Toxic Air Emissions from Burning Wood and Agricultural Plastics – A Cone Calorimeter Study

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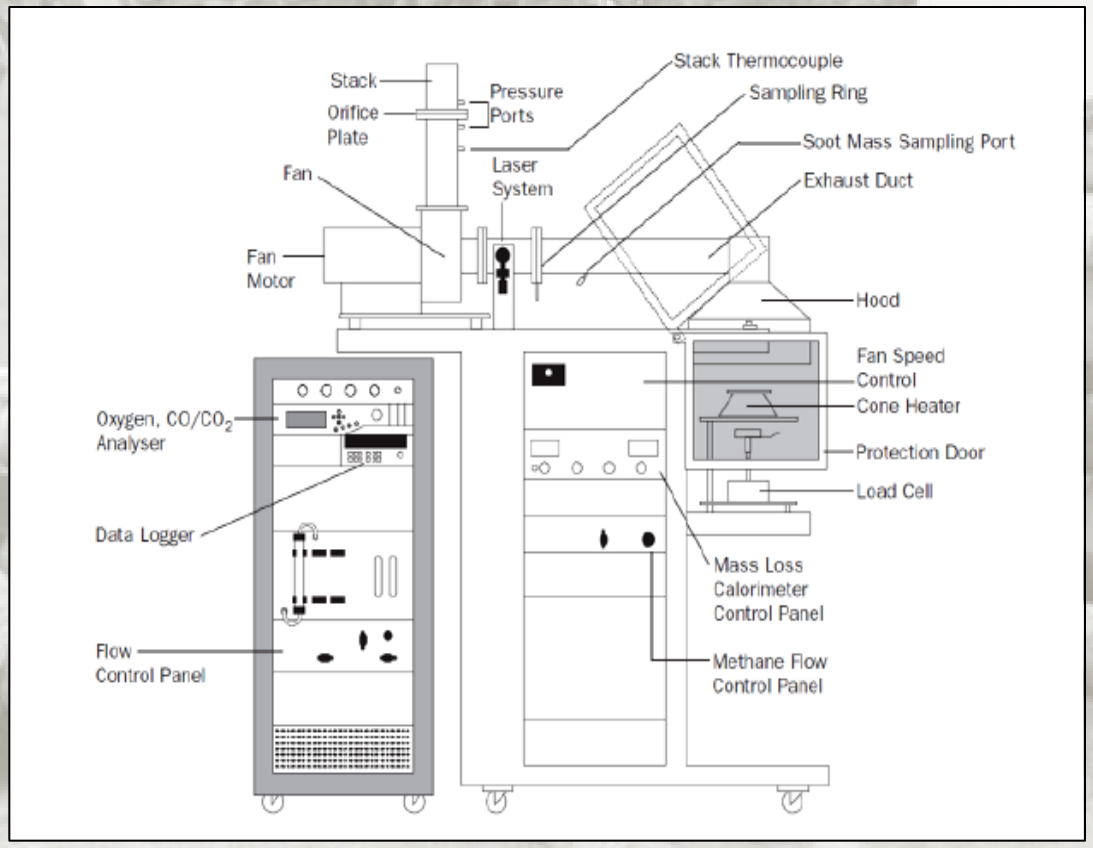
Objective

- Characterize emissions
  - Wood commonly used in boilers in the great lakes and upstate NY region
  - Waste Agricultural Plastics

- Investigate use of the Cone Calorimeter as a tool to obtain data on emissions from biomass and waste combustion

Experimental System
Cone Calorimeter



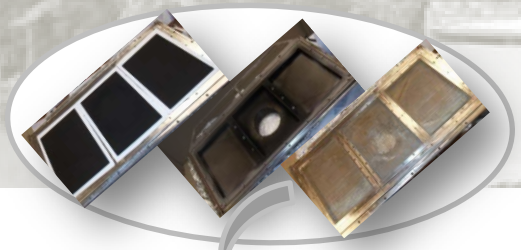
Fire testing equipment that mimics well ventilated combustion under a constant heat flux and air flow

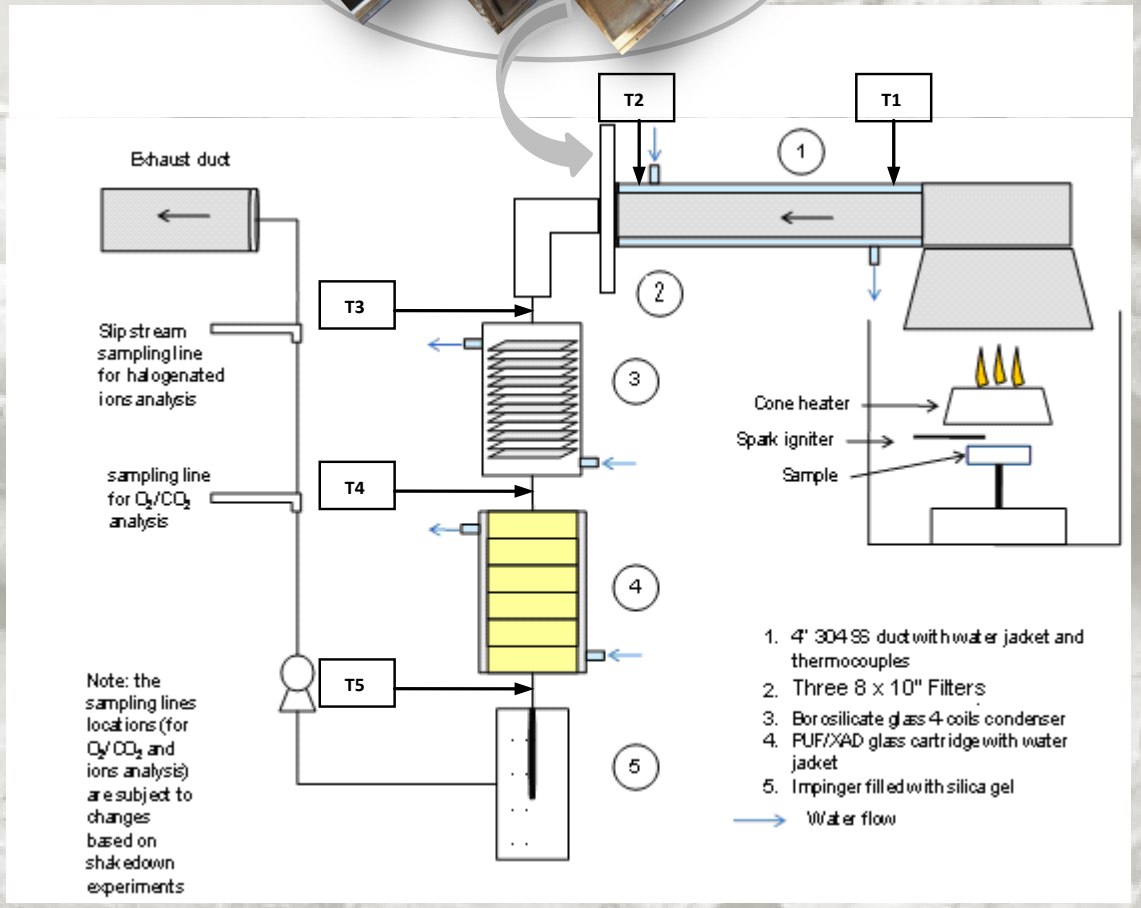
Cone Calorimeter data:

