

Polycyclic aromatic hydrocarbons (PAHs) and mutagenicity of soot particulates in air emissions from two-stage incineration of polystyrene

Jiann-Hwa You^a, Pen-Chi Chiang^a, Kun-Ten Chang^b and Shenq-Chyi Chang^b

^a *Graduate Institute of Environmental Engineering, National Taiwan University, Taipei (Taiwan, R.O.C.)*

^b *Department of Biochemistry, National Yang-Ming Medical College, Taipei (Taiwan, R.O.C.)*

(Received October 5, 1992; accepted in revised form March 16, 1993)

Abstract

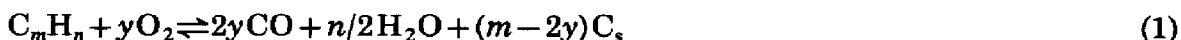
Polycyclic aromatic hydrocarbons (PAHs) and mutagenicity of particulates from incineration of polystyrene were analyzed by GC/MSD and TA-98 Ames test, respectively. The results of this investigation indicate that a critical temperature exists of 1000 °C–1100 °C in the stage-two incinerator for the formation of PAHs and soot particulates. The major precursor of PAHs formation (i.e., C₆H₆) is produced in large amounts in nitrogen atmosphere when the stage-two temperature rises to 900 °C. The mutagenicity of particulates and polyurethane foam (PUF) extracts increased as the pyrolysis temperature was increased from 900 to 1200 °C. The mutagenicity of PUF extracts is weaker than the mutagenicity of particulates extracts. Moreover, the mutagenicity of samples is much higher in the presence of rat liver microsomal fraction (S9 mixture) than in its absence.

1. Introduction

During the incineration process of organic compounds [1–3], the air emissions might possess certain highly toxic compounds such as dioxins, polycyclic aromatic hydrocarbons (PAHs). The PAHs, which are thought to be the precursors of soot and have been also known to be mutagenic or carcinogenic after being metabolized, are commonly produced from incomplete combustion [4–6]. The propensity to form PAHs and soot is strictly dependent upon the incineration temperature, residence time and supply of oxygen in the incineration process of plastics.

Most plastic materials decompose thermally in the temperature range of 200 to 400 °C. In principle, the decomposed and fragmented molecules mix with oxygen to produce CO₂ and H₂O in the complete combustion reaction. From a thermodynamic point of view, PAHs and soot formation should begin at a C/O ratio of unity, corresponding to the condition $m=2y$

in eq. (1)



Thus even well mixed incineration systems are observed to form PAHs and soot when the C/O ratio is greater than 0.5. That also indicates that some of the oxygen is tied up in the relatively stable combustion products CO₂ and H₂ and is thus unavailable for reaction with C_s on the time scale of incineration systems [7, 8].

PAHs and soot can be decreased by oxidation occurring predominantly via molecular oxygen attack on aromatic radicals when the oxidants, such as O₂ and ·OH are supplied in the incineration process. Also, due to similar reactions of O₂ with C₂H₃· and C₄H₃· radicals (and of ·OH with C₂H₃·, etc.), the concentrations of these precursors of PAHs formation are decreased, which in turn reduces the formation rate of the first aromatic ring [9-11]. Otherwise, the presence of O₂ in incineration process also has a promoting effect on aromatics formation because of the accelerated chain branching that leads to an increase in the C/O ratio and to enhance the fuel pyrolysis and thus increased precursors of PAHs formation such as C₂H₂, C₂H₃·, C₂H₄ and C₄H₃·.

Fundamental mechanisms are involved in PAHs and soot formation in the incineration process such as oxidation, pyrolysis, Diels-Alder reaction, nucleation, coagulation, aggregation, and agglomeration [7-9]. Furthermore, the PAHs formed can grow, condense or adsorb onto the emitted particulates which will diffuse to the atmosphere. These air pollutants are a potential danger to human health because of their mutagenicity or carcinogenicity. Thus, the objectives of this research work are focused to characterize the precursors of PAHs formation i.e., C₆H₆, PAH compounds and soot formation under various incineration temperatures and oxygen supply conditions. The mutagenicity of the emitted gas from polystyrene incineration is also considered and focused on.

2. Materials and methods

A 0.2 gram sample of polystyrene (PS) was incinerated at various temperatures and oxygen supplies in a two-stage incinerator. The feed gas consisted of a mixture of oxygen and nitrogen. The feed rate was controlled at 2.0 NL/min and at various oxygen/nitrogen ratios by use of a flotation flow meter and needle valves. The two-stage incinerator consisted of two furnaces, two quartz tubes, an electronic balancer, a computer and a data acquisition system which is used for auto sampling, signal transfer and autorecording the mass losses of the PS and temperature changes with time from the PS incineration process. The setup is shown in Fig. 1. The temperature in the first incinerator was raised at 40 °C/min to 500 °C. The temperature in the second incinerator was controlled at various temperatures (clean-up temperature), between 900 °C and

1200 °C. The theoretical residence time was about 0.5 to 1.0 seconds in the second stage incineration process. Samples of C_6H_6 , $C_6H_5CH_3$, $C_6H_5C_2H_3$ and $C_6H_5C_2H_5$ were taken with a pyrex tube at intervals of 30s and analyzed by GC/FID (HP 5890). The operating conditions were: oven temperature 70 °C (3 mins) to 170 °C (7.5 °C/min), inject temperature 150 °C, detection temperature 200 °C, carrier gas 20 ml/min N_2 , capillary column 30 m \times 0.53 mm I.D.

