Loss prevention in the petrochemical and chemical-process high-tech industries in Taiwan

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A B S T R A C T

Industrial safety has noticeably improved in recent years in Taiwan. Despite these improvements, however, serious accidents including explosions, chemical releases, and fires have still occurred in companies such as the Fu Guo Chemical Company (2001), Sin Hun Chemical Company (2005), Motech Industries, Inc. (2005) and Nanpao Resin Co. (2010). These accidents resulted in great loss of life and property, and further caused demands for improvement. Chemical disasters usually result from the combination of several mistakes or gross carelessness and are seldom caused by a single episode. To ensure the safety of operating, handling and storing chemicals, as well as to prevent chemical disasters, one must take many critical points into account, such as techniques, manufacturing processes, operators, chemicals, and emergency response. In Taiwan, the hazards and risks of high-tech companies are higher than in other industrial sectors. Therefore, a variety of safety management methods and regulations appropriate for high-tech companies have been generated. We studied the current status of the indigenous loss prevention protocols based on the safety management of petrochemical and chemical-process high-tech industries in Taiwan.

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1. Introduction

Highly developed industrial technology has not only resulted in great advances, but also in the expansion of the complexity and scale of chemical processes resulting from the development of process technologies in the chemical industries, such as thin film transistor-liquid crystal displays (TFT-LCD), light emitting diodes (LED), photovoltaics, and semiconductor-related industries. However, the harm from chemical disasters caused by machine breakdowns, operational mistakes, poor design, and mismanagement, among others, has steadily increased (Chang, Chang, Shu, & Lin, 2005; Wu, Shyu, Yet-Pole, Chi, & Shu, 2009). In retrospect, serious fires, explosions, and chemical release accidents that have happened in recent years in Taiwan have been disastrous. For example, on May 18, 2001, a 6-ton reactor at the Fu-Kao Chemical plant located at an industrialized park in the northern part of Taiwan exploded due to a violent runaway polymerization reaction of a batch production of acrylic resin. Due to the lack of a proper emergency relief and disposal system on the reactor, the flammable chemicals were released and blanketed the entire process area. The catastrophic explosion leveled the plant and other nearby plants, including 16 high-tech companies. The shock wave was so violent that thousands of windows within a 500 m radius were shattered (see Fig. 1). Roughly 100 people were injured from flying glass and several were hospitalized. Fortunately, the Fu-Kao workers were able to escape in time and there were no deaths (Kao & Hu, 2002).

The second infamous example of an accident from a gross safety violation was a fire at Advanced Semiconductor Engineering (ASE), which was a global leader in the integrated circuit (IC) packaging industry. On May 1, 2005, its semiconductor packaging and testing facilities were ruined by a fire in its substrate plant in Chungli, Taiwan (see Fig. 2). The facilities were not in operation at the time of the fire, although some operators working overtime were on the premises. In total, several firefighters, five ASE employees and two employees of outside contractors suffered minor injuries and had to receive medical attention. The fire had spread to the third floor of the eleven-floor building and higher floors were spoiled by smoke. The losses from the fire were expected to be enormous, including rebuidling costs as well as $19 million USD per month in lost capacity. Clients were also significantly hampered by this accident;
this may have resulted in remunerative compensation or even the causation of clients shifting orders to ASE’s competitors. In summary, the damages were anticipated to reach $320 USD million, which is a huge loss for any company to take (Taipei Times, 2005; The China Post, 2005; The Epoch Times, 2005).

The third example happened on January 8, 2010. In this case, a huge blast with a mushroom cloud occurred at 2:48 pm at the Nanpao Resin Co. The fire, after a couple of explosions, was not extinguished until the following dawn (see Fig. 3). Roughly 4298 m² of production and warehouse space was subsequently destroyed. Additionally, Taiwan Steel & Iron Co., its neighbor, was partly damaged. The accident took place at the cumene oxidation tower, in which a fluid leak was identified in the broken recycling line. A lack of a buffer zone at the bottom of the recycling line resulted in the leaking, followed by an unidentified ignition source. The firm is one of the major producers for cumene hydroperoxide (CHP) and dicumyl peroxide (DCP) in Taiwan. Because of the severe damage, the plant was shut down, fenced off and dismantled. The various indirect losses from these accidents are inestimable, including equipment repairs, delay in plant re-commissioning, loss of market share, and increases in insurance costs (Muniz, Peon, & Ordas, 2007).

