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Gas Box Exhaust Design Modification for Accidental Hazardous Gas Releases in Semiconductor Industry

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Abstract: Hazardous substances such as hydrogen and chlorine are used in semiconductor manufacturing. When these gasses are discharged, they are mixed with outside air and are connected to a treatment facility through a duct inside a gas box. This study investigated an optimal exhaust design to prevent fire explosions and toxic exposure by optimizing the exhaust volume when hazardous substances leak from the gas box of semiconductor manufacturing equipment. In this study, carbon monoxide was used for modeling. A 75 mm duct was used, and the tracer gas was released into the gas box at 15.4 LPM. The concentrations were measured at nine points inside and outside the gas box. According to the test results, in an experiment designed with 0% air intake, the internal leakage concentration was measured to be more than 25% of the LEL (lower explosive limit) for 10 min when leakage occurred due to stagnant flow, and the outside toxicity concentration was also measured to be more than 50% of the TWA (time-weighted average) value. When the air intake ratio was designed to be 100%, there was a point on the outside that exceeded 50% of the TWA, confirming that excessive air intake could also cause gas to leak outside. Finally, when the intake ratio was designed to be 50% in both directions, it was confirmed that the airflow was maintained smoothly, and the hazardous gasses were safely diluted and discharged through the duct. This study was conducted to improve the safety of workers in the field in the event of leakage of flammable and toxic gasses by testing the location and area of the air intake hole in the gas box exhaust port. Through this effort, the aim is to present specific standards for gas box design and to assist in establishing a legal framework or standardized guidelines.

Keywords: exhaust ventilation; gas box; SEMI S6-0618; SEMI F-15; SEMI S6; KS C IEC 60079-10-1; IEC 60079-10-1; NFPA 318; tracer gas test; semiconductor manufacturing equipment

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1. Introduction

Electronic products used daily, such as smartphones and TVs, air conditioners, and refrigerators utilized at home, cannot maintain their functions without semiconductors to store, process, or transmit data. Additionally, production lines at large automobile manufacturing plants have recently come to a halt due to an imbalance in the supply and demand of automotive semiconductors. Thus, semiconductors have become essential products in our daily lives. During the manufacture of these semiconductors, several devices are organically connected, forming one process to create a semiconductor. Recently, Korea has shown continued growth in the semiconductor field, ranking first in the world in the semiconductor industry, and this phenomenon acts as a positive factor in national economic and social aspects [1]. Countless chemical substances are used in the equipment required to manufacture semiconductors, including those that are flammable, corrosive, and toxic [2,3]. Semiconductor processes can be roughly divided into supply processes for supplying chemicals, semiconductor manufacturing processes, and treatment processes for treating the reaction byproducts and unreacted substances that remain after use in the semiconductor manufacturing process [4]. Semiconductors are manufactured through wafer processing, manufacturing, and the assembly of various unit processes that are repeated countless times. Numerous chemicals and complex equipment are used in multiple processes, such as wafer processing, manufacturing, and assembly. If an accident occurs due to the leakage of flammable, corrosive, or toxic chemicals during the manufacturing process, it can not only take the lives of workers but can also cause significant damage to residents near the factory and the surrounding environment [5]. In places such as Korea, where semiconductor factories and residential areas are located nearby, safety and health are of particular concern.

In Korea, as specified in the Occupational Safety and Health Act, enforcement ordinances, and enforcement regulations, the Ministry of Employment and Labor has entrusted the Korea Occupational Safety and Health Agency with a process safety management (PSM) submission system to ensure the safety of 51 chemical handling facilities and related facilities, including semiconductor handling processes [6–9]. Effective regulations are advantageous for both industry and workers [10]. Despite these efforts, owing to the risk of materials handled in the semiconductor manufacturing process and the complexity of the process, Korean semiconductor companies are establishing their own safety standards, in addition to legal regulations. Third-party certification is a representative safety standard. Although not a legal standard, most semiconductor companies in Korea apply it to pursue greater safety by utilizing the standards produced by Semiconductor Equipment and Materials International (SEMI) [11]. The gas flow used in the semiconductor manufacturing process is shown in Figure 1. Many types of gas are supplied in various ways, such as from a cylinder inside a gas cabinet, through a supply system such as a Bulk specialty gas supply (BSGS) or using a trailer.

