Comparative Toxicity of Biomass Smoke from Different Fuels and Combustion Conditions

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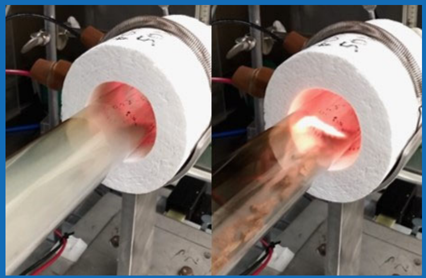
Public Health & Integrated Toxicology Division

Center for Public Health and Environmental Assessment

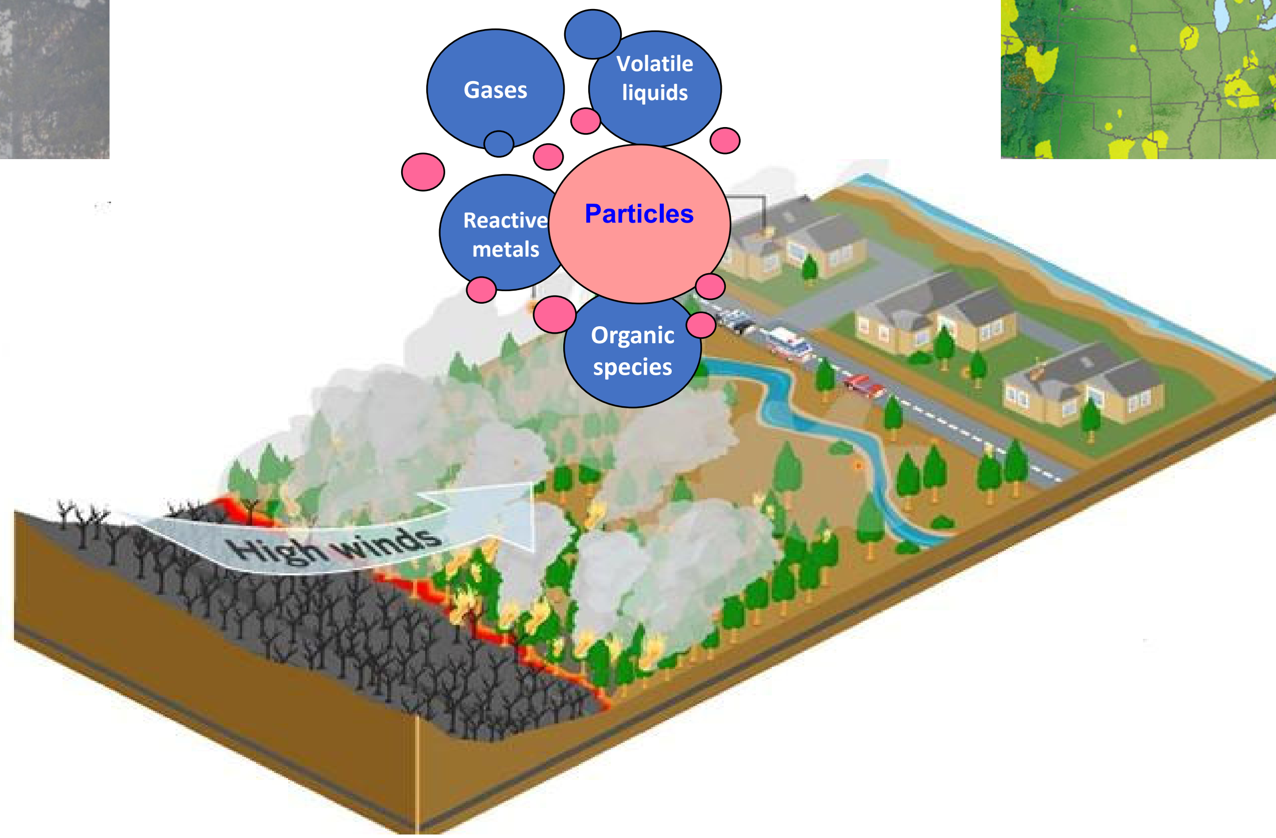


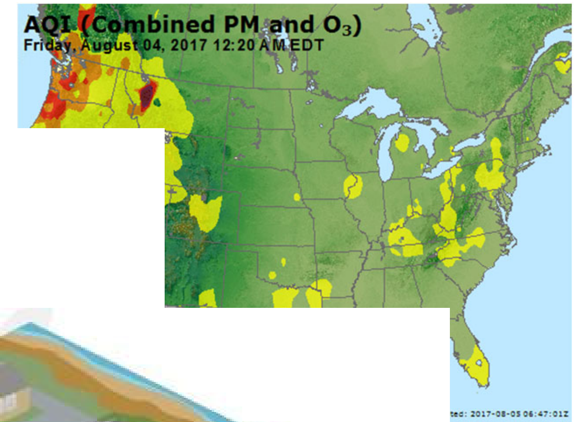
Inhalation and Respiratory Specialty Section Webinair

December 13th 2019

Where There is Smoke There are Health Impacts!

Sept. 1, 2017, Air quality in Seeley Lake had h
pollution readings classified as hazardous in 2
August. (Rion Sanders/AP)





Emissions by Chemical Class for Particle and Vapor Constituents in Woodsmoke

Chemical	Particle-phase (mg/kg wood burned)	Vapor-phase (mg/kg wood burned)
Carbon monoxide	---	130,000
Alkanes (C2-C7)	0.47 - 570	1.01 - 300
Alkenes (C2-C7)	0.58 - 280	92 - 1300
Polycyclic aromatic hydrocarbons (PAHs) and substituted PAHs	5.1 - 32,000	43.4 - 355
Methane	---	4100
Total nonmethane hydrocarbons C2-C7	[Included in vapor phase]	390 - 4000
Unresolved complex mixture (UCM)	300 - 1,130,000	---
Alkanols	0.24 - 5400	120 - 9200
Carboxylic acids	6200 - 755,000	2.4
Aldehydes and ketones	[Included in vapor phase]	0.94 - 4450*
Alkyl esters	0.37 - 4450	---
Methoxylated phenolic compounds	28 - 1000	1200 - 1500
Other substituted aromatic compounds	5.0 - 120,000	110 - 3600
Sugar derivatives	1.4 - 12600	---
Coumarins and flavonoids	0.71 - 12	---
Phytosteroids	1.7 - 34.0	---
Resin acids and terpenoids	1.7 - 41,000	21 - 430
Unresolved compounds	1.2 - 120	20 - 600

* *Only aldehydes reported.*

L.P. Naeher et al, Inhalation Toxicology 2007

*Source-Based Inhalation Toxicology Studies at LRRI **

	Irritation & Inflammation	Allergies & Asthma	Respiratory Defenses	Respiratory & Cardiac Functions	Cancer
Diesel exhaust	*	*	*	*	*
Wood Smoke	*	*	*	*	*
Gasoline exhaust	*	*	*	*	*
Coal emissions	*	*	*	*	*
Cooking fumes	*	*	*	*	*
Road dust	*	*	*	*	*
Tobacco smoke	*	*	*	*	*

- **Study of each atmosphere creates a "layer" in the combined database**
- **Multiple animal models address a range of health concerns**

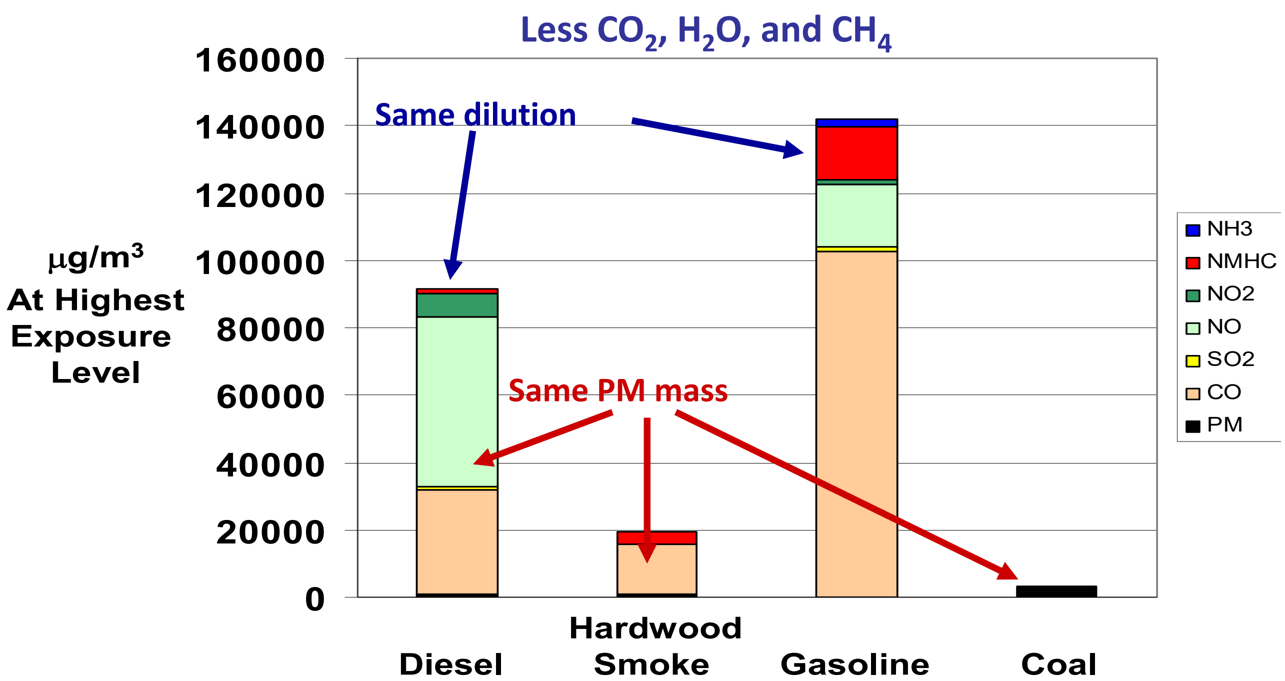
4 Exposure Levels = 6 hr/day, 7 days/wk for up to 6 months

* Lovelace Respiratory Research Institute (LRRI) – National Environmental Respiratory Center

Mauderly and Colleagues. Inhalation Tox, 26(11), 2014

Courtesy, Dr J McDonald

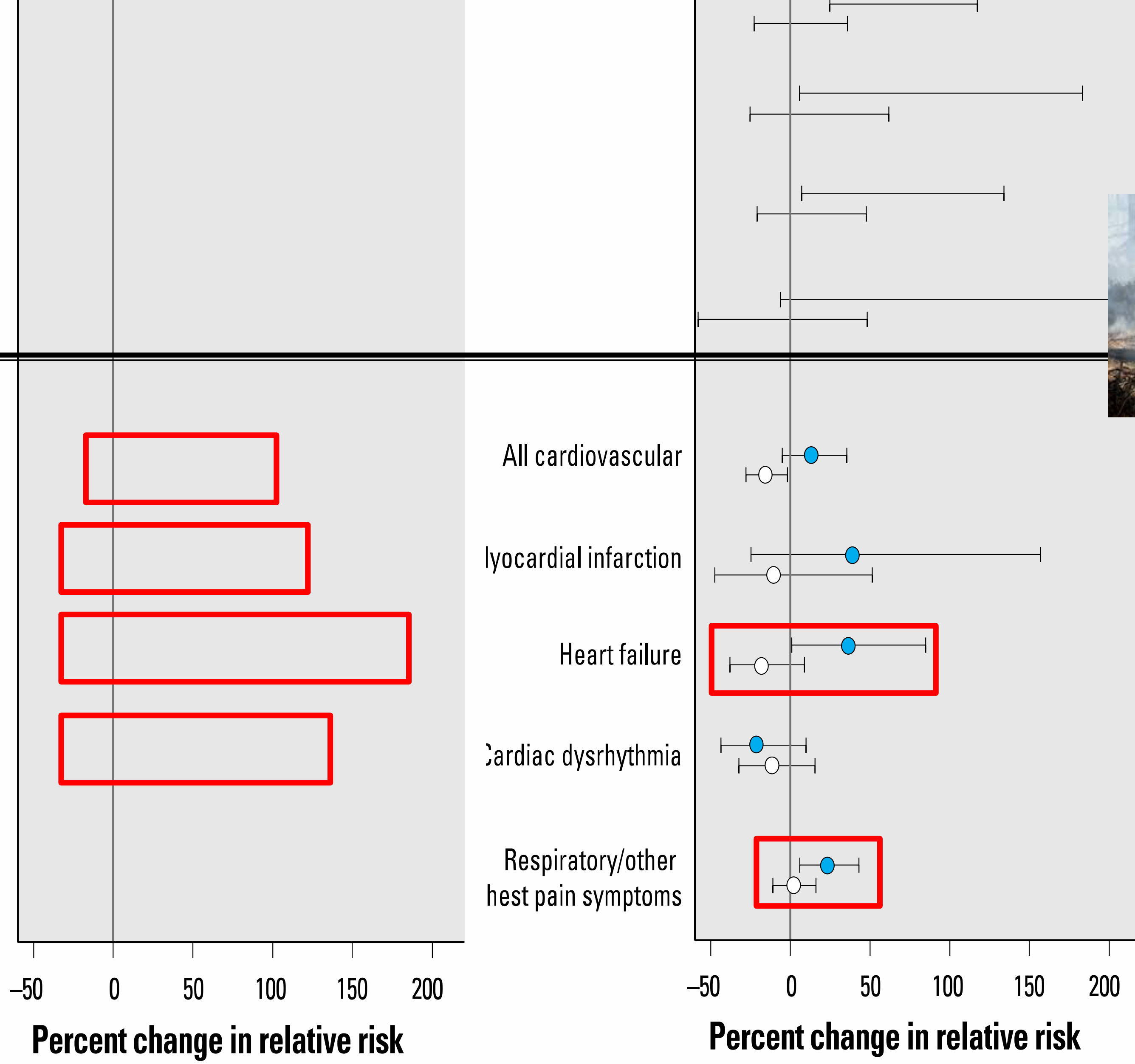
Conclusion from NERC



Diesel significantly affected the most parameters - coal the fewest DE ≥ GE > HWS >>> C

