

Pyrolysis of household plastic wastes

Nasrollah Hamidi^{*1}, Fariba Tebyanian², Ruhullah Massoudi¹, and Louis Whitesides³

* Corresponding author

1. Department of Biological and Physical Sciences, South Carolina State University,
Orangeburg, SC 29117.

2. Transportation Program, Department of Mechanical and Civil Engineering, South Carolina
State University, Orangeburg, SC 29117.

3. 1890-Reserch, South Carolina State University, Orangeburg, SC 29117.

Abstract

This work addresses two fundamental concern of modern civilization: the first is transportation and useable energy, and the second which is as important for a healthy and happy living is environment. Manufacture of plastic containers, utensils, etc. has improved the quality of live for everyone, however these materials produces enormous waste which could be health hazard by polluting our environment. This paper presents the results of our investigations on the methods of recycling plastics wastes into useful liquid chemicals similar to diesel and gasoline fuel. This paper summarizes the thermolysis of three common household plastics wastes, foam plates, shipping protection foam and shopping bags, into liquid fuels. The thermogravimetric studies showed that the decomposition temperature for

these wastes are different from each other. The percent yields of liquid fuel produced from plastic wastes vary depending on the kind of waste and the process of decomposition. The thermal decomposition of wastes occurred at temperatures over 275° to 550°C and produced over 300 chemicals. The major product for the decomposition of polystyrene foam was styrene and the yield varied depending on the kind of wastes and type of pyrolysis. Pyrolysis of shopping bags produced also more than 320 chemicals; however, there was not a major hydrocarbon present in the pyrolysis product. The major hydrocarbons were approximately 20 to 23 pair of homologs straight chains of alkanes and alkenes from C₃ to C₃₄.

Keywords: Environment, health, plastic waste, thermolysis of plastic wastes, foam, shopping bags, plate foam, fuel from plastic wastes

1. INTRODUCTION

One of the troubling environmental challenges is non-degradability of the plastic wastes in the landfills, on the surface and oceans endangering the safe life for animals and humans. On the other hand, one of the transportation challenges is fast depletion of non-renewable fossil fuel and dramatic growth of demand for it. This particular case motivates the researchers and technologists to investigate and develop reliable and renewable energy resources. One single approach to partially resolve these challenges is based on the idea that fuel energy can be obtained from waste plastics that otherwise would be disposed, entering the water stream or filling up landfills or scattering on the earth's surface. The conversion of waste plastics to fuel has several benefits. First, it steps up a new cycle of consumption to the nonrenewable energy sources. Second, it provides a considerable source of fuel energy that

reduces the expenditure of nonrenewable energy resources. Third, it establishes an appropriate, innovation, and alternative solution for removing waste plastics consequently prevent them from polluting the environment either through incineration or filling up landfills and waterways (Sarker et al 2012).

Plastics in different forms are one of the widely used materials due to their diverse benefits and many applications in daily life. Plastic production in the United States during the year 2010 account for almost 14 million tons as containers and packaging, 11 million tons as sturdy goods such as domestic devices, and 7 million tons as insubstantial goods such as plates and cups. However, only 8 percent of total waste plastics in 2010 were recycled (the U.S. Environmental Protection Agency, 2012).

Various techniques for the treatment of waste plastics have been investigated to complement existing landfill and mechanical recycling technologies. The objectives of these investigations were to convert the waste into valuables products such as fuel, synthetic lubricants, and tar for asphalt pavement.

The pyrolysis of polymeric materials including plastics has been studied for many years (Gargallo, L et al 1989). Nowadays pyrolysis is a recycling method used to convert waste plastic into useful product such as fine chemicals, transportation fuel and lubricant oil. It is classified as the chemical and energy recovery system also known as cracking, gasification, and chemolysis methods. There are various form of thermolysis method including thermal cracking (pyrolysis), catalytic cracking, and hydro-cracking (Lee K.H. 2011). The Pyrolysis process uses elevated temperatures to crack down high molar mass materials into smaller molecules. The plastics in this process decompose into three phases of matter: gas (condensable and non-condensable mixture), liquid, and solid. In this manner

chemical recycling of the stored energy inside the plastic wastes takes place with environmental advantage of minimizing the plastic pollution. (Behzadi, S. and Farid, M.).

Styrofoam is a non-sustainable, non-photo-degradable, non-biodegradable, hard to recycle, and heavily pollutant petroleum product (Bandyopadhyay, A., and Basak, G. C. 2007). It is made by blowing gases into heated polystyrene. Depending on the type of foam to 97% percent of the volume of product is air, making it very light, flexible, shock absorbent, and a poor conductor of heat. It is very useful for insulation, transportation, and food container such as beverage cups. While some type of foamed polystyrene such as packaging peanuts is reused, the other products are one-time used materials. (Friend D., 2005).

There are various forms of waste to fuel energy conversion; however, this study focused on the non-catalytic conversion of waste plastics such as expanded polystyrene (shipping protection materials, cups and plates) and polyethylene products (shopping bags) to fuel oil using a non-catalytic pyrolysis method.

2. EXPERIMENTAL SECTION

2.1. Materials

Thermal cracking process without catalyst was used in converting waste plastic into liquid. Three types of waste plastics were selected for this particular study. Styrofoam shipping protection boxes recovered from shipping containers, used as received. Shopping bags were the bags from many stores that were collected during 2011 shopping of a one family household; these bags were used as were collected. The styrofoam plates were

collected after a dinner meeting, rinsed with tap water, air dried and stored in laboratory for 30 days before cutting into small slices suitable to fill the reaction vessel.

2.2. Instrumentation

2.2.1. The thermogravimetric analyzer

A Perkin-Elmer TGA-7 was used to study the thermal stability of the plastic wastes from 70°C to 590°C with heating rate of 10°C/min while the sample was purged with 10 mL/min argon. The TGA was calibrated before uses.

2.2.2. Gas Chromatographer-Mass Spectrometer.

A Shimadzu GC-MS model GCMS-QP 2010s was used to analyze the liquids samples using helium as mobile phase. The oven program was set for 4 min at 45°C, following with temperature increase of 10°C/min to 220°C then keeping isothermal at final temperature for 15 min.

The AOC-20i sampler was set for three rinses before and after injection with acetone and two rinses with the sample, plunger speed and syringe speed were set at high.

The MS was programmed scanning masses $25 < M/z < 350$; scanning time begin from zero to 35 min. The identities of chemical were established by automatic search on NIST library and visual inspection of suggested results.

2.2.3. The Reactor

The reaction vessel consisted of a five liter three-necked round-bottom flask in a heating mantle equipped with a regulator to control the heating intensity. One inlet of flask used for nitrogen, the other for thermometer, and the third outlined to a 30 cm air-cooling condenser

inlet to a three way connector. The three-way connector was inlet into a graduated funnel and outlet to another three-necked round-bottom flask with a vertical water cooling condenser open-end to atmosphere. The thermometers were able to give account of the temperature inside of the reaction vessel, temperature of vapor coming out of the reaction vessel, and the temperature of vapor condensing in the second receiver.

2.3. Pyrolysis Procedures

2.3.1. Foam -- White Foam Dinning Plates

214.12g of white foam plates were shredded to small pieces and filled up into a 5L three-necked round bottom flask as shown in Fig 1a &b. The flask was placed into a heating mantle (1b) connected to a temperature controller. About 20 mL of water was added to flask to vaporize and pushing air out of reaction vessel and slowing the process of re-polymerization of newly produced styrene. After heating for 10 minutes, the temperature inside the flask reached to 91°C. The water vapor occupied the entire volume of the vessel, the heating was suspended after all foam was melted and 25 mL of condensed liquid were collected. The collected liquid has two phase, water and ~60% organics, insoluble in water. When the reactor was reached to the room temperature 287.0 g more shredded white foam plastic plates were added to the reaction vessel. The system was setup for simple distillation with an air cooling condenser (Fig 1c). Once most of materials melted a glass thermometer was placed inside the flask to record the reaction temperature as seen in Fig 1d and another one on top of the neck where the gases were directed to condenser to record the temperature of gases while leaving the reactor. The first drop of condensate collected into recipient after 120 minutes when the temperature of the reactor reached 290°C. As shown in Fig (1e), the liquid is very transparent and clear. Table 1 shows the reactor temperatures during the pyrolysis process. The reaction

was stopped after 330 minutes. Fig 1f shows the tar, leftover of the white foam plates at the end of the pyrolysis process.

Table 1. The temperatures changes during the pyrolysis process of the white foam plates

Reaction	T at the mantel (°C)	T condensing vapors (°C)	Time(min)
1. Melting down	200	25	20
2. Melting and Vaporization	290	28	120
3. Melting ended	300	45	200
4. Distillation began	320	99	220
6. Distillation stopped	330	150	250
6. The reaction was stopped.	330	70	

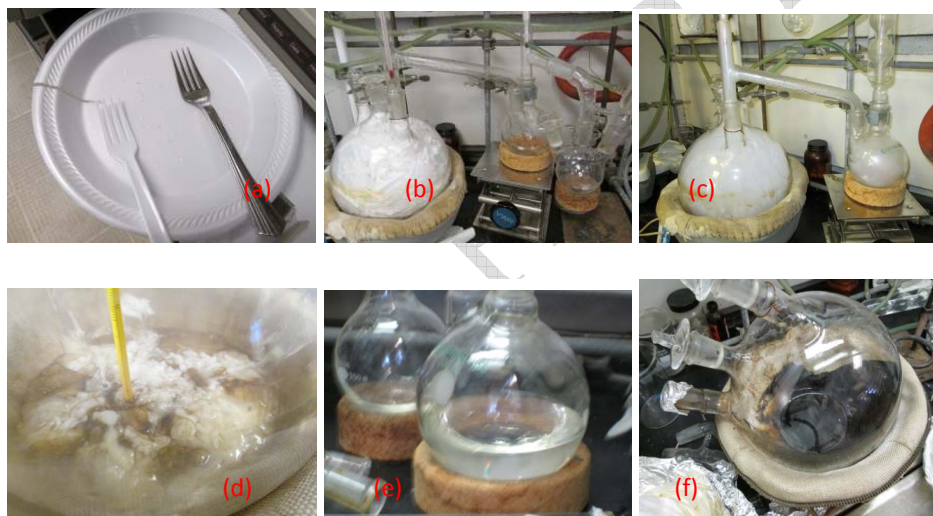


Fig 6. Illustration of step-by-step decomposition process of styrofoam plates: (a) plate and utensils (b) the 5L flask with shredded plates, (c) beginning of evaporation of plates, (d) inserting thermometer into melted plates, (e) condensed liquid, (f) tarlike residue.

