The Analysis of Fire and Explosion Risk at Chemical Material Warehouse of Rocket Technology Research Center, National Research and Innovation Agency

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Abstract— Chemical Material Warehouse at the Rocket Technology Research Center has various flammable and reactive chemicals. One of them is Ammonium Perchlorate, which, at the time of survey, amounts to 21.470.828 g. This condition pose fires and explosions hazard to the chemical material warehouse. To control the risk of fire and explosion hazards in the Chemical Material Warehouse, a fire and explosion risk assessment method is carried out to reduce maximum losses in the event of such hazards. The research methods used are Hazard Identification, Risk Assessment, and Determining Control (HIRADC) and the Dow's Fire and Explosion Index (F&EI). The results showed four main activities in the Chemical material warehouse with potential risks with 19 low-risk levels and two medium risk levels. After Implementing the HIRADC method and the hierarchy of risk control with the design, administrative, and use of PPE, the level of risk improved from initially medium risk level to all low levels. According to the results of the Dow's Fire and Explosion Index method, the value of the potential risk of fire and explosion in the Chemical material warehouse of the Rocket Technology Research Center was 122.14. This result was classified as an intermediate hazard level with a radius of exposure in the event of a fire being 31.26 m. The damage factor to be received by the Chemical Raw Materials Warehouse was 79%. To obtain comprehensive measures in the potential for fire and explosion hazards in the Chemical Raw Material Warehouse of the Rocket Technology Research Center, it is recommended that -i.e. HIRADC and Dow's Fire and Explosion Index are used.

Keywords— Fire and Explosion Risk, Chemical material warehouse, HIRADC, Dow's Fire and Explosion Index.

I. INTRODUCTION

The Chemical Materials Warehouse at the Rocket Technology Research Center, National Research and Innovation Agency functions as a storage area for chemicals raw materials used to manufacture propellants as rocket fuel. There are 40 types of chemical raw materials are classified as flammable and reactive chemicals.

In this condition, of course, the Chemical Raw Material Warehouse has a high potential to cause a significant hazard because it contains flammable, reactive, and toxic chemicals. Significant Hazards generally consist of fires, explosions, and chemical leaks. Fire is the most worrying hazard and has the highest frequency of occurrence compared to other significant hazards [1].

Fire disasters can have a huge impact and a very high level of loss, such as material and loss of life, to disrupt the ongoing propellant research process. To ensure safe storage of chemicals the facility must be temperature and humidity controlled. In addition, storage facilities must provide a grounding system. Lightning strike protection is something that must be available. A minimum of two serviceable fire extinguishers, suitable for the hazards involved, shall be provided for immediate use at any location where explosives are being handled. Finally, the total amount of the chemical must not exceed the amount certified by the storage facility [2][3].

Therefore, to control the risk of fire and explosion hazards in the Chemical material warehouse, a fire and explosion risk assessment method is carried out to provide guidance in reducing losses if such hazards happen. In this research used a combination of methods between Hazard Identification, Risk Assessment, and Determining Control (HIRADC) and the Dow's Fire and Explosion Index (F&EI) are used.

II. METHOD

The research object is the chemical material warehouse located at the Rocket Technology Research Center, National Research and Innovation Agency, in the Rumpin, Bogor Regency. The research was carried out from September to December 2021.

The HIRADC method was a method for identifying potential hazards, determining the level of risk [4], and determining the control hierarchy. Meanwhile, Dow's F&EI method was a method that measured the potential risk of fire and explosion hazards [5].

In the Chemical Raw Materials Warehouse, there are 40 types of hazardous chemicals. Ammonium Perchlorate (AP) being one of the research object referring to requirements on the Dow’s Fire and Explosion Index. The requirements the Dow's Fire and Explosion Index that the minimum amount of chemical is 5000 lb (2268 kg), or about 600 gal (2.27 m3) of the substance. Flammable or reactive [5] whereas the amount of AP contained in the Chemical Raw Materials Warehouse reached 21,470,828 grams or 47335.073 lb, and AP was a flammable chemical.

This research used the HIRADC method to identify hazards and risk mapping in activities in the Raw Material Warehouse. The HIRADC method was conducted by interviewing the person in charge of the warehouse to support a related literature review. Meanwhile, Dow's F&EI method was to calculate the potential risk of explosion and fire that could occur in Chemical material warehouses because this method could assess the level of danger and the area affected by fire and explosion impacts.

