School of Chemical and Process Engineering
FACULTY OF ENGINEERING

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Particle Size Distribution During Pine Wood Combustion on a Cone Calorimeter

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Presented by Hu Li (Dr Li)

For the Cambridge Particles Meeting

23rd June, 2017

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1. The Grenfell Tower Fire Disaster and Particulates
2. Assessing the Toxicity and Particulate Emissions from Material on Fire using a Cone Calorimeter
3. Application of the Cambustion DMS 500 Particle Size Analyser to Wood Fires
4. Conclusion

UK 1955-2014 (Fire fatalities)

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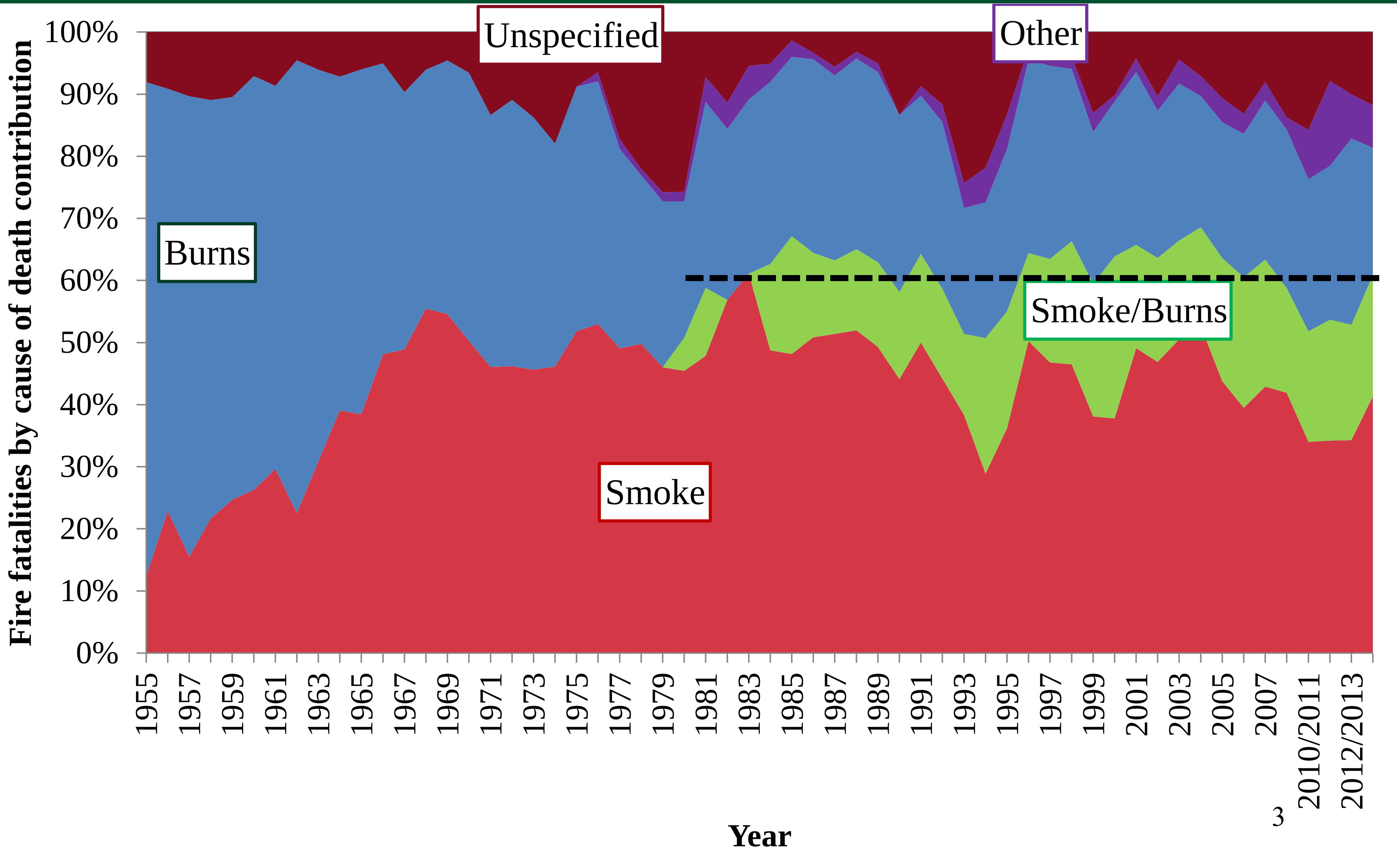

The Grenfell Tower Fire Disaster and Particulates

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- **About 60% of fire deaths are as a result of smoke inhalation.**
- **At the Grenfell Tower fire last week all those who survived and are currently in hospital have severe smoke inhalation problems. One of the Medics reported that they had been flushing black carbon out of the lungs of patients. Some of the survivors in hospital are held unconscious, while they recover from the major effects of smoke inhalation.**
- **The Secretary of State in the Building Regulations Approved Document B has set no limit for smoke production and flaming droplets/particles in UK approved external wall cladding material. Also there are no toxic gas regulations.**

- **Current UK fire testing of products does not require the measurement of particulate or toxic gas production –there are no toxicity related acceptance criteria.**
- **Materials / products which release toxic combustion products (e.g. some acoustic / thermal insulating materials in the façade or within the building) can pass the relevant fire test standard!**
- **There is a need for toxicity assessment, but the methodology needs to be relevant and workable within a regulatory framework.**
- **Q: How can Fire Safety Engineers include the effect of toxic combustion products in Fire Safety Assessment at the design stage?** ***This paper shows that the cone calorimeter is a viable test method.***

The Need to Consider Toxicity in Fire Safety Assessment

Stuart Winter, OveArup & Partners Ltd , International Fire Toxicity Conference (FireTox2016), March 21---23, 2016. University of Central Lancashire, Preston, UK

The relationship between the aerodynamic size of particles and the regions where they are deposited