2.3.2: Foam - Shipping Box Protection–Pyrolysis at Normal Heating

Fig 2 shows the steps of the process as follows: 100 grams of shipping box foam (2a) was cut to small pieces and filled in a three-necked round bottom flask as shown in Fig 2b. The flask was placed into a heating mantle. After heating for 10 minutes, the polystyrene started to melt down. The temperature of heating mantle was measured with a glass thermometer to be 250 °C. After 15 minutes, the system started to evaporate when the heating mantle thermometer was at 330 °C. After 20 minutes the mantle temperature was 360 °C, the first drop of condensed vapor was collected at 60 °C. The temperature of condensing vapors increased quickly up from 60 °C to 131 °C. Table 2 shows the temperatures of the system as pyrolysis progressed. The pyrolysis process was continuing for 80 minutes and it stopped when the temperature of condensing vapors dropped to 70 °C while the heating mantle showing a temperature above 500 °C. The liquid obtained from this pyrolysis process was 70 g, which is a 70% yields to oil. The volatile materials that were not condensing at room temperature were not collected. The char product was a kind of clung material such as tar in the bottom of the container as shown in Fig 2g.

Table 2. The reaction and temperatures changes during the pyrolysis process

Reaction	T (°C) Heating Mantel	T (°C) Condensing vapor	Time (min)
1. Melting down	250	25	10
2. Melting and Vaporization	330	25	15
3. Distillation	360	60	20
4. Distillation (continue)	390	131	30
5. Distillation (continue)	430	110	80
6. Distillation (continue)	Over 430	67	95
7. Vaporization	Over 430	61	100
8. Vaporization	Over 430	44	115
9. The reaction was stopped	Over 430	35	70

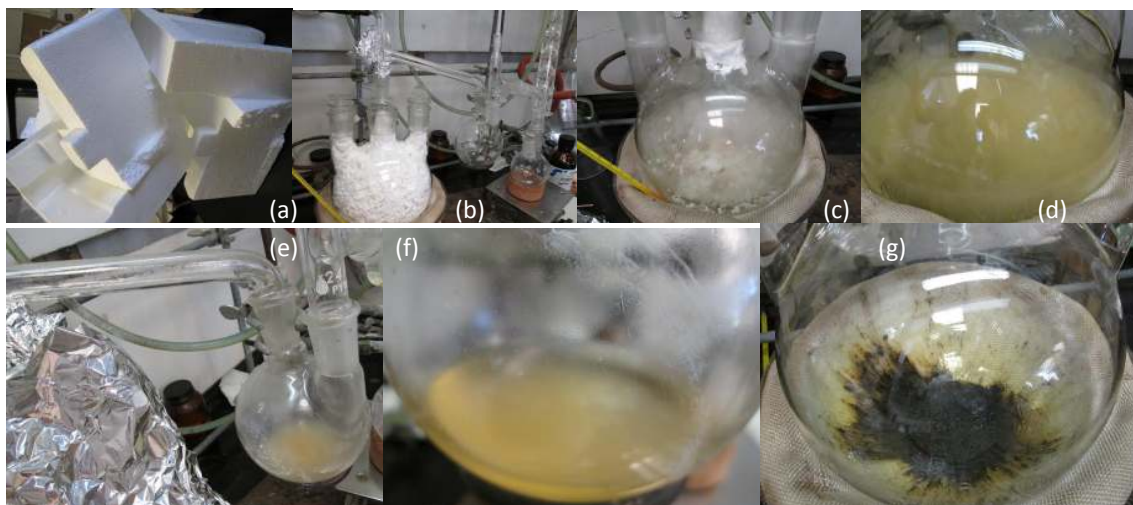


Fig 2. Steps of pyrolysis of shipping box protection foam: (a) White foam (Polystyrene), (b) Foams inside the flask mounted in a heating mantle, (c) Melting foam at 250 °C, (d) Liquid foam begin to evaporate (e) Collection of condensed vapors, (f) The liquid fuel obtained from pyrolysis process, (g) The leftover of the foam at the end of the pyrolysis process

2.3.3. Foam -- Shipping Box Protection Foam – Fast Heating Pyrolysis

A 5L three-necked round bottom flask was filled with 100 grams of white shipping protection foam box. The flask was placed into a heating mantle. The vapors were directed to a 100 mL graduated cylindrical separatory funnel connected to another flask with a tap water cooling condenser. The first drop of condensed liquids was collected at 60°C. The first sample of liquid was collected between 60°C and 100 °C. The second fraction was collected above 150°C. The vaporization process was continuing for 40 minutes and it stopped when the temperature at the condensing vapors dropped to below 80°C. The condensed oil obtained from this pyrolysis process was 80 gram, which means at least 80% of polystyrene has yielded to liquid fuel. Fig 3a shows the color of the last fraction, it is dark because of trace of

char pushed out of the well overheated reaction chamber. Fig 3b shows the tar remains after the decomposition process; a hard solid, hard to remove from the reaction vessel.

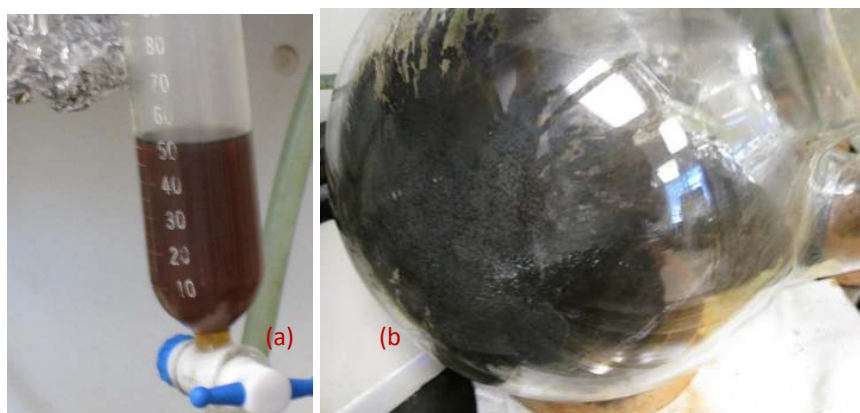


Fig 3. Product of fast heating shipping box protection foam: (a) Distillates, and (b) The leftover tar resulting from the pyrolysis process

2.3.4. Plastic Carrying Bags

Fig 4 shows the pyrolysis steps of plastic bags. A 780 grams sample of mixture of various stores shopping bags were filled up in a three-necked round bottom flask. The bags were pushed one by one into the reaction chamber. The flask was placed into a heating mantle covered with two layers of aluminum foils to conserve the heat. The temperature controller was set to high. A stream of nitrogen gas with a rate of 10 mL/min was introduced to the system to create and maintained an oxygen free environment plus pushing any trace of air or vapors out of reaction vessel. The distillates were directed to a cylindrical separatory funnel (Fig 4c). The waste plastic started to melt down after 13 minutes at 300°C. The first 30 minutes vaporization continued without condensation, the heating mantle temperature was at

400 °C. After complete melt down of plastic bags the liquid started to boil, the reactor temperature was over 500°C. First drop of condensate was observed after 65 minutes at condensing temperature of 60°C. Table 3 shows the reaction and temperatures changes in different time of the pyrolysis process. The temperature of condensing vapor gradually increased to 175°C during 90 minutes of the collection process. Then temperature dropped to 90°C and the condensation gradually halted. Finally, we stopped the pyrolysis process after 240 minutes. Fig 4d shows various samples at different temperatures of the pyrolysis process; six samples were selected for chemical analyses. At the end of the process there was some condensed material in the second flask as well. The char was not uniform, several black and gray tones of color was visible. Top of it looks similar to over-dried fragmented-dirt as shown in Fig 4e.

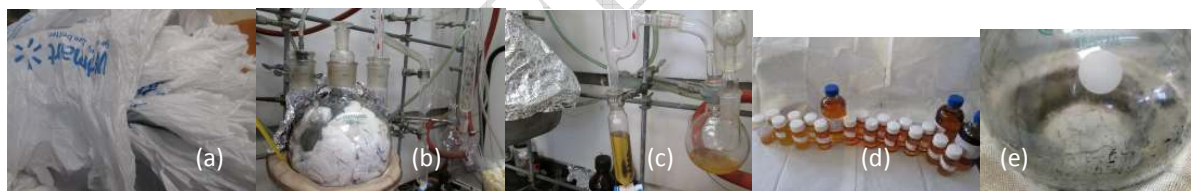


Fig 4. The process of pyrolysis of plastic bags: (a) Waste plastic carry bags (b) Bags inside the 5L flask, (c) The vapors air cooled into graduated funnel and volatiles left the funnel to be condensed in the next flask with a tap water condenser, (d) Samples collected at various temperatures, (e) The leftover of the shopping bags at the end of the pyrolysis process

Table 3. The temperatures of pyrolysis process of shopping bags

Time	Reactor Conditions	T Heating Mantle (°C) ¹	T Distillate 1 (°C)	T Distillate ² 2 (°C)
13	Melting to liquid	300	25	23
37	Melting & Vaporization	420	25	23
45	Melting & Vaporization	Over 420	35	23
60	Melting & Vaporization	Over 420	57	23
65	Boiling, Vaporization, and	Over 420	62	23
70	Distillation (continue)	Over 420	70 first drop	35
80	Distillation (continue)	Over 420	80	50
95	Distillation (continue)	Over 420	105	60
110	Distillation (continue)	Over 420	150	80
117	Distillation (continue)	Over 420	155	95
153	Distillation (continue)	Over 420	160	105
170	Distillation (continue)	Over 420	175	85
180	Distillation (continue)	Over 420	160	62
200	Distillation (continue)	Over 420	155	35
210	Distillation (continue)	Over 420	134	30
240	The Reaction Stopped	Over 420	80	30
1. A glass thermometer range -10 °C to 400°C about 30 °C above 400 could be estimated. 2. A digital thermometer with limited range to 150°C				

3. Result and Discussion

3.1. Thermogravimetric Analysis

Thermal stability of household plastics was studied by Perkin-Elmer TGA 7. Fig 5 compares the results of thermal stabilities of some household plastics. Clear wrapping plastics decomposed in two steps. First phase began to reduce masses at ~ 235°C stopped at ~ 360°C then the second step started at 480 °C, ended at 500 °C, 15% chars remained.