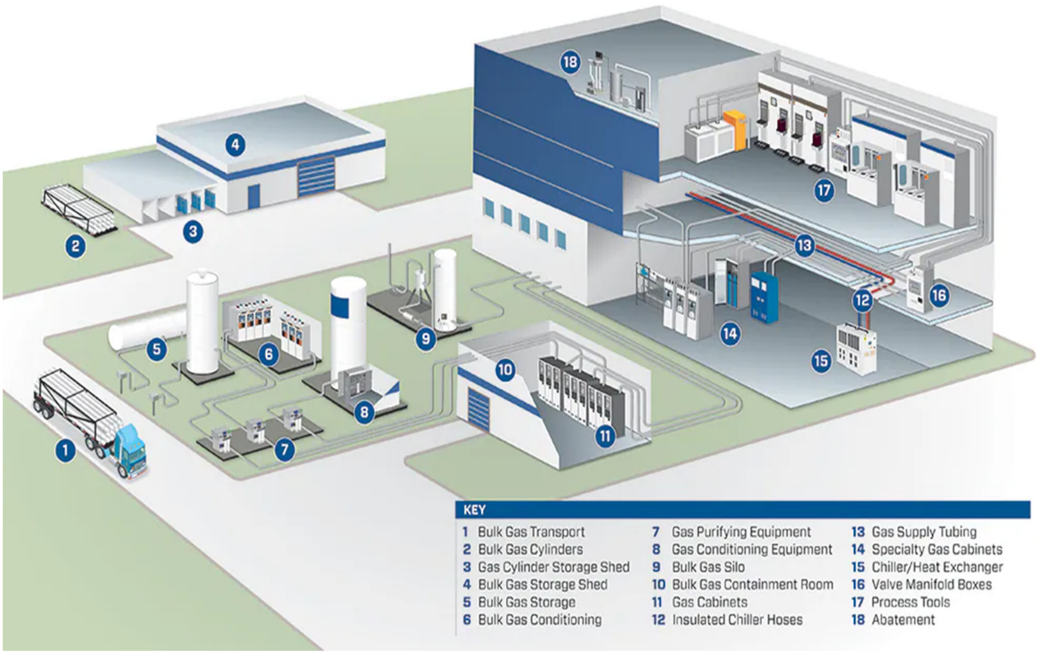


Figure 1. Gas supply system flow in semiconductor manufacturing process (Courtesy copied from the Swagelok website).

These toxic and flammable gasses are supplied to the manufacturing equipment and used for reactions, cleaning, and as carriers. The gas box controls the flow rate and pressure so that they can be used in fabrication equipment [12]. The inside of the gas box must always maintain an efficient equipment exhaust. This prevents flammable or toxic gasses from leaking in the event of a pipe leakage. A leak can occur at any connection point between the MFC and the valve in the gas box. Therefore, adequate exhaust facilities must be provided to prevent the discharge of flammable or toxic gasses.