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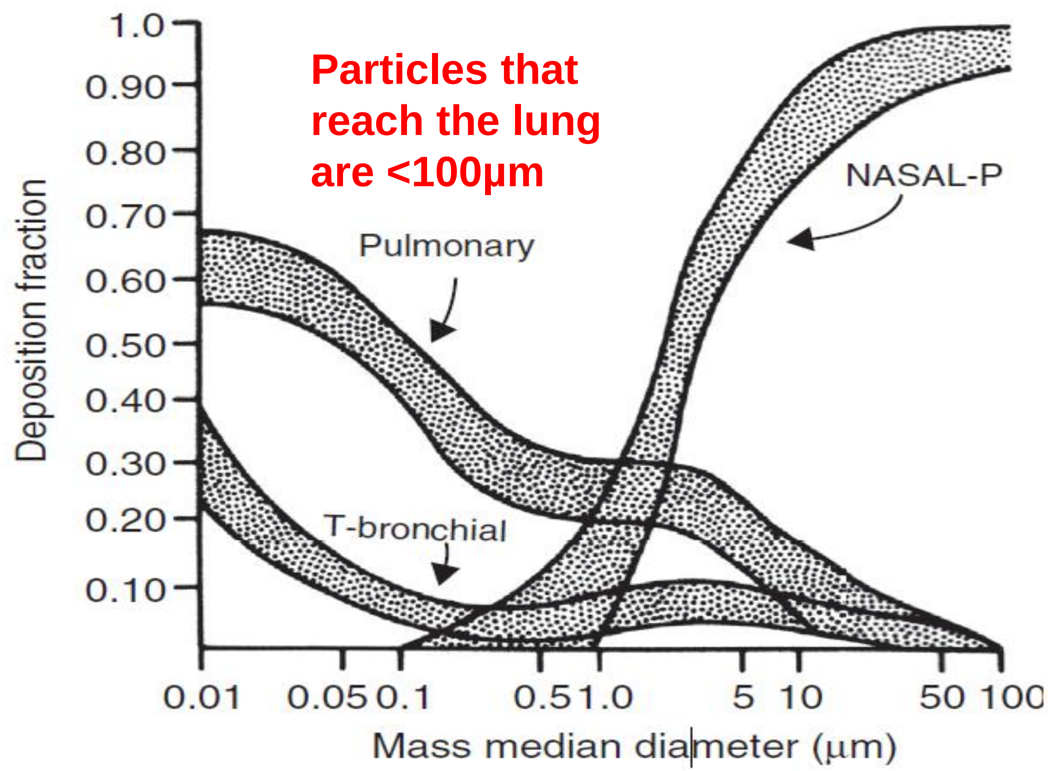
The nasopharyngeal region consists of the nose and throat; the tracheobronchial (T-bronchial) region consists of the windpipe and large airways; and the pulmonary region consists of the small bronchi and the alveolar sacs.



Particle deposition as a function of particle diameter in various regions of the respiratory tract

Fundamentals of Air Pollution, Daniel Vallero, 5th edition 2014

The relationship between the aerodynamic size of particles and the regions where they are deposited

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Larger particles are deposited in the nasal region by impaction on the hairs of the nose or at the bends of the nasal passages.

Smaller particles pass through the nasal region and are deposited in the tracheobronchial and pulmonary regions.

Particles are removed by impacts with the walls of the bronchi when they are unable to follow the gaseous streamline flow through subsequent bifurcations of the bronchial tree.

As the airflow decreases near the terminal bronchi, the smallest particles are removed by Brownian motion, which pushes them to the alveolar membrane.

Mechanism of particle lung filtration and factors affecting its filtration

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Basically, lung filtration consists of four mechanical processes:
(1) diffusion;
(2) interception;
(3) inertial impaction;
(4) electrostatics.

Diffusion is important only for very small particles (≤0.1 μm diameter) because the Brownian motion allows them to move in a “random walk” away from the airstream. Interception works mainly for particles with diameters between 0.1 and 1 μm. The particle does not leave the airstream but comes into contact with matter (e.g. lung tissue). Inertial impaction collects particles sufficiently large to leave the airstream by inertia (diameter 1 μm).

Other important factors affecting lung filtration are surface stickiness, uniformity of particle diameters, the solid volume fraction, the rate of particle loading onto tissue surfaces, the particle phase (whether liquid or solid), capillarity and surface tension, and characteristics of air in the airway, such as humidity, velocity, temperature, pressure, and viscosity.

The Grenfell Tower Fire Disaster and Particulates

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- **The particle size that reaches the alveolar region of the lungs are <100nm**
- **The lungs of survivors from Grenfell Tower were full of black particulates and they must have been <100nm.**
- **There is hardly any information in the literature on the particle size distribution in smoke in fires as the only legal requirement is to measure the smoke obscuration in fire tests and particles are >>1μm to have light obscuration properties.**
- **The present work uses the Cambustion DMS 500 particle size analyser to show that nano particles are generated in wood fires and wood is about 50% of the fire load in most fires.**

