

Investigation of a Smoke Toxicity Fire Model for Use on Wood

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ABSTRACT

Experiments were carried out to investigate the effect of burning conditions on combustion of Douglas fir wood in a proposed smoke toxicity test: a plastic 200 L exposure chamber with a radiant furnace. Research included effects of: incident heat flux, sample surface, initial oxygen level and endpoint criteria.

Wood board sample mass can vary broadly even at equal surface and thickness, suggesting that surface may not be an ideal surrogate for amount of material. The effect of carbon black on ignitability is erratic. Ignitability of blackened wood samples is higher than that of unblackened samples only if both are identical. Irreproducibility increases at low incident fluxes.

Tests carried out with the IT50 concept are hazardous to the operator (oxygen addition can cause explosions) and lead to high irreproducibility (sixfold variations of CO doses in identical tests).

Yields of CO depend on exposure protocol and on sample size. At high initial oxygen levels, however, CO/CO₂ ratios are very low, unless big samples are burnt to completion. This leads to excessive smoke for toxicity purposes. The CO yields and CO/CO₂ ratios are adequate when using very low oxygen levels (0-5%) and high heat fluxes, conditions which simulate those in ventilation controlled fully developed fires.

INTRODUCTION

In the 1970's and early 1980's test methods were developed to measure smoke toxic potency. The ones most widely used are in refs. 1-4. These tests differ in several respects but they have served to show that the toxic potency of smoke from most materials is very similar [5-8]. In fact, the range of toxic potency for almost all combustible materials is less than an order of magnitude. These small differences were the cause for the different rankings in a study of toxic potencies of 14 materials by two methods [9]: the material ranked most toxic by one protocol was ranked least toxic by the other one! Neither of these protocols is in use now, but the work illustrates problems of such toxic potency tests. Smoke is not a uniform material: its composition depends on generation conditions. The same material can thus give smoke of very different composition and toxicity, depending on combustion conditions.

The NFPA Quarterly discussed in 1933 [10] that the main direct cause of death in fires has always been combustion product toxicity. Smoke has two main types of toxicants: asphyxiants and irritants. The individual toxicant associated with the largest fire hazard is carbon monoxide (CO).

CO, a combustion product of any organic material, appears in all fires. When present in blood, it forms carboxyhemoglobin (COHb). While the exact lethal COHb level depends on individual characteristics, values > 20% can lead to death [11]. At least 60% of fire deaths have > 20% COHb, while > 91% of fire victims have levels > 20% COHb [12]. Recent statistical analyses of large data bases involving carbon monoxide from fire and non-fire sources have shown that, once the controlling factors of age, disease and blood alcohol level have been accounted for, the COHb distribution from fire and non-fire fatalities are very similar [13]. Although many other gases are contained in smoke, two studies where fire fighters visited actual buildings on fire, equipped with gas monitors [14, 15] concluded that the main hazardous toxicant in fire is CO.

In the United States, most fire fatalities (specially if they are overcome by smoke inhalation) are remote from the fire origin room and follow a fire that has left its original room [7], suggesting that the fire may have reached "flashover". For such fires, specially if they are controlled by ventilation, smoke toxicity is dominated by CO levels. In such fires too, full scale CO levels are determined mainly by oxygen availability, which is, in turn, affected by variables such as geometry, ventilation, configuration, turbulence and mixing, and only somewhat influenced by chemical properties of the products being burnt [16]. Thus, CO levels in such fires are critical for toxic hazard [17].

As a first approximation fires can be subdivided in three types [18]:

- (1) Non flaming/smouldering fires
- (2) Early or small flaming fires
- (3) Fully developed large scale (post flashover) fires.

Smouldering fires occur with low heat inputs (20 kW/m²) and high oxygen levels. They generally give high carbon monoxide/carbon dioxide (CO/CO₂) ratios, but within low yields of smoke altogether, and rarely affect people other than those intimate with ignition (typically seated in the upholstered furniture or bedding item first ignited). Small flaming fires occur with higher heat inputs (20-35 kW/m²) and fairly high oxygen levels. The yields of smoke are much higher than in smouldering fires but not yet high enough to affect people far from the fire, i.e. only in the room of fire origin. Fully developed fires generally involve very high heat inputs (35 kW/m²) and very low oxygen levels (close to zero). The results are extremely high smoke yields and CO/CO₂ ratios. These fires are overwhelmingly responsible for the fire fatalities found away from the source of the fire. In these cases, most products are virtually pyrolysed and CO is the dominant toxic factor.