Randomly, a gray Orangeburg Wal-Mart plastic shopping bag was selected for thermal decomposition. The plastic bag is more stable than other tested materials; the thermal decomposition of the shopping bag was between 485°C to 520°C with the highest volatilization rate at 498 °C.

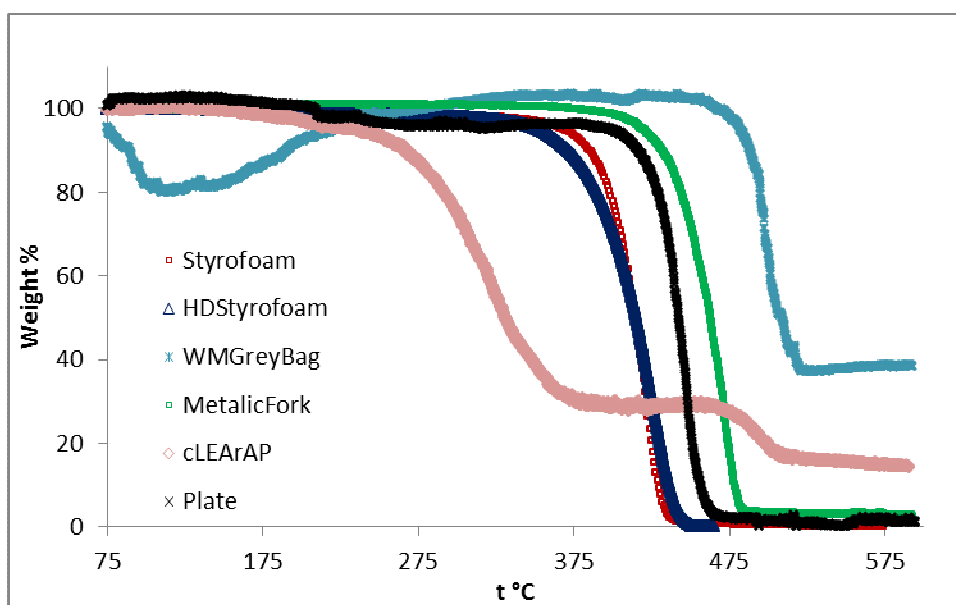


Fig 5. Thermograms of six types of household plastic waste materials from left to right: clear food wrapping plastics < soft foam shipping protection box ~ hard foam shipping protection box < foam plate < utensil-metallic look silver fork, and < Wal-Mart gray plastic shopping bag.

Table 4. Points of interests depicted from thermograms of Fig 5 for the five types of household plastic waste materials.

% Remains	t °C				
	Shopping Bag	Soft Foam	Hd Foam	Plastic Wrap	Fork (Silver)
95	482	368	351	235	420
90	488	385	371	268	432
80	495	398	390	292	444
70	498	405	401	307	452
60	502	410	409	320	458
50	509	415	415	331	463
40	515	418	421	348	467
30	593	422	426	375	472
20		425	431	500	474
10		430	436	565	478
0		446	441		593
Char	38%	0	0	15%	2%

Thermal stabilities of two kinds of foams, physically soft and hard were tested. As Fig 5 shows both kind had very similar thermal stability as was the expectation since both foam are made of polystyrene. The highest decomposition rates were observed at temperatures 418°C and 423°C for soft and hard foams respectively due to packing effects. No leftover char was observed.

Thermal stability of foam plate was higher than shipping protection foams with highest decomposition rate observed at 440°C. About 3% leftover char was observed

To study thermal decomposition of metallic look utensil, a small part of a head tooth of a fork was placed in the TGA pan; thermally it was more stable than the plates. The highest decomposition rate was at 472°C.

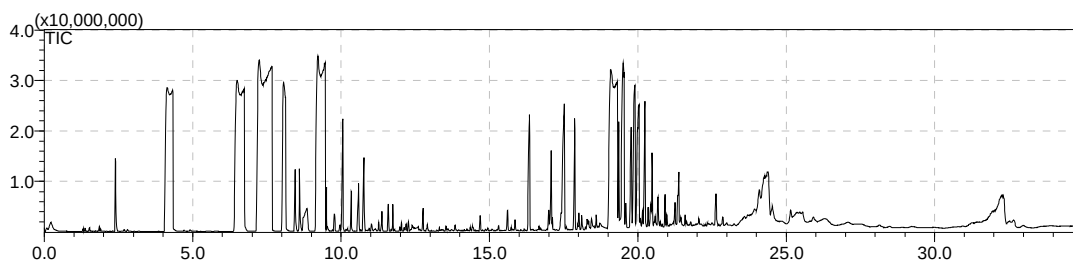
As the thermograms in Fig 5 shown the thermal stability of household plastic increase from clear food wrapping plastics < soft foam shipping protection box ~ hard foam shipping protection box < foam plate < utensil-metallic look silver fork < gray Wal-Mart plastic shopping bag.

3.2. White Foam Plates

Fig 6 shows a chromatogram of the liquid obtained from pyrolysis of foam plates. The most abundant compound resulted from pyrolysis was styrene as expected. Most of the other products also were vinyl derivative as listed in Table 5. As the chromatogram shows there are over 350 chemicals in this sample. Table 5 lists the 50 most abundant chemicals identified by NIST-MS library. Fig 7 shows the distribution of these chemicals with relative abundances; styrene has the highest abundances about 10% of all chemicals following by styrene isomer 1,3,5,7-cyclooctatetraene with abundances of 6%. The doublet of peaks in the chromatogram

249 results from super-saturation of analytical column in GC system. As Fig 7 indicates about
250 50% of product is a mixture of eight chemicals.

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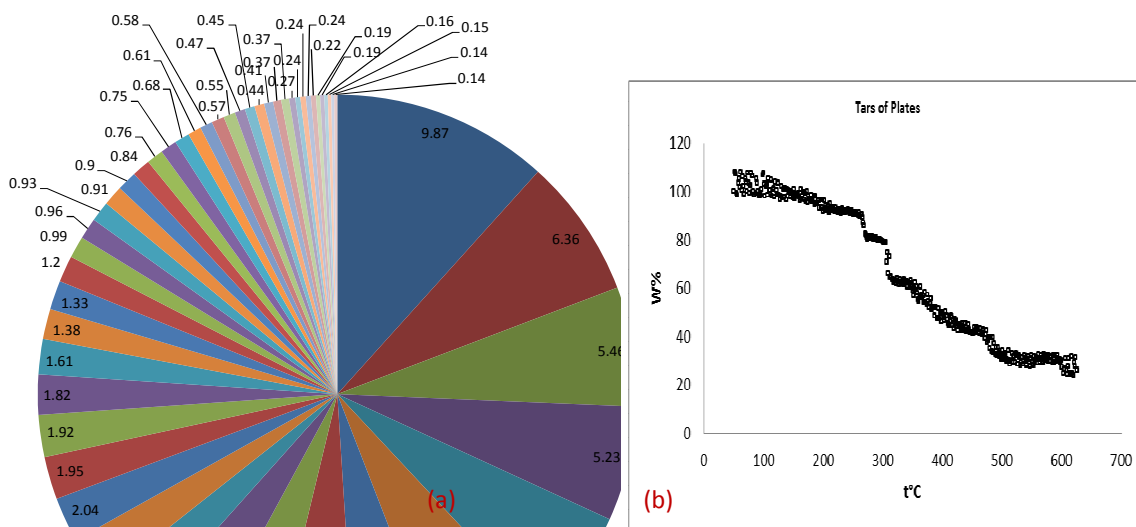
253 Fig 6. Total ion chromatogram (TIC) of a sample of distillates obtained from degradation of whit foam plates.

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256 Table 5. 50 major chemicals outcome of the foam pyrolysis.