- Mass loss rate
- Smoke number
- CO/CO_2 production rates
- O_2 consumption rate
- Temp. and Pressure
- Heat Release Rate (HRR) and other flammability data

Sampling Train: ***1) Iso-kinetic Sampling Train*** ***2) Total Sampling Train***

Schematic of Total Sampling Train

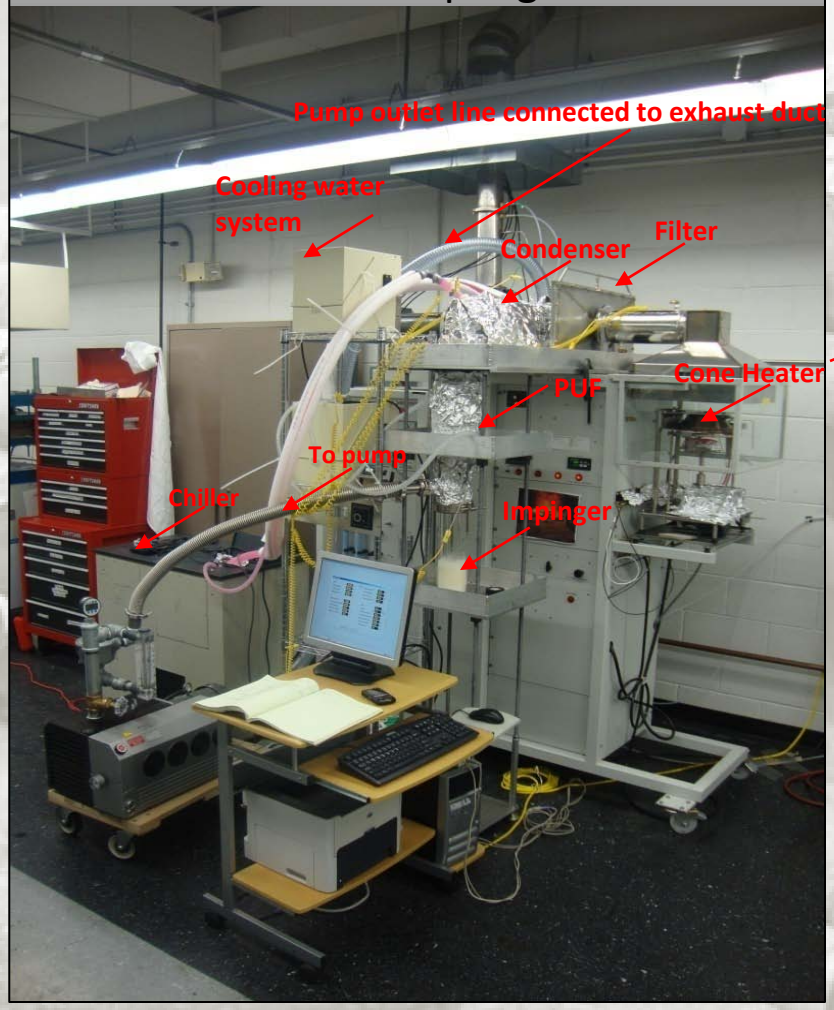




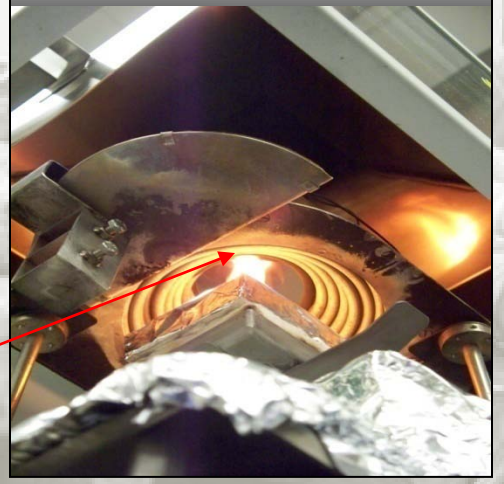
Experimental System

Total Sampling Train Coupled with UDRI Cone Calorimeter

Total Sampling Train



Cone Heater



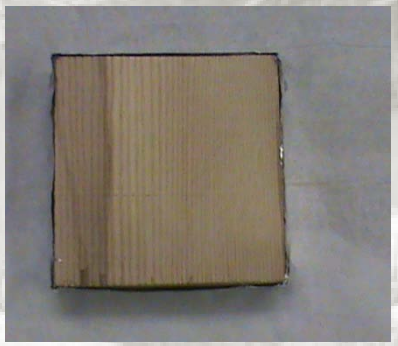
- 4 PUFs - 2” Thick x 4” Diameter
- 3 Filters - 8” x 10”

Modified Method TO9A

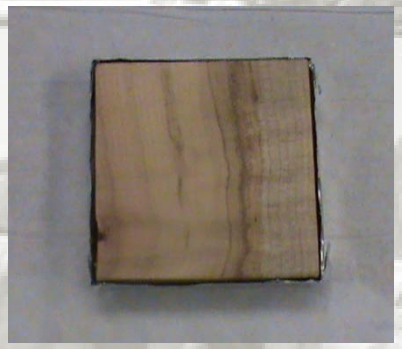
Experimental Conditions

- Sample size ~ 10 x 10 cm (ASTM)
- Air flow rate of 15 l/s (900 LPM)
- Constant heat flux of 50 kW/m^2 (cone temperature of ~760°C)
- Total gas flow was sampled

Types of Wood Tested



Ash



Sugar Maple

Pine

Red Oak

Wood Pellets

UDRI – Cone Calorimeter
Total Mass Burned per Sample

Type of Wood Burned	Total Mass Burned per Sample (g)
Ash	175.3
Sugar Maple	178.6
Pine	130.6
Red Oak	156.9
Wood Pellets	173.8

UDRI – Cone Calorimeter
Analyses of Wood Samples

Type of Wood	C, wt%	Cl, ppm	S, wt%	Ash, wt%	Moisture, wt%
Ash	51.20	0.3	<0.05	0.75	9.00
Sugar Maple	50.03	1	<0.05	1.10	9.00
Pine	51.72	36	<0.05	0.44	9.68
Red Oak	48.70	38	<0.05	1.46	22.52
Pellets	50.10	44	<0.50	0.52	7.24

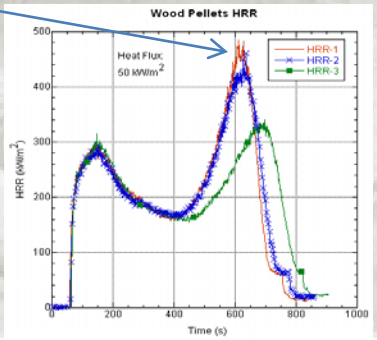
Note: Pine Wood, Red Oak and Pellets data obtained from EPA

