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Development of inherent safety assessment index for e-waste recycling process: flammability parameter

SYAZA IZYANNI Ahmad[1,2,a*], ENGKU SYIFA HAYANI Engku Saifuddin[1,b], MARDHATI Zainal Abidin[1,2,c], MUHAMMAD FIRDAUS Husin[3,d]

[1] Chemical Engineering Department, Universiti Teknologi PETRONAS, Perak, Malaysia

[2] Centre of Advanced Process Safety, Institute of Contaminant Management, Unversiti Teknologi PETRONAS, Perak, Malaysia

[3] School of Chemical Engineering, College of Engineering, Universiti Teknologi MARA, Cawangan Terengganu, Kampus Bukit Besi, Terengganu, Malaysia

[a]syaza.ahmad@utp.edu.my, [b] engku_21000527@utp.edu.my, [c]marhati.zainal@utp.edu.my, [d] firdaushusin@uitm.edu.my

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Abstract. Nowadays, the usage of electronic devices such as computers and mobile phones are crucial in the daily life especially with the growing internet usage globally. The worldwide e-waste production is anticipated to be around 20 to 25 million tonnes per year and is expected to rise through the decade. Increasing amount of e-waste will become a major concern due to its harmful impact to the environment as well as human health. Investigations on the impact of e-waste recycling process in terms of flammability parameter is currently lacking. The objective of this work is to develop an inherent safety assessment index focusing on the flammability parameters assessment of e-waste recycling process. The inherent safety assessment index developed focused on the flammability value of every chemical used in e-waste recycling process particularly the hydrometallurgy and pyrometallurgy processes. Logistic function was used in developing the scores for flammability evaluation of e-waste processes. In this scoring index, higher flammability score indicates higher hazard. A simple case study was conducted to compare the flammability level of two e-waste recycling process, namely Process A and Process B. Process B has higher Total Flammability Score than Process A indicating it as more hazardous due to the existence of hydrochloric acid and cyanide in the process than Process A with only hydrochloric acid as its flammable chemical in terms of flammability level. This indicates that the inherent safety assessment index produced can be used to conduct preliminary evaluation on the flammability level of chemicals involved in an e-waste recycling process particularly the hydrometallurgy and pyrometallurgy processes. However, to achieve a more comprehensive inherent safety assessment, this index needs to be equipped with several others inherent safety assessment parameters for example explosiveness and toxicity.

Introduction

Nowadays, the usage of electronic devices such as computers and mobile phones are crucial in the daily life especially with the growing internet usage globally. These devices after some time will reach their end-of-life and degrade into a complicated waste matter which are referred to as e-waste [1]. Every year, an estimated 20 to 25 million tons of e-waste are generated globally [2], and the volume of e-waste will continue to increase in tandem with technological improvements [3,4]. Globally, 44.7 million metric tonnes of e-waste were produced in 2016 [5], an astounding rise from 20 million tonnes per year in 2006 [4]. The worldwide e-waste production is anticipated to be around 20 to 25 million tonnes per year and is expected to rise through the decade. Increasing amount of e-waste will become a major concern due to its harmful impact to the environment as well as human health [6] if it is not properly managed. Human health is impacted by e-waste through food chain in which the toxic substances end up entering the food chain and direct impact to workers who work in the e-waste pre-treatment plant. The impact of e-waste towards human health has been discussed by various works for example in the assessment of carcinogenic risk involving heavy metals in e-waste [7], detection of copper and lead in scalp hair samples [8] and detection of PCBs in human milk samples [9]. However, investigations on the impact of e-waste recycling process in terms of flammability parameter is currently lacking. The objective of this work is to develop an inherent safety assessment index focusing on the flammability parameters assessment of e-waste recycling process. The scopes involved in this work are;

1. The inherent safety assessment developed focus on the flammability value of every chemical used in hydrometallurgy and pyrometallurgy processes.
2. Logistic function is used in scores assignment for each flammability value.

There are many e-waste processing methods exist for example pyrometallurgy, hydrometallurgy, centrifugal separation and vacuum pyrolysis also surface passivation. However, this work only focuses on assessing inherent safety parameter of hydrometallurgy and pyrometallurgy processes. In hydrometallurgy process, e-waste collected will be dissolved in the appropriate solvent or liquid for the extraction of valuable metals through leaching in acidic or alkaline medium. Then further refining the target metal which is extracting it from the solutions using its chemical properties, either through currents and voltage such as electrolytic cells or simply through precipitation [10]. Pyrometallurgical processes have been used for the processing of metals from various waste materials over the last two decades. Smelting in furnaces, incineration, combustion, and pyrolysis are common e-waste disposal techniques. State-of-the-art smelters and refineries can extract precious metals efficiently and of isolating hazardous substances. These recycling facilities would close the loop for precious metals and reduce the effects of large volumes of e-waste on the environment. E-waste recycling is dominated by pyrometallurgical paths, while the steel industry embraces ferrous fractions for iron recovery and the secondary aluminium industry takes over aluminium fractions. Pyrometallurgical processes work with steps of release, separation/upgrading and purification that are basically like those of mechanical or hydrometallurgical routes. However, the release of precious metals is achieved not by leaching, crushing, or grinding, but by smelting in furnaces at high temperatures. E-waste/copper/lead scrap is fed into a furnace in these pyrometallurgical processes, whereby metals are collected in a molten bath and a slag phase is formed by oxides [11].

