FAILURE ANALYSIS AND SCENARIO PROBABILITY IN GAS LEAK CONTAINMENT SYSTEMS

ASSESSMENT TASK 3 – QUANTITATIVE RISK ASSESSMENT AND DECISION MAKING

49006 RISK MANAGEMENT IN ENGINEERING - SPRING 2024

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INTRODUCTION

A couple of years back, during the global COVID-19 crisis, the world came to the realisation of its reliance on semiconductors. The computer chip shortage severely disrupted supply chains across various sectors, most notably affecting the automotive, electronics, and medical industries. This highlighted the vulnerabilities of silicon-based industries and the critical role they play in our interconnected world.

Semiconductor fabrication plants (fabs) rely on clean rooms, highly regulated environments designed to keep airborne particles at a very low level, preventing the contamination of the wafer production process. Incidents occurring in fabs can have severe consequences, both locally and globally.

There are many examples, such as the fire incident at Renesas Electronics Corporation in 2021 [1], which accelerated the electronic chip crisis. Furthermore, whereas direct fatalities are easy to measure, having issues in silicon chip supply chains can indirectly put the lives of other individuals at risk, notably people who rely on modern medical equipment [2].

Semiconductors, like silicon, are key materials not only in chip manufacturing but also for solar panels. Both industries share similarities in their fabrication processes, relying heavily on controlled environments and the use of hazardous chemicals such as silane gas [3]. The use of this chemical is essential in producing silicon wafers, but it presents significant risks, as evidenced by the explosion that occurred in a photovoltaic cell fabrication plant in Taiwan on November 23, 2005 [4]. The explosion led to extensive damage and a tragic loss of life while also highlighting gaps in risk management protocols.

The aim of this report is to investigate the root causes of the incident, focusing on system failures and safety lapses. Quantitative risk assessment techniques will be employed to break down the sequence of events, using Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and Bow-Tie (BT) methods. These techniques will help to quantify the risks and propose mitigation strategies to prevent similar occurrences.

This report will first provide a case study overview, followed by an in-depth analysis using the FTA, ETA, and BT methods. Finally, it will propose risk reduction measures and evaluate their effectiveness through risk-based decision-making.

INDEX

1. CASE STUDY OVERVIEW

1.1. Case description

On the 23rd of November 2005, silane gas ignited inside a chamber of a photovoltaic cell fabrication plant, leading to an uncontrollable fire. Silane gas, essential for the manufacturing of silicon wafers in both semiconductor and photovoltaic fabrication plants, is stored in gas cylinders. The change of these cylinders is frequently needed as the gas pressure decreases during use. The cylinders must be retrieved from a "gas room" and then connected to link with a furnace chamber.

According to the incident analysis [4], the cylinder replacement process requires two operators. At the time of the incident, only one was present, as the other was absent for trivial reasons. The operator made several critical errors during the replacement process. First, the connection between the cylinder valve and the furnace chamber valve was faulty. Second, the ventilation system, which can be accessed via a window in the gas room, was left inactive as the window remained closed during the operation. Additionally, the operator did not follow the replacement process fully, skipping the essential 'post-purge' and 'leak test' steps. Silane, unfortunately, is highly flammable and capable of spontaneous ignition.

The operator was not wearing any Personal Protective Equipment (PPE). As a result of an auto-ignition, the worker got neutralised from a blast. His body was found incinerated from a following fire. Meanwhile, the leak continued, and the blaze propagated to the other high-pressure gas cylinders in the room, worsening the incident. Finally, the fire was able to spread outside the initial room because of a nearby exhaust duck, made of non-fire-proof polypropylene containing flammable product, linking to the clean room containing other employees. Still, the incident resulted in this one and only stated victim.

1.2. Boundaries

Even though the fire stopped production in the whole fab, we must limit ourselves to a limited system to simplify the analysis. Here, the process is *the silane gas replacement*, and not the production of solar panel cells. That means we will not consider the furnace chamber in the boundary but only the valve connection to it. We will consider both operators in the boundary, even if one was absent at the time of the incident. The gas room (and the gas cylinders that were inside), physically speaking, will form most of the boundary. The factory ventilation system will be linked to the room via the window. The PPE will also be considered, albeit the negligence of the operator at the time. In addition, the exhaust duck should be added to the boundary as it participated in the escalation of the incident.

1.3. Sub-systems and components/equipments

The *silane gas replacement* system involved in the incident can be broken down into three primary sub-systems: Gas Containment (GC), Gas Transfer (GT), and Ventilation (V). Each of these subsystems contains critical components that played a role in the incident.

