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# Safety management of hazardous chemicals in semiconductor wafer cleaning equipment focus of subcontractor practices

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**Abstract:** This study investigates current safety management practices for hazardous chemicals handled in semiconductor wafer cleaning equipment, with a particular attention to substances requiring subcontract approval under the Occupational Safety and Health Act of Korea. Based on standard operating procedures (SOPs) and safety evaluation reports, this research analysed the management of hydrofluoric acid (HF), sulfuric acid ($H_2SO_4$), nitric acid ($HNO_3$), and hydrochloric acid (HCl).

The findings indicate that subcontractors generally comply with legal requirements by Personal protective equipment (PPE), local exhaust ventilation, line flushing, leak testing, neutralizer placement, and work zone isolation. Nevertheless, existing risk assessments are mainly qualitative, relying on checklists and HAZOP studies, with limited quantitative analysis and Minimal integration of real-time monitoring data. These limitations suggest that existing management systems fulfill compliance-level requirements but remain insufficient for proactive, predictive risk control. The study highlights the need to apply Bayesian Network-based quantitative risk assessment models to estimate accident scenario probabilities, validate mitigation measures, and prioritize safety investments in semiconductor manufacturing.

***Keywords:*** *Semiconductor, Cleaning Equipment, Regulatory-controlled Hazardous Chemicals, Safety Management, Risk Assessment, Bayesian Network*

## 1. INTRODUCTION

Semiconductor manufacturing requires an extremely high level of cleanliness to support ultra-fine circuit formation, with cleaning equipment plays a critical role in the overall process. This equipment employs substantial quantities of highly concentrated acids such as hydrofluoric acid (HF), sulfuric acid ($H_2SO_4$), nitric acid ($HNO_3$), and hydrochloric acid (HCl) to remove organic residues, metallic impurities, and particles from wafer surfaces (Kern 1990). The use of these substances presents severe hazards. For instance, in the 2012 Gumi HF leak accident, five workers were killed, 18 were injured, and extensive damage occurred to nearby agriculture areas and the surrounding community (KOSHA 2020).

In response to serious industrial accidents and the associated risks, the 2019 revision of the Occupational Safety and Health Act (enforced in January 2020) strengthened the subcontract approval system by mandating prior authorization. Under this amendment, principal contractors are required to pre-assess the safety and health management capabilities of subcontractors. Subcontractors, in turn, are required to conduct mandatory risk assessments for each task to ensure compliance and prevent industrial accidents (SEMES 2019–2021). Major semiconductor manufacturers, including SEMES, have accordingly established standard operating procedures (SOPs) for subcontractors and implemented a range of management measures. These include pre-task safety training, mandatory use of personal protective equipment (PPE), pipeline flushing and leak testing, provision of neutralizing agents, and the designation of isolated work zones (Ministry of Environment 2021).

Nevertheless, the current safety management framework is largely dependent on qualitative risk assessment methods, such as checklists and job safety analysis (JSA), lacking integration of quantitative factors like actual chemical consumption, equipment aging, and historical accident data (Khakzad et al. 2011, Jensen 2001). Moreover, despite the fact that HF, $H_2SO_4$, $HNO_3$, and HCl have the potential to cause severe incidents, including leaks, explosions, and fires—that pose threats not only workers but also nearby communities—the current safety system lacks the capacity to predict accident probabilities or assess cascading consequences.

Therefore, this study addresses the safety management practices for subcontractor handled hazardous chemicals specifically HF, $H_2SO_4$, $HNO_3$, HCl, used in semiconductor cleaning equipment, subcontractor safety and health evaluation data and SOPs from SEMES. The analysis focuses particularly on high-risk tasks such as equipment modification, dismantling, demolition, and removal tasks. Specifically, SOPs, permit-to-work (PTW) systems, and JSA documents were systematically reviewed to evaluate safety measures implemented before, during, and after work (including flushing, leak testing, PPE usage, local exhaust operation, and emergency response readiness). Subsequently, a case-based risk assessment was conducted on representative tasks-such as modification of the concentration gauge in a phosphoric acid supply unit, Bowl Drain modification, utility piping work, and $H_2O_2$ valve replacement, to systematically assess potential hazards, existing control measures, and residual risks.

