

# FIRE TESTS FOR SMOKE CHARACTERIZATION

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## ABSTRACT

*Characterization of smoke from its generation through aging has been investigated as a part of a long-range non-thermal damage assessment program. Six materials---polyethylene, polypropylene, filter paper, PMMA, heptane, and polystyrene---were burned inside an enclosure. Temperatures near and far from the fire, smoke particle number concentrations, particle aerodynamic diameters, smoke particle first moments, and mass concentrations were measured. In addition, smoke particles deposited on 4 or 6 disks on the floor were weighted to estimate the amount of smoke sedimentation on the floor during the tests. The collected data indicate that: (1) The mass concentration of smoke correlates well with the temperature of smoke plume. (2) Particle coagulation becomes much more pronounced as soon as fire is extinguished. (3) It is apparent, due to velocities higher by orders of magnitude than the respective velocities for individual particles, that smoke particles in fires move as constituents of large aerosol clouds rather than each individual particles. (4) In general, the growth of smoke particle diameter by particle coagulation seems to progress much faster than the mixing of bulk of smoke inside the enclosure. (5) The smoke particles' geometric-number-mean-aerodynamic diameters grow to an about 0.5  $\mu\text{m}$  range in 2 hours of smoke aging processes except for the smoke particles from the filter paper, which stay around a 0.2  $\mu\text{m}$  range. The mass concentrations of the smoke particles from the filter paper are also about one or two orders of magnitude smaller than those from the others. (5) Among the burned materials, the ranking in the normalized maximum mass concentration of the smoke particles, as well as the amounts of smoke particles deposited on the floor, match well with the ranking by the smoke yield of the materials: i.e., PS, PP, PE, heptane, PMMA, and filter paper. The collected data will be used for the development of a computer model simulating smoke transport.*

**Key Words:** smoke characterization, smoke particle measurement, smoke transport

## 1. INTRODUCTION

For smoke sensitive occupancies such as clean rooms, information technology facilities, and computer rooms, the damage caused by smoke deposition can be comparable with or even greater than the traditional fire damage associated with heat or sprinkler water. Non-thermal smoke damage is caused by the smoke particles deposited on the surfaces of commodities in warehouses or sensitive elements of vital equipment in high value facilities. The estimation capability of the amount of damage inflicted by smoke is in its

infant stage, as the current knowledge on the scope of the damage is limited to a qualitative nature. One of the most promising techniques for the quantitative estimation of the smoke damage is utilizing a CFD-based smoke transport model in conjunction with experimentally measured smoke characterization information. This paper is about obtaining the smoke characterization data to be used in the computer model. The data are: (1) Heat release rate and generation rate of smoke in free burning, and (2) Smoke mass concentration and particle size distribution during and after flaming fires. Smoke here is defined as all the airborne products from materials that are undergoing flaming or non-flaming combustion---a mixture of gases, vapors, and suspended particulate matter, or aerosols.

Traditionally, smoke in the fire safety community has been extensively studied for its hazards associated with life safety in fire. In consequence, many studies were conducted related to the smoke particle transport and deposition on the human respiratory system [1, 2]. By replacing the respiratory system with the floor or the surface of sensitive equipment, a similar analysis can be extended to estimating non-thermal damage by smoke. The smoke particles and adsorption and desorption of gases on them will be responsible for the malodor, stain, odor, and surface corrosion caused by smoke deposition. In general, the deposition mechanisms and rates are all related to the particle sizes and concentrations. Typical mechanisms are sedimentation, thermophoresis, diffusion, and turbulent deposition [1, 2, 3]. The smoke particle size also has a strong influence on clean up of the facility after a fire. For instance, adhesive forces of the particles to the surface are proportional to  $d_p$ , particle diameter, while removal forces are proportional to  $d_p^3$  for gravitational, vibrational, and centrifugal forces and  $d_p^2$  for air current [2], suggesting that as the particle size decreases, it becomes more difficult to remove the particles from the surface. This illustrates the importance of smoke particle size in not only understanding the contamination by deposition but also deploying proper schemes for a salvage process after a high value facility is exposed to fire.