The GC subsystem is responsible for securely holding the silane gas. It includes the Cylinder Body (C) and the Pressure Relief Ports (PR), which are designed to control the internal pressure of the cylinder and prevent any leaks.

The GT subsystem manages the movement of silane from the cylinder to the furnace[1]. Key components here include the Gas Cylinder Valve (VG) and the Valve Connection System (VC), which must function properly to ensure a secure transfer of gas. The Furnace Valve (VF) also plays a vital role in regulating the transfer of gas into the furnace. Operator involvement is critical in this subsystem, with both Operator A (OA) and Operator B (OB) required to safely manage the gas cylinder change.

[1] The valve system is highly detailed in the source analysis, but it will be simplified here as a three-part system.

The V subsystem is crucial for maintaining a safe environment by preventing gas accumulation. It includes the Ventilation Window (W), the Ventilation Fan (F), and the Ventilation Blade (B), which together work to remove any leaked gas from the room. The Exhaust Duct (E), made of polypropylene, was another critical component, as its flammable material allowed the fire to propagate outside the gas room, exacerbating the situation.

This decomposition of the *Silane Gas Replacement* system is summed up in Table 1.

Table 1: List of sub-systems and their components

Sub-system		**Component**	
Name	**Symbol**	**Name**	**Symbol**
Gas Containment	**GC**	Cylinder Body	**C**
		Pressure relief ports	**PR**
Gas transfer	**GT**	Gas cylinder valve	**VG**
		Valve connection system	**VC**
		Furnace Valve	**VF**
		Operator A	**OA**
		Operator B	**OB**
Ventilation	**V**	Ventilation window	**W**
		Ventilation fan	**F**
		Ventilation blade	**B**
		Exhaust duct	**E**

2. IMPLEMENTATION AND RESULTS

2.1. Fault Tree Analysis (FTA)

A Reliability Block Diagram (RBD) has been realised in assessment task 1. We will use this diagram as a reference for the following analysis.

Figure 1 illustrates the FTA of the silane gas leak incident. The top event is the Silane Gas Leak, which can occur due to either Gas Containment Failure or Ventilation Failure.

The Gas Containment Failure branch is driven by two key factors: Operator Failure and Valve Connection Failure. Operator failure arises when the operators fail to follow the proper procedure, which is compounded by the absence of a second operator. Valve connection failure occurs when any of the components involved in the gas transfer, including the Gas Cylinder Valve (VG), the Valve Connection System (VC), or the Furnace Valve (VF), malfunctions.

The Ventilation Failure branch highlights the failure of the ventilation system to evacuate the leaked gas. This includes failure to open the Ventilation Window (W), and mechanical failures in either the Ventilation Blade (B) or the Ventilation Fan (F).