No	Component Name	Formula	Retention Tm	Start Tm	End Tm	Area%
1	Styrene ,	C ₈ H ₈	7.67	7.367	7.775	9.87
2	1,3,5,7-Cyclooctatetraene,	C ₈ H ₈	7.239	7.092	7.367	6.36
3	Benzene, 1,1'-(1,3-propanediyl)bis-,	C ₁₅ H ₁₆	19.092	18.98	19.2	5.46
4	Benzene, 1,3-dimethyl-,	C ₈ H ₁₀	6.497	6.358	6.6	5.23
5	Benzene, 1-ethenyl-3-methyl-,	C ₉ H ₁₀	9.217	9.083	9.308	5.22
6	alpha.-Methylstyrene,	C ₉ H ₁₀	9.463	9.308	9.483	5.13
7	Toluene ,	C ₇ H ₈	4.141	4	4.217	4.14
8	Cyclopentene, 1-ethenyl-3-methylene-	C ₈ H ₁₀	6.738	6.6	7.092	4.04
9	Benzene, (1-methylethyl)-,	C ₉ H ₁₂	8.065	7.975	8.383	3.48
10	Benzene, 1,1'-(1-methyl-1,3-propanediyl)bis-,	C ₁₆ H ₁₈	19.504	19.38	19.57	3.13
11	Benzene, 1,1'-(1,3-propanediyl)bis-,	C ₁₅ H ₁₆	19.287	19.23	19.33	2.31
12	Benzene, 1,1'-cyclopropylidenebis- ,	C ₁₅ H ₁₄	20.038	19.93	20.13	2.16
13	Octacosane ,	C ₂₈ H ₅₈	32.307	31.98	32.42	2.04
14	Sulfoxide, methyl phenethyl ,	C ₉ H ₁₂ O ₂ S	17.522	17.32	17.56	1.95
15	1,5-Hexadien-3-yne, 2-methyl-,	C ₇ H ₈	4.323	4.267	6.3	1.92
16	Ethanedioic acid, mono(phenylmethyl) ester ,	C ₉ H ₈ O ₄	19.896	19.82	19.93	1.82
17	Heneicosane ,	C ₂₁ H ₄₄	24.258	24.14	24.32	1.61
18	Benzylcyclopentane,	C ₁₂ H ₁₆	4.251	4.217	4.267	1.38
19	Tetracosane,	C ₂₄ H ₅₀	24.389	24.32	24.47	1.33
20	Diphenylmethane ,	C ₁₃ H ₁₂	16.347	16.25	16.39	1.2
21	Benzene, 1,1'-(1,4-butanediyl)bis-,	C ₁₆ H ₁₈	20.238	20.18	20.31	0.99
22	1-Propanone, 1-phenyl-3-,	C ₂₂ H ₂₀ O ₂	19.218	19.2	19.23	0.96
23	Eicosane ,	C ₂₀ H ₄₂	24.091	23.99	24.14	0.93
24	Benzene, 1,1'-(1-methyl-1,2-ethanediyl)bis-,	C ₁₅ H ₁₆	17.875	17.81	17.93	0.91
25	Benzene, 1,1'-(1,2-ethenediyl)bis-, (Z)-,	C ₁₄ H ₁₂	19.773	19.69	19.82	0.9
26	Benzene, 1-ethenyl-4-methyl-,	C ₉ H ₁₀	10.054	9.992	10.12	0.84
27	Heptadecane ,	C ₁₇ H ₃₆	23.936	23.78	23.99	0.76
28	9-Hexacosene,	C ₂₆ H ₅₂	24.533	24.47	24.75	0.75
29	Acetophenone ,	C ₈ H ₈ O	8.848	8.683	9.083	0.68
30	1,2-Diphenylcyclopropane,	C ₁₅ H ₁₄	19.355	19.33	19.38	0.61
31	1H-Indene, 1-(phenylmethylene)- ,	C ₆ H ₁₂	21.376	21.31	21.42	0.58
32	Benzene, 1,1'-ethylidenebis-,	C ₁₄ H ₁₄	17.08	17.02	17.11	0.57
33	Acetophenone ,	C ₈ H ₈ O	10.764	10.7	10.82	0.55
34	Benzene, 1,1'-(1,2-dimethyl-1,2-ethanediyl)bis-	C ₁₆ H ₁₈	20.484	20.45	20.52	0.47
35	Benzene ,	C ₆ H ₆	2.395	2.358	3.083	0.45
36	Benzene, propyl- ,	C ₉ H ₁₂	8.599	8.55	8.683	0.44
37	Benzene, 2-propenyl-,	C ₉ H ₁₀	8.449	8.383	8.55	0.41
38	Benzene, (1-methylenepropyl)-,	C ₁₀ H ₁₂	10.589	10.52	10.64	0.37
39	2-Phenylnaphthalene,	C ₁₆ H ₁₂	22.633	22.57	22.7	0.37
40	Benzene, 1,1'-(2-methyl-1-propenylidene)bis-,	C ₁₆ H ₁₆	20.68	20.63	20.73	0.27
41	Benzene, 3-butenyl-,	C ₁₀ H ₁₂	10.337	10.29	10.52	0.24
42	Benzene, 1,1'-(1,5-hexadiene-1,6-diyl)bis- ,	C ₁₈ H ₁₈	20.914	20.87	20.95	0.24
43	Benzoic acid, (4-benzoyloxy-2-chlorophenyl)	C ₂₀ H ₁₃ ClO	21.25	21.21	21.31	0.24
44	Benzene, 1,1'-(3-methyl-1-propene-1,3-	C ₁₆ H ₁₆	20.435	20.38	20.45	0.22
45	Benzene, 1-ethenyl-2-methyl-	C ₉ H ₁₀	9.507	9.483	9.733	0.19
46	1,3-Bis(4-methylphenyl)propane	C ₁₇ H ₂₀	19.593	19.57	19.69	0.19
47	Benzene, 1,1'-(1,1,2,2-tetramethyl-1,2-	C ₁₈ H ₂₂	20.344	20.31	20.38	0.16
48	Benzene, 2-butenyl-	C ₁₀ H ₁₂	11.59	11.5	11.65	0.15
49	Benzene, (1-methyl-1-propenyl)-, (E)-,	C ₁₀ H ₁₂	11.744	11.71	11.78	0.14
50	Naphthalene ,	C ₁₀ H ₈	12.757	12.7	12.8	0.14

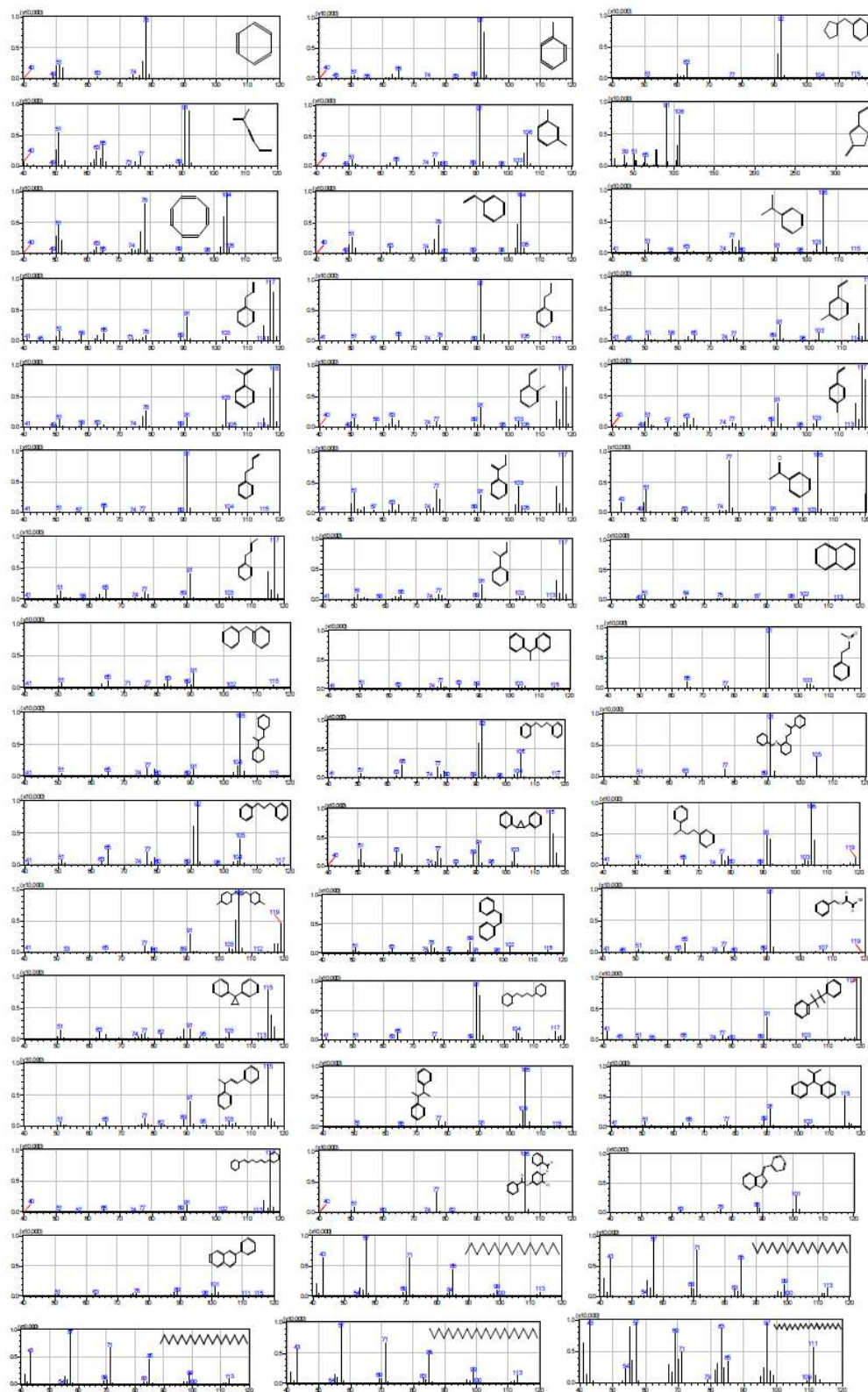


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259 Fig 7. (a) Distribution of the chemicals resulting for decompositions of foam with relative
 260 abundances; (b) Thermogram of tar residues obtained after decomposition

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262 Fig 7b. Shows the thermogarm of the tar obtained from thermolysis of the white foam plates.
 263 The thermogarm shows that about 80% of this tar could be decomposed if we were able to
 264 reach to a tempearture as high as 600°C. No study on the nature of volatile material from
 265 decompositon of tar or plstics was done.



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267 Fig 8. Mass spectrometer of 42 most abundants chemicals resulting from pyrolysis of foam.

3.3. Foam -- Shipping Box Protection --Pyrolysis at Normal Heating

Fig 9 shows the total ion chromatogram of a sample of distillates obtained from degradation of shipping box protection foam. In this experiment, 70% of foam was converted to liquid material that is a mixture of over 300 compounds. Fig 10 shows the distribution of 50 most abundant chemicals resulting from decompositions of foam; about 19% of the chemicals were styrene following with p-toluene sulfonic acid phenyl ethyl ester being about 9%. In summary, 5 fine chemicals constitute more than 50% of mixture. It will be of more value if a mixture such as this separated to fine chemicals before to be used as fuel. Table 7 lists the name, retention time, area under chromatogram, and the percent abundances of 50 highest ample chemicals in the liquid. About 20% of residue leftover from pyrolysis remained in the bottom of flask at temperatures above 430 °C.