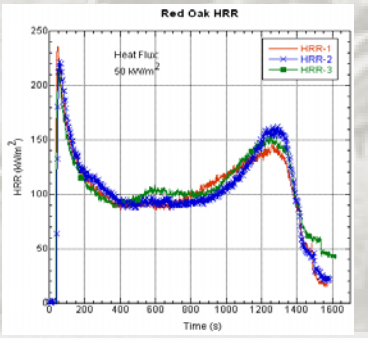
UDRI – Cone Calorimeter

Heat Release Data and Flammability

Sample Description	#	Time to Ignition (s)	Peak HRR (kW/m2)	Time to Peak HRR (s)	Time to Peak HRR - Tig (s)	Average HRR (kW/m2)	Total Heat Release (MJ/m2)	Avg. Effective Heat of Comb. (MJ/kg)	MAHRE (kW/m2)	FIGRA
Ash	1	34	220	58	24	123	162.1	11.33	125	3.79
	2	36	249	58	22	135	161.4	11.41	134	4.29
	3	48	260	66	18	130	162.2	11.22	131	3.94
STDEV		8	21	5	3	6	0.4	0.10	5	0.25
Average Data		39	243	61	21	130	161.9	11.32	130	4.01
Pine	1	5	295	29	24	118	165.7	16.67	198	10.17
	2	18	263	38	20	110	136.1	13.79	146	6.93
	3	7	260	34	27	124	165.1	16.55	168	7.64
STDEV		7	19	5	4	7	16.9	1.63	26	1.70
Average Data		10	273	34	24	117	155.6	15.67	170	8.24
Sugar Maple	1	36	252	55	19	133	170.8	11.98	140	4.58
	2	30	254	59	29	108	166.9	11.67	141	4.30
	3	32	275	63	31	128	164.2	11.60	144	4.37
STDEV		3	13	4	6	14	3.3	0.20	2	0.15
Average Data		33	260	59	26	123	167.3	11.75	142	4.42
Red Oak	1	28	236	47	19	110	160.0	11.80	130	5.02
	2	34	223	58	24	111	161.6	11.62	125	3.85
	3	28	218	50	22	111	167.1	12.12	122	4.35
STDEV		3	9	6	3	1	3.7	0.25	4	0.59
Average Data		30	226	52	22	111	162.9	11.85	126	4.41
Wood Pellets	1	52	485	612	560	229	163.9	12.37	230	0.79
	2	52	461	636	584	223	165.5	12.44	226	0.72
	3	56	341	697	641	210	164.9	12.52	208	0.49
STDEV		2	77	44	42	10	0.8	0.08	12	0.16
Average Data		53	429	648	595	221	164.8	12.44	221	0.67

MAHRE - Maximum average heat rate emission
FIGRA - Fire growth rate





UDRI – Cone Calorimeter

Smoke Release

Sample Description	#	Sample Thickness (mm)	Starting Mass (g)	Total Mass Loss (g)	Weight % Lost (%)	Total Smoke Release (m^2/m^2)
Ash	1	24.4	163.3	126.9	77.7	507
	2	24.1	162.7	125.1	76.9	634
	3	23.3	163.8	125.6	76.7	642
STDEV		0.55	0.6	0.9	0.6	75
Average Data		23.9	163.3	125.9	77.1	594
Pine	1	25.6	104.8	87.8	83.7	2623
	2	25.3	106.1	86.6	81.6	690
	3	25.6	106.2	88.7	83.5	2614
STDEV		0.17	0.8	1.1	1.2	1113
Average Data		25.5	105.7	87.7	83.0	1976
Sugar Maple	1	24.6	153.8	122.1	79.4	383
	2	25.4	158.2	125.9	79.6	222
	3	25.6	162.4	124.6	76.7	376
STDEV		0.49	4.3	1.9	1.6	91
Average Data		25.2	158.2	124.2	78.6	327
Red Oak	1	25.0	149.4	116.5	78.0	111
	2	24.7	149.6	116.5	77.9	72
	3	24.7	148.6	115.6	77.8	149
STDEV		0.16	0.5	0.5	0.1	39
Average Data		24.8	149.2	116.2	77.9	111
Wood Pellets	1	29.7	169.2	132.5	78.3	431
	2	29.7	169.4	133.0	78.5	459
	3	29.7	169.1	131.6	77.8	517
STDEV		0.00	0.2	0.7	0.3	44
Average Data		29.7	169.2	132.4	78.2	469

UDRI – Cone Calorimeter
CO/CO_2 Emission Factors

Sample	#	CO Yield (kg/kg)		CO_2 Yield (kg/kg)	
Description		Pre Ignition	Post Ignition	Pre Ignition	Post Ignition
Ash	1	0.004	0.007	0.870	1.22
	2	0.003	0.007	0.590	1.19
	3	0.009	0.007	0.570	1.20
STDEV		0.003	0.000	0.168	0.02
Average Data		0.006	0.007	0.677	1.20
Pine	1	0.000	0.015	0.000	1.58
	2	0.000	0.009	0.590	1.42
	3	0.000	0.014	-	1.57
STDEV		0.000	0.003	-	0.09
Average Data		0.000	0.013		1.52
Sugar Maple	1	0.004	0.006	0.610	1.26
	2	0.001	0.009	0.550	1.27
	3	0.002	0.007	0.660	1.20
STDEV		0.001	0.001	0.055	0.04
Average Data		0.002	0.007	0.607	1.24
Red Oak	1	0.003	0.006	0.610	1.28
	2	0.003	0.006	1.040	1.29
	3	0.002	0.008	0.740	1.30
STDEV		0.001	0.001	0.221	0.01
Average Data		0.003	0.007	0.797	1.29
Wood	1	0.001	0.006	0.410	1.24
Pellets	2	0.001	0.006	0.450	1.24
	3	0.003	0.006	0.390	1.23
STDEV		0.001	0.000	0.031	0.01
Average Data		0.001	0.006	0.417	1.24

UDRI – Cone Calorimeter

Particulate Mass (PM) Emission Factors

Type of Wood	PM, g/kg fuel in
Ash	5.6
Sugar Maple	5.5
Pine	29.5
Red Oak	2.1
Wood Pellets	5.6

