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Assessment of Coal Handling Facility using the Swiss Cheese Model: A Case Study of Fire Incident in Coal-Fired Power Plant

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Fire accidents in a coal-fired power plant (CFPP) can be defined as any event of undesired fire that causes a catastrophic event, particularly in a coal handling facility (CHF). In a specific case, low-rank coal dust particles are sufficient to create an explosion hazard if these particles accumulate in large quantities. This paper aims to describe an integrated effort to define and measure organizational factors related to power plant safety, particularly CHF, using the Swiss Cheese Model (SCM) as an assessment method. The model was used to investigate the accident and prevent accidents as a lesson learned. The evaluation began by reviewing existing conditions. The process consists of assessing loss prevention and loss reduction. Each barrier was evaluated by compliance-defined criteria to mitigate hazard loss events. The assessment result shows that the condition of the equipment was unhealthy, with an ineffective program and unclear standard procedures. By SCM, the existing conditions show a high probability of hazard, which cause potential loss events. Finally, several recommendations were conveyed for each barrier parameter to mitigate and prevent fire accidents in CFPP. Compliance with defined criteria is expected to decrease the occurrence of hazards in the future.

Keywords: fire incident, fire investigation, coal handling facility, swiss cheese model.

1. Introduction

The coal handling system on CFPP is a system of distributing coal from the barge unloader in the jetty to the coal bunker, where coal is previously stored in the coal yard with a shelter or silo (Martin Engineering, 2009). Using the low-rank coal (LRC) type, which was selected as economical fossil fuel in CFPP, brings another hazard of self-combustion, dust spreading with higher ash content than medium-rank coal (MRC) (Irawan, 2020). The coal handling system shall be furnished with a dust suppression system, dust collector and vacuum system which are located in the boiler bunkers, coal transfer points and on the distribution system of coal along the conveyor belt and other locations (EPRI, 2006).

Several methods were applied to investigate an accident in the industry. Soft system methodology (SSM) provided benefits in improving CHF caused by coal dust hazards (Zuniawan & Sriwana, 2019). It results decreasing the spread of coal dust and the working environment. Another method using SCM was used (da Cunha et al., 2022)(Suryoputro et al., 2015) that generates evaluation in every cased (plant, process, and people) to know loss prevention and getting loss events (Power, 2010).

This study case of a fire accident in CFPP uses SCM to evaluate the existing condition of CHF and provide the solution as a lesson learned to prevent in another power plant with the same cases.

2. Literature Review

2.1. Understanding CHF accident

The equipment component of CHF consists of a belt conveyor, supporting equipment that moves continuously and is integrated (Zhao & Lin, 2011). With conditions like this, it illustrates that personnel working in this surrounding area have dangerous risks at work, so knowledge of potential hazards that arise must be mitigated. Comprehensive system monitoring, housekeeping, and predictive maintenance are critical in controlling hazards. Accidents in the conveyor system cause both direct and indirect costs. Dust coming out of the conveyor system is one of the things that must receive great attention from the coal handling process. The potential hazard from dust is the risk of explosion. Low-range coal dust particles measuring 1 millimeter are enough to create an explosion hazard if the particles accumulate in large quantities.
Five components can cause dust explosions to occur (OSHA, 2015):

a. Fuel (combustible dust)
b. Source of fire (heat or electric spark)
c. Oxygen (Oxygen in the air)
d. Dust suspension into the cloud (efficient quantity and concentration insufficiency)
e. A collection of dust clouds

There are several ways to view relationships between dust with fire hazard events (Martin Engineering, 2009):

a. Sparks
   A spark of fire dust from self-ignition or other sources is usually localized and can cause significant damage and create conditions for a secondary explosion, leading to catastrophic damage and more fatal injuries.
b. Explosion
   When dust accumulates in the room is limited and burning will cause an explosion. This explosion generates a more destructive pressure that can destroy the conveyor infrastructure building.
c. Primary or secondary
   A primary dust explosion can cause a secondary explosion by flying burning dust particles, triggering a new source far away from the original explosion. A secondary explosion can be more destructive than a primary explosion, and each explosion can cause an additional secondary explosion.
d. Deflagration index
   Constituting the magnitude of dust's speed and explosive force is a direct function of the measured characteristics. Dust explosions can be more dangerous than explosions caused by combustible gases.