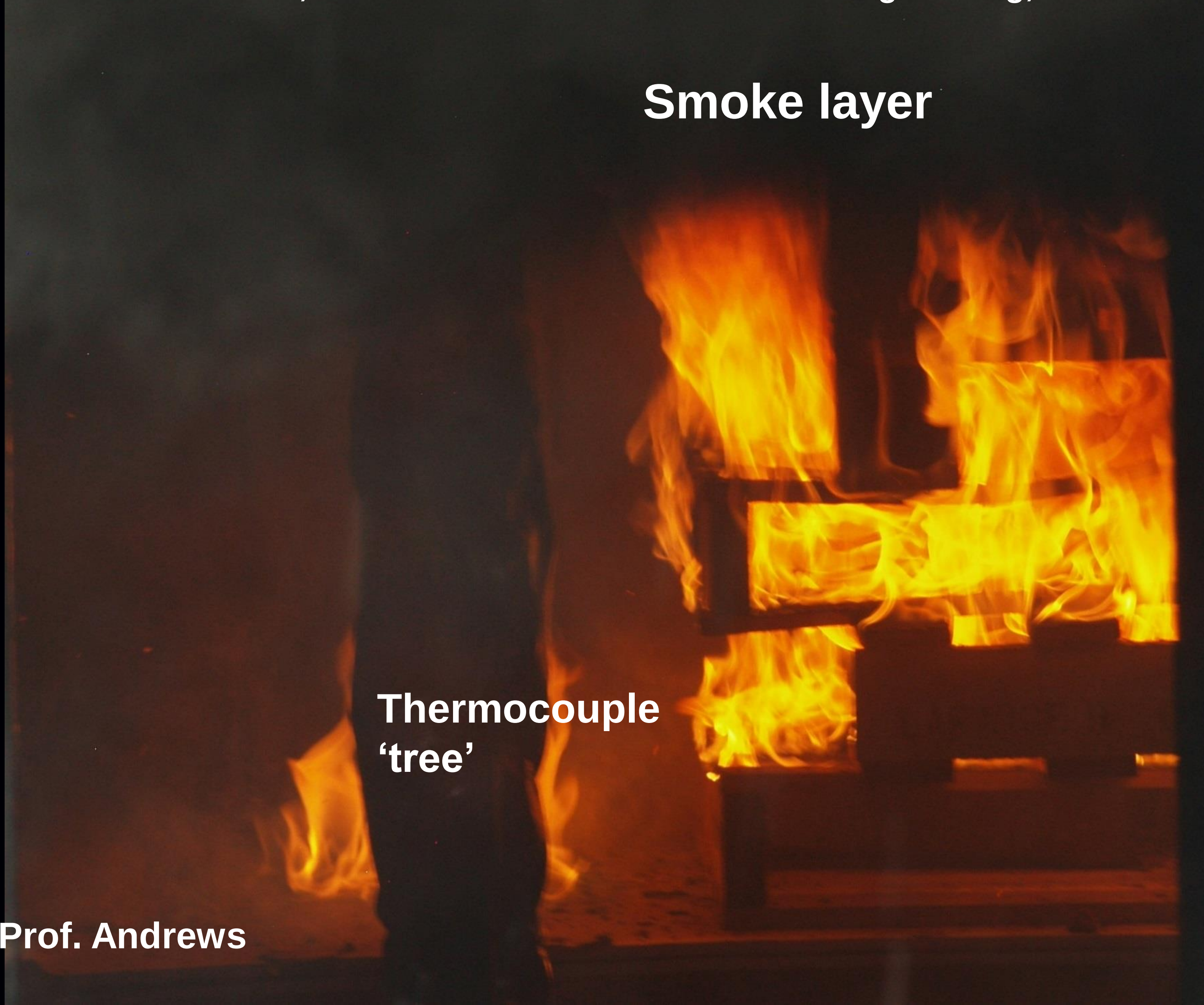

Photo Prof. Andrews

The Grenfell Tower Fire Disaster and Particulates

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- Smoke comprises of a mixture of gases, vapours and particulates on the other hand Particulates comprise of both micro-droplets formed as a result of organic vapour condensation and soot (carbon).

- In the mid 1990s, epidemiological data in the USA and UK showed that 1% extra deaths occurred for every $10\mu g/m^3$ of PM_{10} in ambient air within days of the high particulates.

- The only medical explanation of this effect is that particles <100nm must be present.
- A person breathes about $10m^3$ of air per day which at $10\mu g/m^3$ is a lung loading of 0.1mg.
- In wood fires the particle production is $100mg/m^3$ and it takes 0.144mins. to breathe in 0.1mg. For polypropylene it is x 20 higher

- The time for escape in a fire should be as little at 10 mins but 7 mg of nano particles from the fire would be breathed and this will cause the same health effects as exposure to a high air pollution incident for 70 days. Exposure for 1 hour would cause deaths, as occurred at Grenfell Towers

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METHODOLOGY

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The Cone Calorimeter:

- **The Cone Calorimeter is a standard piece of bench scale laboratory equipment for heat release and smoke production measurements.**
- **The authors have adopted it for the measurement of toxic gas species using a heated Gasmet FTIR in conjunction with a Cambustion DMS500 particle size analyser to determine the particle size distribution**
- **The Standard Cone calorimeter was modified to have an air tight box around the test specimen to simulate a compartment fire. This created a rich burning fire.**

METHODOLOGY-2

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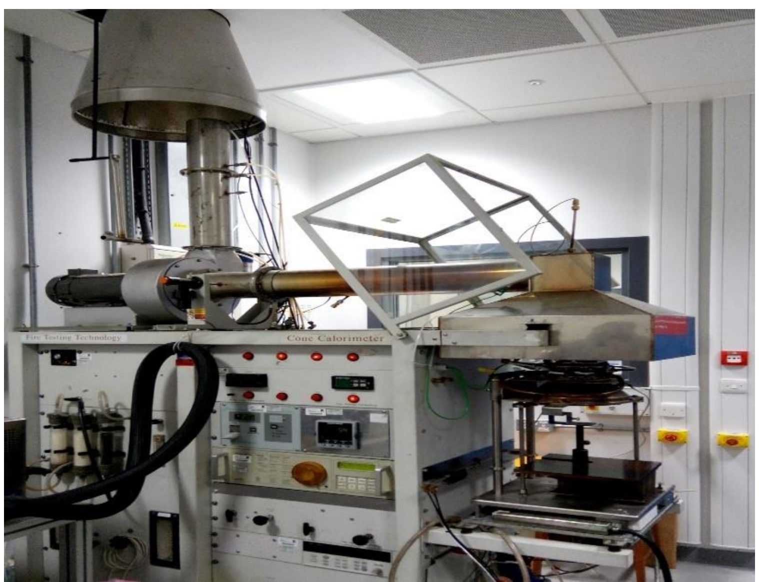
- **The FTIR measurements were from raw gas emissions from the Chimney from the fire compartment while the DMS500 measurements were from the diluted exhaust on the cone calorimeter with a dilution ratio of 112.**
- **Both Raw and Dilute sample measurements were made via Heated sample lines to avoid condensation**



The Standard Cone Calorimeter

METHODOLOGY-3

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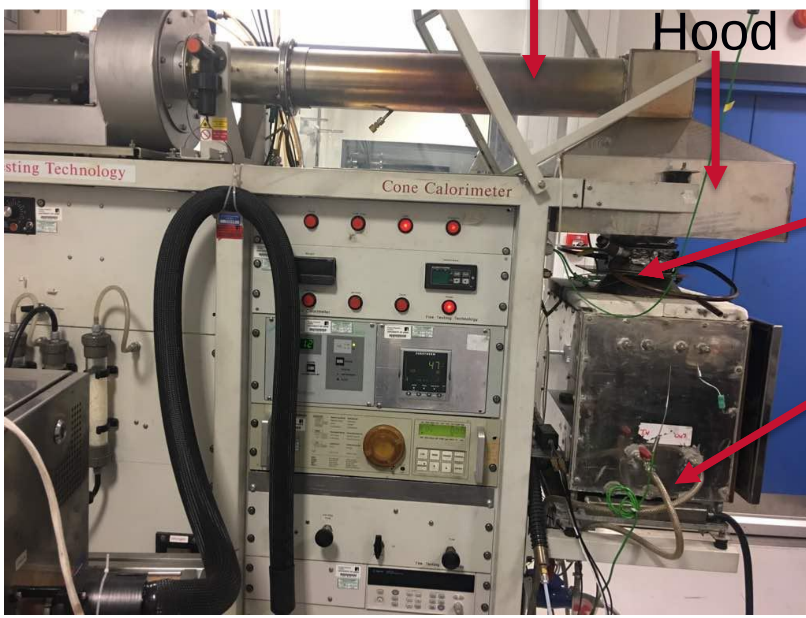
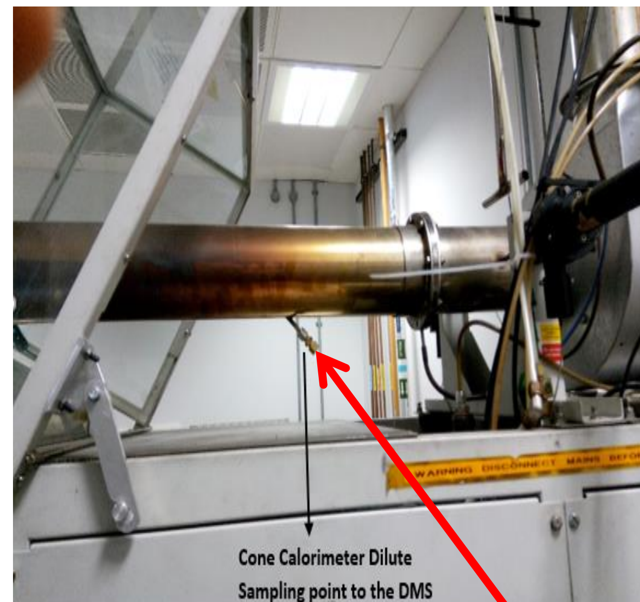
Exhaust

