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Is Carbon Monoxide Sensing an Effective Early Fire Detection Option for Underground Coal Mines?

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IS CARBON MONOXIDE SENSING AN EFFECTIVE EARLY FIRE DETECTION OPTION FOR UNDERGROUND COAL MINES?

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ABSTRACT: The ability of carbon monoxide (CO) sensing to detect early stage smouldering of fixed plant fires in underground coal mines was recently assessed as part of an ongoing fire detection research project. Experiments were carried out to record the level of CO concurrent at the time of alarm activation of a Video Based Fire Detection (VBFD) system. The tests were carried out under simulated mine conditions within the SIMTARS facility at Redbank, Queensland. The experimental setup initially located the CO sensors in the positions at where they would typically be installed underground. On testing the experimental setup, it was found that the amount of CO produced from simulated overheating conveyor belt bearing housings did not display a reading on the CO sensors. The VBFD system however detected smoke and alarmed on each of the trial tests. To enable the experiments to proceed and a comparison to be made, the CO sensors were moved considerably closer to the weak pyrolysis fire source. The question of CO sensor capability in typical operational mine positions was highlighted as a result of this experiment. Computational Fluid Dynamics (CFD) modelling was used to estimate the fire size required to activate CO sensors under typical mining conditions. This modelling reinforced the limitations in using CO detectors on fixed plant. As such, the study presented here indicates that CO sensing may not be the most effective early fire detection option available, and that further research and development work with VBFD should be undertaken.

INTRODUCTION

A recently completed stage of an ongoing fire detection experimental research project recorded the levels of carbon monoxide (CO) from a series of comparable small fires (Mendham, *et al.*, 2013) concurrent with the time of smoke recognition by a Video Based Fire Detection (VBFD) system. Whilst the project is part of an investigation into the potential to improve fire life safety and asset loss control in underground coalmines (Mendham, *et al.*, 2012) using VBFD, it revealed some interesting conclusions in relation to the limitations of CO detection.

The initial challenge in developing VBFD was perceived to be the underground mining environment itself, which has poor light levels, variable ventilation rates and the possible presence of water mist, dust and other pollutants, potentially obscuring the target video image from the VBFD. This situation seems not to provide a very suitable environment for quality video capture (Damjanovski, 2005), so the primary purpose of the experiments was to simulate such conditions to test the capability of the VBFD whilst comparing its performance with CO detection.

To obtain consistent and repeatable results, a controlled and closely monitored simulated underground mining environment was sought. Additionally, an aim of the experiments was to acquire a base line for possible modifications that may be required to develop VBFD to operate effectively underground. SIMTARS (Mendham, *et al*., 2013) at Redbank in Queensland, Australia, was able provide a suitable testing environment.

Although the proposed reference fire was considered 'small' in fire engineering terms (ABCB, 2005), it was appropriate for its intended purpose. The aim was to simulate the overheated housing of a conveyor belt bearing undergoing seizure whilst being layered with combustible coal debris and grease. The resultant designed fire produced a non-flaming pyrolysis plume with the heating source being a propane gas heated 250 mm diameter circular surface. The fire source was estimated to have a Heat Release Rate (HRR) of 0.99 kW (Mendham, *et al*., 2013). This heat release rate is analogous to the heat release rate of a typical single bar household electric strip heater.

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Figure 1 shows the experimental test rig with the propane burner obscured from the remote video detectors using a metal shield to prevent false activation caused by the burner flames. A thermocouple in the centre of the coal covered heated metal surface can also be seen. The CO sensors are not shown in this image, however they were suspended from the ceiling using taut metal wire in predefined proximity to the test rig.

