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INTEGRATION OF SAFETY ANALYSIS USING HAZOPS AND FTA ON PRECIPITATION PROCESS IN URANIUM REFINING AND CONVERSION FACILITY

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ABSTRACT
INTEGRATION OF SAFETY ANALYSIS USING HAZOPS AND FTA ON PRECIPITATION PROCESS IN URANIUM REFINING AND CONVERSION FACILITY. The safety in nuclear facilities must be implemented as well as possible. This is related to particular with operators who carry out the process directly. In the uranium refining and conversion facility, safety analysis by using HIRADC has been implemented to support safety in carrying out the process, especially in the uranyl nitrate precipitation process. However, this is not enough to ensure for maintaining of the safety during the precipitation process at the uranium refining and conversion facility as complement the existing HIRADC, hence another safety analysis is needed, such as HAZOPS and FTA. The HAZOPS will complement the safety side of the facility by using an indicator control system that will automatically eliminate the risk of hazards that occur during the operation of the facility. Meanwhile, the FTA will analyse the causes of failure that can cause accidents, hence the causal factors of the accident can be identified. The results of the HAZOPS shows that it was found 1 potential hazard in low risk category, and 11 potential hazards in medium risk category. Meanwhile, the results of the FTA was obtained 15 events that cause product failure in the precipitation tank. The results of the safety analysis that has been carried out, it can be concluded that both HAZOPS and FTA can be used as complement to the HIRADC for maintaining safety during the process.

Keywords: Uranium refining and conversion facility, precipitation, HIRADC, HAZOPS, FTA.

INTRODUCTION

The uranium refining and conversion facility are one of the facilities for refining and conversion process from yellow cake raw materials to nuclear-grade UO_2 powder with a production capacity of 100 kg of UO_2 powder per day (design capacity). The uranium refining and conversion facility consist of several main processes such as dissolution, purification, evaporation, precipitation, drying, calcination and reduction. All processes in the uranium refining plant have potential accident and radiological hazards that can affect operators and the environment around the facility. The radiological hazard that may occur in the facility, such as inhalation, ingestion, or absorption through the skin of the nuclear material into the body. This is dangerous because yellow cake nuclear material emits alpha radiation which can be an internal transmitter in the human body. The radioactive material undergoing decay into stable isotopes will continue to irradiate body tissues until eventually being released through faeces and urine [1]. Accidents can occur due to equipment failure or human error. Accidents in nuclear facilities will be more severe due to radiological hazards. There are several cases of nuclear facility accidents due to misoperation, such as the accident at Forsmark, Sweden, in 2006 in which safety function was failure, resulting failure of the emergency power supply system in the nuclear power plant. The worst accident occurred in Chernobyl Nuclear Power Plant, Ukraine, in 1986 in which reactor number four exploded, resulting in a fire and a large leak of radioactive substances [2]. Nuclear accident in Tokaimura (a small fuel preparation plant operated by Japan Nuclear Fuel Conversion Co) in 1999, three people were seriously exposed to radiation and two people died. In addition, 667 public members were exposed. The accident occurred in a uranium deposition tank and was caused by the operator's lack of knowledge of the process [3].

For maintaining safety in the implementation of processes in nuclear facilities, the need of the safety analysis is to support safety for both operators and the environment. Uranium refining and conversion facilities in Indonesia have currently implemented safety analysis by using Hazard Identification, Risk Assessment, and Determining Control (HIRADC). The HIRADC method has several advantages, including an assessment of the combination of likelihood, severity, and control measures taken, and the risk analysis extends to safety in the office area. In addition, the use of the HIRADC method in the process stage of a equipments and risk analysis is easier to understand. However, HIRADC has several disadvatages, including a lack of focus in analyzing risks in one equipments or process. The data is not comprehensive because the analysis is only in the process stage and cannot be used to make recommendations for modifications in a process that involves the equipments control system. Consequently, it is necessary to complement the existing references. ~~So~~ In this research, risk analysis will be carried out using other methods to be integrated with HIRADC in maintaining process safety, namely Hazard and Operability Studies (HAZOPS) and Fault Tree Analysis (FTA). HAZOPS is a standard hazard analysis technique used in preparation for safety determinations in a new or modified system to identify potential hazards or operability problems of the system that can occur when the plant is in start-up, normal, or shut-down conditions [4]. The HAZOPS method also does not require large costs, is a systematic and comprehensive method, and is easy to use, simpler, and more intuitive [5]. Meanwhile, FTA is a technique for identifying and analyzing factors that may contribute to certain undesirable events (called "main or key events"). FTA is a top-down method used to map the relationship between events such as sub-system failures and their causes [6]. Causal effects are identified deductively, organized logically, and shown using a tree diagram depicting the causal factors and their logical relationships with respect to the main event [7].