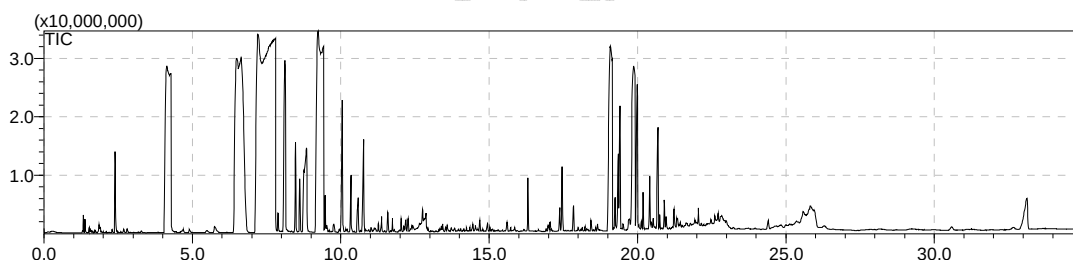


Fig 9. Total ion chromatogram of a sample of distillates obtained from degradation of shipping box protection foam.

285 Table 7. 50 major chemical components identified in the pyrolysis of styrene shipping box

No	Component Name	Formula	Retention T _m	Start T _m	End T _m	Area %
1	Styrene	C ₈ H ₈	7.796	7.342	7.858	18.85
2	1,3,5,7-Cyclooctatetraene	C ₈ H ₈	7.21	7.058	7.342	8.46
3	Cyclopentene, 1-ethenyl-3-methylene-	C ₈ H ₁₀	6.638	6.55	7.058	7.3
4	.alpha.-Methylstyrene,	C ₉ H ₁₀	9.233	9.092	9.317	6.4
5	Toluene	C ₇ H ₈	4.14	3.942	4.233	5.91
6	Benzene, 1,1'-(1,3-propanediyl)bis-	C ₁₅ H ₁₆	19.09	18.967	19.18	5.32
7	Benzene, 1,3-dimethyl-	C ₈ H ₁₀	6.495	6.358	6.55	5.09
8	Ethanedioic acid, mono(phenylmethyl) ester	C ₉ H ₈ O ₄	19.87	19.758	19.93	4.37
9	Benzene, (1-methylethenyl)-	C ₉ H ₁₀	9.413	9.358	9.442	2.7
10	Benzene, (1-methylethyl)-	C ₉ H ₁₂	8.117	8.033	8.417	2.6
11	Benzeneacetic acid, .alpha.-methyl-	C ₉ H ₁₀ O ₂	19.99	19.933	20.03	1.71
12	Benzene, 1-ethenyl-4-methyl-	C ₉ H ₁₀	9.344	9.317	9.358	1.67
13	1,5-Hexadien-3-yne, 2-methyl-	C ₇ H ₈	4.269	4.233	6.358	1.57
14	Benzaldehyde	C ₇ H ₆ O	8.844	8.767	8.967	1.55
15	Benzene, 1-propenyl-	C ₉ H ₁₀	10.05	9.983	10.12	1.07
16	Sulfoxide, benzyl methyl	C ₈ H ₁₀ OS	33.12	32.825	33.23	0.97
17	Benzene, 1,1'-(1-methyl-1,3-propanediyl)bis-	C ₁₆ H ₁₈	19.41	19.367	19.44	0.94
18	Benzene, 1,1'-(1-butenylidene)bis-	C ₁₆ H ₁₆	20.69	20.617	20.72	0.9
19	Pentadecane, 8-hexyl-	C ₂₁ H ₄₄	25.59	25.442	25.7	0.83
20	Acetophenone	C ₁₀ H ₁₂	10.77	10.692	10.82	0.77
21	Benzene, 1,1'-(3-methyl-1-propene-1,3-diyl)bis-	C ₁₆ H ₁₆	19.35	19.292	19.37	0.64
22	Benzene, 2-propenyl-	C ₉ H ₁₀	8.474	8.417	8.542	0.6
23	Tricosane	C ₂₃ H ₄₈	25.83	25.8	25.92	0.59
24	Benzaldehyde	C ₇ H ₆ O	8.754	8.683	8.767	0.56
25	Eicosane	C ₂₀ H ₄₂	22.84	22.75	22.93	0.5
26	Benzene	C ₆ H ₆	25.94	25.917	26.1	0.49
27	Octacosane	C ₂₈ H ₅₈	2.394	2.358	3.942	0.49
28	Sulfoxide, methyl phenethyl	C ₉ H ₁₂ OS	17.46	17.417	17.54	0.45
29	Heptadecane, 2,6,10,15-tetramethyl-	C ₂₁ H ₄₄	25.79	25.7	25.8	0.42
30	Benzene, 1,1'-(2-methyl-1-propenylidene)bis-	C ₁₆ H ₁₆	20.41	20.358	20.44	0.41
31	Benzeneacetaldehyde	C ₈ H ₈ O	10.34	10.292	10.42	0.4
32	Benzene, propyl-	C ₉ H ₁₂	8.617	8.542	8.683	0.36
33	Diphenylmethane	C ₁₃ H ₁₂	16.31	16.25	16.36	0.34
34	Naphthalene	C ₁₀ H ₈	12.75	12.675	12.79	0.33
35	Benzene, (1-methylenepropyl)-	C ₁₀ H ₁₂	10.58	10.492	10.63	0.32
36	Furane, 2,5-diphenyl-		22.72	22.65	22.75	0.29
37	1,2-Diphenylcyclopropane	C ₁₅ H ₁₄	19.24	19.175	19.29	0.27
38	p-Toluenesulfonic acid phenethyl ester	C ₁₅ H ₁₆ O ₃ S	22.05	22.017	22.12	0.25
39	Benzene, 1,1'-(1,4-butanediyl)bis-	C ₁₆ H ₁₈	20.90	20.858	20.94	0.24
40	Benzene, 1,1'-(1,5-hexadiene-1,6-diyl)bis-	C ₁₈ H ₁₈	20.19	20.158	20.23	0.24
41	Ethanone, 2-(formyloxy)-1-phenyl-	C ₉ H ₈ O ₃	21.23	21.192	21.29	0.22
42	Benzene, 2-propenyl-	C ₉ H ₁₀	9.472	9.442	9.517	0.21
43	Tridecane	C ₁₃ H ₂₈	12.87	12.833	12.93	0.19
44	Ethylene, 1,1-diphenyl-	C ₁₄ H ₁₂	17.84	17.8	17.9	0.17
45	Benzene, 1,1'-(1-methyl-1,2-ethanediyl)bis-	C ₁₅ H ₁₆	17.38	17.325	17.42	0.17
46	Butyrolactone	C ₄ H ₆ O ₂	11.59	11.525	11.64	0.14
47	Benzene, 2-butenyl-	C ₁₀ H ₁₂	7.887	7.858	8.033	0.14
48	Benzeneacetaldehyde, .alpha.-methyl-	C ₉ H ₁₀ O	11.37	11.317	11.43	0.12
49	Naphthalene, 3-benzyl-1,2-dihydro-	C ₁₇ H ₁₆	20.75	20.717	20.78	0.11
50	Formaldehyde	CH ₂ O	1.326	1.267	1.358	0.09

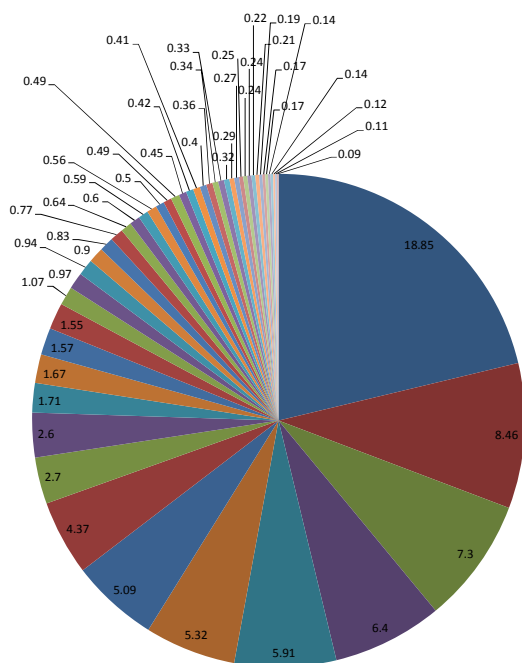


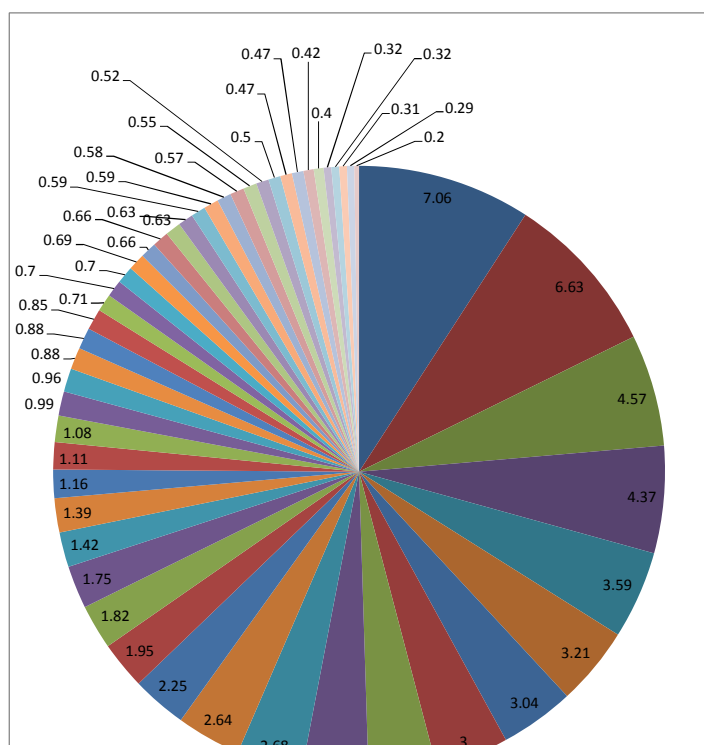
Fig 10. Distribution of the chemicals resulting from the decompositions of foam

3.4. Foam -- Shipping Box Protection Foam -- Fast Heating Pyrolysis

This experiment had the same feedstock as the previous one; however, the heating process was faster, the temperature of reactants reached higher and maintained high till the end of experiment. As Fig 3a shows, the product is physically dark red with small carbonized particle spinning in the liquid. In both experiments, condensation started at 60°C. In the fast-heating reaction the temperature of condensing vapors passed over 150 °C indicating the vapors were overheated; the color of vapors resulting of decompositions of foam in the reaction vessel was brown to black. In medium heating experiment, the condensing vapor temperature did not rise above 130 °C; the vapors inside the flask were clear yellow. Fig 11 shows the distribution of the chemicals identified from this process and Table 7 provides a list of 50 major chemicals identified in the resulting liquid. Only 4.6% of the chemicals were

300 identified as styrene. Therefore, overheating resulted in reducing the amount of styrene in the
301 liquid products

302



303

304 Fig 11. Distribution of the chemicals resulting from the fast decomposition of shipping
305 protection box.

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307 Table 7. 50 major chemicals resulting from the fast decomposition of foam box (fast heating).