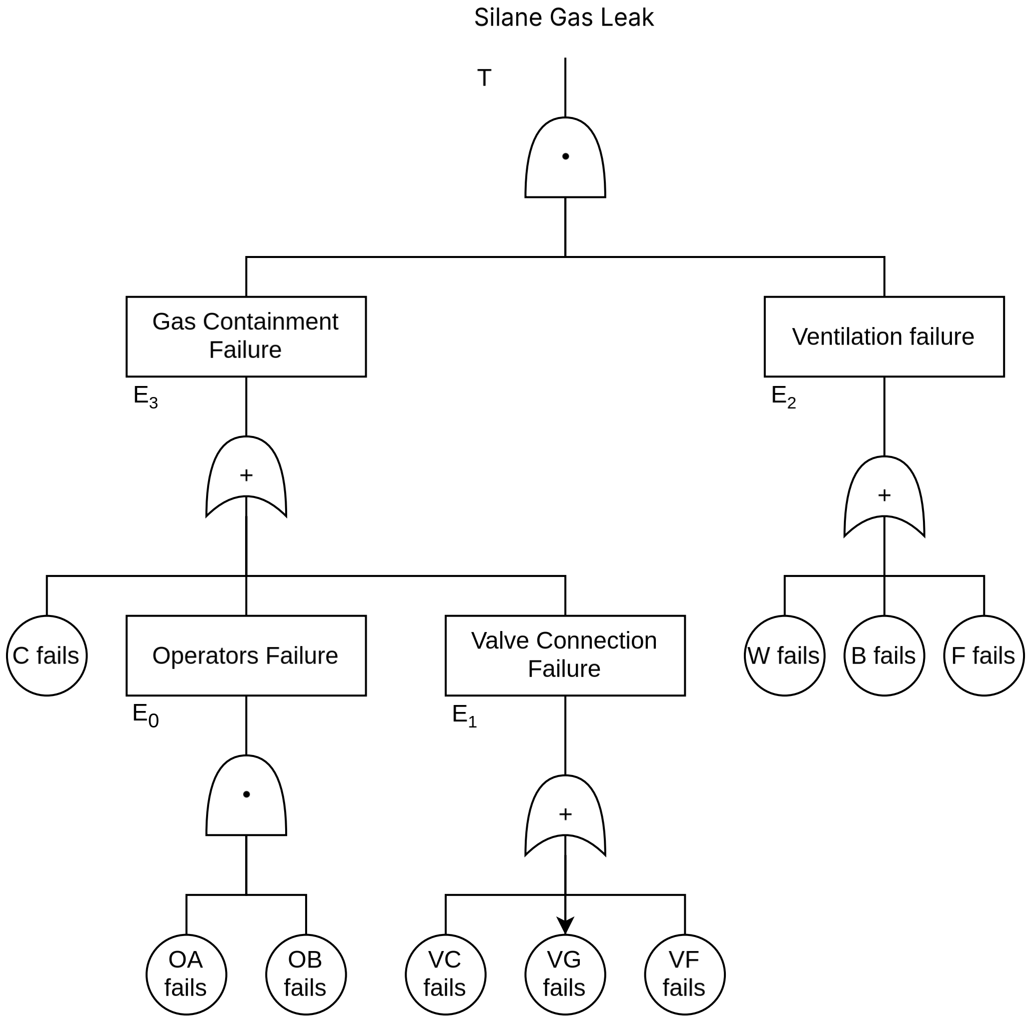


Figure 1: FTA of the saline gas incident

Table 2 and Table 3 list the probabilities of failure of these components and the events linked to these failures.

Table 2: Object Failure Rate

Object		Failure Probability
Name	**Symbol**	
Cylinder Body	C	0.000001
Operator	OA & OB	0.02
Gas Cylinder Valve	VG	0.001
Valve Connection System	VC	0.05
Furnace Valve	VF	0.015
Window	W	0.02 (same as operator error)
Ventilation Blade	B	0.0001
Ventilation Fan	F	0.01

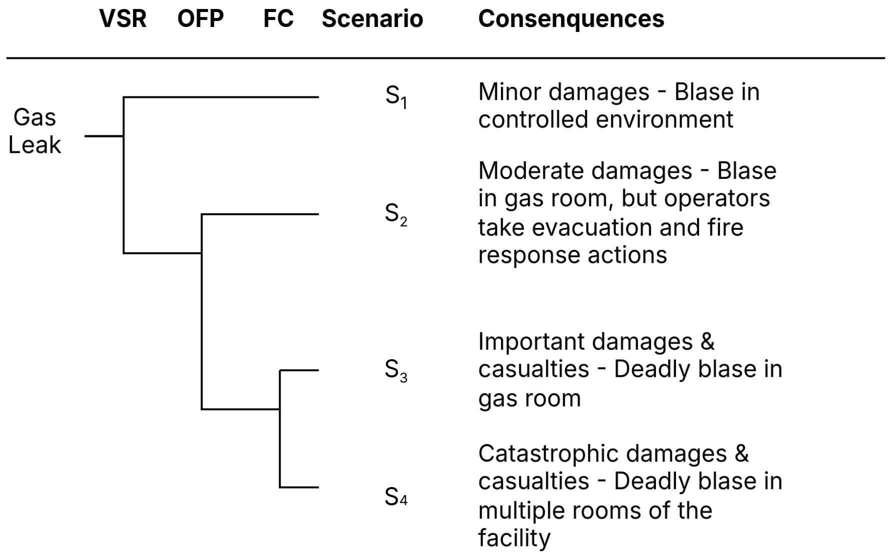
Table 3: Event Failure Rate

Event		Failure Probability
Name	**Symbol**	
Operator Failure	E_0	(AND Gate) $P(E_0) = P(O_A) \times P(O_B) = 0.0004$
Valve Connection Failure	E_1	(OR Gate) $P(E_1) = P(\text{VC}) + P(\text{VG}) + P(\text{VF}) - (P(\text{VC}) \times P(\text{VG})) - (P(\text{VG}) \times P(\text{VF})) - (P(\text{VC}) \times P(\text{VF})) = 0.065$
Ventilation Failure	E_2	(OR Gate) $P(E_2) = P(W) + P(B) + P(F) - (P(W) \times P(B)) - (P(B) \times P(F)) - (P(F) \times P(W)) = 0.030$
Gas Containement Failure	E_3	(OR Gate) $P(E_3) = P(C) + P(E_0) + P(E_1) - (P(C) \times P(E_0)) - (P(E_0) \times P(E_1)) - (P(E_1) \times P(C)) = 0.065$
Gas Leak	T	(AND Gate) $P(T) = P(E_2) \times P(E_3) = 0.00195$