Hood



Chimney (Raw Sampling point)

Air tight box



Cone calorimeter diluted gas sampling position for the DMS500

Modified Cone Calorimeter

METHODOLOGY- 4

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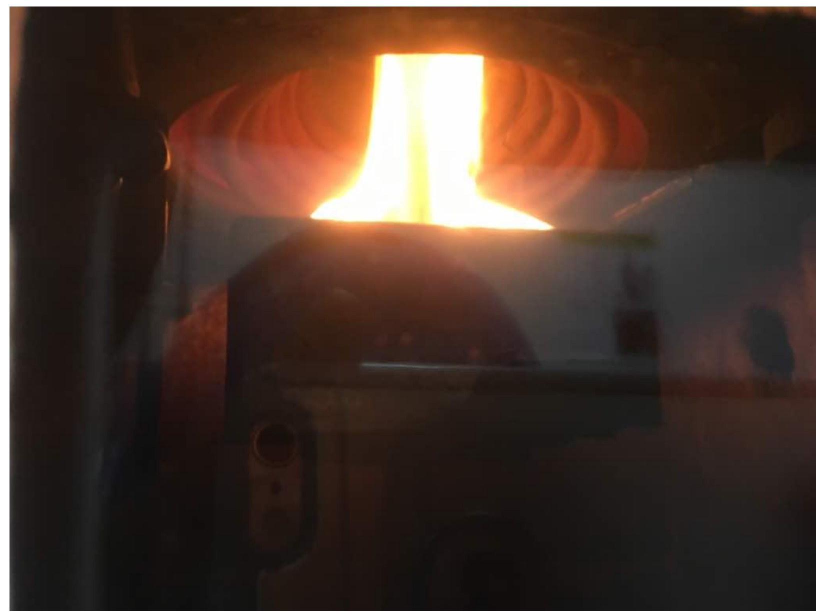
- **The Cone calorimeter was operated at $35kW/m^2$ radiant flux with a fixed ventilation rate of 0.192kg/s and the ignition delay was 29s**

Pine Wood in a sample holder



Pine Wood Test
The yellow flame is due to rich combustion and soot formation.

Methodology - 5

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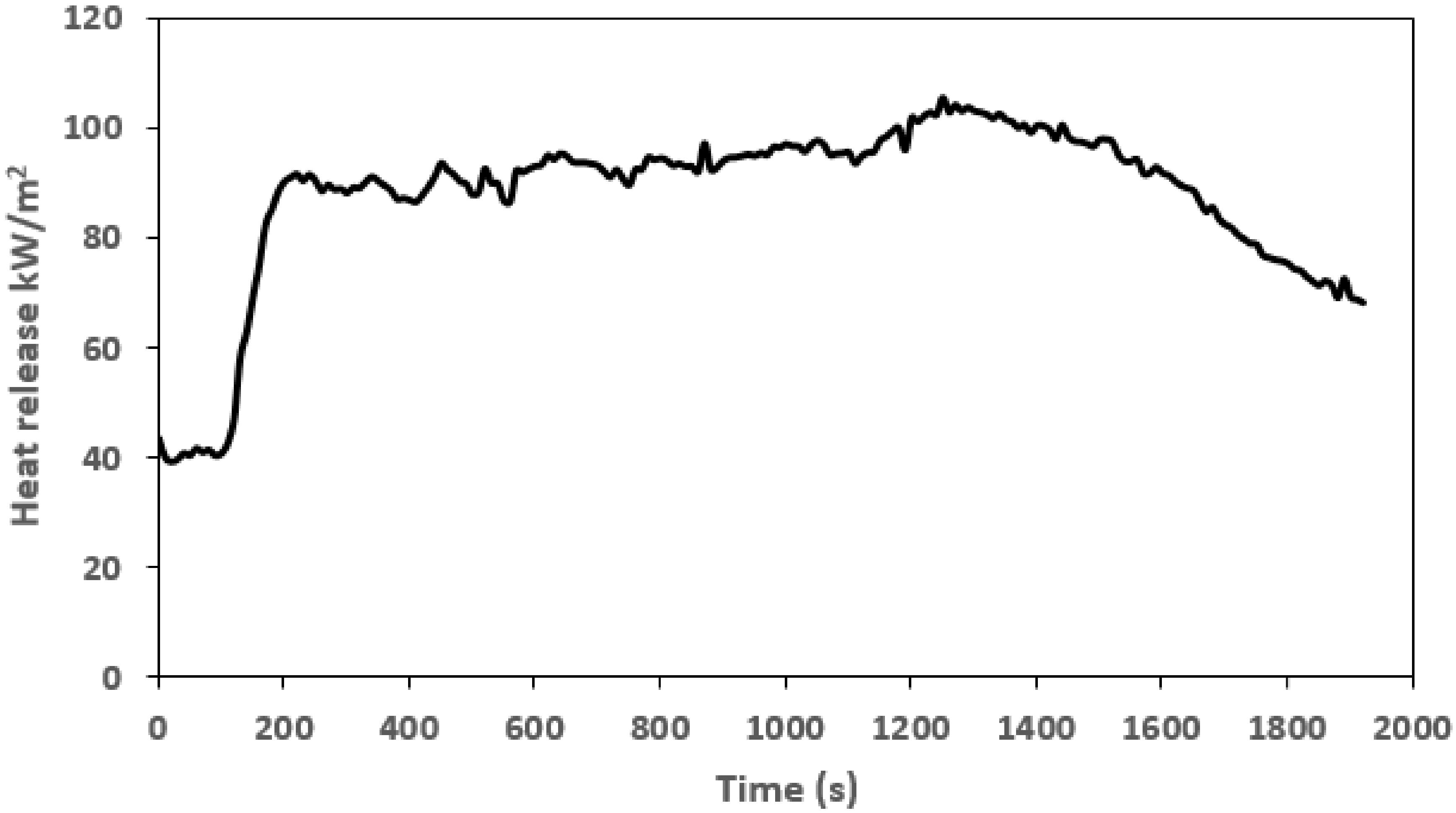

