify the risk of occurrence of fire which is necessary in e. g. nuclear industry.

5. Create an easy-to-use tool or guidance for damage assessment and cost / benefit for a fire protection system with oxygen reduction. This is to support efficient risk management, underwriting, etc. for users and insurers.

6. Increase the knowledge of fire behavior and the production of hazardous gases, primarily carbon monoxide for under ventilated fires. This is in view of the fact that more energy efficient buildings are being constructed and these are tighter which will increase the number of fires of this type.

1.3 Methods

In order to achieve the objectives of the project, the following methods were used: literature studies, interviews, tests / experiments and technical analysis.

1.4 Limitations

Depending on the available resources the number of materials and tests can be reduced. The project will where possible also try to use data which is being published during the project period. For this reason, the project report will refer in a number of cases to the report which was written by the authors in cooperation with Brian Meacham and Martin Nilsson as part of a study for ORS systems in warehouses. A clear reference will be made in this report to that study (Van Hees et al 2018).

2 Literature

In order to obtain detailed information about the literature review the reader is also to the NFPA report by van Hees, Barton, Nilsson and Meacham (van Hees et al 2018). This report investigates the influence of low oxygen on the following hazard conditions:

- Ignition
- Heat release rate and mass loss rate
- Flame spread
- Smoke, soot, and corrosives development

The following paragraphs summarizes the results of this study and where appropriate additional material has been added. Smoldering is not included in this study as it was not part of the project description. Data can be found in Van Hees et al 2018.

2.1 Experimental apparatuses

The two methods mainly used for this type of evaluation in the literature are the cone calorimeter according to ISO 5660 (ISO 2015) and the FPA apparatus (ISO 2011). They were even used in this study and are more explained in chapter 3. These two methods are For determination of the oxygen level in the design of ORSs a test method described in VdS 3527 (VdS 2007) and EN 16750 (EN 2017) is used which can be more defined as a small flame (although with a high momentum) ignition tests. This test method has been criticized as not covering all type of ignition sources. (van Hees et al 2018). In the same report information is given to motivate this critique.

2.2 Influence of reduced oxygen on ignition

When the ORS is designed to be a fire prevention method (i.e. prevention the occurrence of a fire), the major parameter to be determined to define the oxygen level in an ORS is the ignition properties of a material, product or system. In principle ignition times are increasing when oxygen reduction is applied until a level where no ignition will occur but all depends on the type of heat source (radiative, small flame, etc.) or level of energy in the ignition source (spark, flame, etc.). In Table 2 and 2 it can be seen how different materials having a range of limiting oxygen concentration levels (LOC) which also depends on the type of measurement and configuration and heat flux.

Fuel	Irrad.	O_2
	kW/m^2	%
PMMA	30	13,8
	15	15,1
ABS	30	14,0
	20	15,2
PE	40	14,3
	15	14,6
DF	50	14,6
	25	15,2

Table 1 Minimum oxygen concentration for complete burning (Adapted from Mulholland et al. (1991))

Material	Extinction $[O_2]$ (%vol.)	Re-ignition $[O_2]$ (%vol.)	(kW/m²)
Liquid fuel			
Unleaded gasoline (dish)	12,48	11,48	0
Methanol (dish)	11,64	11,64	0
Methanol (wick)	12,33	12,33	0
Ethanol (dish)	12,40	12,40	0
Ethanol (wick)	13,35	13,35	0
Corn oil (dish)	12,29	12,29	0[a]
Solid fuel			
Polyethylene (low density)	11,39	12,12	30
Polystyrene (high density)	11,21	12,12	30
PMMA	10,48	11,64	30
Red oak	12,26	13,52	50
White maple	14,66	15,41	30
Corrugated paper (tri-wall)	12,86	18,23	30
Corrugated paper (single layer)	12,94	14,87	30
Kraft linerboard	12,33	16,12	30
Fabrics			
Wool	17,04	NA[b]	30
Cotton	14,55	16,45	30
Polyester	12,65	13,60	30
[a]The corn oil is ignited using $\dot{q}''_{ext}$ = 50 kW/m². Once ignition occurs, $\dot{q}''_{ext}$ is turned off			
[b]NA - re-ignition not observed			

Table 2 Limiting oxygen concentration at extinction and re-ignition (Adapted from Xin and Khan (2007))

2.3 Influence of reduced oxygen on heat release and mass loss rate

Experimental data from a literature review by Nilsson and van Hees (2014) showed that the peak heat release rate (HRR) and peak mass loss rate (MLR) for solid materials, products and liquids generally decrease when the oxygen concentration is decreased below 21% by volume with either N_2, CO_2, or combustion products. However, the decrease in the HRR and MLR was not a constant percentage for a given oxygen concentration. The study by Marquis (Marquis et al 2014) shows that the HRR as a function of time changes but at a certain level there is almost no HRR due to non ignition despite the fact that a mass loss rate is observed. This can be seen when comparing Figure 3 and Figure 4. It can be seen that there is still HRR at levels as low as 10%.

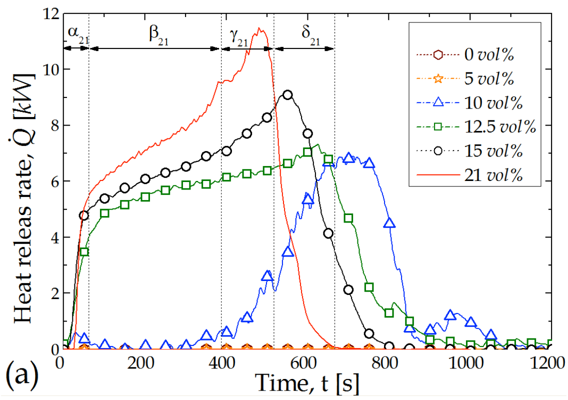


Figure 3 Heat release rate for PMMA at different oxygen levels in the CACC. (Marquis et al 2014, with permission of IAFSS)

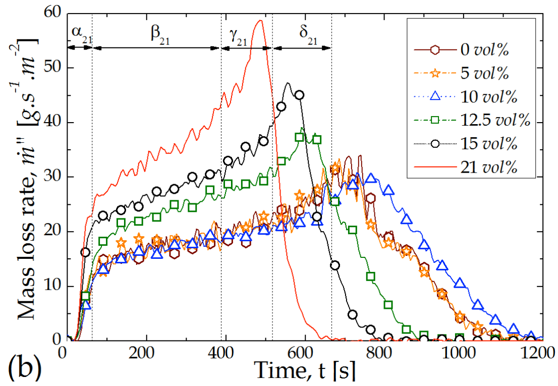


Figure 4 Mass loss rate for PMMA at different oxygen levels in the CACC (Marquis et al 2014, with permission of IAFSS)

2.4 Influence of reduced oxygen on smoke, soot and corrosives development

The smoke, soot and corrosive production rates are also depending on the level of oxygen. The most general trend is given in the graph from Tewarson which gives data as a function of the equivalency ratio. Further data can be found in van Hees et al (2018).

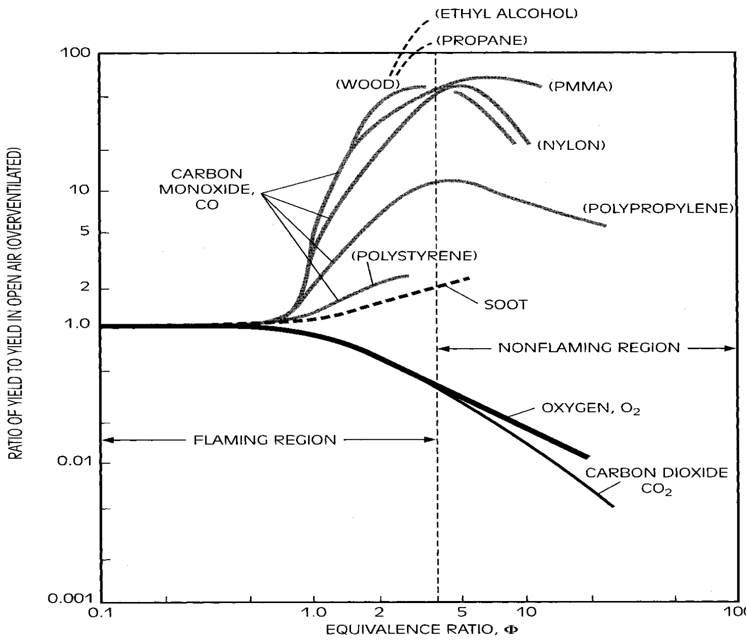


Figure 5 Production rates depending on the equivalency ratio for a number of fuels (redrawn from Karlsson and Quintiere 1999).

Productions rates are also reported by Marquis et al (2014) for PMMA. Figure 6 shows the CO_2 production rate for different oxygen levels. It can be that for levels around 10% the shape of the production rate changes but that generally the trend is similar at the HRR rate. (see Figure 3). For the CO production rate it can be seen that the highest levels are at the extinction moment for the higher oxygen levels and that appear as a short peak. But for the lower levels (even production at very low levels) the CO production is more present during the whole burning period and even at low levels where no HRR is produced there is a production of CO (see Figure 7)

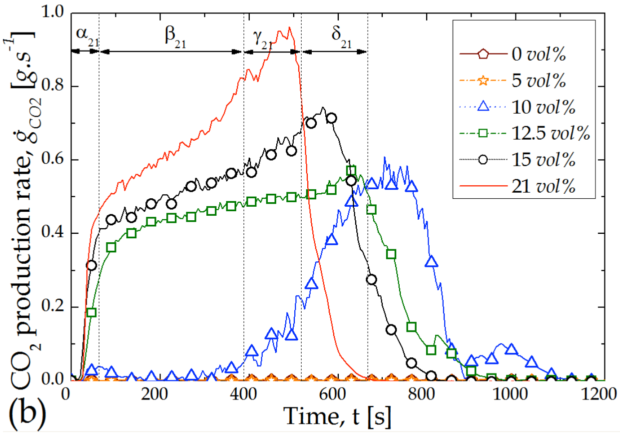


Figure 6 CO_2 production rate for PMMA at different oxygen levels in the CACC (Marquis et al 2014, with permission of IAFSS)

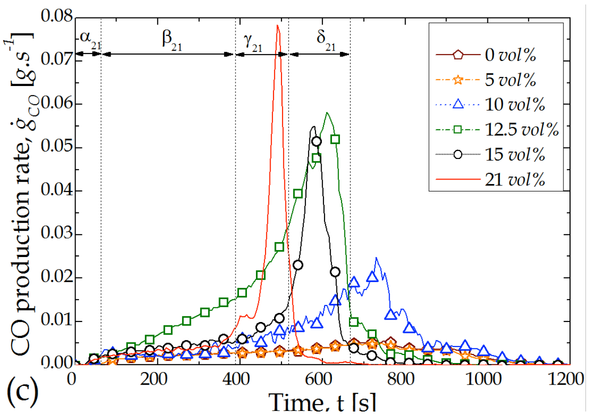


Figure 7 CO production rate for PMMA at different oxygen levels in the CACC (Marquis et al 2014, with permission of IAFSS)

2.5 Full or real scale tests

The literature up to now has very little information about full scale test with have been conducted at lower oxygen levels. Some data is available for room tests at high altitude but the only major contribution today is the full-scale test series conducted by FM Global (Zhou et al 2018). In their set-up, they simulated an ORS in a two-tier fuel array of standard commodities in a rack storage configuration was set up in an enclosure.

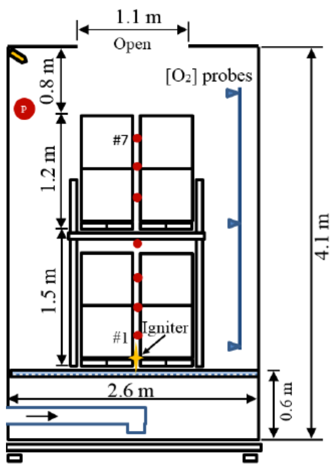


Figure 8 Set-up of full-scale tests (redrawn and adapted from Zhou et al 2018).

A constant N2/Air mixture flow was supplied to the enclosure with a specific oxygen level. The oxygen concentration ranged from 9% up to 17%. A premixed flame which represents potential heat sources such as electric arc and hot work was used as the ignition source to maintain repeatable test 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 LOC was defined as an oxygen concentration at 0.05 probability of flame spread by using statistical analysis. The resulting limiting oxygen concentration (LOC) values measured for different commodities in a two-tier rack storage were (Zhou et al 2018):

- 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%.

The difference between hard and soft limit is depending on the definition given by Zhou et al. The limits with a sustained ignitor approach the fundamental LOC values for gaseous fuels such as 11.1% - 12.0% for methane [Zlochower and Green 2007] and these are 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.

It can be seen that the LOCs are generally lower than the oxygen design concentrations recommended by existing standards such as the VdS 3527 and EN 16750 which is mainly because of different test conditions. As mentioned above, the hard limits resemble fundamental LOCs 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 by Zhou et al that the hard limits are more suitable for ORS design purposes.

2.6 Conclusions

This chapter gave information on the impact of reduced oxygen on HRR, smoke production, etc. Few literature sources are available where actual products and systems are investigated, and it should be determined how the oxygen level should be determined and if a similar approach such as commodities for sprinkler can be applied. From the literature it is clear that there is no information about validation of the test methods in EN 16750:2017 and VdS 3527 with respect to real-scale scenarios and that considerable research is needed to further develop the test methods through full-scale fire tests. Other ignition scenarios should also be investigated in real-scale and linked to small scale tests. This has been demonstrated e.g. by the full-scale tests performed by Zhou et al (Zhou et al 2018).

Further detailed information on the literature review is available in the main body of this report and in the NFPA report (van Hees et al 2018).

3 Experimental results

This chapter summarizes the different experimental results performed in the project. Both test with the cone calorimeter and the FPA apparatus were conducted. The cone calorimeter test results focus on the ignition behaviour at lower oxygen levels while the FPA results were designed to test a small-scale set-up including a cable set-up.

3.1 Cone Calorimeter

With the cone calorimeter results two objectives were envisaged. One was to investigated the effect of oxygen level on the HRR, productions rates in different test set ups and one was to investigate the ignition times. The HRR levels were measured in a BSc thesis by Linnå and Wahlström (2013) while the ignition tests were performed by Barton (Barton 2016).

3.1.1 Experimental Set-up

An open CACC with a 30 cm long chimney was used to measure the effect of oxygen concentration on ignition times for transparent PMMA. The open CACC is an enclosure box attached to the cone calorimeter and has been used by other researchers to observer the burning behavior of materials at different oxygen concentrations (Marquis et al. 2012; Marquis et al. 2014; Werrel et al. 2014; Mikkola 1993). The enclosure box is not directly connected to the exhaust duct so ambient air will mix with the combustion gases before reaching the cone calorimeter's gas analyzers. The box has a door, an observation window, a cone heater, and a scale to place the sample on. The diameter of the chimney used was 10 cm.

The flow rates of compressed air and nitrogen were measured individually using rotameters and then mixed together. The compressed air and nitrogen mixture was introduced into the box using a gas inlet on the box. The oxygen concentration is calculated using the flow rate of the compressed air and nitrogen and compared to an oxygen analyser connected to the enclosure box. A diagram of the experimental setup can be seen in Figure 9 and photographs of experimental setup in Figure 10.

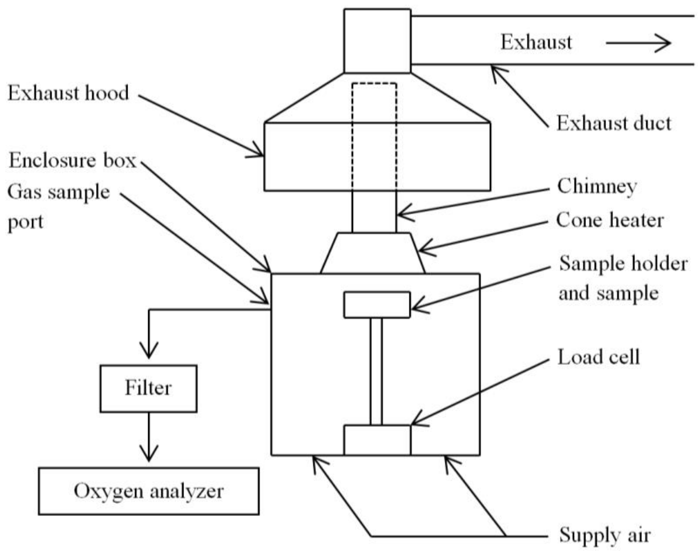


Figure 9 Experimental setup

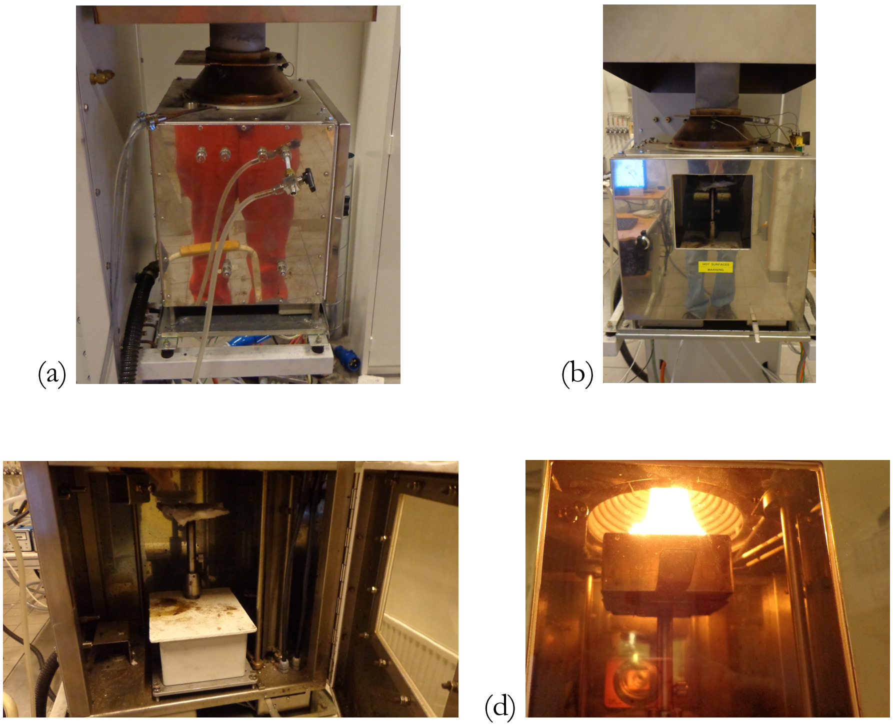


Figure 10 Open CACC (a) side view of open CACC (b) front view of open CACC (c) inside enclosure (d) burning sample

Two different materials were used. For the HRR measurements a commercial particle board was used with a thickness of 10 mm. For the ignition tests, transparent PMMA samples were used being 12 mm thick and having sides that were 98±2 mm. The masses of samples were 133±4 g. The manufacturer specified density was 1.18 g/cm^3. A sample holder and retainer frame conforming to ISO 5660-1:2015 was used. The samples were wrapped in aluminum foil and pieces of refractory fiber blanket (nominal thickness 13 mm, nominal density 65 kg/m3) were used as the backing insulation.

The test procedure was slightly different in both test series as the first test series on HRR has shown the influence of the pre-heating time. The procedure below was the one used for the ignition tests. For the one on the HRR more details can be found in Linnå and Wahlström (2013) but in principle different set-ups were also compared with and without chimney.

For the PMMA tests, the time needed for the box to reach equilibrium after the door of the box is opened to place the sample inside was determined. A worst-case scenario was used to determine the time needed to wait for equilibrium. The box with the door closed was initially at 21% O_2 with 120 l/min of compressed air flowing through it. The nitrogen flow rate was then set at 40 l/min. The oxygen concentration of the oxygen analyzer on the cone calorimeter was recorded and it was determined how the long oxygen concentration took to reach steady state. It was determined that for a flow rate of 120 l/min of compressed air mixed with 40 l/min of nitrogen that the oxygen concentration inside the box could be reduced from 21% to 16% in approximately 60 s. This is consistent with the range of equilibrium waiting times, 60-90 s, given by Werrel (2014).

During operation, the exhaust flow rate of the cone calorimeter was set to 24 l/s. The temperature of cone heater was set to a temperature corresponding to the required heat flux. The heat flux was measured using a heat flux meter where the center of sample surface would be placed. The temperature of the cone heater was then adjusted and the measured heat flux was allowed to reach a steady value. The heat flux was considered set after the measured heat flux was within 2% of the required level for 10 minutes. Between the tests the heat flux was measured to ensure that it was within 2% of the set heat flux. No adjustment was needed between any of the tests.