The HAZOPS method is one of the most commonly used Process Hazard Analysis (PHA) methods to identify hazards and is viewed by many practitioners as the most thorough and complete method because it is not only analyzing the hazards of a system but also its operability issues by analyzing any effects of deviations from design conditions [8]. It is also designated as an acceptable PHA method by regulations worldwide, such as the Occupational Health and Safety Assessment Series (OHSAS's) and Process Safety Management (PSM) standards [9]. Likewise, the FTA method is also effective in finding the core of the problem because it ensures that an undesirable event or loss does not originate at

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a single point of failure. FTA identifies the relationship between causal factors and is displayed in the form of a fault tree involving simple logic gates.

The integration between HAZOPS and FTA has been done several times. FTA is used to investigate failure modes and failure mechanisms (represented as basic events) by assigning consequences or hazards from HAZOPS to the top event in the FTA diagram [10]. Some examples of the application of integration between HAZOPS and FTA are research conducted by Cozzani et al. [11] by developing a specific methodological approach to analyze the risk of hazardous materials in stacking sites; by Casamirra et al. [12] by integrating HAZOPS, FTA, and Failure Mode and Effects Analysis (FMEA) to assess the safety of hydrogen refueling stations; and by Kim et al. [13] by combining HAZOPS and FTA to conduct a safety assessment of hydrogen refueling stations in Korea. Barques et al. [7] analyzed the chemical and petroleum product loading and unloading terminals and fuel storage facilities of two companies in the port of Valencia (Spain). HAZOPS showed that the loading and unloading area was the most sensitive area in the plant, and the most significant hazard was fuel spillage. The FTA analysis showed that the most likely event was a fuel spillage in the tank truck loading area. Sensitivity analysis of the FTA results showed the importance of human factors in all possible accident sequences. Hence the need for improved training for the plant staff.

The integration between HAZOPS and FTA will be a complement to the HIRADC method that has been applied to the uranium refining plant. HIRADC explains about safety in the implementation of operations in the facility in terms of human error (operator) and process failure due to damage to the equipment, and its control is more to the use of PPE (Personal Protective Equipment) by operators and also rechecking the equipment before operation. The HAZOPS will complement the safety side of the facility using an indicator control system that will automatically eliminate the risk of hazards that occur during the operation of the facility, while the FTA will analyze the causes of failure that can lead to accidents, hence the basic causal factors of the accident can be identified. With this integration, it is expected that the potential hazards in the deposition process can be known, thus a risk mitigation action can be taken in the form of nuclear emergency countermeasures caused by accidents in the operation of equipment in the deposition process of the uranium refining and conversion facility.

METHODOLOGY.