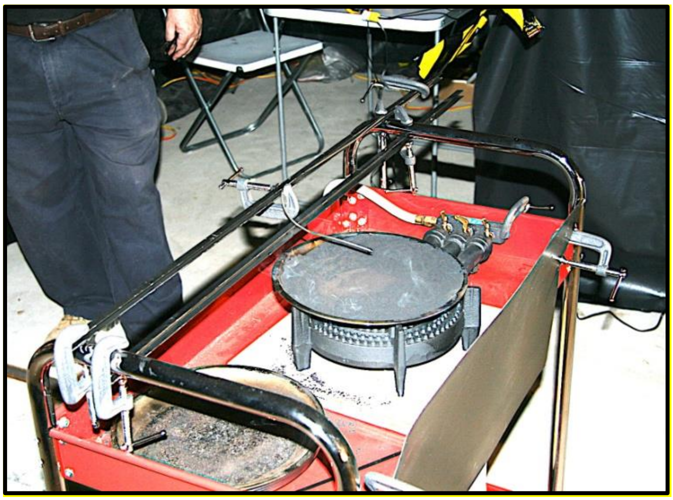


Figure 1 - Experimental test rig used to simulate an overheated bearing housing

The experimental plan initially located the three CO sensors, with respect to the position of the fire source and as viewed from the VBFD end of the room, in the following positions:

- 10 m outbye the fire source (i.e.10m outwards towards the mine portal)
- 1.2 m above the fire source
- 9.5 m inbye the fire source (i.e. 9.5m inwards into the mine with respect to the fire source)

The experimental setup located two independent VBFD cameras adjacent to each other with both focussed on the fire source on the outbye end of the room. The purpose of this was to compare the VBFD response time between cameras. When the first VBFD camera detected smoke, CO readings from the three strategically located CO sensors (Mendham, *et al.*, 2013) were recorded, as were the VBFD alarm times.

It was found during the initial setup experiments that display readings greater than the default value of "0.00 ppm" of CO would not display on the CO sensors in any of the planned experimental setup positions even though the VBFD system detected smoke on each test at an early fire growth stage. The CO sensors were subsequently rechecked for operability and calibration by the SIMTARS technicians and found to be correctly functioning (Mendham, *et al*., 2013).

The CO sensors were progressively moved closer to the fire source after each unsuccessful setup test until the correct readings were eventually displayed. This action was essential, as the planned VBFD experiments could not proceed without comparative CO levels at the time of VBFD activation.

The final positions of the three suspended CO sensors are shown in Figure 2. These were the CO sensor positions that allowed the final VBFD experiments to proceed. Note that Figure 2 shows a light haze of visible smoke at the ceiling level concurrent with the time that the CO sensors commenced to display values of CO.

In summary, the final positions of the CO sensors used in the experiments were:

- 1.0 m outbye the fire source
- 0.1m adjacent the fire source
- 0.8 m inbye the fire source

This paper addresses the following research question:
"What is the approximate Heat Release Rate (HRR) of a belt fire that can generate CO at a concentration recognised under legislative requirements so as to activate CO sensors in locations where they would typically be installed in an operational underground coal mine"

Figure 2 - Positions of CO sensors during the experimental setup showing low-level readings

METHOD

Following the SIMTARS experiments, a Computational Fluid Dynamics (CFD) model (McGrattan, *et al.*, 2007) was developed to simulate the subject small pyrolysis plume formed from the combustion of coal fines and grease (Mendham, *et al.*, 2013) on the surface of an overheated conveyor belt bearing housing. CO production was one of several outputs modelled and it was found that the numerically estimated CO levels were consistent with the recorded levels of CO produced in the experiments. Based on this verification, it followed that by increasing the design fire size in the CFD model, a virtual increase in CO would result. This CO modelling capability provided the means to test the hypothesis that VBFD sensing is a more effective means than CO sensing for detecting fixed plant fires in the very early stage of development in underground coalmines.