According to the annual reports of occupational disasters published by the Council of Labor Affairs (CLA), Executive Yuan, Taiwan, the industries that have greater opportunities of having a chemical disaster or accident are involved in the manufacturing of chemical products or chemical materials, are high-tech electronic industries (semiconductors, TFT-LCD, and printed circuit board-related sectors), and participate in the manufacturing and repair of electrical and electronic machinery. These three types of industries are classified as chemical-process industry. In Figs. 4 and 5, the data collected from 2004 to 2007 show that 60 out of 156 fire and explosion accidents and 419 out of 605 harmful substance contact disasters occurred in these industries.

As far as economic development is concerned, these industries are key sectors in Taiwan. In 2007, the output value of all manufacturing in Taiwan was approximately $485 billion USD. Among these, petrochemical industries were about $52 billion USD, and the high-tech electronic industry was worth $119 billion USD. Therefore, the output value of the chemical-process industries was more than one-third of all manufacturing industries in Taiwan. If these accidents continue to occur, they will damage the local economy and adversely affect the international reputation of Taiwan (Chen, Wu, Wang, & Shu, 2008; Lin, Tseng, Wu, & Shu, 2008; Tseng, Liu, Chang, Su, & Shu, 2008).

Countries all over the world have their own ways of preventing and coping with the serious detrimental effects resulting from chemical disasters. For instance, in 1992 the OSHA of the USA promulgated the Process Safety Management standards for manufacturing highly hazardous chemicals to regulate companies that handle large quantities of dangerous chemicals. In Taiwan, the Labor Inspection Law was launched in 1993, of which Articles 26 and 38 state that dangerous workplaces of petrochemical industries, including sites of manufacturing, handling, and use of dangerous or hazardous materials and sites for manufacturing agricultural chemicals, should be approved or inspected by the labor inspection authority. It is expected that the establishment of safety management systems in dangerous workplaces will help identify and correct deficiencies in the application of safety techniques. However, there is no single management system that can be used to totally eliminate the risk of all accidents (Beatriz, Manuel, & Camilo, 2007; Crowl & Elwell, 2004).

In the last two decades, there have been various scales of chemical disasters occurring in the chemical-process industries in Taiwan. Accordingly, we considered and investigated the current status of loss prevention in the petrochemical and chemical-process industries in Taiwan.  

2. Current status of loss prevention in the petrochemical industries in Taiwan

In chemical plants, except for several well-known foreign companies (e.g., E.I. du Pont de Nemours and Company, BASF, and the Dow Chemical Company) and large domestic companies (e.g., Taiwan
Fig. 2. The Advanced Semiconductor Engineering, Inc. fire of 2005 (The Epoch Times, 2005).

Fig. 3. The Nanpao Resin Company explosion in January 2010 (The Epoch Times, 2010).
Semiconductor Manufacturing Company (TSMC), United Microelectronics Corporation (UMC), China Petroleum Corporation (CPC), Formosa Plastic Co. (FPC), and AU Optronics (AUO) Corp.) that have established comprehensive safety systems, the medium and small indigenous chemical firms in Taiwan are still administered in traditional ways. Although the manufacturing process is fast and the product quality is well maintained, safety issues are often neglected or are lacking for a variety of reasons (Guidelines for Hazard Evaluation Procedures, 2008).

The CLA, the authority of industrial and occupational safety in Taiwan, investigated labor safety and health counseling with medium and small chemical plants from 2004 to 2006. In total, 190 plants participated in this project, which was categorized based on the following safety issues.

2.1. Process safety information

Most plants had basic protocols on accidents when they were originally established. However, about half never updated the information or reevaluated the potential hazards when process parameters, equipment, or raw materials were altered. This led to two consequences:

a. Due to neglecting the safety issues associated with new techniques and new reagents, or insufficient safety equipment in plants, and to a lack of professional analysis to completely ascertain the risk during the process, poor operation control or improper storage was possible.

b. Although the equipment may have been regularly replaced, the piping and instrumentation diagrams (P&IDs) were not revised on a regular basis. This situation led to unforeseen risks for the personnel engaged in the maintenance of equipment due to the unknown equipment conditions.