Tests were done at 16% O_2 and 21% O_2 at radiant heat fluxes of 18 kW/m^2 and 35 kW/m^2. Three tests were done for each combination of oxygen concentration and radiant heat flux. The compressed air was set to a flow rate of 160 l/min for tests at 21% O_2. For tests at 16% O_2, the flow rate of compressed air was set to 120 l/min and the nitrogen flow rate was set to 40 l/min. The samples were tested in a horizontal orientation.

To begin a test the compressed air and nitrogen were set to the required flow rates. The box door was closed and the box was allowed to reach equilibrium for at least 3 min. Baseline data was then taken for 1 min. The radiation shield was then closed and the sample placed in the enclosure box. After 1 min the radiation shield was opened and the igniter put in place. The time to flashing and the ignition time were recorded. The sample was then allowed to burn until self-extinction.

3.1.2 Caculations of HRR for the CACC set-up

The equations for the calculation of the HRR in the CACC are using the principles as outlined in (Werrel, et al., 2014).

The HRR is calculated with equation 1:

$$\dot{q} = E \cdot 1{,}10 \cdot \left(X_{O_2}^{A^0}\gamma - X_{O_2}^{A^S}(\gamma - 1) \right) \cdot C\sqrt{\frac{\Delta p}{T_e}} \left[\frac{\phi - 0{,}172(1-\phi)\, X_{CO}^{A}/X_{O_2}^{A}}{(1-\phi) + \phi\left(1 + 0{,}5\left(X_{O_2}^{A^0}\gamma - X_{O_2}^{A^S}(\gamma-1)\right)\right)} \right] \left(1 - X_{H_2O}^{S}\tilde{\gamma}\right)$$

Equation 1

$$\phi = \frac{\left[\left(X_{O_2}^{A^0}\gamma - X_{O_2}^{A^S}(\gamma-1)\right)\left(1 - X_{CO_2}^{A} - X_{CO}^{A}\right)\right] - \left[X_{O_2}^{A}\left(1 - X_{CO_2}^{A^S}\tilde{\gamma}\right)\right]}{\left(1 - X_{O_2}^{A} - X_{CO_2}^{A} - X_{CO}^{A}\right)\left(X_{O_2}^{A^0}\gamma - X_{O_2}^{A^S}(\gamma-1)\right)}$$ Equation 2.

$$\gamma = \frac{\dot{m}_e^0}{\dot{m}_e}$$ Equation 3.

$$\tilde{\gamma} = 1 - \frac{\dot{m}_g^B}{\dot{m}_e}$$ Equation 4.

where:

$\dot{q}$ − HRR [kW]

E − oxygen depletion factor. $E = 13{,}1\ [kJ/g_{O_2}]$

$X_{O_2}^{A^0}$ − Initial mole fraction of oxygen in duct [-]

$X_{O_2}^{A^S}$ − Mole fraction of oxygen in surrounding air [-]

C − Calibration coefficient of measuring flange $C = 0{,}043531$ [$m^{1/2}kg^{1/2}K^{1/2}$]

Δp − Pressure drop over the measuring flange [Pa]

T_e − Smoke gas temperature at flow opening [K]

X_{CO}^{A} – Mole fraction CO in smoke gases. [-]

$X_{O_2}^{A}$ – Mole fraction oxygen in smoke gases. [-]

$X_{H_2O}^{S}$ – Mole fraction water vapour in surrounding air [-]

$X_{CO_2}^{A}$ – Mole fraction carbon dioxide in smoke gases. [-]

$X_{CO_2}^{A^S}$ – Mole fraction carbon dioxide i surrounding air. [-]

$\dot{m}_e^0$ – Mass flow in smoke duct before the test. [kg/s]

$\dot{m}_e$ – Mass flow in smoke duct during the test. [kg/s]

$\dot{m}_g^B$ – Mass flow in the burning chamber. [kg/s]

3.1.3 Experimental Results

3.1.3.1 Measurements of HRR, SPR, CO and CO2 on particle board

A first study was conducted at LTH by Linnå and Wahlström (Linnå and Wahlström 2014) by means of a BSc thesis with supervision of one of the authors of this report. In total 8 configurations were studied as given in Table 3. Instead of PMMA a commercial particle board of 10mm thickness was used and different set-up were compared.

Test set-up	Heat Flux [kW/m²]		Oxygen level [%]		CACC chamber used	Chimney used
	25	50	20,95	15*		
1 (50 ISO 20,95)		X	X			
2 (50 CACC 20,95)		X	X		X	
3 (50 CACC 15)		X		X	X	
4 (50 CACC 20,95-C)		X	X		X	X
5 (50 CACC 15-C)		X		X	X	X
6 (25 ISO)	X		X			
7 (25 CACC 20,95-C)	X		X		X	X
8 (25 CACC 15-C)	X			X	X	X

*The oxygen content during the test varied between 15,1 and 15,8 %.

Table 3 Overview of the different test set-ups.

In Figure 11 and Figure 12 the HRR per unit area is given for each of the test set-ups. Annex B give detailed results of the test for each set-up and for each set of data.

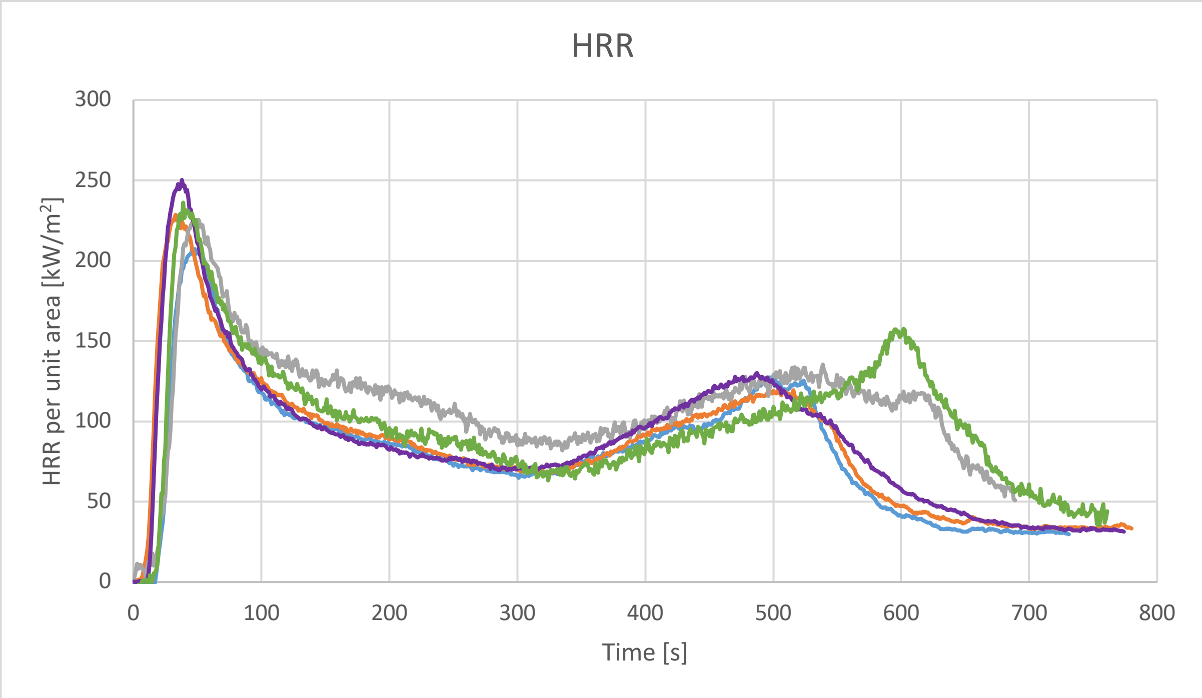


Figure 11 HRR for particle board at 50 kW/m^2 for the different set-ups. (blue line test set-up 1 (50 ISO), orange line test set-up 2 (50 CACC 20,95), gray line test set-up 3 (50 CACC 15), purple line test set-up 4 (50 CACC 20,95-C), green line (50 CACC 15-C)

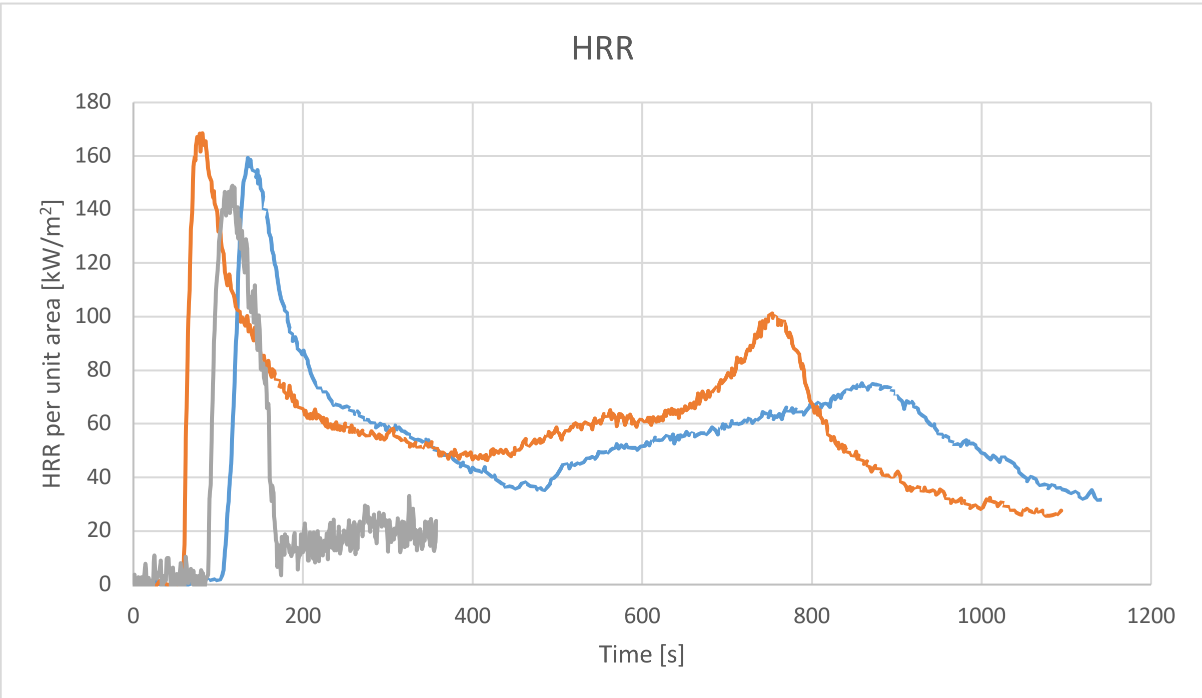


Figure 12 HRR for particle board at 25 kW/m^2 for the different set-ups. (blue line test set-up 6 (25 ISO), orange line test set-up 7 (25 CACC 20,95-C), gray line test set-up 8 (25 CACC 15-C)

The outcome of the experiments revealed that a chimney gave overall the best results and that the particle board still ignites at levels of 15 % oxygen.

3.1.3.2 Measurements of ignition time for PMMA.

The ignition times and times to flashpoint are seen in Table 4 and Table 5. Flashing was observed for all tests at 16% O_2 except for one at a radiant heat flux of 35 kW/m^2. Flashing was not observed for any of the tests at 21% O_2. It can be seen that the time to flashpoint of the tests at 16% O_2 are very close to the ignition times at 21%. The mean ignition time for 16% at a radiant heat flux of 18 kW/m^2 is 196 s longer than at 21% O_2. This is in contrast to the small difference in mean ignition times for 16% O_2 and 21% O_2 at a heat flux of 35 kW/m^2.

	21% O_2 by vol. Ignition time [s]	16% O_2 by vol. Ignition time [s]	16% O_2 by vol. Time to flashpoint [s]
	373	553	380
	331	546	355
	366	559	377
average	357	553	371

Table 4 Transparent PMMA at 18 kW/m^2

	21% O_2 by vol. Ignition time [s]	16% O_2 by vol. Ignition time [s]	16% O_2 by vol. Time to flashpoint [s]
	73	78	78
	71	78	64
	77	84	76
average	74	80	73

Table 5 Transparent PMMA at 35 kW/m^2

It was expected that there would be some preheating during the 60 s that the sample is in the enclosure box before the test is started and the radiation shield is opened. Previous experiments done using the same enclosure box had seen shorter ignition times for particleboard tested in the enclosure box with a potential preheating time of 75 s than in the normal cone calorimeter setup without preheating (Linnå & Wahlström 2014). The radiation shield was metal and covered with insulation on the top. Between some of the tests the heat flux meter was put in place and the radiation shield closed. The heat flux was then recorded every 10 seconds for 120 seconds by hand. This was done once for each radiant heat flux. The results are in Table 6 and Table 7.

Time [s]	Heat flux [kW/m^2]
0	-
10	0.7
20	0.7
30	0.7
40	0.8
50	0.9
60	0.9
70	1
80	1.1
90	1.2
100	1.1
110	1.2
120	1.2

Table 6 Transparent PMMA at 18 kW/m^2

Time [s]	Heat flux [kW/m²]
0	-
10	1.5
20	1.6
30	1.8
40	1.8
50	2
60	2.3
70	2.5
80	2.7
90	2.9
100	3.1
110	3.3
120	3.4

Table 7 Transparent PMMA at 35 kW/m^2

3.2 FPA apparatus

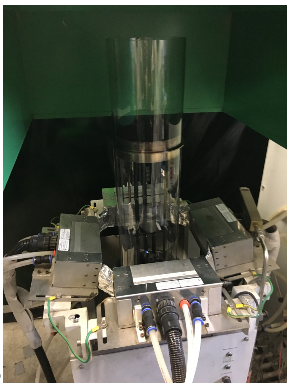
The FPA allows for testing of materials at different oxygen concentrations and in different orientations. Two connected quartz tube pieces enclose the volume around the test sample, which allows the oxygen concentration around the sample to be changed. The two quartz tube pieces connected together extend 644 mm from the bottom sample holder. An ethylene/air pilot flame is used to ignite the sample and four infrared heaters that use tungsten quartz lamps provide a radiant heat flux to the sample. More details on the equipment can be found in the ASTM E2058 – 13a. (ASTM 2013) and ISO 12136 (ISO 2011).

3.2.1 Experimental Design

A vertical sample holder was used to test a N1XV-U 4G2.5 ground cable with a classification of E_{CA} at oxygen concentrations of 15% and 21%. Three 40 cm long cables segments with a nominal diameter of 10.6 mm were attached to the holder using metal wiring. The cables were placed one diameter apart from each other.

The heat flux from the infrared heater was set to 50 kW/m^2 for each test using a heat flux gauge. The heat flux gauge was placed in a horizontal position at height that corresponded to the bottom of the cables. This position of the heat flux gauge was same as used to set the heat flux for horizontal samples in the FPA.

The pilot flame was an ethylene/air flame. For test one and two, the length of pilot flame was approximately 1 cm and placed 0.5 to 1 cm from the surface of the middle cable. For test three, the pilot flame was approximately 2 cm and paced 0.5 to 1 cm from the surface of the middle cable. The height of the pilot flame was 7.5 cm from the bottom of the cables for tests one and two and 13 cm from the bottom of the cables for test three. Figure 13 shows some photographs of the experimental setup.

(a)  (b) 

(c) 

Figure 13 FPA test setup (a) sample inside quartz tubes (b) sample without quartz tube (c) sample holder.

The inlet flow rate to volume enclosed by the quartz tube was set to 120 l/min and the exhaust flow rate was set to 150 l/s. An oxygen analyser was used to check the oxygen concentration of the inlet flow.

The test procedure was to place the sample in the FPA and place the pilot flame 0.5 cm to 1 cm from the middle cable. The quartz tube was then put in place. The oxygen concentration inside the volume enclosed by the quartz tube was allowed to stabilize for at least one minute. The water-cooled radiation shield was then raised and the infrared radiant heaters were turned on. The water-cooled radiation shield was lowered after one minute and this was considered the start of the test.

3.2.2 Experimental Results

The heat release rate was calculated using the generation of CO_2 and CO. The calculation procedure from ASTM E2058 – 13a was used to calculate the heat release rate.

The first test was done at 15% oxygen concentration with the pilot flame at a height of 7.5 cm. The peak heat release was 4.7 kW and the heat release rate vs. time is shown in Figure 14.

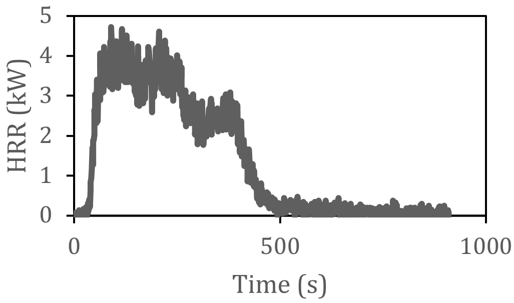


Figure 14 Heat release rate of N1XV-U 4G2.5 ground cable at 15% O2 with pilot flame height of 7.5 cm

The second test was done at 21% oxygen concentration with the pilot flame at a height of 7.5 cm. The peak heat release was 5.8 kW and the heat release rate versus time is shown in Figure 15.

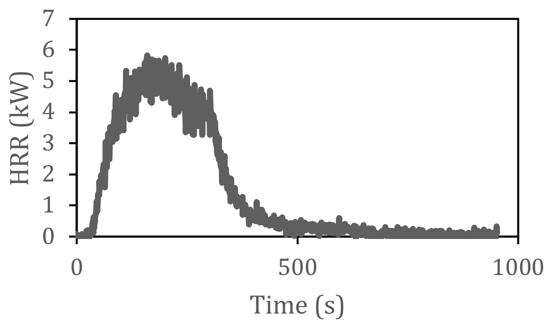


Figure 15 Heat release rate of N1XV-U 4G2.5 ground cable at 21% O_2 with pilot flame height of 7.5 cm

The third test was done at 15% oxygen concentration with the pilot flame at a height of 13 cm. The peak heat release was 4.1 kW and the heat release rate vs. time is shown in Figure 16.

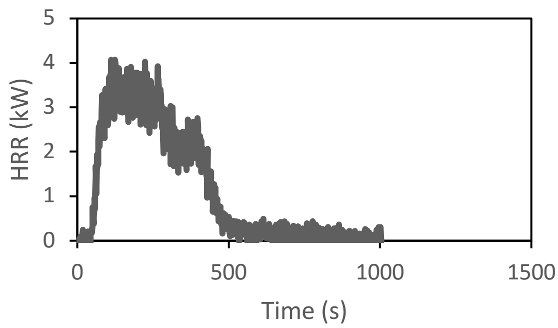


Figure 16 Heat release rate of N1XV-U 4G2.5 ground cable at 15% O_2 with pilot flame height of 13 cm

It was difficult to determine the time to ignition because of the build of pyrolysis gases and the ignition seemed to occur away from the pilot. In addition, for the tests at 15% oxygen concentration the pilot was extinguished at the end of the test while at 21% oxygen concentration the pilot was still burning. It was not possible to see the pilot flame during test because of the lamps used for the infrared radiant heater.

The outcome of this test series resulted in data where cables ignited at 15% of oxygen and showed that it was possible to test a cable tray inside the FPA apparatus. However further development is needed but promising results were obtained.

3.3 Conclusions

The work was mainly performed on two different apparatuses and gives a first indication on ignition, HRR and other fire parameters for materials such as particle board and PMMA and products such as cables. Both the cone calorimeter and the FPA apparatus are instruments which are very suitable for determining fire behaviour of materials under lower oxygen level for small scale tests but some additional further development is needed in order to include procedures for products and small components. Together with a guidance document for real scale tests (see an example in chapter 2) this would be the way forward for experimental determination of the oxygen level. Additional information is also available in van Hees et al (2018) on the needs for a future test methods to design the oxygen level in an ORS.

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4 Risk Analysis

In case ORS systems are to be installed in enclosures a detailed risk analysis needs to be one. This has been explained in the NFPA study by the authors and their collaborators (van Hees et al 2018). A first step should be an overview of the possible ignition sources in the facilities as well as the type of fuels present in the facility as well as their configuration. With that information one should start conducting a risk analysis as part of a performance-based design as given in the guide for performance-based design (SFPE 2007). This will result in a number of fire scenario for which can be used in the analysis such as explained in van Hees et al (van Hees et al 2018).