The precipitation process is a conversion process from uranium in solution form to uranium in solid form by precipitating using ammonium hydroxide solution (NH_4OH). By using hazardous materials such as uranium and ammonium hydroxide, of course, the potential for accidents during the process is quite large. The precipitation process is carried out in the C-901/C-902 precipitation tank. The uranyl nitrate (UN) solution from the concentration process, which has a U content of ± 200 g/L, is flown into the precipitation tank. The UN solution reacts with the NH_4OH solution at temperature of ±60–70^oC to be converted into ammonium diuranate (ADU). The optimum amount of ADU that can be produced in the precipitation tank is 12.5 kg (pH reached 9) [14]. The analysis began with a detailed study of the process under review and the materials used. Next, a historical accident analysis is carried out, which is a study and analysis of accidents that may occur or have occurred in the process to identify risks and causes. This stage can be done by referring to the experience during the process as well as specialized scientific publications and literature reviews that use processes similar to the process to be reviewed. With these available information, the HAZOPS is then performed. Once the results of the HAZOPS are obtained, the FTA is performed by identifying the initial event and then by modelling the fault propagation process. Quantitative analysis is then performed, and the results obtained rank the risks to prioritize corrective and/or preventive actions. Figure 1 represents the work steps carried out in this study.

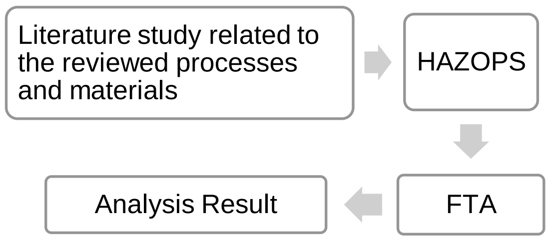

Figure 1. Work steps for safety analysis of the precipitation process.

Hazard and Operability Study (HAZOPS)

HAZOPS is an inductive technique for identifying and analyzing potential hazards and operational problems in a system. HAZOPS was originally developed to analyze chemical process systems, but was later extended to other types of complex systems, for example, nuclear power plants, railway systems, and air traffic management systems [15]. Hazard identification using the HAZOPS method follow the following steps:

a. Examine the sequence of processes that exist in the object of research, taking into account the P&ID.
b. Determine the study point and identify hazards around the study point.
c. Complete the criteria in the HAZOPS worksheet in the following order:
   - Classify the hazards found (source of hazard and frequency of hazard findings).
   - Describe the deviation or deviations that occur during the operation process.
   - Describe the cause of the deviation.
   - Describe the likely impact of the deviation (consequences).
   - Determine interim measures that can be taken.
   - Assess the risk (risk assessment) that arises by defining the likelihood and consequences (severity) criteria. The likelihood criterion used is frequency where the calculation is quantitative based on company data or records over a certain period of time. The consequences (severity) criteria used are the consequences caused by considering the severity of the impact.
   - Rank the hazards that have been identified by using the HAZOPS worksheet by taking into account likelihood and consequence, then by using a risk matrix to determine the priority of hazards for improvement.
   - Perform design improvements for risks in an "Extreme" level, then formulate recommendations for improvement.

After determining the study point based on the existing P&ID, then appropriate guide words can be determined. Hence, deviations and their possible causes can be determined. From these deviations, the consequences are obtained, along with the level of consequences. Consequence levels are defined in the Standard Australia/New Zealand (AS/NZS 4360:2004) [16].

To determine the value of the hazard risk level of the deviation, the likelihood value must be determined first. Likelihood is evaluated by the number of occurrences of the hazard. Likelihood is a measure of the frequency of the possibility of an event or incident occurring and is expressed in the probability of occurrence within a certain time interval [17]. The likelihood frequency can also be evaluated based on historical data from the same component or from failures that have occurred on the component based on failure rate data. The failure rate is the number of failures that occur divided by the total operating time elapsed during the failure, or the total number of requests [18]. The likehood level value can also be determined based on the description in The Standard Australia/New Zealand (AS/NZS 4360:2004) [16]. The risk level is calculated by multiplying the likelihood and concequence values, then adjusted to the risk matrix based on the Standard Australia/New Zealand (AS/NZS 4360:2004) [16].