Gas phase components had a significant contribution

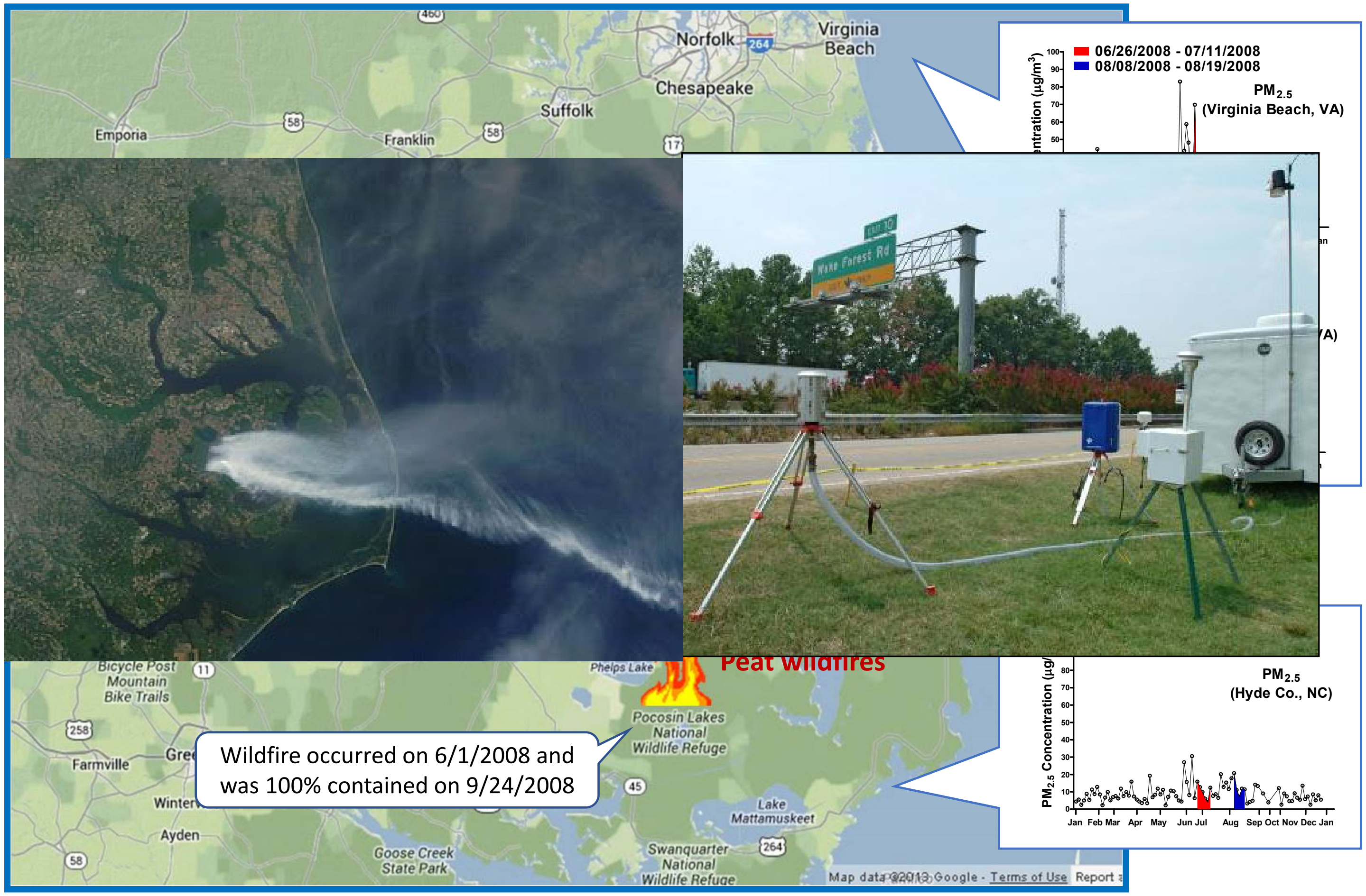
Courtesy, Dr J McDonald
Mauderly, Inhalation Tox, 26(11), 2014



Percent change in cumulative RR by discharge diagnosis category for exposed and referent counties in NC during 3-day period of high exposure compared with the entire 6-week study period.

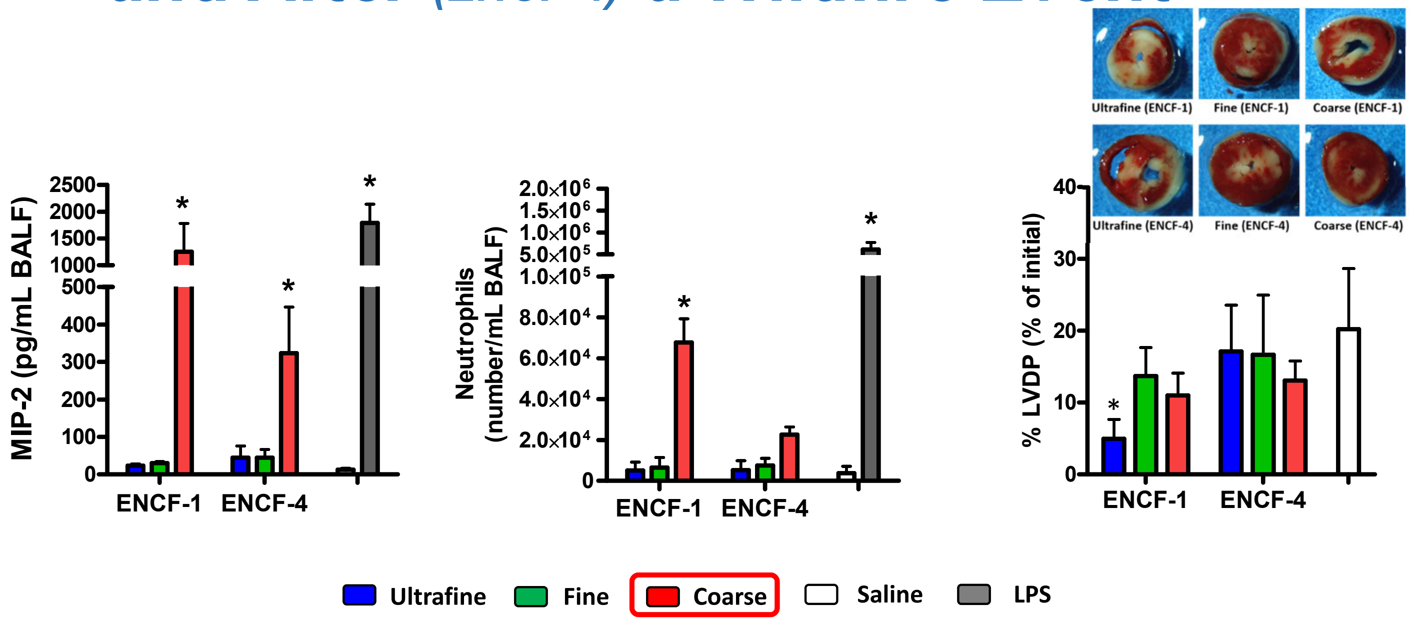
Rappold AG et al. Environ. Health Perspectives 2011

Location of Chemvol PM Sampler and Monitoring Data for (ENCF-1 and ENCF-4)



Kim et al Particle, Fiber Tox, 16,2014

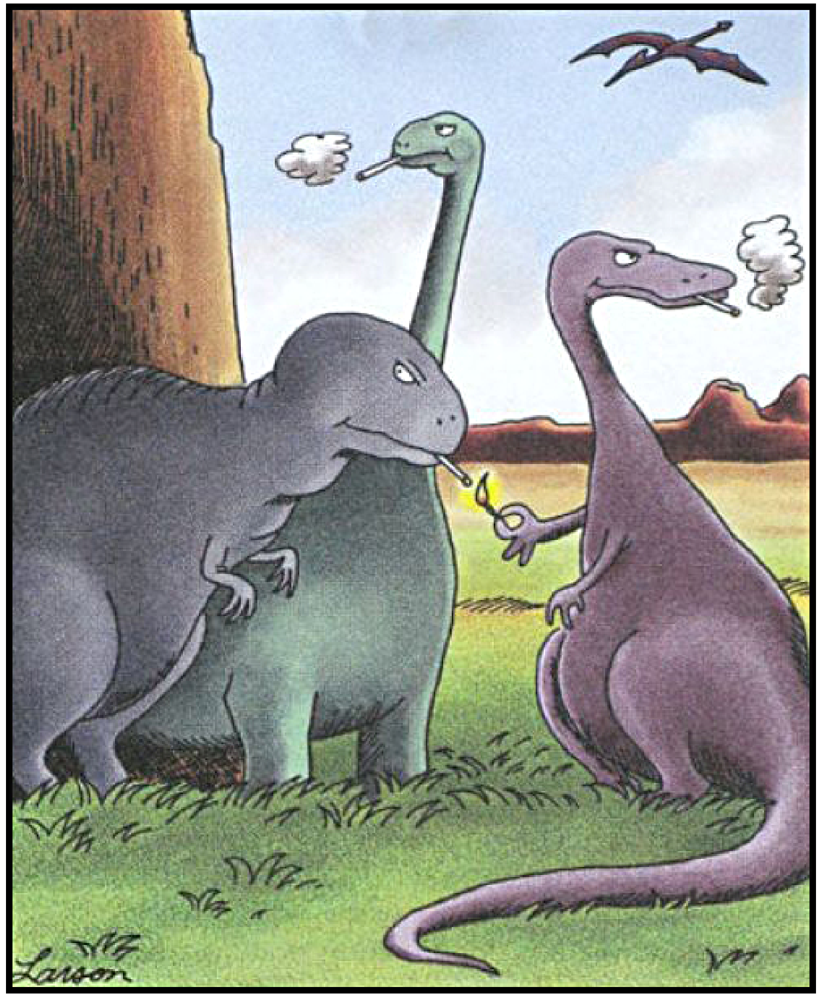
Comparative Toxicity of PM During (ENCF-1) and After (ENCF-4) a Wildfire Event



Exposure to the coarse PM significantly increased the levels of cytokines (IL-6, TNF-α, and MIP-2) and neutrophils in BALF of mice and this was higher with ENCF-1.