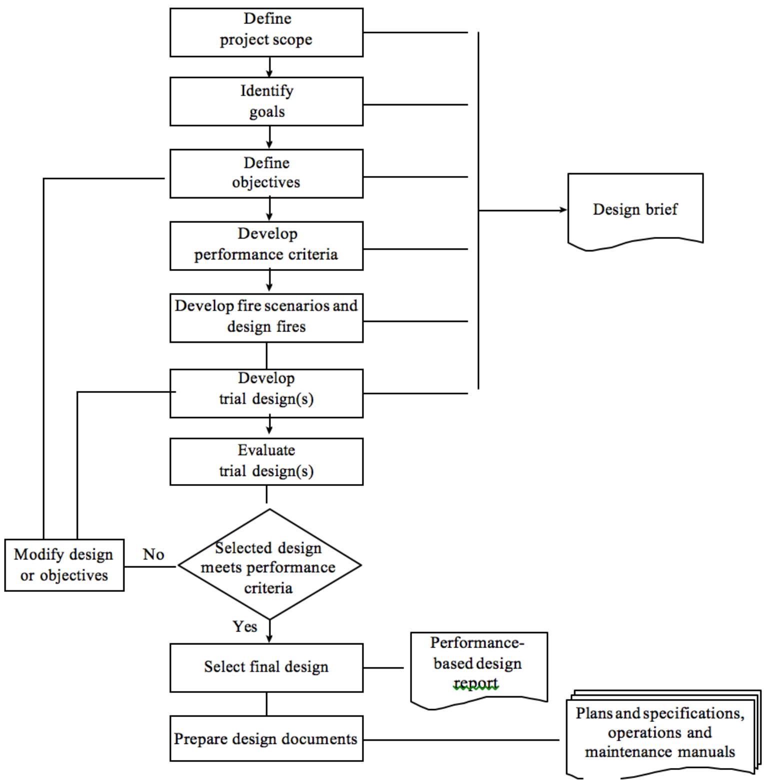

Figure 17 Performance Based Design process. (adapted from SFPE 2007)

In order to assist the choice of level of oxygen for the design of an ORS system a simple risk analysis tool by means of a flow chart has been developed. It can be used as a guidance but there is still need to further establish data to compare the tool with real data. Especially the part to determine the consequences for those cases where the oxygen level acceptable for buildings with occupancy is higher than the threshold level for ignition. Here determination methods need to be developed. A similar reasoning applies for defining this threshold values as could be seen in the literature review and test results but here at least some data and test methods are available.

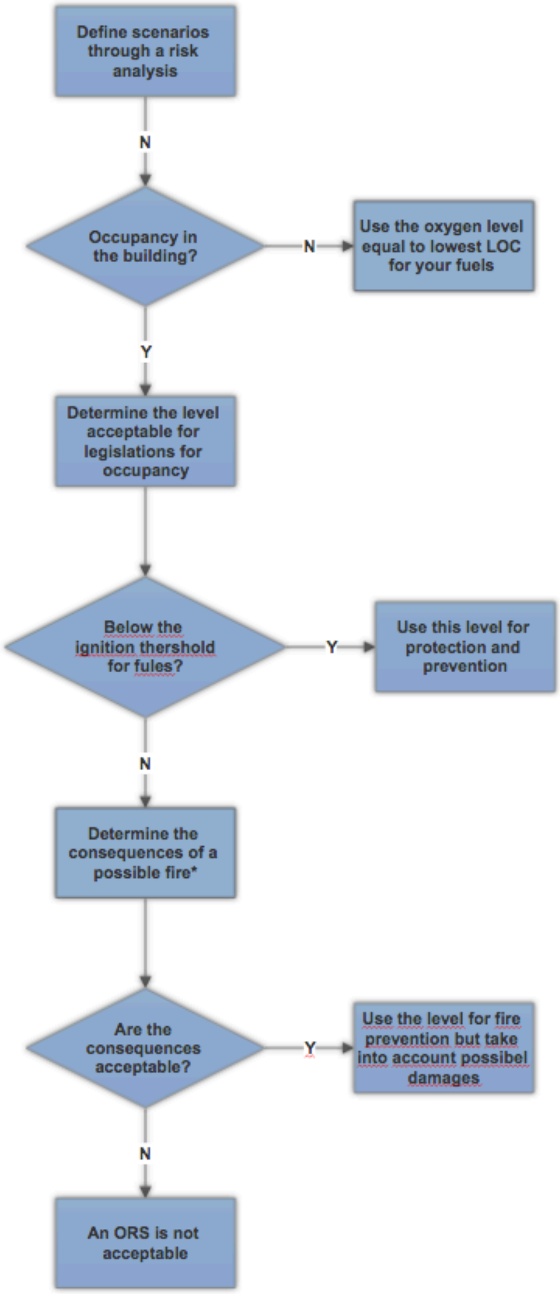

Figure 18 Risk evaluation tool for selecting design criteria for an ORS

5 Conclusions and Future work

5.1 Conclusions

This report should be considered as a complementary report to the NFPA report issued by van Hees, Barton, Nilsson and Meachem. The report focused on warehouses but gives a large amount of information for ORSs in general. This Brandforsk research project has been focused on the determination of the oxygen levels for an ORS and some preliminary guidance on how to determine the level. The research in this report confirmed once more that the test methods in EN 16750:2017 and VdS 3527 may not be sufficient to cover all real-scale scenarios and that a considerable overall risk analysis is needed before the ORS can be implemented. Especially when ignition is tried to be prevented in the real-scale scenarios, the oxygen concentrations determined in EN 16570:2017 and VdS 3527 may result in too high values. Both tests in cone calorimeter and FPA on a number of typical materials used in enclosures were conducted. The results show that the ignition concentrations are lower when radiative heat source are involved and this should be considered when determining the final oxygen level.

The project shows that both the cone calorimeter (CACC) and the FPA apparatus are much more suitable to use for determining a realistic oxygen level in the ORS. For full set-ups with complex systems even full scale tests might be necessary.

The project also gives some guidance to determine the oxygen levels. Here it is proposed to separate this selection from buildings with or without occupancy and make a risk evaluation whether fire prevention or protection is used.

5.2 Future work

While oxygen reduction systems (ORS) are used more and more, there are still a number of research gaps to be filled up. These were clear from the NFPA report and are summarised here and should be considered as citations. For more detailed information on each of the items the reader is referred to the NFPA report.

5.2.1 Research/Development needs with respect to ORS test methods

1. Data on real scale scenarios with the systems are very limited.
2. No full- or real-scale validation has been done for the EN 16750:2017 and VdS 3527 methods.
3. The test method in the EN and VdS standards have only one type of ignition source. Other ignition sources / strengths should be studied and incorporated into the test method.
4. There is need for development of alternative test method(s) or procedure with existing test method to investigate radiative and electrical high energy arc ignition sources.
5. More data on ignition potential based on material type and storage arrangement, in different O_2 concentrations, would be helpful.
6. Further research on required oxygen concentration is needed

5.2.2 Research/Development needs with respect to ORS Operation and the specific application

1. Research into failure rates / reliability of ORS components is needed.
2. There needs to be a failure mode analysis of ORS to determine appropriate industry standard Inspection, Test and Maintenance (ITM) programs as well as a failure analysis of the components in order to determine relevant requirements for listing of systems and components (required indications, alarms etc.).
3. There needs to be a failure mode analysis of ORS.
4. A development of acceptance (compliance / commissioning) testing procedures for ORS is needed
5. There needs to be an industry-standard calculation method for ORSs and required documentation for plan review as was explained in the previous tasks.
6. Information should be gathered on operational costs for ORSs to aid in benefit-cost decisions.
7. There needs to be research into how leakages in buildings, particularly those targeted for ORS application, increase over time.
8. Research is needed to gain an understanding of how tightness tests can be done for large volume spaces.
9. ORS reliability and availability are important, and research on back-up system needs should be conducted.
10. Interaction of ORS and active fire protection, including smoke and heating venting systems, and sprinkler systems, would be beneficial.
11. The effect of moving a commodity into an ORS-protected space, that has been previously been stored at ambient oxygen conditions, should be investigated.

5.2.3 Research/Development needs Associated with Planned & Emergency Interventions in ORS-Protected Spaces

More understanding and assessment / modelling of manual firefighting interventions, such as smoke and heat venting, opening doors for firefighter access, etc., on ORS effectiveness and reliability is needed.

5.2.4 Other Research/Development Gaps and needs

1. Level of oxygen acceptable with respect to medical conditions of people inside an ORS environment
2. Knowledge and data (e.g. experimental data) on the fire protection abilities of ORS, i.e., how much is fire spread reduced when an ignition occurs, despite the reduced oxygen level. This is especially important if oxygen levels are chosen which still allow ignition.

6 References and Bibliography

The references in this list are only related to the ones which are specific for this report. A very good overview of bibliography is given in the NFPA report "Review of Oxygen Reduction Systems for Warehouse Storage Applications" by Van Hees, Barton, Nilsson and Meachem (Van Hees et al. 2018).

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Annex A - Acronyms

ORS: Oxygen reduction system

Brandforsk: Swedish Board for Fire Research

CACC: Controlled atmosphere cone calorimeter

CFD: Computational Fluid Dynamics

FDS: Fire Dynamics Simulator software programme

FPA: Fire propagations apparatus

FSE: Fire Safety Engineering

HRR: Heat release rate

ISO: International Standardisation Organisation

LOC: limiting oxygen concentration value

QRA: Qualitative Risk Analysis

SFPE: Society for fire protections engineers.

Annex B Detailed Test results Cone Calorimeter Particle board

In this annex the results are presented from the work conducted by Erik Linnå and Viktor Wahlström in their thesis work. Data such as HRR, mass loss, mass loss rate, and production rate of CO and CO2 are given for the different set-ups. Test set-ups 1-6 were tested in triplicate. Each replicate is called A, B and C. Test set-ups 7 and 8 were only tested once due to technical problems of the instrument.

Set-up 1

In this paragraph the results are presented for Set-up 1, which is the standard cone calorimeter with a heat flux level 50 kW/m^2.

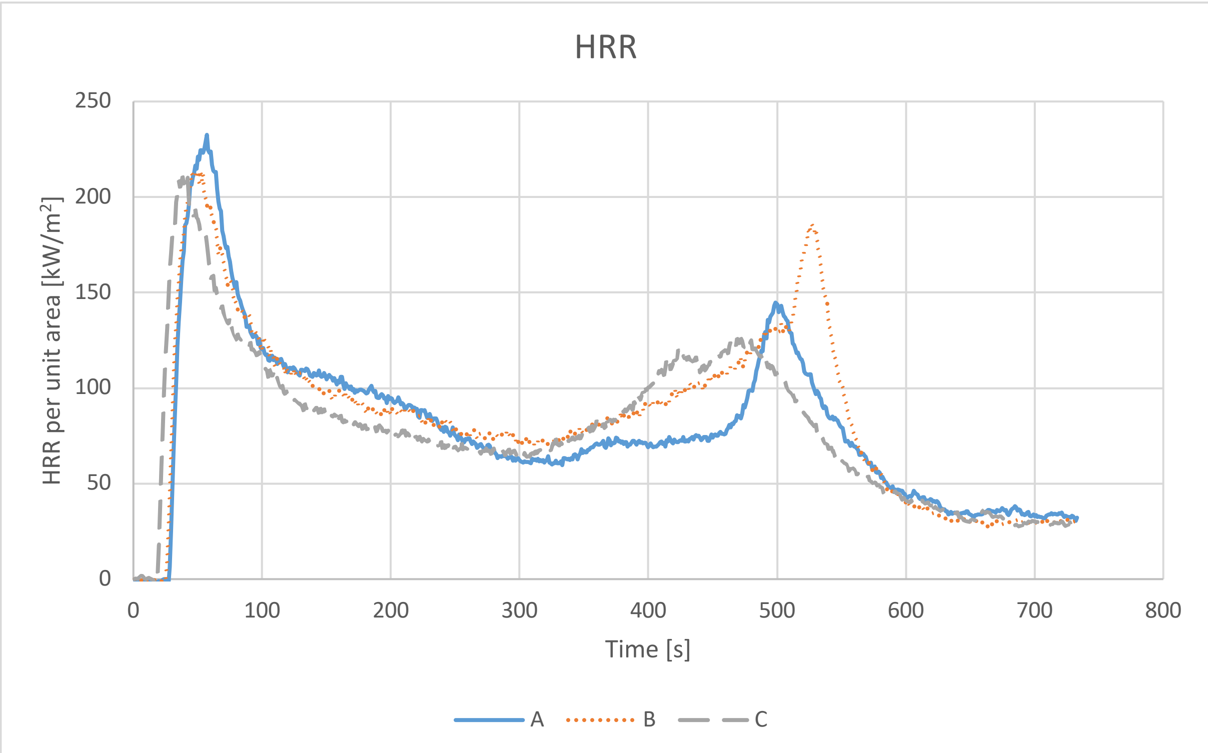

Figure 19 HRR per unit area for Set-up 1.

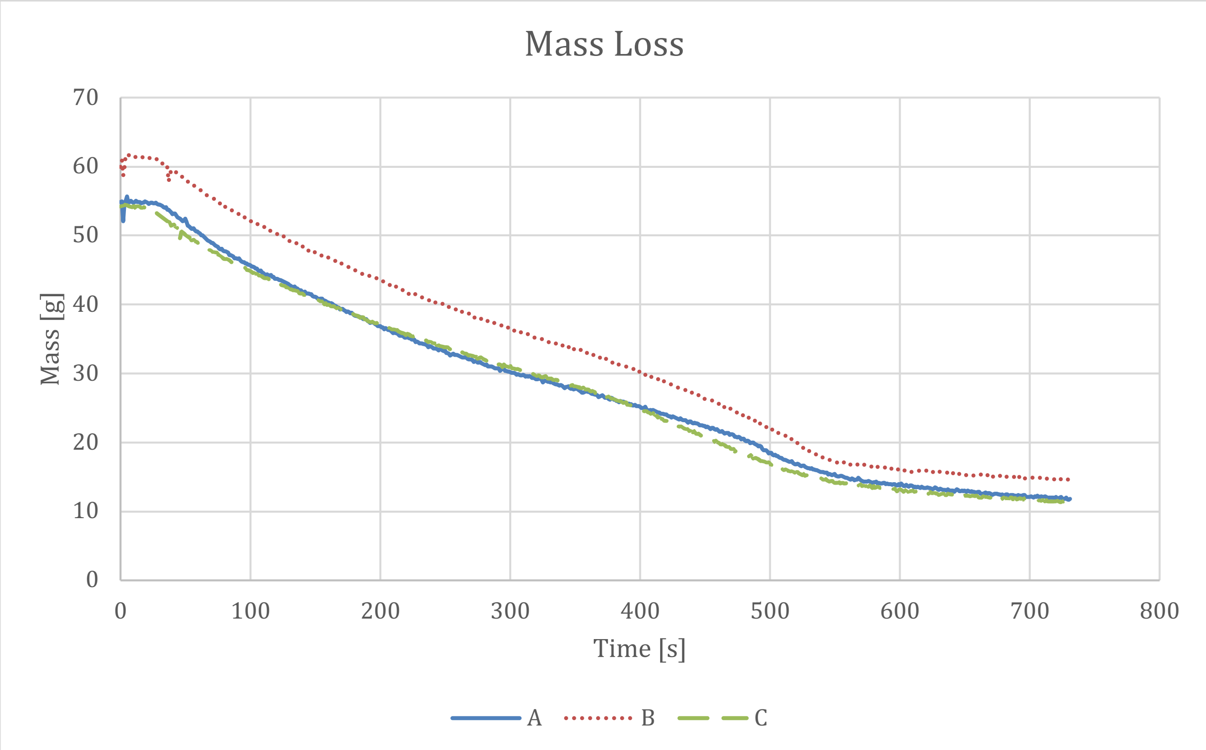

Figure 20 Mass Loss for Set-up 1.

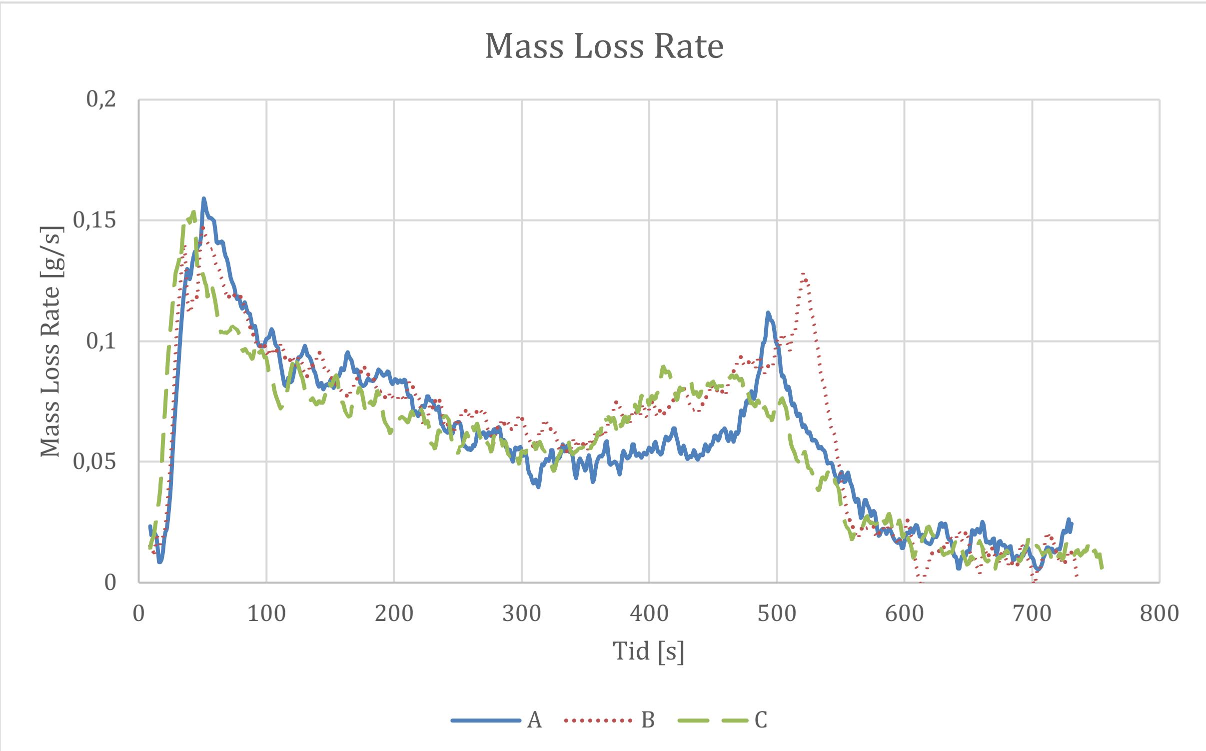

Figure 21 Mass loss rate for Set-up 1.

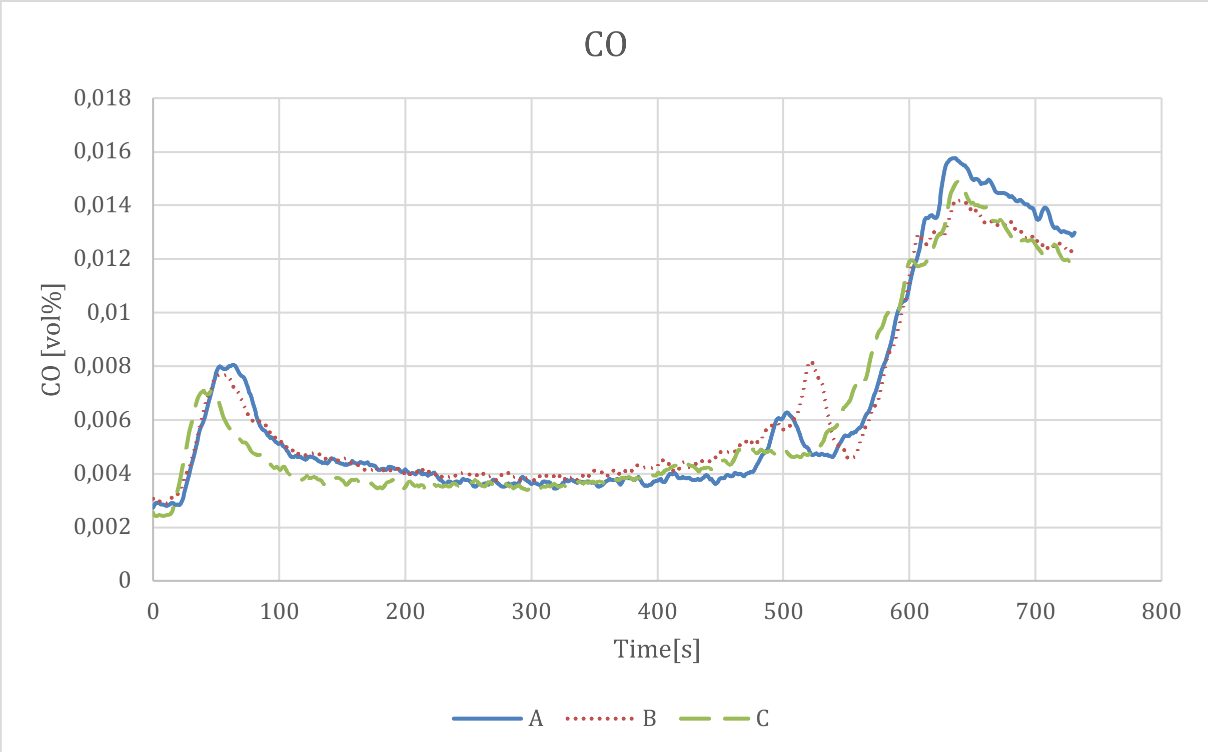

Figure 22 CO production for Set-up 1.