Development of Flammability Scoring Index for E-Waste Recycling Process

i. Brief Description on Flammability Parameter

Heikkila [12] defines flammability as how easily a material burns in air. In this work, flash point of a liquid is used to measure the flammability of the chemicals involved in the e-waste recycling process. The flash point of a liquid refers to the lowest temperature at which the liquid emits sufficient vapour to form an ignitable mixture with air [13]. Thus, chemicals with lower flash points present greater hazard risks compared to chemicals with higher flash points. Similar flammability value was used in the Numerical Descriptive Inherent Safety Technique for inherent safety assessment of flammability parameter in petrochemical industry [14], Inherent Benign-ness Index (IBI) [15], and Prototype Index for Inherent Safety (PIIS) [16].

ii. Brief Description of Logistic Function

The flammability scoring for the proposed inherent safety assessment index is developed through the application of logistic function. Equation 1 shows the general equation of logistic function

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[17]. Equation 1 is supported by Equation 2 and 3. y variable in Equation 1 represents the flammability score for every flash point value, while x variable in Equation 1 indicates the flash point value to be evaluated. There are three main constants in Equation 1 namely C, B and A where C refers to the maximum score limit in which the y value will always be less than or equal to C. This feature of logistic function makes it suitable to be used in a scoring index. As an example, if the C value is set to 100, the maximum value for output y is 100. Equation 2 determines parameter B via the m value while Equation 3 determines parameter A via the k value.

$$y = \frac{C}{1 + Ae^{-Bx}} \quad (1)$$

$$B = \frac{4m}{C} \quad (2)$$

$$A = e^{Bk} \quad (3)$$

Research Methodology

a) Data Collection

Information on the types of chemicals used in hydrometallurgy and pyrometallurgy processes was conducted. Resources used from the available literatures such as journal papers and reports. Then, data on the flash point values for the chemicals identified were collected. Table 1 shows the chemicals identified in hydrometallurgy and pyrometallurgy processes along with their respected flash point.

Table 1 *Chemicals Involved in Hydrometallurgy and Pyrometallurgy Processes*

Chemicals	**Flash Point (°C)**
Carbon Monoxide	-191
Nickel	-25
Hexane	-22
Cyanide	-18
Acetone	-18
Thiourea	-9.3
Methanol	9
Lithium	18
Phosphorus	30
Acetic Acid	39
Hydrochloric Acid	48
Tri-N-Butyl Phosphate	145
Di-(2-ethylhexyl)phosphoric Acid	168.5
Ascorbic Acid	214.6
Raw and Modified Palm	250
Fructose	274.9
Sucrose	343.9
Zinc	680
Sodium Sulphide	950
Sodium Chloride	1413

b) Data Analysis

The data collected as shown in Table 1 was then divided into several range as shown in Table 2 and analyzed to identify the frequency and cumulative frequency of each range. Then, a cumulative curve of the flash point range versus cumulative frequency is plotted as shown in Figure 1. A linear trendline is plotted on the cumulative curve to identify its slope. According to Figure 1, the slope identified is 2.57. This value is used as the basis value in developing the flammability score using the logistic function in the next step.

Table 2 Frequency Analysis

Chemicals	**Flash Point (°C)**	**Flash Point Range (°C)**						
		< -50	**-49 to 0**	**1-50**	**51-100**	**101-150**	**151-200**	**>200**
Carbon Monoxide	-191	x						
Nickel	-25		x					
Hexane	-22		x					
Cyanide	-18		x					
Acetone	-18		x					
Thiourea	-9.3		x					
Methanol	9			x				
Lithium	18			x				
Phosphorus	30			x				
Acetic Acid	39			x				
Hydrochloric Acid	48			x				
Tri-N-Butyl Phosphate	145					x		
Di-(2-ethylhexyl) phosphoric Acid	168.5						x	
Ascorbic Acid	214.6							x
Raw and Modified Palm	250							x
Fructose	274.9							x
Sucrose	343.9							x
Zinc	680							x
Sodium Sulphide	950							x
Sodium Chloride	1413							x
Frequency		**1**	**5**	**5**	**0**	**1**	**1**	**7**
Cumulative Frequency		**2**	**7**	**12**	**12**	**13**	**14**	**21**