UDRI – Cone Calorimeter

PCDD/F Emission Factors

Analyte	Ash, g/kg fuel in	Sugar Maple, g/kg fuel in	Pine, g/kg fuel in	Red Oak, g/kg fuel in	Pellets, g/kg fuel in
(ND=0, EMPC=EMPC)					
2,3,7,8-TCDD	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.27E-12
1,2,3,7,8-PeCDD	6.50E-11	2.02E-11	0.00E+00	0.00E+00	0.00E+00
1,2,3,4,7,8-HxCDD	6.67E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1,2,3,6,7,8-HxCDD	7.47E-10	1.01E-10	0.00E+00	6.95E-11	4.54E-11
1,2,3,7,8,9-HxCDD	2.41E-10	4.13E-11	0.00E+00	0.00E+00	4.52E-11
1,2,3,4,6,7,8-HpCDD	1.85E-09	3.31E-10	6.28E-10	2.70E-10	2.36E-10
OCDD	1.21E-09	4.31E-10	2.21E-09	5.19E-10	5.46E-10
2,3,7,8-TCDF	9.01E-11	1.85E-10	2.15E-10	1.13E-10	1.12E-10
1,2,3,7,8-PeCDF	1.13E-10	2.52E-10	3.32E-10	1.41E-10	1.39E-10
2,3,4,7,8-PeCDF	3.18E-10	4.01E-10	4.64E-10	2.30E-10	0.00E+00
1,2,3,4,7,8-HxCDF	2.88E-10	1.61E-10	2.19E-10	1.36E-10	8.40E-11
1,2,3,6,7,8-HxCDF	1.29E-10	1.55E-10	2.07E-10	1.11E-10	8.05E-11
2,3,4,6,7,8-HxCDF	7.59E-11	1.62E-10	2.61E-10	1.10E-10	7.94E-11
1,2,3,7,8,9-HxCDF	0.00E+00	0.00E+00	2.37E-10	0.00E+00	9.66E-11
1,2,3,4,6,7,8-HpCDF	1.80E-10	1.72E-10	2.33E-10	1.52E-10	1.20E-10
1,2,3,4,7,8,9-HpCDF	4.20E-11	8.06E-11	0.00E+00	7.14E-11	5.22E-11
OCDF	1.40E-10	7.95E-11	4.18E-10	1.10E-10	1.17E-10
Totals					
TCDDs	6.62E-10	2.75E-09	1.61E-09	1.33E-09	6.56E-10
PeCDDs	8.84E-10	2.44E-10	1.49E-10	1.75E-10	5.57E-11
HxCDDs	2.46E-09	3.17E-10	0.00E+00	2.08E-10	2.12E-10
HpCDDs	2.65E-09	5.16E-10	9.26E-10	1.81E-10	2.36E-10
OCDD	1.21E-09	4.31E-10	2.21E-09	5.19E-10	5.46E-10
TCDFs	4.35E-09	9.01E-09	8.42E-09	4.85E-09	5.67E-09
PeCDFs	2.71E-09	4.29E-09	5.12E-09	2.60E-09	2.04E-09
HxCDFs	1.29E-09	1.49E-09	1.19E-09	1.07E-09	5.75E-10
HpCDFs	2.22E-10	2.53E-10	4.85E-10	3.23E-10	1.85E-10
OCDF	1.40E-10	7.95E-11	4.18E-10	1.10E-10	1.17E-10
Total PCDD/Fs (ND=0; EMPC=0)	1.66E-08	1.93E-08	2.01E-08	1.13E-08	1.03E-08
Total PCDD/Fs (ND=0; EMPC=EMPC)	1.84E-08	2.03E-08	2.55E-08	1.39E-08	1.18E-08
Total PCDD/Fs (2378-X ND=DL; EMPC=EMPC)	1.85E-08	2.04E-08	2.64E-08	1.40E-08	1.18E-08
WHO-2005 TEQ (ND=0; EMPC=0)	3.26E-10	2.27E-10	2.17E-10	1.14E-10	4.58E-11
WHO-2005 TEQ (ND=0; EMPC=EMPC)	3.49E-10	2.35E-10	2.73E-10	1.33E-10	6.67E-11
WHO-2005 TEQ (ND=DL; EMPC=EMPC)	3.71E-10	2.52E-10	5.05E-10	1.99E-10	9.84E-11

UDRI – Cone Calorimeter

PAH Emission Factors

Analyte	Ash, g/kg fuel in	Sugar Maple, g/kg fuel in	Pine, g/kg fuel in	Red Oak, g/kg fuel in	Pellets, g/kg fuel in
Naphthalene	1.18E-03	2.36E-04	1.49E-03	2.31E-04	4.14E-04
Acenaphthylene	1.83E-03	8.34E-04	3.00E-02	3.68E-04	1.16E-03
Acenaphthene	1.06E-04	2.64E-05	4.40E-04	1.29E-05	2.94E-05
Fluorene	3.01E-04	1.35E-04	4.97E-03	7.71E-05	1.69E-04
Phenanthrene	1.07E-03	5.35E-04	4.33E-03	2.73E-04	8.40E-04
Anthracene	1.67E-04	9.29E-05	2.41E-03	3.63E-05	1.35E-04
Fluoranthene	6.39E-04	3.38E-04	1.75E-03	1.41E-04	5.17E-04
Pyrene	1.44E-04	6.22E-05	1.60E-04	5.88E-05	1.28E-04
Benzo(a)Anthracene	8.50E-05	4.46E-05	1.70E-03	1.80E-05	6.67E-05
Chrysene	1.03E-04	4.64E-05	1.74E-03	1.99E-05	6.96E-05
Benzo(b)Fluoranthene	2.13E-04	9.57E-05	4.21E-03	3.73E-05	1.46E-04
Benzo(k)Fluoranthene	9.41E-05	3.99E-05	2.22E-03	1.58E-05	7.54E-05
Benzo(a)Pyrene	1.06E-04	9.35E-05	2.26E-03	3.27E-05	1.37E-04
Indeno(1,2,3-cd)Pyrene	1.29E-04	7.45E-05	2.77E-03	3.28E-05	1.39E-04
Dibenzo(a,h)Anthracene	1.56E-05	6.89E-06	6.00E-04	4.86E-06	1.08E-05
Benzo(ghi)Perylene	1.67E-04	7.39E-05	3.89E-03	4.12E-05	1.71E-04
Total 16 EPA PAHs	**6.35E-03**	**2.74E-03**	**6.50E-02**	**1.40E-03**	**4.21E-03**
2-Methylnaphthalene	1.71E-04	4.56E-05	6.82E-04	4.68E-05	6.21E-05
Benzo(e)Pyrene	9.41E-05	4.71E-05	1.58E-03	1.88E-05	8.34E-05
Perylene	3.87E-05	4.10E-05	1.23E-03	2.13E-05	7.08E-05

Additional PAHs →

UDRI – Cone Calorimeter

Chlorobenzenes / Chlorobutadiene Emission Factors

Analyte	Ash, g/kg fuel in	Pine, g/kg fuel in	Red Oak, g/kg fuel in	Pellets, g/kg fuel in
1,2,3,5-Tetrachlorobenzene	1.64E-07	4.28E-08	1.71E-07	3.62E-08
1,2,4,5-Tetrachlorobenzene	1.52E-07	4.84E-08	1.37E-07	3.88E-08
1,2,3,4-Tetrachlorobenzene	5.42E-07	1.56E-07	4.60E-07	1.22E-07
Pentachlorobenzene	1.03E-06	7.89E-07	4.24E-07	6.56E-07
Hexachlorobenzene	3.57E-07	4.77E-07	3.07E-07	2.88E-07
Total (Tetra to Hexa) Clbz	**2.25E-06**	**1.51E-06**	**1.50E-06**	**1.14E-06**
Hexachlorobutadiene	7.93E-09	0.00E+00	1.12E-08	1.81E-08

Outdoor Wood Fired Hydronic Heaters (OWHH)