2.2. Swiss Cheese Model (SCM)

The Swiss Cheese Model (SCM) is one of the theories in occupational safety and health (Hollnagel & Pariès, 2006). SCM is often used in accident investigation and occupational accident prevention. Professor James Reason from the University of Manchester, who first invented the SCM. According to Professor James Reason, accidents are more caused by human error, which is usually related to system designers, high-level decision-makers, managers, and maintenance personnel. However, after further analysis, other causes of failure are activities related to maintenance, decision-making errors in the organization, and managerial matters (latent error).

Accidents include individual accidents and organizational accidents (Reason, 2004). Individual harm to certain people or groups is both the cause and the victim of the accident. Meanwhile, organizational accidents involve many people at varying levels in companies whose impact affects uninvolved populations, assets, and the environment. In organizational accidents, there is a relationship between hazards, defenses (barriers), and losses, as shown in Fig. 1.

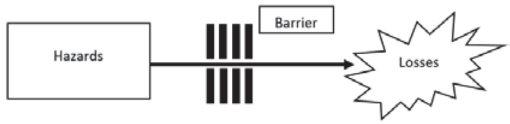

Fig. 1. Relationship between hazards, defenses, and losses.

Protection and barriers (defenses) separate hazards from people and vulnerable assets (losses). Organizational accidents/failures occur when defenses are breached/breached by humans, technical/technology, and organizations.

The components in the SCM consist of:

a. Defenses, barriers, and safeguards are defenses from risks that take an important role, especially in the systems approach. Technical layers of defense such as alarms, physical barriers, automatic engine extinguishers and rely on people such as control room operators but still require procedural and administrative control.
b. Holes are holes, such as in Swiss cheese, that indicate weaknesses in the protection system. The existing holes can be opened, closed, and moved places. The presence of holes in a layer does not always result in anything bad. A bad thing can only happen if the holes in the many layers are at some point in a straight line, allowing danger to inflict damage to the system.
c. Active failures are insecure behaviors performed by people who are in direct contact with the system.
d. Latent conditions are "resident pathogens" that are inevitable in a system. It can come from decisions made by designers, experts, procedure makers and top-level management.

The SCM theory can be implemented as a framework for investigating an accident/failure for both the system and each piece of equipment.

3. Methods

SCM is kind of method conducted in this study. The process of layers swiss cheese slices consists of assessing loss prevention and loss reduction. Each barrier was evaluated by compliance-defined criteria to mitigate hazard loss events. The result of the implementation of SCM will be analyzed and assessed. The analysis result will be analyzed as a whole and then we will see which part needs preventive improvement.

Analysis of CHF accident were performed based on loss prevention (by three barrier parameters) and loss reduction (by one barrier parameter). Three barrier parameters that will be evaluated in the loss prevention were:

a. Plant barrier (technical risk management, critical system, alarm and instrument management)
b. Process barrier (maintenance management and operation management)
c. People barrier (staff competence).

Analysis in this method by semi quantitative for plant barrier and qualitative perspectives on process barrier and people barrier. This output perspective can show loss event that should be mitigated.

CHF is the main facility that supports the production of CFPP. Although it has the advantage of high security, it does not guarantee the least number of accidents. Many cases of CHF accidents that occurred in Indonesia are in belt conveyor areas. This study focuses on the case fire accident in one of the CFPP in Indonesia with SCM analysis and is shown in Fig. 2.