It is also important to understand that in many fire situations, individual particle motion in smoke is negligible compared with motion on a larger scale. Smoke is an *aerosol cloud* that can be defined as a region of high aerosol concentration having a definite boundary in a much larger region of clean air. Even when there is no difference in gas density between an aerosol cloud and its surroundings, there are still situations in which the cloud as an entity can move much faster than the individual particles that make up the cloud [2]. When *Cloud settling* occurs, the particles in the cloud move at a velocity significantly greater than the individual particle settling velocities. This can be caused solely by the particle loadings and needs not depend on differences in gas density inside and outside the cloud [2]. The measured smoke data in this work would indicate that smoke particles in large-scale fires are likely to settle orders of magnitude higher than that of individual particles due to the cloud settling. Another aspect of smoke that must be considered is coagulation. Smoke particles undergoing Brownian motion collide and stick together forming agglomerates, which reduces the number of particles while maintaining the total mass of the particles unchanged [4].

Thus, the smoke particle size and concentration are the critical aspects of smoke characterization. In order to investigate particle aspects of smoke from various materials, six materials were burnt to generate smoke inside an enclosure. The materials were: polyethylene, polypropylene, filter paper, PMMA, heptane, and polystyrene. The burning rate, temperatures near the flames, temperatures inside the smoke plume generated by the burning material were measured by a load cell and thermocouples to characterize the test fires. The number concentrations and geometric-number-mean-aerodynamic diameters of smoke particles were measured by an electrical low-pressure impactor (ELPI) and an electrical aerosol detector (EAD); and mass concentrations of smoke particles were measured by a tapered element oscillatory microbalance (TEOM) and a Dustrak mass monitor. The amounts of smoke deposited on the floor were also measured through 4 or 6 disks that were spread out across the floor. The smoke particle properties were measured during and after flaming fires in order to characterize smoke from its generation to aging.

TABLE 1. TEST CONFIGURATION

Test No	Test Sample	Fuel Mass (g)	Max.Steady Burning Rate (g/s)	Max. Steady Burning Duration (s)	Aging Process (Y or N)
1	High Density Polyethylene 254 by 216 by 13 mm thick	680	1.012	1000<t<1600	No
2	High Density Polyethylene 254 by 216 by 13 mm thick	680	1.020	1100<t<1600	No
3	High Density Polyethylene 254 by 216 by 13 mm thick	680	1.080	2400<t<2800	Yes for 2 hours
4	High Density Polypropylene 254 by 216 by 13 mm thick	706	1.175	1290<t<1694	No
5	High Density Polypropylene 254 by 216 by 13 mm thick	706	1.025	150<t<706	Yes for 2 hours
6	Filter Paper; Med. Porosity; D=241 mm; 200 sheets	682	0.643	0<t<1060	No
7	Filter Paper; Med. Porosity; D=241 mm; 200 sheets	682	0.601	0<t<1106	Yes for 65 hours.
8	Filter Paper; Med. Porosity; D=241 mm; 200 sheets	682	0.630	0<t<1055	No
9	PMMA (Black) 216. by 127 by 13 mm thick	345	0.295	28<t<1167	No
10	PMMA (Black) 216 by 127 by 13 mm thick	345	0.312	117<t<1211	Yes for 2 hours
11	Heptane 100 ml; Pan Dia.= 76 mm; Depth= 51 mm	75	0.088	147<t<900	No
12	Heptane 200 ml; Pan Dia.= 89 mm; Depth= 51 mm.	150	0.128	515<t<1490	Yes for 2 hours
13	Polystyrene 216 by 127 by 6 mm thick	165	0.579 0.314	211<t<356 356<t<541	No
14	Polystyrene 216 by 127 by 6 mm thick	165	0.576 0.291	332<t<464 464<t<615	Yes for 2 hours
15	High Density Polyethylene 254 by 216 by 13 mm thick	680	0.920	511<t<1170	No

The enclosure, 6.1 m by 6.1 m by 3.0 m high with a wooden door, 2.10 m high by 0.91 m wide, at its south-east corner, was built with wood frames outside and gypsum board walls and a ceiling inside. A total of 15 tests were conducted. Table 1 shows an overall configuration of the 15 tests. The fourth column in the table shows the mass loss rate of the material in each test for the duration that corresponds to almost steady burning with the highest mass loss rate. The fifth column shows the flaming fire durations that correspond to the steady and maximum burning rate shown in the fourth column. The last column shows whether smoke aging process and relevant smoke particle measurements during the process were carried out in the test. In Test 7, although the smoke inside the enclosure was left to settle on the disks on the floor for 65 hours after the fire was extinguished, the data collection regarding the particle measurements was carried out for only one hour.

