

## OXIDATIVE PYROLYSIS OF EXAMINATION RUBBER GLOVES IN THE INTEGRAL PYROLYSIS TEST PLANT

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### ABSTRACT

In order to visualize the practical application of pyrolyzing examination rubber gloves, a new test plant is designed and constructed. This 2 kg/hr test plant incorporates innovative features to ensure sufficient heat transfer to pyrolyze un-shredded gloves. This paper addresses the performance of the plant inclusive of time temperature profile, gas evolution profile and product yield. The performance of this plant is compared against the ideal zero-oxygen pyrolysis rig that was used to pyrolyze 10 grams of cut-up gloves in the bench scale study. It is found that the presence of the oxygen in the plant is inevitable due to imperfect sealing resulting in significant water formation and altering the tail gas and chemical composition of the oil. The main compositions of the oil were found to be esters and phthalic acid.

**Keywords:** Pyrolysis, rubber gloves, plant performance, oxidative, composition

### 1. INTRODUCTION

The latex industry has expanded over the past years to meet the world demand for examination gloves, condoms, and latex threads. However, gloves were the main reason for the rising natural rubber latex uptake over the past 20 years, it was and still is playing the leading role in the latex world (Rajan *et al.*, 2006). A study in Thailand showed that the rubber gloves made up 20% of the medical waste composition (Suwannee, 2002). The disposal of rubber gloves in medical wastes, in particular, presents several problems as they are hazardous biologically, non-biodegradable as well as when mixed with chlorinated components, do generate chlorinated organic compounds upon incineration, thus the World Health Organization (WHO) is opposed to land filling or incineration of this waste. Therefore, a new technology is required to process this waste that is both environmentally friendly and biologically safe. There is still lack of data concerning the characteristics of medical waste under pyrolysis, as such pyrolysis characteristic of each component of the medical waste need to be developed for better understanding of the kind of product produced. A study on kinetic properties of pyrolysis of selected medical components were conducted by a number of researchers such as absorbent

cotton, medical respirator, bamboo sticks (Zhu *et al.*, 2008) and cotton gauge, packaging boxes, capsule plates and transfusion tubes (Li Chuantong *et al.*, 2004). Previously, pyrolysis of examination rubber gloves was conducted at a laboratory scale using fixed bed reactor with a sample size of 10 grams (Hall *et al.*, 2009) and upgrading of the pyro-oil produced product that emulate diesel fuel (Zakaria *et al.*, 2008). The study showed that pyrolyzing rubber gloves with presence of catalyst did not only treat the rubber gloves in environmental friendly manner but managed to produce end product that has chemical compounds emulating diesel with attractive calorific value of 42 MJ/kg. Following the success of the laboratory study, a scaled-up plant is designed and developed in order to establish a visible industrial design and real practical scenario. At this scale, it does not only require the powering up elements like oil, gas, electricity to be covered, but also a sound knowledge on amounts of residue, products, and heat and energy balance parameter need to be established for assessing the operation of the plant. Thus, the objective of this study is to translate the work from the laboratory bench scale study to a test plant in which enable us to assess the technical feasibility as well as understanding the systems behaviour under certain conditions.

### 2. EXPERIMENTAL

#### 2.1 Input Material

There are many different rubber gloves manufacturers and countless different types and formulations available in the market place. These rubber additives include accelerators, preservatives, antioxidants, antiozonants and plasticizers. Ultimate and proximate analysis of the sample used in the experiment is tabulated in Table 1 and Table 2.

Table 1 Ultimate analysis of the rubber gloves sample

Element	Percentage (%)
C	71.3
H	10.1
N	0.4
S	0.8
Others (O+ Fillers)	17.4

Table 2 Proximate analysis of the rubber gloves sample

Element	Percentage (%)
Residual Moisture	1.72
Volatile Matter	67.85
Fix Carbon	1.00
Ash	29.43

## 2.2 Design and Construction of the Integral Test Plant

A test plant named the Integral Pyrolysis Test Plant is developed in this study. The test plant comprises of 3 main sections that are integrated into one enclosure. The

three sections are the sand combustor, the flue gas combustor and the pyrolysis reactor or the pyrolyzer. The total plant covers an area of 3.2 m length x 1.7 m width, with approximately 3.4 m height. The aforementioned enclosure is cyclone in geometry where the burner is mounted tangentially. The cyclone used in this system serves at least three purposes: apart from being the sand heating section and fuel (auxiliary) combustion section, it also functions as the air pollution control section whereby uncondensable gases containing hydrocarbons are burnt completely into combustion gases and ultimately used as the energy recovery section. A block flow diagram of the Integral Pyrolysis Test Plant is shown in Figure 1.