Heat Release Rate

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Application of the Cambustion DMS 500 Particle Size Analyser to Wood Fires

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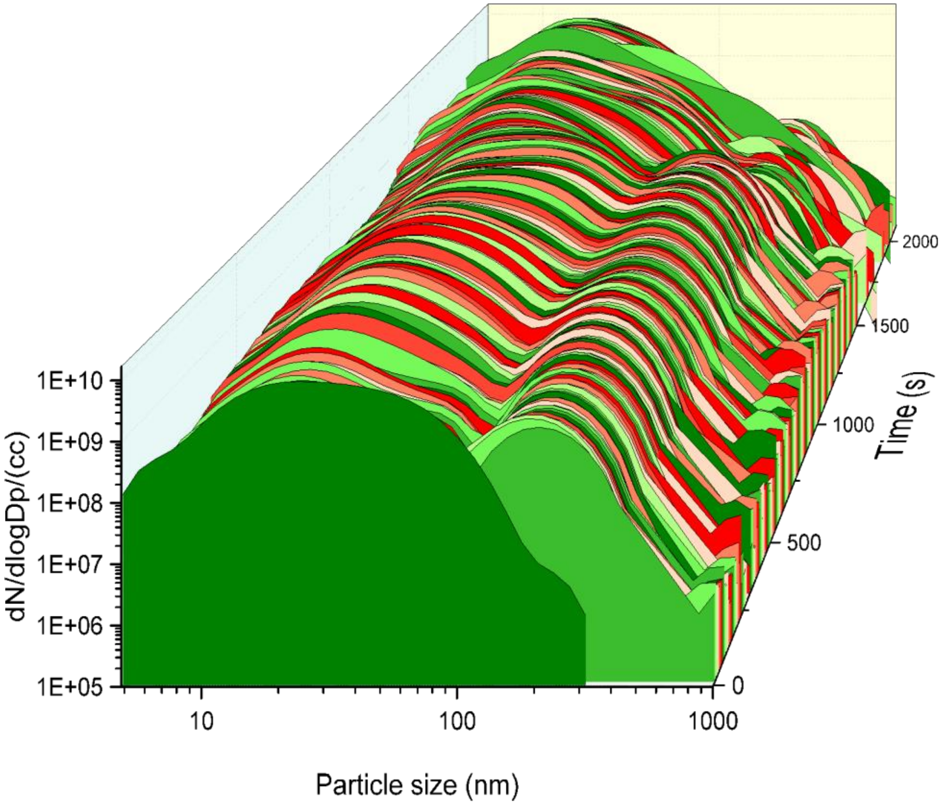
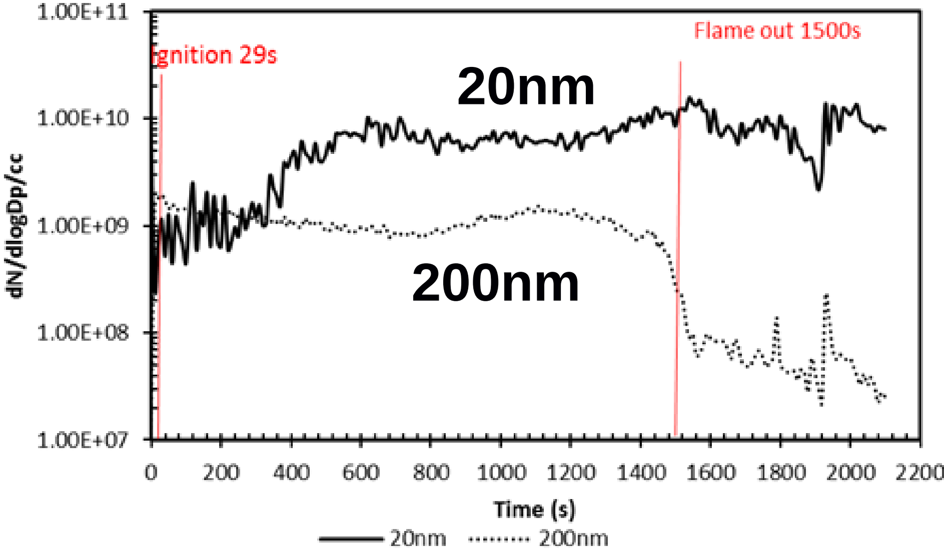


Smoke Particle Number and Size Distribution



20nm and 200nm Sizes Particle Number

Application of the Cambustion DMS 500 Particle Size Analyser to Wood Fires

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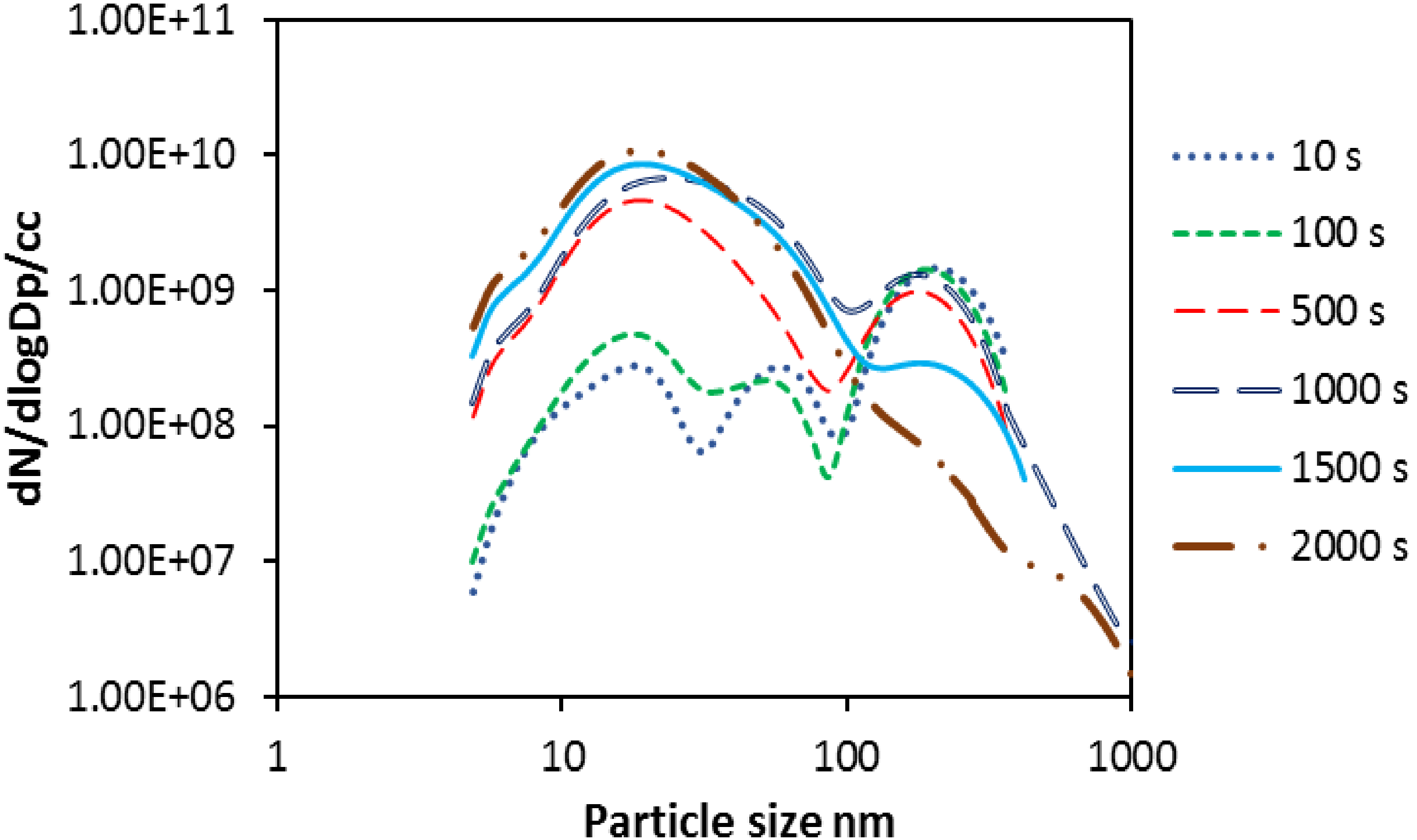