This analysis reveals key strengths such as regulatory compliance, SOP adherence, and the presence of a foundational safety culture. However, it also identifies critical limitations such as overreliance on qualitative assessment methods, lack of real-time data integration, subcontractor variability, and insufficient consideration of complex or cascading accident scenarios. To address these shortcomings, the study investigates the application of a Bayesian Network–based quantitative risk assessment model, highlighting its potential to estimate accident probabilities, validate safeguard effectiveness, and prioritization of safety investments-thereby enabling a more predictive and proactive risk management.

## 2. THEORETICAL BACKGROUND ON CLEANING EQUIPMENT AND SUBCONTRACT APPROVAL

### 2.1. Review of Previous Studies

Research on cleaning equipment in semiconductor manufacturing has largely focused on chemical cleaning technologies and equipment development to ensure wafer surface cleanliness. Kern and Ohmi have proposed the evolution of silicon wafer cleaning techniques and the concept of Total Clean Technology for ULSI processes, emphasizing that the use of high-purity chemicals directly affects process yield and product reliability, respectively. In Korea, multiple studies have address both efficiency improvement and safety assurance of clean equipment. For example, Park and Kim [12] conducted a risk assessment of clean equipment in the semiconductor industry, highlighting that high-risk substances such as HF, $H_2SO_4$, $HNO_3$, and HCl pose significant hazards to worker safety. However, most of these studies relied on qualitative methods such as checklists and job safety analysis (JSA) and did not provide quantitative estimates of accident probabilities or the potential scale of resulting damage.

In the international context, following the introduction of process safety management (PSM) systems, numerous studies have focused on quantitative risk assessment (QRA) and scenario-based analysis. Khakzad et al. (2011) compared traditional Fault Tree Analysis (FTA) with Bayesian Networks (BN), illustrating that BN can more dynamically capture complex accident scenarios and allow for conditional probability calculations. Yang and Khan [16] proposed a data-driven dynamic risk assessment method using sensor data, highlighting its potential to address the limitations of conventional static assessments approaches.

In summary, prior studies have demonstrated the technological necessity of cleaning equipment and the use of qualitative risk assessment methods, but systematic research remains limited, particularly in areas such as subcontractor management discrepancies, the lack of real-time data utilization, and the insufficient evaluation of complex accident scenarios. Furthermore, both domestic and international studies rarely applied Bayesian Network–based quantitative risk assessment focused on targeting hazardous substances approved for subcontractor use. Thus, this study aims to fill this research gap and lay a foundation for future application of BN-based models in the safety management.

### 2.2. Necessity of Cleaning Equipment

Wafer surface cleanliness is a critical factor influencing circuit linewidth, manufacturing yield, and overall product reliability in semiconductor manufacturing. Following front-end processes such as lithography, etching, and deposition, metallic contaminants, organic residues, and particles remain on the wafer surface. To remove these impurities, specialized cleaning system, commonly referred to as Clean equipment, are employed, using highly concentrated acids to clean surface and remove oxide layer (Kern 1990).

Clean equipments consist of multiple units—HF Unit, $H_2SO_4$ Unit, $HNO_3$ Unit, HCl Unit—each designed to handle specific acid-based cleaning process to remove particular impurities. For instance, HF is used for silicon oxide removal, sulfuric acid–hydrogen peroxide mixtures (SPM) target organic residues, nitric acid oxidizes metallic ions, and hydrochloric acid controls metallic impurities (OSHA 2017).