As the Fire Dynamics Simulator (McGrattan, *et al.*, 2007) CFD model could be used to simulate larger fires involving increased products of combustion, including CO, the development of the numerical assessment method necessarily incorporated the following steps:

1. Determine the target fire alarm concentration of CO required under legislation

The target concentration of CO typically indicative of a fire alarm event in an underground mine in ppm was sourced to be used as a reference value in describing the effectiveness of CO sensors compared with VBFD. Supplementary information was also sought from a Queensland coalmine Senior Ventilation Officer and an Underground Mine Manager.

2. Define additional CO sensor locations to simulate an actual mine setup

Additional CO sensors were required to be incorporated in a new CFD model. The final SIMTARS experiments located the CO sensors in positions much closer to the fire source than they were intended (Mendham, *et al.*, 2013). The two (2) other scenarios relating to additional CO sensor positions involved the positioning of the sensors at increased distances from the fire source.

a. One scenario involved the CO sensors being positioned according to the initial experimental plan.

b. The other scenario involved the location of further CO sensors where they would typically be installed in an operational underground coalmine (Qld Dept. Mines and Energy, 2005).

3. Develop the CFD model/s to simulate a larger model space for the experimental design fire and a further model using the same model space simulating a larger design fire capable of producing significantly greater levels of CO.

A CFD model was originally developed to simulate the pyrolysis plume formed from the combustion of 40g of coal fines and 40g of grease (Mendham, *et al.*, 2013) being typical of deposits on the surface of an overheated conveyor belt bearing housing in a 35 m model space. The updated numerical modelling achieved:

a. The existing input parameters and assumptions of the actual experiments into two redefined CFD models. One model maintained the original small pyrolysis design fire, but in an increased model space length of 135 m. Some of the experimental parameters included air velocity, temperature, coal and grease characteristics. The second model incorporated a larger design fire (1 m^2 of coal surface) in order to achieve a much greater CO production to activate remote CO sensors and to demonstrate more onerous escape conditions for mine workers under simulated conditions in the 135 m model space.

b. The incorporation of six in total additional CO sensors including the three sensors associated with the original planned experimental locations, which were found to be unsuccessful in the experimental setup tests and a further three sensors located at 25 m, 50 m and 100 m inbye the fire. Each detector was located at a height of 2m above floor level, except for the detector, which was 0.1 m adjacent to the fire source, as it was located 1.3 m above floor level, which was the height of the fire source itself above floor level.

4. Compare the CFD results showing CO levels between the two different fires and a comparison of heat release rates between the fires. Develop graphs from the FDS (McGrattan, *et al.*, 2007) output that:

a. Compare the growth in fire size in HRR in kW with the amount of CO produced in ppm over time.

b. Compare the response times for the CO sensors at each location to reach legislated alarm levels in ppm. indicative of a fixed plant fire underground.

RESULTS

Methods headings Parts1 to 4 above correspond respectively with Results headings Parts 1 to 4, as follows: -

1 The target fire alarm concentration of CO required under legislation

Both New South Wales statute (Coal Mine Health and Safety Regulation (NSW), 2006) and Queensland coal mining legislation (Coal Mining Safety and Health Regulation (Qld), 2001) are risk based, so do not prescribe the concentration levels of CO indicative of an event that would require a fire alarm alarm to be activated.

For example, the legislative requirement for Queensland (Coal Mining Safety and Health Regulation (Qld), 2001) is: "when the products (of combustion) are detected, the automatic activation of an alarm located on the surface in a position that is generally under observation to warn persons of the products' presence" is required. To understand how this risk is managed, information received from a Queensland coalmine Senior Ventilation Officer stationed at an anonymous mine, but indicative of many Australian coalmines indicated that:

"The monitors that are setup for the purpose of monitoring for fire in the belt roads alarm at 2 ppm and 5 ppm and the returns from the panels are 5 ppm and 10 ppm." (Anonymous, 2013, pers. comm., 15 May) and;

"There is only one monitor installed along the length of the belt, at the down wind end, and one in the return of each panel." (Anonymous, 2013, pers. comm., 15 May) and