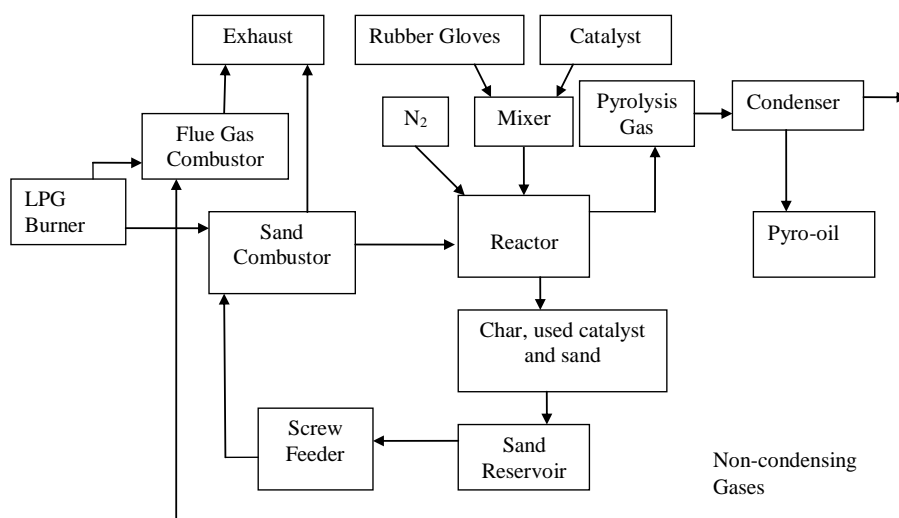


Figure 1 Block flow diagram of the Integral Test Plant

The pyrolyzer is a cylindrical chamber with a height of 1210 mm and inner diameter of 254 mm. The tubular reactor is constructed from two tubes, joint as one. The bottom tube is permanent (static), while the top tube is free to rotate up to 180°. The two tubes are joined by a window coupling system. A mechanical agitator is fixed at the bottom of the reactor to stir the sand bed and the rubber glove. Feed material is introduced vertically down from the top of the pyrolyzer. The chute is positioned at the top of the reactor, approximately at 600 mm above the pyrolyzer. In order to prevent heat dissipating to the feed container, double door system is utilized. The door (flap seal) is made of from stainless steel plate and the movement is controlled by a spring and actuator. Considering the thermal inertia characteristics of the sand, there is also a provision of sand jacket inside of the reactor for the purpose of conserving the heat. Approximately, 35 to 40 kg of sand was used to make up the sand bed as well as the sand jacket. The overall engineering drawing of the Integral Test Plant is as shown in Figure 2.

## 2.3 Experimental Set Up

In this study, 500 grams of un-cut rubber gloves were left to pyrolyze for 30 minutes per batch. LPG was used to

heat up the sand bed to the desired temperature. Once the operating temperature was attained, the burner was switched off and the gloves were fed into the pyrolyzer. Suction was employed to draw out the pyro-gases from the pyrolyzer into the condensing section downstream. Liquid pyrolyzates (oil and water) were condensed in a series of condensers. Five thermocouples are installed in this plant to record the temperature where T1 dictates the pyro-gas temperature, T2 dictates the auxiliary burner temperature, T3 dictates the flue gas temperature leaving the reactor, T4 records the sand temperature in the sand combustion section and T5 records the pyrolyzer temperature. Three operating temperatures were selected ie. 350°C, 400°C, and 450°C based on TGA data. Temperature readings were logged into data acquisition system. The concentration of O<sub>2</sub>, CO<sub>2</sub>, CO, NO<sub>x</sub> and SO<sub>2</sub> were measured online using portable flue gas analyzer IMR2800P (IMR Instrument, USA). The solid residue that was a mixture of char and sand, were drawn out from the reactor at the end of the experiment after being cooled naturally to a safe handling temperature. Oil speciation was conducted using GCMS (Shimadzu QP 5050A) using ZB-1 (30m x 0.25mm). The identification of the compounds was made by comparing against the library of the GC-MS as well as from standard diesel mixture obtained from Supelco. The temperature

program used was as follows: Starting temperature at 45°C, holds for 3 minutes, then ramped to 300°C, at 7.5°C/min. The final temperature (300°C) was hold for 5 minutes. An aliquot of the oil was injected into the GCMS using splitless mode. The oil was diluted using ethyl acetate solvent of HPLC grade. Physical properties of the oil were determined by the Petroleum Laboratory Services, UTM according to ASTM methods namely sulphur (ASTM D129-91), viscosity (ASTM D445-94), chlorine (ASTM D808-91), ash (ASTM D482-91) and water content (ASTM D95-83). The calorific value of the oil was determined using bomb calorimeter (IKA, model C5000).