The data collected was re-examined to ensure its completeness and consistency to maintain the validity and reliability of the data. Next, the data was entered into the Fire and Explosion Index form for calculations under the instructions contained in the Dow's F&EI Guidelines. Calculations are done manually and by using Microsoft Excel software. After that, the implementation of a risk control hierarchy was carried out to minimize existing risks.

This research used primary data and secondary data. The primary data consisted of:

1. Fire protection system installed at the research site.
2. Potential risks could occur in the Chemical material warehouse, especially in the AP storage section.
3. Observation of the conditions of the chemical storage area.

Meanwhile, secondary data included:

1. Safety Data Sheet AP.
2. Chemical material warehouse building layout.

III. RESULTS AND DISCUSSION

1. Initial Hazard Identification and Risk Mapping

Hazard identification was carried out directly by observing the Chemical material warehouse and interviews with the Chemical material warehouse. Identifying general activities that occurred in the Chemical material warehouse, then identifying the risks that could occur.

After the risks were obtained, the source or cause of the risk could occur, and the consequences could be accepted.

Table 1: *Identification of Potential Hazards*

No	Activity	Hazard	Source/ Cause	Consequence
1	Receipt of Chemical Goods	Unavailability of Safety Data Sheet Documents	Lack of understanding of chemical hazards by operators	Delay in handling response when exposed to chemicals
		Exposure to Harmful Chemicals to Breathing (Inhalation)	Not using the right PPE, not doing the correct procedure	Respiratory disorders
		Topical (Physical) Exposure to Hazardous Chemicals	Not using the right PPE, not doing the correct procedure	Skin Irritation
		Chemical Data Incompatibility	Documentation of chemicals is not done carefully and appropriately	Material inventory data does not match when audited by the inspectorate / BPK
2	Chemical Storage and Placement Process	Exposure to Harmful Chemicals to Breathing (Inhalation)	Not using the right PPE, not doing the correct procedure	Respiratory disorders
		Topical (Physical) Exposure to Hazardous Chemicals	Not using the right PPE, not doing the correct procedure	Skin Irritation

		Hit by a Forklift	Less Width Between Chemical Racks for Forklifts to Move	Minor Injury, Serious Injury
		Chemical Spill	Human Error, the chemical container is not tightly closed	Physical Loss, Material Loss
		fall	Human Error, Falling from a High Place	Minor Injury, Serious Injury
3	Chemical extraction process	Exposure to Harmful Chemicals to Breathing (Inhalation)	Not using the right PPE, not doing the correct procedure	Respiratory disorders
		Topical (Physical) Exposure to Hazardous Chemicals	Not using the right PPE, not doing the correct procedure	Skin Irritation
		Hit by a Forklift	Less Width Between Chemical Racks for Forklifts to Move	Minor Injury, Serious Injury
		Room Temperature Increase	Lack of Air Conditioning, Lack of Air Circulation	Humidity Drops, Fires
		Chemical Spill	Human Error, the chemical container is not tightly closed	Physical Loss, Material Loss
		Water-Mixed Chemicals	There are drops of water on the Exhaust Fan when it rains	Material Losses
4	Chemical material warehouse Maintenance	Fire	Sabotage, Terrorism, Lights in Warehouses Not Explosion Proof, Lightning Strikes	Physical Loss, Material Loss
		Lightning Strike	No Grounding System	Fire
		Sting or Bitten by Dangerous and Venomous Animals	Not using the right PPE, Human Error	Minor Injury, Serious Injury
		Dusty	The Dust in the Warehouse	Eye Irritation, Skin Irritation, Respiratory Disorders
		Falling	Human Error, Falling from a High Place	Minor Injury, Serious Injury
		Environmental Temperature Rises around Chemical Warehouse	Natural Activity	Physical Loss, Material Loss, Fire

After obtaining the data on identifying potential hazards, it was necessary to pay attention to the controls carried out to determine how to handle them if these risks occurred.
The risk value multiplied the probability score and the severity impact score experienced. In determining the level of risk based on equation [6]:
R (Risk) = P (Probability) x S (Severity)

In the process of assessing the level of risk, a matrix would be made to input the risk value that had been obtained. The matrix was an analysis that aimed to provide a level of risk for the risk that would occur with High, Medium, and Low levels [7].

After knowing the consequence value and probability value, it could be inputted into the matrix to relate the consequence and probability value.

In determining the initial risk level, it was carried out on the existing available control conditions or control efforts at the Chemical material warehouse from the beginning.