Smoke was sampled from three locations during the tests. The ELPI, Dustrak, and EAD pulled a common sample near the ceiling and the floor close to fire, which are referred to as SIC and SIF, respectively. The TEOM samples were taken near the center of the enclosure close to the ceiling, referred to as SIT. The masses of the accumulated smoke particles that fell down on the floor were measured with two sets of disks, one set were 47-mm diameter aluminum foil filters and the other were 37-mm diameter Teflon filters. They were spread around the floor at either four or six target locations.

## **2. TEST RESULTS AND DISCUSSION**

The smoke data obtained in each test were reviewed collectively based on the burned material. Under the assumption that the smoke data for the same material with the same burning rates are likely to behave in a similar manner, the collected data were shifted in such a way that the initial time would be matched with the beginning of the maximum steady burning rate of the material in each test. Due to the space limitation, results from only four materials---polyethylene, filter paper, heptane, and polystyrene---will be discussed with some details. The summary, however, will discuss smoke from all the six materials.

### **2.1 High Density Polyethylene (HDPE)**

Tests 1, 2, 3, and 15 were conducted by burning a HDPE panel. The material was laid on a 478K hot plate for 30 min so that the material pyrolysis was well advanced before each test started. After the material was placed inside a pan for ignition, which is on the Marinite plate equipped with a load cell, 100 ml methanol was poured and lit. As mentioned above, the collected data from the four tests were re-arranged with the adjusted times, so that the initial point of the data coincided with the beginning of the maximum burning rate in each test. In order to make a distinction between the real time  $t$  in the tests and the adjusted time, which is the real time  $t$  minus the initial burning period before the fire reached the point at which the maximum burning rate occurs, the adjusted time will be represented as  $\tilde{t}$  in this paper.

Fig 1 shows the number concentrations of the smoke particles collected through SIC and SIF in Tests 1, 2, 3 and 15. The maximum number concentrations in Test 1 and 3 look very close, while that in Tests 2 is slightly lower and that in Test 15 is the lowest. After about  $\tilde{t} = 600$ , at which the flaming fires no longer existed in any of the tests, all the four number concentration at SIC seemed to be converged into one. The figure shows, however, there were substantial differences in number concentrations between the smoke samples taken at the ceiling and the floor when  $\tilde{t} < 1800$ . Fig 2 shows how the geometric-number-mean-aerodynamic diameter of the smoke particles grows with time. The geometric-number-mean-aerodynamic diameters in Tests 1, 2, 3, and 15 in Fig 2 show that, unlike the cases with the number concentrations, there were almost no differences in the particles sizes between the smoke collected at the ceiling and the floor. It indicates that the smoke coagulations among the PE smoke particles proceeded much faster than the mixing of the smoke at the ceiling, which had high buoyancy while the flames existed, with that at the floor. The figure shows that the particles grew to approximately  $0.53 \mu\text{m}$  at the end of the two-hour-smoke-aging process in Test 3. Fig 3 shows the mass concentrations of PE smoke particles in Tests 1, 3, and 15.

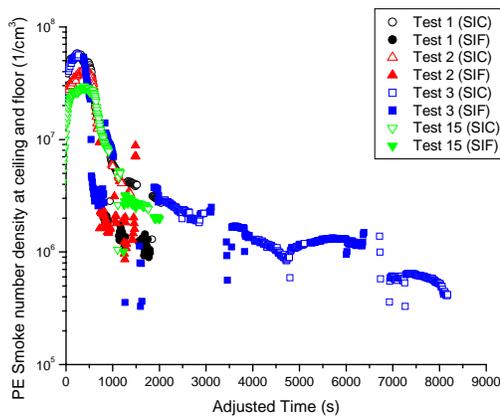


Fig 1. Number concentrations of PE smoke particles at SIC and SIF.