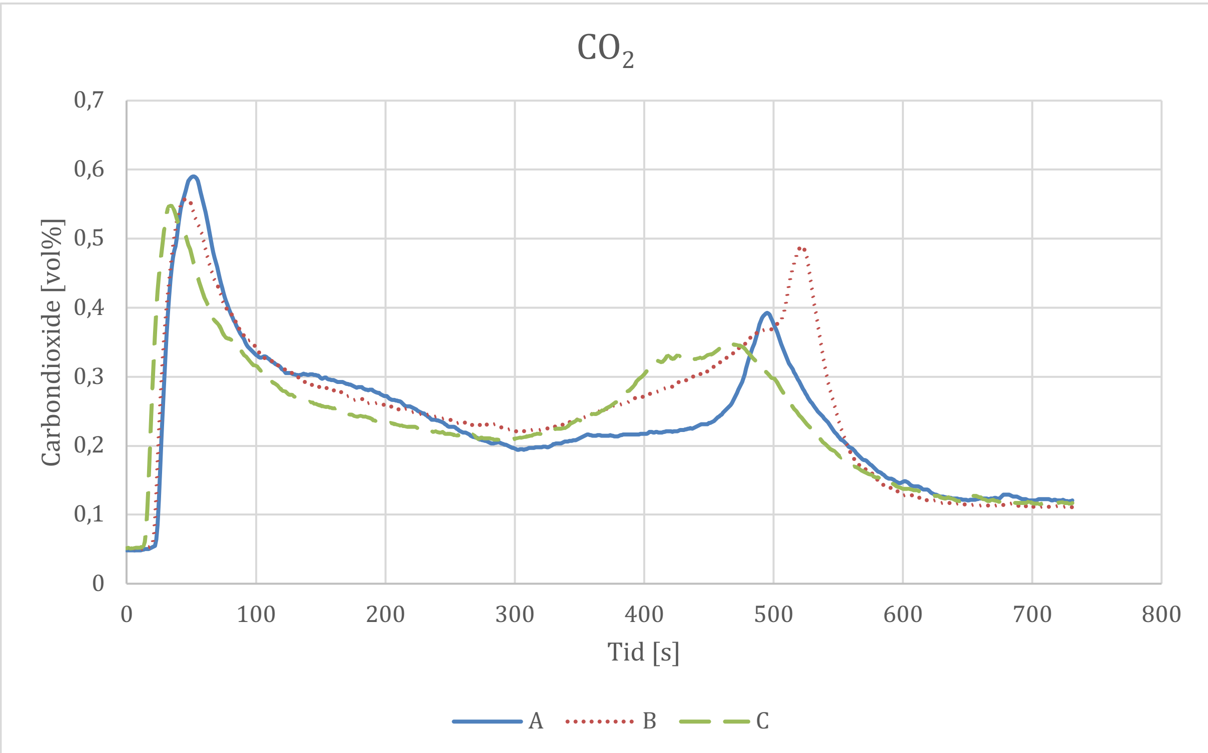

Figure 23 CO_2 production for Set-up 1.

Set-up 2

In this paragraph the results are presented for Set-up 2, which is the controlled atmosphere cone calorimeter with a heat flux level 50 kW/m². The oxygen level is 20,95 %.

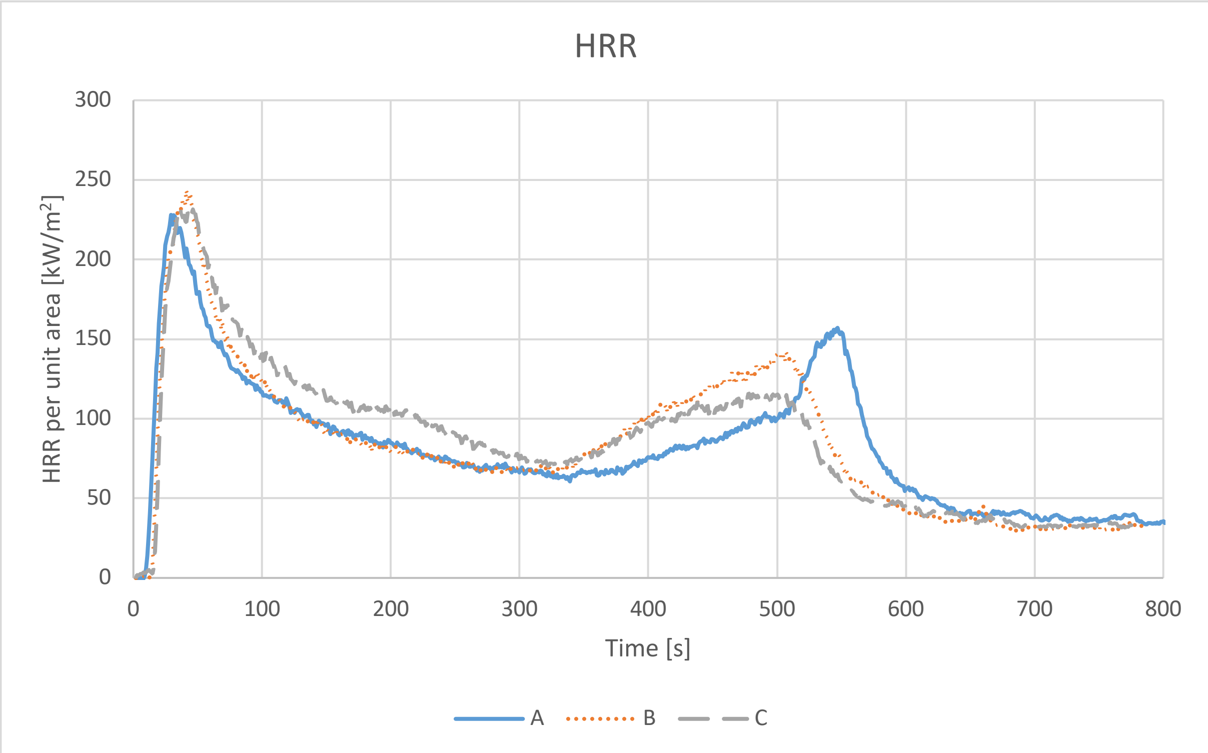

Figure 24 HRR per unit area for Set-up 2.

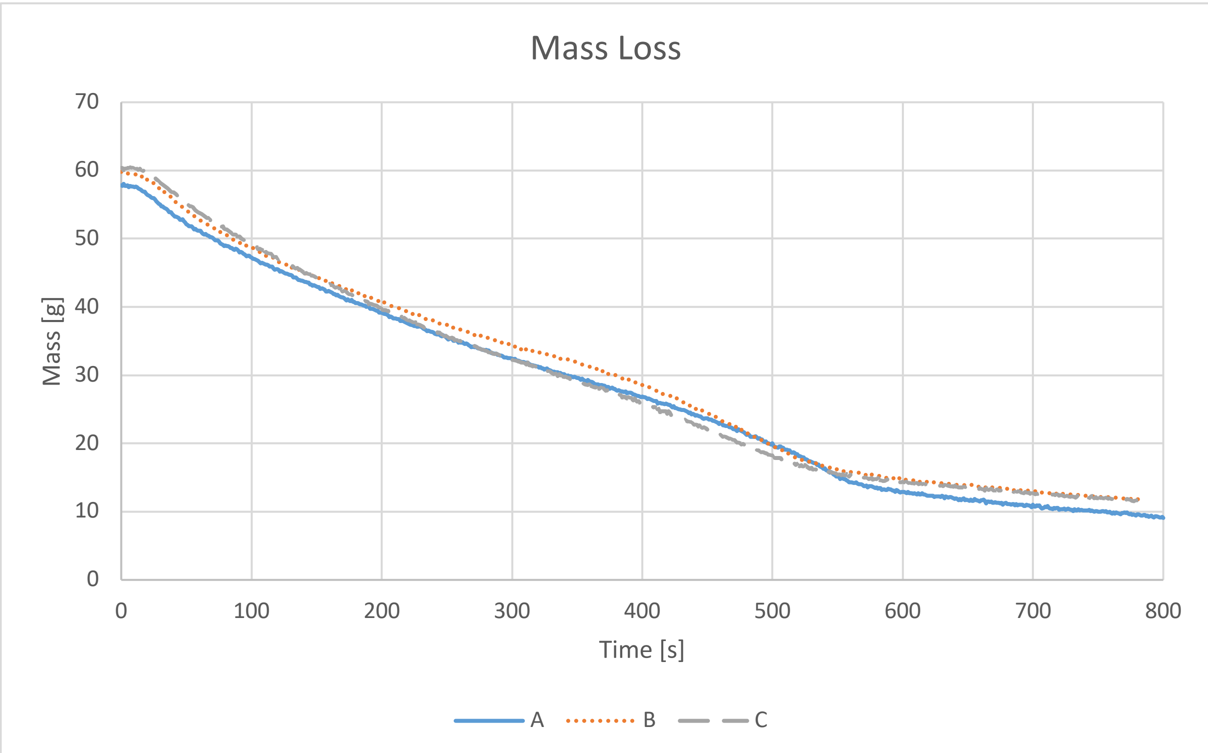

Figure 25 Mass Loss for Set-up 2.

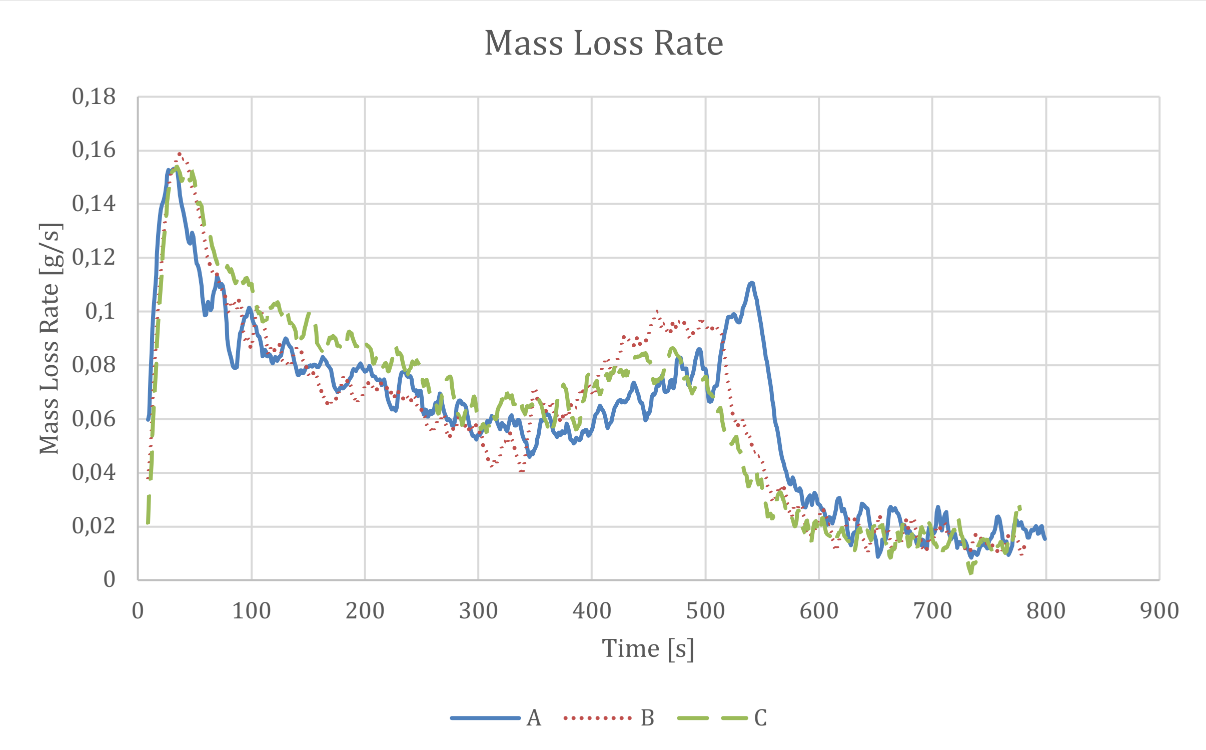

Figure 26 Mass loss rate for Set-up 2.

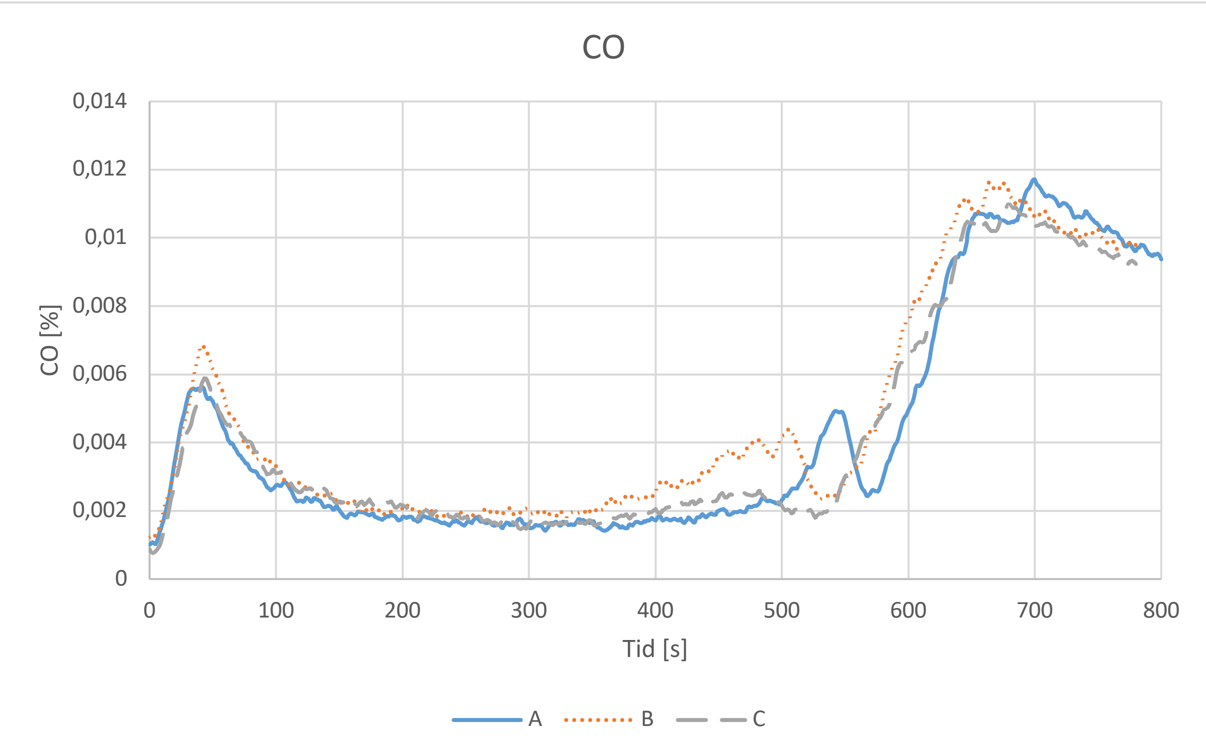

Figure 27 CO production for Set-up 2.

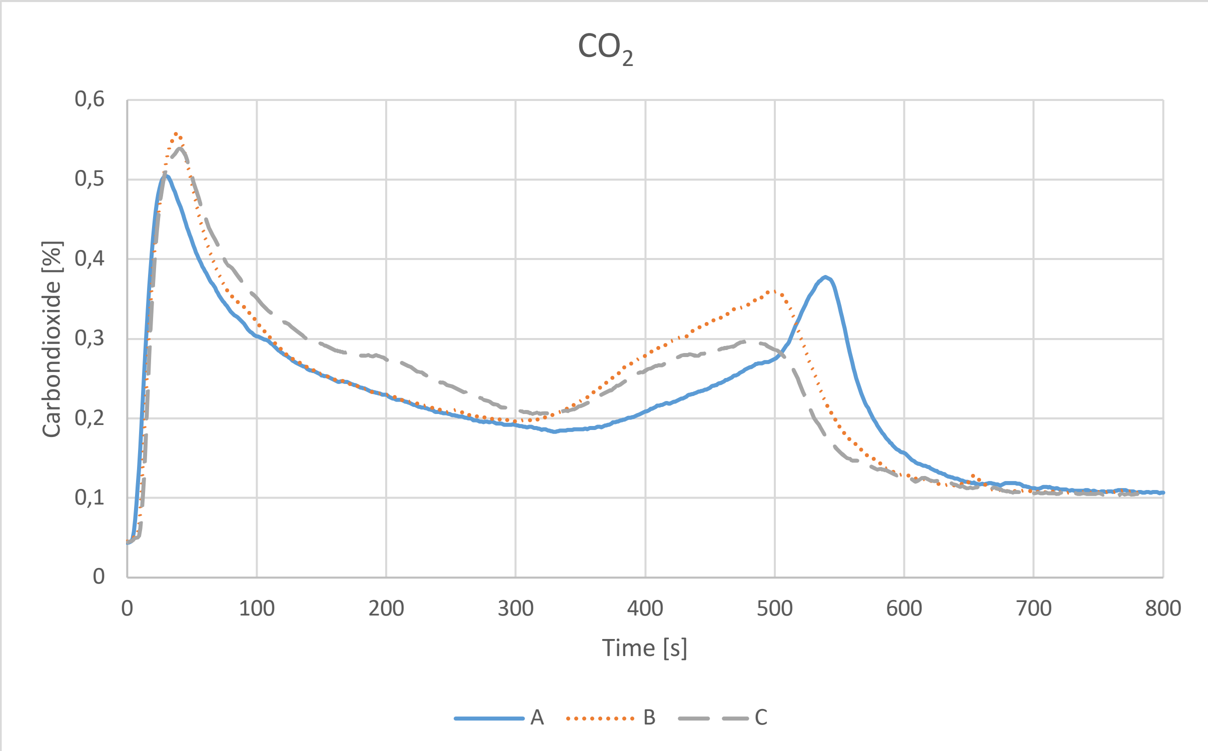

Figure 28 CO_2 production for Set-up 2.

Set-up 3

In this paragraph the results are presented for Set-up 3, which is the controlled atmosphere cone calorimeter with a heat flux level 50 kW/m^2. The oxygen level is 15 %.

Figure 29 HRR per unit area for Set-up 3.

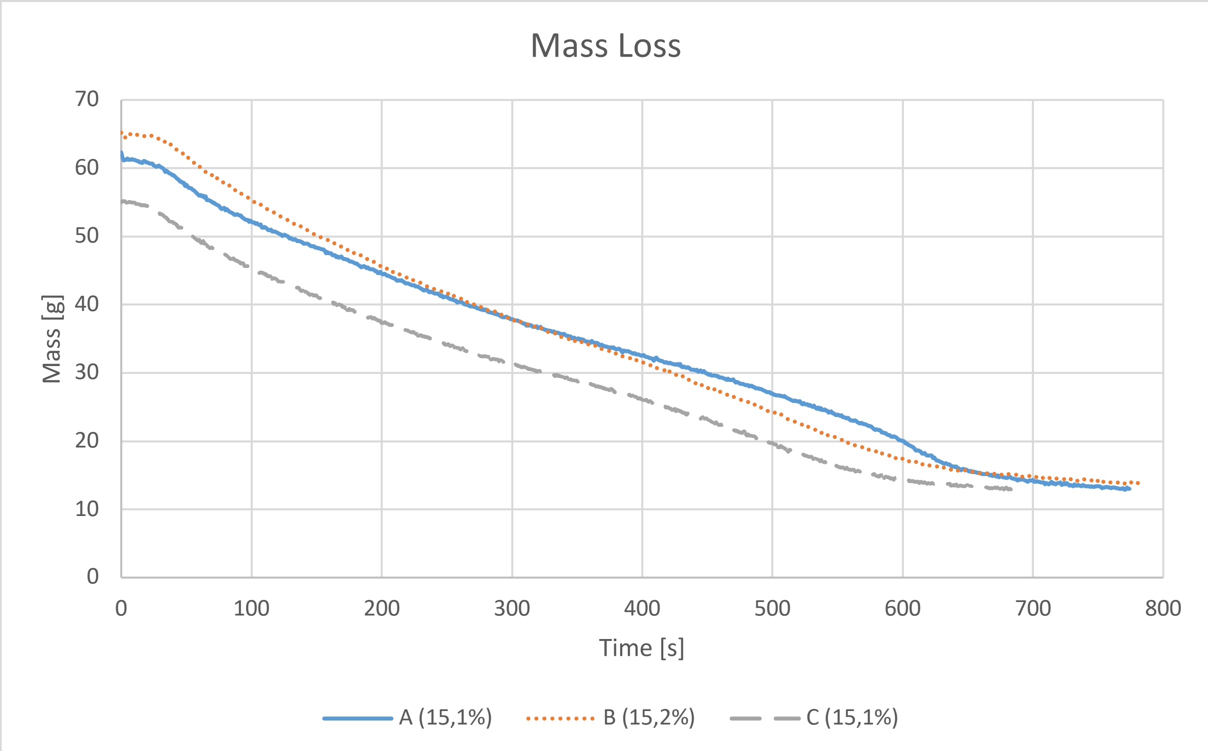

Figure 30 Mass Loss for Set-up 3.