A glassfiber filter was used for sampling the particles and PAHs which were in the solid phase. Polyurethane foam (PUF) was used for sampling the PAHs which were in the gas phase. The samples were pretreated in a series of processes: extraction, concentrating and purification, then the GC/MSD was used to analyze the 14 species of PAHs as shown in Table 1. The operating conditions were: initial temperature 50 °C and time 3 min, rate of temperature increase during stage one 12 °C/min, media temperature 170 °C and time 13 min, rate of temperature increase during stage two 6 °C/min, final temperature 310 °C and time 38 min, capillary column 25 m \times 0.2 mm I.D. During the extraction process, samples were extracted in a soxhlet extractor with 250 mL of dichloromethane at 40 °C for about 16 h. After extraction, the dichloromethane extract was concentrated to 1 mL–2 mL by use of a rotary evaporator. The residue of the extract was purified with 100 mL hexane–dichloromethane (7:3 v/v) in a tube purifier ($\phi = 1$ cm, $L = 20$ cm) which was packed with 2 grams of activated aluminum and 3 grams of silica gel. Finally, the purificatory samples were once concentrated to 2 mL by use of a rotary evaporator, and dried to 1 mL by use of the nitrogen.

The mutagenic activity of the particulates and PUF extracts was tested by the Ames Salmonella/microsomal assay system [12, 13]. From previous studies, it was noted that the mutagenic response of strain TA98, which was used to

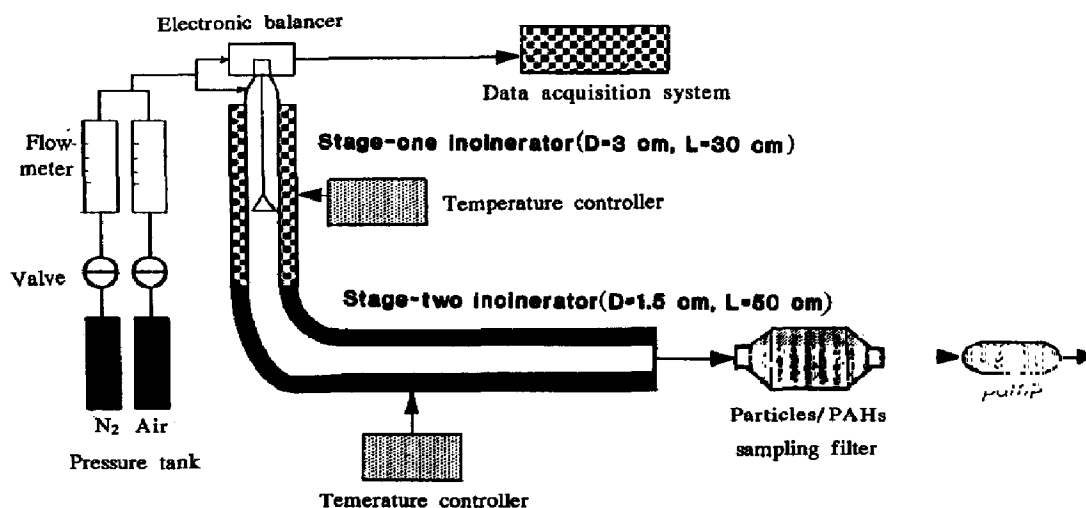


Fig. 1. Schematic diagram of apparatus.

The name and characteristics of PAHs

Name	Chemical formula	Molecule weight (g/mol)	Melting point (°C)	Boiling point (°C)	Carcinogenicity*	Chemical structure
PhA (Phenanthrene)	C ₁₄ H ₁₀	178	101	340	-	
Flu (Fluoranthene)	C ₁₆ H ₁₀	202	110	393	-	
Pyr (Pyrene)	C ₁₆ H ₁₀	202	156	404	-	
Ben (Benzo[b]fluorene)	C ₁₇ H ₁₂	216	N.D.	N.D.	-	
BaA (Benz[a]anthracene)	C ₁₈ H ₁₂	228	158	435	+	
Chr (Chrysene)	C ₁₈ H ₁₂	228	254	448	+	
Tri (Triphenylene)	C ₁₈ H ₁₂	228	199	425	-	
BbF (Benzo[b]fluoranthrene)	C ₂₀ H ₁₂	252	N.D.	393	+	
BeP (Benzo[a]pyrene)	C ₂₀ H ₁₂	252	178	312	-	
BaP (Benzo[e]pyrene)	C ₂₀ H ₁₂	252	179	496	++	
Pr (Perylene)	C ₂₀ H ₁₂	252	273	500	-	
DbA (Dibenz[a,h]anthracene)	C ₂₂ H ₁₄	278	266	535	+++	
IP (Indeno[1,2,3-cd]pyrene)	C ₂₂ H ₁₂	276	N.D.	534	+	
BghiPr (Benzo[g,h,i]perylene)	C ₂₂ H ₁₂	276	273	542	-	

* - Not carcinogenic, + uncertain or weakly carcinogenic, ++ carcinogenic, +++ very strongly carcinogenic.

detect frame-shift substitution mutation, was significantly higher than that of strain TA100, which was used to detect base-pair substitution mutation, upon incubation with the dichloromethane extract of airborne particulates. Thus, *Salmonella typhimurium* strain TA98 was employed to carry out the mutagenicity test in this study.

An aliquot of sample extracts in DMSO was delivered to a test tube containing 2 mL of molten top agar supplemented with 0.1 mL test solution, 0.1 mL of an overnight broth culture of the tester strain, with or without 0.5 mL S9 mixture. The S9 homogenate was prepared from the liver of Sprague-Dawley male rats pretreated for 5 days with Aroclor 1254 (500 mg/kg body weight) according to Maron and Ames [13]. After a two-day incubation of the culture plates at 37°C, histidine revertants of TA98 were counted. A positive mutagenic response was defined as a dose-dependent response giving at least a two fold increase in revertant colonies per plate as compared with spontaneous reversion.

3. Results and discussion

Figure 2 shows the mass loss of the PS versus decomposition time and pyrolysis temperature, respectively. The decomposition time was about 3 min and the range of the decomposition temperature of the 0.2 gram PS was 350°C to 500°C when it was pyrolysed with 0.2 NL/min nitrogen supplied.