New knowledge from external safety information, such as recently launched laws and regulations, emerging safety technology, and updated chemical information, among others, has been rapidly conveyed to each company through various means, like seminars, assistance counseling, and inspection, because authorities now pay much more attention to chemical hazards. This external safety information is accepted by most companies, but the practical act of carrying out the required actions varies depending on the human resources and level of safety awareness in the plants.

2.2. Process hazard analysis

Most medium and small companies considered the process hazard analysis as preliminary hazard recognition. Therefore, safety management emphasized the safety equipment in coping with specific hazards. Only a few companies systematically analyzed the operating steps and safety procedures, such as sequence, flow, pressure, temperature, composition, and facility breakdown for accident prevention.

Older plants, unlike newer ones, have not updated safety requirements and lack subsidiary safety devices for temperature and pressure control or monitoring, devices to prevent overheating, and alarm devices to monitor, maintain, and control plant safety. If the systems have not experienced an accident for a long time, they may believe their plants are safe and that there is no problem with the facility or the safety management system in place. This complacency is how many out of control accidents happen. Therefore, it is important to carry out systematic process safety analyses, like a hazard and operability study (HAZOP) or failure modes and effects analysis (FMEA), to study how to protect the operating unit from accidents with the current equipment (Bernatik & Libisova, 2004).

2.3. Operating procedures

Eighty percent of the plants have already formulated complete standard operating procedures (SOPs) for their major processes. However, in most cases they are not properly carried out. The SOPs for safety issues are usually only a formality for real tasks and are not routinely updated in many plants. Operators often perform their assignments based on experience so that the SOPs are different from real operating procedures. Consequently, new operators or apprentices are often confused and this creates hidden hazards (Meel et al., 2007).

2.4. Management of process change

Management of process change is often the most neglected aspect of process safety management in plants. In Taiwan, processing research and development is of a high standard, which means that the process parameters and raw materials are continuously tested and modified in plants. In addition, unregulated pipelines and devices are often replaced by established methods, but some management of process changes have not been established.
2.5. Training

Plants with potential risks and chemical hazards should plan necessary staff training in basic safety knowledge. The necessary safety knowledge differs depending upon the characteristics of the plant. However, all personnel must be well trained to understand the hazardous character of the chemicals being used and the basic concepts of preventing disasters and emergency response.

According to our investigation, over 60 percent of the training done in chemical-process plants that have taken part in the assistance project was disqualified. This was because of less-than-capable trainers, the incorrectness of the training courses, long intervals between training sessions, the lack of approval and testing of trainees, and the use of workers without proper training. The most common mistakes that could be averted by proper training are unintentionally misusing protection equipment, unknowingly using non-flameproof tools in a classified flameproof area, and storing incompatible chemicals in the same location.

2.6. Contractor management

Although most plants have some system for managing contractors, hazard awareness in satellite-affiliated organizations is not normally well managed. The basic reason for contractor management regulations is that the safety systems are not well executed in over 50 percent of the plants. An example of this would be not conforning to specific regulations in the use of hot work permits or the failure to use flameproof tools. Therefore, high risks associated with improper contractor management are inevitable.

2.7. Incident investigation

Incident investigation is very important for all levels of industry. According to the accident iceberg theory, for each severe accident, many near misses and minor incidents with similar causes occur. The level of accident severity in small and medium chemical plants is higher than in many other industries, but the implementation of incident investigation in small and medium chemical plants is typically inferior to other sectors. Investigations were carried out completely in only 56 percent of the plants involved in the study. To prevent severe accidents from happening again, incident investigations should be strengthened in plants in the process industries (Basso et al., 2004).

2.8. Hot work permit

Hot work permits have received much attention in chemical plants that have a high risk for fire and/or chemical release. Despite this attention, it has been shown that 8 percent of chemical plants never controlled hot work, whereas only 60 percent controlled it completely. Hot work was not governed completely in the remaining approximately 30 percent, probably due to lack of awareness of ignition sources, such as uncontrolled vehicles.