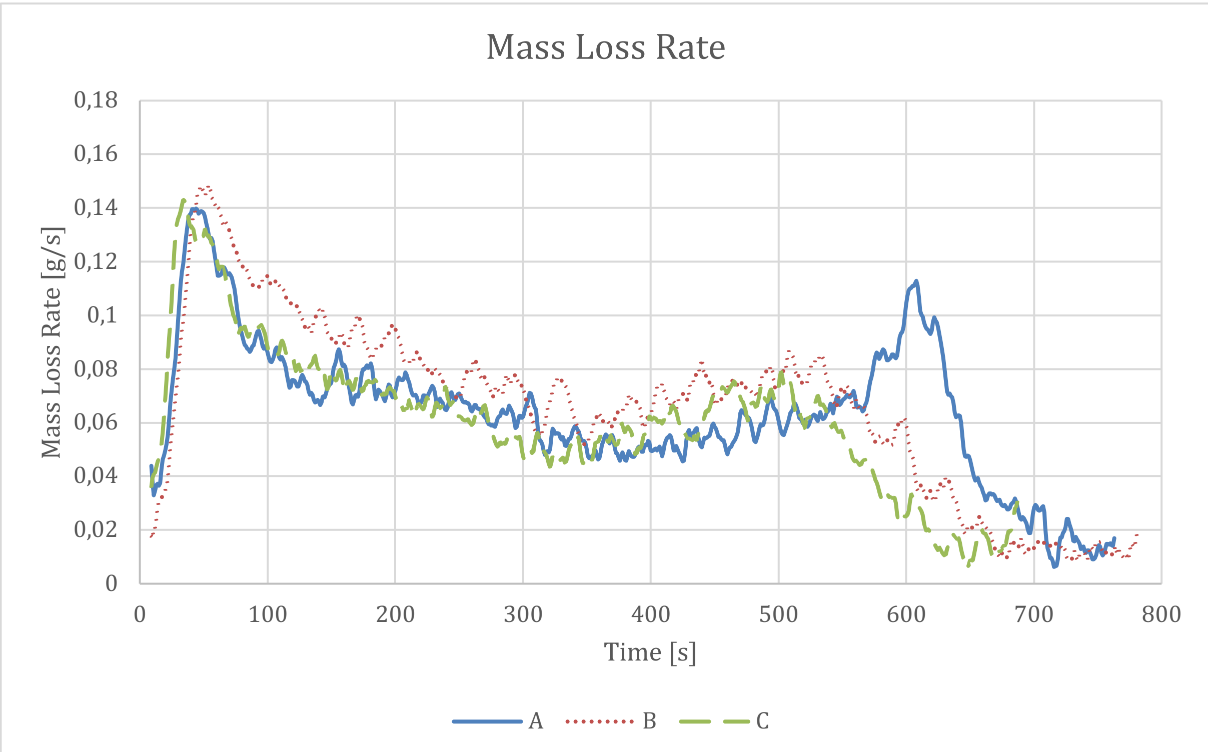

Figure 31. Mass loss rate for Set-up 3.

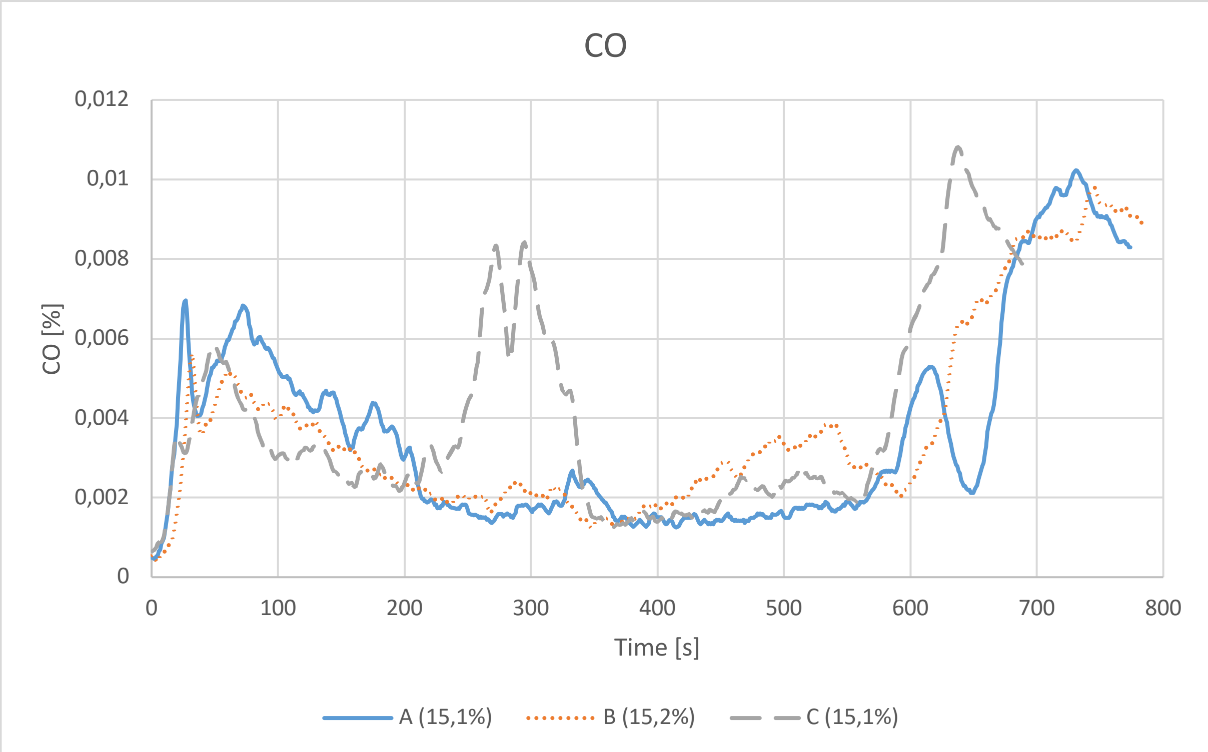

Figure 32 CO production for Set-up 3.

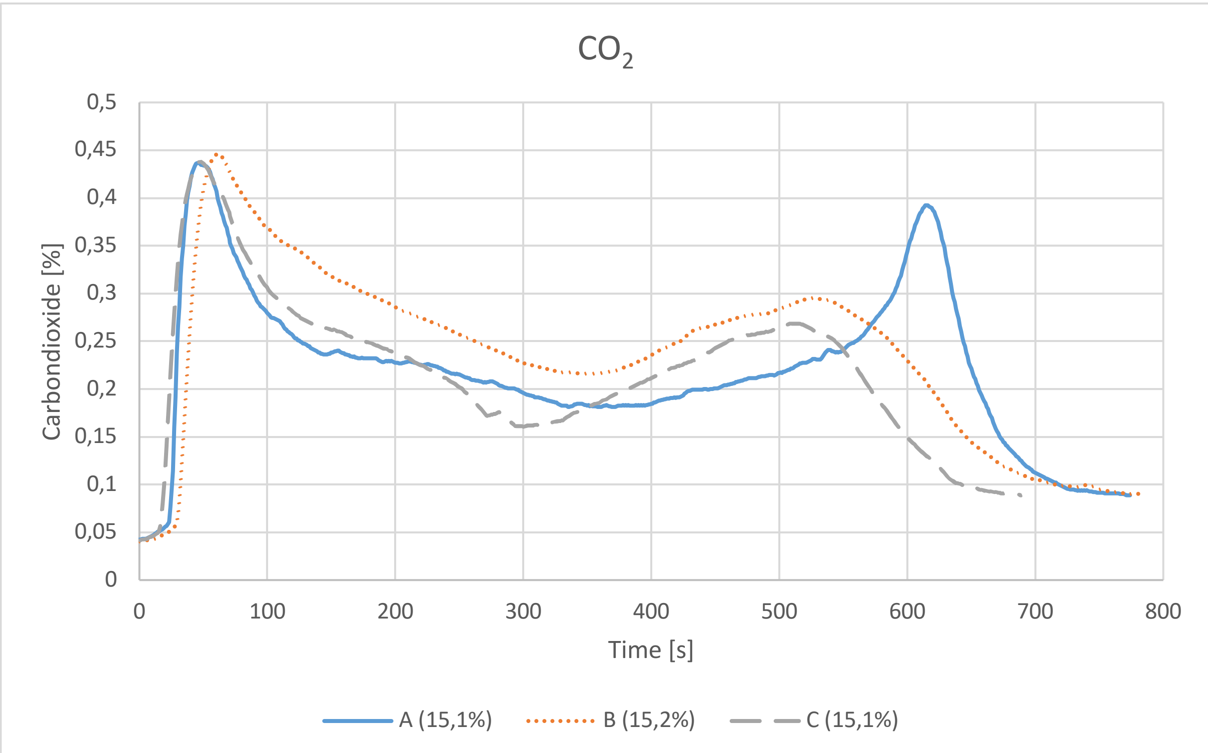

Figure 33 CO_2 production for Set-up 3.

Set-up 4

In this paragraph the results are presented for Set-up 4, which is the controlled atmosphere cone calorimeter with a heat flux level 50 kW/m^2. The oxygen level is 20,95 %. On top of chamber a 30 cm high chimney is installed.

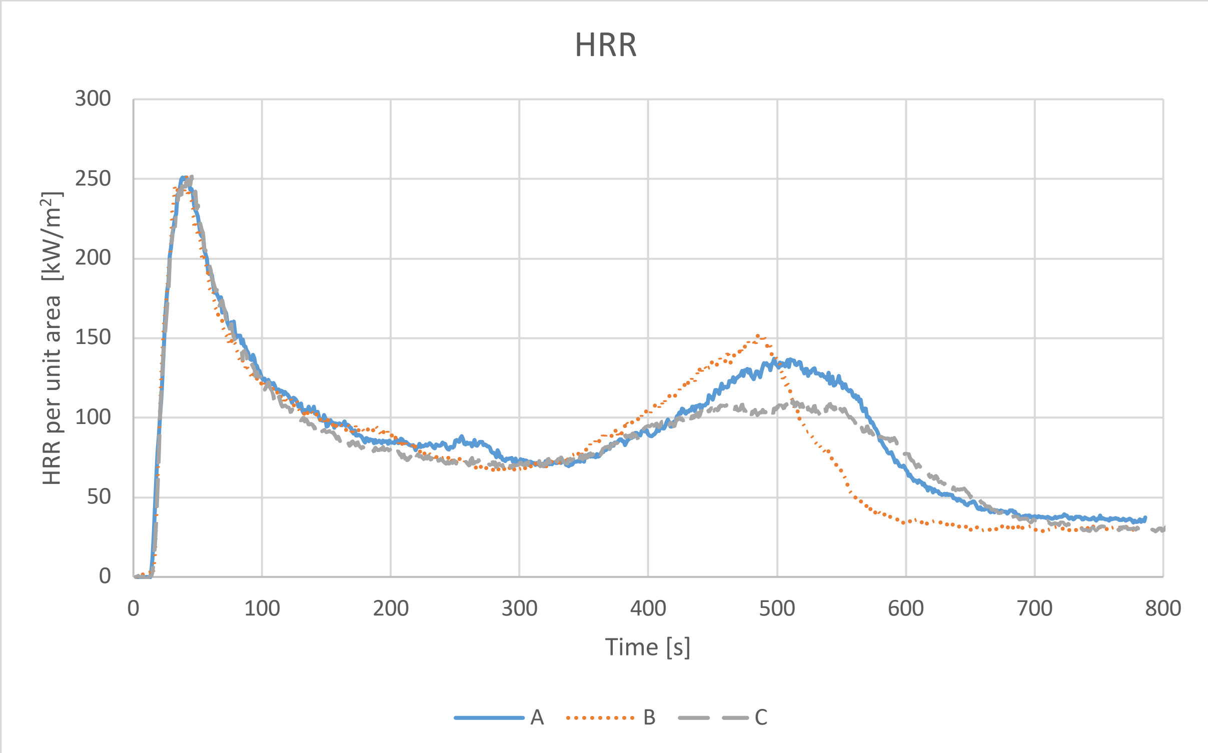

Figure 34 HRR per unit area for Set-up 4.

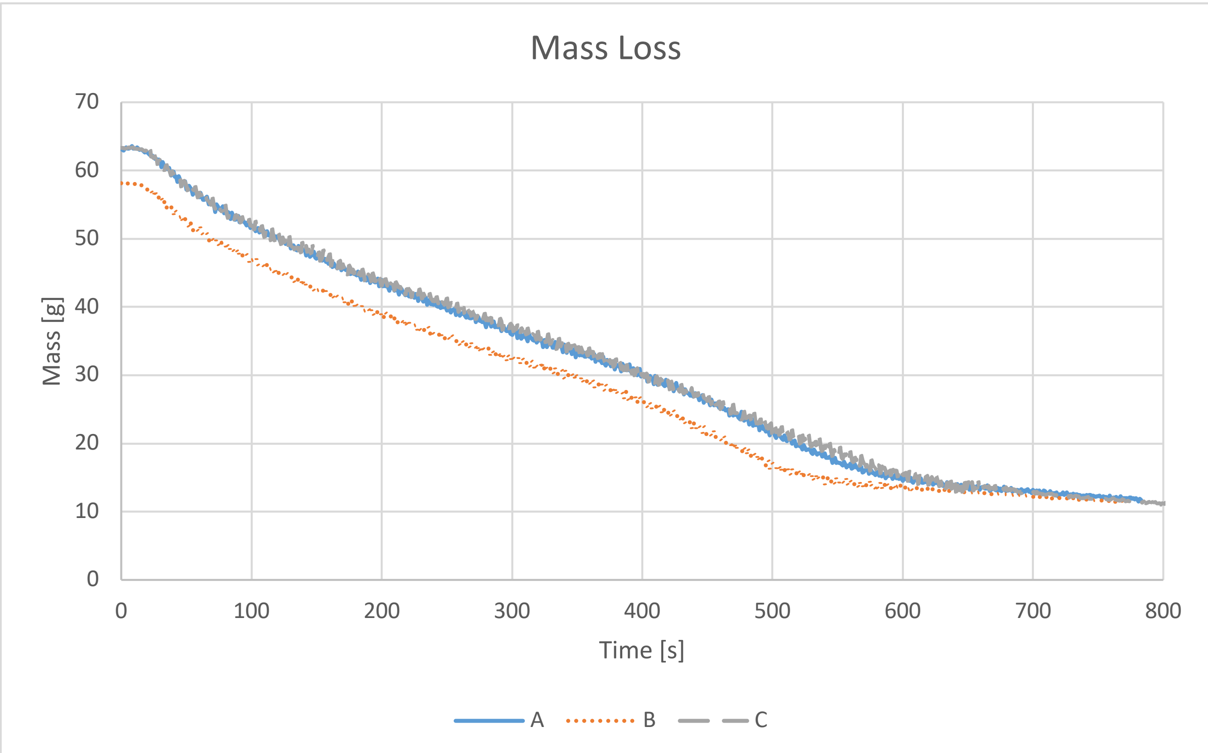

Figure 35 Mass Loss for Set-up 4.

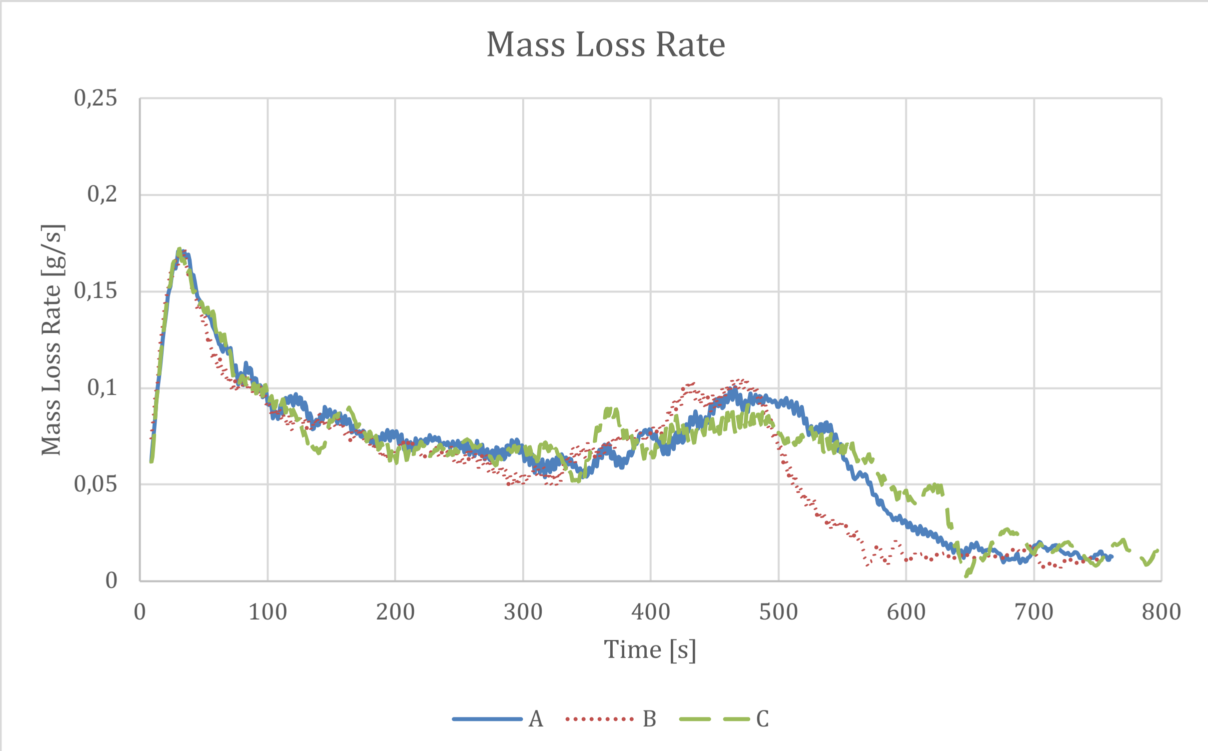

Figure 36 Mass loss rate for Set-up 4.

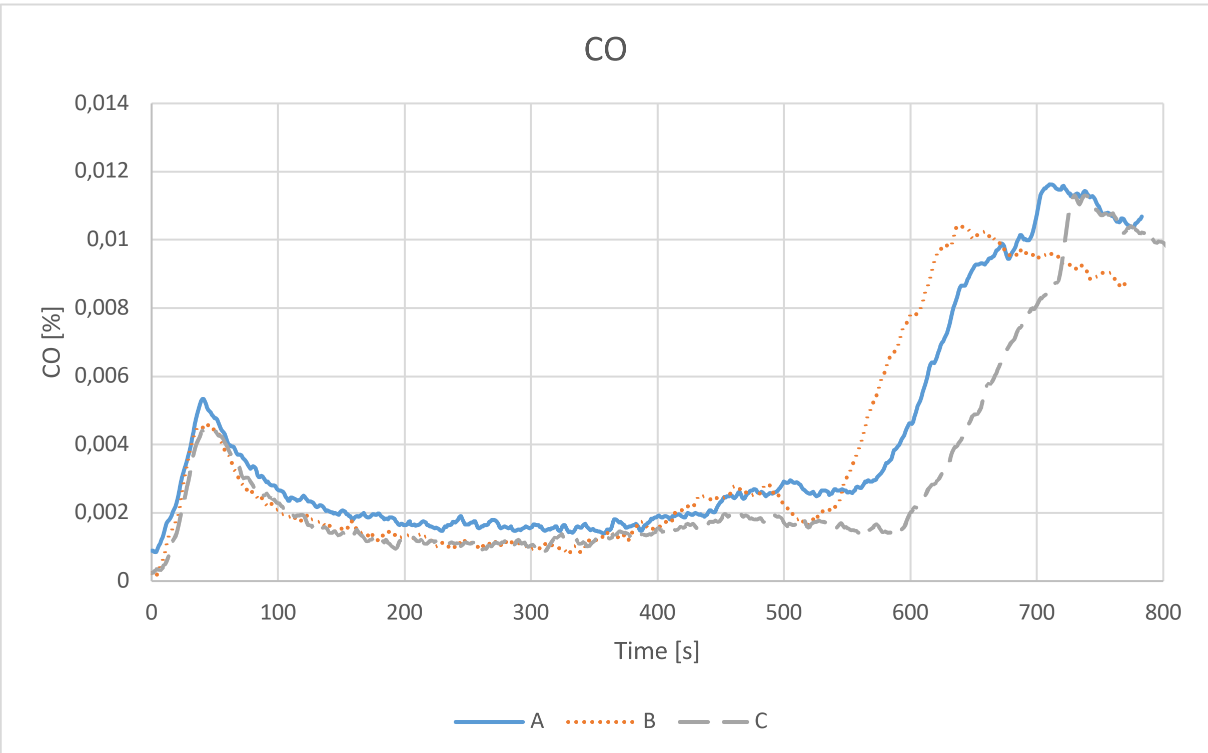

Figure 37 CO production for Set-up 4.

