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Study of chemical supply system of high-tech process using inherently safer design strategies in Taiwan

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ABSTRACT

The photoelectric, semiconductor and other high-tech industries are Taiwan's most important economic activities. High-tech plant incidents are caused by hazardous energy, even when that energy is confined to the inside of the process machine. During daily maintenance procedures, overhauling or troubleshooting, engineers entering the interior of the machines are in direct contact with the source of the energy or hazardous substances, which can cause serious injury. The best method for preventing such incidents is to use inherently safer design strategies (ISDs); this approach can fully eliminate the dangers from the sources of hazardous energy at a facility.

This study first conducts a lithography process hazard analysis and compiles a statistical analysis of the causes of the fires and losses at high-tech plants in Taiwan since 1996, the aim being to establish the necessary improvement measures by using the Fire Dynamics Simulation (FDS) to solve relevant problems. The researchers also investigate the lithography process machine in order to explore carriage improvement measures, and analyse the fires' causes and reactive materials hazardous properties, from 1996 to 2012. The effective improvement measures are established based on the accident statistics. The study site is a 300 mm wafer fabrication plant located in Hsinchu Science Park, Taiwan.

After the completion of the annual maintenance jobs improvement from September 2011 to December 2012, the number of lithography process accidents was reduced from 6 to 1. The accident rate was significantly reduced and there were no staff time losses for a continuous 6882 h. It is confirmed that the plant safety level has been effectively enhanced. The researchers offer safety design recommendations regarding transport process appliances, chemical storage tanks, fume cupboard devices, chemical rooms, pumping equipment, transportation pipelines, valve manual box (VMB) process machines and liquid waste discharge lines. These recommendations can be applied in these industries to enhance the safety level of high-tech plants, facilities or process systems.

1. Introduction

Many major Taiwanese high-tech plant accidents have occurred in the past year. A fire incident occurred at a semiconductor circuit packaging and testing facility at 2 pm on May 1, 2005, which resulted in injuries to 7 people, including one firefighter. The fire in the 1F boiler ignited nearby acid drain substances and the fire burned along the channeling of the acid exhaust pipe. Another accident occurred in the same year at 11:30 on November 23rd. In this instance, a fire and explosion occurred in a cylinder room for silane and ammonia gases at a solar cell production, resulting in the death of one employee; many others were hospitalized due to choking or inhalation of harmful substances. The following year, at 8:23 on December 17th, an explosion in the furnace at a crystal growth high-tech facility resulted in the death of two workers (Yang, Yang, Yu, & Chen, 2009).

Photoelectric, semiconductor and other high-tech industries are some of Taiwan's most important economic activities. The completed raw materials, pre-processing, product manufacturing and final disposal in the production supply chain are important for whole operation activists because any fire, explosions, gas leaks, power outages and other disasters, will result in the interruption of the supply chain, thereby, causing an unsustainable operational dilemma (Chang & Chen, 2007).

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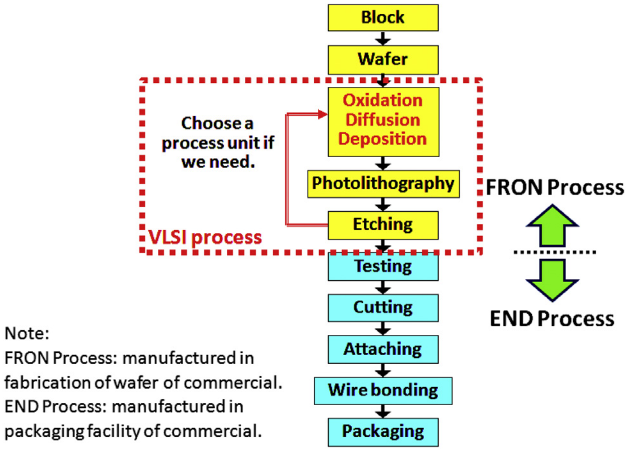


Fig. 1. Semiconductor manufacturing process flow diagram.

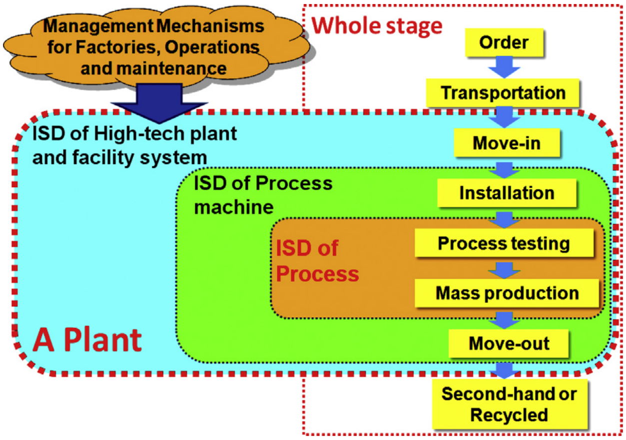


Fig. 2. Whole stage of high-tech process and facility safety using ISD strategies.

In a large-scale high-tech plant, in order to achieve physical vapor deposition (PVD), chemical vapor deposition (CVD), photolithography, etching, diffusion, ion implantation and the oxidation process, as shown in Fig. 1 (Sze & Ng, 2006), the process tool uses a lot of flammable, spontaneous combustion; toxic, corrosive, special gases and chemical materials. High-tech plants are filled with large amounts of toxic substances at any given time. Fire, explosions and chemical spills occasionally occur from flammable chemicals. High toxicity, high risk environment and a variety of disasters often increase the general public's fear of high-tech industry. Therefore, the aim of this study was to investigate the implementation of inherently safer design strategies in order to enhance the safety of the workers and the facilities.

Kletz (1984, 1985, 1998) first proposed the inherently safer design (ISD) principle, which includes the Minimize, Substitute, Moderate and Simplify strategies. Edwards and Lawrence (1993) and Crowl (1997) discussed Assessing the Inherent Safety of Chemical Process Routes, asking the question, "Is there a relation

Table 1
Statistical analysis of the cause of the fire and the loss of high-tech plant over the years from 1996 to 2010, in Taiwan.