"No we don't have *CO monitor points* at transfers, as there is a monitor mounted at the down wind end of the belt." (Anonymous, 2013, pers. comm., 15 May)

Further information was sought from an experienced Underground Mine Manager relating generally to underground coalmines. "The setting for underground CO monitors varies but generally is in the range of 4 to 10 ppm. They are set after determining background levels, which are normally determined by diesel equipment exhaust concentrations. They are also set differently for different mining panels e.g. a mains panel see's the total exhaust concentrations from vehicles travelling into the mine whereas a longwall panel will only see concentrations from the machinery operating in that panel during long wall moves where there is a large number of operating equipment, the levels again will be different. Another place where levels will need to be set higher is on the return side of a diesel service bay where diesel equipment is tested." (Hart, 2013, pers. comm., 1 July)

For the purposes of the CFD modelling developed for this research, the CO sensor threshold point was set at 10 ppm being an average level recorded experimentally.

2 Additional CO sensor locations

The CO sensor locations used in the experiments and included in the original CFD model were: -

- 1.0 m outbye the fire source at 2 m above floor level
- 0.1 m adjacent the fire source at 1.3 m above floor level
- 0.8 m inbye the fire source

The additional CO sensor locations defined in the original experimental plan, but found to be unsuccessful during the experimental setup and now included in the additional CFD model, are as follows:

- 10 m outbye the fire source at 2 m above floor level
- 0.8 m above the fire source at 2 m above floor level
- 9.5 m inbye the fire source at 2 m above floor level

The additional CO sensor locations based on the expert independent advice provided by a) the experienced Underground Manager (Hart, J 2013, pers. comm., 1 July) and b) the Ventilation Officer In Charge (Anonymous, 2013, pers. Comm., 15 May), indicated that the CO monitor could be located a significant distance from the source of the fire in practice. These further CO sensors were located: -

- 25m inbye the fire source at 2m above floor level
- 50m inbye the fire source at 2m above floor level
- 100m inbye the fire source at 2m above floor level

The fire source was located between 30 m and 30 m from the opening of the model space, so effectively 30m inbye the simulated mine portal.

In the CFD model, CO sensors are numerically ordered from 'CO#1' to 'CO#9'. Table 3 summarises the CO sensor locations and CO sensor reference numbers, as well as the fire source location.

3 Redefine and develop the CFD model

CFD model results

'CFD Model 1' (CFD1) simulated the experimental pyrolysis fire representing the overheating of the surface of a conveyor belt bearing housing undergoing failure due to seizure, whereas 'CFD Model 2' (CFD2) simulated a larger coal fire where the coal surface was 1m^2, therefore representing fire spread beyond the point of origin. Figure 4 compares the fire plume development for both CFD1 and CFD2 at the same time (750 seconds). Note that a considerably larger smoke yield in CFD2 compared with CFD1 indicating the larger fire size of the CFD2 model.

4 Compare the CFD results showing CO levels between the two (2) different fires and a comparison of heat release rates between the fires.

CO Production

Figure 5 graphically compares the CFD1 simulation with the CFD2 simulation showing considerably greater CO development in the latter compared with the former. The tenability for escaping mine workers in the scenario represented by CFD1 simulation is less onerous compared with the scenario represented by the CFD2 simulation, based on CO production (Qld Dept. Mines and Energy, 2005 – 2012) and on visible smoke.

Note that even with a large fire producing up to ten (10) times more CO than the smaller fire, only CO#2 and CO#5 exceeded 10 ppm. CO.