The Central Boiler Classic CL 5036

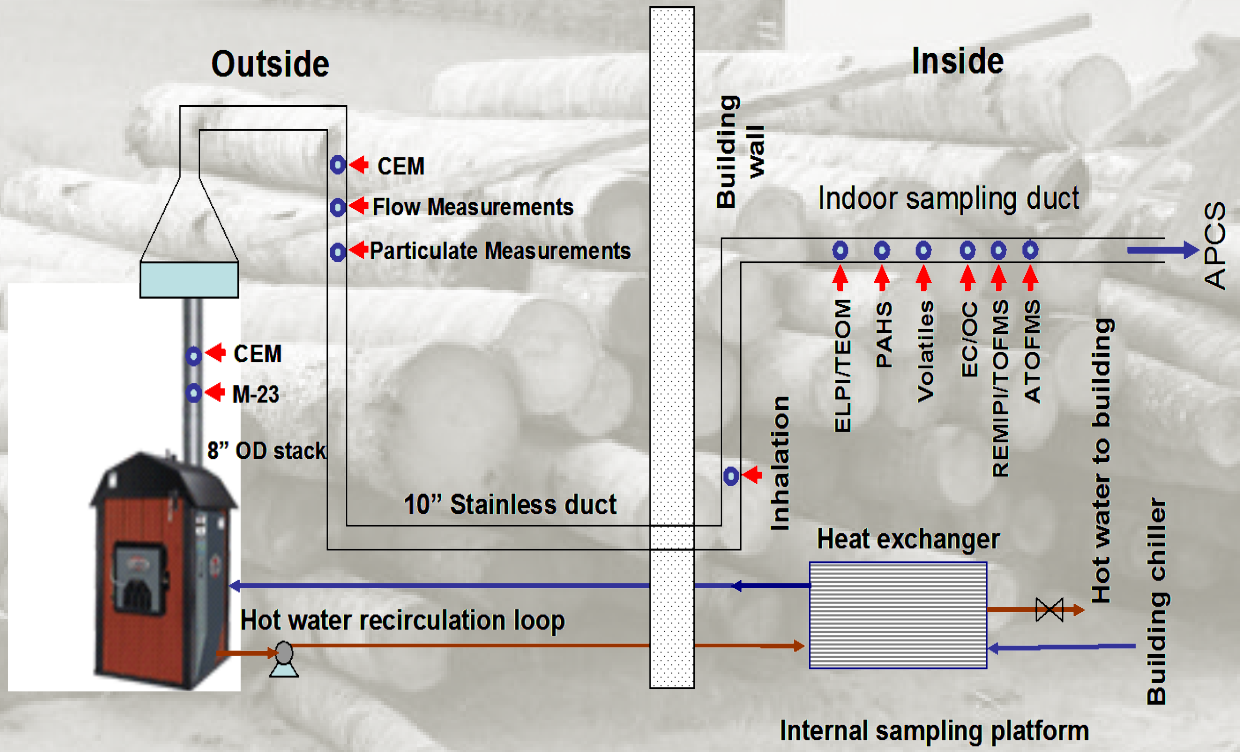
Unit Model	Technology
Central Boiler Classic CL5036	Single stage Combustion Process
Central Boiler E-Classic 2300	Three stage Combustion Process
Australian Pellet burner by ACT	Two-stage Combustion Process
The AFB Econoburn Gasification boiler	Two-stage: Combustion and Gasification with heat storage

The Central Boiler E-Classic 2300

The ACT pellet burner – CAT fire

The AFB Econoburn Gasification Boiler

Outdoor Wood-Fired Hydronic Heater (OWHH) Testing Facility Setup (US EPA, NC)



EPA vs.UDRI
CO_2 Emission Factors

Fuel	EPA				UDRI
	g/kg fuel in				
	CL 5036	E2300	ACT	AFB	Cone Calorimeter
Red Oak	1330 (±29)	1560 (±37)	-	1537 (±136)	2087
Pine	1529 (±177)	-	-	-	-
Ash	1556 (±34)	-	-	-	1880
Wood Pellets	-	-	1817 (±2)	-	1653
Sugar Maple	-	-	-	-	1847

• The total CO_2 emission factors from the cone calorimeter are slightly higher than most of the OWHHs except for the ACT where wood pellets were burned.

•When compared, the CO_2 emission factors from CL5036 are ~85% of ash and ~65% of red oak and from the E2300 and AFB are ~70% of red oak emission factors from the cone calorimeter. The CO_2 emission factors from the cone calorimeter are ~90% of the ACT for wood pellets.

EPA vs.UDRI
CO Emission Factors

Fuel	EPA				UDRI
	g/kg fuel in				
	CL 5036	E2300	ACT	AFB	Cone Calorimeter
Red Oak	194 (±20)	117 (±17)	-	127 (±60)	9
Pine	190 (±38)	-	-	-	13
Ash	205 (±22)	-	-	-	13
Wood Pellets	-	-	8 (±3)	-	7
Sugar Maple	-	-	-	-	9

• With the exception of the ACT (where CO emission factors are comparable), the total CO emission factors from the cone calorimeter are an order of magnitude less than the OWHHs.

EPA vs.UDRI
*Combustion Efficiency**

Fuel	EPA				UDRI
	%				
	CL 5036	E2300	ACT	AFB	Cone Calorimeter
Red Oak	81.35	89.46	-	88.51	99.33
Pine	83.66	-	-	-	-
Ash	82.85	-	-	-	98.93
Wood Pellets	-	-	99.31	-	99.34
Sugar Maple	-	-	-	-	99.24

* Calculated based on [C of CO_2] / [C of ($CO + CO_2$)] x 100%

EPA vs.UDRI
Particulate Mass (PM) Emission Factors

Fuel	EPA				UDRI
	g/kg fuel in				
	CL 5036	E2300	ACT	AFB	Cone Calorimeter
Red Oak	23.92 (±0.86)	4.48 (±2.47)	-	2.96 (±0.83)	2.1
Pine	46.42 (±6.95)	-	-	-	29.5
Ash	28.48	-	-	-	5.6
Wood Pellets	-	-	1.70 (±1.11)	-	5.6
Sugar Maple	-	-	-	-	5.5

• The PM emission factors from the cone calorimeter are lower when compared to CL 5036 (by a factor of ~1.5 for Pine, 5 for Ash and 11 for Red Oak), within experimental uncertainty comparable to E2300 and AFB, and is higher than from ACT (by a factor of ~3).

EPA vs.UDRI

WHO-2005 TEQ PCDD/F Emission Factors

Fuel	EPA				UDRI
	g/kg fuel in				
	CL 5036	E2300	ACT	AFB	Cone Calorimeter
Red Oak	1.05E-09 (±7.58E-10)	1.10E-10 (±2.15E-11)	-	7.95E-11 (±7.69E-12)	1.33E-10
Pine	6.27E-10 (±2.10E-10)	-	-	-	2.73E-10
Ash	3.81E-10 (±5.33E-11)	-	-	-	3.49E-10
Wood Pellets	-	-	2.80E-10	-	6.67E-11
Sugar Maple	-	-	-	-	2.35E-10

EPA vs.UDRI
PAH (16 EPA) Emission Factors

Fuel	EPA				UDRI
	g/kg fuel in				
	CL 5036	E2300	ACT	AFB	Cone Calorimeter
Red Oak	4.48E-01	1.61E-01	-	2.23E-01	1.40E-03
Pine	1.54E+00	-	-	-	6.50E-02
Ash	2.83E+00	-	-	-	6.35E-03
Wood Pellets	-	-	4.44E-01	-	4.21E-03
Sugar Maple	-	-	-	-	2.74E-03

• When compared to the cone calorimeter experiments, the PAH emission factors from the OWHHs are about two orders of magnitude higher and don't follow the same trend.