2.9. Mechanical integrity

The number of accidents that occur due to equipment breakdown or wear has increased yearly since 1994. This reveals that, due to lack of appropriate maintenance and repairs, the equipment is gradually deteriorating in manufacturing plants. The common mistakes are electrical equipment deterioration, flameproof equipment having lost its protection, pipelines being broken, safety equipment being broken or malfunctioning, safety relief valves not functioning properly, and maintenance records and documents being neither verified nor current. Although the authorities audit and check these plants, the fixes are delayed to try to get the work done hurriedly in order to make a profit. This is a common phenomenon in the small and medium chemical plants studied.

Fig. 6 is a radar chart that presents the proportion of the process safety management implementations carried out by small and medium chemical plants that joined this assistance project.

3. Current status of loss prevention in chemical-process high-tech plants in Taiwan

The chemical-process high-tech industry, such as semiconductor, TFT-LCD, LED, and photovoltaic fabrication, is the dominant economic lifeline in Taiwan. Because the processes are complicated and many of the chemicals used are toxic, highly flammable, or explosive (Tables 1–3 show the characteristics of common chemicals and specialty gases in the high-tech industry), high-tech manufacturing buildings are all built to the highest standards of safety. Moreover, the newest regulations and safety management methods are introduced to avoid accident occurrence (Hirano, 2004; Reyes & Beard, 2008). Yet, even though the high-tech industry has been developing for nearly three decades, incident information and experience is lacking (Rotaru et al., 2008). Although every plant apparently has faultless safety equipment and safety management, toxic gas and chemical leaks or fire accidents frequently occur in Taiwan. The current status of loss prevention programs in high-tech plants in Taiwan is described as follows.

3.1. Process safety information

Due to sufficient human resources and complete safety systems in high-tech plants, the process safety information seems abundant, complete, and impeccable. All information, such as material safety data sheets (MSDS), equipment information, and P&IDs, is intact and updated periodically. However, this new industry uses a variety of toxic and exotic chemicals. Therefore, many chemical characteristics are unknown or occasionally intentionally ignored, bringing imminent danger or long-term health threats to the work environment (Rigas, Konstandinidou, Centola, & Reggio, 2003).

3.2. Process hazard analysis

Most high-tech plant buildings fall within the definition of a dangerous workplace. Because they use many kinds and large
Table 1
Characteristics of common corrosive chemicals utilized in high-tech companies (Urban, 2006).

<table>
<thead>
<tr>
<th>Material</th>
<th>Application</th>
<th>TLV-TWA</th>
<th>IDLH</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCl</td>
<td>Etching</td>
<td>5 ppm</td>
<td>—</td>
</tr>
<tr>
<td>H2PO4</td>
<td>Etching</td>
<td>1 mg/m³</td>
<td>100 ppm</td>
</tr>
<tr>
<td>H2SO4</td>
<td>Etching</td>
<td>1 mg/m³</td>
<td>80 ppm mg/m³</td>
</tr>
<tr>
<td>HF</td>
<td>Etching</td>
<td>3 ppm</td>
<td>20 ppm</td>
</tr>
<tr>
<td>HNO3</td>
<td>Etching</td>
<td>2 ppm</td>
<td>100 ppm</td>
</tr>
<tr>
<td>TMAH</td>
<td>Photo</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

TLV-TWA: threshold limit value—time weighted average.
IDLH: immediately dangerous to life and health.
TMAH: tetramethylammonium hydroxide.

Table 2
Characteristics of common solvents used in high-tech companies (Pohanish & Greene, 2003; Urban, 2006).

<table>
<thead>
<tr>
<th>Material</th>
<th>Application</th>
<th>TLV-TWA</th>
<th>IDLH</th>
<th>Explosive limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPA</td>
<td>Photo/etching</td>
<td>750 ppm</td>
<td>20,000 ppm</td>
<td>2.5–12.8%</td>
</tr>
<tr>
<td>IPA</td>
<td>Photo/etching</td>
<td>400 ppm</td>
<td>20,000 ppm</td>
<td>2–12%</td>
</tr>
<tr>
<td>HMDS</td>
<td>Photo</td>
<td>—</td>
<td>—</td>
<td>0.7–31%</td>
</tr>
<tr>
<td>Photoresist</td>
<td>Photo</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

IPA: isopropyl alcohol.
HMDS: hexamethyldisiloxane.