This study looks at several issues associated with using a radiant apparatus with a protocol suggested for smoke toxicity. The fuel used in the investigation was Douglas fir, mainly because wood combustion has been studied very widely and is well understood. In view of the crucial importance of CO levels in wood smoke toxicity, the emphasis of the research was placed on carbon oxide yields, under various conditions.

EXPERIMENTAL

Materials

The fuel used for these experiments was Douglas fir wood, 19 mm (0.75") thick. All the wood used had a single source, so that its water content and density were fairly uniform. The wood was kept at ca. room temperature and 50% relative humidity until use. The carbon black used to blacken the surface was Raven 410 (Columbian Chemicals).

Apparatus and Procedure

The apparatus used has a plastic exposure chamber, (Volume ca. 200 L), identical to that used in the NBS cup furnace toxic potency test [2] and a quartz combustion chamber. The heat source are 4 infrared lamps, set out symmetrically on two sides of the sample; the incident energy can be varied by changing incident flux or irradiation time (IT). The sample dimensions can vary, up to a maximum of 76 x 127 mm (3" x 5"), with a maximum thickness of 51 mm (2"). The igniter is a sparkler, placed 25 mm above the centre of the sample. Gases were analysed by pumping smoke through standard analysers (non dispersive infrared for CO and CO₂ and paramagnetic for oxygen) and recirculating the smoke. Mass loss was measured with a load cell. A carbon black layer was added with a brush, in some experiments, in order to get a homogeneous black surface.

Tests I.1 and II.1 both involved normal air and samples were burnt for a long time (until burning virtually ceased). Tests I.2 and II.2 differed from I.1 and II.1 only in that the starting atmosphere had 18% oxygen; in I.3 and II.3 starting atmospheres had just enough oxygen to cause flaming ignition (12-14%). In tests I.4 and II.4, burning started in air, but nitrogen was added rapidly, to ramp the oxidant concentration to 4% oxygen in a few minutes; in I.5 and II.5, oxygen was added, to ensure oxygen concentrations 16%. In tests labelled III, the initial sample surface was 9677 mm² (15 in²), and the end point was a smoke concentration sufficient to cause a lethal CO atmosphere (IT50 mode). Tests labelled IV were carried out to investigate the effect of very low oxygen levels (0, 5, 10%), at a fixed surface area simulating pyrolysis in vitiated atmospheres (high intensity ventilation-controlled fires). The V-VII series of tests had carbon black on the sample surface, while the VIII series were tests similar to I.1 or II.1, but with pairs of samples specially selected from the same Douglas fir wood board, to investigate ignition time, in the absence and presence of carbon black.

RESULTS

The procedures followed were designed towards investigating different different ways in which the apparatus could be used as a smoke toxicity test. In particular, two protocols have been proposed for use with this apparatus. The Smoke Toxicity Working Group at NIBS (National Institute of Building Sciences) [19] suggested the use of an IT50 concept (time of irradiation required to create a lethal atmosphere killing half (50%) the exposed animals). More recently, NIST (National Institute of Standards and Technology) suggested a novel way of measuring smoke toxicity with the hardware, based on corrected LC50 values [20]. Table 2 contains some basic results of the present study and will be discussed in detail.

Table 1. Exposure procedures used

Type	Flux kW/m ²	Init. Oxygen %	Oxygen Addition	End point	C Black	IT range min
I.1	50	21	No	Consumption	No	11-24
I.2	50	18	No	Fixed time	No	20
I.3	50	13	No	Fixed time	No	20
I.4	50	21	Add nitrogen	Fixed time	No	20
I.5	50	21	Yes: to 16%	Fixed time	No	20
II.1	30	21	No	Fixed time	No	20
II.2	30	18	No	Fixed time	No	20
II.3	30	13	No	Fixed time	No	20
II.4	30	21	Add nitrogen	Fixed time	No	20
II.5	30	21	Yes: to 16%	Fixed time	No	20
III.1	50	21	Yes	Predicted CO	No	IT50
III.2	30	21	Yes	Predicted CO	No	IT50
III.3	50	18	No	Predicted CO	No	IT50
III.4	50	13	No	Predicted CO	No	IT50
III.5	50	21	Add nitrogen	Predicted CO	No	IT50
III.6	30	18	No	Predicted CO	No	IT50
III.7	30	13	No	Predicted CO	No	IT50
III.8	30	21	Add nitrogen	Predicted CO	No	IT50
IV.1	50	0	No	Fixed time	No	20
IV.2	50	5	No	Fixed time	No	20
IV.3	50	10	No	Fixed time	No	20
V.1	50	21	No	Ignition	Yes	Ignition
V.3	50	14	No	Ignition	Yes	Ignition
V.5	50	21	Yes: to 16%	Consumption	Yes	Ignition
VI.1	30	21	No	Fixed time	No	20
VII.1	50	21	Yes	Predicted CO	No	IT50
VIII.1	50	21	No	Ignition	Yes	Ignition
VIII.2	50	21	No	Ignition	No	Ignition
VIII.3	30	21	No	Ignition	Yes	Ignition
VIII.4	30	21	No	Ignition	No	Ignition