Fault Tree Analysis (FTA)

FTA can be used qualitatively to identify potential causes and ways of failure (peak events) or quantitatively, or both, to calculate the probability of peak events from the probability of causal events [19], [20]. The steps for the application of FTA are as follows:

a. Determine the peak event.
b. Create Fault Tree

From the top occurrences, the probable direct causes of the failure modes are established, and it is possible to identify how these failures may occur at a basic level or in basic occurrences.

c. Evaluate in qualitative manner

The goal is to find the minimum set of faults by establishing a mathematical formulation of the relationships defined in the fault tree. To achieve this, the "OR" gate is replaced with a "+" sign (not a sum but a union of conjunctions) and the "AND" gate with an "x" sign (equivalent to the intersection of conjunctions). Qualitative evaluation is done by finding the minimum cut set using Boolean algebra. Boolean algebra is an algebra that can be used to simplify or decompose complicated and complex logic circuits into simpler logic circuits [21].

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d. Evaluate in quantitative manner

From the failure frequency of the base event, the frequency of possible accidents is calculated (if they occur) as well as the most critical fault routes (i.e., the most likely among vulnerable combinations of events that can cause the main event). Quantitative evaluation enables a complete risk analysis before implementing and prioritizing measures to improve the safety and reliability of the system under study. Complementary sensitivity analyses can be performed to examine the effects of baseline events on the global risk assessment. This data make it possible to prioritize preventive measures and risk control processes.

By performing the HAZOPS, the peak event can be determined to create a tree diagram. Tree diagrams are often also used in analyzing accident events, in which modified tree diagrams are used in calculations, which are then called fault trees [22]. The fault tree consists of the most basic causes that cause a fault to occur. Once the fault tree is established, mathematical equations are defined, and probability values are calculated based on the Boolean algebra associated with the FTA. Then a qualitative evaluation is performed to obtain the failure frequency at the peak event. Finally, quantitative evaluation is used to obtain the priority value of each peak event based on failure frequency.

RESULTS AND DISCUSSION

The determination of nodes in the precipitation tank C-901 is based on each part of the equipment that is directly related to and affects the process. These nodes are then combined with the appropriate process parameters. Process safety and risk control are closely related to the installed instrumentation system. Therefore, to get the study point, it is necessary to look at the process instrumentation diagram (P&ID). The P&ID of the UN solution precipitation process in the precipitation tank C-901 is presented in Figure 2.

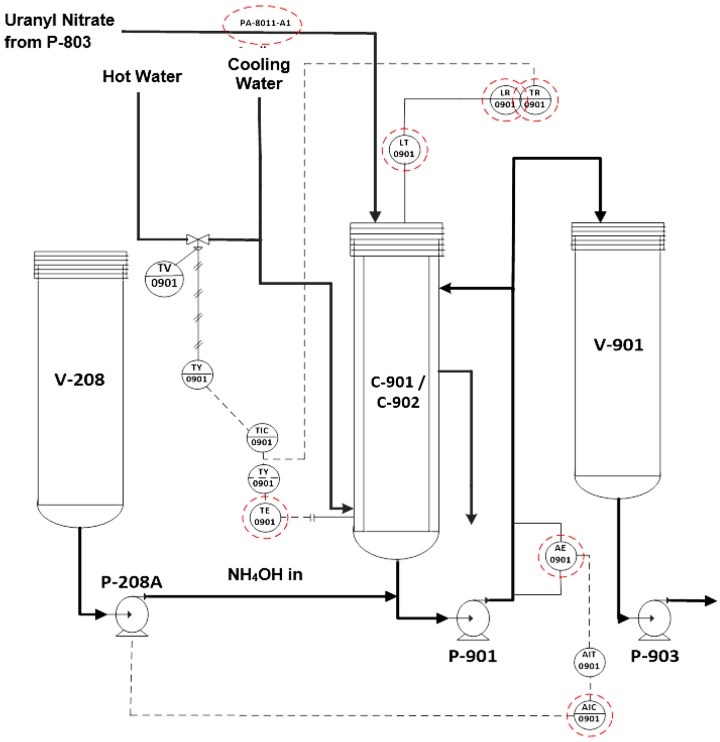


Figure 2. Process Instrumentation Diagram (P&ID) of Precipitation Tank C-901 [23]

Based on the P&ID in Figure 2, seven (7) nodes were selected along with the parameters that affect the C-901/C-902 settling tank. The nodes determined in the settling tank are then identified as potential hazards or deviations that may occur from the combination of parameters and guidewords to the possible causes of deviations and possible consequences. The possible consequences, the consequence level (C) and likelihood level (L), are presented in Table 1.