Types of disasters	Time of occurrence	Type of company	Causes	Casualties	Property damage cost (US$)
Fire	1996.10.14	Semiconductor manufacturers	Wet cleaning machine ignition of flammable liquids	No injury	More than 2 hundred million
Fire	1997.10.03	Semiconductor manufacturers	Silane leaks	No injury	More than 2.9 hundred million
Fire	1997.11.11	Semiconductor manufacturers	Wet cleaning machine ignition of flammable liquids	No injury	More than 5.72 million
Fire	1999.09.22	Semiconductor manufacturers	Generator overheating	No injury	More than 0.71 million
Fire	2000.03.31	PCB materials	Boiler room heavy oil ignition of flammable liquids caused by leak and spray liquids.	2 Dead 11 injured	More than 1.14 million
Fire	2000.06.09	LED materials	Silane leaks	13 Injured	More than 5.7 million
Explosion	2000.09.10	PCB manufacturers	Boiler explosion	No injury	More than 28.5 thousand
Fire	2000.12.25	Semiconductor manufacturers	Generator overheating	No injury	More than 0.85 million
Fire	2001.01.18	PCB materials	Unknown	No injury	More than 0.14 million
Fire	2001.05.12	Electronic materials	Fire caused by flame	No injury	More than 1.43 hundred million
Fire	2001.05.31	PCB manufacturers	Unknown	No injury	More than 2.86 million
Fire	2001.06.28	NB manufacturers	Unknown	No injury	More than 1.71 million
Fire	2001.06.28	Smart phone manufacturers	Unknown	No injury	More than 4.29 million
Fire	2002.02.25	PCB manufacturers	Unknown	No injury	More than 22.8 million
Fire	2002.02.26	Electronic materials	Electrical fire	No injury	More than 0.85 million
Fire	2002.08.22	Automated trading equipment	Unknown	No injury	More than 0.22 million
Fire	2002.09.01	PCB manufacturers	Machine damage	No injury	More than 28.6 million
Fire	2002.12.10	Wafer manufacturers	Machine failure	No injury	More than 10 million
Fire	2003.10.02	PCB manufacturers	Unknown	No injury	More than 12.8 million
Fire	2004.01.10	Electronic materials	Machine overheating	No injury	More than 4.3 million
Fire	2004.06.10	Semiconductor manufacturers	Machine overheating	No injury	More than 0.43 million
Fire	2004.08.25	DVD manufacturers	Unknown	No injury	More than 0.429 million
Fire	2004.09.19	NB manufacturers	Electrical fire	No injury	More than 1.05 million
Fire	2004.06.11	LCD materials	Chemical fire	7 Injured	More than 8.57 million
Explosion	2005.05.01	IC packaging	Boiler explosion	1 Injured	More than 2.86 hundred million
Fire	2005.08.15	Tech chemicals	Chemical fire	1 Dead	More than 57 thousand
Explosion	2005.11.23	Solar cell manufacturers	Leakage explosion	1 Dead	More than 1.43 hundred million
Fire	2006.03.02	PCB manufacturers	Hydrochloric acid and bleach water leaks	No injury	More than 8.5 thousand
Fire	2006.04.07	DVD manufacturers	Drying chamber fire	1 Dead	More than 1.43 million
Explosion	2006.12.17	Solar wafer manufacturers	Crystal growth furnace explosion	2 Dead	More than 28.6 thousand
Fire	2010.03.30	Pharmaceutical manufacturing	Chemical fire	No injury	More than 0.29 million

Note: 1. PCB: Printed Circuit Board; 2. LED: Light Emitting Diode; 3. NB: Note Book computer; 4. DVD: Digital Video Disc; 5. IC: Integrated Circuit.

between plant costs and inherent safety?" Because of the harmfulness of chemical processes and the wide range of plant facilities, accidents might occur at any time, so consideration of inherently safer levels is necessary. Heikkilä (1999) discussed Inherent safety in process plant design as an index-based approach, and gave a detailed description of the process and application methods of inherently safer design strategies. Khan and Amyotte (2004) also suggested that the current attitude of industry regarding ISD was inadequate, especially the importance of applying ISD in the early stages of plant design. Other studies have also investigated high-tech processes using ISD strategies in Taiwan (Chang & Chen, 2007; Chen, Chang, Lu, & Wang, 2013; Chen, Chang, & Wang, 2013).

A high-tech plant uses a lot of equipment. Among these machines, lithography equipment is the key in process technologies. Taking the most advanced 12-inch wafer fabrication internal scan system as an example, the old and the new machines cost close to NT$ 30–70 billion. Often a 12-inch wafer fabrication requires 20–30 units of lithography equipment; capital spending accounts for 30–60% of the total investment of the entire wafer. Affected by the high price of the device due to the precision of the equipment, equipment manufacturers need to communicate with customers so that they will understand the demands for equipment-related delivery and installation. Finally, equipment manufacturers must inspect plants five months in advance to discern whether the plants are able to receive delivery of equipment meeting the requirements for shipment and on-site installation of the equipment, and they must do a follow-up to ensure that the plant is capable of ongoing commercial production. These are the main reasons why we selected the lithography process for the study.

Integrating the literature discussed, the authors find that research in the high-tech manufacturing process is still too weak regarding safety issues; and all sectors of high-tech plant safety only focused on the operational phase of the overall high-tech process. Machine safety should cover the whole stage (as shown in Fig. 2), and the inherently safer goal could only be reached from ordering, transportation, on-site installation and cross machining before the process capability test.

2. Methodology

After the toxic gas leak occurred in Bhopal, India in 1984, which caused the death of two thousand people, Kletz (1984, 1985, 1998) proposed five inherent safety principles: intensification, substitution, simplification, moderation and limitation of effects. Chen, Chang, Lu, et al. (2013) and Chen, Chang, and Wang (2013) proposed their idea for applying ISD strategies in high-tech processes,

Table 2
Summary of semiconductor process operating purposes and reactive materials used.

Process	Name of reactive gas	Operating purposes	Hazardous	Property type of exhaust/drain	State
Chemical vapor deposition (CVD)	SiH_4	Dielectric layer material	Poisoning, explosion, spontaneous combustion	Toxic gases	Gases
	B_2H_6	BPSG	Poisoning, burning, exploding	Toxic gases	Gases
	NH_3	Si_3N_4	Poisoning, corrosion	Toxic liquid	Liquid
	H_2	Oxide layer	Combustion, explosion	Combustible gas	Gases
	TEOS (tetra ethyl ortho silicate)	SiO_2 and glass	Poisoning	Toxic liquid	Liquid
	SiH_2Cl_2	Si_3N_4	Poisoning, burning, explosion, corrosion	Toxic gases	Gases
	$TiCl_4$	TiN/Ti	Poisoning	Toxic liquid	Liquid
	WF_6	Wsix or W	Poisoning, corrosion	Toxic gases	Gases
Wet etching	CF_4	SiO_2, Si_3N_4, Al	Micro-toxic, non-flammable, suffocation	Toxic gases	Gases
Dry etching	CHF_3	SiO_2, Si_3N_4	Poisoning, noncombustible	Toxic gases	Gases
	O_2	Dry etching	Combustion-supporting	General gas	Gases
	SF_6	SiO_2, poly, TiN, W	Poisoning, noncombustible	Toxic gases	Gases
	H_2SO_4	Wet etching	Corrosion	Acidic liquid	Liquid
	H_3PO_4	Wet etching	Corrosion	Acidic liquid	Liquid
	HCl	Wet etching	Poisoning, corrosion	Acidic liquid/toxic gases	Liquid/gases
	Methanol	Wet etching	Combustion, volatile	Organic solvents	Liquid
Ion implantation	PH_3	N-type (trivalent)	Poisoning, burning, explosion, spontaneous combustion	Toxic gases	Gases
	BF_3	P-type (pentavalent)	Poisoning, burning	Toxic gases	Gases
	AsH_3	N-type (trivalent)	Poisoning, burning, explosion, spontaneous combustion	Toxic gases	Gases
	BCl_3	P-type (pentavalent)	Poisoning, corrosion	Toxic liquid	Liquid
Photolithography	AZP4620 (name of developer)	Photoresist	Poisoning, volatile	Organic solvents	Liquid
	S1813 (name of developer)	Photoresist	Poisoning, volatile	Organic solvents	Liquid
	HMDS (adhesion study of hexamethyldisilazane)	Priming	Poisoning, volatile	Organic solvents	Liquid
	N-butyl acetate	Development	Poisoning, volatile	Organic solvents	Liquid
	NaOH	Development	Corrosion	Alkaline liquid	Liquid
	TMAH (tetra-methyl ammonium hydroxide)	Development	Poisoning, corrosion	Alkaline liquid	Liquid
	Acetone	Photoresist removal	Poisoning, volatile	Organic solvents	Liquid
	H_2SO_4	Photoresist removal	Corrosion	Acidic liquid	Liquid
	H_2O_2	Photoresist removal	Corrosion	Acidic liquid	Liquid
Chemical mechanical polish (CMP)	KOH	SiO_2	Corrosion	Alkaline liquid	Liquid
	H_2O_2	Cu, W	Corrosion	Acidic liquid	Liquid
	NH_4OH	Afterward CMP, SiO_2	Corrosion	Alkaline liquid	Liquid
	Trichloroethylene	Clean	Poisoning, volatile	Organic solvents	Liquid
	HF	Afterward CMP	Corrosion	Acidic liquid	Liquid
	Acetone	Clean	Poisoning	Organic solvents	Liquid
	H_2SO_4	Clean	Corrosion	Acidic liquid	Liquid
Carrier gas	N_2, Ar, He	Carrier gas	Noncombustible, suffocation, combustion-supporting	Inert gas	Gases