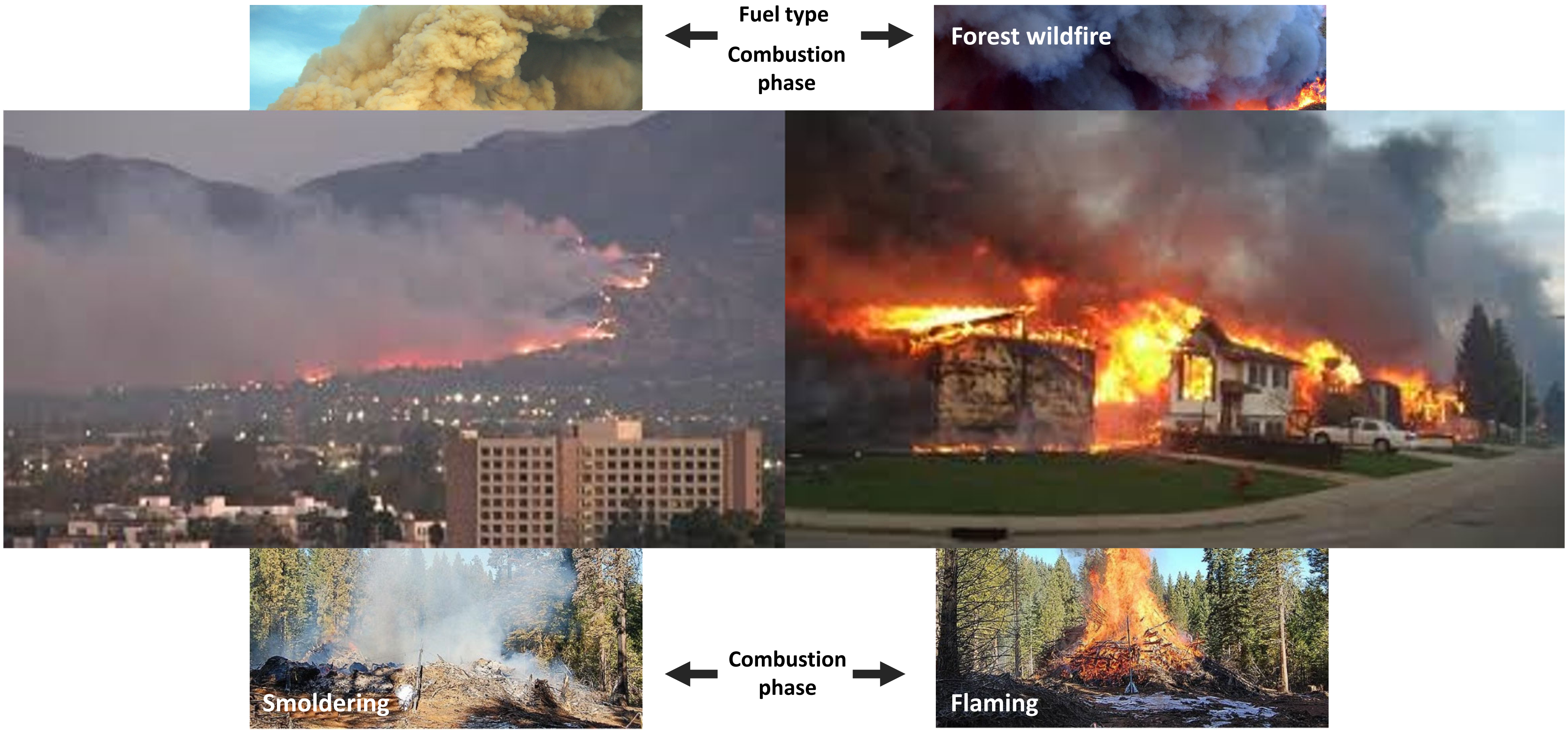
Exposure to the ultrafine PM from ENCF-1 significantly decreased cardiac function (left ventricular developed pressure) in mice compared to all other samples.

Kim et al Particle, Fiber Tox, 16,2014



The real reason dinosaurs became extinct

All Smoke Is Not Created Equally!



Laboratory Generated Smoke Collection and Analysis with Subsequent Toxicity Testing

Objective:

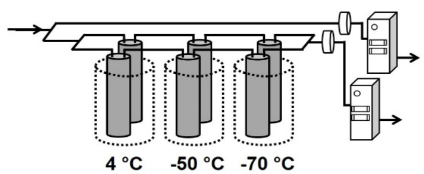
Compare the relative cardiopulmonary toxicity and mutagenicity of coarse and fine/ultrafine emissions from four distinct fuel types (pine, oak, peat, and a mixed pine and deciduous Southeastern forest biomass) obtained from both smoldering and active flame phases.

Combustion

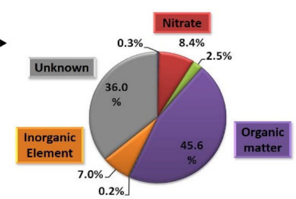
Fire enclosure
(28 m^3)
Mixed fuels

Collection/ Analysis

Cyclone/Cryotrap system



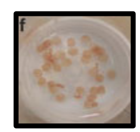
Particle and gas phase chemistry and mass balance



Toxicity Test

WT and K/O mice

Cells, Tissue slices

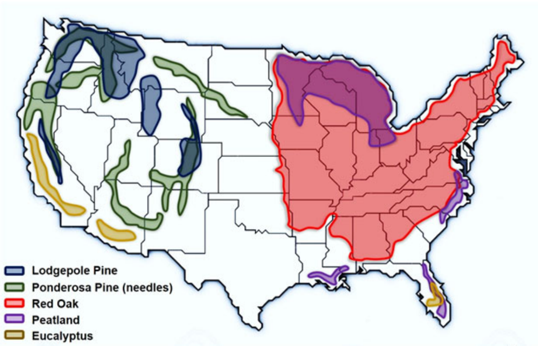


Toxicity Ranking matrix

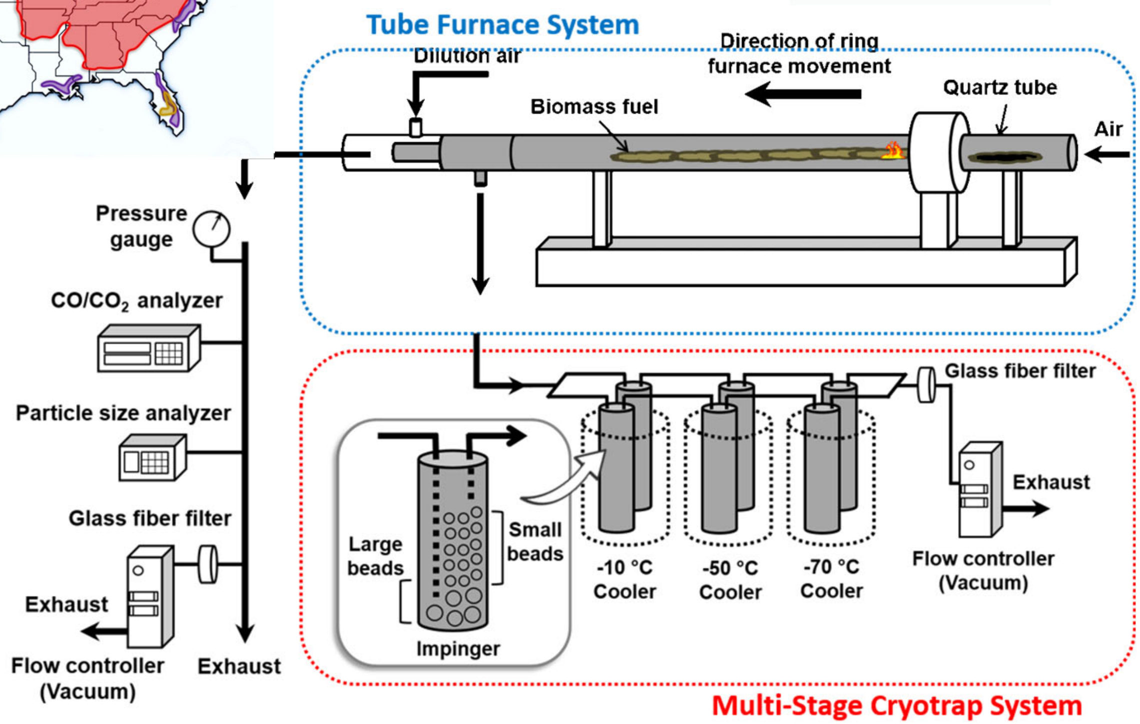
5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15
2	2	4	6	8	10
1	1	2	3	4	5
	1	2	3	4	5

Joint Fire Science Program, Dept of Interior. FY 15-17 Project #14-1-04

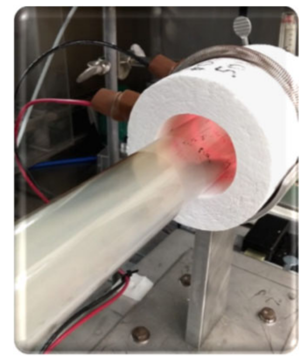
Biomass Combustion and Smoke Sampling System



Yong Ho Kim



Ring-Type Electric Heater



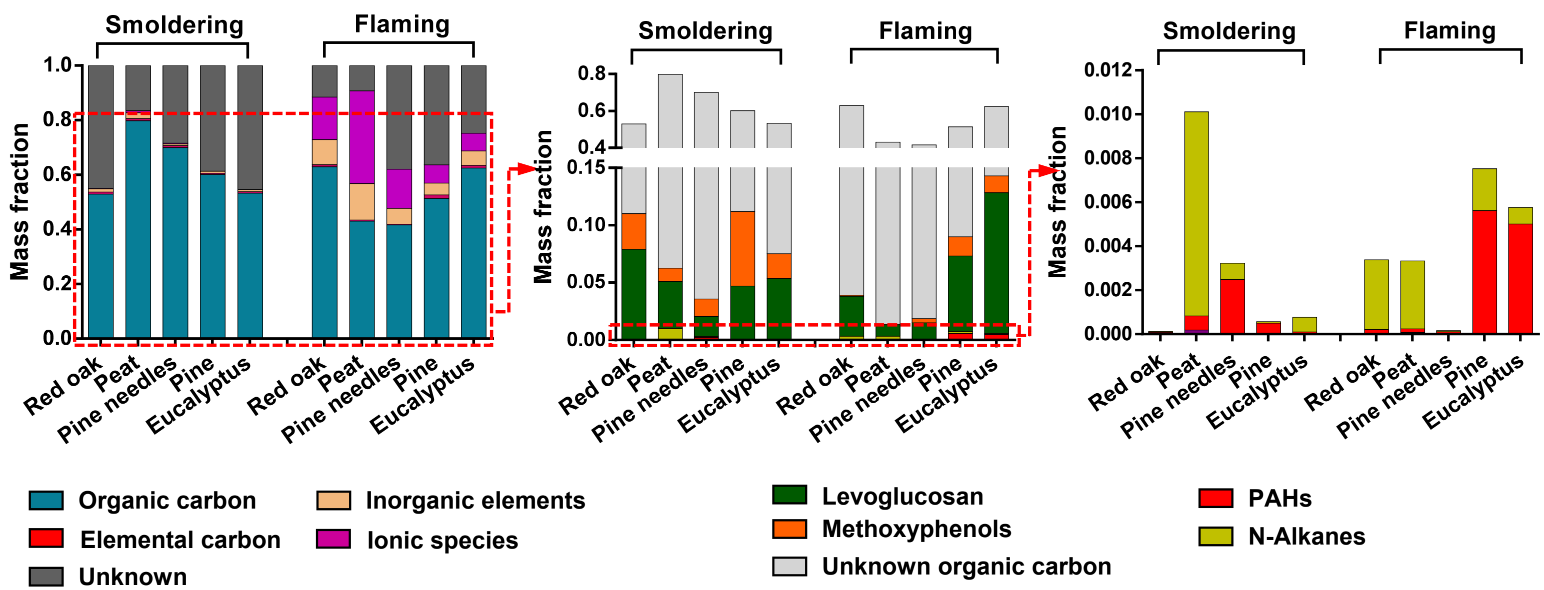
Transition from smoldering to flaming combustion

- The tube furnace is able to sustain stable flaming or smoldering phase consistently for 60 min.
- The cryotrap system is able to collect PM and semi-volatile compounds.