Table 1. Potential Hazards or Deviations in Settling Precipitation C-901

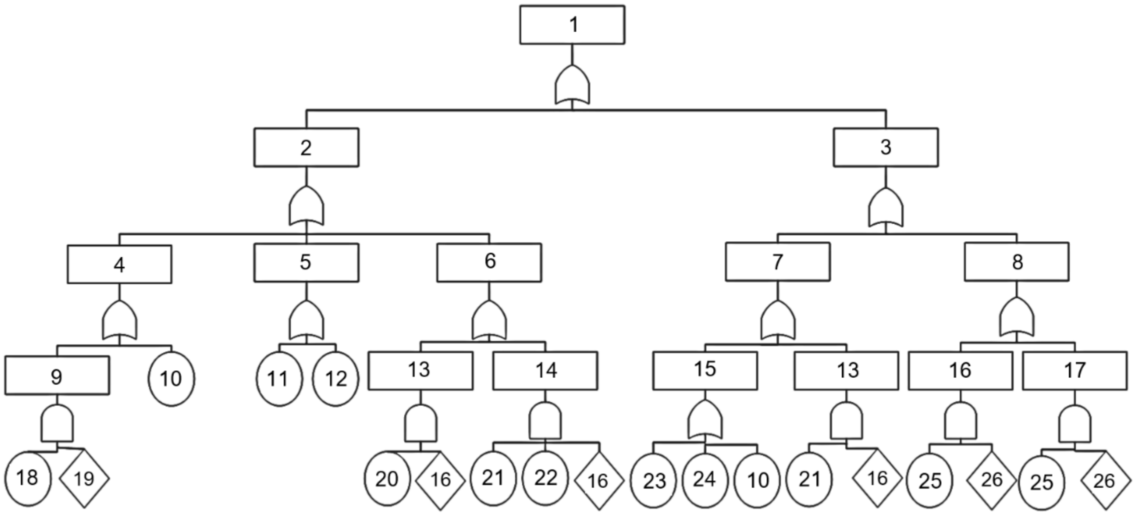
Node	Guide word	Deviation	Possible Causes	Possible Consequences	C	L
Temperature Element (TE-0901)	Less	Solution temperature in the precipitation tank C-901 is less than 333K	Valve TV-0901 stuck unable to open	The product failed because the uranil nitrate in the precipitation tank C-901 did not settle entirely	3	1
			Temperature element (TE-0901) malfunction		3	2
	More	Solution temperature in the precipitation tank C-901 is more than 333K	Valve TV-0901 ~~is~~ stuck unable to close	Too high temperatures raise the pH level of the solution, resulting in product failure	4	2
			Temperature element (TE-0901) malfunction		4	2
Temperature Recorder (TR-0901)	Early	Pressure signal captured faster than the actual temperature condition	Temperature Recorder (TR-0901) malfunction	Due to a temperature reading inaccuracy, the final product did not entirely settle since the temperature was not high enough, resulting in product failure	3	2
	Later	Pressure signal captured lower than the actual temperature condition	Temperature Recorde (TR-0901) malfunction	Too high temperatures raise the pH level of the solution, resulting in product failure, although the system can still run	4	2
Acidity Element (AE-0901)	Less	pH of the solution in the C-901 settling tank is less than pH 6	*Acidity Element* (AE-0901) malfunction	A low pH will cause the final product to not settle entirely, leading to product failure	3	1
Acidity Indicator Control (AIC-0901)	Early	The captured pH signal is faster than the actual pH condition	*Acidity Indicator Control* (AIC-0901) malfunction	Due to a pH reading inaccuracy, the final product did not entirely settle since the temperature was not high enough, resulting in product failure	3	1
Level Trasmitter (LT-0901)	Less	The solution level in the C-901 precipitation tank is less than 20%	*Level Trasmitter* (LT-0901) malfunction	In the state that the solution of the C-901 settling tank is less than 20%, it can cause the pressure in the tank to rise due to heating, which can cause an explosion so that the system cannot operate	4	1
	More	The solution level in the C-901 precipitation tank is more than 80%	*Level Trasmitter* (LT-0901) malfunction	Contamination and internal radiation exposure could result from overflow	2	1
Level Recorder (LR-0901)	Later	The level signal sent from the transmitter is slower than the actual level condition	*Level Recorder* (LR-0901) malfunction	Can cause overflow due to incorrect reading of the level, which can cause contamination and exposure to internal radiation because the solution is a radioactive substance	2	2
Anorganic Phase Pipeline (PA-8011-A1)	No	No uranyl nitrate feed flow into precipitation tank C-901	Pump P-803 dosing control malfunction	No deposition process occurs and with an empty tank condition, the pressure can rise due to heating and can cause an explosion so that the system cannot operate	4	1