A recent accident where approximately 100 people were evacuated due to toxic gas leaking from a gas box at a semiconductor manufacturing plant had many implications for semiconductor safety and health management. The toxic gas was first detected by a gas detector installed in the gas box; a few minutes later, it was detected using a gas detector outside the gas box. Fortunately, no casualties were reported. However, when the accident occurred, the gas detector in the gas box detected a gas leak, but the toxic gas was not automatically blocked. Additionally, even if toxic gas does leak, it must be treated using an exhaust system connected to the gas box. However, toxic gas leaked outside, and the gas detector was activated outside the gas box. After the accident, safety measures were taken at domestic semiconductor manufacturing plants by sealing the gaps in all pipes connected to the gas box. At the site, the equipment manufacturer's engineers were installing the equipment, and those in charge of operations lacked an understanding of the standards for gas boxes requiring airflow or duct differential pressure for safety and health. These design standards had to be queried by foreign design departments. Additionally, many gas boxes do not have air intakes. If air is not injected into the gas box, the negative pressure inside the gas box increases, and if toxic gas leaks, a problem may occur where proper dilution cannot be achieved inside the gas box [13]. The gas box must be opened at some point for maintenance; therefore, if toxic gas remains inside, opening it can have a fatal effect on workers.

In Korea, the leakage rate of flammable or toxic gasses must be calculated based on the Korean Industrial Standard KS C IEC 60079-10-1, 2nd edition [9,13,14]. This standard contains formulas for calculating leakage rates and hazardous areas using other methods, such as NFPA497 or API RP505. However, this cannot be applied to the semiconductor industry because it is designed to be used only in specific areas to reduce explosion hazard areas, and API RP505 is a document written specifically for petrochemical plants [15–17]. In addition to legal regulations, Korean semiconductor companies are establishing their own safety standards. Representative examples include leakage rate calculations and exhaust gas testing according to SEMI S6-0618 (releases from disconnected gas piping and test methods for determining fugitive emissions using tracer gas) [11].

A review of previous studies confirmed that they were conducted to present safety standards for gas box designs for flammable gasses. However, previous studies have shown that there are limitations in establishing specific design methods due to insufficient verification of toxic gasses and research on the specific size and location of air intakes. The objective of this study is to identify safety measures for each risk characteristic in the event of a gas leak in a gas box using gasses with both flammable and toxic properties. Each scenario measured the concentration below the lower risk limit (including toxicity and flammability standards), not only at the internal ignition source and the worker's breathing area but also near the air intake hole. An experimental study was conducted to suggest appropriate design criteria for the air intake hole of the gas box based on the exhaust flow.

2. Experimental Setup

2.1. Determination of Test Gasses

The dry etching process mainly uses process gasses such as CF_4, CHF_4, and HF. Here, adding plasma and CO gas can further increase the selectivity of Si. Among these gasses, CO gas is a hazardous gas that has both toxic and flammable properties. Therefore, CO gas was selected as a simulated gas in this paper. The lower explosive limit (LEL) of the carbon monoxide used in this study is 12.5%, and the upper explosive limit (UEL) was 74.2%. The Occupational Safety and Health Act defines a flammable gas as one where the lower explosion limit is less than 13%, or the difference between the upper and lower explosion limits is more than 12%; therefore, carbon monoxide is considered a flammable gas [7–9]. In other words, it can be defined as a gas that readily mixes with air when leaked, forming an explosive atmosphere and quickly causing fire or explosion. Toxic gasses are harmful to the human body when they exist in the air in specific amounts or higher and are treated separately from other gasses. The toxic gasses defined in the High-Pressure Gas Safety

Management Act include carbon monoxide and chlorine, which have a time-weighted average (TWA) of less than 200 ppm (parts per million). The lower the allowable human concentration, the higher the risk. Carbon monoxide is a toxic gas with a time-weighted average (TWA) of 25 ppm [18,19]. Carbon monoxide (CO) is a colorless, odorless, non-irritant, toxic gas that can harm the human body due to its toxic effects, ranging from cardiovascular and respiratory impairments to neuropsychiatric presentations [20,21].