Kim et al EHP (126:1), 2018

Chemical Components in Biomass Smoke Condensate

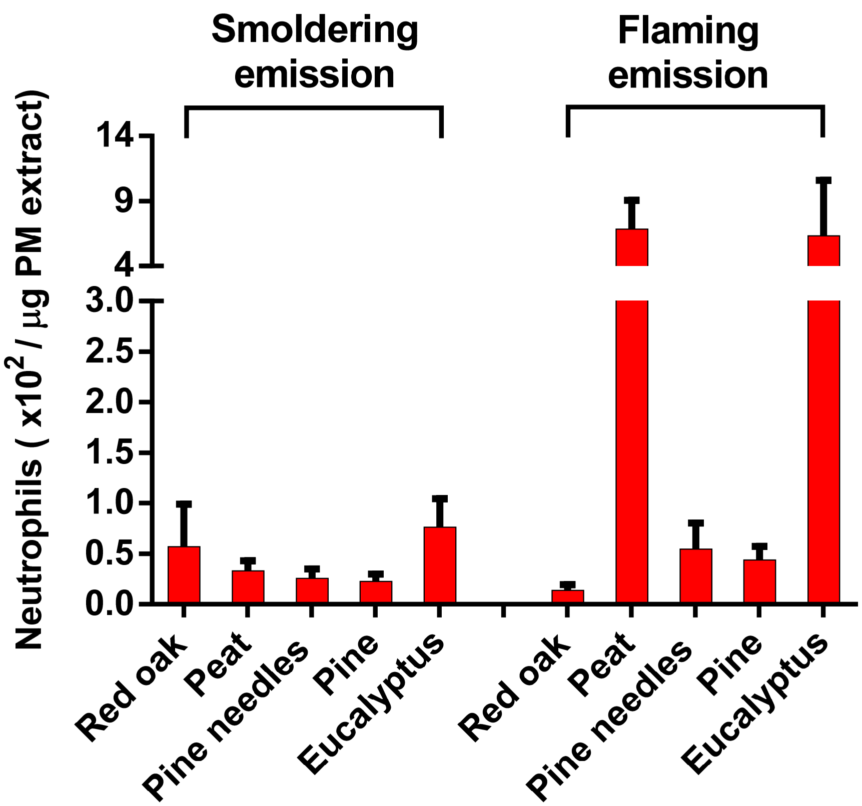
Major chemical compounds **Semi-volatile organic compounds**



- Chemical properties of biomass smoke varied depending on fuel types and combustion phases.
- Inorganic elements (e.g., heavy metals) and PAHs were higher in the flaming smoke PM.

Kim et al EHP (126:1), 2018

*Lung Toxicity of the Biomass Smoke Condensates Based on **Equal Mass***



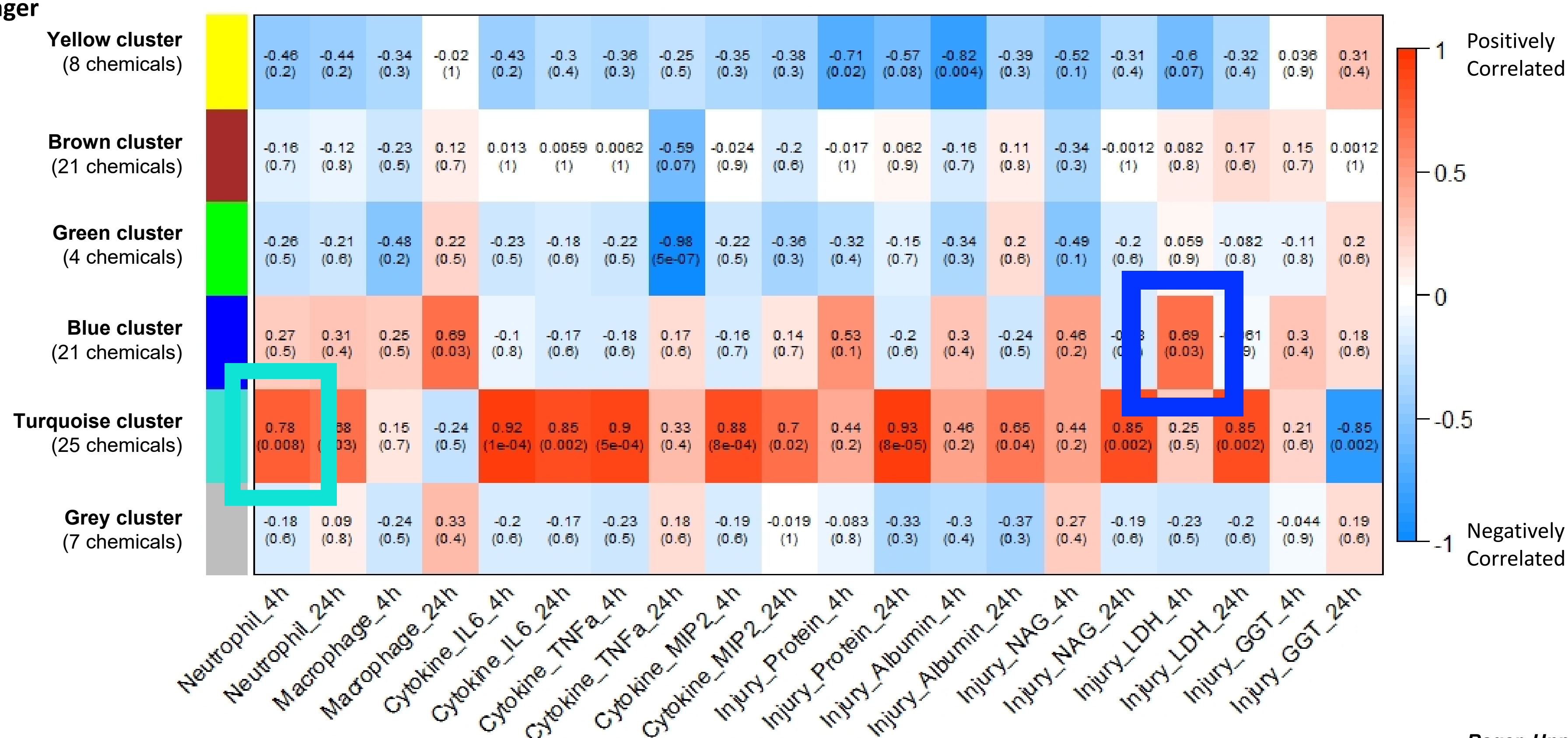
Lung toxicity
BAL fluid of CD-1 mice at 24 h exposure

Flaming emissions ❯ **Smoldering emissions**

Kim et al EHP (126:1), 2018

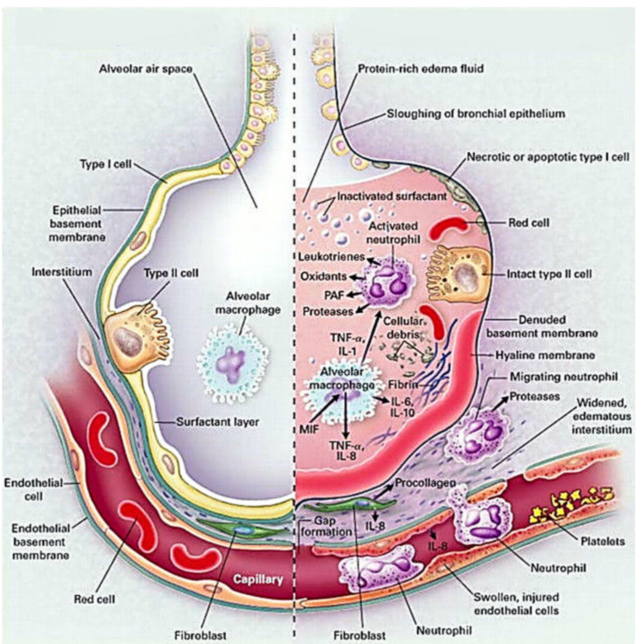
Julia Rager

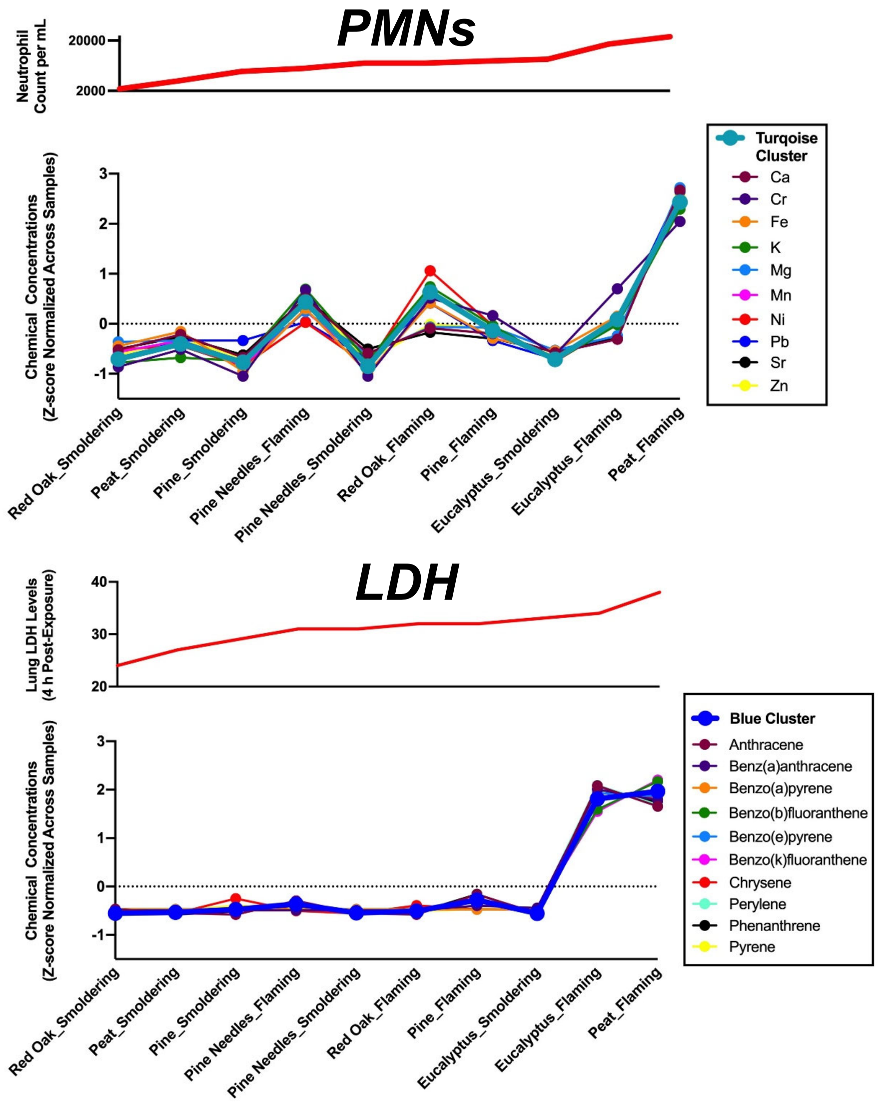
Bioinformatics Approach to Link Toxicity Responses with Chemical Clusters



Rager. Unpublished

Top-Ranking Species Across Biomass Burns Associated with Neutrophil Inflammation (PMNs) and Lung Injury (LDH)