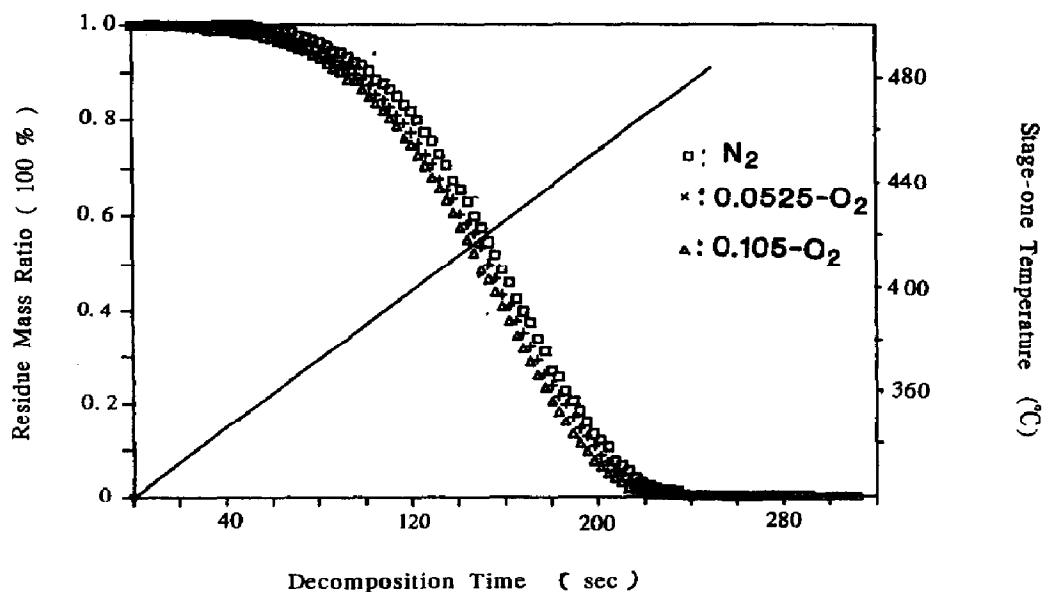


Fig. 2. Thermal decomposition of polystyrene vs. decomposition time and temperature.

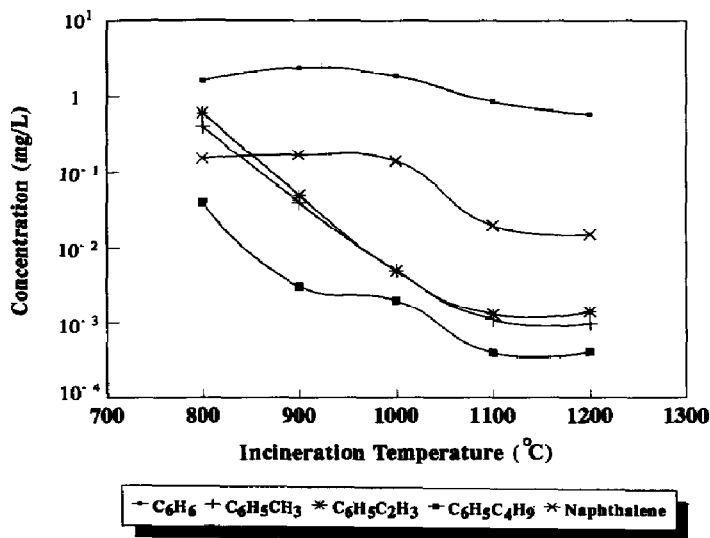


Fig. 3. Formation of aromatic compounds from 0.2 g PS incineration at various stage-two temperatures.

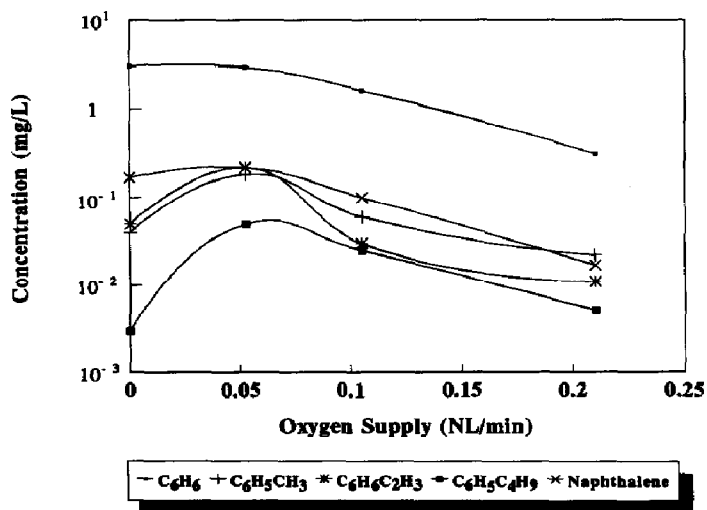


Fig. 4. Formation of aromatic compounds from 0.2 g PS incineration at 900 °C and various oxygen supplies.

From the analyses of the emitted gas in the thermal decomposition process, it was found that ethylbenzene, xylene, 1,3,5-trimethylbenzene, 1,2,4-trimethylbenzene, *p*-isopropyltoluene formed very less. Only the formation of styrene was higher in quantity with an average concentration of about 12.9 mg/L. The formation of naphthalene and toluene was low, but that of the other compounds was much lower.