The first interesting result in this study was variability of mass for a specified surface area and thickness (Figure 1). In fact, the mass range for the 5800 mm² samples is > 30 g (while the average mass is only 50-60 g). This has already been found before in other wood burning studies, but it indicates an inherent irreproducibility inevitable when using surface area for wood toxicity results rather than sample mass.

The effect of carbon black on ignitability yielded curious results. In series VIII, sets of identical samples were cut from a single wood board; half of them were tested covered with a carbon black layer and the other half uncovered. The blackened samples ignited more readily than the unblackened ones, but with poor reproducibility. Samples, at random (series V-VII), were also tested covered with carbon black, and compared with samples run under apparently identical conditions, but not designed specifically for direct comparison. The results showed no clear trends. It appears that the relative locations of sample and igniter although fixed in the apparatus are critical and thus smoke can pass close to the sparker without becoming ignited. This is especially noticeable at the lower incident flux, and is exacerbated by the use of carbon black.

The most important issue investigated was the yield of carbon oxides: CO and carbon dioxide (CO₂). Peak concentrations of CO or CO₂ both increase roughly proportionately to the initial sample surface, to the mass charged, and even to mass lost. However, this finding in itself is of little real interest, since it simply indicates that more carbon oxides are generated when more smoke is produced, without an indication of whether the quality (or toxicity) of the smoke changes. Of much more interest is the effect of mass lost (or mass charged) on carbon oxide yields, and their ratios, in different experiments.

The yield of a combustion product is the mass of product generated per mass of sample burnt (g/g). For species that do not decay, yields can probably be calculated equally well from peak concentrations or from integrating the concentration-time curve over a fixed time period (which for all these experiments was set at 30 min). In fact, the two values turned out to be quite different, with the value calculated from peak concentrations invariably higher than that calculated from integrated amounts. Interestingly, differences between results were not the same for both carbon oxides: in almost all cases the ratio of carbon monoxide to carbon dioxide calculated from peak values appeared higher than that calculated from integrated amounts of carbon oxides. Results discussed in this paper refer to yields from integrated values. Carbon balances were not made, since no soot or unburnt hydrocarbons were measured.

Results of Individual series

Tests of type I.1 were carried out with small sample surfaces (3870 mm², 6 in²); CO yields (from integrated CO values) ranged between 0.006 and 0.056, with a weak positive dependence on mass loss (almost within experimental noise). Carbon dioxide yields ranged from 0.26 to 0.75, with a strong negative dependence on mass loss. The ratio of carbon oxides (CO/CO₂) was low, but ranged from 0.025 to 0.165, with an accelerating positive dependence on mass loss. This refers to successive experiments, indicating that yields of both carbon oxides are affected by sample mass charged and time of exposure. Time to ignition ranged from 0.55 to 1.75 min; the differences, however, seem unrelated to mass loss or sample surface, so that time to ignition is 1.02 ± 0.27 min.

Tests of type II.1 (with incident flux level of 30 kW/m²) had higher CO yields than the corresponding type I.1 tests. There did not appear to be a dependence on sample mass loss. The CO₂ yields were lower than those for type I.1 tests, but had a very similar negative dependence on mass loss. The ratio of carbon oxides appeared to be slightly higher than for Type I.1, with a similar type of dependence. Time to ignition was much higher than for Type I.1 tests, which is very logical because less energy is applied. It ranged from 2.4 to 4.95 min, and appeared to increase with sample surface.

Tests of Type I.2 gave higher CO yields and lower CO₂ yields than Type I.1 tests. They resembled Type II.1 tests in their carbon oxide yields. They resembled the Type I.1 tests, however, in terms of their time to ignition, although the time to ignition appeared to be slightly higher than for Type I.1 tests. If the same type of test was carried out at a lower incident flux (Type II.2) this did not seem to make much difference to carbon oxide yields, but it raised the time to ignition, which, again, seemed to increase with sample surface.