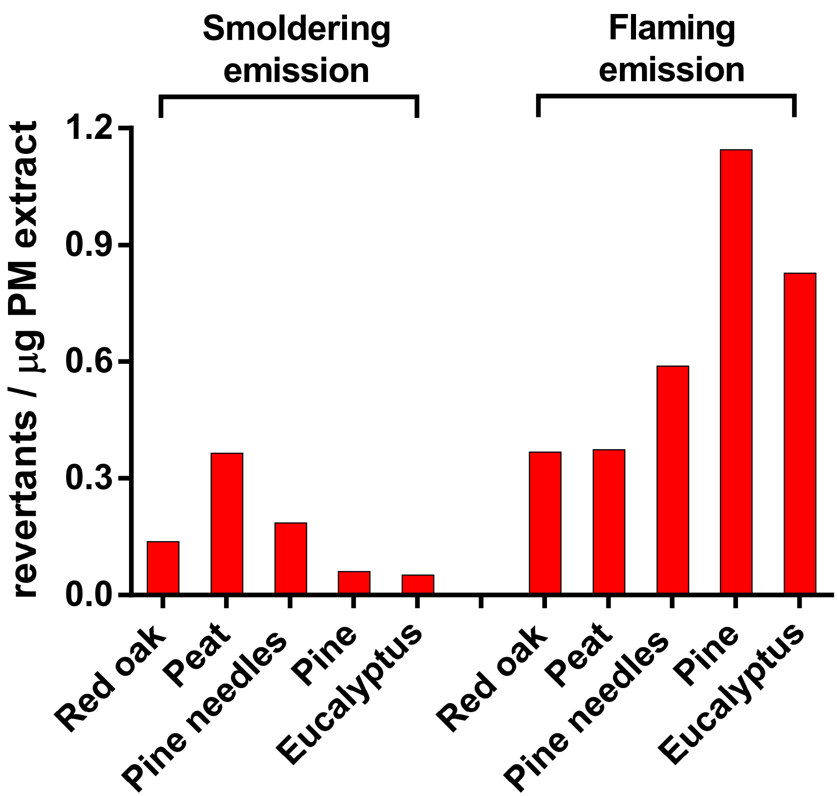




Rager. Unpublished

*Mutagenicity of the Biomass Smoke Condensates Based on **Equal Mass***

David DeMarini



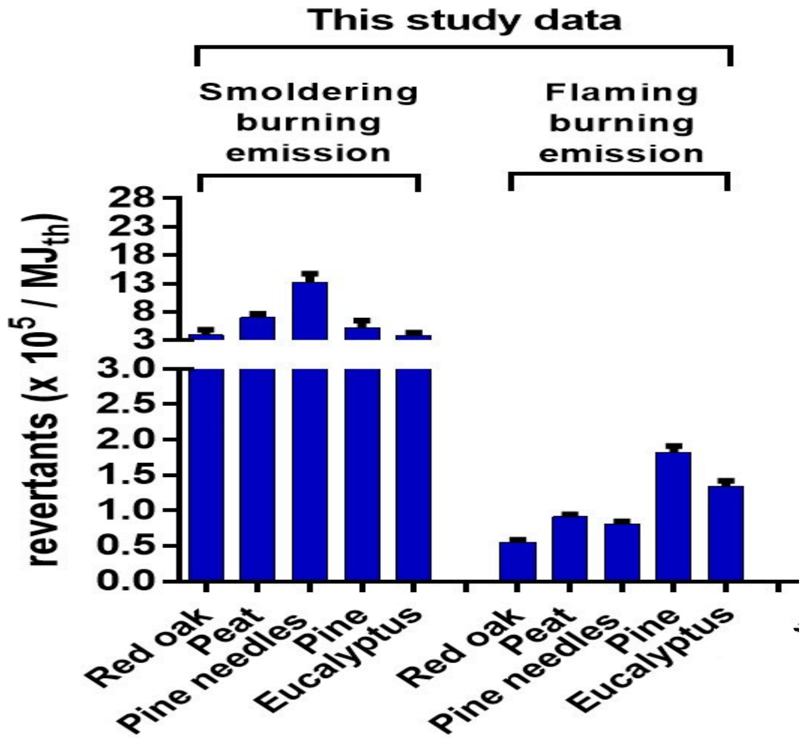
Mutagenicity

Salmonella strain TA98 +S9

Flaming emissions ❭ Smoldering emissions

Kim et al EHP (126:1), 2018

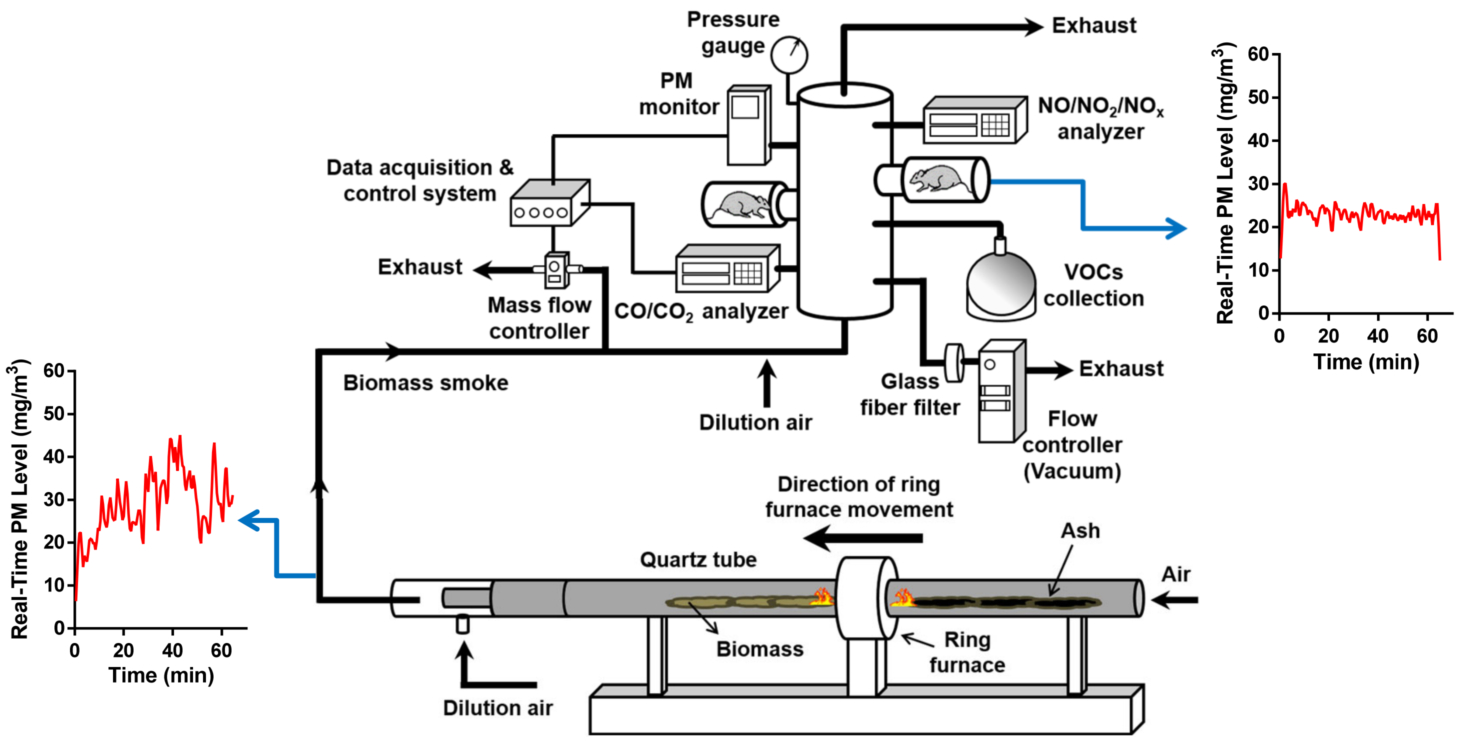
Comparison of Mutagenicity Emission Factors (EFs) of Various Combustion Emissions



The mutagenicity EFs (rev/kg fuel; Figure 6C) were converted to rev/MJ_{th} u..g the values for the heat energy of each fuel (MJ_{th}/kg fuel). The mutagenicity EFs for wood burning cookstove emissions were 0.2, 1.2, and 2.4×10^5 rev/MJ_{th} for the force-draft stove, natural-draft stove, and three-stone fire, respectively, and the data were obtained from a previous report (Mutlu et al. 2016). The mutagenicity EFs for non-wood burning emissions were 0.4, 0.4, 2.5, and 22.7×10^5 rev/MJ_{th} for the municipal waste, diesel exhaust, agricultural plastic, and tire, respectively, and the data were obtained from previous reports (DeMarini et al. 1994; Linak et al. 1989; Mutlu et al. 2015; Watts et al. 1992).

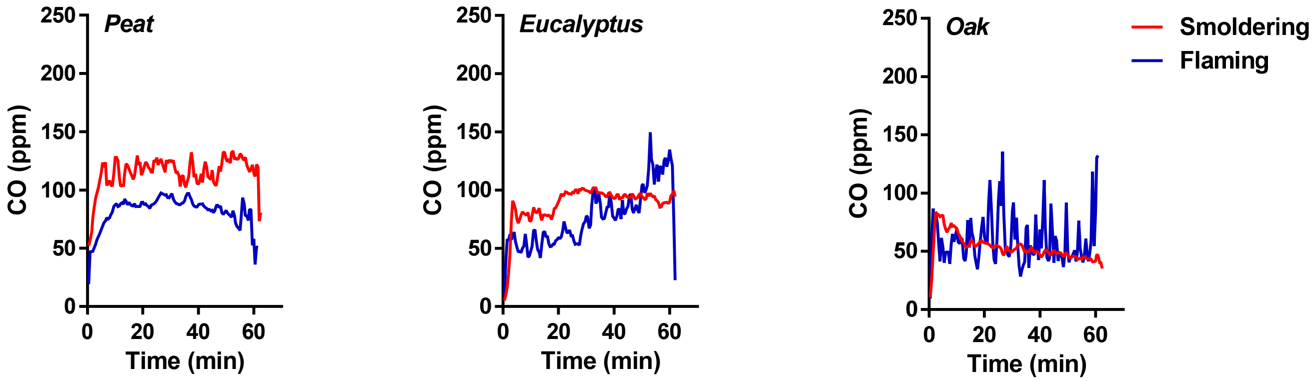
Kim et al EHP (126:1), 2018

Creating Stable Biomass Emissions in a Computer-Controlled Inhalation Exposure System



Kim et al Arch Tox 93(6), 2019.

Stable Biomass Smoke Atmospheres Created Through a Feedback Control Loop



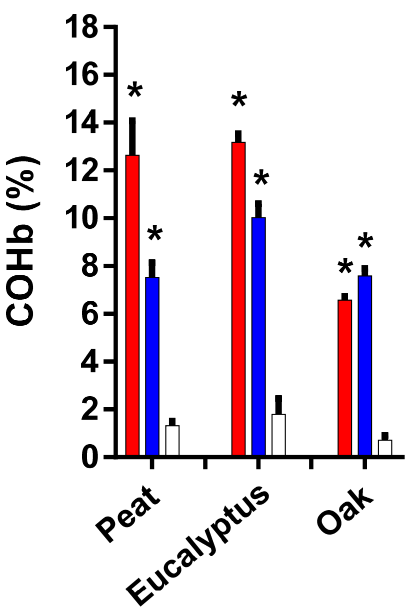
Kim et al Arch Tox 93(6), 2019.

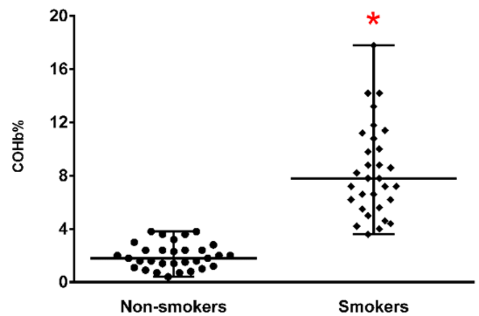
Effect of Fuel and Combustion Conditions on Carboxyhemoglobin and Lung Inflammation

<u>Inhalation Exposure</u>

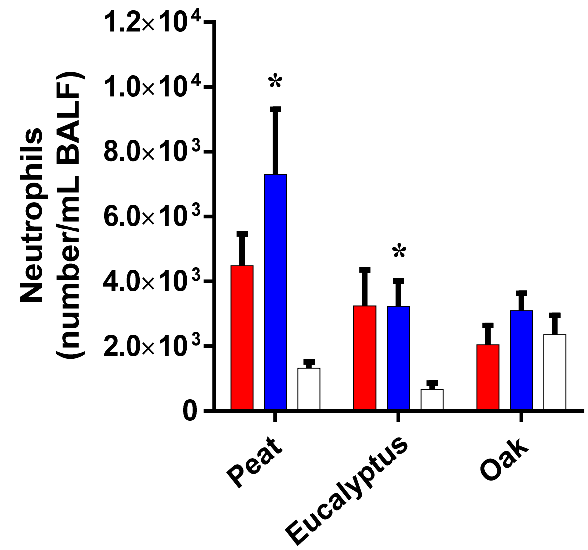
~40 mg/m³ of smoldering smoke PM

~4 mg/m³ of flaming smoke PM





Boehm et al, PLOS One, (0204102, 2018)



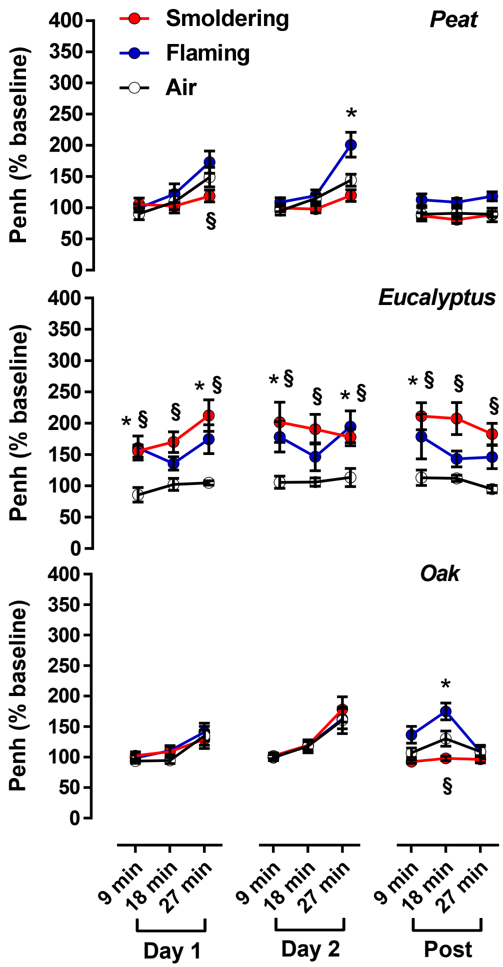
Carboxyhemoglobin mirrored CO exposure levels (mean is 5-8 % in smokers)

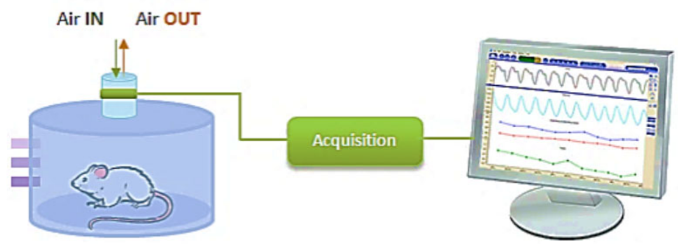
The flaming peat and eucalyptus were as potent as smoldering samples despite 10-fold lower PM concentration

Kim et al Arch Tox 93(6), 2019.