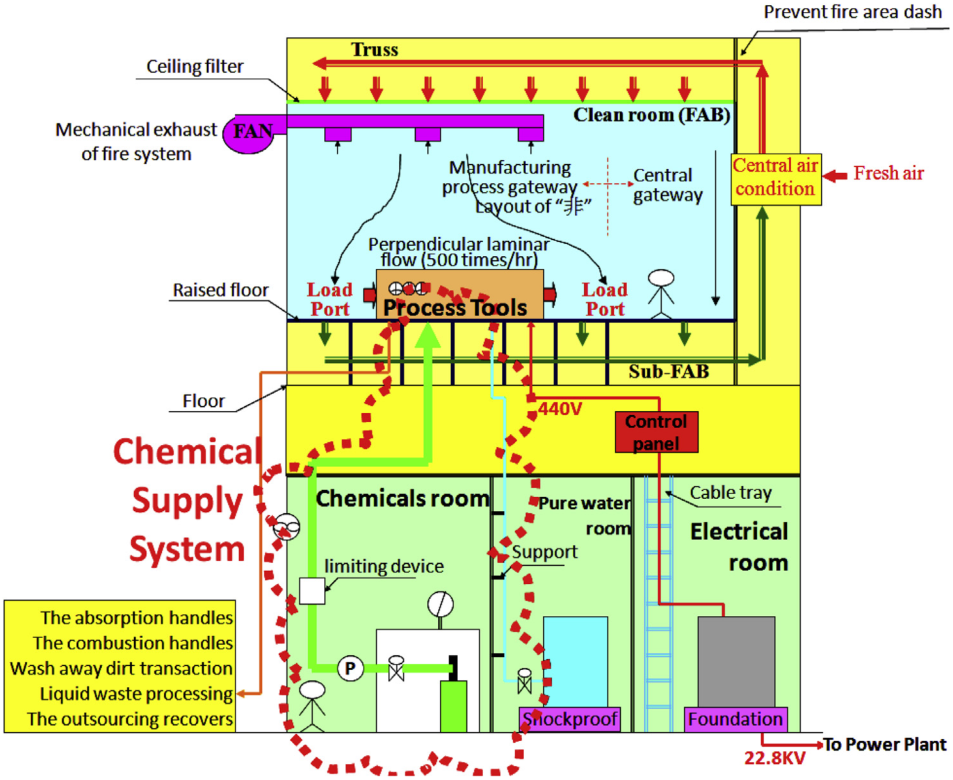


Fig. 3. Chemical supply system configuration diagram of a high-tech plant (Chang & Chen, 2008).

pointing out that, for the main reactor of the system, the available ISD strategies included: intensification, substitution, attenuation and limitation of effects; while for system sub-element structures, the feasible ISD strategies included simplification, avoiding knock-on effects, making incorrect assembly impossible, making the status clear, tolerance, ease of control and software.

In order to understand the hazards of the installation of high-tech manufacturing equipment, this study used FMEA (Stamatis, 2003) as an analytical tool. Sharma, Kumar, and Kumar (2005), using the fuzzy theory failure mode and performance analysis, verified that FMEA was an effective tool to grasp the actual problem. Su and Chou (2008) also proposed that FMEA was a method that could be suitably applied to the high-tech industry.

Considering the lithography process machine transport container fire situation, in order to understand the accident before temperature, velocity and plume dispersion, this study uses the FDS software tool for fire heat of Maelstrom-scale calculations (Large Eddy Simulation, LES), equations related to fire simulation application software, and a computational fluid dynamics model. This simulation software can be used in a fire scenario simulating three-dimensional space. The analog range is divided into several cubes of a computational grid, numerically solving the equations of conservation. The results will be more reasonable and precise, with accurate estimates of the physical data of the fire, including: when the fire broke out, pressure, temperature, speed and plume flow fire, as well as accurately predicting and determining the projects

(a) Setting in the sub-Fab chemical storage cabinet (clean booth), chemicals were delivered to the clean room by the pump power of lithography process machine

(b) Chemicals stored in glass bottles sated directly in the single process tool

Fig. 4. Chemicals supply system of lithography process. (a) Setting in the sub-Fab chemical storage cabinet (clean booth), chemicals were delivered to the clean room by the pump power of lithography process machine. (b) Chemicals stored in glass bottles sated directly in the single process tool.

Table 3
Chemical usages and hazards of a high-tech plant.