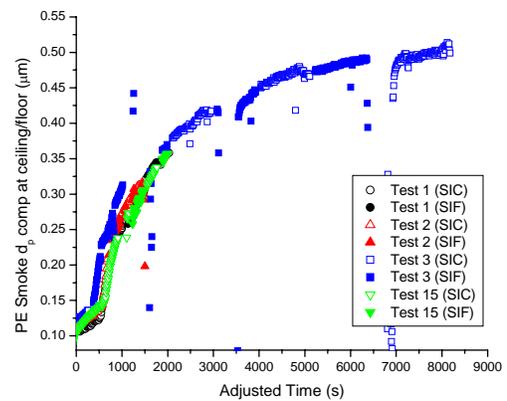


Fig 2. The aerodynamic diameters of the PE smoke particles in Tests 1, 2, 3, and 15.

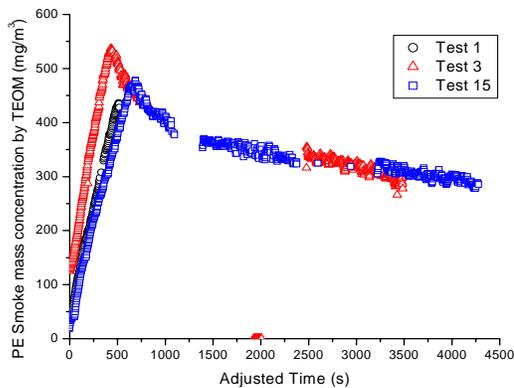


Fig 3. Mass concentrations of the PE smoke particles measured by TEOM at SIT.

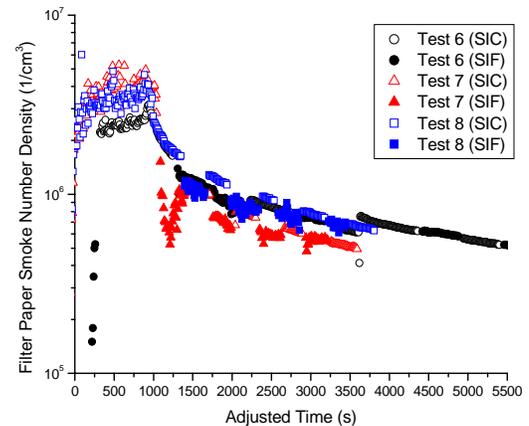


Fig 4. Number concentrations of the filter paper smoke particles at SIC and SIF.

## 2.2 Filter Paper

Ignition for 200 sheets of filter paper was provided by 20 ml of methanol in Tests 6, 7, and 8. Fig 4 shows the number concentrations of the smoke particles collected through SIC and SIF. The maximum number concentration in the figure is an order of magnitude lower than that in HDPE smoke in Fig 1. Fig 5 and 6, respectively, show the geometric-number-mean-aerodynamic diameter and the mass concentration of the smoke particles. The geometric-number-mean-aerodynamic diameter in filter paper smoke is smaller than that in the HDPE smoke; the maximum mass concentration is almost two orders of magnitude smaller than that in the HDPE smoke. Again, as in the previous case, there was substantial difference in the number concentration when  $\tilde{t} < 2000$  while there was almost no differences in the particle diameters between the smoke samples taken at the ceiling and the floor, indicating particle coagulation proceeded faster than the uniform mixing of smoke.

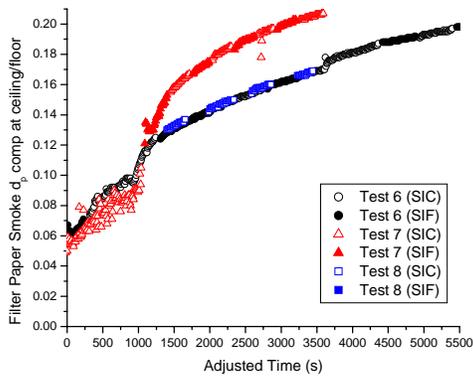


Fig 5. The aerodynamic diameter of the filter paper smoke particles at SIC/SIF.

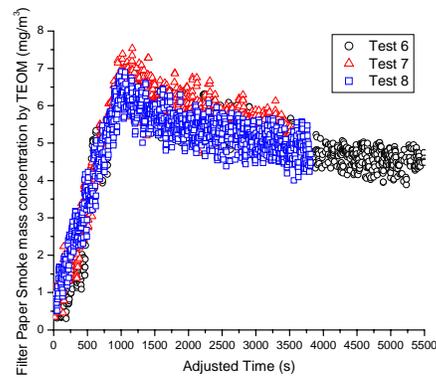


Fig 6. The mass concentrations of the filter paper smoke measured by TEOM.