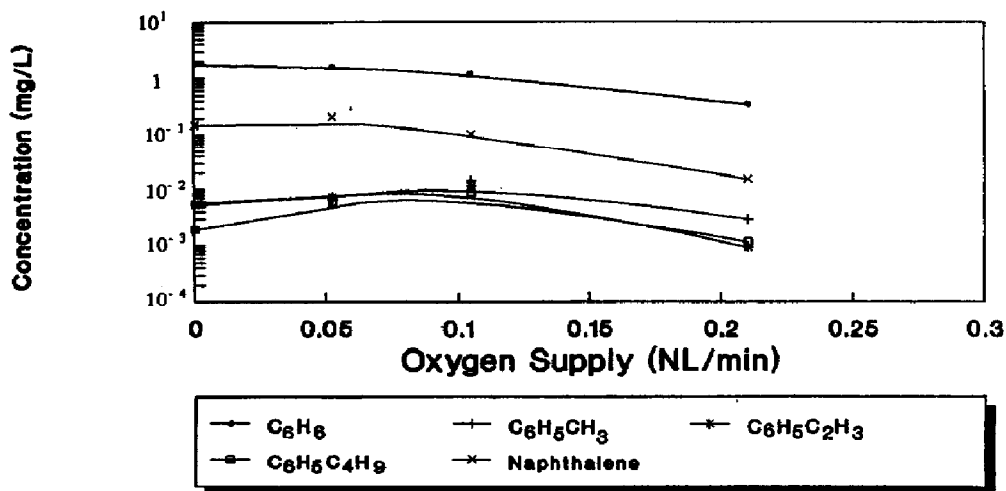


Fig. 5. Formation of aromatic compounds from 0.2 g PS incineration at 1000 °C and various oxygen supplies.

TABLE 2

Comparison of the PAHs distribution in solid and gas phases from 0.2 g PS incineration under various stage-two temperatures and oxygen supplies (PAHs in µg/g-PS)

Feed gas	Phase	Pyrolysis temperature (°C)			
		900	1000	1100	1200
N ₂	S ^a	5322.6	10797.2	3011.1	2312.3
	G ^b	270.2	2100.2	684.6	836.9
0.0525-O ₂ ^c	S	5.9	892.1	930.4	68.9
	G	2456.2	2099.2	1535.3	338.9
0.105-O ₂	S	41.0	107.5	159.5	6.5
	G	276.1	737.3	369.9	272.0
0.210-O ₂	S	77.7	0.4	0.1	- ^d
	G	4.7	13.1	23.6	-

^aS denotes "Solid phase".

^bG denotes "Gas phase".

^c0.0525-O₂ denotes "oxygen supply is 0.0525 NL/min".

^d- denotes "no data available".

These results indicate that PS in the stage-one incineration process melted and gasified. As a result the long chain of polymer structure was broken to a shorter chain of polymer structure, i.e., a monomer (styrene) and toluene. Because the thermal temperature was controlled at the lower temperature of

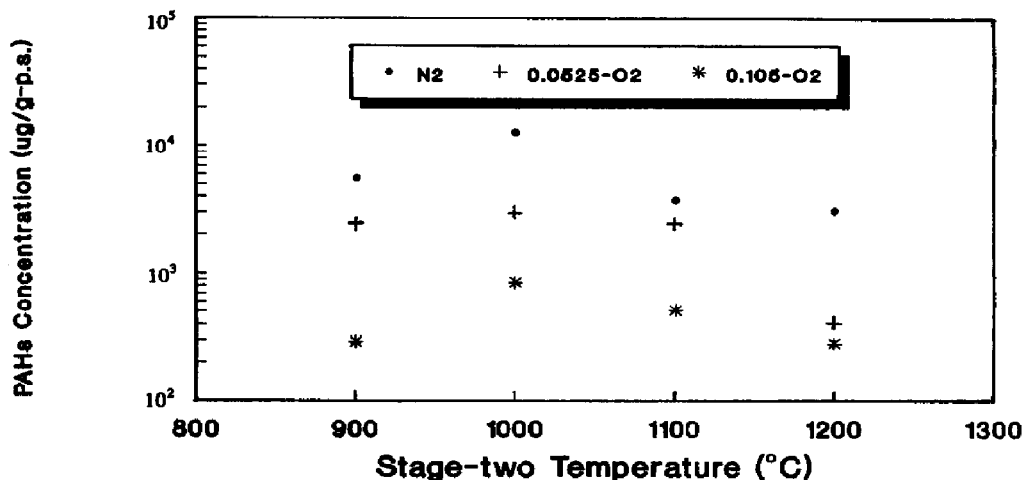


Fig. 6. Formation of 14 PAHs from 0.2 g PS incineration at various oxygen supplies and stage-two temperatures.

TABLE 3

Formation of PAHs during 0.2 g PS pyrolysis at various stage-two temperatures (PAHs in $\mu\text{g/g-PS}$)

PAHs	Pyrolysis temperature (°C)			
	900	1000	1100	1200
PhA	3766.28	5100.55	1077.59	378.37
Flu	634.48	3235.38	1287.06	598.22
Pyr	287.79	1825.43	938.17	760.57
Ben	554.78	542.63	22.46	87.99
BaA	5.89	785.77	114.94	34.83
Chr + Tri	46.08	166.20	20.50	15.76
BbF	297.04	376.44	101.24	59.98
BeP	- ^a	210.03	30.49	67.92
BaP	-	394.22	103.27	397.89
Pr	-	260.05	-	-
DbA	-	-	-	-
IP	-	-	-	268.45
BghiPr	-	-	-	479.23

^a Not detected.

350°C–500°C, there was not enough energy for the polystyrene compound to be effectively decomposed and to form CH_4 , C_2H_2 and C_6H_6 .

When the PS was decomposed at temperatures of 800–1200°C in the second stage incinerator, the formation of benzene, toluene, styrene, n-butylbenzene

and naphthalene was shown in Fig. 3. The formation of styrene, toluene and n-butylbenzene decreased as the temperature in the second stage increased. The formation of benzene and naphthalene appeared to be the highest in concentration at 900 °C in the second stage incinerator. At 800 °C, the concentration of benzene was less than 1.58 mg/L. When the temperature was increased to 900 °C, the product of benzene was increased to be 2.4 mg/L (753.8 ppm v/v) on the average. However, the concentration was decreased to 0.58 mg/L when the temperature was increased to 1200 °C.