2.2. Event Tree Analysis (ETA)

Table 4 shows the ETA for the incident, starting with a gas leak as the initial hazard. We will consider the gas leak the same as gas ignition, considering the characteristics of silane gas. The outcome depends on three main barriers: Ventilation System Response (VSR), Operators Following Procedure (OFP), and Fire Containment (FC). If all barriers succeed, the incident results in minor damage (S1). However, if the ventilation system fails and operators do not follow procedures, the incident escalates, leading to more serious consequences, including important damages and casualties (S3) or even catastrophic damage if fire containment also fails (S4).

Table 4: ETA of the incident



2.3. Bow-Tie (BT)

Table 5 illustrates the BT of the incident, with the gas leak as the central event. On the left side, the diagram identifies key causes of the gas leak, including operator failure and valve connection failure under gas containment, as well as ventilation failure. Notably, the operator appears twice—first as a cause when procedures are not followed, and later as a barrier tasked with detecting the gas leak through proper testing, such as the post-purge and leak test.

Table 5: BT of the incident

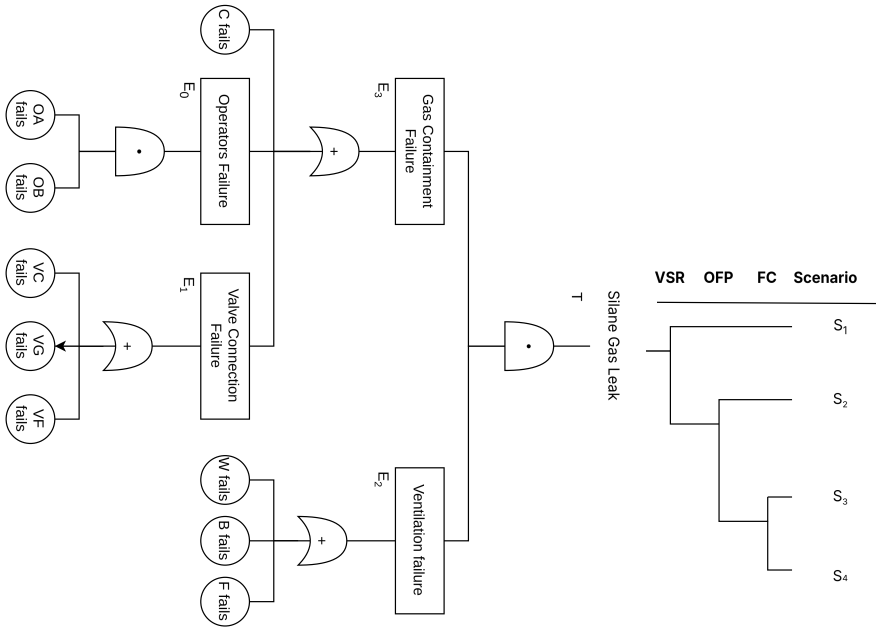


Table 6 and Table 7 present the success rates of various safety barriers and the corresponding probabilities of different incident scenarios. Table 6 outlines the success probabilities for key barriers involved in preventing and mitigating gas leaks, while Table 7 provides the calculated scenario rates for potential outcomes ranging from minor to catastrophic damages.

Table 6: Barrier Success Rate

Barrier		**Success Probability**
Name	**Symbol**	
Gas Leak	T	0.00195
Ventilation System	VSR	0.97
Operators Follow Protocol	OFP	0.9996
Fire Containment	FC	0.9999

Table 7: Scenario Probability Rate

Scenario		**Probability**
Name	**Symbol**	
Blase in controlled environment	S_1	$P(T) * P(\mathrm{VSR}) = 0.0019$
Blase in gas room, but operators take evacuation and fire response actions	S_2	$P(T) * (1 - P(\mathrm{VSR})) * P(\mathrm{OFP}) = 0.00006$
Deadly blase in gas room	S_3	$P(T) \times (1 - P(\mathrm{VSR})) \times (1 - P(\mathrm{OFP})) = 0.000000023$
Deadly blase in multiple rooms of the facility	S_4	$P(T) \times (1 - P(\mathrm{VSR})) \times (1 - P(\mathrm{OFP})) \times (1 - P(\mathrm{FC})) = 2.34 \times 10^{-13}$

Table 8 outlines the estimated risks associated with four potential damage scenarios from the silane gas leak incident, ranging from minor to catastrophic damages.