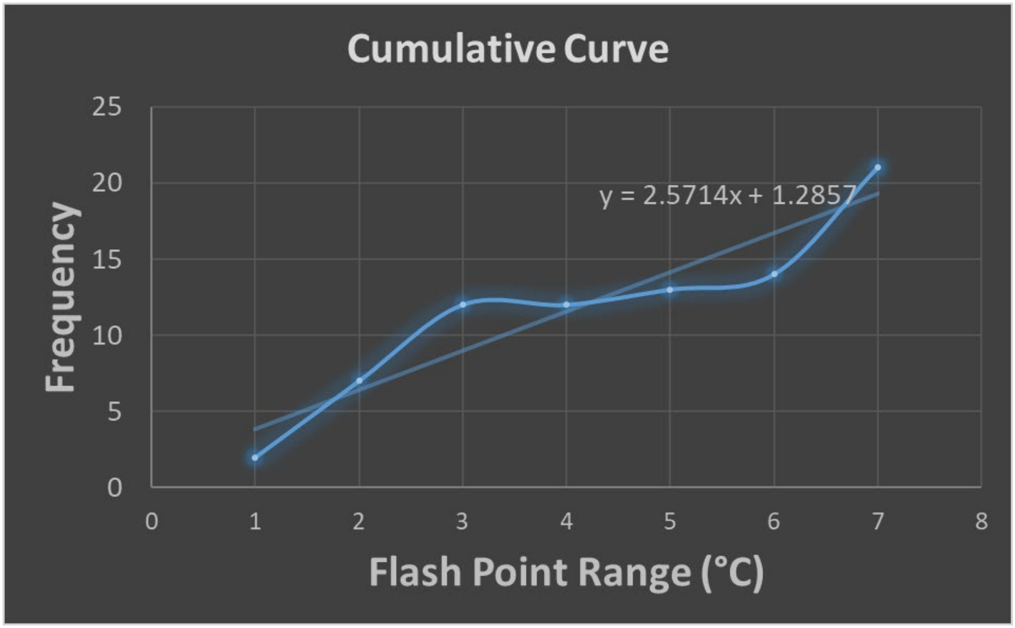

Figure 1 Cumulative Curve

c) Development of Flammability Scoring using Logistic Function

There are three values that need to be determined first before the logistic function as shown in Equation 1 can be used for score development. The first value is the C value which refers to the maximum score to be assigned in the logistic function. In this work, the C value is set as 100 indicating 100 as the highest score available for the flammability scoring index. The second value is the k-value which indicate the middle score of the scoring index. As 100 is the maximum score, 50 is taken as the k-value. The third value is the m value which can be used to determine coefficient B as shown in Equation 2. The slope value obtained from the cumulative curve in Figure 1 is used as the first m value to obtain coefficient B. After the B value was obtained, coefficient A value can be obtained using Equation 3 and lastly the final flammability score can be obtained using Equation 1. Equation 1 is used to produce a logistic curve, specific for flammability parameter of e-waste processing. The m value needs to be adjusted (either by reduction or addition, for this work the adjustment was done through reduction) so that a smooth logistic curve can be obtained as the final product.

Results and Discussion

Equation 4 shows the final logistic function developed while Figure 2 shows the final logistic curve developed for the flammability scoring of e-waste processing. In Equation 4, x_{FP} refers to the flash point of the chemical to be evaluated. If a user wanted to identify the flammability level of a chemical involved in e-waste processing, the user must insert the flash point value of the chemical into Equation 4 and can directly obtain its flammability score. This is similar to the approach taken by Ahmad et. al. [14] in the development of inherent safety assessment index for petrochemical processes. In addition, the user can also use the flammability score curve in Figure 2 to graphically obtain the score of the chemicals. Figure 2 can also be used in identifying the root-cause of flammability hazard in an e-waste recycling process as discussed by Ahmad et. al. [18]. In this scoring index, higher flammability score indicates higher hazard.

$$Flammability\ Score = 100 \times \frac{1}{1 + 2.7182e^{-0.02x_{FP}}} \quad (4)$$