Table 2 Summary of the Results of the Douglas Fir Experiments in the Radiant Apparatus

Type	Flux kW/m ²	Init. Surf. m ²	Init. Mass g	Ign. Time min	Ign. Loss min	Mass Loss g	Peak CO ppm	Peak CO ₂ ppm	Min. CO %	Peak CO/CO ₂	Integ. CO/CO ₂	Integ. CO yld g/g	Integ. CO ₂ yld g/g	Peak CO yld g/g	Peak CO ₂ yld g/g	Carbon Black
IV-1	50	2903	13.80	20.0	2.40	81.3	12600	84000	11.0	0.150	-	0.057	0.45	0.089	0.59	no
I-1	50	3871	39.48	20.0	0.95	82.2	11800	104800	7.5	0.113	0.165	0.043	0.26	0.071	0.63	no
I-1	50	3387	32.28	24.0	1.10	85.9	13700	97700	8.4	0.140	0.101	0.056	0.56	0.096	0.69	no
I-1	50	2903	30.18	12.0	1.05	81.5	9510	95500	9.5	0.058	0.048	0.028	0.57	0.044	0.76	no
I-1	50	2903	28.52	20.0	1.25	88.4	8630	97900	8.6	0.088	0.068	0.041	0.59	0.067	0.76	no
I-1	50	2903	28.27	22.0	1.10	87.7	9100	88400	8.0	0.103	0.083	0.046	0.56	0.071	0.69	no
I-1	50	2419	24.59	14.0	0.75	87.6	9500	94700	9.2	0.058	0.046	0.032	0.58	0.050	0.86	no
I-1	50	2419	24.45	20.0	0.90	86.5	6110	86800	10.4	0.070	0.051	0.032	0.64	0.056	0.80	no
I-1	50	1935	19.96	11.0	0.80	83.6	2200	78900	12.2	0.029	0.027	0.019	0.72	0.027	0.92	no
I-1	50	1935	19.60	14.6	0.55	94.9	940	22500	18.4	0.042	0.035	0.006	0.77	0.010	0.24	no
I-1	50	1935	18.10	20.0	1.75	88.3	4660	74100	12.2	0.066	0.050	0.034	0.68	0.059	0.90	no
I-1	50	968	8.54	23.6	1.00	99.4	1850	35900	17.0	0.052	0.050	0.033	0.66	0.042	0.82	no
I-1	50	968	8.50	20.0	0.95	103.2	1200	42200	16.5	0.030	0.025	0.019	0.75	0.027	0.89	no
I-1	50	968	8.28	20.0	1.15	99.2	2030	37300	16.8	0.054	0.050	0.037	0.73	0.048	0.88	no
I-2	50	5806	66.09	20.0	1.15	79.5	43600	111000	5.0	0.393	0.269	0.085	0.30	0.162	0.41	no
I-2	50	2903	32.40	20.0	1.25	81.3	11600	78400	9.0	0.144	0.130	0.060	0.46	0.086	0.28	no
I-2	50	1935	22.61	20.0	1.55	86.4	7650	70500	10.7	0.076	0.071	0.039	0.55	0.054	0.70	no
IV-3	50	2903	20.32	20.0	1.60	82.0	7650	71800	13.6	0.105	0.095	0.042	0.44	0.062	0.60	yes
I-3	50	5806	64.58	20.0	1.30	79.6	39000	91100	12.4	0.421	0.326	0.090	0.25	0.148	0.35	no
I-3	50	3871	45.33	20.0	1.50	80.6	21400	84000	12.5	0.255	0.206	0.072	0.35	0.114	0.45	no
I-3	50	3871	44.20	20.0	1.50	80.9	36800	68600	11.5	0.381	0.328	0.087	0.27	0.146	0.37	no
I-3	50	2903	34.60	20.0	1.55	81.5	15900	70300	13.1	0.213	0.181	0.069	0.37	0.104	0.49	no
I-3	50	2903	30.04	20.0	1.20	81.8	14700	70600	11.3	0.208	0.185	0.077	0.42	0.116	0.56	no