Table 3
Characteristics of common specialty gases used in high-tech companies (Carson & Munford, 1995; Urban, 2006).

<table>
<thead>
<tr>
<th>Material</th>
<th>Application</th>
<th>TLV-TWA</th>
<th>IDLH</th>
<th>Explosive limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>AsH3</td>
<td>Implant</td>
<td>0.05 ppm</td>
<td>6 ppm</td>
<td>4.5–78%</td>
</tr>
<tr>
<td>BF3</td>
<td>Implant</td>
<td>1 ppm</td>
<td>100 ppm</td>
<td>—</td>
</tr>
<tr>
<td>B2H6</td>
<td>Implant</td>
<td>0.1 ppm</td>
<td>40 ppm</td>
<td>0.8–88%</td>
</tr>
<tr>
<td>SiCl4</td>
<td>Diffusion</td>
<td>0.5 ppm</td>
<td>—</td>
<td>4.1–99%</td>
</tr>
<tr>
<td>SiH4</td>
<td>Implant</td>
<td>0.3 ppm</td>
<td>200 ppm</td>
<td>1.6–98%</td>
</tr>
<tr>
<td>SiH4</td>
<td>Deposition</td>
<td>5 ppm</td>
<td>—</td>
<td>1.4–96%</td>
</tr>
<tr>
<td>SF6</td>
<td>Etching</td>
<td>1000 ppm</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>NF5</td>
<td>Etching</td>
<td>10 ppm</td>
<td>2000 ppm</td>
<td>—</td>
</tr>
</tbody>
</table>

quantities of chemicals, they must follow the regulations mandated by the CLA in Taiwan to assess the process safety for a dangerous workplace. However, these assessments are only for restricted chemical processes and equipment, so the regulations do not encompass the entire process.

Furthermore, most of the high-tech plant buildings have established occupational health and safety assessment systems (OHSAS 18001), and they obey the requirement to carry out periodic risk assessment. The depth and width of the risk assessment, however, depends on the experience and ability of the assessment staff. Moreover, according to the trends of the high-tech industry in Taiwan, incident and minor loss information is treated as confidential, making accessing and learning from it very difficult for anyone in other plants.

Proprietary processes and operating procedures are complex and loss prevention information is exclusively shared within high-tech plants, so it is very important for the staff at a particular plant to have the ability to conduct their own, independent risk assessment. The hidden hazard that fails to be identified is always the key to a subsequent accident (Suardin, Mannan, & Halwagi, 2007).

3.3. Operating procedures

To meet the request of international organizations for standardization (ISO), high-tech plants have all established required SOPs. However, because the equipment is so precise and intricate, and the procedures are so minute and complex, it is difficult to encompass all the safety procedures in the SOP. Besides, operators do not always follow the guidelines and the SOPs are not always suitable for their processes, points which are usually ignored, leading to accidents in these plants.

3.4. Management of change (MOC)

Parameters and processes for equipment maintenance are changed frequently and procedures for MOC are not always elaborated on in high-tech plants. Therefore, industrial safety staff does not always know of the changes to the usual process parameters. Because the alterations are often too frequent and complicated to be recorded, it is not clearly defined what should be announced or accessed for the hazard. More than half of all fire and chemical release accidents occur because the MOCs are not well implemented.

3.5. Emergency planning and response

The emergency response plan in high-tech plants is usually developed for ideal conditions. If a large-scale accident occurs, it becomes difficult to address by the procedures and organization in the emergency response plan. Because the occurrence and evolution of an accident cannot be predicted, the emergency response plan should not put emphasis on the response flow but on the principles of treatment of the victims of a disaster, of evacuation, of the requirements for shutting down the gas/liquid supply, and of the requirements for transferring the command in a timely manner.

By instituting and training employees on well-developed plans, fatal accidents due to mistakes made by the staff during an emergency response can be avoided. One example of this type of accident was the fire that resulted from a silane cylinder leak that happened at one photovoltaic fabrication plant in Taiwan.

3.6. Employee participation

Practically, there may be up to a thousand employees in a single high-tech plant, and they likely have an educational background that is higher than those in other industrial sectors. Having employees participate in safety work or risk-reducing safety measures depends on the safety awareness of senior managers and organizations (Shaluf, Ahmad, & Shariff, 2003).