Table 3 - Summary of CO sensor and fire source locations

Point	Location (All set at 2m above floor level except CO#2, which was set at 1.3m.)	Comment
Fire Source	Between 30m and 30.2m from the simulated mine portal (CFD1)	The fire associated with CFD2, the larger fire, is between 29.6m and 30.6m from the simulated mine portal.
CO#1	0.7m outbye the fire source	CO#1 – 3 represents the CO sensor locations that were the result of their relocation closer to the fire source until a CO reading occurred on at least one (1) sensor. These sensor locations were those used in the experiments
CO#2	0.1m adjacent the fire source	
CO#3	0.8m inbye the fire source	
CO#4	10m outbye the fire source	CO#4 – 6 are the additional sensor locations included in the CFD models representing the CO sensor locations that were planned to be used, but unsuccessful as the CO sensors could not detect CO.
CO#5	0.8m above the fire source	
CO#6	9.5m inbye the fire source	
CO#7	25m inbye the fire source	CO#7 – 9 are the additional sensors based on typical mine sensor locations informed by expert independent advice.
CO#8	50m inbye the fire source	
CO#9	100m inbye the fire source	

CFD1

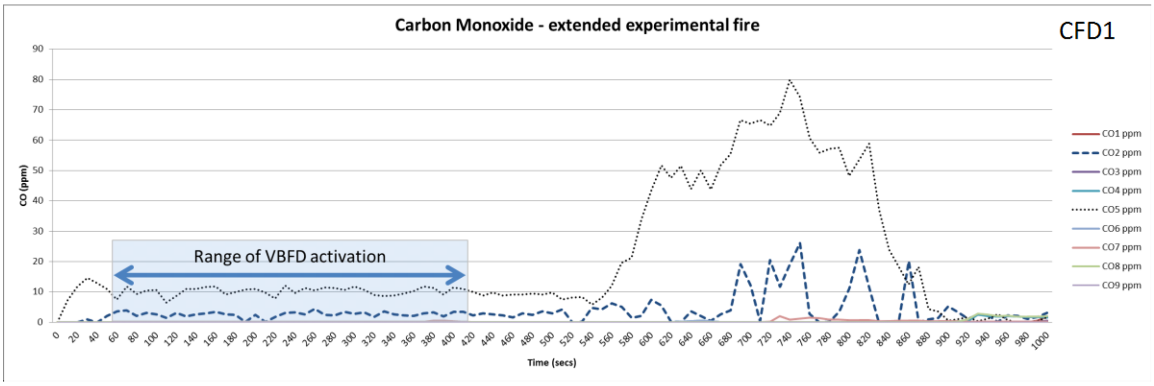
CFD2

Figure 4 - Comparison of simulated smoke plume development CFD1 and CFD 2 at 750 seconds

Heat release rate

CFD1 is based on a weak pyrolysis plume resulting from the overheating of a coal fines covered bearing housing associated with an underground conveyor belt. CFD2 is based on a 1m^2 coal fire representing the growth of the fire beyond CFD1 to a much larger section of belt. The heat released from the fire estimated in CFD2 is significantly greater (nearly 30 times greater) than that of CFD1. This demonstrates that if a fire is left undetected it may fully develop (ABCB, 2005) and be more difficult for mine workers to traverse the section of roadway where the larger fire exists compared with the smaller fire typical of CFD1.

The estimated maximum HRR of CFD1 is approximately 11 kW, whereas should the fire grow to a 1m^2 surface area in the same time period, the estimated HRR for CFD2 is almost 340 kW.