Chemicals	Process purpose	Hazards	Taste	Health effects	Usage amount
Isopropanol (IPA)	Wet cleaning process	Fire, explosion, central nervous system poisoning, skin irritation	Rubbing alcohol flavor	If happen inhalation will be cause to central nervous system disorders, coma, and fatal breathing disorder.	Large
Methanol (CH_3OH)	Wet cleaning process	Fire, explosion, central nervous and optic nerve anesthesia	Slight smell of alcohol	If happen inhalation of vapors can cause central nervous system and optic nerve anesthesia, overexposure to have headaches, fatigue, nausea, vomiting, blurred vision, coma and other symptoms.	Large
Positive photoresist (AR-2450)	Photolithography process	Fire, explosion, and respiratory irritation	Sweet	It will be absorbed through the skin, causing irritation to the skin, redness, and pain.	Small
Photoresist (SR-2430)	Photolithography process	Fire, explosion, allergic contact dermatitis	Sweet	If happened skin contact may cause allergies	Small
Positive photoresist of UV type (UV8-1.0)	Photolithography process	Fire, explosion, organic solvent poisoning	Slightly fragrant	If prolonged exposure to high concentrations of vapor may cause organic solvent poisoning (damage to the liver and kidneys).	Small
Photoresist adhesion strengthening liquid (OAP)	Photolithography process	Fire, explosion, central nervous anesthesia	No	If excessive inhalation of its vapors can irritate the respiratory tract, and may accumulate in the lungs, the substance is narcotic.	Small
Wafer edge cleaning liquid (OK82)	Photolithography process	Fire, explosion, and respiratory tract irritation	No	If the contact will be cause irritation to the respiratory tract, to exceed 100 ppm there will be odor causing unpleasant, exceeding 1000 ppm there will be headache, dizziness, and drowsiness produce.	Medium
Cyclohexanone (ONNR20)	Photolithography process	Fire, explosion, poisoning	Like acetone taste	If exposed to 75 ppm exposure time of 3–5 min can irritate the nose and throat, and high concentrations of vapor can cause inhibition of the nervous system, such as headache, dizziness, drowsiness and mental confusion, and even cause loss of consciousness and death.	Small
Developer (AZ A-515)	Photolithography process	Fire, explosion, poisoning of the central nervous system	Like acetone taste	If the contact will be because irritation of the respiratory system, causing coughing, shortness of breath, high concentrations can cause anesthetic phenomenon, there will be dizziness, mild headache and other symptoms. May cause central nervous system depression or in a state of intoxication.	Small
Developer (AD-10)	Photolithography process	Causticity	Like ammonia odor	If you exposed can cause skin burns.	Medium
Rotary coated glass solution (NFC SOG04)	Photolithography process	Fire, explosion, stimulation and anesthesia	No	If you exposed can stimulation of the nose and throat caused by anesthesia, prolonged contact and repeatability of skin, then cause irritation and dermatitis.	Small

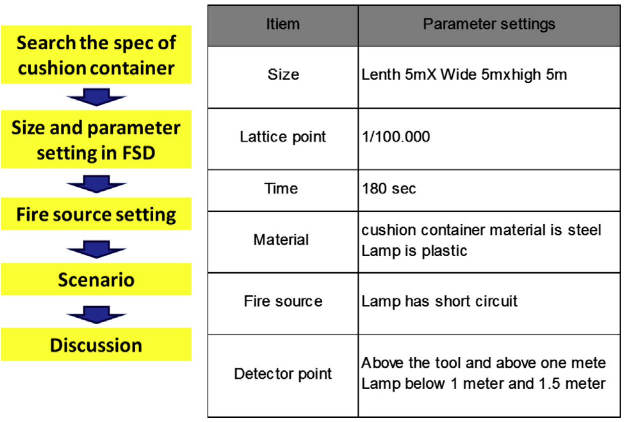
that the author may have overlooked. FDS refers mainly to the Navier–Stokes Equations to calculate the fluid flow and effect of the heat of the fire on the buildings and space transfer changes, as in the following conservation equations (Floyd, McGrattan, Hostikka, & Baum, 2003; McGrattan, 2007; McGrattan, Baum, & Rehm, 1998; Ryder, Sutula, Schemel, Hamer, & Brunt, 2004).

3. Lithography process hazard analysis

This study compiled Taiwan's statistical analysis of the cause of the fires and the loss of high-tech plants over the years since 1996, as shown in Table 1 (Chang & Chen, 2007; Cheng, 2011; Lin, 2003, 2007). The most serious fire cases were semiconductor plants;

Table 4
Status of the design principles of the lithography process in chemical supply system.

List name of chemicals	Volume of use	Supply method and system scale
Photoresists, cyclohexanone, developer, rotary coating glass solution	Small	Supply system of Single process tool, chemicals stored in glass bottles, and setting directly in the machine, used of the internal pump of the machine to the pressured and conveyed to the process chamber, this supply system mode is short supply distance and small piping diameter supply, its minimum size of whole system.
Wafer edge cleaning liquid, developer, Photoresist stripping liquid	Medium	Central supply system of small-scale, pumping from 1F pump room (Central Utility Building, CUB) and coordinating with SUB-FAB the PN2 (supply pressure of approximately 2–3 kg/cm^2) pressurized supply to process chamber, tank or bottle of chemicals are storied in clean booth.
Isopropanol, methanol	Large	Central supply system of Medium-scale, pumping from 1F pump room (CUB) and transportation to buffer tank of SUB-FAB, and then pumping to process chamber in the clean room.



Itiem	Parameter settings
Size	Lenth 5mX Wide 5mxhigh 5m
Lattice point	1/100.000
Time	180 sec
Material	cushion container material is steel Lamp is plastic
Fire source	Lamp has short circuit
Detector point	Above the tool and above one mete Lamp below 1 meter and 1.5 meter

Fig. 5. FDS software application to processes and parameter settings.

obviously, they should be regarded as the primary targets for disaster prevention in high-tech processes of semiconductor processes in Taiwan.

This research focused on the analysis and collection of key process reactive materials in a semiconductor process, as shown in Table 2. Spontaneous combustion, combustion, explosion, poisoning and corrosion are more hazardous in the reaction of the original material type and its physical characteristics in a production process in a semiconductor high-tech plant. Managers should not neglect the raw materials that will cause plant fires and explosions.

The chemicals supply system occupies an important position in the high-tech plant. There are many large organic solvent supply systems in the lithography process, and the system structure pumps the chemicals from a tank in the ground. In addition, in order to prevent micro-leakage and accumulation of chemical vapors, chemical storage barrels should be located in an exhaust cabinet or separate storage room. The chemical supply system architecture is shown in Fig. 3 (Chang & Chen, 2008), and the actual setup is shown in Fig. 4.

Based on the foregoing analysis, this study discussed usage and hazards in a semiconductor process using liquid chemical raw materials, as shown in Table 3, and illustrated through the use of organic solvents on a wet cleaning process, followed by the lithography process. This result has been consistent over the years, as shown by fire statistics and trends; however, it also points out that safety management only focuses on a wet cleaning process rather than the potential problems of a lithography process. This study suggests strengthening the lithography process chemical management.

The high-tech plant chemical supply system is generally based on the principles set, as shown in Table 4. The central supply systems for small-scale organic solvent require a large supply of power, so the impact on staff is more significant. An unfortunate leak may cause a fire with an explosion severity greater than the stand-alone supply system, but part of the stand-alone system for highly toxic hazardous chemical applications still cannot be taken lightly, as its main purpose is as a lithography process developer, tetramethyl ammonium hydroxide (TMAH) solution. In Taiwan, a number of fatalities have occurred (Wu, 2003). The chemical supply system of the actual commercial lithography process is the situation shown in Fig. 5, wherein (a) a sub-fabrication chemical storage cabinet was provided. The chemicals are delivered by means of pump power to the clean room lithography process machine; (b) the lithography process machine is located in Taichung, while chemical bottles are stored in a stand-alone supply system.

4. The lithography process hazard prevention measures establishment and execution

This study examines statistics where accidents occurred in the lithography process of high-tech companies located in a 300 mm wafer fabrication cluster in Hsinchu Science Park, Taiwan, from August 2009 to August 2011. The results are shown in Table 5. The analysis of accidents occurring in December 2009 and May 2011 were a result of the disassembly of the chemical supply system. Operating personnel were not really equipped with personal protective equipment, and the yellow machine freight container fire in

Table 5
Accident statistics of lithography process occurred in a 300 mm wafer fabrication of high-tech companies located in Hsinchu Science Park, Taiwan (from August 2009 to August 2011).