I-3	50	1935	22.21	20.0	1.45	84.2	8700	42500	13.3	0.205	0.190	0.067	0.35	0.091	0.44	no
I-3	50	1935	18.90	20.0	1.20	81.1	8640	47300	11.2	0.181	0.160	0.040	0.44	0.110	0.60	no
I-3	50	968	10.00	20.0	1.25	89.8	2600	34500	11.5	0.075	0.069	0.041	0.60	0.056	0.75	no
I-3	50	968	9.69	20.0	2.00	92.6	1930	32200	13.4	0.060	0.056	0.032	0.57	0.042	0.76	no
I-4	50	3871	44.13	20.0	1.20	79.5	16700	82700	5.3	0.202	0.143	0.044	0.31	0.093	0.40	no
I-4	50	2903	28.90	20.0	1.10	82.9	5200	72400	4.9	0.072	0.065	0.022	0.34	0.042	0.59	no
I-4	50	1935	22.21	20.0	1.30	80.0	2500	66000	10.3	0.038	0.036					no
I-4	50	1935	17.59	20.0	1.15	86.8	2900	44300	4.6	0.065	0.067	0.018	0.26	0.037	0.56	no
I-4	50	968	11.16	20.0	1.30	85.5	760	34000	6.3	0.022	0.032	0.012	0.38	0.016	0.69	no
IV-5	50	2903	30.75	20.0	1.55	84.0	7130	74700	18.5	0.095	0.090	0.037	0.41	0.054	0.56	yes
I-5	50	5806	68.36	15.9	1.25	92.6	19600	120000	18.2	0.163	0.115	0.032	0.28	0.060	0.37	no
I-5	50	5806	67.48	15.0	1.10	80.0	22300	136000		0.177	0.134	0.048	0.36	0.080	0.45	no
I-5	50	5806	66.77	15.8	1.55	60.0	20300	129000		0.157	0.118	0.058	0.49	0.099	0.63	no
I-5	50	5806	56.91	15.7	0.85	80.5	36400	88600	16.6	0.411	0.333	0.092	0.28	0.155	0.38	no
I-5	50	5806	49.63	15.0	0.80	81.7	23400	102300	18.6	0.228	0.186	0.072	0.39	0.112	0.49	no
I-5	50	5806	48.62	15.1	1.00	82.9	21900	98000	16.5	0.223	0.179	0.068	0.38	0.106	0.47	no
I-5	50	2903	30.11	20.0	1.25	83.6	4150	82700		0.050	0.044	0.022	0.51	0.032	0.64	no
I-5	50	2903	28.32	15.5	0.95	82.9	2340	77700	18.6	0.030	0.027	0.014	0.52	0.019	0.64	no
I-5	50	2903	28.32	15.0	1.00	84.1	6910	70400	16.5	0.098	0.088	0.041	0.46	0.056	0.58	no
VI-1	30	2903	33.59	21.6	4.55	91.7	7730	77760	11.8	0.099	0.079	0.025	0.32	0.049	0.49	yes
II-1	30	5806	65.71	20.0	4.95	76.0	21700	96400		0.225	0.191	0.045	0.24	0.085	0.38	no
II-1	30	3871	44.89	20.0	2.90	78.4	15200	86900		0.175	0.154	0.053	0.35	0.084	0.48	no
II-1	30	2903	33.38	20.0	3.35	76.8	10500	75500		0.139	0.123	0.051	0.41	0.080	0.57	no
II-1	30	1935	19.81	20.0	2.40	81.3	4700	60800		0.077	0.061	0.033	0.55	0.057	0.73	no
II-2	30	3871	45.28	20.0	3.40	78.2	13500	78600	9.5	0.172	0.141	0.041	0.29	0.074	0.43	no
II-2	30	2903	35.46	20.0	3.60	78.6	9560	73700	10.3	0.130	0.107	0.038	0.35	0.067	0.51	no
II-2	30	1935	22.07	20.0	2.95	81.5	5760	49500	12.7	0.116	0.106	0.043	0.40	0.062	0.54	no