Environmental Impact from Burning Wood

Pollutants	Units per ton of fuel in	Emission Factors	
		Est. Min	Est. Max.
PM	g	590	53370
WHO-2005 TEQ PCDD/F*	ng	67	1808
PAH	g	1	2830

*Calculated based on world health organization toxic equivalency factors given in 2005 for PCDD/Fs

Conclusions

- From the four types of wood and the wood pellets burned Pine has the highest flammability and emissions for most of the emissions characterized.
- The PM emission factors from the cone are less than those from conventional OWHH and similar to advanced OWHH.
- The PCDD/F emission factors from both the cone and OWHH tests are in the same order of magnitude.
- The PAH emission factors from the cone are up to two orders of magnitude less than the OWHH.
- The differences are attributed to the two different combustion conditions i.e. the well ventilated condition in the cone tests vs. the oxygen starved conditions in the conventional OWHHs.
- The emission factors from OWHHs with advanced technologies (higher combustion efficiencies) are closer to the emission factors observed with the cone calorimeter.
- ***It is recommended that if the cone calorimeter is to be used as a viable tool to obtain emission factors more representative of emissions from OWHHs that a range of conditions (i.e. from well ventilated to oxygen starved) be investigated.***

Agricultural Plastics Tested

Polypropylene Nursery pots

HDPE Jars

Polyethylene Silage bags

UDRI – Cone Calorimeter
Total Mass Burned per Sample

Type of Agricultural Plastics Burned	Total Mass Burned per Sample (g)
PP Nursery pots	57.1
PE Silage bags	56.2
HDPE Jars	54.9

UDRI – Cone Calorimeter

Analyses of Agricultural Plastic Samples

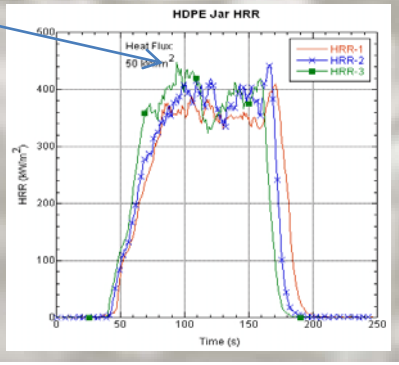
Type of Agricultural Plastics	C, wt%	Cl, ppm	S, wt%	Ash, wt%
PP Nursery pots	97.58	<200	<0.04	<0.6
PE Silage bags	98.72	<200	<0.04	<0.6
HDPE Jars	99.15	<200	<0.06	<0.5

UDRI – Cone Calorimeter

Heat Release Data and Flammability

Sample Description	#	Time to Ignition (s)	Peak HRR (kW/m2)	Time to Peak HRR (s)	Time to Peak HRR - Tig (s)	Average HRR (kW/m2)	Total Heat Release (MJ/m2)	Avg. Effective Heat of Comb. (MJ/kg)	MAHRE (kW/m2)	FIGRA
PE Silage bags	1	26	441	133	107	291	43.7	43.32	259	3.32
	2	19	476	95	76	253	43.6	43.02	276	5.01
	3	27	510	129	102	276	43.7	43.26	284	3.95
STDEV		4	35	21	17	19	0.1	0.16	13	0.85
Average Data		24	476	119	95	274	43.7	43.20	273	4.09
PP Nursery pots	1	36	503	64	28	283	41.6	42.41	278	7.86
	2	28	483	50	22	273	41.0	41.21	286	9.66
	3	36	516	63	27	347	41.4	-	274	8.19
STDEV		5	17	8	3	40	0	0.85	6	0.96
Average Data		33	501	59	26	301	41.3	41.81	279	8.57
HDPE Jars	1	39	409	171	132	294	42.1	41.96	232	2.39
	2	38	445	167	129	314	42.3	41.84	245	2.67
	3	35	447	94	59	321	42.0	41.26	253	4.76
STDEV		2	21	43	41	14	0	0.37	11	1.30
Average Data		37	434	144	107	309	42.1	41.69	243	3.27

MAHRE - Maximum average heat rate emission
FIGRA - Fire growth rate



UDRI – Cone Calorimeter

Smoke Release

Sample Description	#	Sample Thickness	Starting Mass	Total Mass loss	Weight lost	Total Smoke Release
		(mm)	(g)	(g)	(%)	(m2/m2)
PE Silage bags	1	27.9	10.0	10.1	100.9	445
	2	27.9	10.1	10.1	100.5	434
	3	27.9	10.1	10.1	100.5	409
STDEV		0.0	0.1	0.0	0.2	18
Average Data		27.9	10.1	10.1	100.6	429
PP Nursery pots	1	27.9	10.1	9.8	97.2	538
	2	27.9	10.0	9.9	99.0	562
	3	27.9	10.1	-	-	529
STDEV		0.0	0.1	0.1	1.3	17
Average Data		27.9	10.1	9.9	98.1	543
HDPE Jars	1	27.9	10.0	10.0	99.8	484
	2	27.9	10.0	10.1	100.8	445
	3	27.9	10.0	10.2	101.7	449
STDEV		0.0	0.0	0.1	1.0	22
Average Data		27.9	10.0	10.1	100.8	459

UDRI – Cone Calorimeter
CO/CO_2 Emission Factors

Sample Description	#	CO Yield(kg/kg)		CO2 Yield (kg/kg)	
		Pre Ignition	Post Ignition	Pre Ignition	Post Ignition
Polyethylene Silage bags	1	0.001	0.030	1.75	2.93
	2	0.000	0.030	3.20	2.82
	3	0.008	0.030	1.27	2.86
STDEV		0.004	0.000	1.00	0.06
Average Data		0.003	0.030	2.07	2.87
Polypropylene Nursery pots	1	0.005	0.040	1.75	2.74
	2	0.002	0.040	1.00	2.69
STDEV		0.002	0.000	0.53	0.04
Average Data		0.004	0.040	1.38	2.72
HDPE Jars	1	0.035	0.030	1.84	2.91
	2	0.044	0.030	3.14	2.87
	3	0.025	0.030	2.52	2.79
STDEV		0.010	0.000	0.65	0.06
Average Data		0.035	0.030	2.50	2.86

UDRI – Cone Calorimeter

Particulate Mass (PM) Emission Factors

Type of Agricultural Plastics	PM, g/kg fuel in
PP Nursery pots	74.43
PE Silage bags	64.23
HDPE Jars	76.68

UDRI – Cone Calorimeter

PCDD/F Emission Factors

Analyte	PP Nursery pots	PE Silage bags	HDPE Jars
	g/kg fuel in		
(ND=0, EMPC=EMPC)			
2,3,7,8-TCDD	6.36E-11	1.90E-11	0.00E+00
1,2,3,7,8-PeCDD	1.11E-10	3.90E-11	0.00E+00
1,2,3,4,7,8-HxCDD	0.00E+00	1.04E-10	0.00E+00
1,2,3,6,7,8-HxCDD	4.26E-10	3.70E-10	2.57E-10
1,2,3,7,8,9-HxCDD	2.03E-10	1.80E-10	1.68E-10
1,2,3,4,6,7,8-HpCDD	2.05E-09	2.01E-09	1.49E-09
OCDD	3.61E-09	3.90E-09	2.71E-09
2,3,7,8-TCDF	2.19E-09	7.94E-10	1.27E-09
1,2,3,7,8-PeCDF	4.40E-09	1.35E-09	1.48E-09
2,3,4,7,8-PeCDF	4.76E-09	1.58E-09	1.44E-09
1,2,3,4,7,8-HxCDF	2.63E-09	9.56E-10	7.76E-10
1,2,3,6,7,8-HxCDF	3.03E-09	8.22E-10	6.08E-10
2,3,4,6,7,8-HxCDF	3.27E-09	8.86E-10	5.28E-10
1,2,3,7,8,9-HxCDF	0.00E+00	0.00E+00	0.00E+00
1,2,3,4,6,7,8-HpCDF	2.15E-09	8.97E-10	4.92E-10
1,2,3,4,7,8,9-HpCDF	2.08E-09	4.93E-10	3.33E-10
OCDF	1.35E-09	6.67E-10	3.99E-10
Totals			
TCDDs	2.01E-09	2.14E-09	4.15E-09
PeCDDs	1.09E-09	6.69E-10	9.25E-10
HxCDDs	1.23E-09	2.35E-09	1.45E-09
HpCDDs	2.05E-09	2.01E-09	1.49E-09
OCDD	3.61E-09	3.90E-09	2.71E-09
TCDFs	7.04E-08	3.10E-08	9.62E-08
PeCDFs	6.43E-08	1.94E-08	1.89E-08
HxCDFs	3.36E-08	9.77E-09	5.83E-09
HpCDFs	7.50E-09	1.85E-09	3.33E-10
OCDF	1.35E-09	6.67E-10	3.99E-10
Total PCDD/Fs (ND=0; EMPC=0)	1.87E-07	7.37E-08	1.32E-07
Total PCDD/Fs (ND=0; EMPC=EMPC)	1.91E-07	7.63E-08	1.44E-07
Total PCDD/Fs (2378-X ND=DL; EMPC=EMPC)	1.91E-07	7.65E-08	1.44E-07
WHO-2005 TEQ (ND=0; EMPC=0)	2.80E-09	9.32E-10	3.81E-10
WHO-2005 TEQ (ND=0; EMPC=EMPC)	2.98E-09	1.02E-09	8.62E-10
WHO-2005 TEQ (ND=DL; EMPC=EMPC)	2.99E-09	1.03E-09	1.01E-09