Steve Gavett

Lung Function Responses (*In Vivo*)





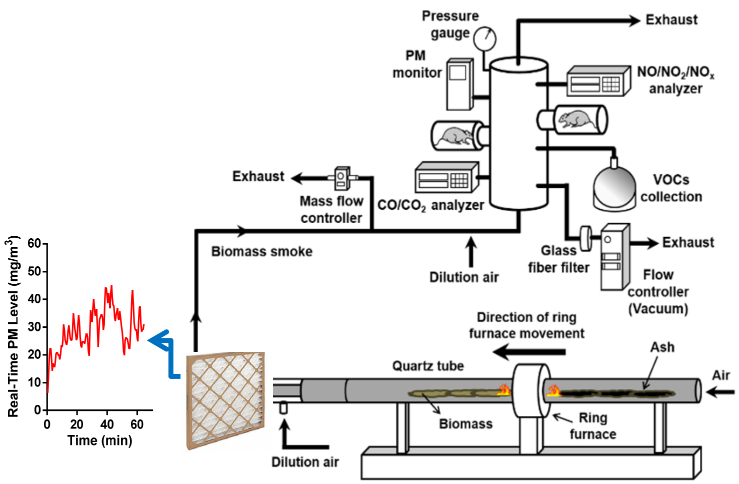
<u>Mouse Ventilatory Function Analysis</u>

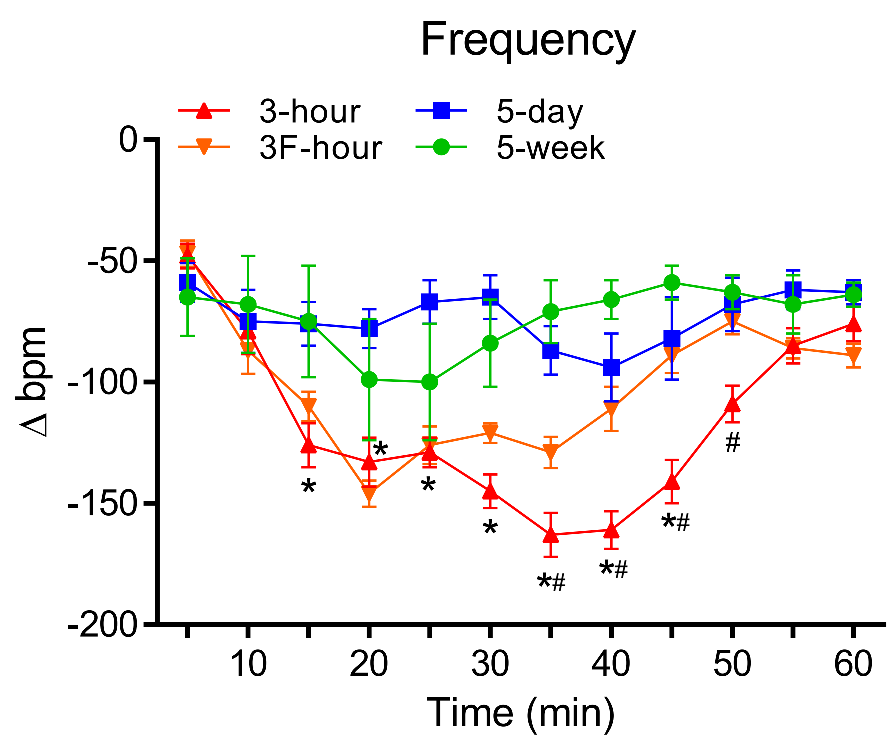
Ventilatory function parameters were measured at 9 min intervals in the 30 min before exposure (baseline), right after exposures (Day 1 and Day 2), and 24 h after the second day exposure (Post), respectively.

- **A significant increase in airflow obstruction (as measured by Penh) was observed in mice exposed to flaming peat (*) and eucalyptus (*), and smoldering eucalyptus (§) smoke immediately after each day of exposure.**

Kim et al Arch Tox 93(6), 2019.

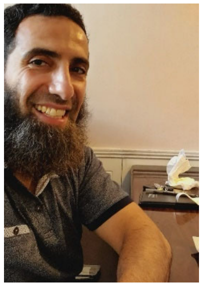
Inhalation Exposure Shows Greater Effects of 1-Day CxT vs. Longer CxT Exposure Protocol on Breathing Frequency, and Partial Benefit from Filtering the Smoke





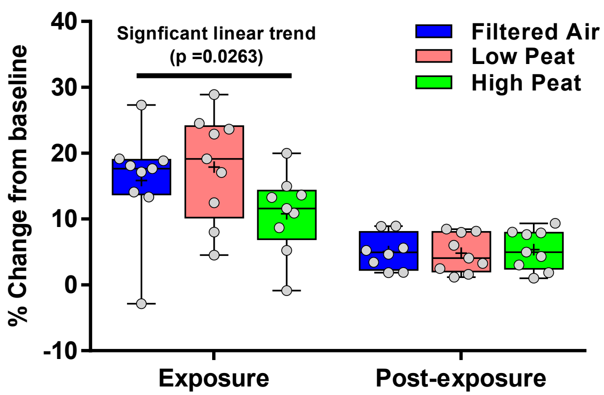
Hargrove et al Inhalation Tox 31 (6), 2019.

Cardiovascular Impacts of Single Exposure to Low or High Smoldering Peat

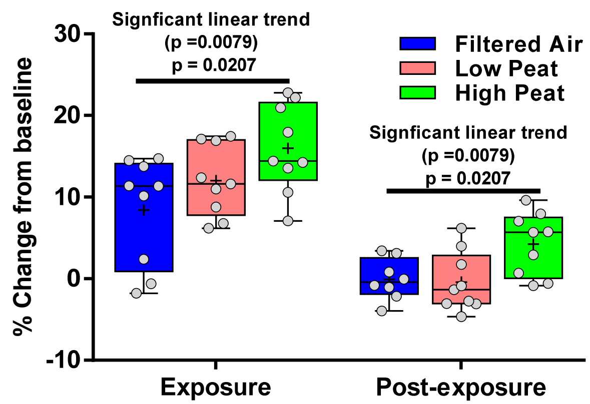


Aimen Farraj

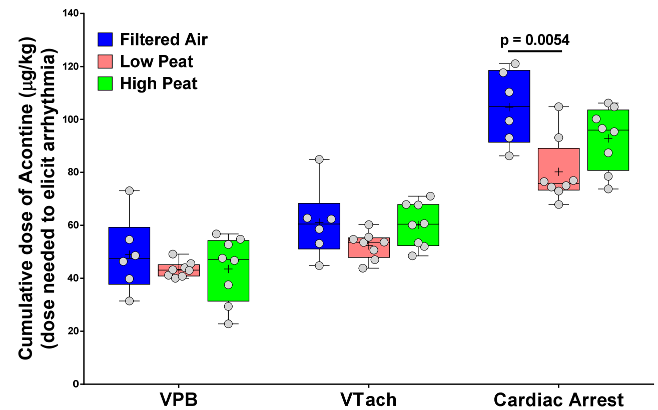
Heart rate



Diastolic Blood Pressure



Sensitivity to Aconitine Challenge



- VPB – ventricular premature beat
- VTach – ventricular tachycardia

Farraj. Unpublished

Conclusions

The combustion system and associated methods provide stable and reproducible smoke atmospheres that can be used for emission testing and toxicity assays.

Fuel composition and combustion conditions influence the chemistry, toxicity and mutagenicity of biomass smoke with peat and eucalyptus smoke being more potent (on a PM mass basis) than e.g. oak.

Biomass smoke inhalation has significant effects on lung injury and inflammation, and decreases breathing frequency and heart rate, while increasing blood pressure and risk of cardiac disease.

Depending on the fuel type, filtration can partially but not completely abrogate pulmonary effects.

Where do we go from here?

Continue exploring effects of acute, intermittent and chronic exposures from various scenarios (including combustion of man-made materials) on health endpoints.

Utilize these and other toxicological approaches to identify most effective interventions (e.g. air purifiers, filtration, anti-oxidants etc).

Determine relative potency of fresh and “aged” biomass smoke against other sources: e.g. mobile sources, power plant emissions and urban “smog”.

Assess the effect of smoke exposure on higher throughput in vitro systems e.g. 3D human lung cell cultures at the air liquid interphase (ALI).

Perform mechanistic studies under both healthy and at-risk (e.g. asthma diabetes, COPD, in utero) conditions.

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- Todd Krantz
- Charly King
- John McGee

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- David DeMarini
- Sarah Warren

U.S. EPA / Air Pollution Prevention and Control Division (APPCD)

- Mike Hays
- Bill Preston
- Kasey Kovalcik

University of North Carolina

- Julia Rager

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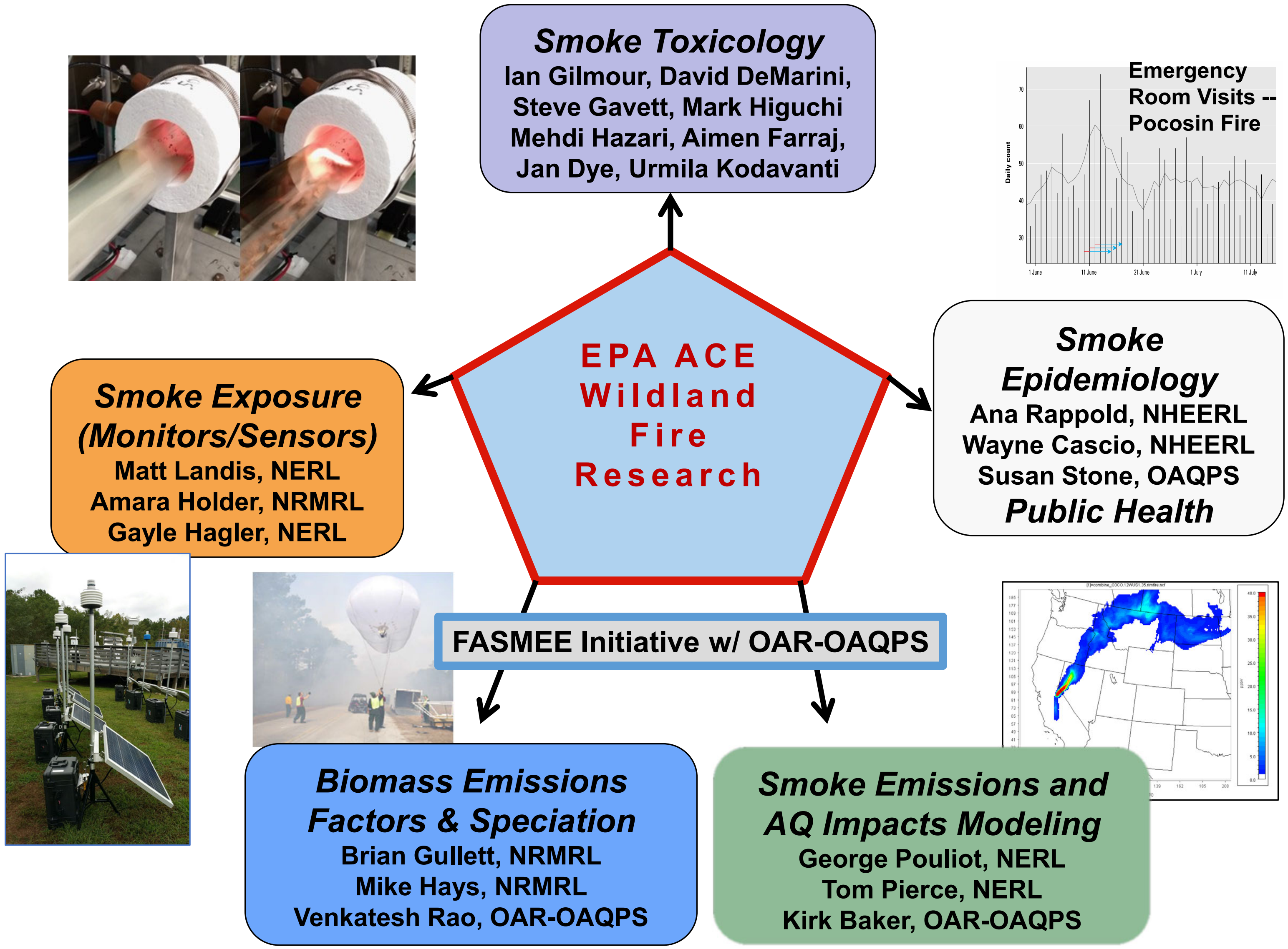
- Shawn Urbanski