Particle Number and Size Distributions at different burning time

Application of the Cambustion DMS 500 Particle Size Analyser to Wood Fires

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- **The particle size showed a bimodal distribution representing the Nucleation and Accumulation mode**
- **The nucleation peak was 20nm and the accumulation mode was 200nm**
- **High peak of 20nm particles occurred during the ignition delay possibly indicating a vaporised aerosol of high MW compounds from the wood, as 80% of wood PM is volatile.**
- **Future Work will use a Dekati Thermo-denuder to prove this**

Comparison with a modern diesel engine particle number emissions (engine out)

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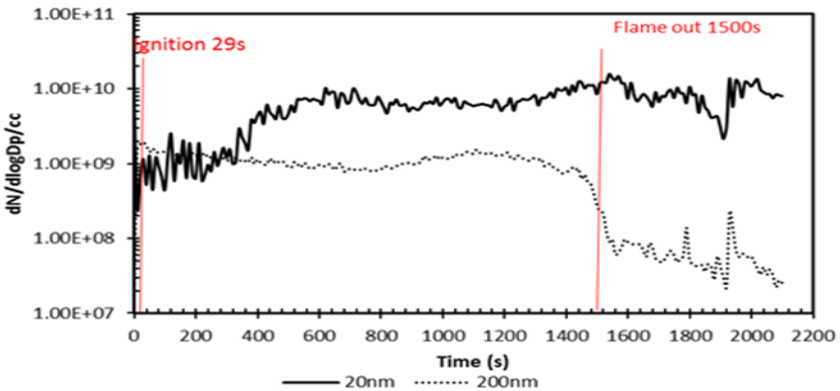