No	Component Name	Formula	Retention Tm	Start Tm	End Tm	Area%
1	Benzene 1 1'-(1 3-propanediyl)bis-,	C ₁₅ H ₁₆	16.298	15.767	16.37	7.06
2	Unknown,		33.553	32.967	33.6	6.63
3	Styrene,	C ₈ H ₈	7.274	7.092	7.392	4.57
4	Unknown,		17.873	17.583	17.95	4.37
5	Benzene 1 1'-(1 3-propanediyl)bis-	C ₁₅ H ₁₆	19.121	18.975	19.24	3.59
6	Toluene,	C ₇ H ₈	4.172	4.042	5.642	3.21
7	Unknown,		19.933	19.792	20.02	3.04
8	Bicyclo[4.2.0]octa-1,3,5-triene,	C ₈ H ₈	7.729	7.592	7.767	3
9	2-Methylbenzyl benzoate,	C ₁₅ H ₁₄ O ₂	7.579	7.45	7.592	2.77
10	.alpha.-Methylstyrene,	C ₉ H ₁₀	9.249	9.092	9.317	2.72
11	Ethylbenzene,	C ₈ H ₁₀	6.634	6.575	7.092	2.68
12	o-Xylene	C ₇ H ₈	6.53	6.383	6.575	2.64
13	Benzene (1 3-dimethyl-3-butenyl)-	C ₁₂ H ₁₆	18.131	17.992	18.17	2.25
14	Unknown,		33.882	33.775	33.97	1.95
15	Unknown,		32.953	32.5	32.97	1.82
16	Benzene 1 1'-(1-methyl-1 3-propanediyl)bis-	C ₁₆ H ₁₈	16.915	16.708	16.98	1.75
17	3-Buten-1-one 1 4-diphenyl-,	C ₁₅ H ₁₄ O ₂	20.074	20.017	20.12	1.42
18	Benzene 1 1'-(1-methyl-1 3-propanediyl)bis-	C ₁₆ H ₁₈	19.472	19.342	19.5	1.39
19	Tetrahydro-6-[phenylmethyl]-tetrazine-3-thio	C ₉ H ₁₂ N ₄ S	33.676	33.6	33.69	1.16
20	Indan, epoxide , C ₈ H ₈	C ₈ H ₈	7.431	7.392	7.45	1.11
21	Unknown,		33.756	33.692	33.78	1.08
22	Benzaldehyde, C ₇ H ₆ O	C ₇ H ₆ O	8.81	8.683	9.092	0.99
23	Benzene, (1-methylethyl)-, C ₉ H ₁₂	C ₉ H ₁₂	8.088	8.017	8.167	0.96
24	Unknown,		20.263	20.217	20.35	0.88
25	Benzene 1 1'-(2-methyl-1-propenylidene)bis-	C ₁₆ H ₁₆	20.472	20.408	20.54	0.88
26	Benzene (1-methylethenyl)- , C ₉ H ₁₀	C ₉ H ₁₀	9.352	9.317	9.4	0.85
27	Unknown,		22.108	22.058	22.18	0.71
28	Benzene 1 1'-(1 4-butanediyl)bis-, C ₁₆ H ₁₈	C ₁₆ H ₁₈	18.478	18.383	18.53	0.7
29	Benzene 1 1'-(1-butene-1 4-diyl)bis- (Z)-	C ₁₆ H ₁₆	20.96	20.875	20.99	0.7
30	Benzene1'-(3-methyl-1-propene-1 3-diyl)bis-,	C ₁₆ H ₁₆	19.297	19.242	19.34	0.69
31	Benzene11'-(3-methyl-1-propene-13-diyl)bis-	C ₁₆ H ₁₆	20.724	20.675	20.77	0.66
32	Benzene 1 1'-(1 4-pentadiene-1 5-diyl)bis-	C ₁₇ H ₁₆	22.021	21.9	22.06	0.66
33	Unknown,		20.177	20.117	20.22	0.63
34	.beta.-Phenylpropiophenone	C ₁₅ H ₁₄ O	21.291	21.25	21.35	0.63
35	Benzene 1 1'-(1-butene-1 4-diyl)bis- (Z)-	C ₁₆ H ₁₆	19.649	19.583	19.68	0.59
36	Benzene 1-methyl-4-(4-methyl-4-pentenyl)-	C ₁₃ H ₁₈	19.744	19.675	19.79	0.59
37	Unknown,		21.229	21.15	21.25	0.58
38	Unknown,		17.97	17.95	17.99	0.57
39	Unknown,		21.383	21.35	21.44	0.55
40	Benzene 1-ethenyl-2-methyl-	C ₉ H ₁₀	10.047	9.975	10.13	0.52
41	1 2-Diphenylcyclopropane,	C ₁₅ H ₁₄	18.193	18.167	18.23	0.5
42	Naphthalene 1 2 3 4-tetrahydro-1-phenyl-	C ₁₆ H ₁₆	18.784	18.708	18.82	0.47
43	Hex-1-ene 2 5-diphenyl-,	C ₁₈ H ₂₀	21.019	20.992	21.09	0.47
44	Naphthalene 3-benzyl-1 2-dihydro-	C ₁₇ H ₁₆	22.785	22.717	22.83	0.42
45	Unknown,		20.579	20.542	20.63	0.4
46	Benzene 1-ethenyl-4-methyl-,	C ₉ H ₁₀	8.466	8.392	8.542	0.32
47	Bibenzyl,	C ₁₄ H ₁₄	17.481	17.442	17.53	0.32
48	Benzeneacetaldehyde,	C ₈ H ₈ O	10.349	10.3	10.42	0.31
49	Acetophenone, C ₈ H ₈ O	C ₈ H ₈ O	10.773	10.708	10.99	0.29
50	Benzene propyl-, C ₉ H ₁₂	C ₉ H ₁₂	8.614	8.542	8.683	0.2

3.5 Plastic Carrying Bags

The plastic carrying bags are the main transportation means of goods in daily shopping in the United States. The consumers and retailer have accepted the plastic carrying bags for their benefits such as light-weight, strength, inexpensive, practical, and sanitary way of transporting goods and foods. The 'singlet' bag made of high density polyethylene (HDPE), mostly used in grocery stores to carry foods and goods, and the 'boutique' bag made of low density polyethylene (LDPE), usually used in department and fashion stores (Australian Bureau of Statistics, 2004). Polyethylene is a product of petroleum, a non-renewable resource (Schuler K, 2008) which takes almost thousand years to break down when put in landfill (Usha R. et al., 2001).

Liquid materials formed from pyrolysis of bags were classified into six fractions according to the temperature they were collected (Table 3). The most volatiles did not condensed into first flask but was collected in the second flask with a tap water cooling condenser; it was named here as fraction (f). Five additional samples (a) to (e) were collected at various temperatures for GC-MS analysis. Fig 12 (a) to (f) showing the chromatograms of selected samples. Chromatogram (f) in Fig 12 shows a higher amount of chemical below four min retention time; these are the most volatiles vapors condensed in the second container as it was expected. Chromatograms (a) to (e) in Fig 12 are very similar to each other. Fig 13 shows relative abundances of 50 major chemicals identified in the fraction (a), (e) and (f). The produced hydrocarbons covers a wide ranges of compounds from C₄ to C₃₄ consisting of alkene and alkane. It is worthy to mention the highest TIC picks are gremials; first is alkene and the peak immediate after it is alkane with the same number of carbons. The similarities of chromatograms (a) to (e) indicate that the differences in temperatures of condensing vapors

331 were not related to the chemical nature of the vapors, but to overheating of the vapors in the
332 reactor. Fig 14 shows the mass spectrometer of most abundant compounds in fraction (f) as an
333 example. As Fig 14 shows, these are all straight chain hydrocarbons with very small aromatic
334 components among them.

335 The yield of liquid hydrocarbons in this experiment under the experimental conditions was
336 over 70%. The leftover ashes were about 20%, hence some 10% of the materials were
337 incondensable volatiles under room temperature and pressure. No further studies were done
338 on these volatiles.