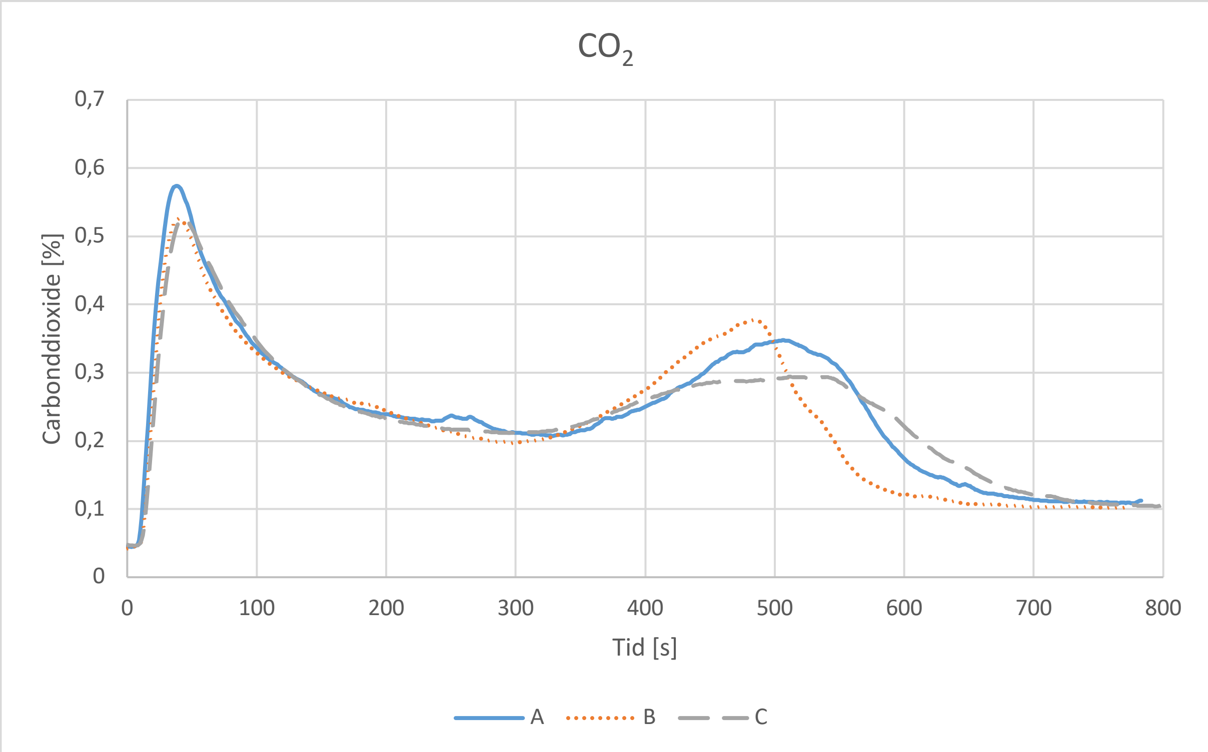

Figure 38 CO_2 production for Set-up 4.

Set-up 5

In this paragraph the results are presented for Set-up 5, which is the controlled atmosphere cone calorimeter with a heat flux level 50 kW/m^2. The oxygen level is 15 %. On top of chamber a 30 cm high chimney is installed.

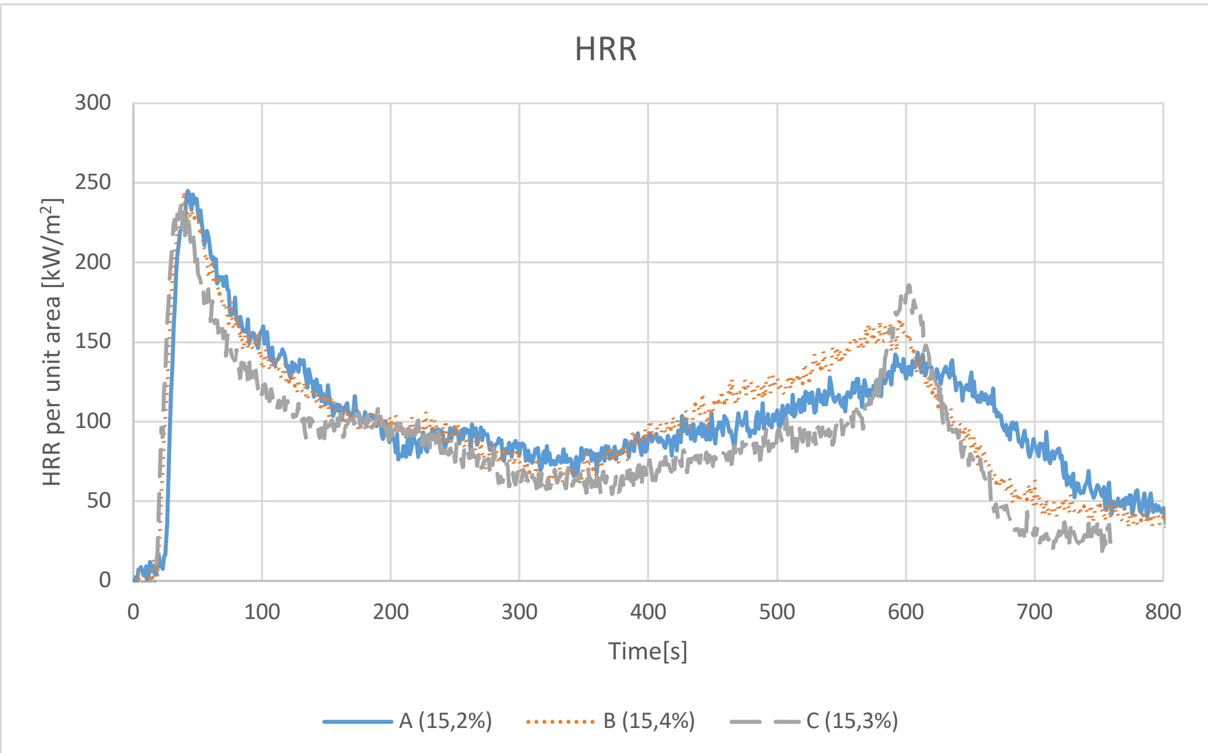

Figure 39 HRR per unit area for Set-up 5.

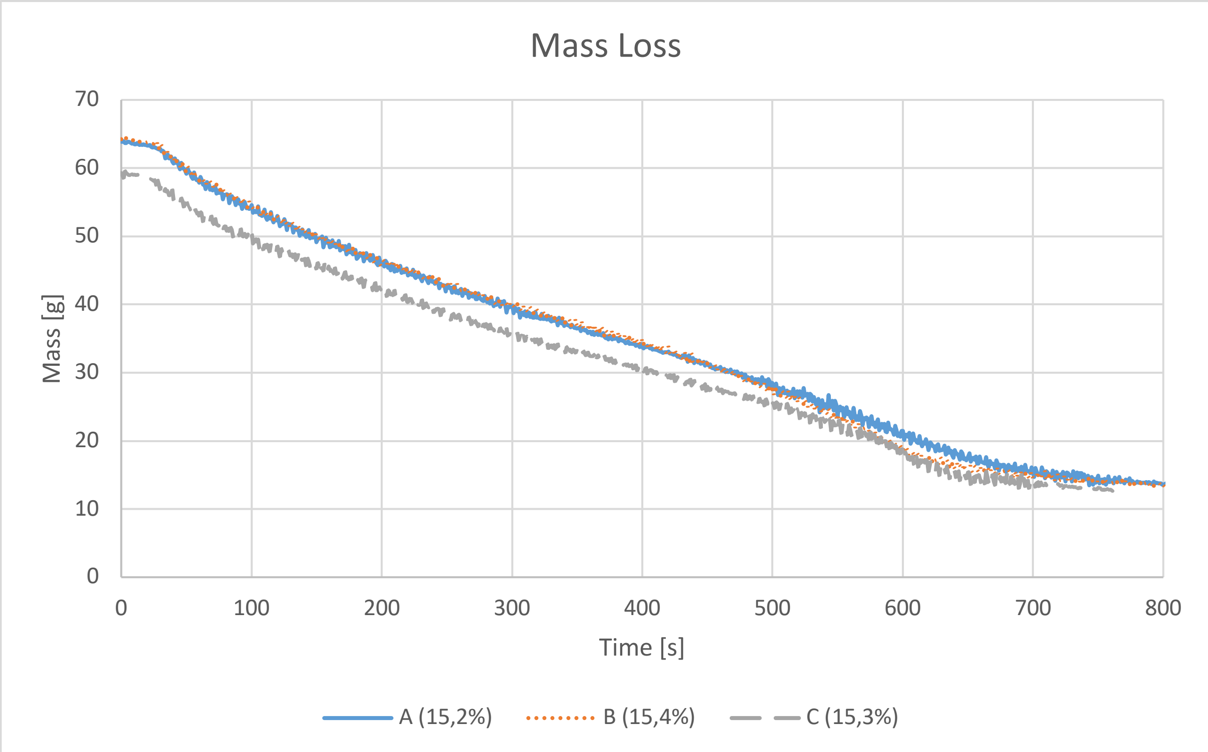

Figure 40. Mass Loss for Set-up 5.

Figure 41 Mass loss rate for Set-up 5.

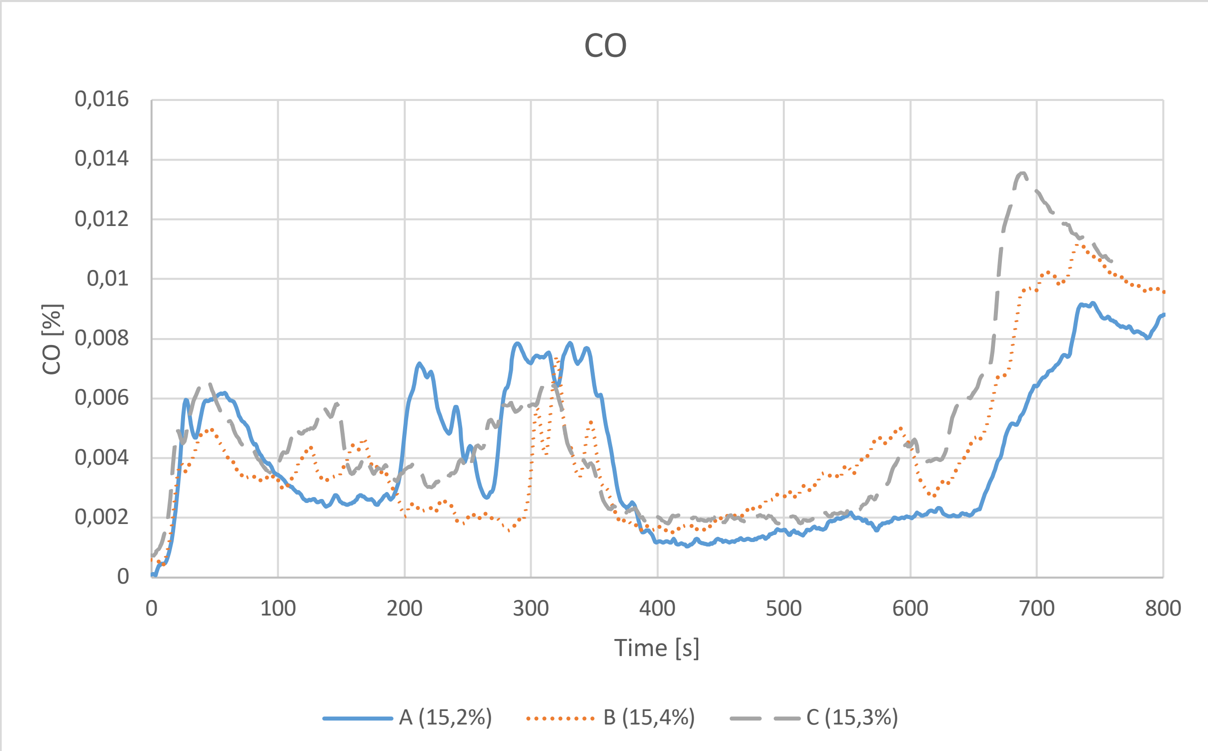

Figure 42 CO production for Set-up 5.

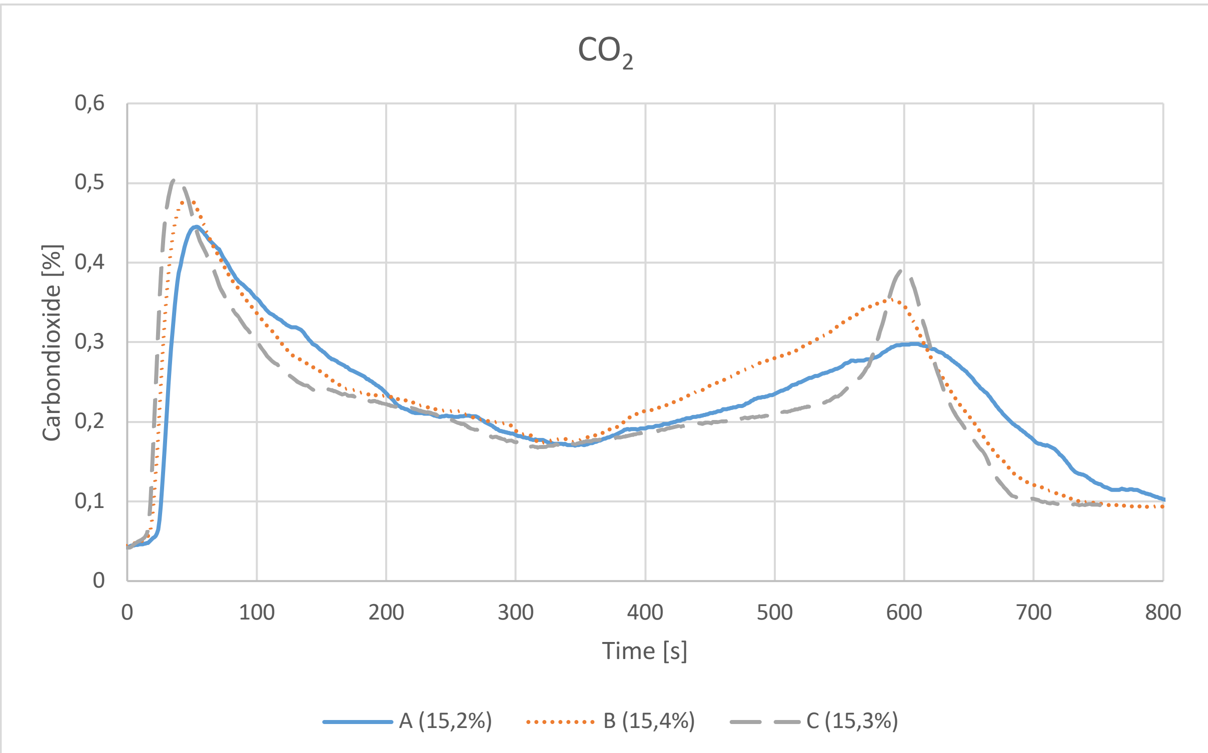

Figure 43 CO_2 production for Set-up 5.

Set-up 6

In this paragraph the results are presented for Set-up 6, which is the standard cone calorimeter with a heat flux level 25 kW/m^2.

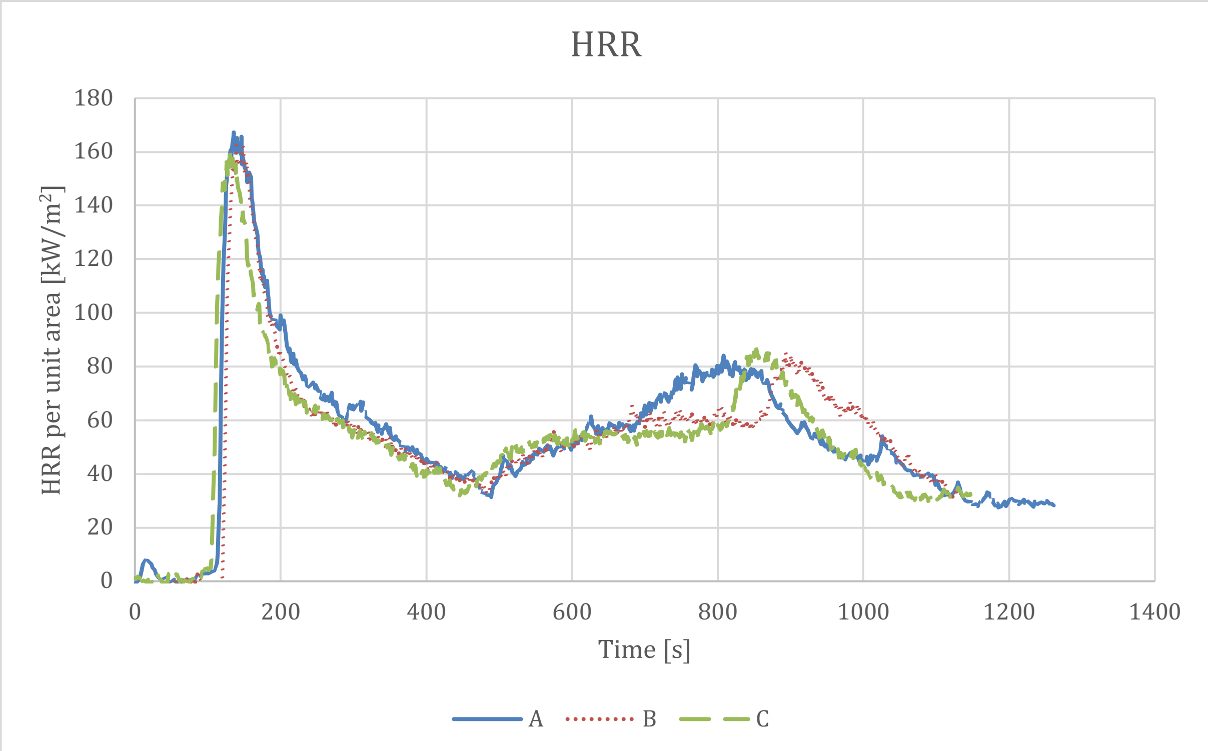

Figure 44 HRR per unit area for Set-up 6.