Table 8: Risk Estimation

Damages	Cost	Symbol	Probability	Risk
Minor damages	$10,000	S_1	0.0019	$19
Moderate damages	$100,000	S_2	0.00006	$6
Important damages & casualties	$50,000,000	S_3	0.000000023	$1.15
Catastrophic damages & casualties	$100,000,000	S_4	2.34×10^{-13}	$0.0234
			Total:	$26.17.

2.4. BN

2.4.1. FTA to BN

Figure 2 illustrates the conversion of the FTA into a BN for the silane gas incident using the GeNIe software. These values align with those listed in Table 3.

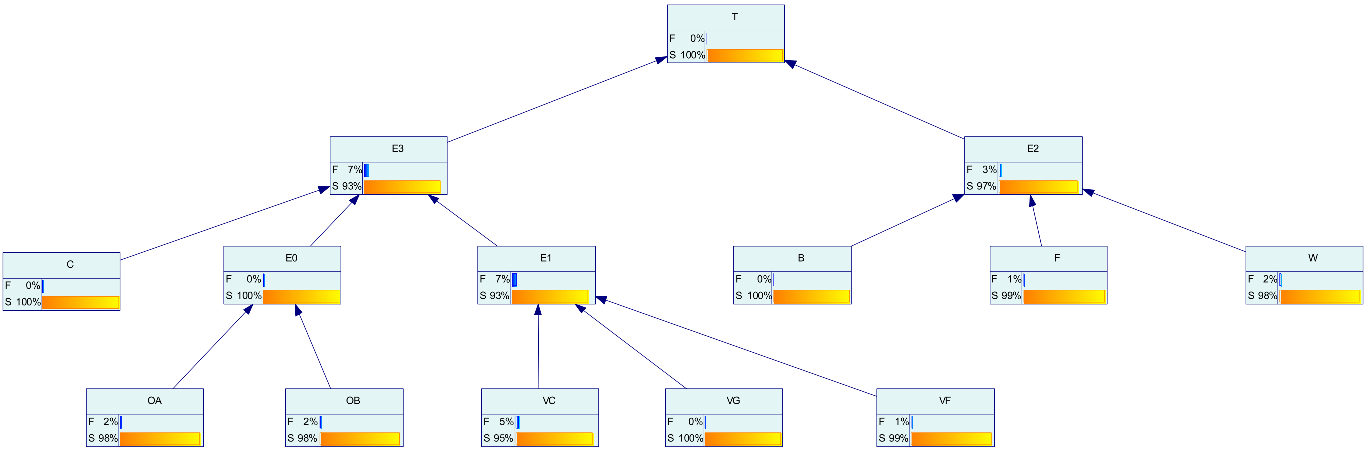


Figure 2: FTA to BN Conversion

Figure 3 is a posterior BN. It reflects the updated probabilities after adding evidence of the accident event (gas leak). With this evidence, the failure (F) and success (S) probabilities for each component have been recalculated. The updated values for each component are provided in Table 9.