UDRI – Cone Calorimeter

PAH Emission Factors

Analyte	PP Nursery pots	PE Silage bags	HDPE Jars
	g/kg fuel in		
Naphthalene	9.21E-03	8.31E-03	2.93E-03
Acenaphthylene	3.31E-03	2.70E-03	8.52E-03
Acenaphthene	1.89E-03	1.06E-03	6.78E-03
Fluorene	1.37E-02	1.19E-02	1.70E-02
Phenanthrene	3.99E-03	4.02E-03	9.56E-03
Anthracene	5.71E-03	5.46E-03	1.34E-02
Fluoranthene	3.43E-03	3.56E-03	7.85E-03
Pyrene	3.01E-04	3.56E-04	6.32E-04
Benzo(a)Anthracene	5.01E-03	4.22E-03	1.00E-02
Chrysene	4.85E-03	4.18E-03	9.11E-03
Benzo(b)Fluoranthene	6.25E-03	4.50E-03	1.09E-02
Benzo(k)Fluoranthene	5.24E-03	3.27E-03	1.02E-02
Benzo(a)Pyrene	7.06E-03	6.01E-03	1.48E-02
Indeno(1,2,3-cd)Pyrene	1.12E-02	8.22E-03	1.95E-02
Dibenzo(a,h)Anthracene	1.52E-03	8.11E-04	1.88E-03
Benzo(ghi)Perylene	1.18E-02	9.31E-03	2.39E-02
Total 16 PAHs	**9.45E-02**	**3.39E-01**	**1.67E-01**
2-Methylnaphthalene	2.80E-03	2.58E-03	1.73E-03
Benzo(e)Pyrene	5.29E-03	4.18E-03	8.52E-03
Perylene	2.82E-03	1.78E-03	2.30E-02

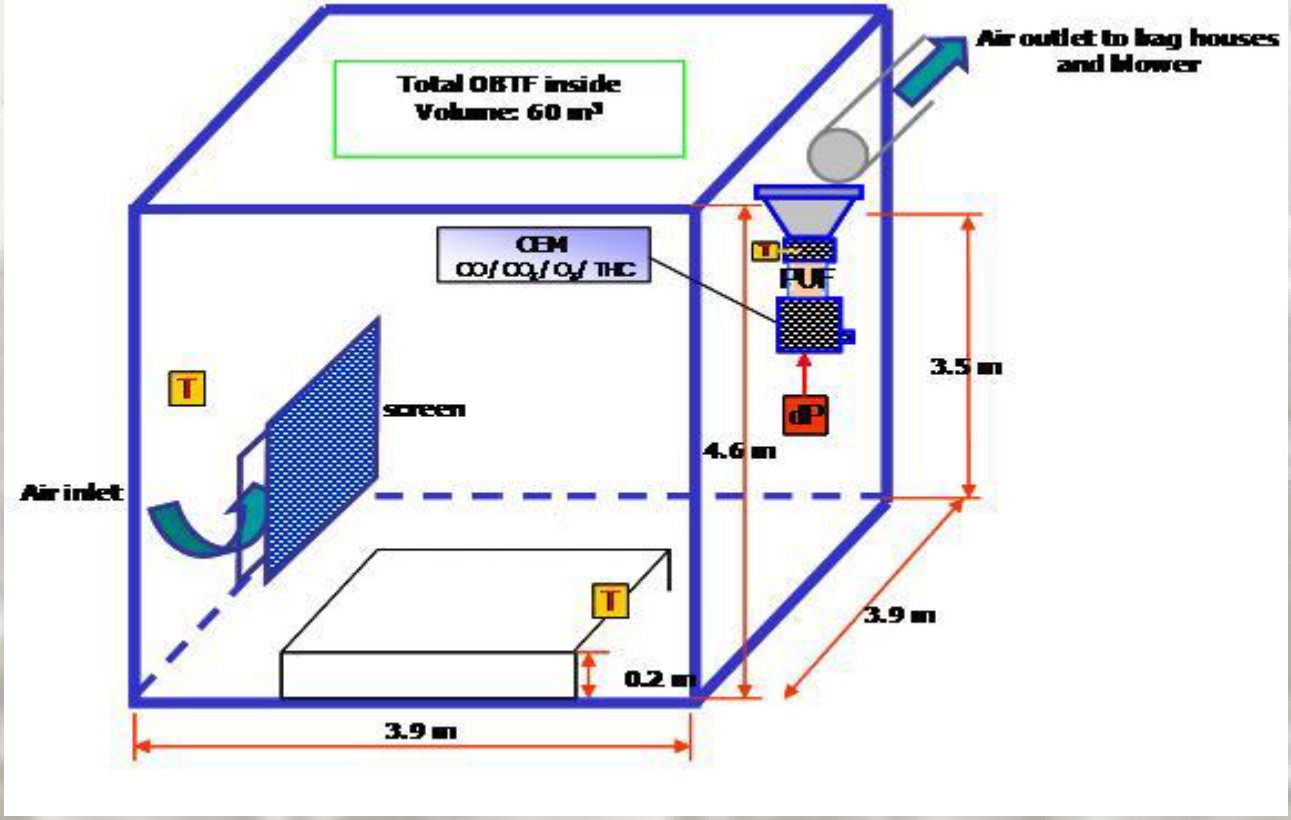
Additional PAHs →

UDRI – Cone Calorimeter

Chlorobenzenes/ Chlorobutadiene Emission Factors

Analyte	PP Nursery pots	PE Silage bags	HDPE Jars
	g/kg fuel in		
1,2,3,5-Tetrachlorobenzene	8.09E-07	4.06E-07	5.99E-08
1,2,4,5-Tetrachlorobenzene	8.56E-07	2.08E-07	6.76E-08
1,2,3,4-Tetrachlorobenzene	2.80E-06	8.91E-07	1.84E-07
Pentachlorobenzene	5.80E-07	7.14E-07	1.20E-06
Hexachlorobenzene	1.06E-06	1.30E-06	1.91E-06
Total (Tetra to Hexa)Clbz	**6.11E-06**	**3.52E-06**	**3.42E-06**
Hexachlorobutadiene	4.97E-08	7.49E-08	5.79E-08

Open Burn Test Facility (OBTF) at US EPA, NC



T = thermocouples; PUF = polyurethane foam absorbent; CEM = control emission monitors; THC = total hydrocarbons; dP = differential pressure.