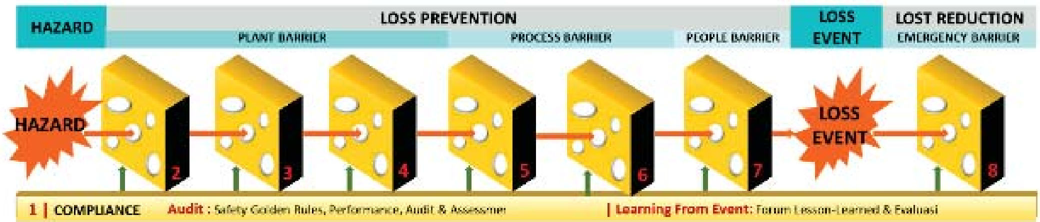

Fig. 2. SCM analysis

4. Result and discussion

Regarding the design of the CHF equipment, the evaluation is based on the book foundations: The Practical Resource for Cleaner, Safer, More Productive Dust & Material Control and the provisions of technical standards with FMAC: Coal-Handling Maintenance Guide - EPRI 1013349 in accordance with Table 1.

Table 1. *Map of equipment condition risk to potential fire*

No	Color	Definition	CHF Equipment
1	Red	The condition of the equipment is unhealthy and significant to the possibility of potential fires	1. Unloading equipment 2. Dust control system
2	Yellow	The condition of the equipment is unsanitary and moderate to the possibility of a potential fire	1. Belt scale 2. Unloading the hopper 3. Sampling equipment 4. Magnetic separator 5. Conveyor belts, pulleys, idlers, and rollers
3	Green	The condition of the equipment is healthy and does not have an impact on the potential for fire	1. Slide gate 2. Coal crusher 3. Stacking and reclaiming 4. Belt tripper device 5. Gearbox

Based on the CHF conditions according to Table 1, it can be known that the red category will be the focus area for immediate improvement. This is because the CHF equipment is related to the control of coal dust both in terms of coal acceptance and transfer to the coal bunker. As for the yellow category, in general, the equipment needs to be carried out with regular inspections and ensure that the function of the equipment is functioning properly. Fig. 3 shows the SCM analysis result.

There are several gaps that if associated with the SCM theory, then these gaps that show weaknesses in the protection system that can be the cause of fire or can be the cause of the increasing impact of fire hazards or can also be referred to as loss events, including:

i. Plant Barrier
   - From the risk map of equipment conditions to potential fires, CHF equipment is obtained which is red with

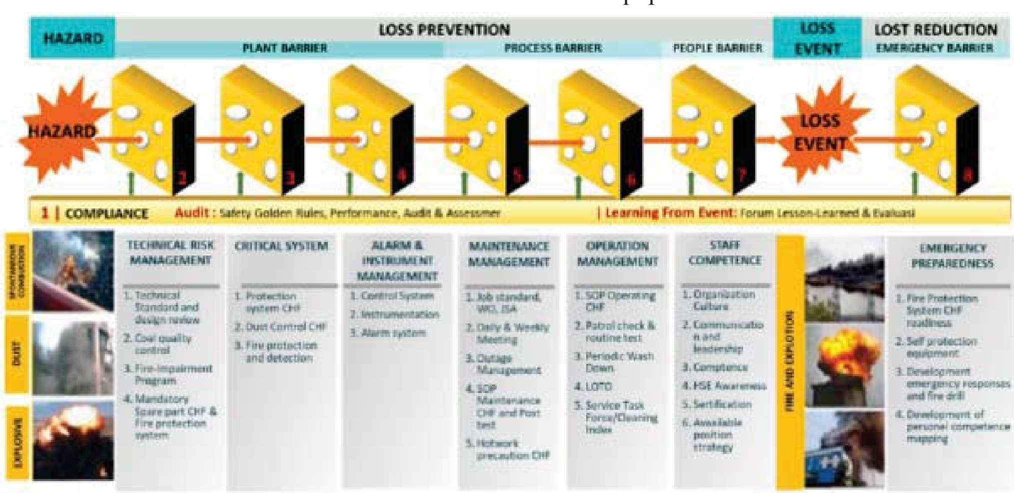

Fig. 3 SCM Analysis Result

unhealthy equipment conditions and is significant to the possibility of potential fires, namely unloading equipment and dust control systems. As for the condition of the equipment, it is unhealthy and moderate to the possibility of potential fires such as belt scales, unloading hoppers, sample equipment, magnetic separators, conveyor belts, pulleys, idlers and rollers.