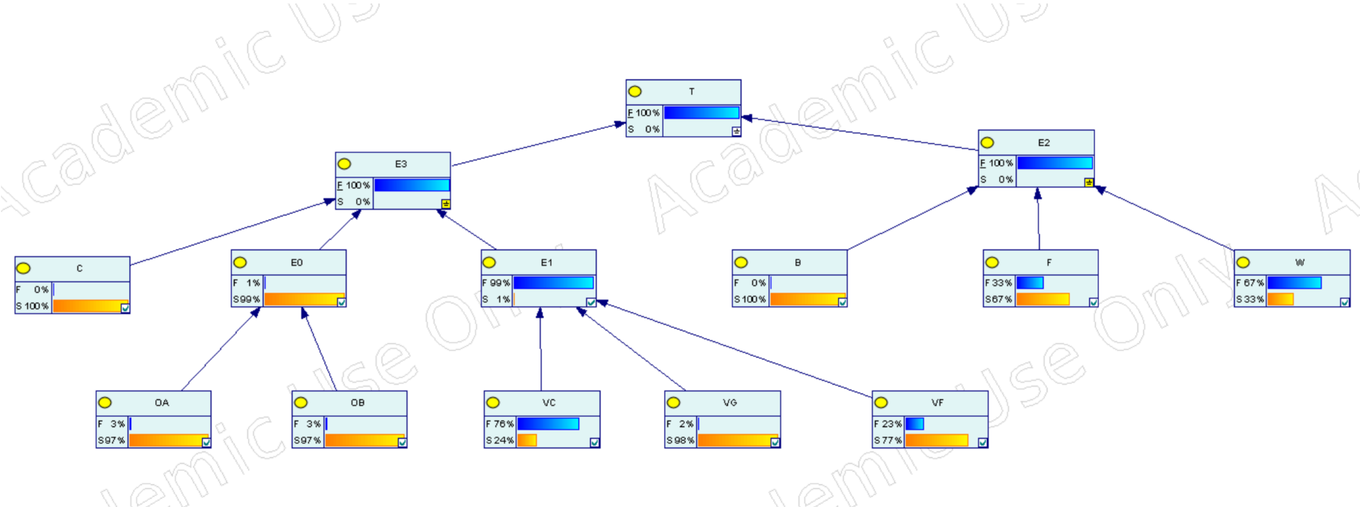


Figure 3: BN, Posterior variation

Table 9: Posterior Model Rates

Event	Failure Probability	
	Prior	Posterior
C	0.000001	$1.5253061e-05$
OA & OB	0.02	0.025589436
VG	0.001	0.015253061
VC	0.05	0.76265306
VF	0.015	0.22879592
W	0.02	0.66896299
B	0.0001	0.003344815
F	0.01	0.3344815
E_0	0.0004	0.0061012245
E_1	0.065	0.99428224
E_2	0.030	1
E_3	0.065	1
T	0.00195	1

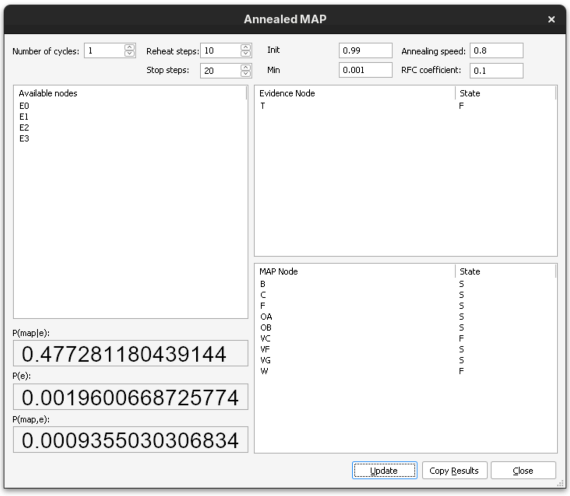


Figure 4: Most probable scenario calculation

The Annealed MAP (Figure 4) analysis in the image above shows the most probable scenario leading to the gas leak, indicating that the Valve Connection System (VC) and the Ventilation Window (W) are failing, while all other components state. $P(\text{MAP}|e)$ is 0.0477, making it the highest-probability configuration for explaining the failure.

2.4.2. BT to BN

Figure 5 shows the BN derived from the BT analysis of the silane gas incident.

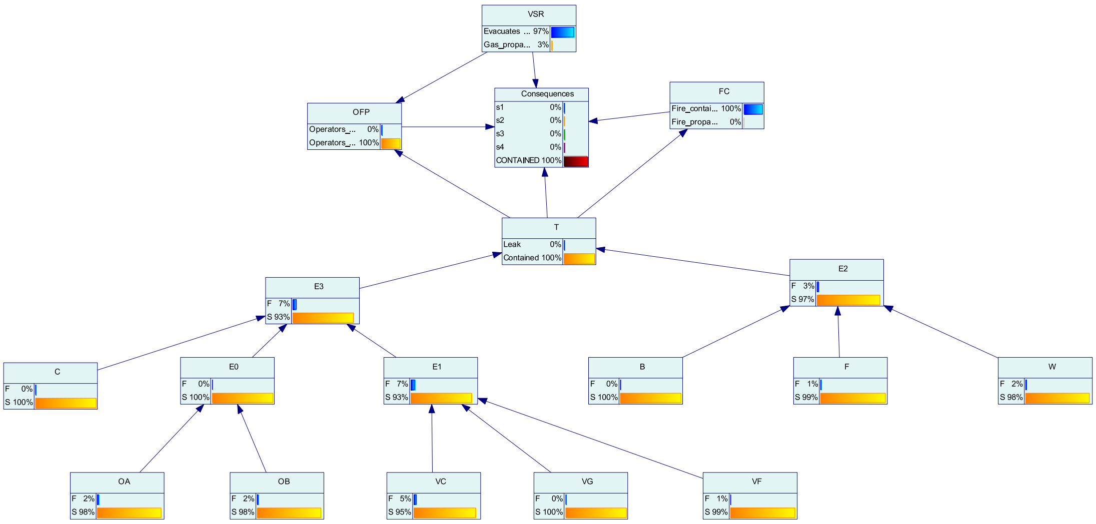


Figure 5: BT to BN Conversion

Table 10 presents the updated probability rates for each scenario (S1 to S4) in the model[2].