When the stage-two temperature was controlled at 900 and 1000 °C and the O₂ supply rate was 0.0525–0.210 NL/min, the formation of benzene decreased as the oxygen supply increased. But, the toluene, styrene, and n-butylbenzene content increased when the oxygen supply increased and the maximum concentration occurred at 0.0525 and 0.105 NL/min, respectively, as shown in Fig. 4 and Fig. 5. The observed trend of the formation of the aromatic compounds in the second stage at various temperatures is the same as observed in previous studies [14] in which the residence time was controlled at 2–4 s. However, the concentration of the aromatic compounds can be seen to decrease. The reasoning is that probably polystyrene is not effectively decomposed to form styrene, toluene and benzene at the relatively shorter residence time in the second stage.

The analysis results of the 14 species of PAHs in the emission in the solid and gas phases are shown in Table 2 and Fig. 6, which indicates the critical

TABLE 4

Formation of PAHs during 0.2 g PS incineration at oxygen supply of 0.0525 NL/min (PAHs in µg/g-PS)

PAHs	Incineration temperature (°C)			
	900	1000	1100	1200
PhA	1118.85	1217.35	497.47	59.10
Flu	681.40	739.06	561.51	79.62
Pyr	303.50	461.98	721.03	171.00
Ben	178.84	50.00	19.05	–
BaA	162.72	133.24	105.11	11.33
Chr + Tri	1.58	30.92	15.13	0.46
BbF	2.31	99.58	95.56	1.79
BeP	2.50	65.15	91.45	2.44
BaP	9.21	140.11	301.34	11.03
Pr	– ^a	54.01	56.76	1.23
DbA	–	–	–	–
IP	–	–	–	8.56
BghiPr	–	–	–	61.05

^a Not detected.

TABLE 5

Formation of PAHs during 0.2 g PS incineration at oxygen supply of 0.105 NL/min (PAHs in $\mu\text{g/g-PS}$)

PAHs	Incineration temperature ($^{\circ}\text{C}$)			
	900	1000	1100	1200
PhA	173.36	280.10	91.49	33.40
Flu	62.93	199.15	79.81	3.92
Pyr	26.40	194.82	145.33	167.67
Ben	16.04	39.29	16.02	—
BaA	21.31	38.59	11.41	9.46
Chr + Tri	1.69	3.92	4.41	0.35
BbF	2.81	10.18	64.75	0.69
BeP	3.05	10.74	14.82	1.27
BaP	9.59	30.87	67.44	2.27
Pr	— ^a	3.37	33.91	—
DbA	—	1.91	—	—
IP	—	17.61	—	—
BghiPr	—	14.02	—	—

^a Not detected.

TABLE 6

Formation of PAHs during 0.2 g PS incineration at oxygen supply of 0.210 NL/min (PAHs in $\mu\text{g/g-PS}$)

PAHs	Incineration temperature ($^{\circ}\text{C}$)		
	900	1000	1100
PhA	21.64	2.73	1.36
Flu	23.95	2.50	0.33
Pyr	13.42	6.02	0.68
Ben	10.16	1.05	—
BaA	11.92	0.83	—
Chr + Tri	0.07	0.37	—
BbF	0.28	—	—
BeP	0.31	—	—
BaP	0.61	—	—
Pr	— ^a	—	—
DbA	—	—	—
IP	—	—	—
BghiPr	—	—	—

^a Not detected.

temperature at which enough thermal energy is provided to form PAHs and soots from PS was about 1000 °C, for two-stage incineration with a residence time of 0.5–1.0 s in the second stage. When the “stage-two temperature” increased to the critical temperature, the PAHs formed in large amount and soot particles were also formed in substantial quantity. Phenanthrene, fluoranthene and pyrene were the major species found among the 14 PAHs. When the temperature of the second stage was increased, the production of the 14 PAHs was significantly decreased. From Tokio Morikawa’s study [3], the maximum evolution of BaP occurred at about 950 °C from PS pyrolysis. The results are very consistent. The reason seems to be that the low-ring PAHs grew and shifted to form high-ring PAHs and soot particulates.

For various oxygen concentrations supplied at 1000 °C, the formation of PAHs decreased about one order of magnitude with each doubling of the oxygen supply. When oxygen supply was controlled at 0.210 NL/min, the PAHs and particulate matter formed scarcely. The rationale is that the oxidation of PAHs, nuclei and precursors occurs when oxygenated species are present. Indeed less precursors (acetylene and benzene) of PAHs were formed, when more molecular oxygen was supplied. The 14 species of PAHs formed are shown in Tables 3 to 6, respectively.

When the pyrolysis temperature in the second stage was controlled at 900 °C, the color of the filtered material was light brown and the production of particles was less. When the temperature increased to 1000 °C, the formation of liquid products and black particles, such as tar, sharply increased to large amounts. At incineration temperatures above 1100 °C, the soot particles had the characteristics of black powder and the quantities of soot particles formed increased with temperature, as shown in Fig. 7.

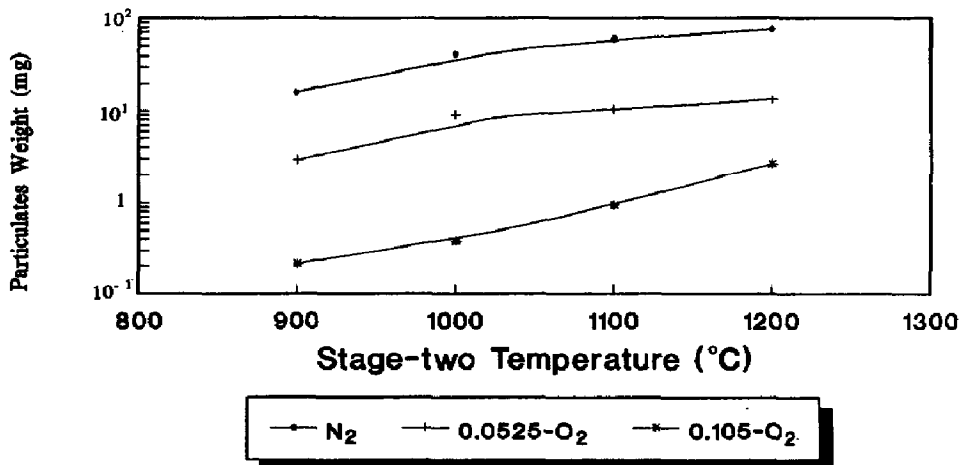


Fig. 7. Formation of particulates from 0.2 g PS incineration at various oxygen supplies and stage-two temperatures.