## 2.3 Heptane Fire

Tests 11 and 12 were conducted respectively by burning 100 ml (75 g) and 200 ml (150 g) heptane. Figs 7 and 8 show, respectively, the number concentrations of the smoke particles and the geometric-number-mean-aerodynamic diameters of the heptane smoke particles in Tests 11 and 12. There seem to be almost no differences in the number densities whether the smoke samples were collected through SIC or SIF, which is a different trend from that shown in the smoke from PE, PP, and filter paper. The difference between the maximum smoke plume temperature at the ceiling and that at the floor was less than 11 °C in the heptane fires, while that in the other fires (PE, PP, filter paper) was close to 44 °C. This relatively small difference between the temperature at the ceiling and that at the floor seemed to have resulted in a uniform mixing in a relatively short time compared with the times in the previous cases. The smoke particle sizes at  $\tilde{t} = 9000$  are smaller than those in PE, PP, and PMMA smoke particles in the previous tests at the same time, but larger than those in the filter-paper smoke. Fig 9 shows the mass concentration of the heptane smoke particles measured by TEOM in Tests 11 and 12.

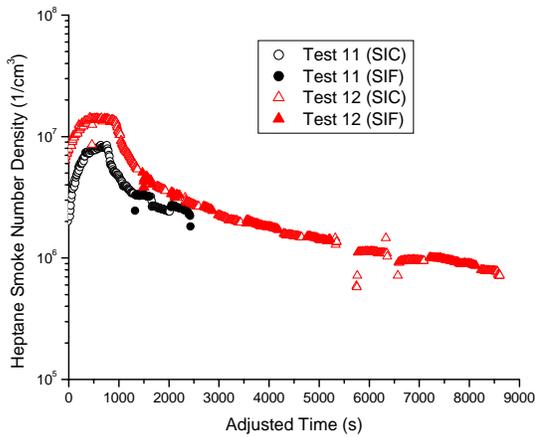


Fig 7. The number concentrations at SIC and SIF of smoke particles from heptane fire.

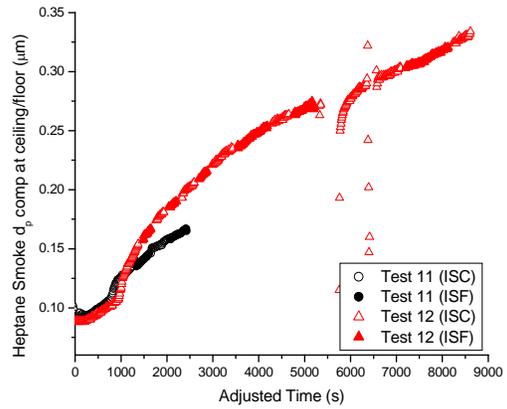


Fig 8. The aerodynamic diameter of smoke particles from heptane fire.

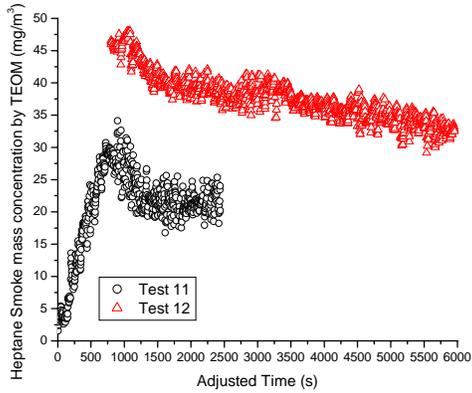


Fig 9. Mass concentrations of the smoke particles from heptane fire measured by TEOM

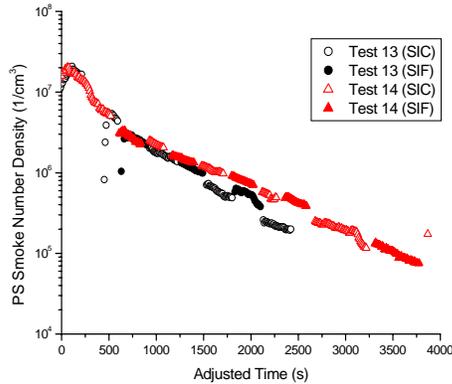


Fig 10. The number concentrations of the polystyrene smoke particles.