- The application of the fire impairment program, which is mandatory in the management of fire extinguishing systems, refers to the NFPA report in 2009 regarding the U.S. experience with sprinklers and other fire extinguishing equipment. This CFPP does not have the solid organizational structure needed to run this program in order to ensure that the fire extinguishing system is in standby operating conditions.
- Fire protection systems are not a focal point in the reserve material strategy.

i. Process Barrier

a) Operation Management

- Work instruction and SOP of CHF Operations

  There is no clear distinction between SOP (Standard Operating Procedure) for an activity, both O&M and non-O&M in general) and work instruction (detailing work steps on SOP) and checklist (list of work steps along with parameters that are used as normal operating standards), especially in CHF. This is necessary to minimize errors in the implementation and monitoring of work and know in advance the condition of the equipment carried out work.
- Patrol Check & Routine Test

  This activity has been carried out and there is regular monthly reporting, but it is necessary to improve the quality of activities, field conditions, and recommendations for the implementation of activities in the field so that the occurrence of unsafe conditions and unsafe actions can be minimized and prevented as early as possible.
- Periodic Wash Down

  The implementation of this activity is hampered by water availability, so it is necessary to reorganize according to the water balance of the CFPP. A comprehensive study is immediately made separating the water needs of the unit's operating needs, other routine needs (needs for activities in the office, MCK, periodic wash down etc.), and the needs of a fire fighting system according to NFPA 20 standards.
- Log Out and Tag Out (LOTO)

  Awareness, commitment, and consistency to all stakeholders at CFPP in carrying out LOTO activities from the beginning to the end of the implementation of work coordinated by Health Safety and Environment (HSE) officials need to be improved to maintain HSE during the implementation of work in minimizing and preventing work accidents and preventing occupational diseases.

- Service Task Force/Cleaning Index

  These activities need to be improved in quality, for example, an appropriate and proportional SLA is made to the executor of the work and is still monitored by the Field of Operations. The absence of this makes the quality of cleanliness in the field still need to be improved. In addition, it also requires the commitment and consistency of all stakeholders of the CFPP in carrying it out.

b) Maintenance Management

- Work Order (WO), Job Safety Analysis (JSA)

  The implementation of this document should have been integrated into the Computerized Maintenance Management System (CMMS) from the beginning to the completion of the work so that HSE officials can monitor, evaluate and control work that has the potential for explosion and/or fire. This activity is still started with the formation of HSE officials who have Job Desk as Permit to Work (PTW) Officers.

- Daily & Weekly Meeting

  The implementation of daily & weekly meetings has been carried out, but it needs to be improved in efficiency and effectiveness so that arrangements are also needed from timekeepers, evaluator meetings, and firm leader meetings. The large number of service request that arises from operators often traps in protracted discussions and has not been found a solution due to a lack of data and information even though the executor of the work is waiting for the results of the agreement from the meeting on that day.

- Outage Management

  This activity has been carried out according to existing criteria, but it is necessary to improve its activities and monitoring considering the location and geography of the CFPP which requires better planning. It is also necessary to plan equipment repairs in the CHF area considering that much equipment can only be done when the Unit stops (Overhaul).

- SOP of CHF maintenance

  This document has not yet been found due to an understanding of SOPs and work instruction. It is better to immediately make separate SOPs and work instruction, especially in the CHF area.