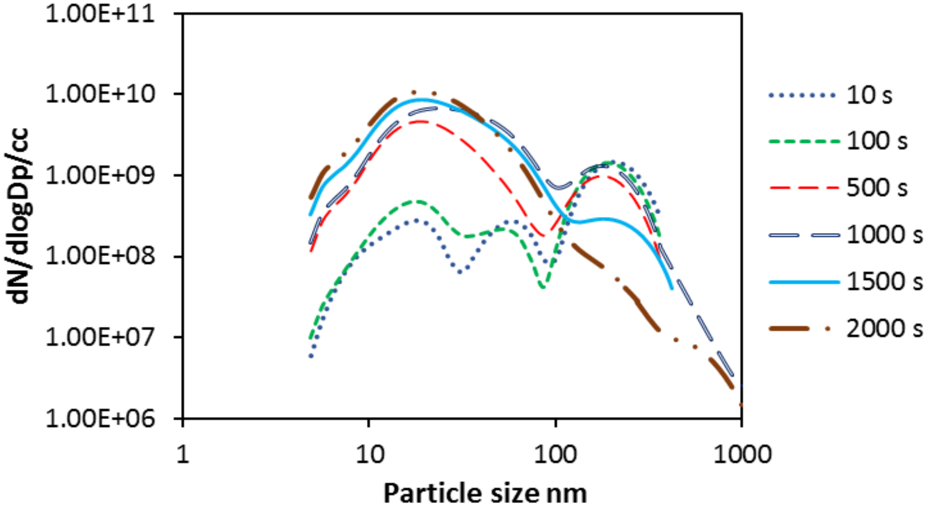
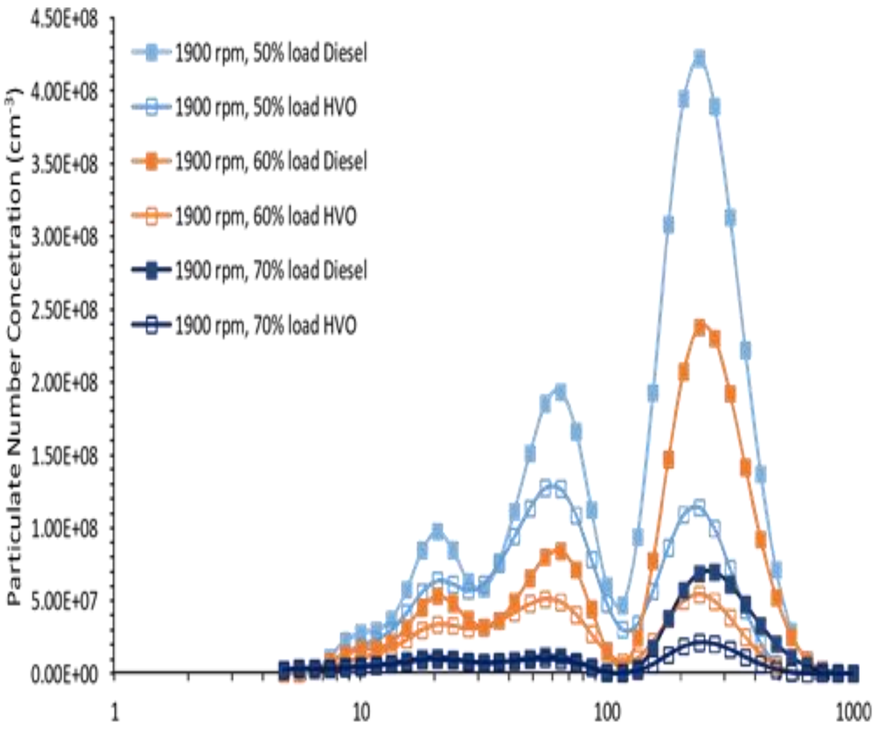
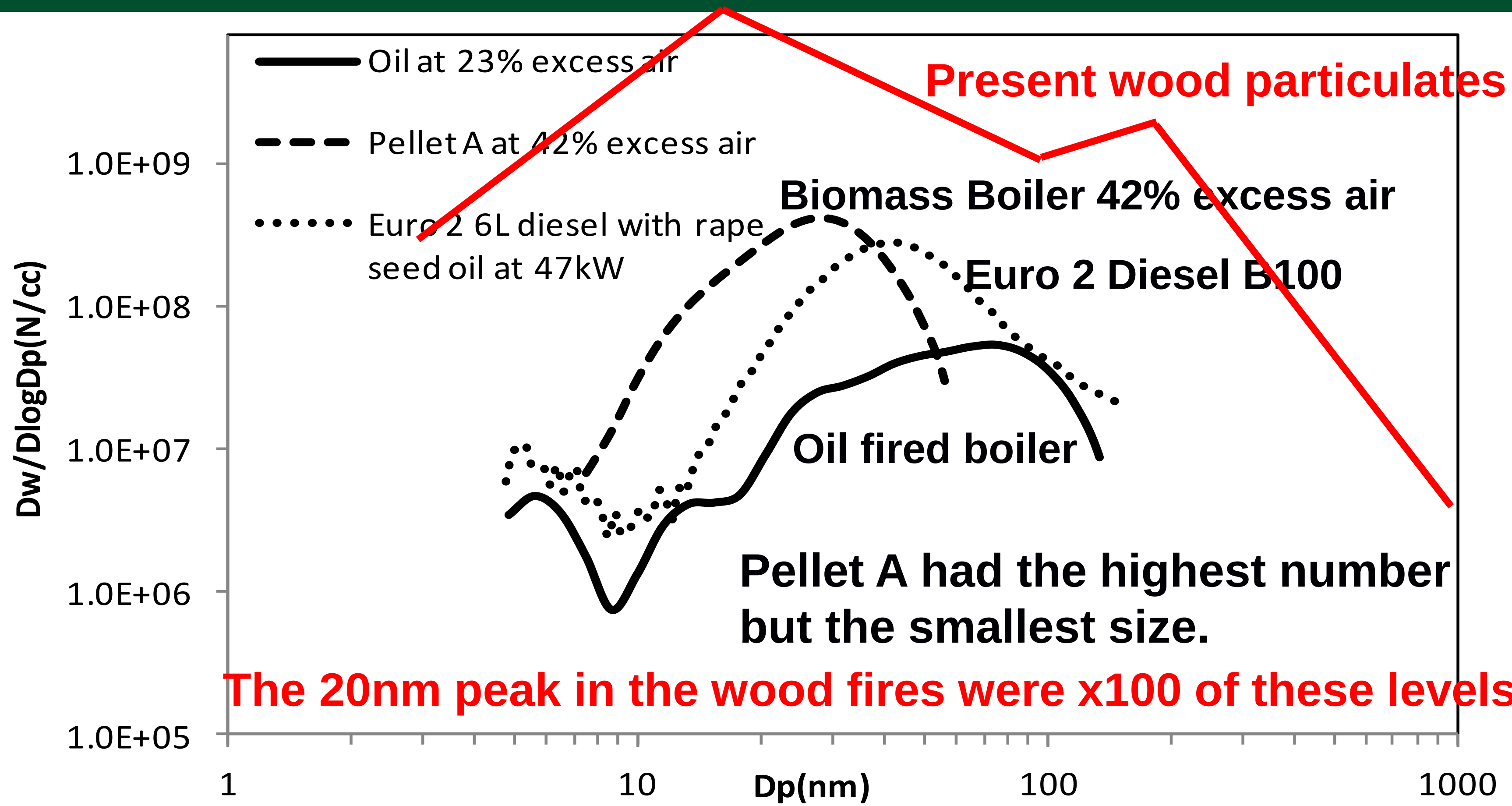


Figure 7: Particle Number and Size Distributions at different burning time



Engine out diesel particle number concentration and size distributions (100kW EURO5 IVECO diesel engine with DOC and DPF)



Particle number distribution as a function of size for pellets A and fuel oil with a comparison with a Euro 2 diesel on B100.

CO and THC by FTIR

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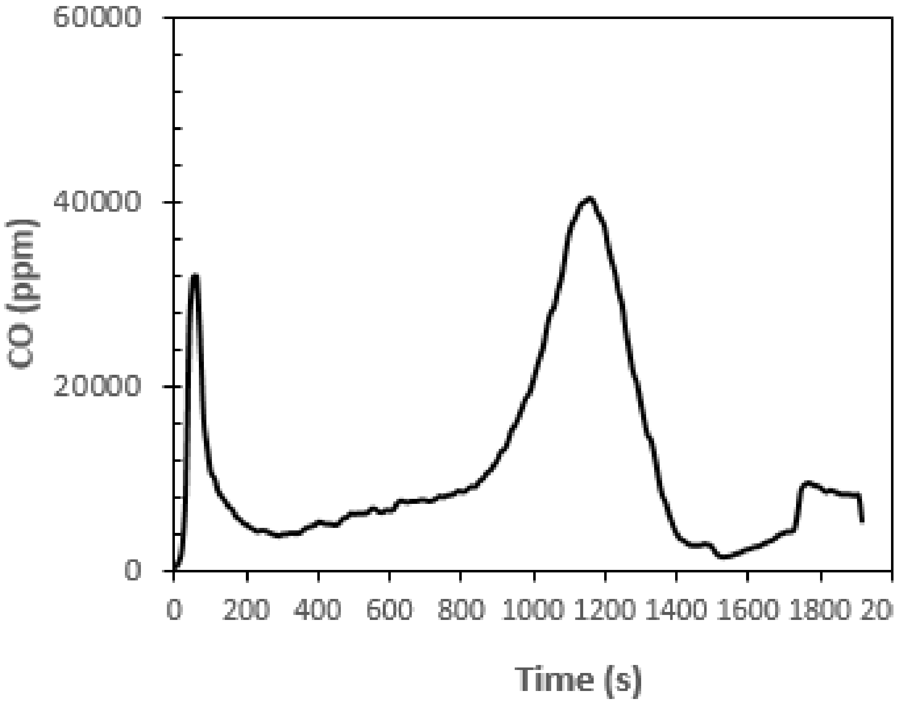
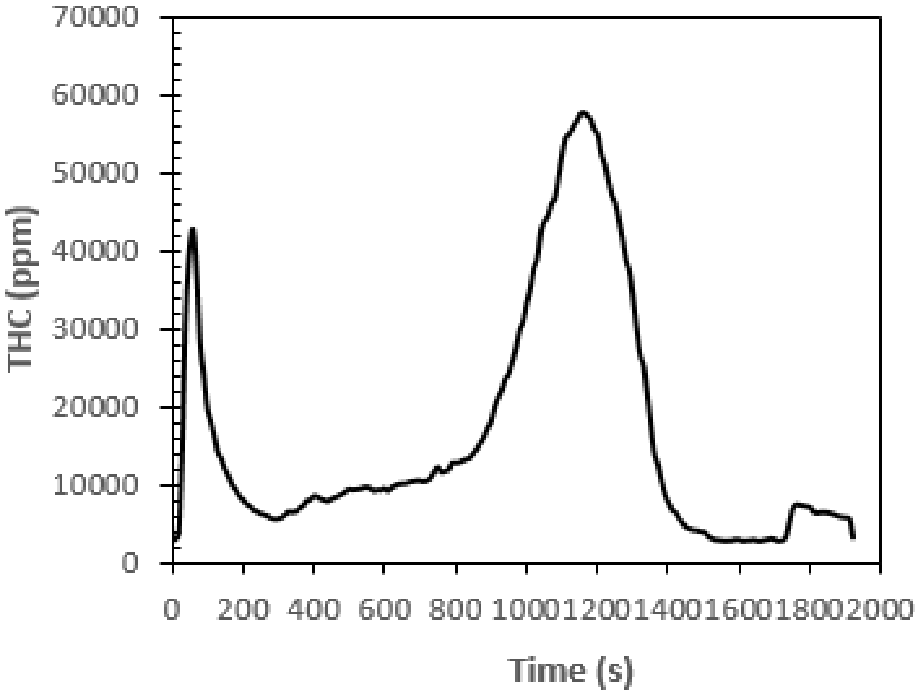