Table 2: *Matrix of Probability and Severity of Risk*

Severity (S)	**Frequency / *Probability* (P)**				
	Very rare (once in more than one year)	Rarely occurs (can happen once in one year)/ Less likely to happen	Occasional (more than once every year)/ Might happen	Often occurs almost every month	Very often happens several times every month
	A	**B**	**C**	**D**	**E**
1. Minor	**A1**	**B1**	**C1**	**D1**	**E1**
2. Medium	**A2**	**B2**	**C2**	**D2**	**E2**
3. Serious	**A3**	**B3**	**C3**	**D3**	**E3**
4. Major	**A4**	**B4**	**C4**	**D4**	**E4**
5. Catastrophic	**A5**	**B5**	**C5**	**D5**	**E5**

Table 3: *Initial Risk Level Assessment*

Existing Controls	**INITIAL LEVEL OF RISK**			
	P	S	Risk Value	TR
There was a Material Safety Card	D	1	D1	Low
Use of PPE, OHS Signs, SOPs	B	1	B1	Low
Use of PPE, OHS Signs, SOPs	B	1	B1	Low
Minutes of Handover (BAST), Material Card, and Material Request or Retrieval Form	B	1	B1	Low
Use of PPE, OHS Signs, SOPs	B	1	B1	Low
Use of PPE, OHS Signs, SOPs	B	1	B1	Low
OHS Signs	B	1	B1	Low
Periodic Inspection of Warehouse Conditions, Coating Anti-Corrosion Coatings on Storage Drums, and Use of Spill Kits	C	1	C1	Low
Use of PPE, SOPs for Room Cleaning	B	3	B3	Low
Use of PPE, OHS Signs, SOPs	B	1	B1	Low
Use of PPE, OHS Signs, SOPs	B	1	B1	Low
OHS Signs	B	1	B1	Low
Use of Thermohygrometer, Use of Air Conditioning (AC)	D	1	D1	Low
Periodic Inspection of Warehouse Conditions, Coating Anti-Corrosion Coatings on Storage Drums, and Use of Spill Kits	C	1	C1	Low
Plastic Covered Chemicals	B	1	B1	Low
Light Fire Extinguisher (APAR), Emergency Response Training	A	5	A5	Medium
There is a lightning rod	B	4	B4	Medium
SOP for Emergency Response, Emergency Response Training	A	3	A3	Low
Use of PPE, SOPs for Room Cleaning	B	1	B1	Low
Use of PPE, SOPs for Room Cleaning	B	3	B3	Low
Use of Air Conditioning (AC)	B	1	B1	Low

2. Fire Risk Assessment

Determination of the Fire and Explosion Index Values

Based on the Dow's Fire and Explosion Index Guidelines, the steps for assessing the potential for fire and explosion hazards started from selecting the processing unit, determining the Material Factor (MF), determining F3 by calculating F1 and F2, and determining F&EI [5].

MF is a value that describes the potential energy released during fires and explosions resulting from combustion or other chemical reactions. MF is obtained from NF and NR, which describe the value of flammability and reactivity, respectively.

According to the Safety Data Sheet (SDS) of Ammonium Perchlorate [9], the specifications for Ammonium Perchlorate (AP) are as follows:

- Healthy Value (NH) : 2
- Flammability Value (NF) : 1
- Reactivity Value (NR) : 4
- Density : 1.95 kg/cm3

Based on Dow's F&EI guidelines, it was found that the Material Factor (MF) value on the AP was 40. Then, this research calculated the F1 value (General Process Hazard Unit Factor) and F2 value (Special Process Hazards Factor). These two values were essential factors that could trigger a potential fire. These values were given sanctions to the factors listed in the Dows' F&EI. The awarding of the penalty value was carried out jointly with the party responsible for the Chemical material warehouse by direct observation and joint discussion.

After obtaining the F1 and F2 values, the F3 value (Process Unit Hazards Factor) could be calculated further to calculate the potential for fire and explosion value.