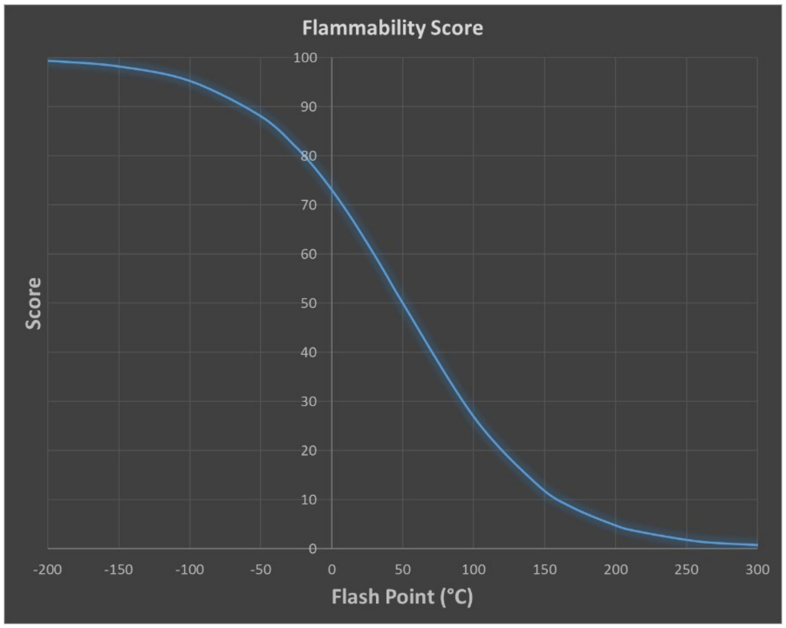

Figure 2 Logistic Curve for Flammability Scoring

If there are several chemicals involved in a process, the score for each chemical can be totalled up (Equation 5) to produce a score that can represented the whole process.

$$Total\ Flammability\ Score = \sum_i Flammability\ Score_i \tag{5}$$

Application of the Developed Index to a Case Study

A simple case study was conducted on two e-waste recycling process namely Process A and Process B to identify the flammability level of the chemicals involved in both processes. The purpose of the case study is to illustrate the usage of the scoring equation developed as shown in Equation 4. Process A involved four chemicals namely sulfuric acid, hydrogen peroxide, magnesium chloride, and hydrochloric acid while there are three chemicals involved in Process B which are nitric acid, hydrochloric acid, and cyanide. After identifying their flash point values, it was identified that sulfuric acid, hydrogen peroxide, and magnesium chloride in Process A while nitric acid in Process B are non-flammable which are assigned as having 0 flammability score. This is aligned with the score's assumption used in this scoring index in which higher flammability score indicates higher flammability hazard. The identified flash point values were inserted into Equation 4 to produce the flammability score for each chemical. Table 3 shows the chemicals involved in both processes as well as their flash point values and designated flammability scores.

Table 3 Chemicals involved in Process A and Process B

Process	Chemical Involved	Flash Point (°C)	Flammability Score
A	Sulfuric Acid	Non-flammable	0
	Hydrogen Peroxide	Non-flammable	0
	Magnesium Chloride	Non-flammable	0
	Hydrochloric Acid	48	51
B	Nitric Acid	Non-flammable	0
	Hydrochloric Acid	48	51
	Cyanide	-18	80

Individually, cyanide is deemed as the most hazardous in terms of flammability compared to the other chemicals used in Process A and Process B. Comparison can also be made between Process A and Process to identify which process possessed the most hazardous flammability level. This can be done by totalling the flammability scores using Equation 5. Table 4 shows the comparison between Process A and Process B in terms of their flammability level. According to Table 4, Process B has higher Total Flammability Score than Process A indicating it as more hazardous than Process A in terms of flammability level. Comparison of both processes indicates Process B as the most hazardous due to the existence of two flammable chemicals namely hydrochloric acid and cyanide.

Table 4 Comparison between Process A and Process B in terms of Flammability Level

Process	Chemical Involved	Flammability Score	Total Flammability Score
A	Sulfuric Acid	0	51
	Hydrogen Peroxide	0	
	Magnesium Chloride	0	
	Hydrochloric Acid	51	
B	Nitric Acid	0	131
	Hydrochloric Acid	51	
	Cyanide	80	

This inherent safety index developed specifically for flammability parameter needs to be equipped with several other inherent safety parameters, such as explosiveness, toxicity, and operating conditions, for a more comprehensive inherent safety evaluation. Furthermore, relationships between flash point and operating pressure of the process might also affect the inherent safety level of the process indicating its necessity for future investigations.

Conclusions

In conclusion, the inherent safety assessment index scoring equation produced can be used to conduct preliminary evaluation on the flammability level of chemicals involved in an e-waste recycling process particularly the hydrometallurgy and pyrometallurgy processes. Assessment on simple case study of two e-waste processing methods namely Process A and Process B were conducted. In process A, out of the four chemicals involved, hydrochloric acid is the most flammable represented by the highest flammability score of 51. Meanwhile, cyanide is identified as the most hazardous in Process B in terms of flammability parameter due to its highest score of 80. Comparison of both processes indicates Process B as the most hazardous due to the existence of two flammable chemicals namely hydrochloric acid and cyanide. However, to achieve a more comprehensive inherent safety assessment, this index needs to be equipped with several other inherent safety assessment parameters for example explosiveness and toxicity.

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