The formation of PAHs and soot particulates under various incineration conditions was found to be very similar to that in our previous study [14], in which the residence time was controlled at 2-4 s, except that the temperature range was shifted from 900-1000 °C to 1000-1100 °C.

When the stage-two temperature was increased to 1000 °C, enough thermal energy was provided to form PAHs and soot. The concentration of PhA increased to 5100 µg/g-PS and four-ring and five-ring PAHs were also produced in reasonable quantity. However, during the physical observation, some liquefaction and black particles, such as tar, were found, but there were no powder-black soot particles. It is considered that the temperature of 1000 °C was not high enough for PAHs production, and so soot particles were not formed. When the pyrolysis temperature was increased to 1100 °C, soot particles began to form.

When the stage-two temperature was increased to 1100 °C, the benzene formed caused the following two types of reaction to occur:

- (1) Pyrolysis: H₂, CH₄, C₂H₂, and so on, formed.
- (2) Addition and polymerisation: phenyl radical, acetylene and hydrogen atom reacted to form naphthalene, and/or phenyl radical and benzene reacted and formed biphenyl, to further form PAHs and soot particulates by series reaction.

TABLE 7

Comparison of the mutagenicity of particles and PUF extract from 0.2 g PS incineration under various stage-two temperatures and oxygen supplies (mutagenicity in revs./plate)^c

Feed gas	Extract	Pyrolysis temperature (°C)							
		900		1000		1100		1200	
		S9(+)	S9(-)	S9(+)	S9(-)	S9(+)	S9(-)	S9(+)	S9(-)
N ₂	S ^a	852	48	518	206	936	244	6184	454
	G ^b	194	22	179	13	876	70	1292	45
0.0525-O ₂	S	972	348	2172	634	8244	1052	1572	96
	G	276	53	265	93	630	96	1852	59
0.105-O ₂	S	169	101	776	273	1712	190	614	104
	G	146	61	402	55	616	169	1232	58
0.210-O ₂	S	98	53	46	24	49	66	- ^d	-
	G	71	41	103	28	98	51	-	-

^aS denotes "particle extract".

^bG denotes "PUF extract".

^c0.0525-O₂ denotes "oxygen supply is 0.0525 NL/min".

^d- denotes "no data available".

^eThe number of spontaneous revertants: S9(+): 30-40, and S9(-): 27-38.

The results also indicated that PAHs would effectively react with C_6H_6 and C_2H_2 and grow to larger PAHs when the pyrolysis temperature was increased to the higher temperature of $1000^\circ C$. Reactions of soot formation such as nucleation, condensation, coagulation, aggregation mechanisms occurred effectively. Because the change in free energies caused by the series reaction of PAHs and soot formation were so large, reactions became practically irreversible. This, in turn, had the effect of pulling the reaction sequence forward towards formation of larger PHAs and soot particles.

From the result of the Ames test, as shown in Table 7, it was found that dichloromethane extracts of the samples were mutagenic to *Salmonella typhimurium* TA98 when PS was incinerated at deficient oxygen supply, lower than 0.105 NL/min . The mutagenicity of particulates and PUF extracts caused the significantly higher potency of revertants to *Salmonella typhimurium* TA98 in the presence of S9 mixture than that observed in its absence. This indicates that the emitted gas from PS incineration at deficient oxygen supplies contains not only direct-acting mutagens but also indirect mutagens, which are usually activated by the mixed-function oxygenases in the microsomes (contained in the S9 mixture) of animal liver to become ultimate mutagens.

Three types of the mutagenicity pattern were observed, viz: (1) the mutagenicity increased with stage-two temperature, (2) the maximum mutagenicity occurred at $1000\text{--}1100^\circ C$ of stage-two temperature, and (3) the mutagenicity decreased with the stage-two temperature. When PS was pyrolysed from $900^\circ C$ to $1200^\circ C$, the mutagenicity was increased as the stage-two temperature increased, as shown in Fig. 8. The maximum mutagenicity of

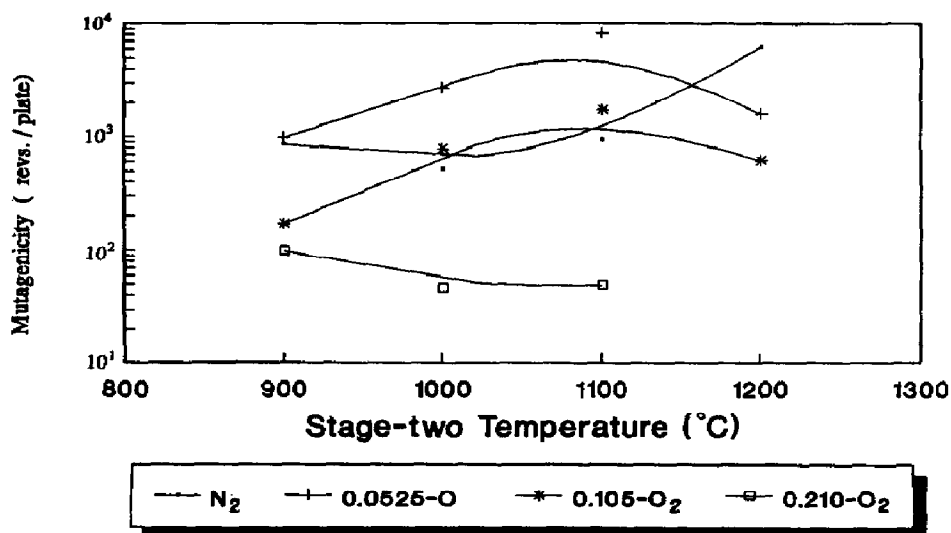


Fig. 8. The mutagenicity of particulates extracts from 0.2 g PS incineration at various stage-two temperatures and oxygen supplies (residence time: 0.5–1.0 s).