Risk assessment is determined by taking into account the obtained consequence and likelihood values using the risk matrix table to determine the risk level. After the risk level value is known, then an assessment of each deviation is carried out to develope control recommendations, thus the predicted potential hazards can be avoided or eliminated. Table 2 presents the risk assessment and recommendations needed based on the risk level values that have been obtained. .

Table 2. Risk assessment results and recommendations on precipitation Tank C-901

Node	Possible Causes	C	L	Risk Level	Recommendation
Temperature Element (TE-0901)	Valve TV-0901 stuck unable to open	3	1	M3 (Medium)	• Equipments calibration and preventive maintenance periodically within a certain period of time • Installation of additional pipes and valves in parallel as a back up valve
	Temperature Element (TE-0901) malfunction	3	2	M6 (Medium)	• Equipments calibration and preventive maintenance periodically within a certain period of time • Installing a TAL (temperature alarm low) alarm that will sound when the temperature is less than the operating temperature
	Valve TV-0901 stuck unable to close	4	2	M8 (Medium)	• Calibration of equipment and preventive maintenance periodically within a certain period of time • Installation of additional pipes and valves in parallel as a back up valve
	Temperature Element (TE-0901) malfunction	4	2	M8 (Medium)	• Equipment calibration and preventive maintenance regularly within a certain period of time
Temperature Recorder (TR-0901)	Temperature Recorder (TR-0901) malfunction	3	2	M6 (Medium)	• Equipment calibration and preventive maintenance regularly within a certain period of time
	Temperature Recorder (TR-0901) malfunction	4	2	M8 (Medium)	• Equipment calibration and preventive maintenance regularly within a certain period of time
Acidity Element (AE-0901)	Acidity Element (AE-0901) malfunction	3	1	M3 (Medium)	• Equipements calibration and preventive maintenance periodically within a certain period of time • Installing an AAL (acidity alarm low) alarm that will sound when the pH is less than pH 6
Acidity Indicator Control (AIC-0901)	Acidity Indicator Control (AIC-0901) malfunction	3	1	M3 (Medium)	• Equipment calibration and preventive maintenance regularly within a certain period of time
Level Trasmitter (LT-0901)	Level Trasmitter (LT-0901) malfunction	4	1	M4 (Medium)	• Calibration of equipment and preventive maintenance periodically within a certain period of time • Installation of an alarm as an initial level reader to warn of irregularities when the solution level in the tank is below 20%
	Level Trasmitter (LT-0901) malfunction	2	1	L2 (Low)	• Equipment calibration and preventive maintenance regularly within a certain period of time
Level Recorder (LR-0901)	Level Recorder (LR-0901) malfunction	2	2	M4 (Medium)	• Equipment calibration and preventive maintenance regularly within a certain period of time
Anorganic Phase Pipeline (PA-8011-A1)	Pump P-803 dosing control malfunction	4	1	M4 (Medium)	• Calibration of equipments and preventive maintenance periodically within a certain period of time • Installing of additional pumps such as the P-401 A/B pump which can be alternately used if one of them is damaged