Carbon Monoxide Concentration



Total Hydrocarbon Concentration

The CO and THC emissions show two stages in the fire,
~ 100s there was a peak in CO and THC just after ignition
~ 1200s there was a peak in CO and THC just before flame out.

Benzene and Formaldehyde by FTIR

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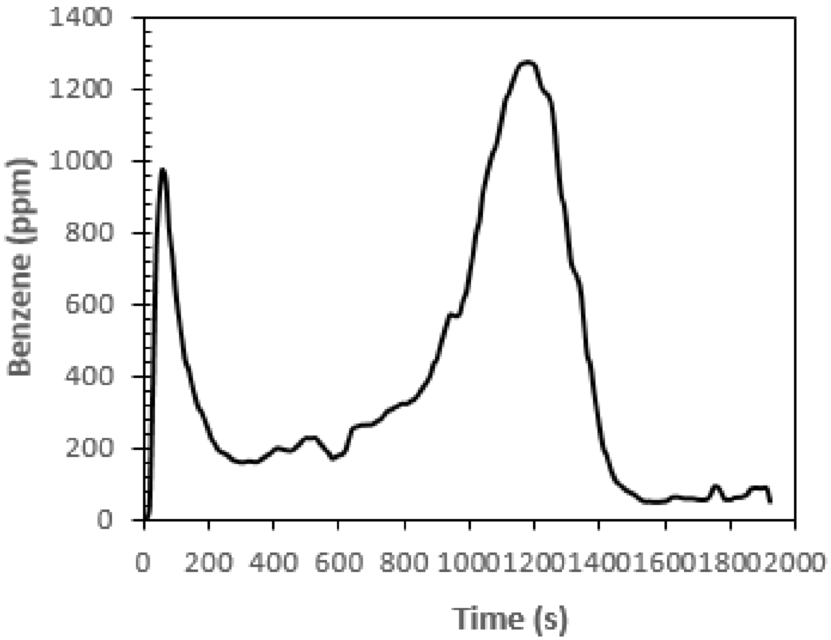
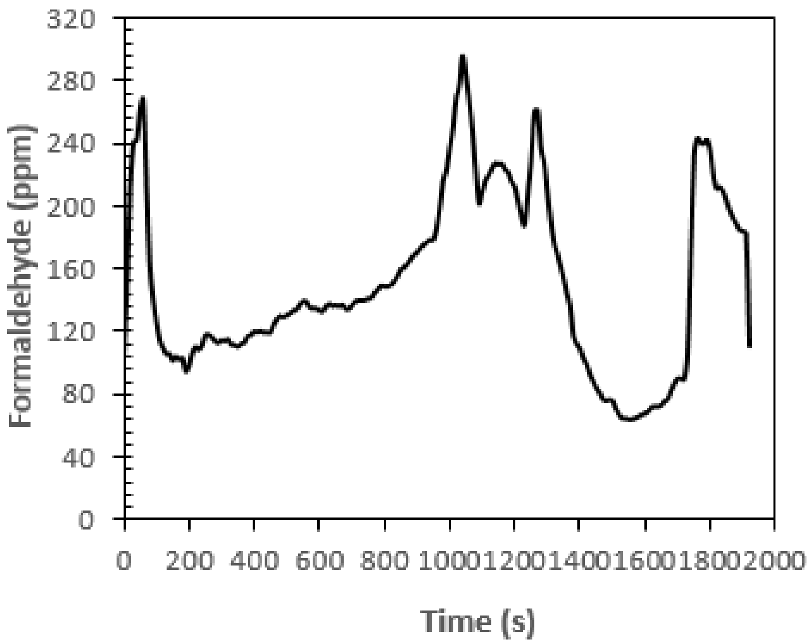


Benzene Concentration



Formaldehyde Concentration

Benzene Showed two Stages in the fire while Formaldehyde showed three stages;
~ 100s there was a peak in Benzene and Formaldehyde just after ignition
~ 1200s there was a peak in Benzene and ~ 1000s for Formaldehyde just before flame out
~ 1800s there was a peak in Formaldehyde during the smouldering combustion

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Conclusions

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1. Ultra Fine and nano-particles in Fires are a Health Problem and a Potential Cause of Deaths
2. Ultra fine particles are generated in wood fires at a level much higher than for diesel engines or biomass pellet combustion in boilers.
3. These 20nm particles will penetrate to the lungs in fires and death and impairment of escape from fires due to the effect of fine particles on the lungs, make fine particles a major toxic hazard in fires.
4. The fine particulate emissions at the Grenfell Towers fire were likely to be a major cause of death and impairment of escape.
5. Legislation to include particulate production to be determined in fire tests is urgently required.
6. The modified cone calorimeter is a good technique to use for realistic determination of particle size distributions in fires.