Table 10: Scenario Probability Rate From the model

Scenario		Probability
Name	Symbol	
Blase in controlled environment	S_1	0.0019
Blase in gas room, but operators take evacuation and fire response actions	S_2	$5.7037946e-05$
Deadly blase in gas room	S_3	$1.7640425e-06$
Deadly blase in multiple rooms of the facility	S_4	$1.7640602e-11$

In the Annealed MAP (Figure 6) analysis for this BT to BN model, the most probable explanation was determined with S1, which is the most probable scenario. According to this scenario, the most likely cause involves failures in both the valve connection and ventilation window, with all other components operating successfully. It has a probability of 0.48.

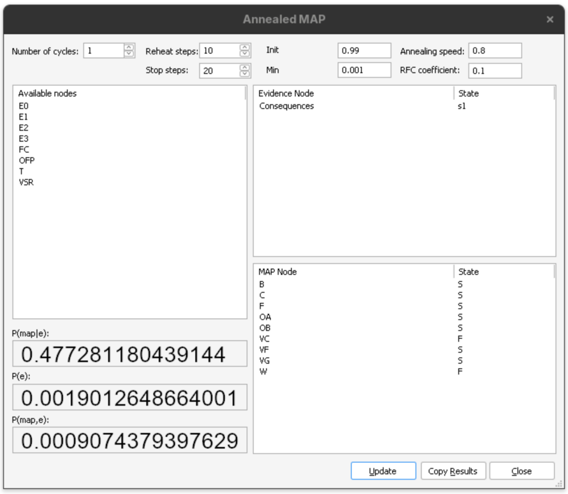


Figure 6: MPE analysis for minor damage scenario (S_1)

[2] These values differ from previous estimates, suggesting possible inaccuracies in the model assumptions or potential miscalculations.

2.5. Risk-based decision making

In response to the silane gas leak incident, a risk-based decision-making approach helps evaluate various risk control measures. By examining both the costs and expected benefits of these measures, we can prioritise the most effective solutions. Below, we calculate the cost-benefit ratios for three mitigation strategies:

1. Given that a fire escalated from the initial gas leak, a sprinkler system could act as a critical barrier in suppressing fires early, reducing the risk of widespread damage and injury. Sprinklers are often one of the most effective containment methods for fire hazards involving flammable gases like silane, aiming to mitigate high-severity scenarios like S_4
2. An alarm system can immediately alert personnel to a gas leak, allowing for rapid evacuation and containment efforts. This measure addresses the importance of timely response in preventing moderate to severe outcomes. By focusing on scenarios ranging from S_2 to S_4, an alarm system could significantly enhance safety without requiring continuous human oversight.
3. Human error was a key factor in the incident, as procedural lapses contributed to the gas leak. Enhanced training for operators emphasises safe handling of silane gas and adherence to critical steps, such as leak testing and post-purge processes. This measure directly addresses low- to mid-severity scenarios (S_1 and S_2), as improved procedural adherence reduces the likelihood of minor to moderate incidents.

Table 11: Benefit–Cost Analysis

Control Measure	Cost	Expected Risk Reduction	Calculation of Risk Reduction	Benefit-Cost Ratio
Sprinkler System Installation	\$45,000	85% of S_4	$85\% \times 0.0234 = 0.01989$	$\frac{0.01989}{45000} = 4,42 \times 10^{-7}$
Alarm System Installation	\$20,000	70% across S_2 to S_4	$70\% \times (6 + 1.15 + 0.0234) = 5.02138$	$\frac{5.02138}{20000} = 2,51069 \times 10^{-4}$
Operator Training Program	\$10,000	60% accross S_1 to S_2	$60\% \times (19 + 6) = 15$	$\frac{15}{10000} = 1,5 \times 10^{-3}$

Table 11 provides a benefit–cost analysis of three proposed risk control measures for the silane gas incident. The results indicate that the operator training program has the highest benefit-cost ratio, making it the most cost-effective option. This measure addresses the root cause of the incident, as operator failure was the primary factor leading to the gas leak. The training program aims to improve procedural adherence and reduce human error, particularly in critical tasks such as valve handling and leak testing.