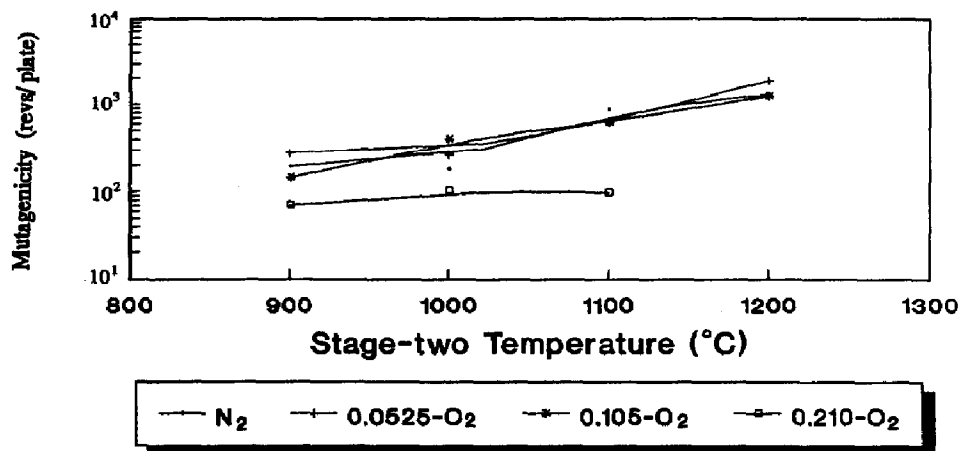


Fig. 9. The mutagenicity of PUF extracts from 0.2 g PS incineration at various stage-two temperatures and oxygen supplies.

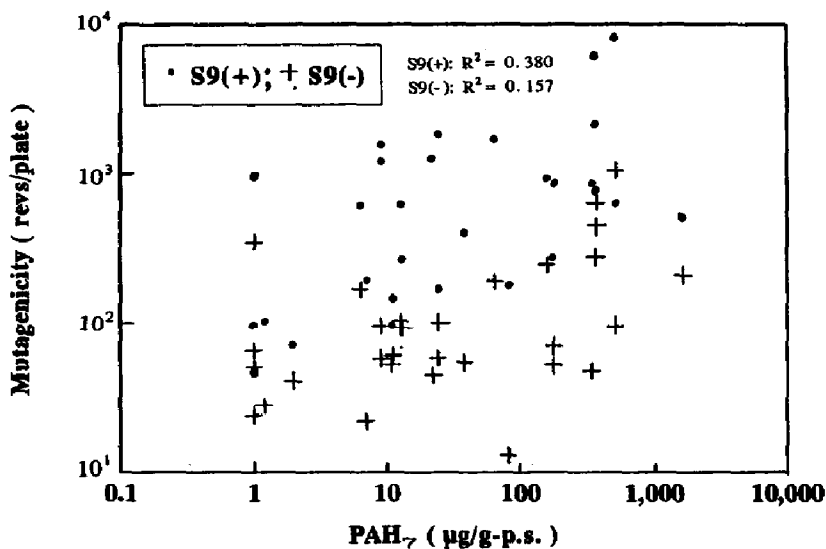


Fig. 10. The correlation between PAH₇ and mutagenicity in the emitted particulates from 0.2 g PS incineration.

particulates and PUF extracts occurred at 1200 °C and were 6184 and 1292 revertants per plate, respectively. It shows that the higher the stage-two temperature was controlled from PS pyrolysis, the more mutagenic product formed. The reasoning is that molecular nitrogen may participate in the reaction when the stage-two temperature is increased, and form acridine compounds and carbazole compounds.

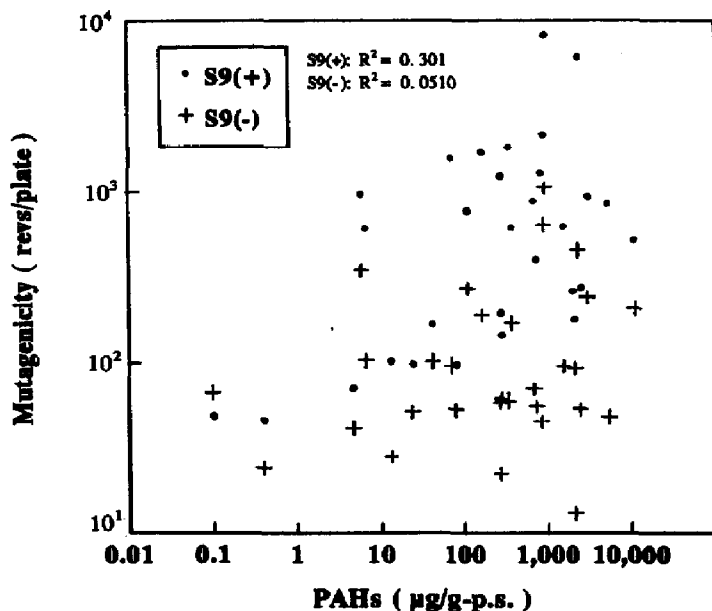


Fig. 11. The correlation between 14 PAHs and mutagenicity in the air emissions from 0.2 g PS incineration.