Accident date	Situation descriptions	Located	Injury situation	Losses
December 2009	Equipment engineer did not equipped PPE of goggle or face shield then developer splashing to face and eyes when disassembly piping lines of lithography process adjustment (management of change, MOC)	FAB (clean room)	Face and eyes swollen	112 h of lost
March 2010	The photoresist supply pipeline joint leaked, operators smelled the odor and notified to emergency response center (ERC), and then equipment engineer inspected and found the leak point. (The leak concentration less than staff withdrawal facilities specification level.)	FAB (clean room)	No injury	Shutdown 2 h of lithography tool
April 2010	The pressurized pump leakage organic solvent of facility side in SUB-FAB, then leak sensor active, ERC action, and operators evacuated.	Chemicals storage room	No injury	Shutdown 2 h of 4 lithography tool, total lost is 8 h.
August 2010	When container trucks unloading photolithography tools, then the top of the container internal happen the electrical short circuit caused by lamps system, then container fire, ERC action for firefighting, one member choking injuries.	Loading/unloading area	Smoke choking injuries	86 h of lost, lithography tool Scrapped by Smoke pollution.
January 2011	Photoresist overflowed and dripped to SUB-FAB floor, and then facility engineers discovered at SUB-FAB and informed ERC for treatment.	Fab and sub-Fab	No injury	Shutdown 3 h of lithography tool
May 2011	When annual repairs of chemical supply pipeline cleaning works of photolithography process, equipment engineers used damaged gloves, he discovered redness of hands until after the job.	Fab (clean room)	The hands skin contact stimulus and redness	8 h of lost

Table 6
FMEA analysis results.

Item	Failure mode	Influence	Severity	Probability	Score	Risk
Human negligence	Equipment engineer did not equip PPE when demolition pipeline operation.	Developer splashing to face and eyes of equipment engineer.	6	10	60	2
System failure	The photoresist supply pipeline joint leaked.	Operators smelled the odor.	1	10	10	4
System failure	The pressurized pump leakage organic solvent of facility side in SUB-FAB.	Lithography tools shutdown.	3	6	18	4
Human negligence	The container internal happened the electrical short circuit caused by lamps system.	Container fire, ERC action for firefighting, one member choking injuries.	6	10	60	2
System failure	Photoresist overflowed and dripped to SUB-FAB floor.	Lithography tools shutdown.	6	6	36	3
Human negligence	Equipment engineers used damaged gloves and contacted chemicals.	Gloves damaged and then chemicals contacted.	6	10	60	2

August 2010 caused the most serious harm to people, with serious loss of equipment as well. The research focuses on these with in-depth explorations.

For effective identification and simulation of equipment transportation and handling possible component failures caused by the operation, this study chose and discussed in detail the risk assessment method, FMEA, based on the August 2010 yellow machine cargo container fire accident, having obtained relevant simulation data and then, comparing them with actual data, and conducting a risk assessment with brainstorming and software applications. Risk level determination of this study refers to the conduct process safety assessment of the risk level judgment standard, SEMI S10 (SEMI, 2007). The FMEA analysis results of this study were based on Table 5. As shown in Table 6, there are three unacceptable risks and three acceptable risks.

1. To explore carriage improvement measures of the lithography process machine using ISD strategies

FDS is a very good tool for exploring the fire temperature field and velocity field. The direction of the stream from a fire plume dispersion scenario could be explored in order to assess the lithography process for machine transport where the container catches fire, and determination must be made regarding how much time it would take to affect the device. The FDS software application used to process and the parameter settings of this study are shown in Fig. 5.

The simulated air cushion container was 5 m in length, 5 m in width and 5 m in height. The grid was designed as 1:100 000, which is the benchmark for fire field simulation. The detection points were located 1 m above the equipment, 1.5 m on either side of the equipment and 2 m below the short-circuited lamp simulated temperature change and smoke descending when the fire broke out. Through a comparison of software simulation data and actual fire conditions, this study determined how long the equipment would be unaffected by temperature and descending smoke, without personnel being present.

Table 7
Required equipment move-in conditions (ASML, 2010).

Parameter	Climatic requirements
Temperature range	15–30 °C (Without time constraints) −20 to 15 °C (Within 2 h) 30–40 °C (Within 2 h)
Maximum temperature gradient	N/A
Relative humidity	30–60% (No rain requirements)
Air pressure	70–150 kPa
Maximum pressure gradient	7.5 kPa/h

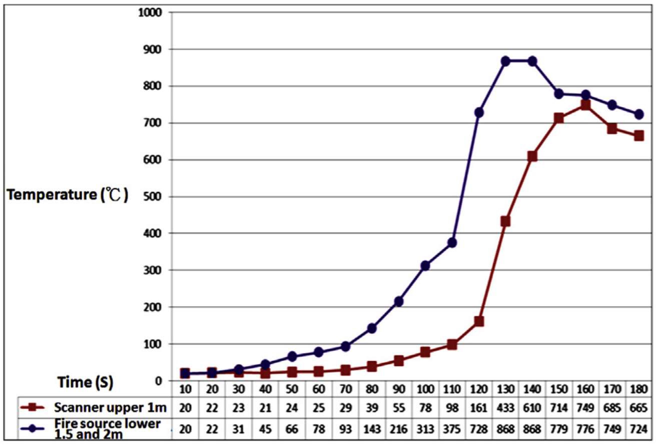


Fig. 6. FDS fire simulation results of temperature vs. time.

When transporting internal precision components of a scanning exposure machine in an air cushion container, regulations of the IRM (Installation requirement manual) (ASML, 2010) should be followed. The transport ambient temperature should be controlled in the range of 15–30 °C, and humidity below 60%. In case of accidental fire, which might lead to complete deviation from the requirements, in terms of internal temperature, FDS software could be applied to preliminarily predict how long it would take before

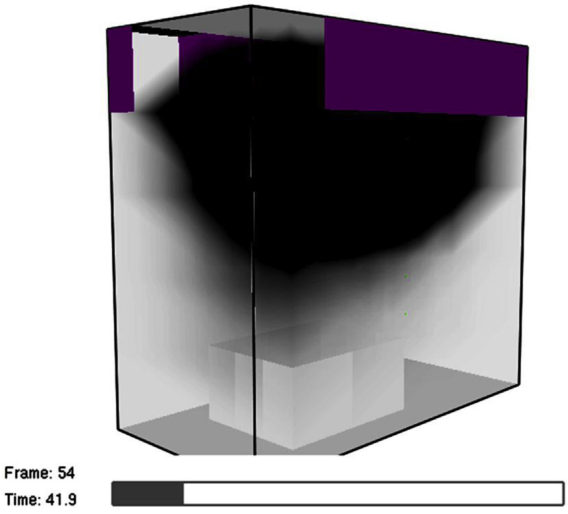


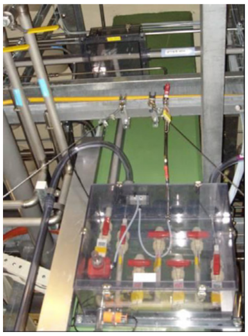
Fig. 7. FDS smoke descending situation.