## 2.4 Polystyrene (PS)

Tests 13 and 14 were conducted by burning a polystyrene panel. Fig 10 shows the number concentrations of the polystyrene smoke particles collected through SIC and SIF in Tests 13 and 14. There seem to be almost no differences in the number densities whether the smoke samples were collected through SIC or SIF. Again, this can be attributed to the small difference in the plume temperatures at the ceiling and at the floor.

Fig 11 shows the geometric-number-mean-aerodynamic diameters of the polystyrene smoke particles in the tests. The figure shows that there were almost no distinctions in particles sizes whether the smoke samples were collected at the ceiling or at the floor. Fig 12 shows the mass concentration of the polystyrene smoke particles measured by TEOM in Tests 1, 2, 3, and 15. Although the total mass of the burned material in the tests was less than ¼ of that of HDPE, the mass concentrations were higher than those in the HDPE smoke.

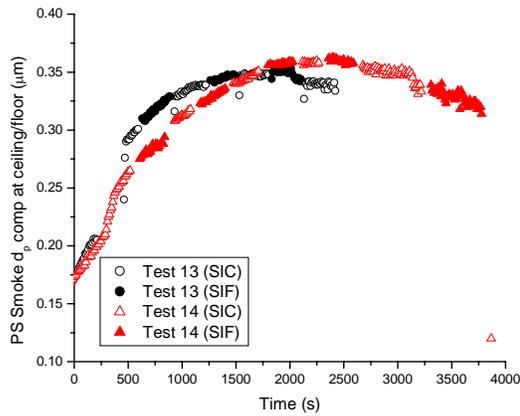


Fig 11. Aerodynamic diameter of the polystyrene smoke particles.

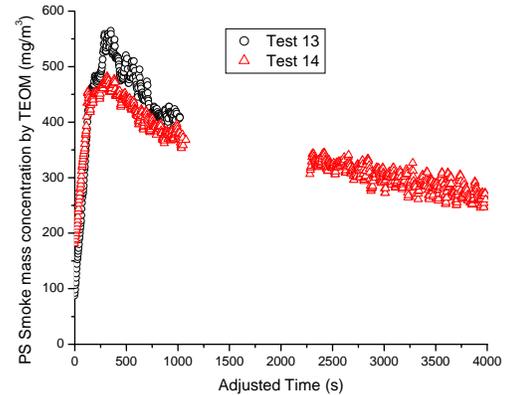


Fig 12. Mass concentrations of polystyrene smoke particles measured by TEOM.

A review of the all test data collected through the 15 tests in Table 1 indicated the following:

- (1) There were no noticeable size differences in the smoke particles in all the tests whether they were collected at the ceiling or at the floor while there were considerable differences in the number concentrations at the early stages in smoke aging between the samples at the ceiling and those at the floor when there was a substantial temperature difference between the two samples. This indicates that the particle coagulation process is much faster than the mixing process of the bulk of smoke.
- (2) The difference in the number concentrations between the smoke collected at the ceiling and at the floor became indistinguishable after  $\tilde{t} = 2000$  in all the tests. In view of that the typical average particle sizes around that time were less than  $0.5\mu\text{m}$  and the settling velocity of that size particle is around  $1 \times 10^{-5}$  m/s, which means that it would take about 83 hours for the individual particles to settle on the floor, this clearly showed that the majority of smoke particles moved as constituents of aerosol clouds, which move orders of magnitude faster than each individual particles would.

## 2.5 Smoke Particle Coagulation/Agglomeration

In this study, the particle growth in a smoke aging period was routinely measured by the ELPI. One example on the coagulation given here is from Test 5, smoke from burning high density polypropylene. All the mass concentrations in smoke plumes measured in the current work kept changing as a result of either ongoing combustion or smoke dilution after the combustion was completed. In order to make a proper comparison of the particle growth vs. the decrease of the number concentration, data at the same mass concentration have to be used. The data in Test 5 provide an opportunity for making proper assessment of the particle growth vs. the change in number concentration.