### 3. RESULTS AND DISCUSSION

Pyrolysis is described as the thermal decomposition of waste solids process effected by the application of heat to yield gaseous, liquid and solid products in the absence of air or under limited air supply (Niessen, 2002). As for many other pyrolysis reactors, high energy requirement due to heating is a common problem. Normally, heating is provided either by heating element or other means of indirect heating. Griffiths *et al.* (2000) introduced flaming pyrolysis whereby flame was directly fired in the reactor chamber, under sub-stoichiometric conditions. Besides heating, it is detrimental to achieve uniform temperature and eliminate cold spots inside the reactor. In this study, a new design scheme is invented that inherits the characteristics of fluidized bed and cyclone combustor. Thus, intimate mixing of the un-cut rubber gloves with the bed material is attained while uniform temperature distribution along the reactor would promote sufficient heat transfer to effect the pyrolysis reaction.

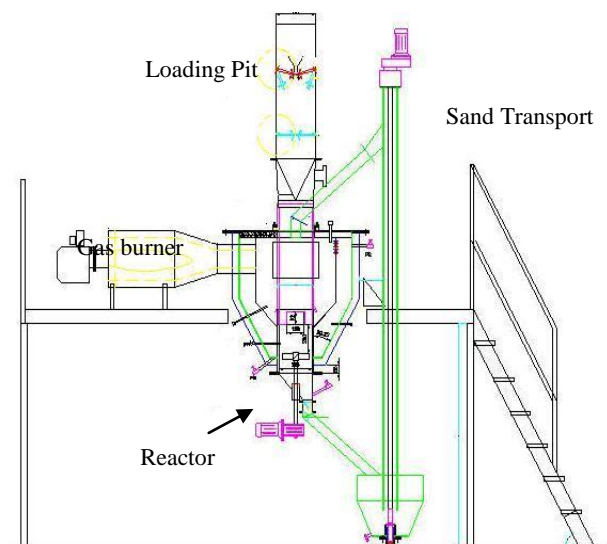


Figure 2 Integral Pyrolysis Test Plant developed at Malaysian Nuclear Agency

Another aspect that is made into considerations during plant development is the possibilities of any side reaction occurring during the course of the pyrolysis reaction. As such, carryover of the sand into the pyro-oil was minimized by having sufficient headspace of the reactor,

that by gravitational forces, the sand could be separated from the gas flow. Another possible side reaction is excessive hydrocarbon cracking at the hot region of the plant and possibility of delayed cooling. Thus, it is essential to draw out the primary gases from the hot region at the quickest opportunity and quenches the gases in order to recover the pyrolysis oil. For this purpose, suction is employed.

Suction is needed to provide the driving force for the pyro-gas to flow out from the reactor chamber into the downstream section for condensation process. The suction rate of the pump was set at 0.5 litres per second. Thus, at steady state, the atmospheric air is deemed to infiltrate into the reactor at a rate of 0.5 liter per second through available gaps at the plant, particularly at the agitator module. This value corresponds to air fuel ratio ( $\lambda$ ) of 1.06 and equivalence ratio ( $\Phi$ ) of 0.06. Ultimately, this air became the permanent source of oxygen in the plant and created a phenomenon known as oxidative pyrolysis. Other works involving oxidative pyrolysis have been carried out by Ming *et al.*, (1997) and Huff and Vasalos (1998). Therefore, it is almost impractical to achieve an oxygen-free environment in a larger scale plant due to imperfect sealing as air infiltrate into the Integral Test Plant through available gaps and voids due to the suction effect from the action of vacuum pump. This pyrolysis environment deviates from the pyrolysis environment created during the laboratory study using Fixed Bed Reactor whereby back then, pyrolysis of rubber gloves were successfully performed under oxygen-free environment.

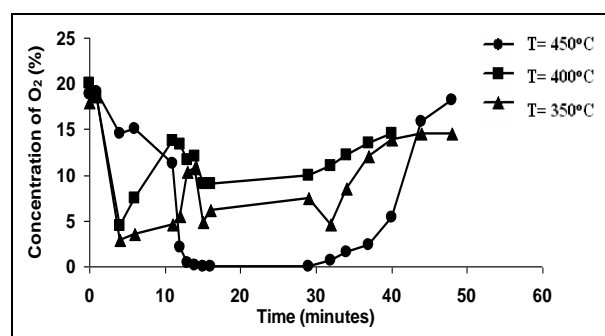


Figure 3 Profile of oxygen in the reactor during pyrolysis of rubber gloves

The profile of oxygen in the reactor of the Integral Test Plant is as shown in Figure 3. Initially, the concentration of Oxygen in the plant was 20%, which then decreased steadily during the pyrolysis reaction as it was being used up for instance in the formation of SO<sub>2</sub> and CO<sub>2</sub>. However, when the pyrolysis reaction has been completed and ceased, the oxygen level returned to its initial level, thus this explains the 'bath-tub' shape of the O<sub>2</sub> profile. Further analysis showed that the presence of oxygen had affected the chemical composition of the oil and the tail gas. Several other observations relating to the presence of oxygen are also noted in this study which is further discussed in later sections of this paper.