When oxygen supply was at 0.0525 NL/min, the maximum mutagenicity of extracts of particulate matter was shifted to occur at 1100 °C, and was 8224 revs./plate. The mutagenicity of the PUF extracts was increased as the stage-two temperature increased, as shown in Fig. 9. The maximum mutagenicity observed was 1856 revs./plate at 1200 °C. When oxygen supply was increased to 0.105 NL/min, a similar trend of mutagenicity with stage-two temperature was observed as with oxygen supply of 0.0525 NL/min. However, the maximum mutagenicity was much lower than that at 0.0525 NL/min, i.e. 1712 and 1232 revs./plate, respectively.

When oxygen supply was increased to 0.210 NL/min, the mutagenicity of particles and PUF extracts at various stage-two temperatures abruptly decreased. The reason for this could be that most PS was decomposed in the oxygen rich incineration process and resulted in a reduction in the formation of PAHs, particulates and other toxic compounds. From regression analysis, the correlations between log(mutagenicity) and log(14 PAHs) or log(PAH₇(BaP, BbF, Ba, A, IP, DbA, Tri and Chr)) for the emitted gases from PS incineration at various operating conditions shown in Figs. 10 and 11 were not so well, which may indicate that other toxic compounds (i.e., nitro-PAHs) were formed that should be identified in future research work.

4. Conclusions

The critical temperature for the formation of PAHs and soot particles was found to be about 1000 °C in the second-stage incinerator. The major precursor

for PAHs, i.e. C_6H_6 , is decreasingly produced as the stage-two temperature is raised up to $1000^\circ C$ without supplying oxygen. The maximum concentrations of PAHs and soot particles are approximately $1.3 \times 10^4 \mu g/g$ -PS and $205 mg/g$ -PS at $1000^\circ C$, respectively. However, the formation of PAHs and soot particles drastically decrease to the level of $13.5 \mu g/g$ -PS and $0.2 mg/g$ -PS, respectively, when the oxygen is supplied at $0.21 NL/min$ and the temperature is controlled at $1000^\circ C$.

The mutagenicity of particles and PUF extracts increased, as the pyrolysis temperature was increased from 900 to $1200^\circ C$. In general, the mutagenicity of PUF extracts is weaker than that of particle extracts. When oxygen is supplied at $0.0525 NL/min$, the mutagenicity of samples increases. Moreover, the mutagenicity is much higher in the presence of rat liver microsomal fraction (S9 mixture) than in its absence. This also shows that most of the samples contain much stronger indirect mutagens.

However, metallic chloride salts in municipal solid waste (MSW) always have been considered as an important factor in the design and operation of MSW incinerators. As cited in the literature, the propensity to form PAHs and exhibit mutagenicity is not only dependent upon the incineration temperature, residence time and oxygen supply, but also relates to metallic salts addition, such as $NaCl$, KCl , $MgCl_2$, and $BaCl_2$, in the MSW incinerator. Thus, the effect of metallic salts addition on the formation of PAHs and mutagenicity potential of the emitted soot particles would be regarded as a major subject for future research work.

References

- 1 C.C. Lee, G.L. Huffman and D.A. Oberacker, An overview of hazardous/toxic waste incineration, *J. Air Pollut. Control Assoc.*, 36 (1987) 922-931.
- 2 T. Morikawa, Evolution of soot and polycyclic aromatic hydrocarbons in combustion, *J. Combust. Toxicol.*, 15 (1978) 347-360.
- 3 T. Morikawa, Evolution of soot and polycyclic aromatic hydrocarbons from combustion and pyrolysis of polymers and low molecular weight hydrocarbons, *Fire Sci. Technol.*, 4 (1984) 27-35.
- 4 J. Josephson, Polynuclear aromatic hydrocarbons, *Env. Sci. Technol.*, 18 (1984) 93-95.
- 5 M. Nishioka, H.C. Chang and M.L. Lee, Structural characteristics of polycyclic aromatic hydrocarbon isomers in coal tars and combustion product, *Env. Sci. Technol.*, 20 (1986) 1023-1026.
- 6 D.C. Chiang, J.H. You et al., Characterization of toxic pollutants from incineration of plastics, man and his ecosystem, In: *Proc. of the 8th World Clean Air Cong.*, Vol. 4, 1989 pp. 289-294.
- 7 O.I. Smith, Fundamentals of soot formation in flames with application to diesel engine particulate emissions, *Prog. Energy Combust. Sci.*, 7 (1981) 252-291.
- 8 B.S. Haynes and H.G. Wagner, Soot formation, *Prog. Energy Combust. Sci.*, 7 (1981) 229-273.
- 9 M. Frenklach, Production of polycyclic aromatic hydrocarbons in chlorine containing environments, *Combust. Sci. Technol.*, 74 (1990) 283-296.
- 10 M. Frenklach and J. Warnatz, Detailed modeling of PAH profiles in a sooting low-pressure acetylene flame, *Combust. Sci. Technol.*, 51 (1987) 265-283.

- 11 M. Frenklach, D.W. Clary, T. Yuan and W.C. Gardiner, Mechanism of soot formation in acetylene-oxygen mixtures, *Combust. Sci. Technol.*, 50 (1986) 79-115.
- 12 B.N. Ames, J. McCann and E. Yamasaki, Methods for detecting carcinogens and mutagens with the Salmonella/mammalian-microsome mutagenicity test, *Mutat. Res.*, 31 (1975) 347-364.
- 13 D.M. Maron and B.N. Ames, Revised method for the Salmonella mutagenicity test, *Mutat. Res.*, 113 (1983) 173-215.
- 14 J.H. You, P.C. Chiang and S.C. Chang, Formation and control of PAHs and particulates from incineration of plastic, presented at the Summer National Meeting of AIChE, Minneapolis, MN, Aug. 9-12, 1992.