Table 4: *Fire & Explosion Index*

MF		**16**
General Process Hazard (F1)	*Penalty Range*	Penalty
Base factor	*1.00*	1
Exothermic Reaction	*0.30 to 1.25*	0.3
Endothermic Reaction	*0.20 to 0.40*	0
Material Handling and Transfer	*0.25 to 1.05*	0
Enclosed or Indoor Process Unit	*0.00 to 0.90*	0.25
Access	*0.20 to 0.35*	0
Drainage and Spill Control	*0.25 to 0.50*	0
F1………………………………………………		1.55
Special Process Hazard (F2)		
Base Factor	*1.00*	1
Toxic Material	*0.20 to 0.80*	0.4
Sub-Atmospheric Pressure	*0.50*	0
Operation In or Near Flammable Range		0
Dust Explosion	*0.25 to 2.00*	0.25
Pressure		0
Low Temperature	*0.20 to 0.30*	0
Quantity of Flammable/Unstable Material:		0.12
Corrosion and Erosion	*0.10 to 0.75*	0.2
Leakage - Joints and Packing	*0.10 to 1.50*	0
Use of Fired Equipment		0
Hot Oil Heat Exchange System	*0.15 to 1.15*	0
Rotating Equipment	*0.50*	0
F2……………………………………………….		1.97
Process Unit Hazards Factor (F1 x F2) = F3		3.0535
Fire and Explosion Index (F3 x MF = F&EI)		122.14

F1 was the main factor that played a role in determining the number of losses due to the incident. It can be seen in Table 4 that the value of F1 was 1.55. This value was obtained from the sum of all penalty values for each item in general process hazard and the penalty from the primary factor (1.00), as follows:

a. Exothermic Reaction

A penalty of 0.30 was given because there was a mildly exothermic reaction, namely a neutralization reaction as a reaction between an acid and a base to produce a salt and water or a base and alcohol.

b. Endothermic Reaction

No penalty was awarded (0.00) for there was no such reaction.

c. Material Handling and Transfer

There was no penalty given (0.00) because no qualifications matched the field conditions at the Chemical Raw Materials Warehouse.

d. Enclosed or Indoor Process Unit

Given a penalty of 0.25 because the Chemical material warehouse was a closed room with a roofed area with four closed sides.

e. Access

No penalty was given (0.00) because the Chemical material warehouse has three doors for access in and out.

f. Drainage and Spill Control

There was no penalty given (0.00) because, according to Dow's F&EI guidelines, this penalty was applied to materials processed above the flashpoint. At the same time, in the Chemical Raw Materials Warehouse, the AP was stored, and no process put the AP at a temperature flash point or more.

F2 was a factor that could increase the likelihood of a potential event. From Table 4, it can be seen that the F2 value was 1.97. This value was obtained from the sum of all the penalty values for each item in a particular process hazard and the penalty from the primary factor (1.00), as follows:

a. Toxic Material

The NH value for AP was 2. The penalty was determined using the formula:

Penalty = 0.20 x NH.

Material = 0.20 x 2 = 0.40

Then, the penalty value was 0.40

b. Sub-Atmospheric Pressure

There was no penalty given (0.00) because in the Chemical material warehouse, the conditions that occurred at atmospheric pressure, 1 atm.

c. Operation In or Near Flammable Range

No penalty was given (0.00) because the Chemical material warehouse did not have characteristics that comply with Dow's F&EI guidelines.

d. Dust Explosion

Given a penalty of 0.25 because the size of the AP contained in the Chemical material warehouse was various microns, from 50 µ - 200 µ. In this penalty, it was decided to use the most significant size owned by the Chemical Raw Materials Warehouse, 200 µ. It was because AP 200 µ dominated in the Chemical Raw Materials Warehouse.

e. Pressure

No penalty was given (0.00) because the measured AP chemical was in the form of dust.

f. Low Temperature

No penalty was given (0.00) because the penalty applied only if the unit process operating temperature was at or below 50ºF or 10ºC, while in the Chemical Raw Materials Warehouse, the applicable temperature was above or according to the average ambient temperature.

g. Flammable or Unstable Material Quantity

The penalty awarded was 0.12. The value was obtained through the following calculations:

Energy Value (Hc) AP = 5.24 KJ/g = 2252.79 Btu/lb

Mass (M) AP = 21,470,878 g = 47,335.0731 lb

Total Energy = 47,335.0731 lb x 2252.79 BTU/lb

= 106,635,979.32 BTU

= 0.106 x 109 BTU

In BTU = 0.106

Ammonium Perchlorate (AP) was a chemical in the form of dust. AP had a density of 1.95 kg/cm3. Therefore, the equation used was curve B for materials whose density was > 10lb/ft3 or 160 kg/m3 according to Dow's fire and explosion index guidelines.

a. Corrosion and Erosion

The penalty was 0.20 because the AP storage container in a drum was coated with a coating layer to minimize the corrosion rate or prevent corrosion.

b. Leakage - Joints and Packing

There was no penalty given (0.00) because, in this section, there was no possibility of experiencing a leak according to the leak category.

c. Use of Fired Equipment

No penalty was given (0.00) because there was no use of incendiary devices.

d. Hot Oil Heat Exchange System

No penalty was given (0.00) because there was no oil exchange system at the Chemical Raw Materials Warehouse.

e. Rotating Equipment

No penalty was given (0.00) because there was no rotating equipment in the Chemical Raw Materials Warehouse.