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UNDER PEER REVIEW

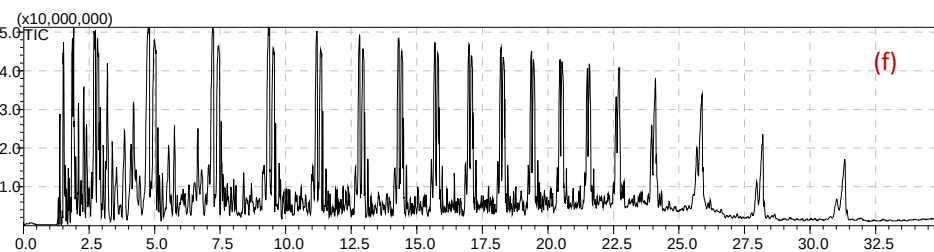
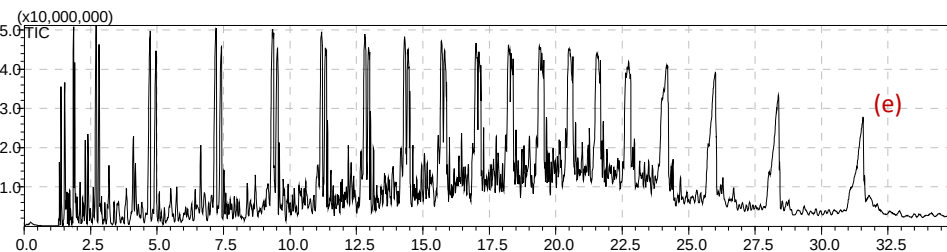
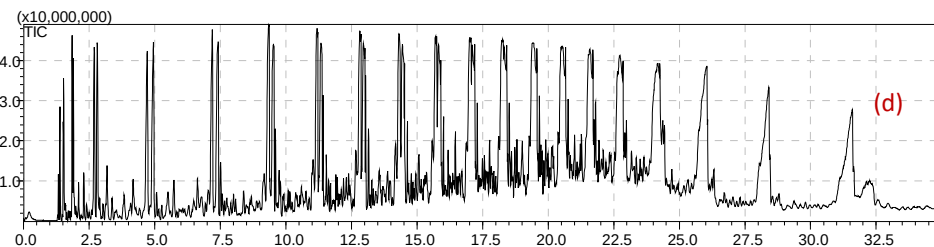
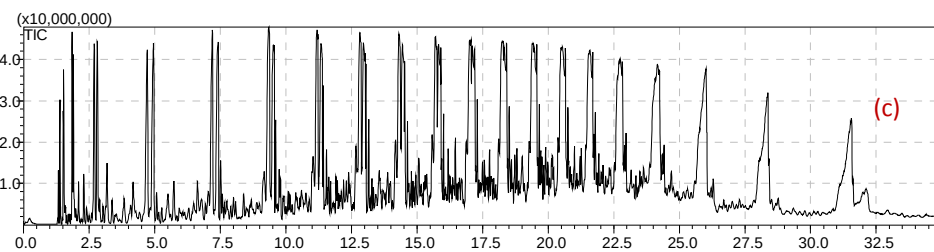
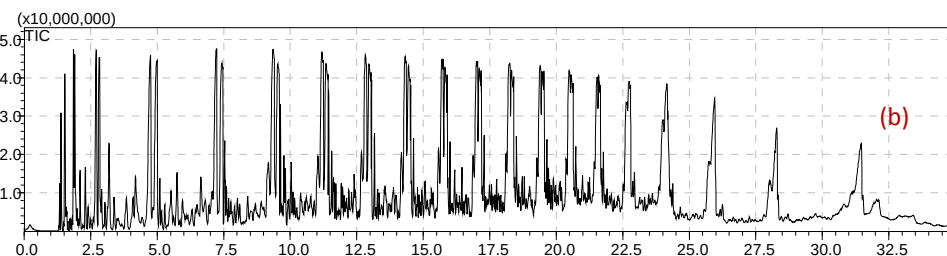
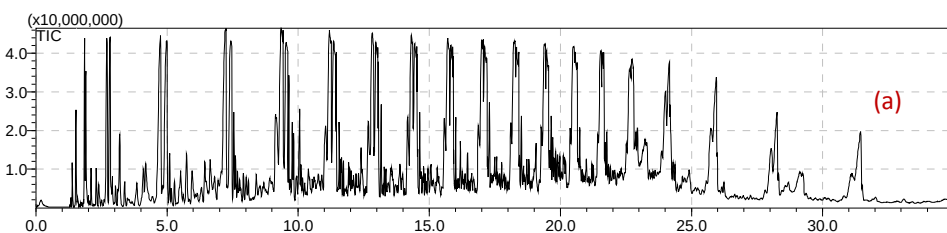


Fig 12 Chromatograms of six selected samples of chemicals collected by pyrolysis of shopping bags.

349 Table 9. The 50 major compounds of liquid sample resulting from shopping bags (e).

No	Component Name	Formula	Retention Tm	Start Tm	End Tm	Area%
1	Heptadecane,	C ₁₇ H ₃₆	4.76	4.517	4.825	2.65
2	Pentadecane,	C ₁₅ H ₃₂	4.99	4.892	5.083	2.32
3	9-Octadecene (E)-,	C ₁₈ H ₃₆	9.346	9.242	9.442	2.14
4	Hexadecene,	C ₁₆ H ₃₂	7.223	7.108	7.275	2.02
5	Borane diethyl(decyloxy)-,	C ₁₄ H ₃₁ BO	7.432	7.325	7.5	1.94
6	2-Butene,	C ₄ H ₈	25.88	25.742	26.05	1.74
7	1-Decene,	C ₁₀ H ₂₀	1.906	1.825	1.967	1.7
8	Hexane,	C ₆ H ₁₄	2.693	2.625	2.775	1.66
9	1-Pentadecane,	C ₁₅ H ₃₂	9.526	9.442	9.575	1.62
10	n-Nonadecanol-1,	C ₁₉ H ₄₀ O	14.426	14.367	14.57	1.61
11	Heneicosane,	C ₂₁ H ₄₄	11.184	11.092	11.23	1.59
12	Cyclohexene, 1-ethyl- ,	C ₈ H ₁₄	18.3	18.242	18.38	1.52
13	1-Heneicosanol,	C ₂₁ H ₄₄ O	17.087	17.033	17.17	1.5
14	2-Hexene,	C ₈ H ₁₆	15.801	15.742	15.88	1.49
15	9-Eicosene (E)-,	C ₂₀ H ₄₀	11.334	11.267	11.38	1.48
16	n-Pentadecanol,	C ₁₅ H ₃₂ O	12.816	12.7	12.85	1.47
17	1-Hexene,	C ₈ H ₁₂	20.541	20.492	20.63	1.44
18	3-Hexene, 3,4-dimethyl- ,	C ₈ H ₁₆	19.451	19.4	19.53	1.41
19	Heptene,	C ₇ H ₁₆	12.947	12.883	13	1.39
20	2-Dodecene,	C ₁₂ H ₂₄	22.729	22.642	22.78	1.39
21	Cyclohexene, 1-ethyl-,	C ₈ H ₁₄	15.689	15.608	15.74	1.37
22	1,4-Pentadiene, 3-propyl-,	C ₈ H ₁₄	16.992	16.908	17.03	1.37
23	1-Tricosene,	C ₂₃ H ₄₆	14.305	14.225	14.33	1.32
24	2-Nonene,	C ₉ H ₁₈	21.581	21.533	21.66	1.27
25	4-Tetradecene,	C ₁₄ H ₂₈	24.105	24	24.13	1.21
26	Pentane,	C ₅ H ₁₂	18.216	18.133	18.24	1.2
27	2,4-Hexadiene,	C ₆ H ₁₀	19.371	19.292	19.4	1.12
28	Cyclohexene,3-(2-propenyl)- ,	C ₉ H ₁₄	20.463	20.392	20.49	1.05
29	1-Heptene,	C ₇ H ₁₄	2.82	2.775	2.85	1
30	7-Hexadecene, (Z)- ,	C ₁₆ H ₃₂	28.199	28.033	28.23	0.95
31	Cyclopentane, methyl-,	C ₆ H ₁₂	21.505	21.442	21.53	0.93
32	2-Octene,	C ₈ H ₁₆	22.605	22.533	22.64	0.9
33	Heptadecane,	C ₁₇ H ₃₆	4.198	4.142	4.267	0.89
34	3-Tetradecene,	C ₁₄ H ₂₈	3.199	3.15	3.317	0.88
35	Heptadecane,	C ₁₇ H ₃₆	3.853	3.75	3.95	0.8
36	1-Heptene,	C ₈ H ₁₆	23.961	23.867	24	0.78
37	Hexane, 2,4-dimethyl-,	C ₈ H ₁₈	1.525	1.492	1.567	0.77
38	Hexadecane,	C ₁₆ H ₃₄	6.649	6.6	6.725	0.62
39	Nonene,	C ₉ H ₂₀	2.296	2.258	2.367	0.61
40	Dodecane, 2,7,10-trimethyl- ,	C ₁₅ H ₃₂	5.758	5.675	5.817	0.59
41	Decane,	C ₁₀ H ₂₂	2.886	2.85	2.908	0.56
42	Tetracosane,	C ₂₄ H ₅₀	2.398	2.367	2.458	0.47
43	1-Nonene,	C ₉ H ₁₈	2.097	2.05	2.167	0.46
44	9-Octadecene,	C ₁₈ H ₃₆	7.541	7.5	7.583	0.41
45	1-Hexadecene,	C ₁₆ H ₃₂	5.128	5.083	5.158	0.33
46	Heptadecane ,	C ₁₇ H ₃₆	9.613	9.575	9.65	0.31
47	Heptadecane,	C ₁₇ H ₃₆	2.927	2.908	2.967	0.29
48	5-Eicosene, (E) ,	C ₂₀ H ₄₀	11.409	11.383	11.44	0.26
49	1-Octene,	C ₈ H ₁₆	1.38	1.358	1.433	0.25
50	Octacosane,	C ₂₈ H ₅₈	13.016	13	13.06	0.22