2.2. Determination of Process Condition

To review the optimal design criteria, the operating conditions of the etching process must be selected accurately. The pressure, hole cross-sections, and physical properties of the fluid affect the calculation of the leakage rate. To determine the leakage rate, the operating conditions of the etching process equipment used in Korea were applied, as shown in Table 1. Parameter descriptions are provided in Table 1; pressure means the pressure of the inside a gas pipe in the gas box. The pressure is between 40 and 60 psi(g) in semiconductor processes. Obviously, the higher pressure, the more risk of gas leaks when the gas line breaks. Therefore, 60 psi(g) was selected as the worst-case scenario. Hole cross-sections mean the cross-section areas of gas lines inside the gas box, and ¼ inch lines are mostly used for semiconductor equipment. In addition, SEMI S6 recommends 4~5 air changes per minute for gas panels. The volume of the test gas box is approximately 0.2 m^3. Applying 5 air changes per minute, the ventilation volume is approximately 1 m^3.

Table 1. Operation condition of etching process.

Item	Specification
Gas box size	600 mm (0.6 m) × 350 mm (0.35 m) × 1000 mm (1 m)
Pipe diameter	0.635 cm (1/4 inches)
Pipe length	600 mm (0.6 m)
Pressure	413,685 P_a (g) (60 psi(g))
Temperature	20 °C

2.3. Calculation of Release Rate of Carbon Monoxide (CO)

If a leak occurs in a pipe inside a gas box, it is essential to select an appropriate leak amount. Gas leaks have various causes, including incorrect assembly, erosion due to high flow speeds, and corrosion, depending on the characteristics of the fluid. Determination of release rates for tracer gas tests is specified in section 8.2.3.3 of the SEMI S6, with reference to Appendix 1 of this standard [11]. This standard assumes that the pipe inside the gas box completely ruptures. The worst-case scenario for a leak is when the pipe ruptures and the fluid within it continues to leak. However, in manufacturing equipment, an interlock was implemented to block the supplied fluid when the gas detector in the gas box detected leaking gas. Additionally, because the pipes in semiconductor manufacturing plants are connected to a gas box in a location that is not accessible to people, all the pipes inside the gas box cannot rupture unless the pipes are intentionally damaged [22]. To determine more realistic leakage rates, we compared the standards KS C IEC 60079-10-1, SEMI S6, and SEMI F15.

2.3.1. KS C IEC 60079-10-1: Release Rate Calculation for Carbon Monoxide

The KS C IEC 60079-10-1 standard is based on IEC 60079-10-1 as revised in Korea. When the 2nd edition was first issued in Korea, there was considerable confusion due to unclear descriptions. Several meetings were held, and content that could be interpreted subjectively within a reasonable range was revised as objectively as possible [23–26].

In KS C IEC 60079-10-1, leakage is classified into continuous, primary, and secondary leakage grades according to the frequency and duration of the leakage. Leaks that are expected to occur continuously, frequently, or for long periods are called continuous grades. Leaks that are expected to occur periodically or often during regular operation are called primary grades. They do not leak during regular operations, and even if they do, in the case of a very rare or short-term leakages, they are classified as a secondary grade of release. In the case of a gas box used to supply carbon monoxide for semiconductors, the gas does not leak during regular operations, and even if it does, it tends to leak very rarely or for a short period; therefore, in this case, it is defined as a secondary grade of release. The equivalent hole sizes that may be considered for secondary grade leakages are listed in Table 2.

Table 2. Suggested hole cross-sections for secondary grade releases.

Type of Item	Item	Leak Considerations		
		Typical Values for the Conditions Under Which the Release Opening Will Not Expand	Typical Values for the Conditions Under Which the Release Opening May Expand	Typical Values for the Conditions Under Which the Release Opening May Expand Up to a Severe Failure
		S (mm^2)	S (mm^2)	S (mm^2)
Sealing elements on fixed parts	Flanges with compressed fiber gasket or similar	≥0.025 up to 0.25	>0.25 up to 2.5	(Sector between two bolts) × (gasket thickness) usually ≥1 mm
	Flanges with spiral wound gasket or similar	0.025	0.25	(Sector between two bolts) × (gasket thickness) usually ≥0.5 mm
	Ring-type joint connections	0.1	0.25	0.5
	Small-bore connections up to 50 mm	≥0.025 up to 0.1	>0.1 up to 0.25	1.0
Sealing elements on moving parts at low speed	Valve stem packings	0.25	2.5	To be defined according to equipment manufacturer data but not less than 2.5 mm^2
	Pressure relief valves	0.1 × (orifice section)	NA	NA