 

### 2.3. Characteristics of Cleaning Equipment

- While essential in semiconductor manufacturing, cleaning equipment is inherently associated with high-risk factors (KOSHA 2020),
- Use of highly concentrated chemicals: Large quantities of acids are used at the ton scale, and leaks can escalate into major accidents.
- High-temperature and high-pressure conditions: Heating is applied to accelerate reactions, increasing risks of corrosion and explosion.
- Volatility and diffusivity: Substances such as HCl and HF are highly volatile, and failures in local exhaust ventilation can lead to plant-wide dispersion.
- Corrosion and equipment aging: Prolonged use results in wear of pipes, valves, and pumps, raising the likelihood of micro-leaks.
- Thus, the safety management of cleaning equipment requires not only routine maintenance but also integrated risk management throughout pre-, during-, and post-operation stages (SEMES 2019–2021).

### 2.4. Characteristics of Subcontractor-Approved Hazardous Substances

- Hydrofluoric acid (HF): High tissue penetration; causes fatal systemic toxicity; used for oxide layer removal.
- Sulfuric acid ($H_2SO_4$): Used at high concentrations and elevated temperatures; poses risk of burns and corrosion; combined with hydrogen peroxide in cleaning processes.
- Nitric acid ($HNO_3$): Strong oxidizer; risk of heat generation and explosion; used for metallic ion removal.
- Hydrochloric acid (HCl): High volatility; potential for atmospheric dispersion; induces metallic corrosion.

### 2.5. Legal Basis of the Subcontractor Approval System

In Korea, the 2019 amendment to the Occupational Safety and Health Act, effective from January 16, 2020, reinforced the subcontractor approval system. According to Article 59, any modification, dismantling, demolition, or removal work involving facilities handles hazardous chemicals, specifically those containing more than 1% by weight of designated hazardous chemicals ($H_2SO_4$, HF, $HNO_3$, HCl) requires prior approval from the Minister of Employment and Labor. The objectives of this system are as follows:

- Clarification of safety management responsibilities between principal contractors and subcontractors,
- Accident prevention through mandatory pre-task risk assessment,
- Verification of subcontractor safety and health management capacity.
- This system serves as a key safety mechanism to prevent accidents in industries handling large volumes of hazardous chemicals, such as semiconductor and petrochemical manufacturing.

## 3. CURRENT SAFETY MANAGEMENT SYSTEM

### 3.1. Principal Contractor Management System

SEMES regularly evaluates the safety management level of subcontractors, and its major management

practices are as follows:

- Subcontractor safety and health evaluation: Conducted annually, subcontractors are graded as Adequate / Conditionally Adequate / Inadequate.
- Permit-to-work (PTW) system: High-risk tasks (Grade A: chemical handling, combined work with welding or working at heights) require approval by a safety manager.
- Joint inspections: Prior to commencing work, SEMES and subcontractors conduct a joint site inspection, and deficiencies must be corrected before work can proceed.
- Emergency response system: In case of leaks involving HF, HCl, or $HNO_3$, procedures include neutralizer application, reinforcement of local exhaust ventilation, and emergency evacuation drills.

### 3.2. Subcontractor Management System

Subcontractors perform tasks in accordance with SOPs, with the following core management requirements:
Training and qualification: Workers must complete chemical safety training and possess appropriate work qualifications.

- PPE compliance: Mandatory use of acid-resistant suits, gloves, full-face respirators, safety goggles, helmets, and safety shoes.
- Equipment and piping checks: Pipeline flushing and leak testing must be performed before work begins.
- Deployment of safety watchers: Work must be performed in pairs (two-person rule) with an external safety watcher always present.
- Post-work reporting: Upon completion, subcontractors must submit work reports including photos, checklists, and JSA results.

### 3.3. Stepwise Safety Management

**Pre-work management**
(1) PTW issuance: Includes work purpose, methods, hazards, and emergency response plan.
(2) JSA execution: Identification of hazards and determination of risk levels.
(3) Equipment decontamination: DIW flushing, residual pressure release, and leak testing for at least 30 minutes.
(4) Work area isolation: Installation of a 3-meter safety fence and posting of access restriction signs.
(5) Emergency material preparation: Neutralizers, absorbent pads, fire extinguishers, and eyewash showers.