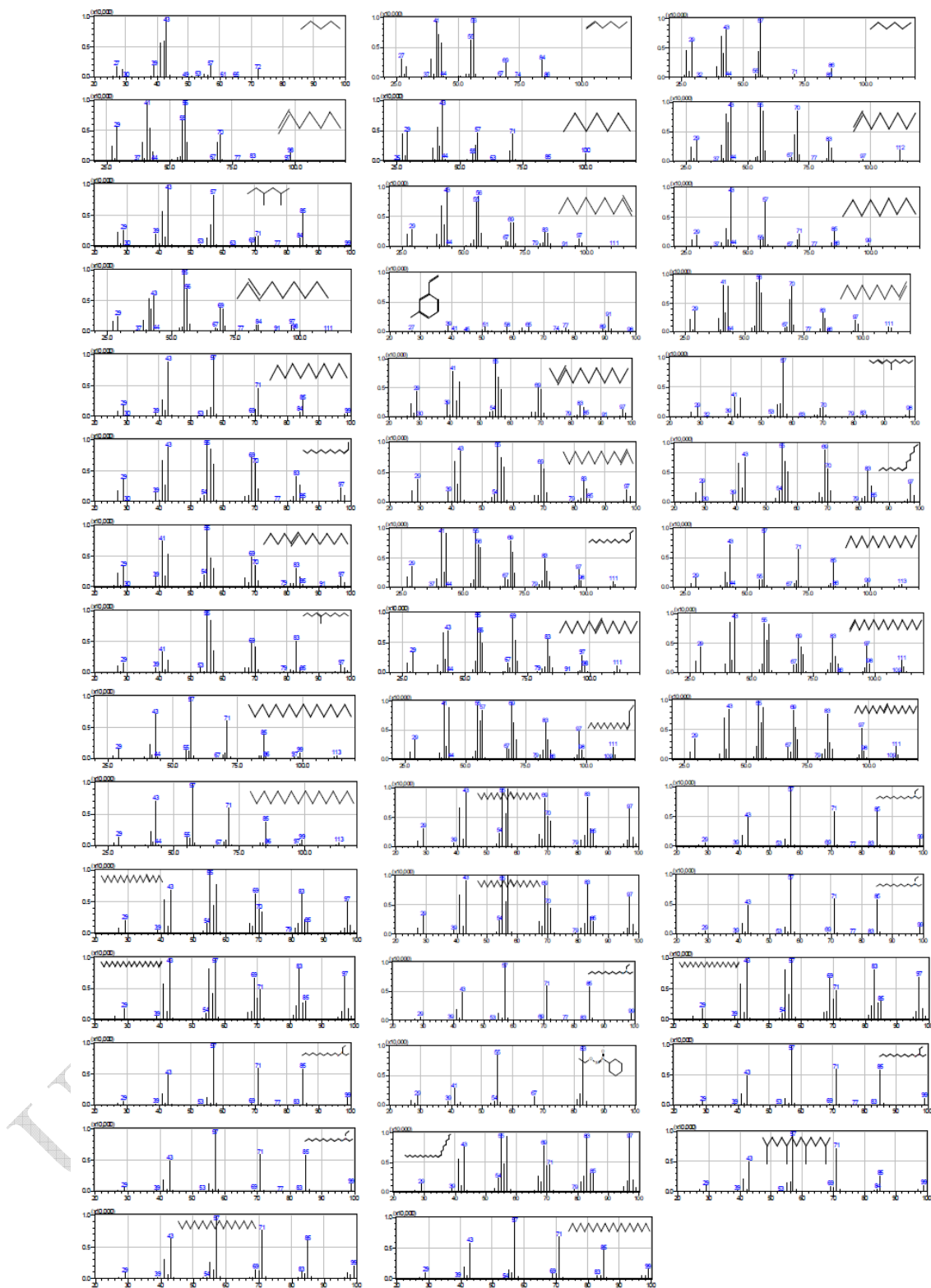


Fig 14. Mass spectrums of the major chemicals resulting from pyrolysis of a mixture of shopping bags fraction (a).

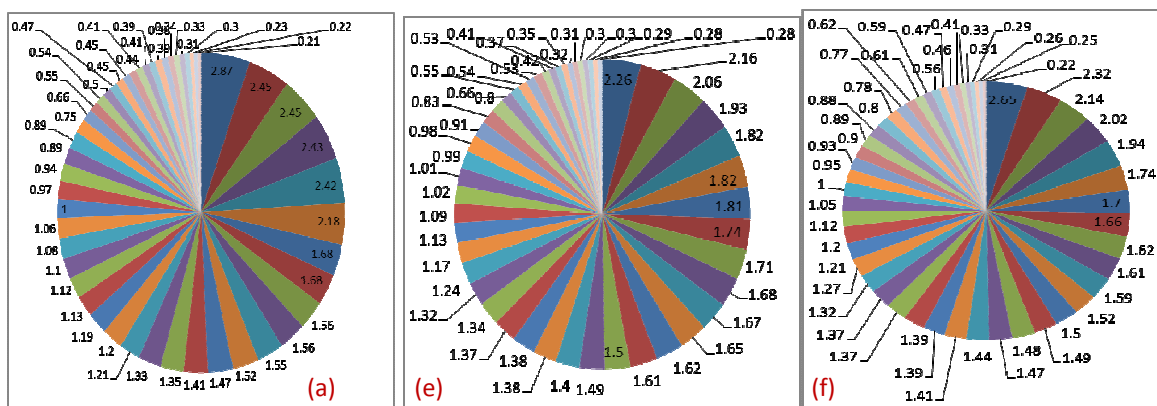


Fig 13. Distribution of major chemicals resulting from pyrolysis of a mixture of shopping bags fractions (a), (e) and (f).

4. Conclusions

The pyrolysis process of waste plastics produces all three phases of matter: gas, liquid and solid. Most of the studies by researchers have focused on the fuel components. The fuel product, fuel yield estimation, and fuel output are quite different depending on process and the quality of the feedstock being used. The liquid materials produced are suitable for use as gasoline and diesel fuel. Also it is suitable to be blended with regular fuels for a better quality. The refinement of liquids resulted from pyrolysis of waste plastics requires further improvements to get a better quality fuel. (4R Sustainability, Inc., 2011). Char or tar is the remaining material at the end of the process. Char resulted by degradation of high polymers under certain condition of temperature and pressure; besides some of the chars have their origins in additives. The additives usually incorporated to plastic products in order to process and reach to certain physical properties. These materials can be clay, carbon, glass, calcium

carbonate, metal, etc. (4R Sustainability, Inc., 2011). Therefore, the ingredients of char could vary depending on the kind of wastes undergo pyrolysis.

The condensed liquids produced from pyrolysis contain highly reactive chemical such as vinyl, alkene, three- and four-member cyclic, which make the storage life of these materials rather short. In relatively short time they condensed to polymers and precipitate as solid in the container. For long time storage, however these products must be stabilized either by stabilizers or hydrogenation of the product promptly after collection.

Hydrogenation of the liquids resulted from pyrolysis of plastic carrying bags result in a mixture of alkanes up to C₃₄. The higher alkanes in this mixture can be used as synthetic lubricants. Also, the portion of C₄ to C₁₁ is suitable for the production of light gasoline and the portion C₁₂ and higher are suitable for diesel fuel (Andras, 2007).

Pyrolysis of foams produced a mixture of more than 350 chemicals. The most abundant compounds are styrene, styrene derivatives and its isomers, vinyl compound and other highly reactive substances. This mixture polymerized stored in dark for two months at room temperature. Refinement of these materials results in styrene and its derivatives that are valuable fine chemicals.

One important observation is that the thermogravimetric results are not consistent with pyrolysis outcome. The thermogram of foam in Fig 5 showed no-char left over, and almost 100% unzipping to styrene as reported by many researchers (Cooley et al and Straus, 1953 et al). However, the actual pyrolysis reported here had a 70-80% liquids with max 20% styrene and more than 20% char.

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References:

- Cooley, James H. and Richard Vaughan Williams 2003 The Pyrolysis of Polystyrene, Chem. Educator, 8, 309-311
- 4R Sustainability, Inc., (2011). Conversion Technology: A Complement to Plastic Recycling, Portland, OR 97203
- Andras, A., Norbert, M., Laszlo, B. (2007). Petrochemical Feedstock by Thermal Cracking of Plastic Waste. *J. Anal. Appl. Pyrolysis*, 79, 409-414.
- Australian Bureau of Statistics. (2004). How Much Energy is Used to Make a Plastic Bag, Year Book Australia. Retrived June 28, 2012, from <http://www.abs.gov.au/ausstats>
- Bandyopadhyay, A. & Basak, G. C., (2007). Studies on photocatalytic degradation of Polystyrene, *Materials Science & Technology*, 23(3), 307-314.
- Behzadi, S. & Farid, M. Liquid fuel from plastic wastes in New Zealand. The University of Auckland, Department of Chemical and Materials Engineering.
- Environmental Protection Agency. (June 23, 2010). Cycling: Frequent Questions. Retrieved June 2010, from <http://www.epa.gov/epawaste/conserves/materials/ecycling/faq.htm> and; <http://www.epa.gov/epawaste/conserves/materials/plastics.htm>
- Friend, D. (2005). Conserving Natural Resources in Illinois. University of Illinois extension, College of Agricultural, Consumer and Environmental Sciences.
- Gargallo, L., Hamidi, N., Radic, D., & Tagles, L.H. Thermogravimetric Analysis of Poly(dialkylphenyl methacrylate)s, *Thermochimica Acta*, 143, 75-84 (1989).
- Lee, K.H. (2011). Pyrolysis of waste polystyrene and High-Density Polyethylene. Korea Institute of Energy Research. South Korea.
- Plastic Waste Management Institute. (1985). Plastic Wastes: Resource Recovery and Recycling in Japan. Tokyo.
- Sarker, M. Rashid, M.M. Rahman, R. & Molla, M. Conversion of Low Density Polyethylene (LDPE) and Polypropylene (PP) waste plastics into liquid fuel using thermal tracking process. *British Journal of Environment & Climate Change* 2(1): 1-11, 2012
- Schuler, K. (2008). Smart plastic guide healthier food uses of plastics. Institute for Agriculture and Trade Policy, Food and Health Program
- Straus, S and S. L. Madorsky 1953 Pyrolysis of Styrene, Acrylate, and Isoprene Polymers” *Journal of Research of the Notional Bureau of Standards* Vol. 50, No. 3, March 1953 Research Paper 2405
- U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of Public and Constituent Affairs, (1999) “Turning to the Sea: America’s Ocean Future;” United Nations Environment Programme (1995) “Global Programme of Action for the

- 430 Protection of the Marine Environment from Land-based Activities.” Note by the
431 secretariat. UNEP (OCA) /LBA/IG.
432 http://www.resources.ca.gov/copc/docs/0811copc_03_ocean_litter_strategy.pdf
433 U.S. Environmental Protection Agency, (2012). Common Wastes and Materials: Plastics,
434 Retrieved Jun 11, 2012, from <http://www.epa.gov/osw/conservation/materials/plastics.htm>
435 Usha, R. Sangeetha, T. & Palaniswamy, M. (2011). Screening of Polyethylene Degrading
436 Microorganisms from Garbage Soil. Department of Microbiology, School of Life
437 Sciences, Karpagam University, India.

438

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