If the pressure inside the gas pipe is higher than the critical pressure (Pc), a choked flow occurs. This occurs in gasses and vapors when the fluid velocity reaches sonic values at any point in the pipe. In this case, the velocity at any point in the downstream pipe was limited to the speed of sound (Mach = 1), and the flow rate was limited to the amount that yielded a sonic velocity in the pipe under specified pressure conditions [27]. The critical pressure was calculated using Equation (1).

$$P_C = P_a \left(\frac{r+1}{2} \right)^{\frac{r}{r-1}} \tag{1}$$

If the pressure inside the gas line is lower than the critical pressure, the leakage rate can be calculated using (2) [23–26]:

$$W_g = C_d SP \sqrt{ \frac{MR}{ZRT} \left(\frac{2}{r-1} \right)^{\left[1 - \frac{P_a}{P}^{\frac{r-1}{r}}\right]} \frac{P_a}{P}^{\frac{1}{r}} } \tag{2}$$

The choked gas velocity is equal to the sonic speed of the gas. This is the maximum theoretical discharge velocity. The leakage rate was calculated using Equation (3) [23–26]:

$$W_g = C_d SP \sqrt{ r \frac{MR}{ZRT} \left(\frac{2}{r+1} \right)^{(r+1)/(r-1)} } \tag{3}$$

The corrosive environment (erosion, vibration, etc.) of the semiconductor industry is considered to be at a relatively low level compared with other industries (petrochemicals, steel, etc.). Accordingly, in May 2023, at the Ministry of Employment and Labor of the Republic of Korea, leak conditions were changed from typical values for conditions where the release opening can be expanded to typical values for conditions where the release opening cannot be expanded. If there is a leak from a pipe installed inside a gas box, the hole cross-section that is most conservatively calculated is 0.25 mm^2 (0.25×10^{-7} m^2) as in Table 2 (describing typical values for the conditions under which the release opening will not expand for valve stem packings). If the critical pressure is calculated using Equation (1), it is 192,412 P_a, which is less than 413,685 P_a, which is the internal piping pressure of the gas box. This implies that the behavior of the fluid in the event of a leak is in a choked flow, and the leakage rate must be calculated by applying Equation (3). Consequently, if a leak occurs from a pipe inside a gas box, 0.000299682 kg/s is calculated. The factors required for these calculations are listed in Table 3. Dividing this value by the density and unit conversion yields 15.4 LPM (liters per minute).

Table 3. Factors required for KS C IEC 60079-10-1 calculation.

Variable	Definition
P_C	Critical pressure ($192,412\ P_a$)
P_a	Atmospheric pressure ($101,325\ P_a$)
P	Internal pressure ($413,685\ P_a$)
γ	Polytropic index (1.41)
C_d	Discharge coefficient (1)
Wg	Mass leakage rate (the result of Equation (3))
R	Ideal gas constant (8314 J/kmol·k)
S	Hole cross-sections ($0.25\ mm^2$)
Z	Compressibility factor (1)
T	Absolute temperature (293 K)
M	Molecular weight (28.01 kg/kmol)
D	Density (1.165 kg/m^3)

2.3.2. SEMI S6-0618: Release Rate Equation for Carbon Monoxide

Releases from the disconnected gas piping formula in SEMI S6 are used to calculate the amount of leakage when the piping in the gas box is disconnected. The flow in a straight tube can be calculated if the tube characteristics and the upstream and downstream pressures are known. As shown in Figure 2, if the upstream (drive side) condition has a subscript of 1 and the downstream (ambient) condition has a subscript of 0, the flow rate in the case of release rate can be calculated using the below equation (the variables are listed in Table 4 [11]).