### 3.1 Temperature Time Profiles

Figure 4 is an example of the time temperature profiles during the heating and pyrolysis reaction at 350°C. The gas burner used in this test plant is of a modulating type with preset upper and lower limit, thus this justifies the sinusoidal pattern of T2 that recorded the combustion temperature of the LPG. The heating process was continued until the temperature inside the pyrolyzer (T5) reached the desired temperature steadily. On average, approximately 2 hours was needed to heat up the plant from room temperature to 400°C, and an additional 30 minutes was needed to reach 450°C. Interestingly, the

plot of the reaction bed, T5, did not show a sink in the temperature as would be expected as pyrolysis is endothermic in nature. Instead, T5 has been steadily consistent with a slight increase in temperature was observed, suggesting that some degree of exothermic reaction is taking place in the reactor. Combustion is more likely to be the exothermic reaction taking place inside of the reactor that consequently produces heat to sustain the sand bed temperature. However, combustion requires oxygen. Thus, the observation suggests that oxygen present in the reactor and some degree of combustion process is taking place along with the pyrolysis reaction.

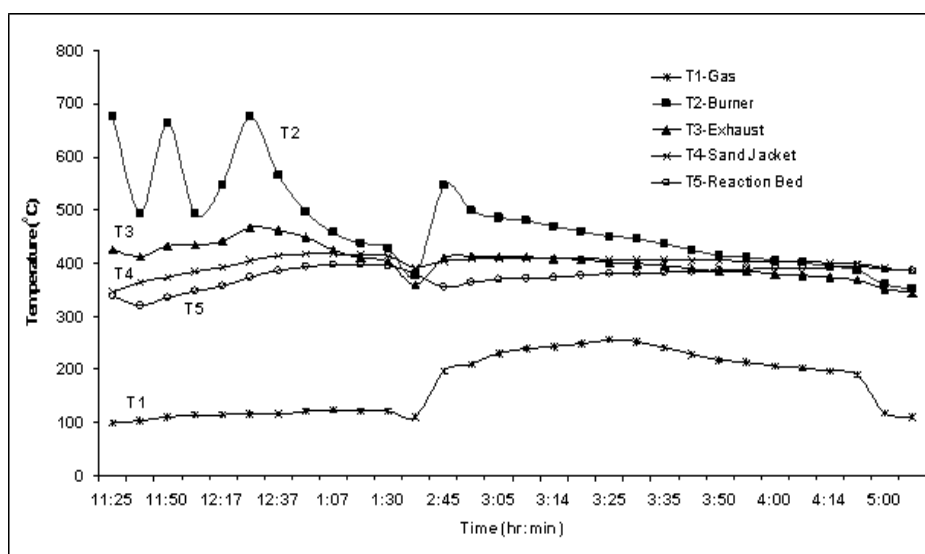


Figure 4 Temperature-time profile of the reactor for pyrolysis of rubber gloves at 350°C

### 3.2 Effect of Throughput Size

The effect of loading size is apparent in this work. Again, it should be noted that these gloves were not cut up into smaller pieces. When the reactor was loaded with 1000 grams of rubber gloves, the oil yield was 26 wt% and the aqueous yield was 17 wt%. There were also a portion of gloves that were left un-reacted which amounted to 12.6 wt%, indicating the heat distribution between the gloves was uneven at this loading rate, leading to formation of cold spot in the reactor, hence ineffective to effect pyrolysis completely. As compared to the yield at 500 grams loading, all gloves were managed to be pyrolyzed resulting to an increase in the oil yield, i.e. 32.18 wt%. Water yield and the char yield also increased to 18.04 wt% and 19.16 wt% respectively. Below 500 grams loading size, the effect onto the oil yield and the gas yield was apparent as can be seen in Figure 5.