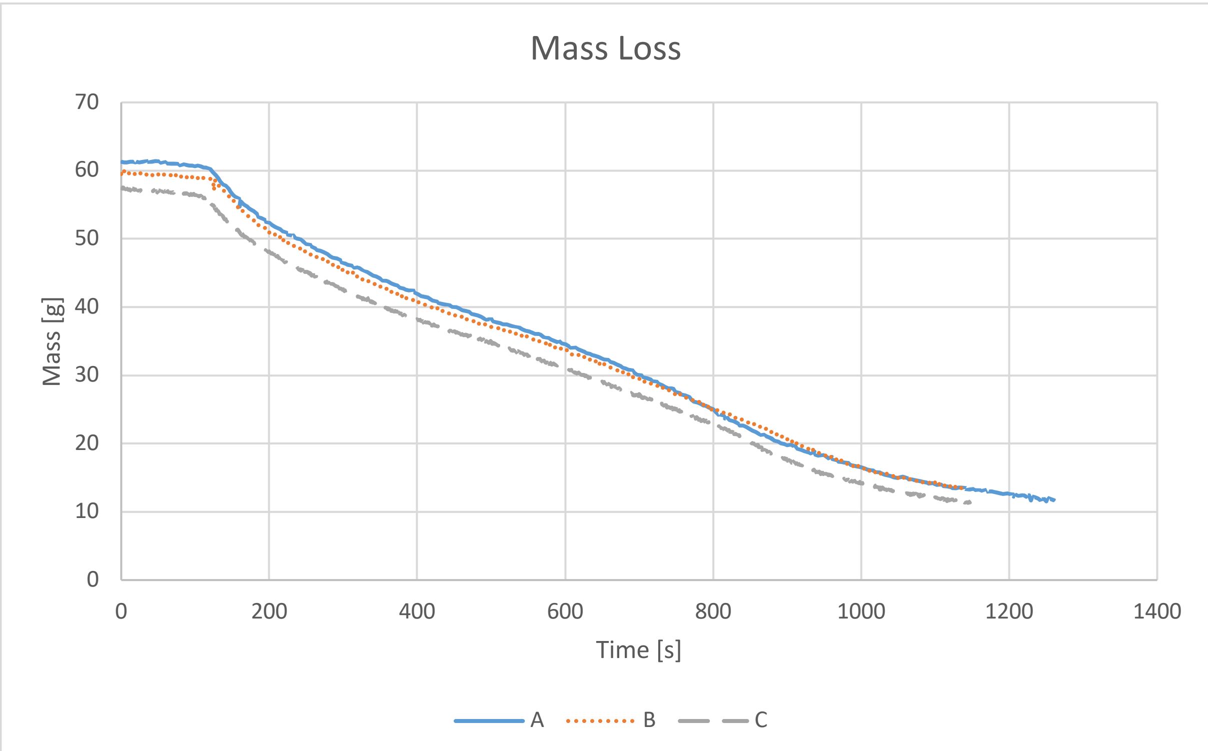

Figure 45 Mass Loss for Set-up 6.

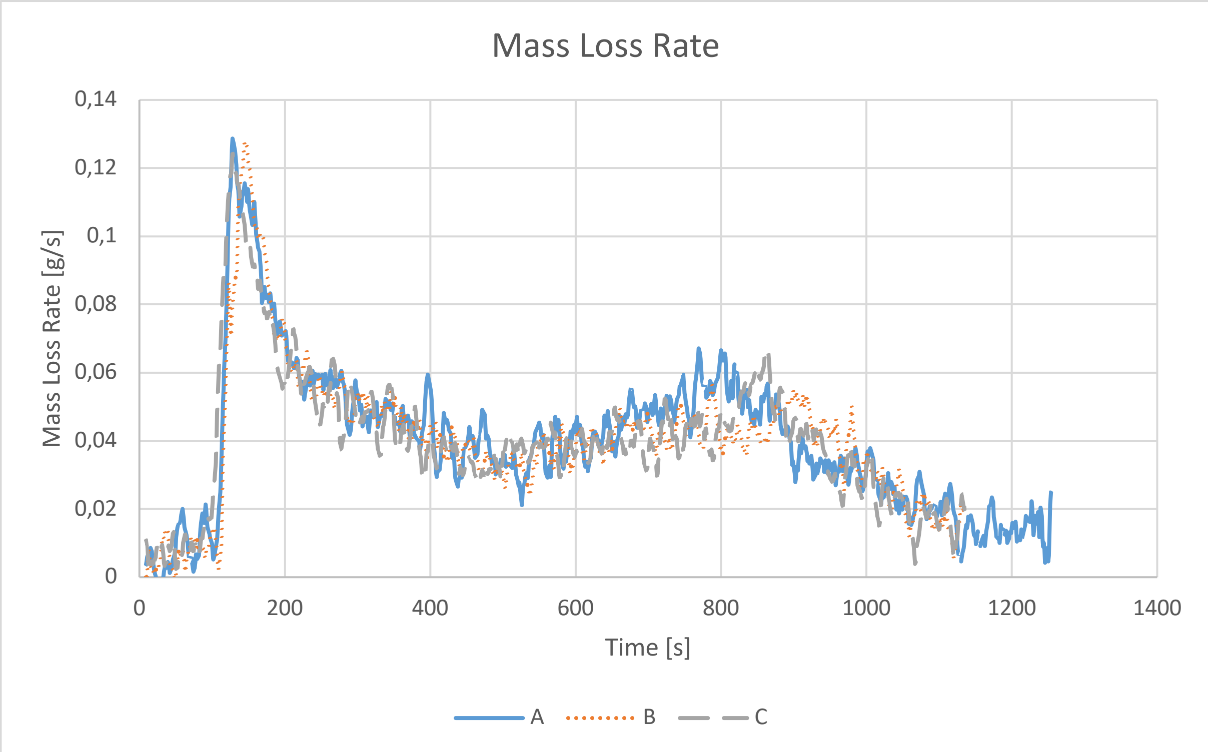

Figure 46 Mass loss rate for Set-up 6.

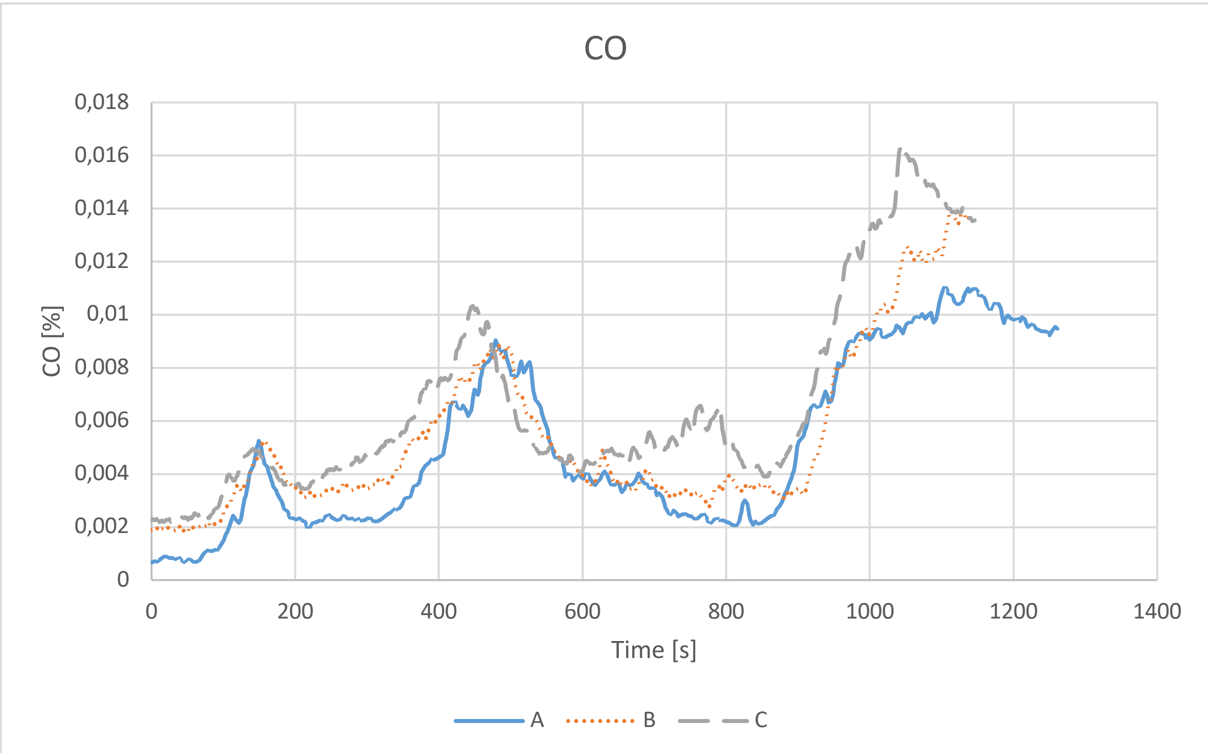

Figure 47 CO production for Set-up 6.

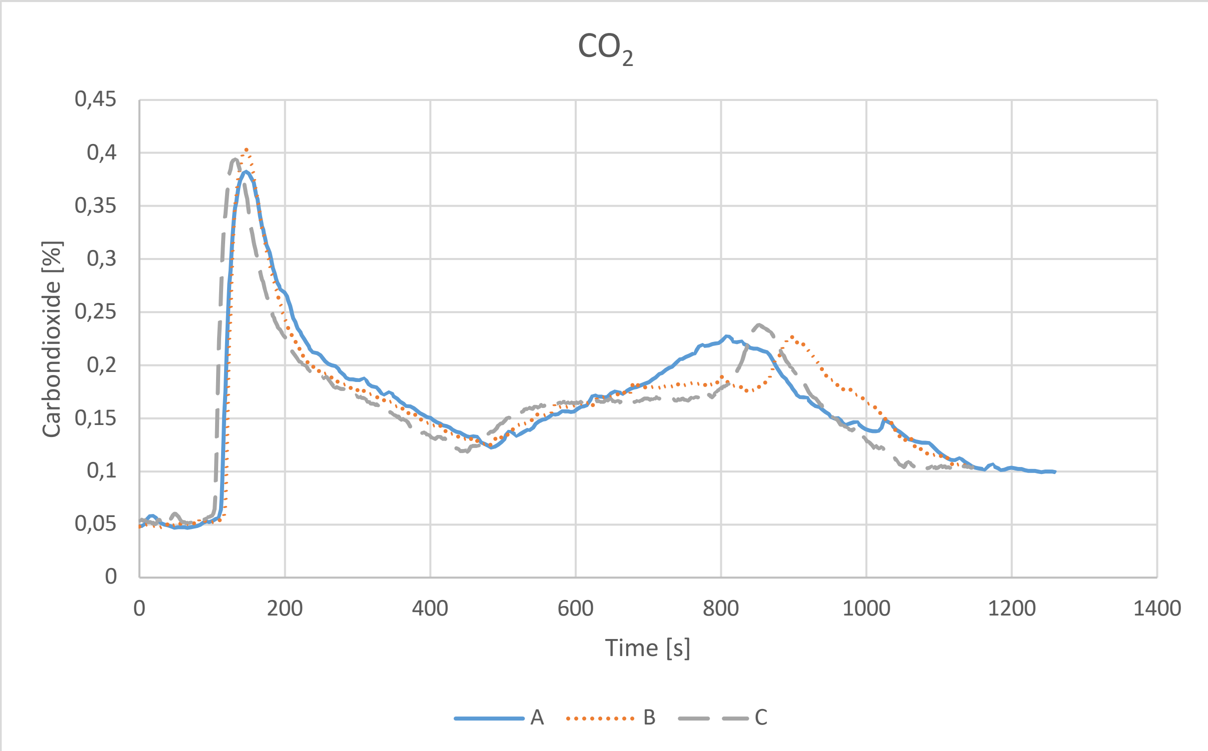

Figure 48 CO_2 production i Set-up 6.

Set-up 7
In this paragraph the results are presented for Set-up 7, which is the controlled atmosphere cone calorimeter with a heat flux level 25 kW/m^2. The oxygen level is 20,95 %. On top of chamber a 30 cm high chimney is installed.

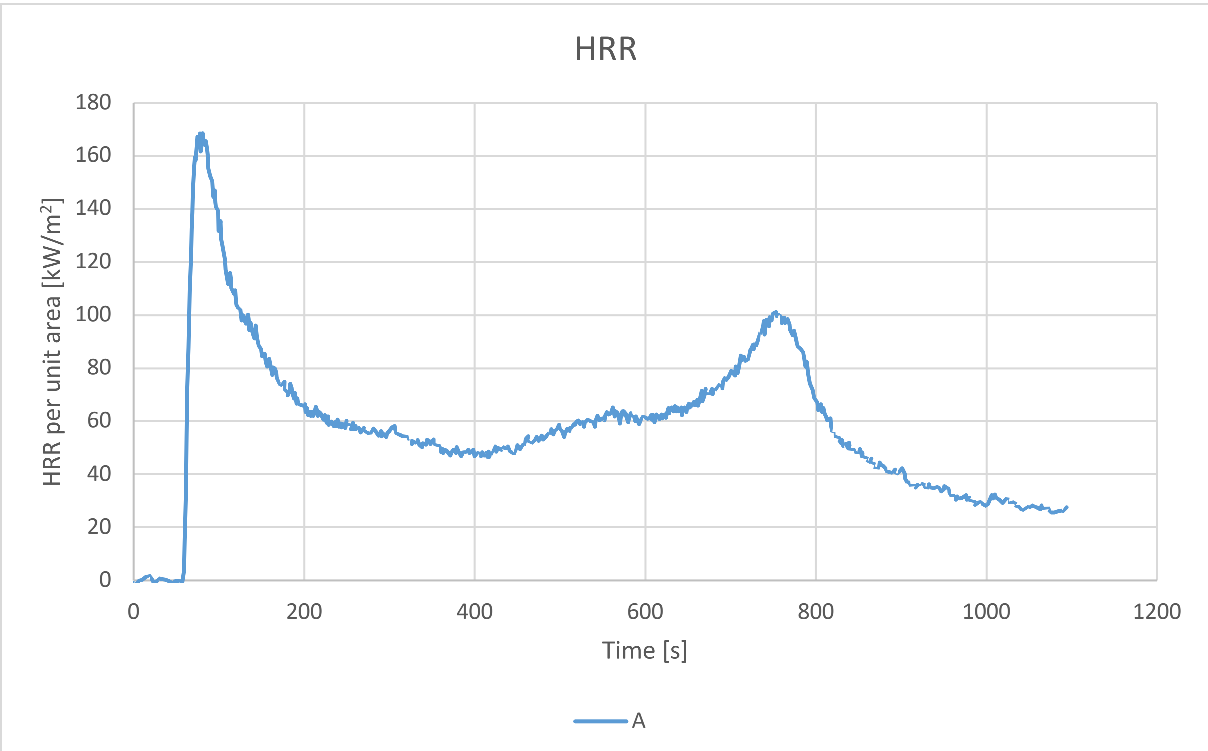

Figure 49. HRR per unit area for Set-up 7.

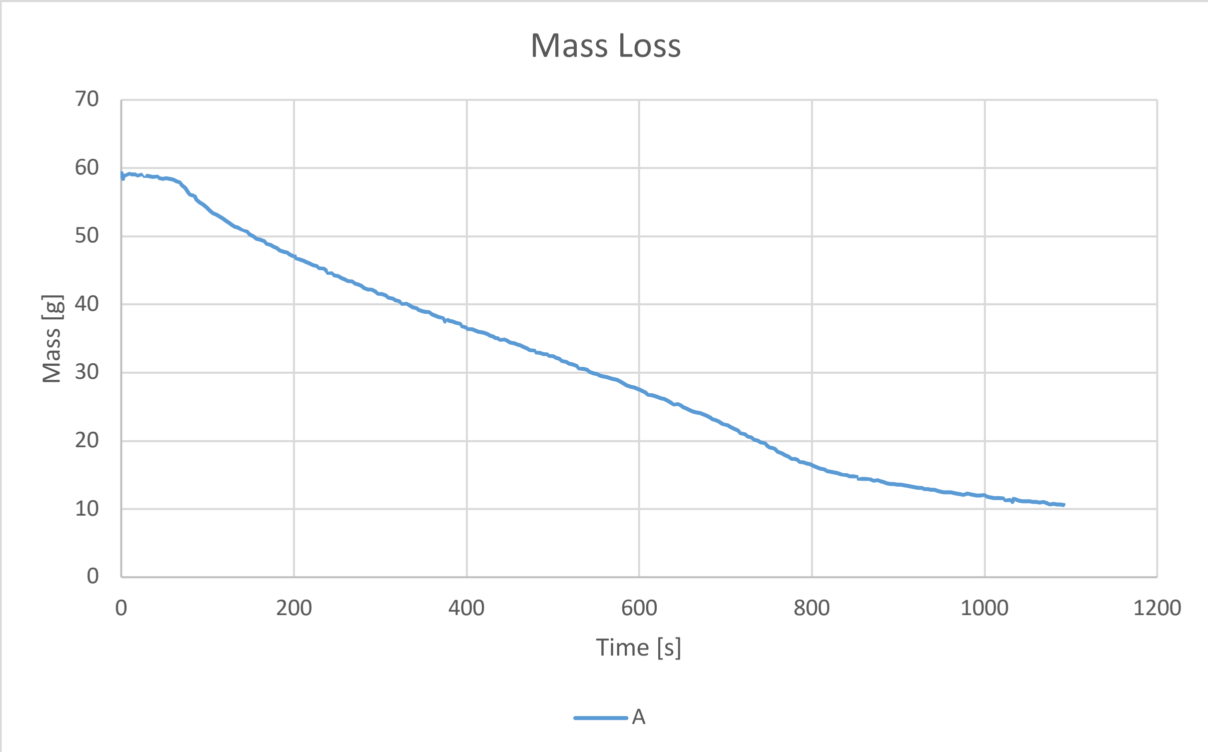

Figure 50. Mass Loss for Set-up 7.

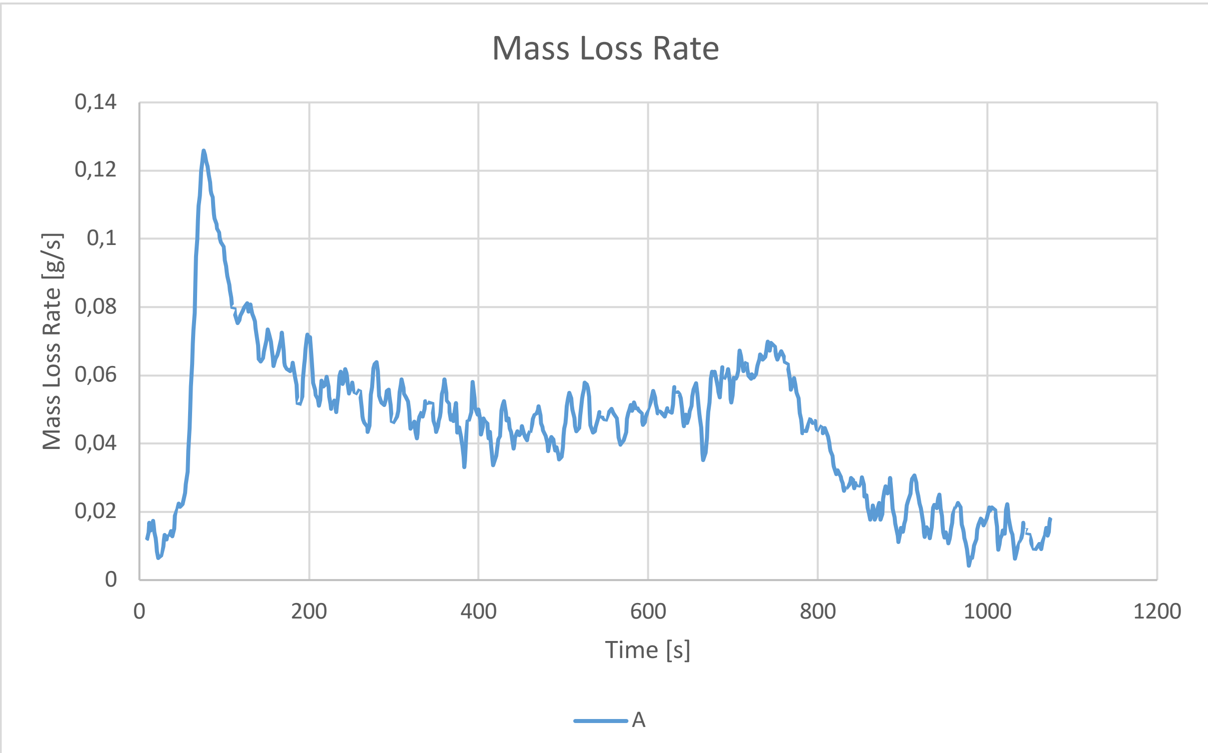

Figure 51 Mass loss rate for Set-up 7.