Whether or not the organization or upper management places a strong emphasis on safety can often be discovered by checking the relationship between plant production and the annual plans in the plants. The high-tech industry has a market cycle. When plants are operating at full capacity, many shorten the duration of annual shutdowns or prolong the period between shutdowns to catch up with orders, and all employees participate in the work to increase production. All of these circumstances can result in accidents.

3.7. Training

High-tech plants should follow sound training protocols with extraordinary diligence. However, because of the nature of the high-tech profession, some problems might occur, such as whether an instructor is competent, whether teaching materials are adequate, and whether employees follow the program to receive the training. One common fault is that the training, which is supposed to be done by a knowledgeable engineer, is instead done by an apprentice or inexperienced engineer, because the advanced employee cannot leave their position for too long. It is difficult to estimate the damage caused by these insufficiently trained personnel.
3.8. Contractor management

Generally speaking, the majority of high-tech companies in Taiwan have good contractor management systems in which various methods are employed to carefully screen contractors in advance. Nevertheless, some serious accidents including fire and leakage have still occurred in high-tech companies due to reckless operation by contractors. For example, an arsine leak in one plant caused many operators to be hospitalized; a silane leak in another plant led to a conflagration; and a filling error of water treatment reagents resulted in a chlorine leak.

3.9. Incident investigation

Incident investigations in high-tech plants are performed cautiously and confidentially. Information regarding incident investigations is closed, not only between one business and another, but also between subsidiary companies in the same business group. The industrial safety staff often encounter the problems of important questions being evaded and intentional concealment when they investigate an incident or false alarm. In the case of an evacuation caused by a false fire alarm, although the engineering department knew the whole story, they were unwilling or reluctant to share the true details, which make incident investigation difficult. However, if a serious accident occurred, the regional labor safety department from CLA would initiate a thorough investigation, seeking out the root cause and proposing prevention measures for future operation.

3.10. Compliance audits

Each high-tech company has its own audit system for safety management. The industrial safety staff usually perform the primary audit, whereas a department manager generally does the secondary audit. The auditor’s experience and ability affects whether a violation of a safety regulation or potential hazard can be identified. However, a high-tech company is comprised of many different technologies and departments, so most industrial safety staff audits only the technology in which they specialize. The safety audits mostly focus on superficial mistakes; therefore, many serious mistakes, such as equipment safety protections being illegally bypassed, are often not discovered.

3.11. Pre-startup safety review

The equipment in high-tech companies usually goes through a pre-startup safety inspection before being put into official regular production. The inspected items include supply systems, safety monitoring equipment, pipelines, vent systems and emergency shutdowns. However, some plants still put the equipment into production without a pre-startup safety inspection due to urgent production demands.

3.12. Hot work permit

A hot work permit receives significant attention in high-tech companies, so very few plants have accidents because of poor management of hot work permits. These hot work permits, however, should be expanded to fire control (i.e., any chemicals that might cause a fire should be kept away from a fire or external thermal source).

3.13. Mechanical integrity

Unlike petrochemical plants, general maintenance in high-tech companies is conducted quite well, and thus accidents are seldom caused by equipment aging and pipeline corrosion.

4. Conclusions

Most of the plants in the chemical industries that are small or medium scale require counseling and assistance to effectively improve loss prevention (Fig. 6). The labor commission will be able to provide personalized assistance based on the actual conditions of each plant if it categorizes and classifies the data accumulated from the 190 plants that accepted counseling and assistance. For example, plants with sufficient manpower, budget, and certain levels of safety management can be provided with thorough assistance regarding safety management. However, those having inferior safety management should be offered extraordinary assistance on key subjects, so that they can obtain the correct knowledge and develop experience to further avoid serious risks. The best effect will be achieved if the plants are guided and assisted on the basis of their individual needs.

In Taiwan, the hazards and risks of high-tech companies are higher than in other industrial sectors. Therefore, a variety of safety management methods and regulations appropriate for high-tech companies have been generated and implemented. However, it is crucial for managers and industrial safety specialists to think carefully about how to completely identify, understand, and control potential hazards associated with the manufacturing processes. Furthermore, they need to determine and address uncertainties that arise from any operational errors or incidents across the whole range of stages in manufacturing.

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