Table 8
Summary of other hazardous improvement for implementation of the measures to lithography process machine.

Engineering improvement measures	Reference picture	Explanation
Pumping equipment		1. Result of ISD strategy of limitation of effects: a comprehensive review of whether the chemical supply pumps with explosion-proof type. Replacing a total of 7 chemical supply pumps in annual repairs in September 2011. 2. Result of ISD strategy of intensification: we installed a new tool of wet cleaning process, the chemical supply pump replacement to Air-action Reciprocating type, and fundamentally eliminated electric energy existence.
Process Tools		1. Result of ISD strategy of intensification: We installed a new tool of wet cleaning process, the internal structure of the full adoption of reinforced plastic material, internal control valves and pressure power source are used pneumatic pressurized, essential eliminate opportunities for contact of electrical energy and organic solvent chemicals.
		1. Result of ISD strategy of avoiding knock-on effects: Organic solvent is flammable liquid, easy to cause a fire and explosion, so we try to check and inspect process tool that did not installed firefighting system, then we completed to install 3 sets of CO_2 system in annual repairs.
		1. Result of ISD strategy of making status clear: We checked and inspected chemical supply system of process tool that hazards marked and labeling is enough in annual repairs, total improved 66 points.
Other improvement works of facilities.		1. Result of ISD strategy of tolerance: We checked and inspected all pipeline materials of chemical supply system, Pipelines 28 m changed to material of SUS316L EP, 137 m changed to double casing.
		1. Result of ISD strategy of limitation of effects and avoiding knock-on effects: clean booth of chemical room did not set fluid-proof dikes and leak sensors; we completed to improve 5 areas for install fluid-proof dikes and leak sensors.

(*continued on next page*)

Table 8 (*continued*)

Engineering improvement measures	Reference picture	Explanation
		1. Result of ISD strategy of making status clear limitation of effects and avoiding knock-on effects: The valve manual box (VMB) of chemical supply system did not marked status of open/close and poor management of unlocked, total 225 improved for status marked, and 47 improved for locked management.
		1. Result of ISD strategy of limitation of effects and tolerance: We checked and inspected of explosion-proof lamps, total replace 3 explosion-proof lamps in annual repairs.
		1. Result of ISD strategy of tolerance: Chemical storage barrels conveying appliances originally not set a fixed chain and chocks, so the chemicals in danger of capsizing, we installed fixed chain and chocks in annual repairs.
Auxiliary administrative measures		In this study, in addition to the engineering improvements to reduce the level of risk, we try to ensure that personnel safety for maintenance and troubleshooting works of chemical supply system and process tools, we conformed SOP for operating and wear personal protective equipment (PPE) when operation observation.

the container temperature would reach an unacceptable level. In this way, it could provide the rescue personnel with preliminary information about the equipment and help them to formulate relevant response procedures. Requirements for relevant precision components of the equipment transported in the air cushion container are shown in Table 7.

After 70 s (Fig. 6), the temperature of the fire source reached 93 °C, and the radiation heat started to indirectly affect the surface temperature, while the scanner temperature of 29 °C reached the deviation temperature of equipment transportation. After 80 s, the equipment surface temperature reached 39 °C, which exceeded the standard for equipment move-in requirements. In other words, the move-in personnel should shift the tool out within 70 s after the breakout of a fire. However, due to a large amount of plastic protection materials being placed above the tool, the plastic would be heated, and thus, shorten the possible time to remove the tool equipment safely.

The above tool equipment should be removed from the air cushion container within 70 s when the temperature is about to reach an unacceptable level for transportation. However, the move-in personnel faces another issue: smoke damage to the tool equipment. The tool equipment should be removed before being damaged or affected. Due to smoke descending, the equipment should be removed within 41 s of the start of the smoke descending, in order to prevent the equipment's cleanliness being compromised and any smoke damage (Fig. 7).

2. To explore other improvement measures to limit the hazards of the lithography process machine using ISD strategy.

As seen in Tables 5 and 6, 300 mm wafer fabrication high-tech companies in Hsinchu, Taiwan, underwent annual repairs in September 2011. The important work is illustrated in Table 8.

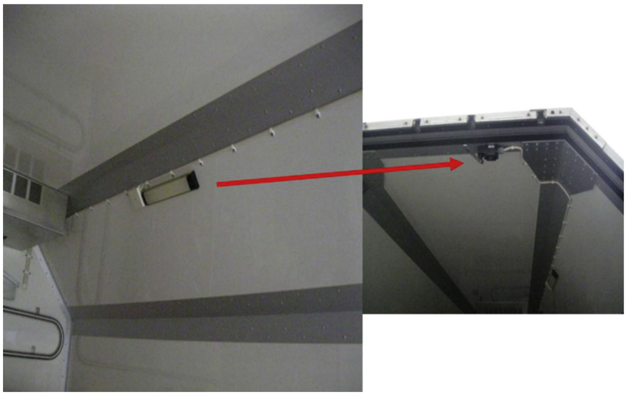


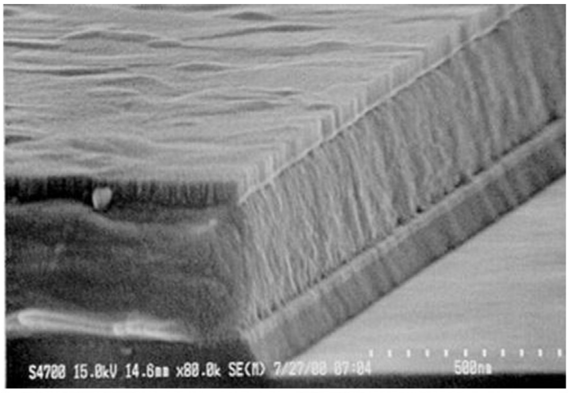
Fig. 8. Installation of safety interlocking device to prevent overheating of electric equipment.

5. Results and discussion

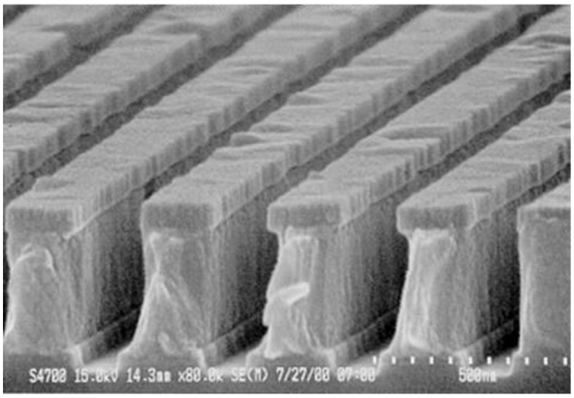
According to simulation results, the researchers recommend 2 important solutions as follows:

1. Follow the necessary design principles to avoid knock-on effects, and make the ISD status clear by installing smoke detectors and connecting them to the indicator and alarm systems. Fig. 8 of this study is based on the aforementioned improvement measures set for smoke detectors and fire interlock to indicators and alarm systems.
2. Strengthen the emergency response capability to rescue the process tool. After setting improvement measures and re-emergency drills, the time required from fire to extinguishment takes less than 2 min, showing that suggestions from this study were very effective (walkthrough process, as shown in Fig. 9).