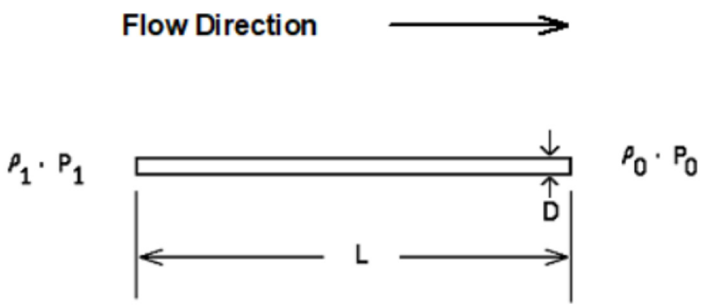


Figure 2. Gas Supply Released from Disconnected Gas Piping Schematic Drawing.

Table 4. Factors required for SEMI S6-0618 calculation.

Variable	Definition
Q	Gas supply releases rate from disconnected gas piping (1221.9 LPM)
ρ_0	Density of gas flowing through straight tube under downstream (ambient) conditions (0.001165 g/cm^3)
ρ_1	Density of gas flowing through straight tube under upstream conditions (0.005921 g/cm^3)
4f	Surface roughness parameter for smooth pipe (dimensionless) (0.02)
γ	Polytropic index (1.41)
w	Mass flow rate of gas flowing in straight tube (kg/s) (the result of Equation (6))
M_1^2	Square of upstream Mach number (dimensionless) (the result of Equation (4))
P_1	Upstream absolute pressure (515,038 Pa)
P_a	Downstream absolute pressure (101,325 Pa)
L	Pipe length (0.6 m)
D	Pipe diameter (0.00635 m)
Q	Volume flow rate of gas (L/min) (the result of Equation (7))
V	Molar ideal gas volume (22.4 (L/mole))
M	Molecular weight (28.01 kg/kmol)
S	$\text{Hole cross} - \text{sec tional area}\ \left(32\ \text{mm}^2\right)$

Because rupture occurs within the gas box, the pipe length was selected as 600 mm (0.6 m), which is the same as the gas box length. The other process conditions are presented in Table 1. As a result, 1221.9 LPM was calculated.

$$rM_1^2 = \frac{1 - \left[\frac{P_0}{P_1}\right]^2}{4f\left[\frac{L}{D}\right] + \ln\left[\frac{P_1}{P_0}\right]^2} \quad (4)$$

$$\rho_1 = \rho_0\left[\frac{P_1}{P_0}\right] \quad (5)$$

$$w = 0.00001S\left[10\rho_1 P_1 rM_1^2\right]^{0.5} \quad (6)$$

$$Q = 60\frac{wV}{M} \quad (7)$$

2.3.3. SEMI F-15-93 [28]: Release Rate Equation for Carbon Monoxide

Due to the closed nature of the semiconductor industry in Korea, there are often cases where clear guidelines on specific discharge amounts cannot be provided. In this case, 28 LPM was applied to the 0.00635 m pipe, as recommended by SEMI F15-93 [28].

2.3.4. Release Rate Calculation Result for Carbon Monoxide

When examining applicability in the actual semiconductor industry, a complete rupture of the pipe inside the gas box is unlikely to occur, and it is not efficient to manufacture a gas box shape and structure based on this scenario. It is also recommended that the 28 LPM flow rate presented in SEMI F15 be selected; however, there is no clear basis for this recommendation. Therefore, based on the standards of KS C IEC 60079-10-1 and those presented by the Ministry of Employment and Labor of the Republic of Korea, 15.4 LPM was selected as the flow rate for the experiment. Table 5 compares the calculated release rates presented in Sections 2.3.1–2.3.3 below in one table.

Table 5. Release rate calculation results.