### 3.3 Yield of Pyrolyzates

#### 3.3.1 Oil Yield

The condensable pyro-gases were condensed in a specially-designed condenser before the tail gases were vented out. Taking the average value, the oil yield at

350°C, 400°C and 450°C are 20.48%, 32.18% and 46.78% respectively. The study shows that the oil yield strongly depends on the heat transfer rate. For a sample size of 500 grams, the rubber gloves formed a bed of 150 to 200 mm height in the Integral Test Plant reactor. Therefore, a temperature gradient and species across the bed during the pyrolysis course was formed. Consequently, this will definitely alter the rate constant. The heat penetration rate can be deduced from the following equation (Velden, 2007).

$$k_{hp} = \frac{ha_m}{cp} \quad (\text{Eqn 1})$$

where;  $h$  is the heat transfer coefficient in the reactor ( $\text{Wm}^{-2}\text{K}^{-1}$ );  $a_m$  is the specific surface area of the particle ( $\text{m}^2\text{kg}^{-1}$ );  $cp$  is the specific heat of the particle ( $\text{Jkg}^{-1}\text{K}^{-1}$ )

The overall reaction rate constant now becomes a function of the combined resistance and can be determined as below (Van de Velden, 2007).

$$\frac{1}{k_{hp}} + \frac{1}{k_r} = \frac{1}{k} \quad (\text{Eqn 2})$$

Where,  $k_r$  is the real reaction rate constant;  $k$  is the overall reaction rate;  $k_{hp}$  is the heat penetration rate

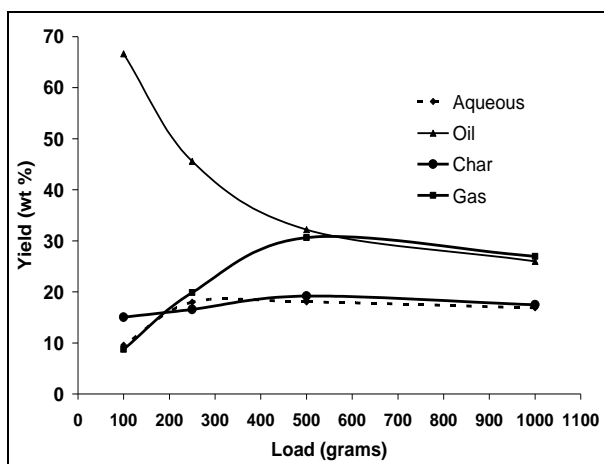


Figure 5 Effect of loading on yield of pyrolysis product

Therefore, the equation suggests that the rate constant for pyrolysis of rubber glove in the test plant will be lowered than the rate constant obtained from TGA analysis due to additional resistance by a factor of  $k_{hp}$ , the heat penetration rate. Thus, it is concluded that the heat penetration rate is the rate controlling step in pyrolysis and it varies according to the sand quantity, the rubber glove quantity and its specimen size. Thus, this justifies for lower oil yield obtained from the Integral Test Plant as compared to the yield produced at the laboratory scale. The yield of the oil could also be affected by the presence of oxygen in the reactor. A study conducted by Conesa et al. (2004), found that, when tyres were pyrolyzed in a 10% oxygen environment, the liquid fraction was lowered than the yield of products in nitrogen environment.

### 3.3.2 Properties of the Oil

The properties of the black pyrolysis oil produced at 400°C are as follows: kinematic viscosity (11.22 cps), ash content (0.028 wt%), pH (3.13), sulfur content (19.87 wt%), chlorine content (1.32 wt%), water content (4 vol%). By pyrolysis, the chemical energy content is partly stored in the oil whereby the energy value of the oil produced at 450°C, 400°C and 350°C were 39.25 MJ/kg, 39.10 MJ/kg and 24.68 MJ/kg respectively. The energy content of the oil is very much dependent on the degree of the pyrolysis reaction taking place, hence when the temperature is low; the amount of energy in the oil is also low as in the case for 350°C. The calorific value of the examination rubber gloves is determined to be 43.3 MJ/kg. Sulfur in the gloves, which originally 0.8 wt%, is released into gas, liquid and solid phase during pyrolysis process. Sulfur in the gas is found to be  $H_2S$  and  $SO_2$ . The result shows that most of the sulfur in the gloves was volatilized and trapped in the oil, while a small amount retained in char and tar deposits. The content of sulfur in char was determined to be 0.5%.

The major constituents of the pyrolysis oil are found to be 1,2-Benzenedicarboxylic acid bis(2-ethylhexyl) ester ( $C_{24}H_{38}O_4$ ), 1,2-Benzenedicarboxylic acid bis(2-methylpropyl) ester ( $C_{16}H_{22}O_4$ ), and methyl naphthalenes compounds. The finding of this study showed that the oil composition obtained from the upscale rig, the Integral Test Plant is different from the oil obtained from the laboratory rig, Fixed Bed Reactor.