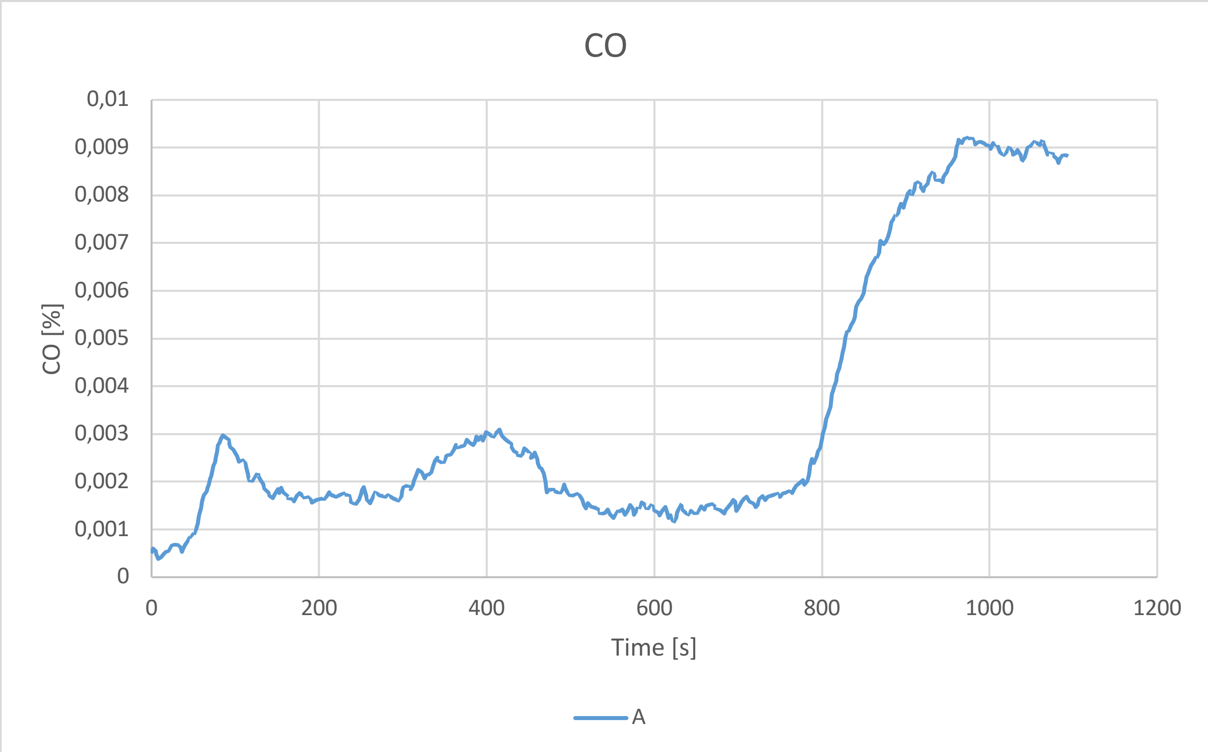

Figure 52 CO production for Set-up 7.

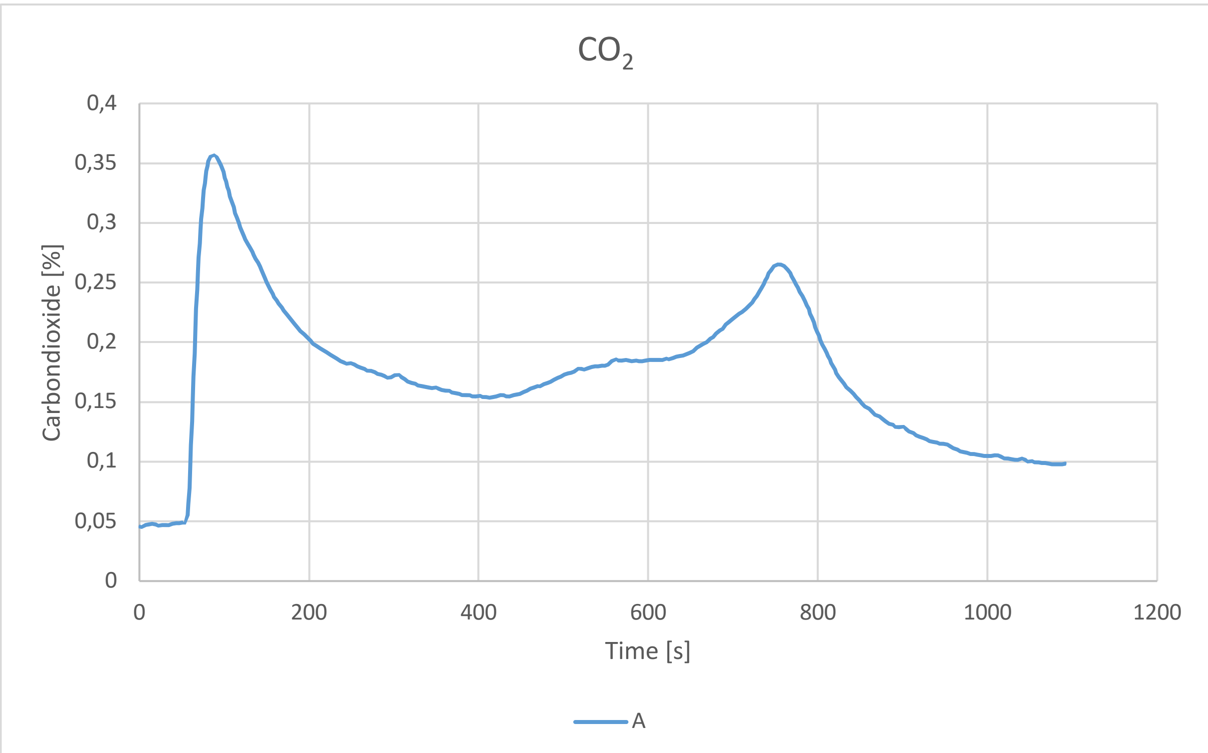

Figure 53 CO_2 production for Set-up 7.

Set-up 8

In this paragraph the results are presented for Set-up 8, which is the controlled atmosphere cone calorimeter with a heat flux level 25 kW/m^2. The oxygen level is 15,8 %. On top of chamber a 30 cm high chimney is installed.

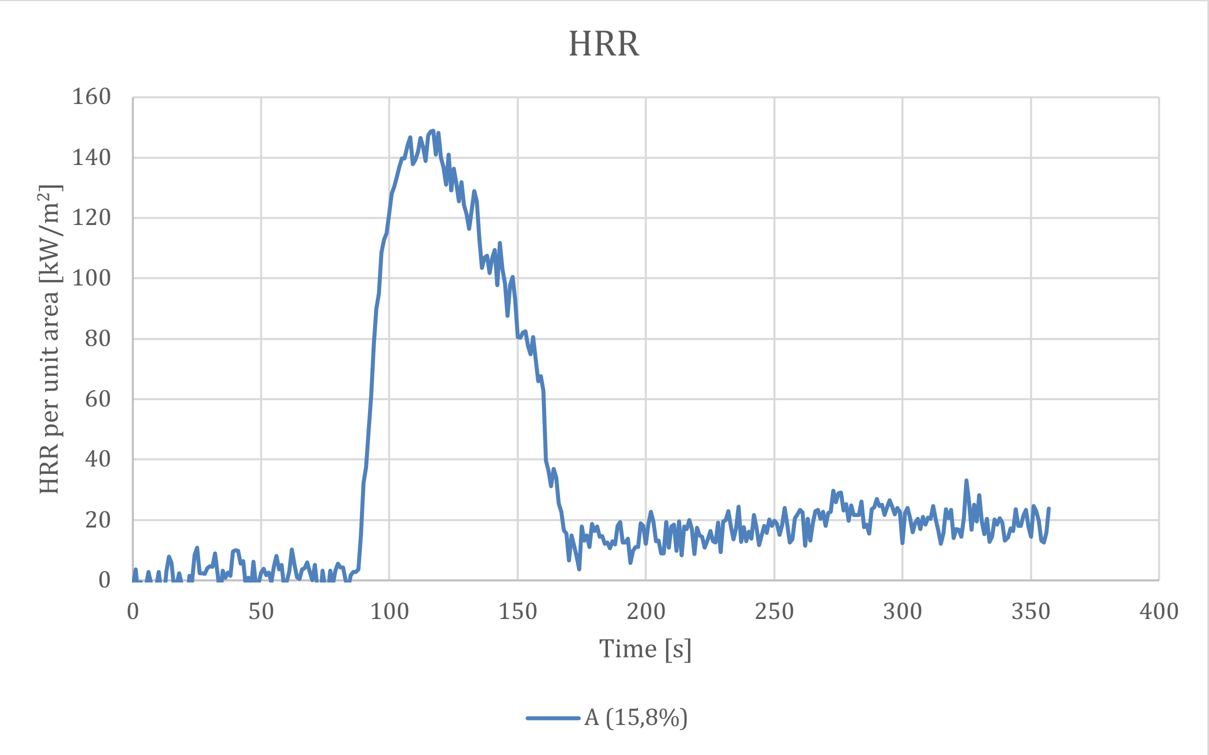

Figure 54 HRR per unit area for Set-up 8.

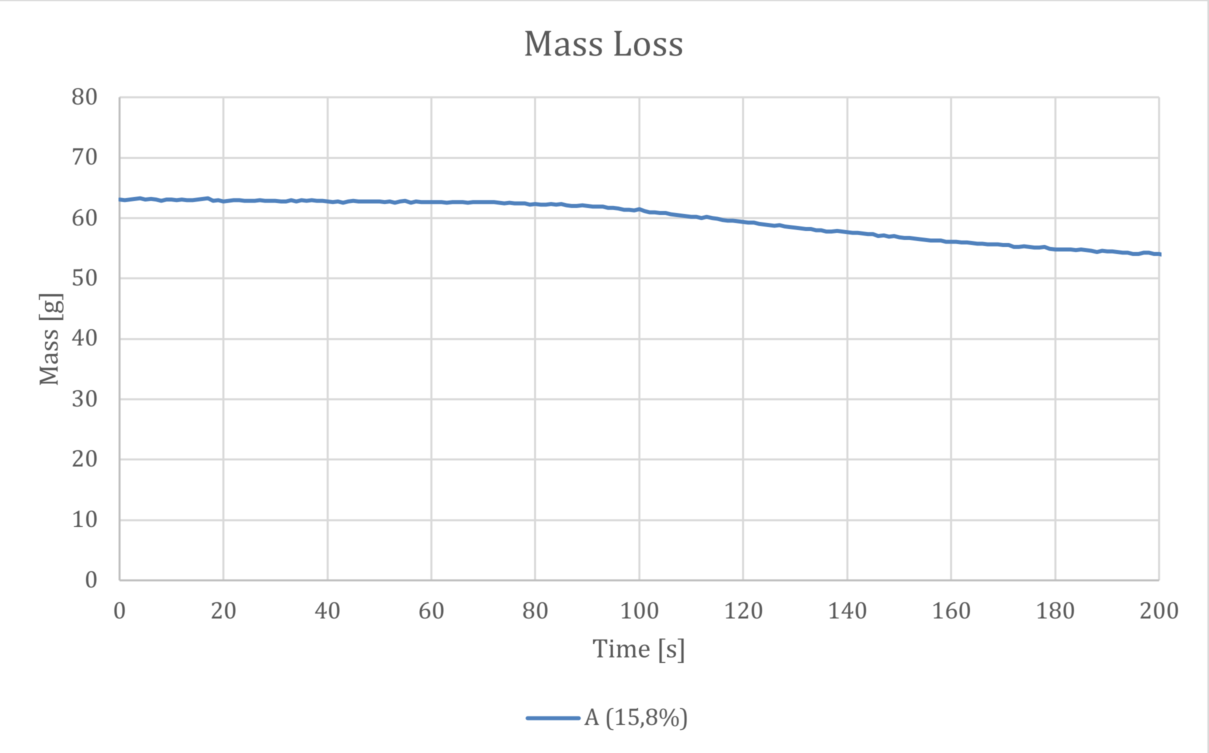

Figure 55 Mass Loss for Set-up 8.

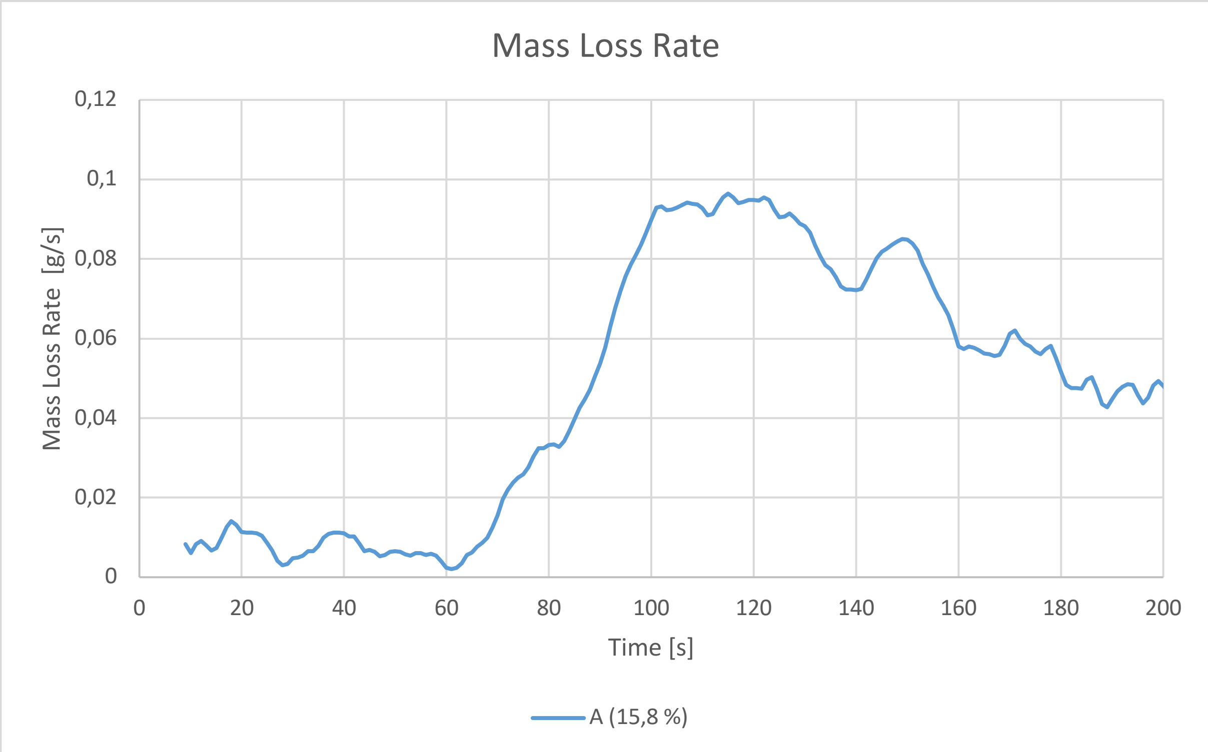

Figure 56 Mass loss rate for Set-up 8.

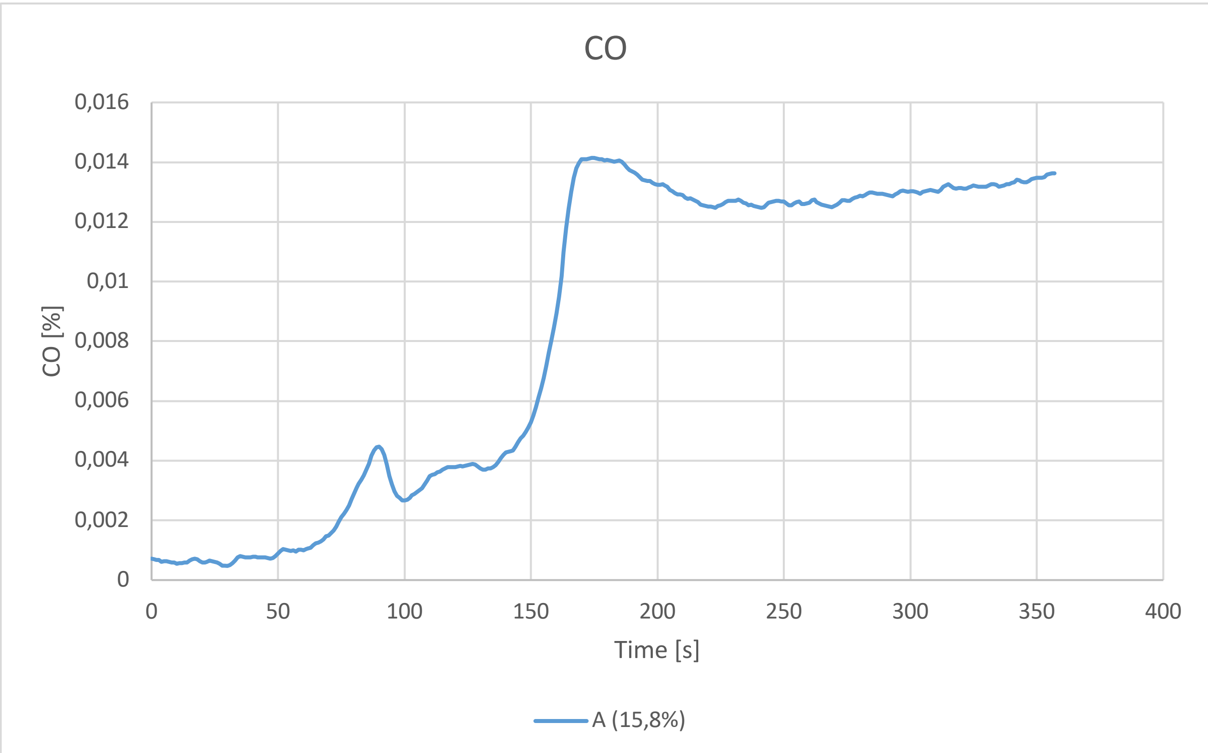

Figure 57. CO production for Set-up 8.

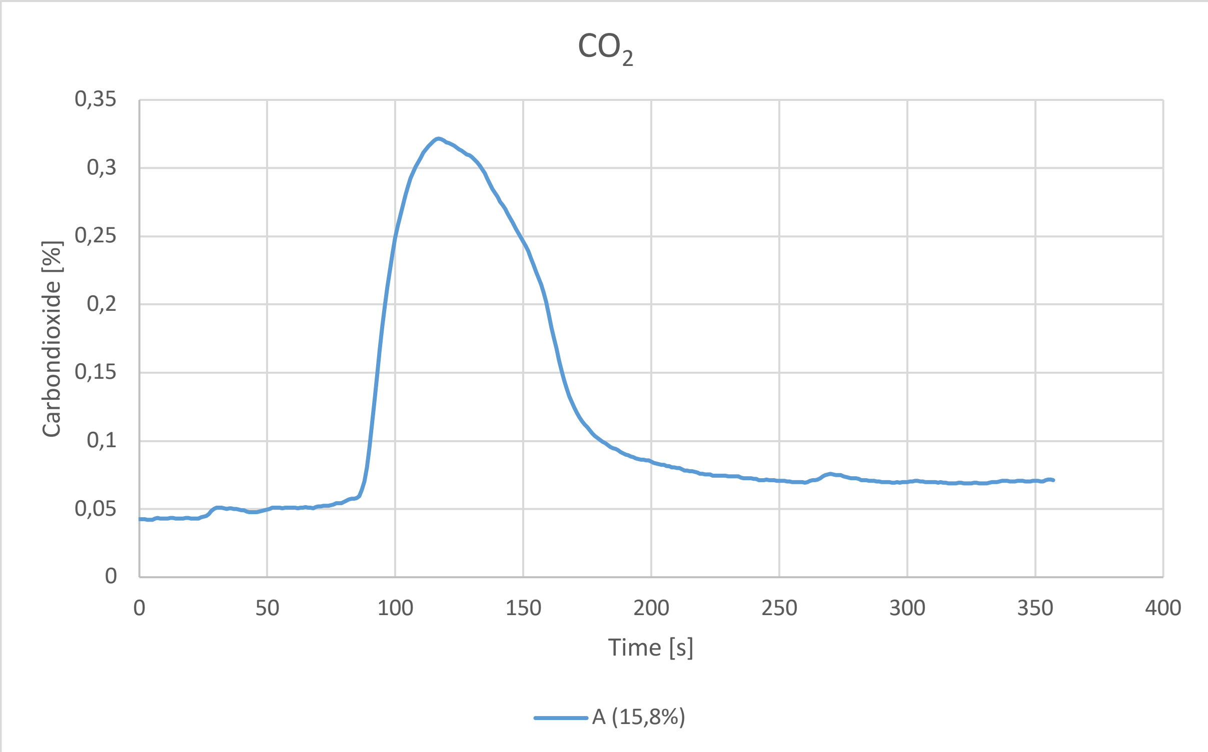

Figure 58 CO_2 production for Set-up 8.

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The Swedish Fire Research Board, Brandforsk, is a non-profit body, formed in collaboration between insurance companies, industry, associations, government agencies and local municipalities. The purpose of Brandforsk is to initiate and fund research and knowledge development within the field of fire safety in order to reduce the negative social and economic impact of fire.

The work is under the leadership of the board of directors and is undertaken in the form of projects at universities, institutes of technology, research organisations, government agencies and industrial enterprises. The Secretariat of Brandforsk shares the pre¬mises of the Swedish Fire Protection Association, SFPA, which is also the principal organization.

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