**During-work management**
(1) PPE compliance check: Verified by the manager prior to work initiation.
(2) Local exhaust operation: Prevents diffusion of chemical vapours.
(3) Two-person work principle: Workers and safety watchers are deployed.
(4) Real-time monitoring: Monitoring via pressure gauges, flow meters, and gas sensors.
(5) Right to stop work: Workers and safety watchers are authorized to halt work immediately upon detection of abnormalities.

**Post-work management**
(1) Flushing: All lines must be flushed and drained.
(2) Waste solution management: Transferred in designated containers to the Environmental Safety Group.
(3) Final inspection: Conducted jointly by SEMES safety managers and subcontractor supervisors.
(4) Work completion reporting: Submission of reports and photographic records.
(5) Reopening approval: Work areas reopened only after final confirmation by safety managers.

### 3.4 Limitations of the Current System

Despite these structured management practices, the following limitations have been identified:
Reliance on qualitative management: Excessive dependence on checklist-based methods prevents probabilistic prediction of accidents (SEMES 2019–2021).
Inconsistencies among subcontractors: While some apply advanced techniques such as HAZOP, most rely on basic inspections, leading to inconsistent management quality (Ministry of Environment 2021).
Insufficient use of real-time data: Monitoring data such as pressure, temperature, and gas concentration are not integrated into risk assessments (Ministry of Environment 2021).
Inadequate consideration of complex accidents: Multi-scenario events such as HF–$H_2SO_4$ mixtures or high-temperature leaks are often simplified into single-event assumptions (Ministry of Environment 2021).

## 4. RISK ASSESSMENT LEVEL AND LIMITATIONS

### 4.1. Current Risk Assessment Methods

In semiconductor cleaning equipment handling subcontract-approved hazardous substances (HF, $H_2SO_4$, $HNO_3$, HCl), risk assessments currently rely predominantly on qualitative methods. Analysis of safety management documents from both the principal contractor and subcontractors revealed the following key approaches:

1. **Checklist Approach**
   - Based on SOP-documented procedures, this method simply verifies the presence of hazards and the implementation of countermeasures.
   - Typical items include PPE compliance, local exhaust operation, flushing implementation, and emergency equipment availability.
   - *Advantages:* Simple, rapid, and easily applied by on-site supervisors.
   - *Limitations:* Does not quantify accident probability or potential consequences; remains at a binary *Yes/No* level of inspection.

2. **Job Safety Analysis (JSA)**
    - Divides work into sequential steps to identify hazards at each stage, and evaluates risk using a matrix of *Frequency × Severity*.
    - Typically, a 4×4 or 5×5 risk matrix is applied.
    - *Advantages:* Enables stepwise hazard identification and emphasizes the need for safety measures.
    - *Limitations:* Criteria for frequency and severity are ambiguous; results vary depending on evaluator subjectivity.
3. **Hazard and Operability Study (HAZOP)**
    - Applied by some subcontractors during equipment modification or installation.
    - Focuses on deviations in process variables (e.g., increased flow, reduced pressure, elevated temperature), deriving potential causes and consequences.
    - *Advantages:* Identifies risks associated with process variable changes.
    - *Limitations:* Meeting-based approach is time- and resource-intensive and does not quantify accident probabilities.

### 4.2. Characteristics of the Current Assessment Level

1. **Compliance with legal requirements:** All subcontractors conduct at least JSA- or checklist-based assessments, formally satisfying subcontract approval conditions.
2. **Recurring deficiencies:** Items such as improper PPE use, absence of neutralizing agents, and insufficient safety training are repeatedly identified each year.
3. **SOP-centered management:** Risk assessments are heavily focused on hazard checklists embedded in SOPs, lacking probability estimation or impact analysis.
4. **Subcontractor variability:** While some subcontractors apply advanced methods such as HAZOP or LOPA, most remain at a checklist-based level.