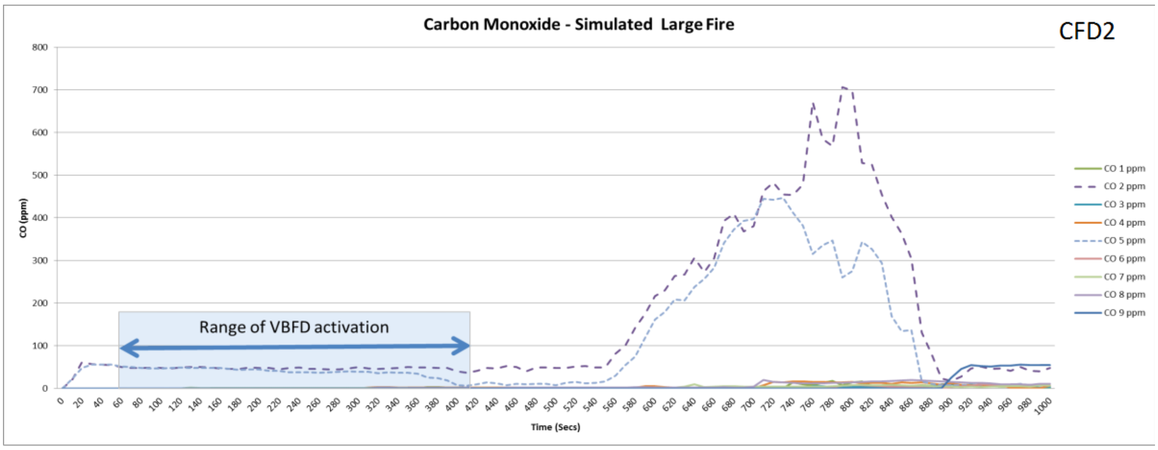


Figure 5 - Comparison of CFD simulations of a small fire validated against the SIMTARS experimental fire (CFD1) with a larger fire (CFD2) both referenced to the experimental VBFD activation range

The Available Safe Evacuation Time (ASET) (ABCB, 2005) under such larger fire conditions is typically less than that for fires detected in their early stage of development, so a significant increase in the fire life safety risk as a result of increased radiant heat flux on mine workers attempting to pass the larger fire source is likely to exist, as well as the increase in products of combustion.

Figure 6 compares the Heat Release Rate (HRR) of the two fire scenarios modelled in CFD1 and CFD2.

DISCUSSION AND CONCLUSIONS

Three significant conclusions were derived from the comparative CFD modelling validated by the testing at SIMTARS:

1. A significant fixed plant fire can be developing that CO detectors, as currently employed by underground coalmines, would not detect but VBFD would.

Figure 5 clearly shows that for either fast growing larger fires (340 kW in 750 seconds) or slow weak smouldering fires (11 kW in 750 secs) VBFD can detect smoke reliably at an early stage of growth (40 to 400 seconds). CO detectors located where they would typically be located in an operational mine however did not receive adequate levels of CO from the either the small or large fires to exceed the notional alarm levels required to initiate an evacuation as a result of CO concentration. Only the CO detectors located very close to the fire source in both simulations received a significant level of CO in the order of 10 to 50 ppm.

2. CO as a detection means is complicated by the other sources of CO in a mine.

Opinion from expert mining officials indicates that varying ambient CO levels result from mine development activities. Under such circumstances, background CO levels could easily mask levels of CO commensurate with an early stage fixed plant fire. This might result in delayed fire detection, therefore delayed evacuation and significantly greater asset loss.

3. If a fire reaches the size where CO detectors would alarm, there already exists a significant risk to life and assets.

The results of the subject experiments and numerical simulations indicate that CO levels from fixed plant fires are slow to migrate throughout a mine to a level required to register a CO detector reading commensurate with the need to evacuate an underground mine. The results show that if typically located CO detectors cause a fire alarm level to be achieved, then the fire is likely to be quite significant. Ominously, CO detection is considered under most legislative regimes to be an effective form of early detection of fires in underground coalmines, but its actual and simulated performance has been shown to be less effective than VBFD in experimental and simulated environments. For this reason, VBFD should be subject to further testing in an operational underground coal mine to validate and check its robustness.

In practice, if mine workers are warned of a potentially growing fire, avoidance action can be taken to escape the fire in its early stages to a place of safety before the fire grows. The activation of an alarm to initiate the evacuation is essential either by means of properly located CO gas level monitoring points or, as proposed in the experimental research, by VBFD. In this research, it was shown that the very early detection of fixed plant fires using VBFD outperformed CO sensing in both the experimental and numerically simulated environment and is likely do so in an operational environment. More robust testing of VBFD in operational mines is required to confirm the reliability of VBFD.