In the Fixed Bed Reactor, the major compound was limonene. Other compounds include dimer (2-ring benzene), trimer (3-ring benzene), tetramer (4 ring benzene) and pentamer (5 ring benzene) group of compounds. However, the chromatogram of the oil obtained from the Integral Test Plant showed that the dimer group diminished, suggesting the compounds in the dimer group were oxidized to form carboxyl and carbonyl group. Trimer group (anthracene, phenanthrene) and tetramer group (pyrene) pattern still exists although not conspicuous as in the oil from Fixed Bed Reactor, indicating that the amount is relatively smaller. Nevertheless, single-ring benzene compounds still consist as the main group in the oil. Figure 6 exemplified the chromatogram of the pyrolysis oil while Table 3 summarizes the compounds speciated in the oil.

### 3.3.3 Char Yield and Tar Formation

The average char yield at 350°C, 400°C and 450°C are 40.86%, 19.16% and 14.92% respectively. Although the proportion of the char was higher as compared to the char yield in the laboratory scale, but the advantage of

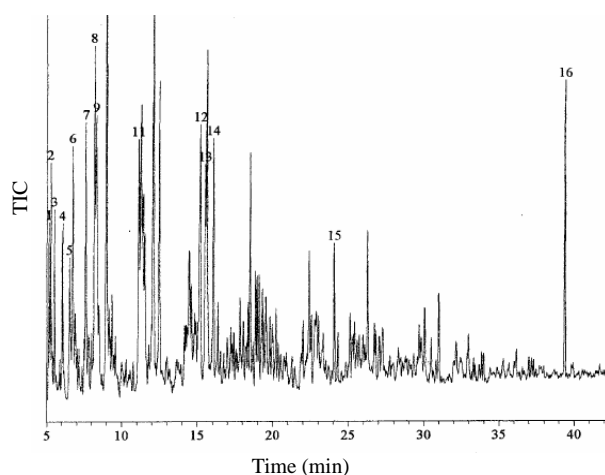


Figure 6 An example of gas chromatogram of the pyrolysis oil from the pyrolysis of rubber glove at 400°C

this test plant is that it produces char that is dry, black and fine, thus making it easier and practical to handle and transport it the energy recovery section of this test plant. Sticky solid residue was previously observed when pyrolyzing rubber glove at 380°C in the fixed bed reactor.

Table 3 Compounds speciated in the pyrolysis oil

Peak No.	Compounds	Relative Concentration		
		350°C	400°C	450°C
	1,2,3-Trimethylbenzene	n/d	1.01	0.48
	p-cymene	0.36	2.92	0.23
	Limonene	0.23	1.26	0.51
2	Indene	n/d	n/d	0.83
	3-propyltoluene	n/d	n/d	0.09
	2-ethylxylene	n/d	0.81	0.21
5	1-methyl-2-isopropenylbenzene	n/d	n/d	0.46
	1-methyl-4-isopropenylbenzene	0.73	1.03	0.29
	1-methyl-4-(1-methylethenyl)benzene	0.38	n/d	0.09
	1,2-diethylbenzene	0.79	n/d	0.33
6	1,2,3,4-tetramethylbenzene	n/d	1.09	0.79
7	1-methylindene	0.64	n/d	n/d
	2-phenylbutadiene	0.96	n/d	2.26
	1-methylphenyl ethanone	0.83	n/d	1.52
10	Azulene	0.54	n/d	1.03
	3-methyl-3-phenylbutene	n/d	n/d	n/d
11	1,2-dihydro-3-methyl naphthalene	n/d	0.75	0.12
	Biphenyl	0.61	n/d	1.27
	2-methylnaphthalene	3.77	0.80	2.95
12	1,3-Dimethylnaphthalene	1.83	0.96	0.36
13	1,7-Dimethylnaphthalene	2.10	1.44	0.25
14	Acenaphthalene	1.90	n/d	0.46
	Methyl ethyl naphthalene	0.67	n/d	0.27
	2,3,5-trimethylnaphthalene	2.49	1.31	0.22
	2,4-dihydroxy-3-6-dimethylbenzaldehyde	0.58	n/d	n/d
	Phenaptrene	n/d	n/d	0.23
15	Anthracene	1.30	n/d	0.07
	1,2-Benzenedicarboxylic acid, bis(2-methylpropyl) ester	3.37	2.07	0.24
	Pyrene	0.54	n/d	0.29
	1,2-benzacenaphthene	0.71	n/d	0.12
16	1,2-Benzenedicarboxylic acid, bis(2-ethylhexyl) ester	4.43	3.77	2.66

Pyrolysis of rubber gloves produces not only useful gases, char and chemicals, but also some byproducts like tar. Tar in the pyro-gas will condense at the temperatures lower than its dew point. In this study, the tar is an aggregate of fly ash and elutriated sand which eventually deposit at the plant installation and lead to blockage. The deposition is worse when the sand was repeatedly cycled and used in the plant as the sand particle became smaller due to attrition. The correlation between the sand density and the number of repeated runs is depicted in Figure 7.