From the HAZOPS analysis results that have been obtained, the peak event is then determined to be analyzed using FTA. One peak event that occurs most often as a result of existing deviations is product failure in the settling tank. After obtaining the top event, a fault tree is made until being obtained a basic error that might cause product failure in the settling tank to occur. After establishing the fault tree, the basic faults that can cause the top event are obtained. This basic error needs to be considered so the top event does not occur. Then the minimum cut set is determined to find out the root cause of product failure in the settling tank. Finding the minimum cut set is a qualitative analysis in which Boolean Algebra is used. The minimum cut set calculation is obtained from the overall fault tree diagram and the description shown in Figure 3.



1. Product failure in precipitation tank
2. Uranil nitrate does not precipitate completely
3. Explosion in precipitation tank
4. Heating/cooling flow cannot be controlled
5. Difficulty in temperature control
6. Acidity (pH) cannot be controlled
7. High temperature heating when the tank is empty
8. Lack of safety support equipments
9. Valve TV-0901 cannot open/close
10. Operator error
11. Temperature Element TE-0901 malfunction
12. Temperature Recorder TR-0901 malfunction
13. Disruption of NaOH dosing pump
14. Disruption of the acidity (pH) controller
15. Level control not working
16. No pressure relief valve
17. No pressure control device
18. Valve TV-0901 malfunction
19. Operation interruption
20. Pump P-803 dosing control malfunction
21. Acidity Indicator Control AIC-0901 malfunction
22. Acidity Element AE-0901 malfunction
23. Level Transmitter LT-0901 malfunction
24. Level Recorder LT-0901 malfunction
25. Fault of the person in charge of the equipment
26. Equipments design errors

Figure 3. Diagram Fault Tree

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Determination of minimum cut set:

Top event = 1
= 2 + 3
= [4+5+6] + [7+8]
= [(9+10) + (11+12) + (13+14)] + [(15+13) + (16+17)]
= [((18x19) + 10) + (11+12) + ((20x16)+(21+22+16)) + ((23+24+10)+(21x16)) +((25x26) + (25x26))]

Hence, the basic events that can cause product failure in the settling tank are:

Code 10	=	Operator error
Code 11	=	Temperature Element TE-0901 malfunction
Code 12	=	Temperature Recorder TR-0901 malfunction
Code 16	=	No pressure relief valve
Code 18	=	Valve TV-0901 malfunction
Code 19	=	Operation interruption
Code 20	=	Pump P-803 dosing control malfunction
Code 21	=	Acidity Indicator Control AIC-0901 Malfunction
Code 22	=	Acidity Element AE-0901 malfunction
Code 23	=	Level Transmitter LT-0901 malfunction
Code 24	=	Level Recorder LR-0901 malfunction
Code 25	=	Fault of the person in charge of the equipments
Code 26	=	Equipments design errors

CONCLUSIONS

Based on the results of identification and analysis by using a HAZOPS, it is found that there are 10 potential hazards caused by 12 equipment failures from the identification of 7 nodes. Risk assessment of the 12 failures, shows 1 potential hazard in low risk category, and 11 potential hazards remaining in medium risk category. Recommendations for the low risk category are to carry out routine handling, such as periodic preventive maintenance, and calibration of equipments within a certain period of time or when deviations found. Recommendations for the medium hazard risk category in addition to recommendations for the low hazard risk category also need other recommendations in overcoming deviations that occur according to the type of deviation. Likewise, the results of the analysis using FTA, obtained basic events that can cause product failure in the settling tank there are 15 events. From the results of the safety analysis that has been carried out, it can be concluded that HAZOPS and FTA can complement HIRADC to ensure safety can be maintained during the process. Things that can become potential hazards need special attention so that it can be ensured that the process runs safely without any disturbances that can occur.

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AUTHOR CONTRIBUTIONS

The main contributors in this paper are Putra Oktavianto, while Ade Saputra and Munisatun Sholikhah are member contributors.

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