This study tested the lithography process machine and conducted statistics for 300 mm wafer fabrication in a high-tech company located in Hsinchu, Taiwan, to make changes in the photolithography machine design and process capability confirmation. The results are in line with expected results, shown in Fig. 9, of the photoresist coating after developing SEM results of photos. Being able to ensure the ability to process cases, we were able to explore, in depth, the process running the security upgrade, convinced that it is more substantial.



(a) Completion of the photo resist layer coating



(b) Photo resists exposure and clear

Fig. 10. SEM photographs of the photoresist coating after developing. (a) Completion of the photoresist layer coating. (b) Photoresists exposure and clear.

Fig. 9. Strengthen the emergency response capability training.

Table 9
Accident statistics after improvements (October 2011 to December 2012).

Date	Situation descriptions	Located	Injury situation	Losses
September 2012	Leakage sensor actives when spill-proof dish of chemical storage cabinet accumulating methanol caused by loose drop from take-off methanol supply pipeline.	Chemical room	No injury	Shutdown 3 h of lithography tool

Table 10
Key recommendations of chemical supply system safety design for the high-tech plant.

System devices	Functionality	Key point of safety design
Trolley	The main consideration is how to safely transported to everywhere of facility between the chemical room, and prevent tipping over, overflow etc.	1. Design decision by (1) Shape, (2) dimension, (3) Weight, (4) Appliance size, (5) Structural strength, (6) Fixed, (7) Transport method, (8) Transport path to reach a smooth, easy to control, and prevent accidents as the main function.
Chemical storage tank	Function is the storage of chemicals, classified as fixed and mobile, small and medium-sized system use mobile type. Two kind supply methods are tankers and bottled.	1. Chemical characteristics will great affect the tanks of materials. 2. The addition should consider the (1) capacity, (2) pumping units, (3) fixed method
Exhaust hood of chemical storage tank	Exhaust system used continuously for 24 h extraction of organic solvent vapors in the chemicals storage cabinet to prevent explosion and Personnel inhalation poisoning.	1. Select materials based on chemical characteristics, If Exhaust Hood have built-in exhaust fan and other electrical equipment should be used explosion-proof devices. 2. Another consideration should be (1) given the amount of ventilation of the cabinet, structural strength, (2) explosion-proof grade, (3) shockproof fixed, (4) leak sensors, (5) firefighting system installation
Chemical room	Chemical room is storage of chemicals tank, clean booth, and bottles, is the second line of defense for chemical spills.	1. Following the amount of chemical storage, characteristics, size of exhaust hood and chemical storage cabinet to (1) determine the size of room space, (2) the overall ventilation system capability, (3) firefighting system, (4) electrical devices of Explosion-proof, (5) Explosion pressure relief design, (6) leak sensor system
Pumping system	The main compression device of the system, also the most likely to occur of the pipeline of leak or burst situations.	1. Select materials based on chemical characteristics and the use of fluid mechanics formula $Q = VA$ decided to (1) flow, (2) output pressure, (3) connection, (4) heat and corrosion resistance, (5) explosion-proof level, (6) leak sensor system design
Pipeline	Function is to transfer of chemicals to process tools, In order to ensure that the pipeline safety will not be install valves without VMB.	1. Select materials based on chemical characteristics and the use of fluid mechanics formula $Q = VA$ decided to (1) diameter, (2) pressure, (3) flow, (4) velocity, (5) pressure loss design, (6) design connection, (7) pipeline type (monolayer or bilayer), (8) heat and corrosion resistance capability, (9) leak sensor system
VMB	For the allocation and transport of chemicals to the input terminal of each independent process tools, VMB Increase system use flexible level, similarly to increase the line number pipelines complexity.	1. Select materials based on chemical characteristics decided to (1) valve of size, (2) type, (3) connection, (4) heat and corrosion resistance capability, 2. Another valve box itself should also follow chemical characteristics to select (1) materials, (2) size, (3) Heat (4) corrosion resistance capability, (5) fixed method, (6) drain and exhaust system, (7) leak sensor system design
Process tool	Core of process for the wafer cleaning, Photoresist coating, exposure etc, wafer transmitted by robots in machine internal, could easily lead to chemical splash in the process chamber, this is	1. Select materials based on (1) chemical characteristics decided to materials, (2) dimension, (3) delivery pressure, (4) Flow, (5) velocity,

Table 10 (*continued*)

System devices	Functionality	Key point of safety design
	the focus of the design considerations in order to reduce the risk of hazards.	(6) exhaust and drain system, (7) leak sensor system design 2. We recommendations for process are sealed, and coordinate the 24 h operation exhaust system for organic solvent vapor extraction to treatment system.
Pipeline of exhaust/ drain	Used to transport the waste liquid after the process chamber to the wastewater treatment plant, or temporary storage tank, for safety the exhaust ducts do not set the valve parts too.	1. Select materials based on chemical characteristics and the use of fluid mechanics formula $Q = VA$ decided to (1) pipe size, (2) pressure, (3) flow, (4) velocity, (5) Pressure loss, (6) piping connection, (7) type of monolayer or bilayer, (8) heat and corrosion resistance capability design

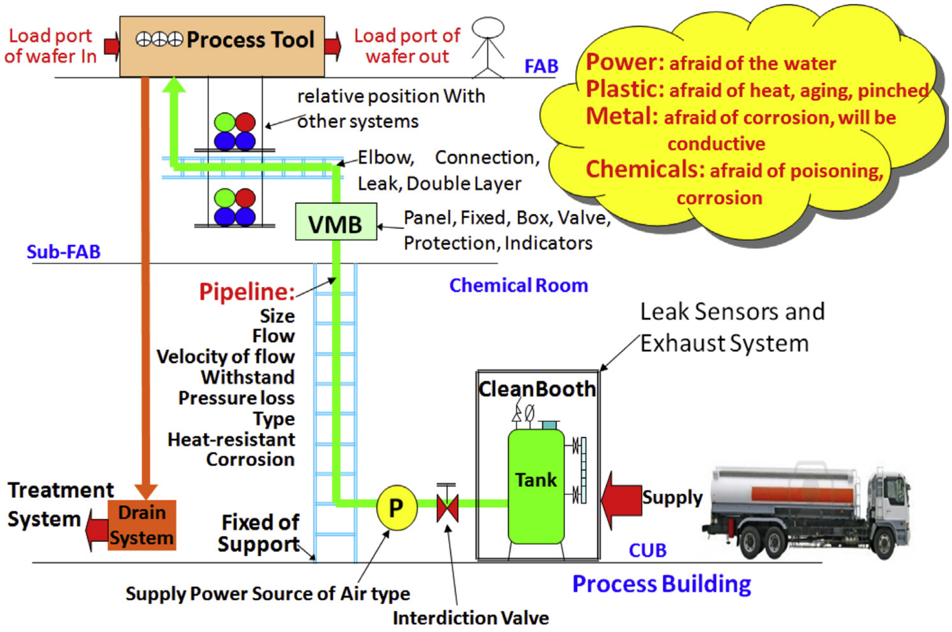


Fig. 11. The high-tech plant in the chemical supply system applying inherently safer design considerations for the proposed framework.