While sprinklers and alarm systems would add important layers of protection, they come at higher costs and lower cost-effectiveness in this analysis. Additionally, it's important to recognise that operator errors can be linked to poor management practices that fail to emphasise training and procedural oversight. Improving operator competence and management accountability are, therefore, essential steps in preventing future incidents and ensuring safer operations overall.

3. DISCUSSION

By evaluating the roles of operator reliability, valve connection integrity, and ventilation system efficacy, we found that even minor changes in these probabilities significantly alter the overall risk, especially in catastrophic scenarios (S_4). This suggests that improvements in operator training and equipment reliability would have a substantial impact on safety, as poor operator performance and faulty valve connections were pivotal in the incident. While at first glance, this may appear to be the result of operator error alone, a deeper examination reveals serious gaps in facility management and infrastructure that contributed heavily to the risk profile. The findings by J.-R. Chen *et al.* [4]

also underscore that silane-related incidents often stem from procedural failures and inadequate facility design.

To improve safety in high-risk environments where silane is handled, robust training programs and strict maintenance protocols are essential. Measures targeting identified vulnerabilities, such as automated leak detectors, advanced ventilation systems, and mandatory training, address critical gaps uncovered in this incident. However, effective risk mitigation requires not only individual compliance but also strong support from management. An absence of essential safety mechanisms, such as automatic leak detection and fire-resistant materials, points to oversight at the management level, which is ultimately responsible for maintaining a safe work environment.

This incident also underscores the importance of continuous monitoring throughout the safety process, from enforcing operator compliance with procedures to performing regular checks on equipment like valves and ventilation systems. Regular reviews of incident data and near-miss reports should be integrated into operations to identify trends in operator performance, equipment deterioration, and procedural gaps that might otherwise go unnoticed. For example, regular audits of training outcomes and routine testing of valve connections could provide early indicators of risk areas.

On a more technical and practical point of view, this case emphasises the importance of robust exhaust and ventilation systems specifically designed to handle flammable and pyrophoric gases like silane, commonly found in semiconductor processes. In similar incidents, poor design and maintenance of exhaust systems, inadequate materials like flammable ductwork, and insufficient real-time gas detection have often exacerbated risks. J. R. Chen takes notice of this in another publication of his [3]. Understanding the behaviour of gases in these systems, especially under varying process conditions, is crucial. This approach aligns with broader safety practices in semiconductor facilities, where integrating enhanced detection, response, and exhaust solutions can reduce the likelihood of incidents escalating into the case we are studying in this report.

4. CONCLUSION

On November 23, 2005, a silane gas explosion in the gas room of a photovoltaic cell fabrication plant in Taiwan caused one fatality, destroyed the gas room, and allowed the fire to spread through a flammable polypropylene duct into adjacent production areas. The incident response required hours of hazardous material management to fully contain and prevent further damage.

This report provides a detailed failure analysis of the incident using FTA, ETA, and BT. Operator error during the cylinder change process was identified as a primary cause, with procedural lapses and a lack of protective equipment leading to delayed ignition and escalation. Design vulnerabilities, including inadequate ventilation and the absence of restrictive flow orifices in the cylinder system, intensified the incident's severity. BN models further revealed high failure probabilities in critical safety barriers, affirming the need for design and procedural improvements in silane gas management.

The analysis led to targeted recommendations: the installation of automated alarm and shutdown systems, the addition of fire containment measures such as sprinklers, and, most importantly, reinforced operator training. Cost-benefit assessments indicated that automation and enhanced training provide the highest impact on safety. These findings underscore the importance of comprehensive operational protocols and robust engineering controls in facilities handling reactive gases.

GLOSSARY

ETA

FC – Fire Containment.

OFP – Operators Following Procedure.

VSR – Ventilation System Response.

Industrial

PPE – Personal Protective Equipment.

Microelectronics

clean room: Highly regulated environments designed to keep airborne particles at a very low level, preventing the contamination of the chip production process.

fab – semiconductor fabrication plant.

wafer: A thin slice of crystalline silicon used as the base material in semiconductor microchips and solar cells manufacturing.

Risk management

BN – Bayesian Network.

BT – Bow-Tie.

ETA – Event Tree Analysis.

FTA – Fault Tree Analysis.

RBD – Reliability Block Diagram.

Sub-systems & Components

B – Ventilation Blade.

C – Cylinder Body.

E – Exhaust Duct.

F – Ventilation Fan.

GC – Gas Containment.

GT – Gas Transfer.

OA – Operator A.

OB – Operator B.

PR – Pressure Relief Ports.

V – Ventilation.

VC – Valve Connection System.

VF – Furnace Valve.

VG – Gas Cylinder Valve.

W – Ventilation Window.

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