At time  $t=541$  in Test 5, the number concentration was  $3.61 \times 10^7 / \text{cm}^3$ , mass concentration was  $536 \text{ mg/m}^3$ , the geometric-number-mean-aerodynamic diameter,  $d_{gn}$ , at the ceiling was  $0.15 \text{ }\mu\text{m}$ , and the geometric standard deviation  $\sigma_g = 1.86$ . At time  $t=1831$ , the number concentration was  $2.83 \times 10^6 / \text{cm}^3$ , mass concentration was  $547 \text{ mg/m}^3$ , the geometric-number-mean-aerodynamic diameter at the ceiling was  $0.36 \text{ }\mu\text{m}$ , and  $\sigma_g = 1.62$ . As the mass concentrations at both times are close enough, one can ignore the effect of smoke dilution. Assuming the particle size distribution was log-normal, the mass-mean particle diameter,  $d_{gv}$ , at  $t=541$  and that at  $t=1831$  can be obtained as  $0.48 \text{ }\mu\text{m}$  and  $0.72 \text{ }\mu\text{m}$ , respectively, by applying the following Eq (1) [4].

$$\log d_{gv} = \log d_{gn} + 6.9(\log \sigma_g)^2 \quad (1)$$

Assuming there was no change in mass concentration, the particle size at time  $t$  will also change as follows:

$$d_{pt} = d_{p0} \left( \frac{N_0}{N_t} \right)^{1/3} \quad (2)$$

Here  $d_{pt}$ ,  $d_{p0}$ ,  $N_0$ , and  $N_t$  are, respectively,  $d_p$  at time  $t$ ,  $d_p$  at  $t=0$ , the particle number corresponding to the particle  $d_{p0}$ , and the particle number corresponding to the particle  $d_{pt}$ . The number of particles at time  $t$  can be computed following a Smoluchowski model as [4]

$$N_t = \frac{N_0}{1 + \Gamma N_0 t} \quad (3)$$

where  $\Gamma$  the coagulation coefficient.

Eq. (2) provides the mass mean diameters expected from the change of the number concentrations given above as  $d_{gv} = 0.48 \times \left( \frac{3.61 \times 10^7}{2.83 \times 10^6} \right)^{1/3} = 1.12 \text{ }\mu\text{m}$ , which is somewhat higher than the measured one,  $0.72 \text{ }\mu\text{m}$ . Eq. (3) provides the  $\Gamma$  value as

$$\Gamma = \frac{\left[ \left( \frac{3.61 \times 10^7}{2.83 \times 10^6} \right)^3 - 1 \right]}{\left[ 3.61 \times 10^7 \times 1290 \right]} = 2.52 \times 10^{-10} \text{ cm}^3/\text{s}.$$

An estimated average coagulation coefficient  $\Gamma$  value in Hinds [2] for the conditions close to those specified above is  $7 \times 10^{-10} \text{ cm}^3/\text{s}$ , which is reasonably close to the value obtained above. Thus, this example illustrates that the measurements of the particle sizes in this study are well within ballpark values estimated by literature.

## 2.6 Smoke Particle Sedimentation Measurement

Smoke particles were allowed to be deposited on either a 47-mm-diameter aluminum disk or a 37-mm-diameter Teflon disk for approximately 2 hours in Tests 3, 5, 10, 12, and 14, and for approximately 65 hours in Test 7. Among them, four target locations were used in Test 3, and six target locations were used in all the other tests. Fig 13 shows

polystyrene smoke particles deposited on a filter paper. The blank circle at the center of the paper is the place where the collecting disk was placed and removed for the weight measurement. The smoke masses deposited on the targets per unit deposit area were normalized by the total mass of the burned material in each test and are plotted in Fig 14. The ranking in the smoke deposition matches well with the ranking by the smoke yield, i.e.,  $Y_s$ .



Fig 13. Photo of the polystyrene smoke particles deposited on a filter paper.

## 2.7 Correlation between temperature and mass concentration inside a smoke plume

In Tests 14 and 15, correlations between the temperature and the mass concentration inside smoke plumes generated by burning polystyrene and polyethylene, respectively, were explored. Fig 15 shows a correlation between the PS smoke mass concentration and the plume temperature in Test 14. It shows a strong correlation between the two properties for the period of rising temperature, and a reasonably good correlation for the period of falling temperature. The result in Test 15 also showed the same trend.