II-2	30	3871	43.85	20.0	3.10	79.3	4500	100600	13.4	0.045	0.034	0.013	0.39	0.025	0.56	no
II-3	30	2903	32.78	20.0	3.30	79.9	2760	79300	13.4	0.035	0.038	0.015	0.41	0.021	0.59	no
II-3	30	1935	20.39	20.0	3.30	65.2	4700	46100	13.0	0.102	0.098	0.045	0.46	0.069	0.67	no
II-4	30	5806	70.91	20.0	2.80	76.7	14400	73150	5.0	0.187	0.198	0.029	0.15	0.052	0.28	no
II-4	30	3871	43.88	20.0	3.15	77.3	6310	81900	4.0	0.069	0.059	0.016	0.27	0.036	0.53	no
II-4	30	2903	33.13	20.0	3.75	77.4	4560	80700	5.3	0.057	0.057	0.017	0.29	0.035	0.61	no
II-5	30	5806	58.63	20.0	2.65	79.1	12600	107700	14.8	0.117	0.092	0.030	0.32	0.053	0.45	no
II-5	30	3871	43.25	21.0	3.40	79.5	4200	83500	15.8	0.050	0.041	0.013	0.32	0.024	0.47	no
VI-1	50	9677	105.24	8.1	0.95	78.3										yes
III-1	50	9677	108.80	4.8	1.75	27.8	6250	54700	18.7	0.114	0.114	0.035	0.31	0.040	0.35	no
III-1	50	9677	107.83	15.0	0.80	85.4	53800	117000	15.5	0.452	0.360	0.072	0.20	0.112	0.25	no
III-1	50	9677	106.64	4.8	1.20	29.9	3840	63200	18.3	0.061	0.061	0.021	0.34	0.023	0.39	no
III-1	50	9677	104.85	4.8	1.25	28.2	2200	60200	18.5	0.038	0.040	0.011	0.29	0.015	0.40	no
III-1	50	9677	96.51	4.8	0.85	33.7	8000	53800	16.5	0.149	0.173	0.041	0.24	0.048	0.32	no
III-1	50	9677	94.73	4.8	1.80	11.2	9530	54900	18.7	0.201	0.052	0.26	0.063	0.36	0.26	no
III-1	50	9677	93.93	4.8	0.85	24.1	7690	55900	19.2	0.138	0.139	0.058	0.42	0.066	0.48	no
III-1	50	9677	86.91	4.8	0.65	34.2	11600	57300	19.4	0.202	0.207	0.068	0.33	0.076	0.68	no
III-1	50	9677	83.74	4.8	0.70	36.1										no
III-2	30	9677	112.02	8.5	3.05	33.4	4840	77200	18.3	0.063	0.061	0.030	0.32	0.025	0.40	no
III-2	30	9677	111.98	15.0	3.00	54.6	36900	109000	19.2	0.339	0.268	0.070	0.26	0.117	0.25	no
III-2	30	9677	110.28	15.0	3.35	79.9	33900	118000	19.2	0.287	0.246	0.046	0.19	0.075	0.26	no
III-2	30	9677	109.65	15.0	2.85	52.5	36900	124000	19.3	0.288	0.242	0.076	0.31	0.125	0.42	no
III-2	30	9677	98.47	20.0	3.20	76.2	33200	119000	18.8	0.279	0.214	0.045	0.21	0.086	0.31	no
III-3	30	9677	110.16	12.8	1.70	69.8	50600	76300	7.2	0.663	0.604	0.095	0.16	0.128	0.19	no
III-3	50	9677	108.78	3.2	1.50	18.2	5830	47800	12.5	0.122	0.137	0.048	0.35	0.057	0.47	no
III-4	50	9677	104.34	3.1	1.35	13.0	5450	28700	12.8	0.190	0.190	0.070	0.27	0.078	0.41	no
III-5	50	9677	107.40	3.4	0.37	17.8	4110	24400	10.2	0.176	0.173	0.038	0.32	0.042	0.24	no
III-5	50															