Calculation Source	Pressure (Pa(g))	Release Opening (mm^2)	Volume Flow Rate of Gas (Liters per Minute)
KS C IEC 60079-10-1	413,685	0.25	15.4
SEMI S6-0618	413,685	31.65	1221.9
SEMI F15	-	-	28

2.4. Gas Box Exhaust Test Method

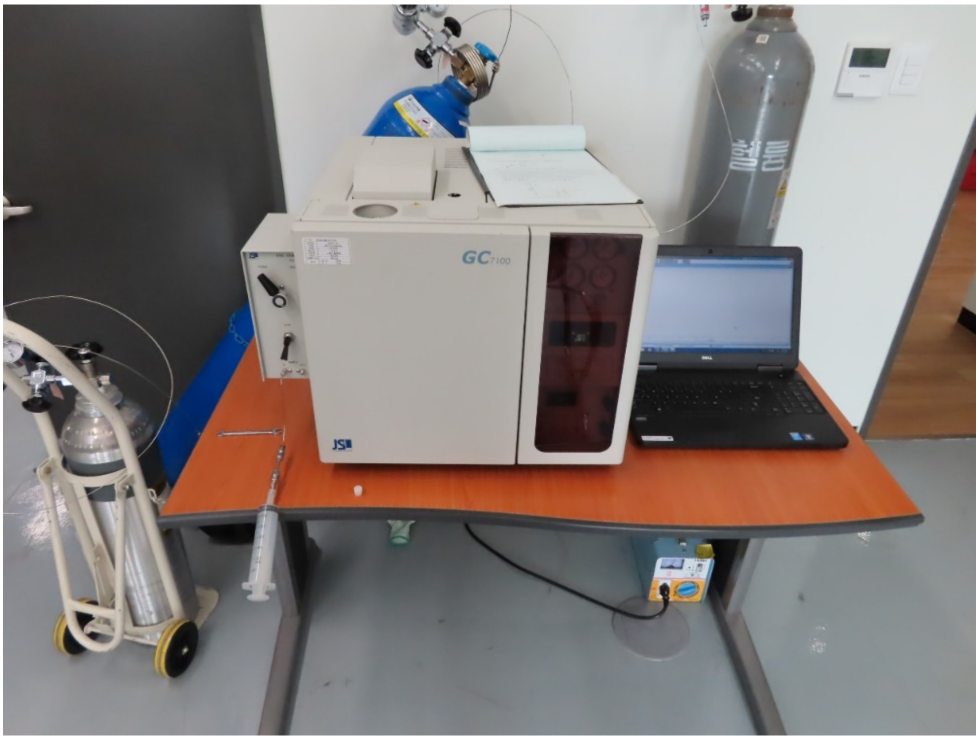
This test was performed based on a leakage rate of 15.4 LPM. Because using actual carbon monoxide gas is dangerous when testing for leaks inside the gas box, 1% SF6 and 99% N_2 gas was used as tracer gasses in the experiments. Gas release was conducted inside the gas box, and the internal and external gasses were collected and analyzed at regular intervals. For the analyzed samples, the equivalent release concentration (ERC) was calculated according to Equation (8), and the concentration of the tracer gas was calculated assuming the actual gas concentration was 100%. Table 6 lists the test equipment specifications. The testing equipment is shown in Figure 3, and the testing conditions were as follows:

1. In accordance with the current trend of semiconductor manufacturing companies producing compact duct sizes, the duct size was decided at 75 mm, and differential pressure was decided at -180 Pa.
2. Selection of the air intake size compared to the determined duct size (a duct area ratio of 0%, 50%, 100%). Tracer gas (SF6 1%, 99% N_2) was leaked inside the gas box for 10 min.
3. Internal and external concentration measurement times are determined as 1 min after tracer gas release. Tracer gas (SF6 1%, 99% N_2) leak, 10 min after the leak starts (at the end of the leak), and 20 min after the end of the leak.

$$ERC = \frac{(Process\ Gas\ Concentration) \times (Measured\ Tracer\ Gas\ Concentration)}{(Injected\ Tracer\ Gas\ Concentration)} \quad (8)$$

Table 6. Test Equipment Specifications.