LRRI Albuquerque (slides)

- Jake McDonald

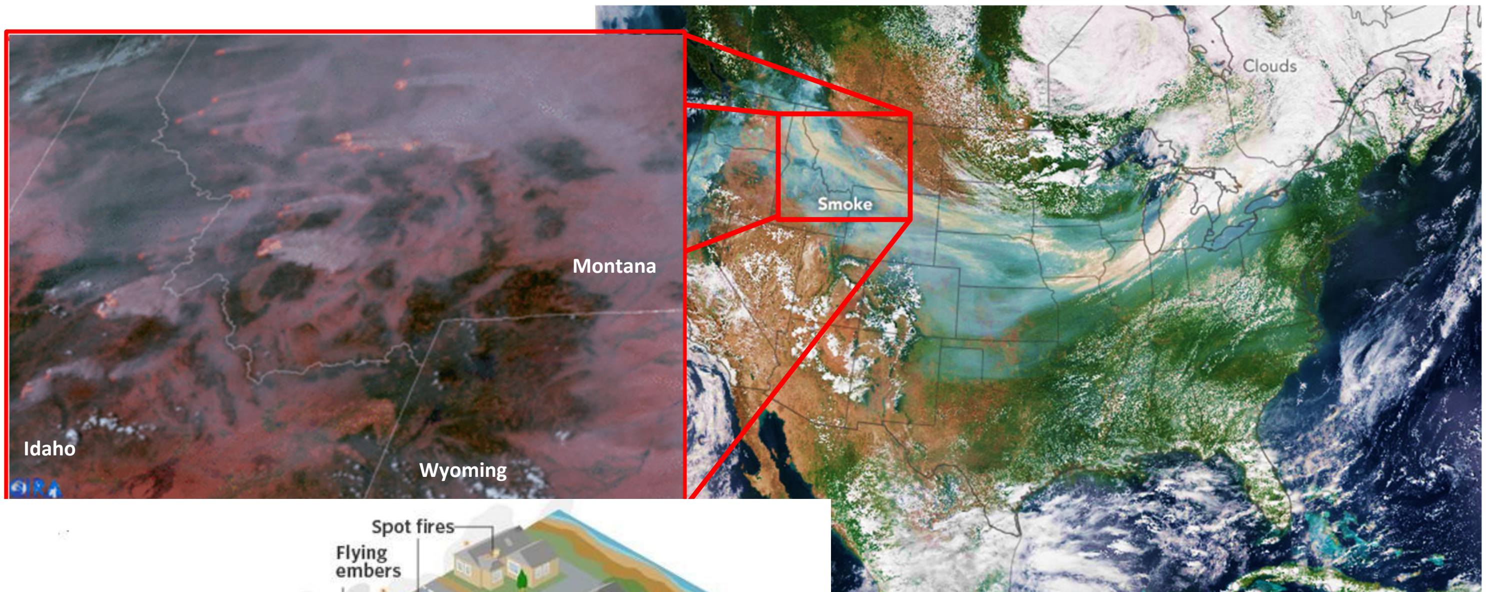


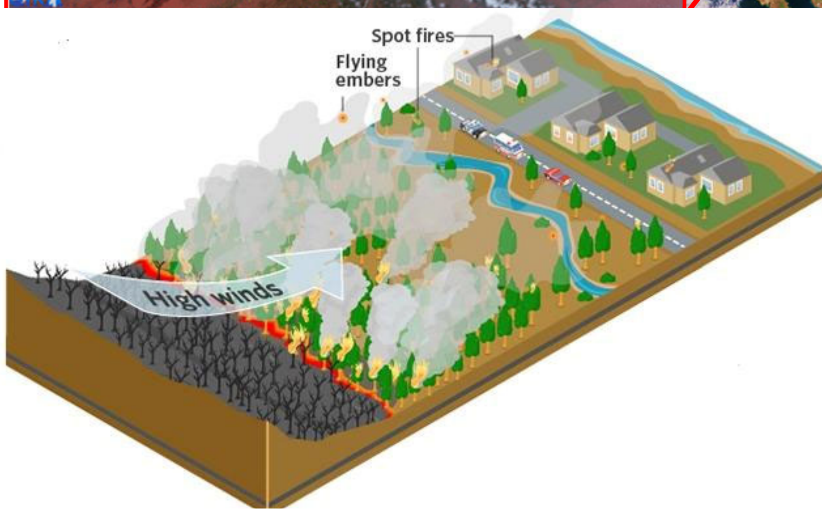
Smoke Toxicology
Ian Gilmour, David DeMarini,
Steve Gavett, Mark Higuchi
Mehdi Hazari, Aimen Farraj,
Jan Dye, Urmila Kodavanti
Emergency
Room Visits --
Pocosin Fire
EPA ACE
Wildland
Fire
Research
Smoke Exposure
(Monitors/Sensors)
Matt Landis, NERL
Amara Holder, NRMRL
Gayle Hagler, NERL
Smoke
Epidemiology
Ana Rappold, NHEERL
Wayne Cascio, NHEERL
Susan Stone, OAQPS
Public Health
FASMEE Initiative w/ OAR-OAQPS
Biomass Emissions
Factors & Speciation
Brian Gullett, NRMRL
Mike Hays, NRMRL
Venkatesh Rao, OAR-OAQPS
Smoke Emissions and
AQ Impacts Modeling
George Pouliot, NERL
Tom Pierce, NERL
Kirk Baker, OAR-OAQPS

Extra slides

What About Atmospheric Aging of Wildfire Smoke?

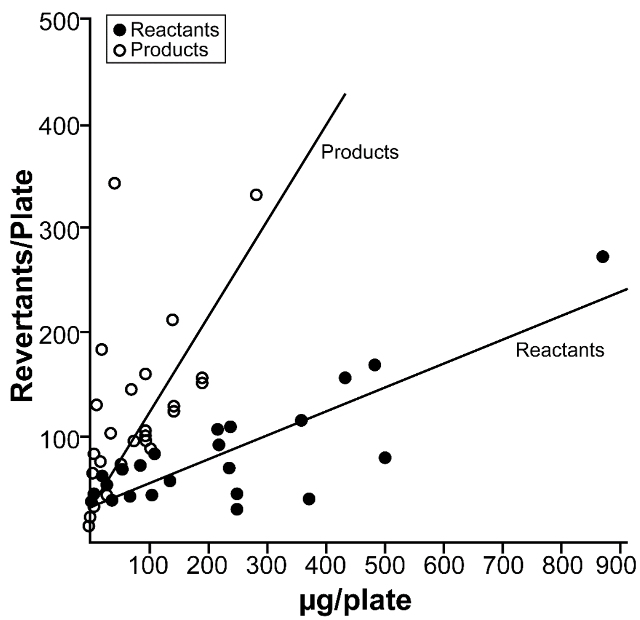
September 4, 2017



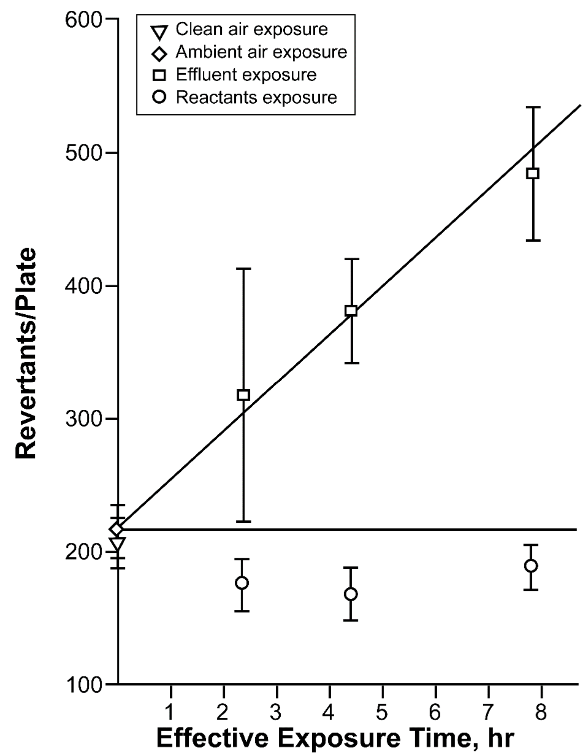


Mutagenicity of Fresh and Aged Wood Smoke

[TE Kleindienst et al., ES&T 20:493, 1986]

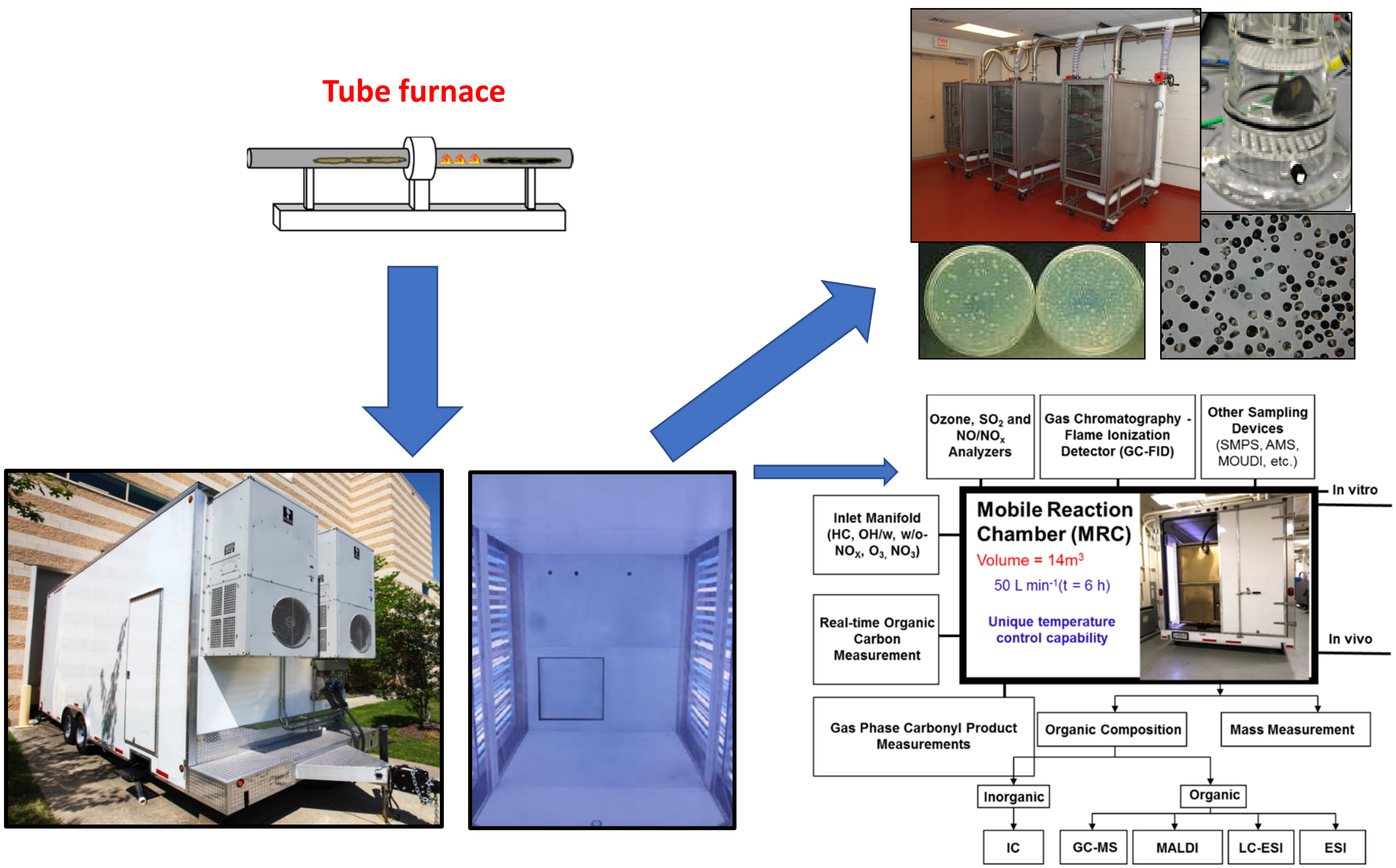


Dichloromethane extracts of PM were 3X more mutagenic in TA98 (+/- S9) with UV lights on (reactants) than when lights were off (products).