In this study, the presence of tar is noted, but neither qualitative nor quantitative analysis of the tar is carried out. However, tar was not present in the bench scale study, where the pyrolysis environment was zero-oxygen. Thus, it is believed that the ingress oxygen from the atmospheric air into the Integral Test Plant during the pyrolysis process, has formed oxygenated compounds, which finally leads to the formation of oxygenated compounds that can be formed at the temperature

window of between 400 to 700°C (Milne *et al.*, 1998).

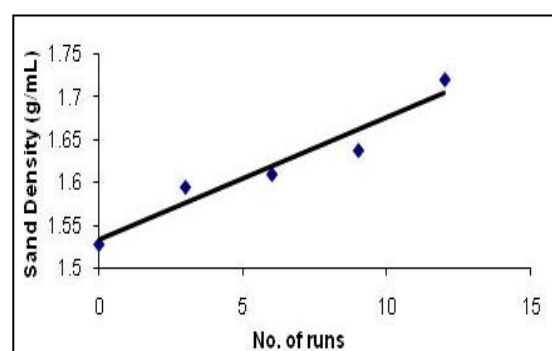


Figure 7 Changes in sand density with number of plant runs

This observation is inline with the literature whereby a pyrolysis of rubber gloves that was conducted in a fluidized bed at the temperature of 600°C, using steam as the fluidizing agent reported the tar content as much as 11% (Walter *et al.*, 2009). The aspect of tar removal in

the plant still remains as one of the most important technical challenges faced.

### 3.3.4 Water Yield

Naturally, water is formed as part of the thermo chemical reactions during pyrolysis. This is thought to be a result of dehydration of carbohydrates and possibly free radical reactions occurring with the hydrogen and oxygen in the high temperature pyrolysis environment (Ringer *et al.*, 2009). Ming *et al.* (1997) examined the effect of air factor in the oxidative pyrolysis of mixed waste and found that the water content increased with increasing air factor due to combustion reactions. In this study, the presence of water was observed at all the conditions studied at a significant amount, i.e at the range between 16% and 37%. This substantiates the fact that some degree of combustion is taking place in the reactor, due to the presence of the oxygen. The amount of water formed is almost doubled at 450°C, as thermodynamically, combustion is more favored at higher temperature. Table 4 depicts the amount of water formed during pyrolysis of rubber gloves in the Integral Test Plant.

Table 4 Amount of liquid produced from pyrolysis of rubber gloves at the Integral Test Plant

Operating Temperature (°C)	Oil Yield (%)	Maximum Water Collected (%)	Total Maximum Liquid Produced (%)
450	46.78	36.8	83.58
400	32.18	19.33	51.51
350	23.65	16.8	40.45

### 3.4 Gas Evolution Profiles

The gas produced from the pyrolysis of rubber gloves in the Fixed Bed Reactor comprised of methane, ethane, ethane, propene, propane, butane, butadiene, in addition to a small amount of hydrogen. Contrarily, pyrolysis of rubber gloves in the Integral Test Plant saw released of NO<sub>x</sub>, CO, CO<sub>2</sub>, SO<sub>2</sub>, and H<sub>2</sub>S.

NO<sub>x</sub> is observed as one of the tail gas compositions. It is important to note that the gas burner was switched off throughout the rubber gloves pyrolysis course. Therefore, the NO<sub>x</sub> observed in the tail gas is not attributed to the fuel NO<sub>x</sub> originated from the combustion of the LPG. It is primarily important to note that the environment in the pyrolyzer was at relatively low temperature for thermal NO<sub>x</sub> formation. On top of that, the reactor was under a fuel-rich conditions and the pyro-gas has a short residence time inside of the reactor. This environment promotes another mechanism which is known as prompt-NO<sub>x</sub> formation. As the rubber gloves pyrolyze, they generate radicals which combines with available atmospheric nitrogen to produce carbon radicals such as cyano (CN<sup>-</sup>). The thermodynamics of the reaction is

more favored at higher temperature, hence higher concentration of NO<sub>x</sub> was observed at 450°C rather than at 350°C as shown in Figure 8.