This study reviewed statistics on 300 mm wafer fabrication lithography process accidents in a high-tech company located in Hsinchu from October 2011 to December 2012. The number of incidents was reduced from the original six to one (Table 9). The accident rate was significantly reduced (as shown in Fig. 10). In addition, the engineering improvements have been completed for 6882 h with no lost staff time from September 2011 until now. Using ISD strategies to improve measures, this study showed that an effective security enhancement has been established.

By way of the analysis and verification of this study, we can confirm that the inherently safer design strategy is very suitable for use in a high-tech plant, and it is also desirable to explore the harmfulness of a chemical supply system for the semiconductor manufacturing process and to establish effective improvement measures. The establishment of the basis of research results is shown in Table 10. We proposed design architecture and chemical supply system security designs focusing on the recommendations for a high-tech plant. Fig. 11 shows a chemical supply system available for the use of reference by the industry, in order to enhance the security level of the plant.

6. Conclusions and suggestion

The high-tech process for security issues-related research is still inadequate, and the study found that all sectors of high-tech plant safety only focus on the operational phase of the overall high-tech process. Machine safety should comprise ordering, transportation, on-site installation and cross-machine process capability for a whole stage discussion, so that an inherently safer target can be reached. In order to grasp the installation hazards of high-tech manufacturing equipment, this study investigated three major areas:

1. By conducting a lithography process hazard analysis and compiling the statistics for the causes of fires and losses at high-tech plants in Taiwan since 1996; then, completing the lithography process hazard prevention measures establishment and certification of the effectiveness
2. By using ISD strategies and FMEA as an analytical tool, as well as establishing improvement measures to the analysis and verification of the lithography process for 300 mm wafer fabrication in Hsinchu, a high-tech company located in Taiwan

3. Following the annual maintenance job improvement in a high-tech company from September 2011 until now, the number of lithography process accidents was reduced from six to one between October 2011 and December 2012. The accident rate was significantly reduced in the 300 mm wafer fabrication operation (from September 2011 to now), and there has been no loss of staff time for 6882 continuous hours.

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References

ASML. (2010). *Installation requirement manual*. ASML.

Chang, K. C., & Chen, C. Y. (2007). A study for inherently safer design and application on high-tech industrial. *Industrial Safety Technology Quarterly, 63-05*, 18–33.

Chang, K. C., & Chen, C. Y. (2008). High-tech manufacturing process organic solvents chemical supply system inherently safer design applications and research. In *Sixteenth strait and Hong Kong Macao occupational safety and health conference*.

Chen, C. Y., Chang, K. C., Lu, C. C., & Wang, G. B. (2013). Study of high-tech process furnace using inherently safer design strategies (II) deposited film thickness model. *Journal of Loss Prevention in the Process Industries, 26*, 225–235.

Chen, C. Y., Chang, K. C., & Wang, G. B. (2013). Study of high-tech process furnace using inherently safer design strategies (I) temperature distribution model and process effect. *Journal of Loss Prevention in the Process Industries, 26*, 1198–1211.

Cheng, H. L. (2011). *A case study of the performance assessment of the very early smoke detection systems in a semiconductor fab* (MS thesis). Taiwan: Degree Program of Industrial Safety and Risk Management, College of Engineering, National Chiao-Tung University.

Crowl, D. A. (Ed.). (1997). *Inherently safer chemical processes: A life cycle approach*. Center for Chemical Process Safety, American Institute of Chemical Engineers.

Edwards, D. W., & Lawrence, D. (1993). Assessing the inherent safety of chemical process routes: is there a relation between plant costs and inherent safety? *Journal of Process Safety and Environmental Protection, 71b*, 252–258.

Floyd, J. E., McGrattan, K. B., Hostikka, S., & Baum, H. R. (2003). CFD fire simulation using mixture fraction combustion and finite volume radiative heat transfer. *Journal of Fire Protection Engineering, 13*.

Heikkilä, A.-M. (1999). *Inherent safety in process plant design. An index-based approach* (pp. 129–384). Technical Research Centre of Finland, VTT Publications.

Khan, F. I., & Amyotte, P. (2004). Integrated inherent safety index (I2SI): a tool for inherent safety evaluation. *Journal of Process Safety Progress, 23*(2), 136–148.

Kletz, T. A. (1984). *Cheaper, safer plants, or wealth and safety at work*. Rugby, Warwickshire, England: The Institute of Chemical Egineers.

Kletz, T. A. (1998). *Process plant: A handbook for inherently safer design*. Taylor & Francis.

Kletz, T. A. (July 1985). Inherently safer plants. *Plant/Operations Progress, 4*(3), 164–167.

Lin, L. K. (2003). *Technology plant disaster and knowledge management* (pp. 1–4). Taipei: Scientific & Technical Publishing.

Lin, H. L. (2007). *Evaluation of blast wall design criteria of bulk silane storage facility* (Master degree thesis). National Central University of Graduate Institute of Environmental Engineering.

McGrattan, K. B. (Ed.). (2007). *Fire dynamics simulator (version 5), technical reference guide*. National Institute of Standards. NIST special publication 1018-5.

McGrattan, K. B., Baum, H. R., & Rehm, R. G. (1998). Large eddy simulations of smoke movement. *Fire Safety Journal, 30*, 161–178.

Ryder, N. L., Sutula, J. A., Schemel, C. F., Hamer, A. J., & Brunt, V. V. (2004). Consequence modeling using the fire dynamics simulator. *Journal of Hazardous Materials*, 149–154.

SEMI S10-0307. (2007). *Risk assessment and risk evaluation process*.

Sharma, R. K., Kumar, D., & Kumar, P. (2005). Systematic failure mode effect analysis (FMEA) using fuzzy linguistic modelling. *Journal of Quality & Reliability Management, 22*(9), 986–1004.

Stamatis, D. H. (2003). *Failure mode effect analysis: FMEA from theory to execution*. ASQ Quality Press, ISBN 0-87389-598-3.

Su, C. T., & Chou, C. J. (2008). A systematic methodology for the creation of six sigma projects: a case study of semiconductor foundry. *Journal of Expert Systems with Applications, 34*(4), 2693–2703.

Sze, S. M., & Ng, K. K. (2006). *Physics of semiconductor devices* (3rd ed.). Wiley, ISBN 978-0-471-14323-9.

Wu, C. L. (2003). *Tetramethylammonium hydroxide exposed fatal case report and literature review*. Chi-Mei Hospital research report, Taipei, Taiwan.

Yang, H. Y., Yang, H. Y., Yu, C. H., & Chen, C. Y. (2009). The study of SWOT analysis on the application of calamity risk in high-tech factories – using the semiconductor factory's clean room as an example. *Journal of China University of Science and Technology, Taiwan, 41*.