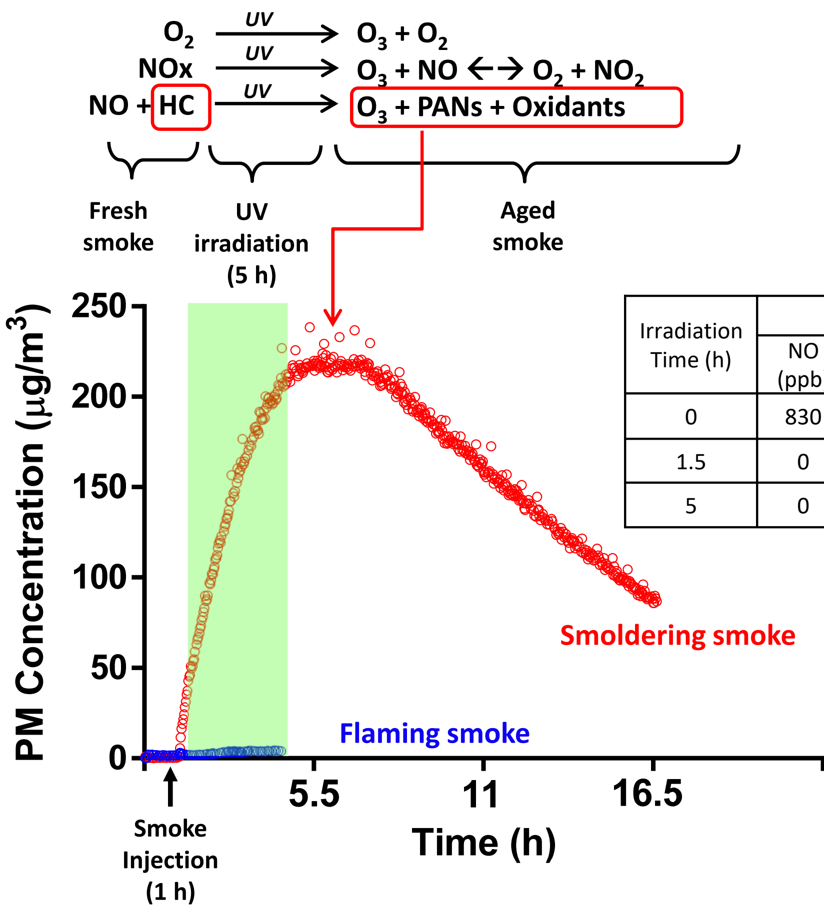
Gas-phase emissions from combustion of burning oak produced 36 revertants/h in TA100 (same + or – S9) with UV lights on. No mutagenicity was observed with lights off.

Photochemical Aging of Smoke with Real-Time or Subsequent Health Impact Testing.



Photochemically Aged Wood Smoke, 2018

Eucalyptus Smoke (filtered)

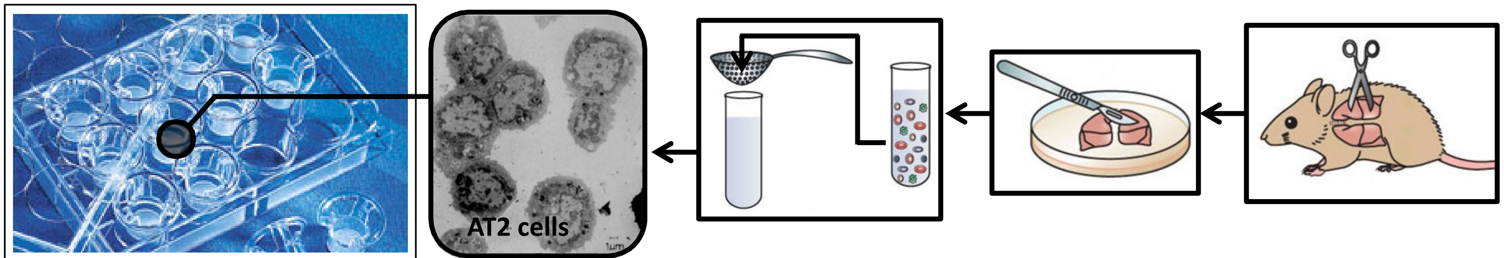


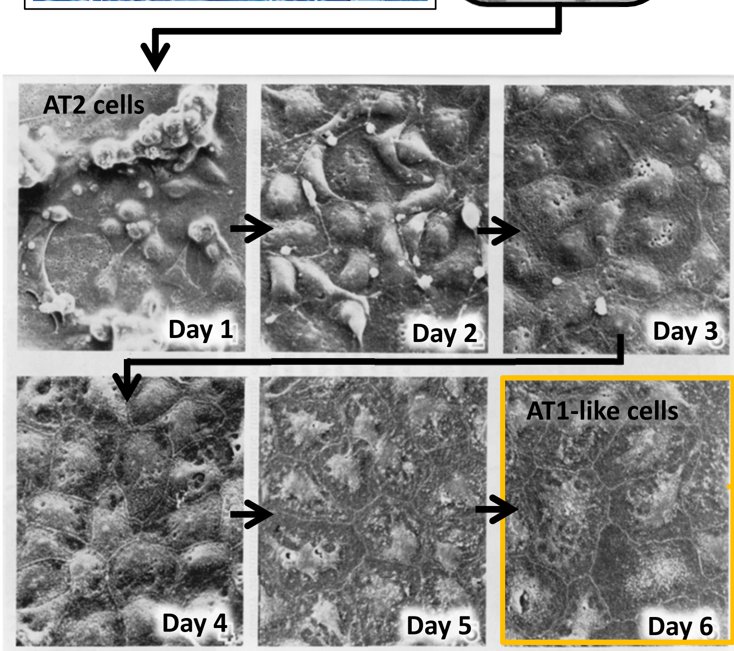
Irradiation Time (h)	Flaming smoke			Smoldering smoke		
	NO (ppb)	NOx (ppb)	THC (ppmC)	NO (ppb)	NOx (ppb)	THC (ppmC)
0	830	1034	0.51	130	**169**	**23**
1.5	0	558	0.32	7	**144**	**28**
5	0	276	0.33	3	**122**	**27**

THC/NOx = ~130

Characteristic (unit)*		Peat		Oak		Eucalyptus	
		Smoldering	Flaming	Smoldering	Flaming	Smoldering	Flaming
Measured Values	MCE (%)	86±0	97±0	84±0	98±0	84±0	99±0
	CO (ppm)	115±1	81±1	56±1	59±2	79±1	79±2
	CO_2 (ppm)	721±5	2,794±40	297±5	2,942±65	415±6	5,358±63
	NO (ppb)	227±54	5,109±892	39±0	1,812±233	30±2	1,863±209
	NO_2 (ppb)	0±0	1,292±187	0±0	502±154	0±0	909±127
	NO_x (ppb)	227±54	6,380±1,079	39±0	2,303±384	30±2	2,758±332
	VOCs (ppb)	2,677	1,694	4,072	1,682	1,911	760
	PM (mg/m^3)	38.7±0.4	3.4±0.1	40.5±0.8	3.5±0.1	41.4±0.6	3.7±0.1

Alveolar Epithelial Type I Cells (*Primary Cell Model*)

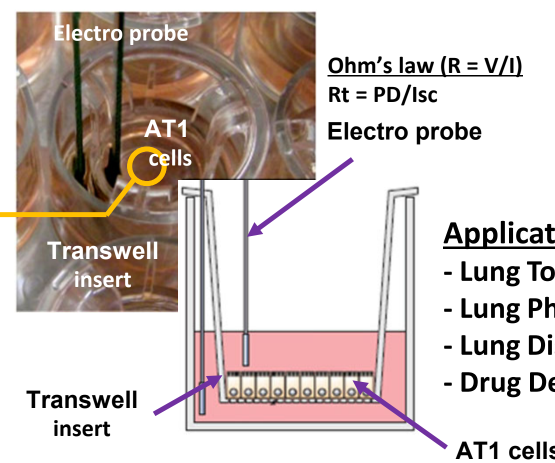




Adapted from Cheek, Evans and Crandall, Exp Cell Res, 1989

Bioelectric Phenotype of AT1

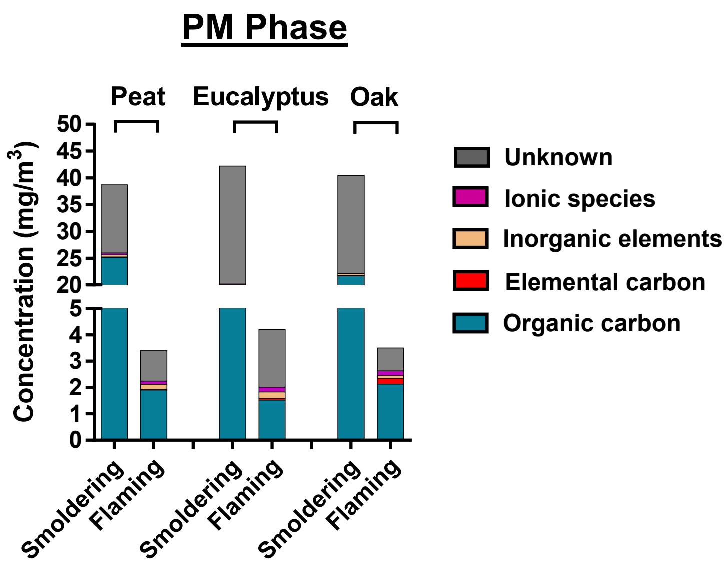
- **Potential difference (PD) ~10 mV**
- **Short circuit current (Isc) ~4.5 µA/cm2**
  :index of active Na+ transport
- **Transepithelial resistance (Rt) ~2.5 kΩcm^2**
  :index of epithelial barrier integrity

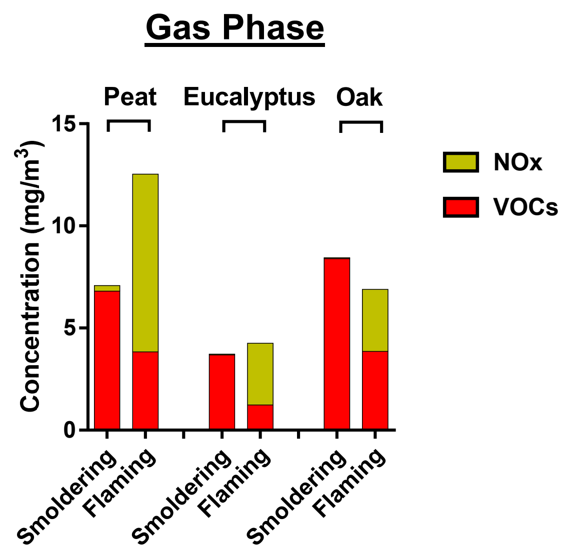


Applications

- **Lung Toxicology**
- **Lung Physiology**
- **Lung Disease**
- **Drug Delivery**

Chemical Components of Biomass Smoke





- Total carbon accounted for ~50 – 60% of PM from the smoke under any combustion conditions.
- Inorganic elements and ions were higher in the flaming smoke PM.
- Acetaldehyde, formaldehyde, and acrolein were found to be a major component of VOCs.

Kim et al Arch Tox 93(6), 2019.