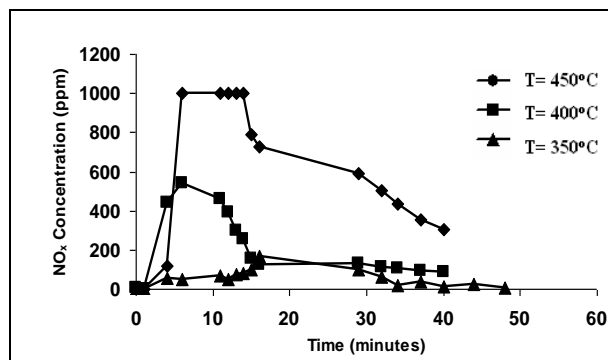


Figure 8 Profile of NO<sub>x</sub> evolved during pyrolysis of rubber gloves

In the pyrolysis process, CO and CO<sub>2</sub> are produced at 200°C (Kuznetsov, 2004). The CO formation is mainly attributed to the decomposition of oxygen-containing functional groups such as hydroxyl, ether and carbonyl at relatively lower temperatures while the decomposition of carboxylic acids and carboxyl group during the initial stage of pyrolysis may be the principal origin of CO<sub>2</sub> formation (Zhang *et al.*, 2010; Jahirul *et al.* 2007). The amount of CO during the rubber gloves pyrolysis was well above 6000 ppm, which was the detector limit. The amount of CO<sub>2</sub> produced from the study was 10% and 6% at 350°C and 400°C respectively, and increased to 13% when the bed temperature was raised to 450°C. Figure 9 shows the CO<sub>2</sub> evolution profile during pyrolysis of rubber gloves.

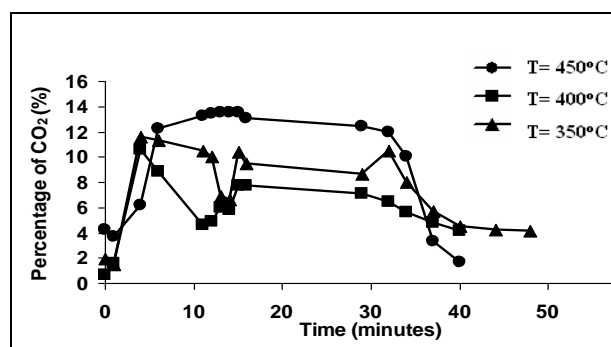


Figure 9 Profile of CO<sub>2</sub> evolved during pyrolysis of rubber gloves

Hydrogen was also detected in the tail-gas of this study. The production of H<sub>2</sub> is thought to be principally originated from the dehydrogenation (through the cleavage of C-H or O-H bond and from the secondary decomposition of their pyrolyzed products like chars, tars and hydrocarbon gases (Zhang *et al.*, 2010; Saidur *et al.* 2007). The sulfur used for vulcanization is formed into mainly hydrogen sulfide, methylthiophene and benzothiazol during pyrolysis (Walter *et al.*, 2009). In this study, SO<sub>2</sub> was detected in the tail-gas. The SO<sub>2</sub>

evolved in the first 15 minutes of the pyrolysis reaction and reached a maximum level of 500 ppm before it decreased gradually towards zero. The temperature of 350°C was found to be insufficient to pyrolyze the rubber gloves effectively, so does the formation of SO<sub>2</sub>, which was the lowest at this temperature. The H<sub>2</sub>S concentration was found to be above the limit of the analyzer detection limit, which was 2000 ppm. Besides these permanent gases, the tail gas also contained volatile hydrocarbons that were not perfectly condensed in the condenser. The composition of the hydrocarbons in the tail gas, as analyzed by GCMS, comprised of toluene, 1,2-dimethylcyclohexene, cyclohexanol, o-xylene, 1,2,3-trimethylbenzene, cyclohexane, tetradecane, hexadecane, heptadecane, dodecane, di-ethylbenzene, limonene and p-cymene.

#### 4. CONCLUSIONS

A compact and integrated test plant of 2 kg/hr capacity was constructed, employing indirect heating method. The newly developed plant has been found to be functioning and working satisfactorily and able to accomplish the objectives of the present work. The plant design is novel as it is energy efficient, easy maintenance yet compact. Due to the combined effect of imperfect sealing and suction effect, oxygen exists in the reactor, creating an oxidative pyrolysis environment. Under this condition, the oil yield and its composition has resulted in significant water formation and changes in the tail gas composition. The tail gas comprised of CO<sub>2</sub>, CO, SO<sub>2</sub>, H<sub>2</sub>S, NO<sub>x</sub> and other hydrocarbon gases. The dramatic increase in CO<sub>2</sub> indicates that some degree of combustion took place in the reactor particularly at high temperature of 450°C. The presence of oxygen also led to pronounce tar formation. This aggregate of fly ash and sand deposited at the wall and along the pipeline which ultimately led to clogging. In this study, the factors that affect the yield of the pyro-oil are established, which are the heat transfer rate, present of oxidizing agent, operating temperature and throughput size and efficiency of the condenser. Rubber gloves tend to produce sticky carbon residue, however, the formation of the sticky solid residue was eliminated in this study. The advantage of this system is that it produces dry and non-stick char thus making it easier to handle plus the energy in the char can be recovered. Another advantage of this system is that the bed temperature can be sustained without additional heating.

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