EPA – OBTF

CO/CO_2 Emission Factors

Sample Description	#	CO Yield	CO_2 Yield
		g/kg fuel in	
PP Nursery pots	1	1.0	3576
	2	1.5	3576
	3	1.1	3576
	4	0.8	3577
STDEV		0.32	0.50
Average Data		1.1	3576
PE Silage bags	1	1.6	3575
	2	1.6	3575
	3	1.3	3576
	4	1.3	3576
STDEV		0.17	0.27
Average Data		1.4	3576

Type of Agricultural Plastics	EPA – OBTF		UDRI – C one Calorimeter	
	CO	CO2	CO	CO2
	g/kg fuel in			
PP Nursery pots	1.1	3576	43.5	4090
PE Silage bags	1.4	3576	33.0	4943
HDPE Jars	-	-	64.7	5357

EPA vs.UDRI
*Combustion Efficiency**

Type of Agricultural Plastics	EPA – OBTF	UDRI – Cone Calorimeter
	%	
PP Nursery pots	99.95	98.36
PE Silage bags	99.94	98.96
HDPE Jars	-	98.14

* Calculated based on [C of CO_2] / [C of ($CO + CO_2$)] x 100%

EPA – OBTF

Particulate Mass(PM) Emission Factors

Particulate Mass (PM)	PP Nursery pots	PE Silage bags
	g/kg fuel in	
PM 10	0.0070	0.0073
PM 2.5	0.0073	0.0114
Total	0.0074	0.0078

Type of Agricultural Plastic	EPA – OBTF (PM 10+2.5)	UDRI – Cone calorimeter (PM)
	g/kg fuel in	
PP Nursery pots	0.0074	74.43
PE Silage bags	0.0078	64.23
HDPE Jars	-	76.68

Note: The differences in PM yields between the cone and OBTF data is because in the cone tests the total particles generated were sampled where as in the OBTF tests only size selected particle sampling was performed i.e. PM < 10 μm and PM < 2.5 μm

EPA – OBTF

PCDD/F Emission Factors

Analyte	PP Nursery pots	PE Silage bags
	g/kg fuel in	
2,3,7,8-TCDD	0.00E+00	4.15E-11
1,2,3,7,8-PeCDD	1.51E-10	4.00E-10
1,2,3,4,7,8-HxCDD	6.47E-12	4.52E-12
1,2,3,6,7,8-HxCDD	2.83E-11	3.40E-11
1,2,3,7,8,9-HxCDD	1.13E-11	2.23E-11
1,2,3,4,6,7,8-HpCDD	7.65E-12	9.06E-12
OCDD	5.36E-13	3.62E-13
2,3,7,8-TCDD	8.85E-11	1.15E-10
1,2,3,7,8-PeCDF	3.08E-11	3.23E-11
2,3,4,7,8-PeCDF	6.08E-10	5.21E-10
1,2,3,4,7,8-HxCDF	2.39E-10	2.12E-10
1,2,3,6,7,8-HxCDF	1.81E-10	1.62E-10
2,3,4,6,7,8-HxCDF	1.40E-11	2.19E-11
1,2,3,7,8,9-HxCDF	1.83E-10	1.98E-10
1,2,3,4,6,7,8-HpCDF	4.69E-11	5.34E-11
1,2,3,4,7,8,9-HpCDF	8.08E-12	4.64E-12
OCDF	4.82E-13	2.58E-13
Totals		
TCDDs	1.08E-08	1.56E-08
PeCDDs	4.01E-09	5.58E-09
HxCDDs	3.58E-09	2.76E-09
HpCDDs	1.61E-09	1.51E-09
OCDD	1.79E-09	8.27E-10
TCDFs	3.63E-08	5.48E-08
PeCDFs	2.82E-08	2.74E-08
HxCDFs	1.79E-08	1.64E-08
HpCDFs	6.44E-09	6.58E-09
OCDF	1.61E-09	8.60E-10
Total PCDD/Fs (ND=O,EMPC=EMPC)	1.12E-07	1.32E-07
WHO-2005 TEQ (ND=0,EMPC=EMPC)	4.10E-10	6.76E-10

Analyte	EPA – OBTF		UDRI – Cone Calorimeter		
	PP Nursery pots	PE Silage bags	PP Nursery pots	PE Silage bags	HDPE Jars
	g/kg fuel in				
Total PCDD/Fs (ND=0; EMPC=EMPC)	1.12E-07	1.32E-07	1.91E-07	7.63E-08	1.44E-07
WHO-2005 TEQ PCDD/Fs (ND=0;EMPC=EMPC)	4.10E-10	6.76E-10	2.98E-09	1.02E-09	8.62E-10

EPA – OBTF

PAH Emission Factors

Analyte	OBTF	
	PP Nursery pots	PE Silage bags
	g/kg fuel in	
Naphthalene	5.88E-02	7.48E-02
Acenaphthylene	2.47E-02	2.75E-02
Acenaphthene	6.96E-04	9.09E-04
Fluorene	4.50E-03	5.95E-03
Phenanthrene	1.55E-02	1.48E-02
Anthracene	2.32E-03	2.75E-03
Fluoranthene	1.35E-02	6.61E-03
Pyrene	9.91E-03	8.63E-03
Benzo(a)anthracene	1.15E-03	7.80E-04
Chrysene	1.52E-03	7.96E-04
Benzo(b)fluoranthene	1.27E-03	9.99E-04
Benzo(k)fluoranthene	5.75E-04	4.55E-04
Benzo(a)pyrene	1.49E-03	1.42E-03
Indeno(1,2,3-cd)pyrene	1.49E-03	1.42E-03
Dibenz(a,h)anthracene	1.47E-04	7.30E-05
Benzo(ghi)perylene	1.49E-03	7.63E-04
Total 16 EPA PAHs	**1.39E-01**	**1.49E-01**

Type of Agricultural Plastic	Total 16 EPA PAHs	
	EPA – OBTF	UDRI – Cone calorimeter
	g/kg fuel in	
PP Nursery pots	1.39E-01	9.45E-02
PE Silage bags	1.49E-01	3.39E-01
HDPE Jars	-	1.67E-01

Environmental Impact from Burning Agricultural Plastics

Pollutants	Units per ton of fuel in	Emission Factors	
		Est. Min	Est. Max.
PM (2.5 + 10 μm)	g	7.4	7.8
WHO-2005 TEQ PCDD/F	ng	410	2980
PAH	g	95	339

*Calculated based on world health organization toxic equivalency factors given in 2005 for PCDD/Fs

Conclusions

- From the three types of agricultural plastics burned, the cone tests show that polypropylene nursery pots have the highest emission factors for most of the emissions characterized.
- Although differences were observed in the emission factors for the plastics tested with the cone calorimeter, the emission factors from the OBTF are similar for the two plastics tested and are within experimental uncertainty.
- Except for PM (where differences were observed due to the sampling methods), the emission factors from OBTF and Cone Calorimeter are similar in magnitude and within experimental uncertainty.
- ***Thus, the cone calorimeter setup can be used to obtain emission factors under well ventilated conditions similar to the open burn scenario.***

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Thank You!

Questions?