### 4.3. Key Limitations

1. **Lack of quantitative data**
    - Evaluations rarely incorporate data such as actual chemical usage, leak probabilities, equipment aging indicators, or accident statistics.
    - Consequently, scenario-specific accident probabilities and damage scales cannot be presented numerically (SEMES 2019–2021).
2. **Simplification of accident scenarios**
    - Current assessments typically consider single-event pathways (e.g., “HF leak → human exposure”).
    - In reality, complex accident sequences exist (e.g., leak → vapor dispersion → local exhaust failure → adjacent equipment damage → fire/explosion), but these are not adequately reflected (Ministry of Environment 2021).
3. **Variability among subcontractors**
    - Even for identical facilities and tasks, assessment quality varies significantly across subcontractors.
    - This reveals a structural issue arising from the lack of an integrated data management system by the principal contractor (Ministry of Environment 2021).
4. **Insufficient integration of real-time data**
    - While pressure, temperature, and gas concentration are monitored via sensors, such information is not incorporated into risk assessments.
    - As a result, evaluations remain static, lacking the capability for **dynamic risk assessment** (Ministry of Environment 2021).

## 5. CASE ANALYSIS

### 5.1. Phosphoric Acid Concentration Gauge Modification Work

1. **Task overview:** Replacement and modification of the concentration gauge sensor in the phosphoric acid ($H_3PO_4$) supply system.
2. **Major hazards:**
    - Residual acid leakage in piping may cause skin and eye injuries.

 

   - Phosphoric acid vapor may disperse into the atmosphere if local exhaust systems fail.
3. **Safety measures:**
   - Pre-work DIW flushing to remove residual chemicals.
   - Availability of neutralizing agents ($NaHCO_3$, $Ca(OH)_2$).
   - Operation of local exhaust systems and installation of a 3-meter safety fence.
   - PPE use (acid-resistant suits, gloves, full-face respirators).
4. **Limitation:** Lack of real-time concentration monitoring; micro-leaks may not be detected immediately.

### 5.2. Bowl Drain Modification Work

1. **Task overview:** Modification of the Bowl Drain line in wet bench cleaning equipment.
2. **Major hazards:**
   - Risk of splashing residual HF and $H_2SO_4$ from piping.
   - Inadequate pressure release may cause chemical ejection.
   - Hot-gun use may lead to burns or fire hazards.
3. **Safety measures:**
   - Leak testing for at least 30 minutes before pipe cutting.
   - Two-person work principle with safety watcher assignment.
   - Pre-operation checks on eyewash and safety shower equipment.
4. **Limitation:** Limited workspace reduces worker mobility when wearing PPE, increasing the potential for human error.

### 5.3. Hydrogen Peroxide ($H_2O_2$) Valve Replacement Work

1. **Task overview:** Replacement of a needle valve in the hydrogen peroxide ($H_2O_2$) supply line.
2. **Major hazards:**
   - Strong oxidizing property of $H_2O_2$; explosive potential if in contact with metallic catalysts.
   - Risk of residual oxidizer leakage during valve removal.
3. **Safety measures:**
   - Drainage and DIW flushing to eliminate residual oxidizers.
   - Pressure gauge checks and leak-tightness testing before and after replacement.
   - Enhanced local exhaust and ventilation.
4. **Limitation:** Due to the intrinsic instability of oxidizers, complete removal of residues cannot be guaranteed.

### 5.4. Utility Piping Construction

1. **Task overview:** Expansion and installation of utility lines for cleaning equipment.
2. **Major hazards:**
   - Risk of falls and fire hazards due to simultaneous high-place work and welding.
   - Chemical leakage during pipe cutting, particularly HF and HCl residues.
   - Potential reactivity between welding sparks and chemical vapors.
3. **Safety measures:**
   - Application of Lock-Out & Tag-Out (LOTO).
   - Deployment of fire watchers within the work radius.
   - Availability of local exhaust ventilation, fire extinguishers, and neutralizing agents.
4. **Limitation:** Multiple subcontractors are often involved simultaneously, making hazard coordination and integrated risk management difficult.