Tests of type I.3 again resulted in higher CO yields and lower CO₂ yields, but the CO/CO₂ ratios were higher than in type I.2 tests. The times to ignition were somewhat higher than in earlier type I series, but did not seem to be greatly affected by sample surface area. If the same type of experiment was carried out at lower incident flux (II.3) the CO yields decreased, the carbon dioxide yields increased and the CO/CO₂ ratios became very small. The times to ignition were similar to those of type II.2 samples, viz. > 3 min.

A comparison of tests of type I.4 and I.3 shows substantial effects on the CO yields due to the change in conditions: they were much higher for I.3! However, the carbon dioxide yields were much less affected by the changes. The times to ignition were lower for I.4 than for I.3. Similar trends can be found on comparing II.3 and II.4.

Tests of Type I.5 and II.5 required severe precautions, because of the hazard involved in adding oxygen. In spite of this, an explosion occurred in one test. Such conditions pose serious risks to the test operator. These tests generated the highest CO₂ yields of any test, as well as high CO yields and CO/CO₂ ratios. Times to ignition were low, averaging at < 1 min, and appeared unaffected by surface sample area.

The NIBS protocol suggests that tests be stopped artificially at the time calculated to give an IT50, which, in the case of wood is determined exclusively from the CO concentration. For this work it was important to investigate the reproducibility of this. The tests carried out in the IT50 mode, i.e. done with the objective of determining the irradiation time needed to obtain a smoke concentration required to cause a lethal atmosphere to be created (Type III.1), gave low CO, high CO₂ yields and very low times to ignition (< 1 min). This was, at least partially, due to the oxygen addition. At the lower incident flux carbon oxide yields were similar, but times to ignition, naturally, increased considerably.

A series of experiments were made in which it was attempted to determine the reproducibility inherent in measuring an IT50. This was done through running an analytical pretest, by irradiating at 50 kW/m², and maintaining oxygen concentrations at a level 16%. The initial test run was used to measure the irradiation time required to obtain an integrated CO concentration time (CT) product of 100,000 ppm min.

It was determined that, for a Douglas fir board 9677 mm² x 19 mm, it took 290 s to obtain smoke containing a CO dose of 100,000 ppm min. Seven additional experiments were thus run, all of which were interrupted after an IT of 290 s. The original sample masses were reasonably close, ranging from 86.9 to 108.8 g, i.e. well within the range indicated in Figure 1. The 30 min CO CT product was determined in all experiments and it ranged from a low of 52,000 ppm min to a high of 311,800 ppm min (average: 172,512 ppm min ± 79,590 ppm min): a sixfold variation!

In the experiments at very low initial oxygen levels the CO yield was virtually unaffected by the initial oxygen concentration, but the CO₂ yield showed two distinct areas: values of 0.05-0.1 g/g at initial oxygen levels < 12% and values of 0.25 at initial oxygen levels > 12%. Thus, the CO/CO₂ ratios also show the same dual trends: values of 0.9-1.4 g/g at low oxygen levels and < 0.4 g/g at high oxygen levels. None of the low oxygen experiments (10%) caused ignition of the wood.

An interesting overall observation is that if a similar sample mass was exposed to radiant heat, the CO/CO₂ ratio increased with IT. In fact, parallel straight lines could be drawn when increasing amounts of wood were exposed to irradiation times ranging from 11-12 min to 24 min (Figure 2). Both oxygen consumption rate and mass loss rate appeared to increase with the sample mass charged, although they did so at different rates: the mass loss rate increased faster than the oxygen consumption rate. The oxygen consumption rate can be equated to heat release rate, an indication of efficiency of combustion. Thus, the results mean that burning becomes less efficient as time goes on, as heat is released more slowly. On the other hand, oxygen consumption rate per unit area decreased as mass charged (or sample area exposed) increased (Figure 3).

DISCUSSION

The yields of carbon oxides (both CO and CO₂) depend on several aspects, mainly the test conditions used and the sample mass burnt.

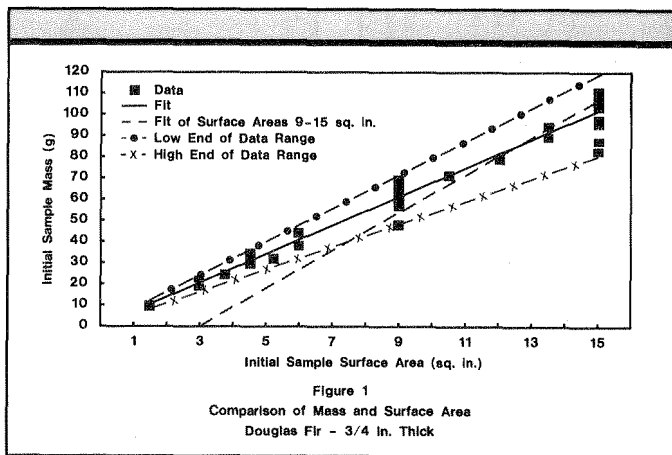
Perhaps the most important finding of this study is that the CO yield is low for most experiments, ranging up to a value of ca. 0.16 g/g mass lost. There is a very weak positive linear dependency of CO yield on mass of sample burnt. The carbon dioxide yield, on the other hand, is much higher (ranging up to > 0.9 g/g mass lost). Moreover it has a very strong negative linear dependency on sample mass lost. The combination of the two previous results means that the fitted ratio of CO/CO₂ ratio has a hyperbolic dependency on sample mass lost. In other words, this fitted ratio is very low at low sample mass lost values and increases until it reaches values of > 1. However, by then over 90 g of sample have been burnt. Figure 4 shows the dependence of CO yield, CO₂ yield, their fitted values and the fitted CO/CO₂ ratio on sample mass lost.