At this time it is recommended that fire detection systems able to detect early products of combustion, such as VBFD, be used in conjunction with CO detection, as considerable detection delay is encountered for small fires where only low levels of CO are released in the early pre-growth stage.

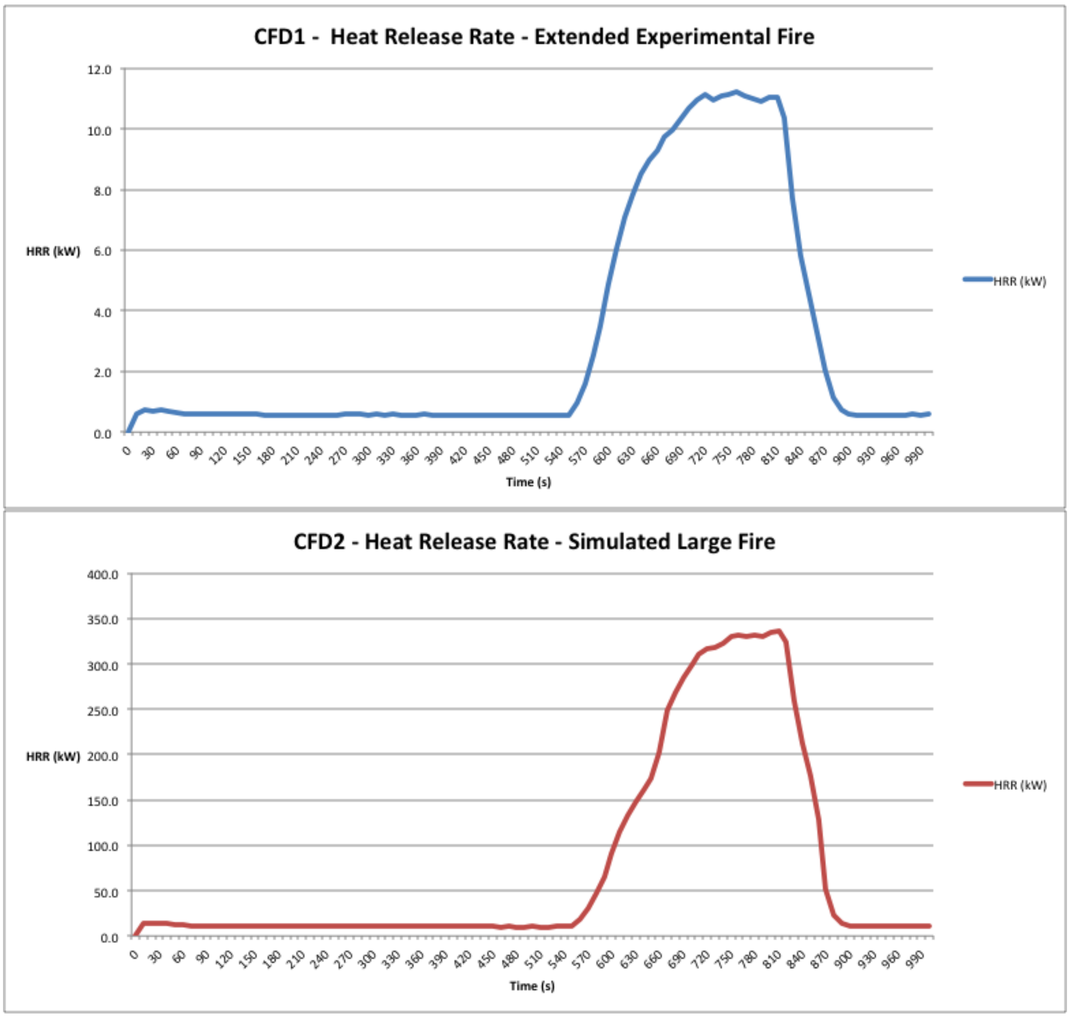


Figure 6 - Comparison of CFD1 and CFD2 - heat release rates

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