F3 was a measure of the degree of hazard exposure of the processing unit with a value range of 1 – 8. F3 was obtained from the F1 and F2 products. Based on Table 4, it can be seen that the F3 value was 3.0535.

F&EI described the potential hazards in the processing unit that could be categorized based on the danger level. F&EI was obtained from F3 and MF products.

Table 5: *Relationship of F&EI and Hazard Level*

DEGREE OF HAZARD FOR F&EI	
F&EI INDEX RANGE	DEGREE OF HAZARD
1 – 60	Light
61 – 96	Moderate
97 – 127	Intermediate
128 – 158	Heavy
159 – up	Severe

Source: [5]

Based on Table 4, it can be seen that the F&EI value was 122.14. Based on the Dow's F&EI Guidelines, it can be seen in Table 5 that the potential for fire and explosion was classified as an intermediate hazard level.

1. Exposure Radius Rating

The exposure radius was the radius affected in the event of fire and explosion. The exposure radius value could be obtained by the equation:

Exposure Radius (R) ft = F&EI values x 0.84

$$= 122.14 \times 0.84$$

$$= 102.59 \text{ ft} = 31.26 \text{ m}$$

Determination of Damage Factor

The material factor (MF) in this research was 40 and the F3 value was 3.0535. Therefore, the equation used for an MF of 40 was as follows:

$$Y = 0.554175 + 0.080772 (X) + 0.000332 (X2) - 0.00044(X3)$$

$$Y = 0.554175 + 0.080772(3.0535) + 0.000332(3.05352) - 0.00044(3.05353)$$

$$Y = 0.79 = 79\%$$

Thus, the damage factor value was 79%.

2. Risk Mapping After Control

After increasing or changing the existing risk control, a risk assessment would be carried out again. It was the mapping of the residual risk level. It was done to see the results of changes in the risk level value contained in the Chemical material warehouse.

Table 6: *Assessment of Residual Risk Level*

ADDITIONAL CONTROLS	RESIDUAL RISK LEVEL			
	P	S	Risk Value	TR
Availability of SOP for Goods Procurement and SOP for handling Chemicals	C	1	C1	Low
Work Accident Handling Training	A	1	A1	Low
Work Accident Handling Training	A	1	A1	Low
Socialization of PJ Inventory Materials for Each Lab	A	1	B1	Low
Work Accident Handling Training	A	1	A1	Low
Work Accident Handling Training	A	1	A1	Low
Replacing Forklifts with Hand Strackers	A	1	A1	Low
Addition of an Additional Compartment to Accommodate Spills	B	1	B1	Low
Work Accident Handling Training	B	2	B2	Low
Work Accident Handling Training	A	1	A1	Low
Work Accident Handling Training	A	1	A1	Low
Replacing Forklifts with Hand Strackers	A	1	B1	Low
Addition of Air Conditioning Units	C	1	C1	Low
Addition of an Additional Compartment to Accommodate Spills	B	1	B1	Low
Special Plastic Box for Chemicals Packed in Paper Sacks	A	1	B1	Low
Use of Smoke Detectors, Heat Detectors, and Gas Detectors, as well as Fire Alarms	A	4	A4	Low
Use of Grounding System	A	4	A4	Low
Work Accident Handling Training (P3K)	A	2	A2	Low
Periodic Warehouse Cleaning, Periodic Inspection by 5R Team	A	1	A1	Low
Work Accident Handling Training	B	2	B2	Low
Addition of Air Conditioning Units	A	1	A1	Low

3. Determination of the Risk Control Hierarchy

The next stage was determining the hierarchy of risk control. It was carried out by following the hierarchical control approach to control risk [10]. The risk control hierarchy was a hierarchy that was carried out sequentially until the level of risk/hazard decreased to a safe point. The control hierarchy included elimination, substitution, design, administration, and personal protective equipment (PPE) [11].