Innumerable smoke toxic potency tests have shown that typical toxic potencies are not too far away from values of ca. 30 mg/L. Thus, in order to obtain a lethal atmosphere in the exposure chamber considered in this work (ca. 200 L), smoke concentration above ca. 30 mg/L, i.e. ca. 6 g, would have no toxicological interest. At such levels of smoke, the CO/CO₂ ratio is only ca. < 0.1 for most experiments with high oxygen, i.e. very much lower than that for fires where there has been full room involvement. On the other hand, the tests carried out under low oxygen conditions resulted in reasonably high CO/CO₂ ratios, probably quite representative of those found in fully developed fires. Thus, this chamber might be ideally suited for use to simulate fully developed fires, if low initial oxygen levels are used. However, this would result in non flaming processes. If this is undesirable, it may be necessary to adjust the CO yields to obtain a value that fits the level found in fully developed full scale fires, e.g. as proposed by NIST [19].

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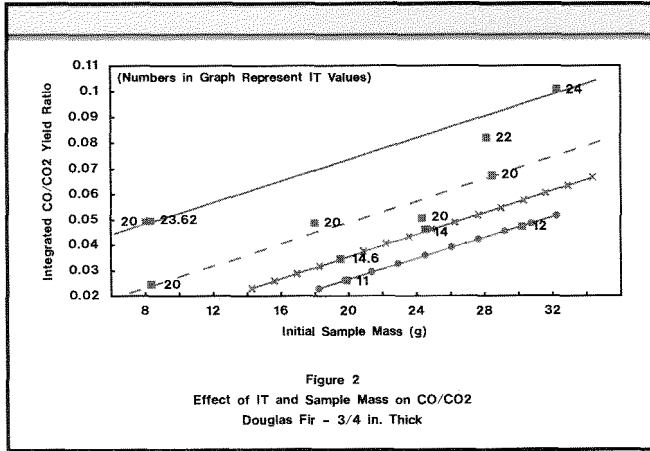


Figure 2
Effect of IT and Sample Mass on CO/CO₂
Douglas Fir - 3/4 in. Thick

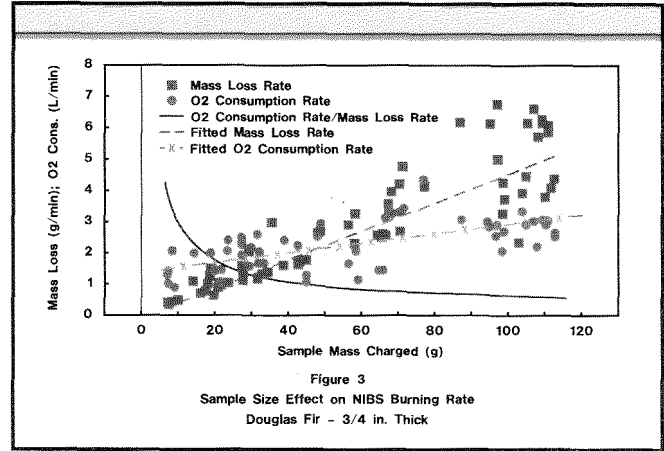


Figure 3
Sample Size Effect on NIBS Burning Rate
Douglas Fir - 3/4 in. Thick

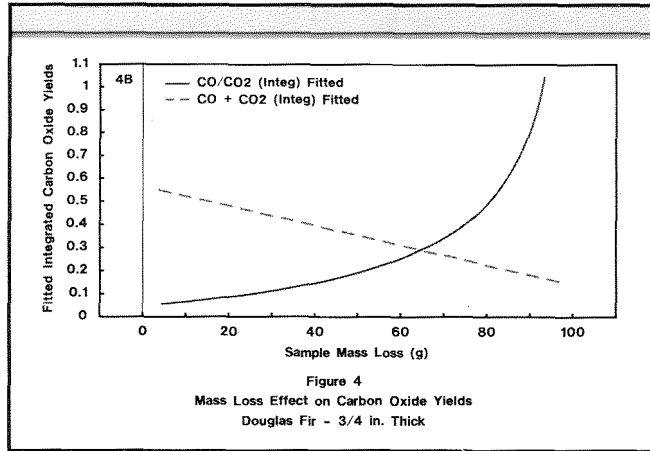


Figure 4
Mass Loss Effect on Carbon Oxide Yields
Douglas Fir - 3/4 in. Thick