- Post Maintenance Test

  This activity is carried out by the Outage Maintenance Engineer (OME) Field to ensure the quality of post-maintenance work so that it can be ensured that it is in accordance with the normal operating standards agreed upon by the OME Field. This activity is still not optimal considering that there are still many reworks on the maintenance work carried out.

i. People Barrier

- There is no workload analysis of the CHF section, so it cannot be determined the need for an optimal number of employees and the number of outsourcings is more than employees where outsourcings lacks a sense of responsibility in their work.
- The saturation of long-time employees at CFPP can reduce motivation at work
- Lack of communication between sections, communication from superiors to subordinates and respect for employees can reduce the trust of fellow employees and trust in management.

Based on loss events above, several recommendations were conveyed for each barrier parameter to mitigate and prevent fire accidents in CFPP.

i. Plant Barrier
- Conduct improvement based on risk mapping of CHF equipment.
- Establish organization and policy of fire *impairment* program.
- Develop preventive maintenance to make sure the fire protection and detection system works properly.

ii. Process Barrier

a) Operation Management
- Make sure that 5S; Sort, Set in order, Shine, Standardize and Self Discipline is embedded in every personnel.
- Re-evaluate of water balance system.
- Monitoring and evaluating quality and quantity implementation of periodical wash down to minimize the hazard of explosion caused of dust.

b) Maintenance Management
- Based on the geographical condition of CFPP which is isolated, it should be well prepared for maintenance planning to optimize resources.
- Execution of hot-work precautions in the CHF area should be supervised and monitored by HSE officer.

iii. People Barrier
- Solid planning of work-life balance program.
- Competency development based on workload analysis and job position.
- Communication and leadership program.
- HSE awareness program.

4.1. Limitation of Method

Swiss cheese model offers a valuable conceptual framework for understanding system failures and can help identify potential areas of improvement and risk mitigation, in another case this method has several limitations such as lack of quantification which assumes that each layer has some level of effectiveness but does not assign specific values or probabilities to the layers; Deterministic perspective where accidents and failures occur when multiple holes align in the defense layers. However, in reality, accidents and failures often involve inherent uncertainties, random events, and human errors that cannot be fully predicted or controlled. The model's deterministic perspective may not adequately address these probabilistic aspects.

This can limit its ability to provide precise risk assessments or prioritize mitigation strategies. It should be used in conjunction with other methods and approaches to gain a more comprehensive understanding of complex systems.

4.2. Investigation Method

During an accident investigation, one or two methods can be used to determine and evaluate the hazard of the process to be analyzed, namely the what if, checklist method. What if/checklist, Hazard and Operability Study (HAZOP), Bow Tie Analysis, Root Cause Failure Analysis (RCFA), Failure Mode and Effect Analysis (FMEA), Fault Tree Analysis or equivalent methodology as appropriate.
As for the CHF case study in one of the CFPPs this time it integrates the method of investigation results using SCM with bow tie analysis. Where the fire that occurred in CHF was caused by the fire extinguishing system not working properly because the availability of fire water stored in the tank did not meet the standards stated in NFPA 22. So that the fire water pump could only work for a few minutes, unpreparedness in meeting the fire water tank level due to problems in the *Sea Water Reverse Osmosis* (SWRO) system in the *Water Treatment Plant* (WTP) so that the fulfillment of fresh water needs is only prioritized to meet the water needs of demin boilers. The problem that occurs in SWRO itself is a lack of mitigation in planning the material requirements of the WTP system based on lifecycle management, where both SWRO systems whose functions are redundant have entered their lifetime

5. Conclusions

SCM was selected an assessment method that define and measure organizational factors related to power plant safety, particularly CHF in case study of CFPP. The model was used to investigate the accident and prevent accidents as a lesson learned. The process of layers swiss cheese slices consists of assessing loss prevention (by three barrier parameters) and loss reduction (by one barrier parameter). The result shows several gaps that if associated with the SCM theory, then these gaps that show weaknesses in the protection system that can be the cause of fire or can be the cause of the increasing impact of fire hazards. This existing conditions show a high probability of hazard, which cause potential loss events and several recommendations were conveyed for each barrier parameter to mitigate and prevent fire accidents in CFPP.

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