The following was the hierarchy of risk control at the Chemical material warehouse, as follows:

Table 7: *Determination of Control / Mitigation*

CONTROL ESTABLISHMENT/ MITIGATION
SOP for Procurement of Goods, SOP for Handling Chemicals
IK General Safety, SOP for Handling Chemicals
IK General Safety, SOP for Handling Chemicals
SOP for Procurement of Goods, SOP for Handling Chemicals
IK General Safety, SOP for Handling Chemicals
IK General Safety, SOP for Handling Chemicals
IK General Safety, SOP for Handling Chemicals
IK for Handling Chemical Spills, and Gas Leaks, Use of Secondary Containment
IK General Safety, SOP for Handling Chemicals
IK General Safety, SOP for Handling Chemicals
IK General Safety, SOP for Handling Chemicals
IK General Safety, SOP for Handling Chemicals
IK General Safety, SOP for Handling Chemicals, Addition of Air Conditioning
IK for Handling Chemical Spills, and Gas Leaks, SOP for Handling Chemicals
IK General Safety, SOP for Handling Chemicals, and SOP for the Transfer and Storage of B3
IK General Safety, SOP for Handling Chemicals, Use of Gas, Heat, and Fire Alarm Detection Systems
IK General Safety, SOP for Handling Chemicals, Use of Grounding System
IK General Safety, IK Handling of Venomous Snakebites
IK General Safety, SOP for Handling Chemicals
IK General Safety, SOP for Handling Chemicals
IK General Safety, SOP for Handling Chemicals, Addition of Air Conditioning

IV. CONCLUSION

According to research results, it was concluded that there were four main activities in the Chemical material warehouse that had potential hazards with 19 low-risk levels and two medium-risk levels.

The implementation of the HIRADC method and the hierarchy of risk control led to the design, administrative interventions, and the use of PPE. As results, there is a change in the level of risk from initially having a medium risk level to all low levels.

Based on the results of calculations using the Dow's Fire and Explosion Index method, it was found that the potential risk of fire and explosion value in the Chemical material warehouse of the Rocket Technology Research Center was 122.14. This result was classified as an intermediate hazard level with a radius of exposure in the event of a fire being 31.26 m. The damage factor to be received by the Chemical Raw Materials Warehouse was 79%.

The combination of the two methods, i.e. HIRADC and the Dow's Fire and Explosion Index in measuring the potential for fire and explosion hazards in the Chemical Material Warehouse of the Rocket Technology Research Center have shown to be comprehensive. Therefore, it is recommended that such method to be used in such research facilities.

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REFERENCES

[1] Lestari, R. A., & Oginawati, K. (2016). Analisis Potensi Ledakan dan Kebakaran Primary Reformer sebagai Unit Proses Produksi Amonia di PT. X. Jurnal Rekayasa Kimia dan Lingkungan Vol. 11, No. 2, 72-81.

[2] Manha, W. D. (2009). Propellant systems safety. In Safety Design for Space Systems (1st ed.). Elsevier Ltd. https://doi.org/10.1016/B978-0-7506-8580-1.00020-8.

[3] NASA. (2010). Safety Standard for Explosives, Propellants, and Pyrotechnics NASA-STD-8719.12A.

[4] Pramadi, M. I., Suprapto, H., & Yanti, R. R. (2020). Pencegahan Kecelakaan Kerja Dengan Metode Hiradc Di Perusahaan Fabrikasi Dan Machining. Jurnal Terapan Teknik Industri, 98-108.

[5] Engineers, A. I. (1994). Dow's Fire & Explosion Index Hazard Classification Guide Seventh Edition. New York: the American Institute of Chemical Engineers.

[6] Sopiah, Y., & Salimah, A. (2020). Analisis Dan Respon Risiko Pada Proyek Konstruksi Gedung. Construction and Material Journal.

[7] Leondro, W. (2017). Analisa Faktor Risiko Terhadap Biaya dan Waktu Pelaksanaan dengan Metode Severity Index (Studi Kasus Proyek Mall TOP 100 Penuin - Batam). Universitas Internasional Batam.

[8] LAPAN. (2021). HIRADC PR Tekroket. Bogor: PR Tekroket.

[9] Sciencelab. (n.d.). Material Safety Data Sheet Ammonium perchlorate MSDS. ScienceLab.

[10] Ramadhan, F. (2017). Analisis Kesehatan dan Keselamatan Kerja (K3) Menggunakan Metode Hazard Identification Risk Assessment and Risk Control (HIRARC). Seminar Nasional Riset Terapan.

[11] Adzim, H. I. (2021). Hierarki Pengendalian Risiko/Bahaya K3.