### 5.5. Comprehensive Analysis of Cases

Synthesizing the above cases, the following **commonalities and limitations** were identified:

1. **Common safety measures:** Flushing, leak testing, availability of neutralizers, operation of local exhaust systems, PPE use, and two-person work rule.
2. **Common hazards:** Residual chemicals in pipelines, inadequate pressure release, confined workspaces, and the intrinsic instability of oxidizing substances.
3. **Major limitations:**
   - Overemphasis on SOP compliance without probabilistic accident prediction.
   - Variability in management quality across subcontractors.
   - Lack of real-time monitoring systems.

- Insufficient consideration of complex accident scenarios (e.g., HF–$H_2SO_4$ mixtures, leaks under high-temperature conditions).

## 6. CONCLUSION AND FUTURE RESEARCH

This study examined safety management practices for semiconductor cleaning equipment, focusing on subcontract-approved hazardous substances (HF, $H_2SO_4$, $HNO_3$, HCl). A review of subcontractor SOPs and safety reports confirmed that current practices maintain basic safety but revealed key limitations: (1) reliance on qualitative methods such as checklists and HAZOP, (2) inconsistencies in SOP detail, training, and PPE use, and (3) lack of integration of real-time monitoring data.

The analysis showed that while the system ensures legal compliance and procedural management, it falls short in providing quantitative risk insights and addressing complex accident scenarios. Based on these findings, the study emphasizes the need for Bayesian Network–based models to quantitatively estimate accident probabilities and strengthen risk management consistency.

This research is significant in using actual subcontractor data to assess system strengths and weaknesses. Future work should focus on developing BN-based models to shift semiconductor safety management from compliance-driven practices to predictive and proactive risk control, fostering a stronger safety culture and reducing the likelihood of major accidents.

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## REFERENCES

Hamilton SH, ElSawah S, Guillaume JHA, Jakeman AJ & Pierce SA (2015) A common language for transdisciplinary teams using a generic conceptual framework. *Environmental Modelling & Software*, 70, 136–146.

Hollnagel E (2017) *Safety-II in practice: Developing the resilience potentials*. Routledge.

Jensen F (2001) *Bayesian networks and decision graphs*, New York, Springer.

Kern W & Puotinen DA (1970) Cleaning solutions based on hydrogen peroxide for use in silicon semiconductor technology. *RCA Review*, 31(2), 187–206.

Kern W (1990) The evolution of silicon wafer cleaning technology. *Journal of the Electrochemical Society*, 137(6), 1887–1892.

Khakzad N, Khan F & Amyotte P (2011) Safety analysis in process facilities: Comparison of fault tree and Bayesian network approaches. *Reliability Engineering & System Safety*, 96(8), 925–932.

Khan FI & Abbasi SA (1998) Models for domino effect analysis in chemical process industries. *Process Safety Progress*, 17(2), 107–123.

Korea Occupational Safety and Health Agency (KOSHA) (2020) *Guidelines for quantitative risk assessment*.

Korea Occupational Safety and Health Agency (KOSHA) (2021) *Guidelines for safety management in semiconductor processes*

Korean Ministry of Employment and Labor (MOEL) (2020) *Occupational Safety and Health Act (Amended 2019)*. Government of Korea.

Lee MJ (2024) Likelihood Estimation Method Applying Bayesian Network Based on Cloud Model, Ph.D thesis, Dept. of Safety Engineering, Korea National University of Transportation.

Ministry of Environment (2013) *White paper on the 2012 Gumi HF accident* (2012). Government of Korea.

Ministry of Environment (2021) *Commentary on the Chemical Substances Control Act*. Government of Korea.

OSHA (2017) *Process safety management of highly hazardous chemicals*. U.S. Department of Labor.

Park and Kim

SEMES (2019–2021) *Safety and health evaluation reports of subcontractors*.

Tsai WT (2019) Hydrofluoric acid: Regulatory history, industrial applications, and occupational health issues. *Journal of Cleaner Production*, 227, 1018–1026.

Yang and Khan