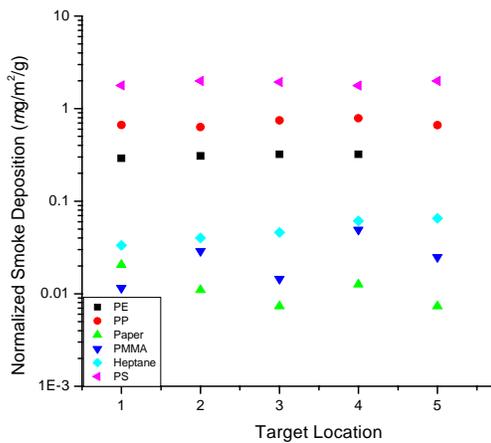


Fig 14. Normalized smoke deposition at each target location.

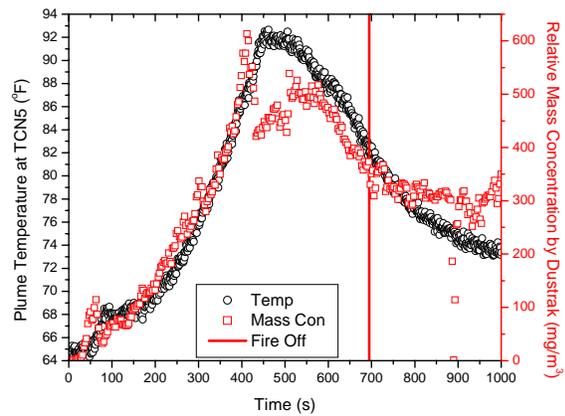


Fig 15. Correlation between the PS smoke plume temperature and the mass concentration in Test 14.

### 3 SUMMARY

As a part of a long-range research program assessing non-thermal damage by smoke, a computer model that can estimate smoke mass concentration at a given location from a known fire source inside an enclosure will be developed. For the first step in developing the computer model, smoke characterization from various burning materials was attempted. The materials burnt to generate smoke inside an enclosure were: polyethylene, polypropylene, filter paper, PMMA, heptane, and polystyrene. The burning rate, temperatures near the flames, temperatures of the plume generated by the burning material were measured to characterize the test fires. In order to characterize the smoke, the number concentrations and geometric-number-mean-aerodynamic diameters, and mass concentrations of the smoke particles were measured while there were flaming fires. The same set of the measurements were carried out for 2 hours after flaming fires were extinguished in order to characterize smoke aging process for each material.

The amounts of smoke deposited on the floor were also measured through 4 or 6 disks that were spread out across the floor. The tests achieved: (1) characterizing smoke particles from generation to transport and to aging, (2) providing input data for the numerical model for smoke transport, and (3) providing data to develop empirical correlations that can be implemented into the computer model.

In addition, a review of the collected data also showed the following:

1. A strong correlation between the smoke mass concentration and the temperature inside a smoke plume was observed for the period of increasing temperature and a reasonably good correlation for the period of decreasing temperature.
2. Particle coagulations became much more pronounced as soon as a fire was extinguished.
3. It was apparent that smoke particles in fires move as constituents of large aerosol clouds rather than each individual particle, which would make them to move and settle with orders of magnitude higher velocities than those of individual particles.
4. The smoke particles' geometric-number-mean-aerodynamic diameters grew to the about a 0.5  $\mu\text{m}$  range in 2 hours of smoke aging processes except for the smoke particles from the filter paper. The smoke particles from the filter paper stayed around a 0.2  $\mu\text{m}$  range. The mass concentrations of the smoke particles from the filter paper were also about one or two orders of magnitude smaller than those from the others.
5. In general, the growth of smoke particle diameter by particle coagulation seems to progress much faster than the mixing of bulk of smoke inside the enclosure.
6. The ranking in the normalized maximum mass concentration of the smoke particles, as well as the amounts of smoke particles deposited on the floor, among the burned materials matched well with the ranking by the smoke yield of the materials: i.e., PS, PP, PE, heptane, PMMA, and filter paper.

The wider significance of the general observations in this study briefed above is expected to be clarified further as the efforts progress in developing the computer model and

validating the model through more experiments. Applications to various smoke detector programs will also be explored

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