Item	(a) Gas Chromatography	(b) Multi-Gas Monitor
Manufacture	J-SCIENCE (Kyoto, Japan)	Luma Sense Technologies (Frankfurt, Germany)
Model	GC 7000EN	INNOVA 1512
Detection method	Non-ECD electron trap detector	IR Filter method
SF6 measuring range	1 ppb or less	5 ppb
Power rating	AC100 V, 50/60 Hz, 1.5 KVA	AC100~240 VAC, 50/60 Hz



(**a**)

(**b**)

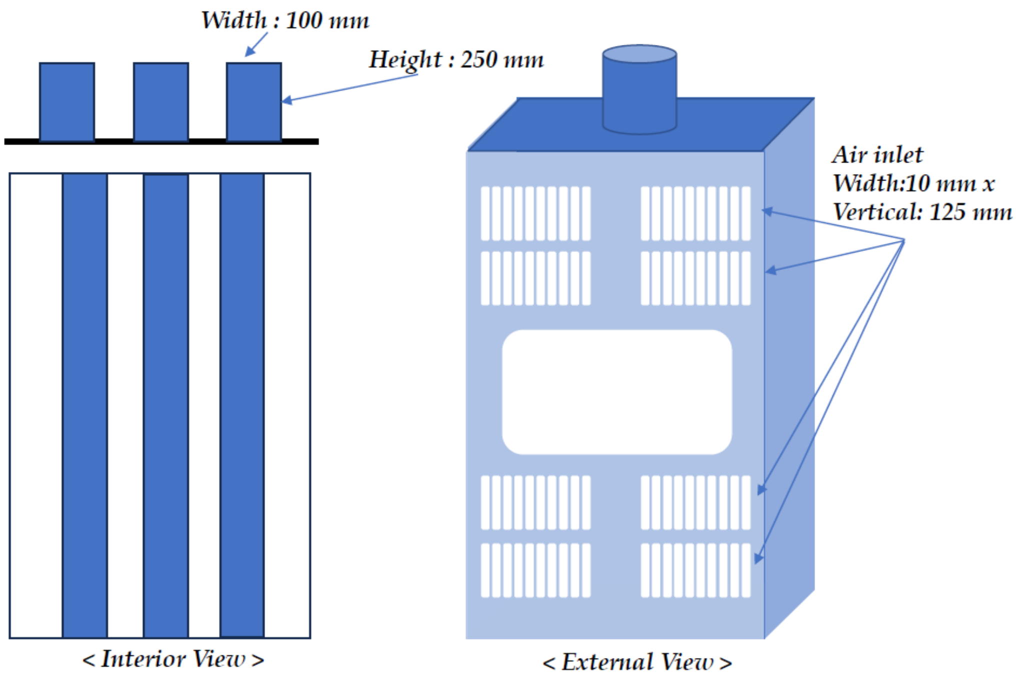
Figure 3. Images of tracer gas testing equipment. (Refer to Table 6. For detailed specifications).

2.5. Gas Box Size Selection

In places where hazardous substances may leak, a surrounding gas box must be installed and connected to an air purification device through an exhaust system. Additionally, an air intake of a specific size must be installed to dilute the leaked hazardous substances smoothly [29,30].

There are no standards for air intakes in the gas boxes of semiconductor manufacturing equipment. Therefore, gas box air intakes with various shapes have been created by each manufacturer. Due to a recent chlorine leak incident, the air intake port is completely sealed; however, in reality, if there is no air intake port, the internal airflow will not be smooth; therefore, if toxic or flammable substances leak, they will stagnate inside the gas box. Consequently, if a worker opens a gas box to maintain the equipment, a hazardous substance that leaks momentarily may cause a fire, explosion, or toxic exposure.

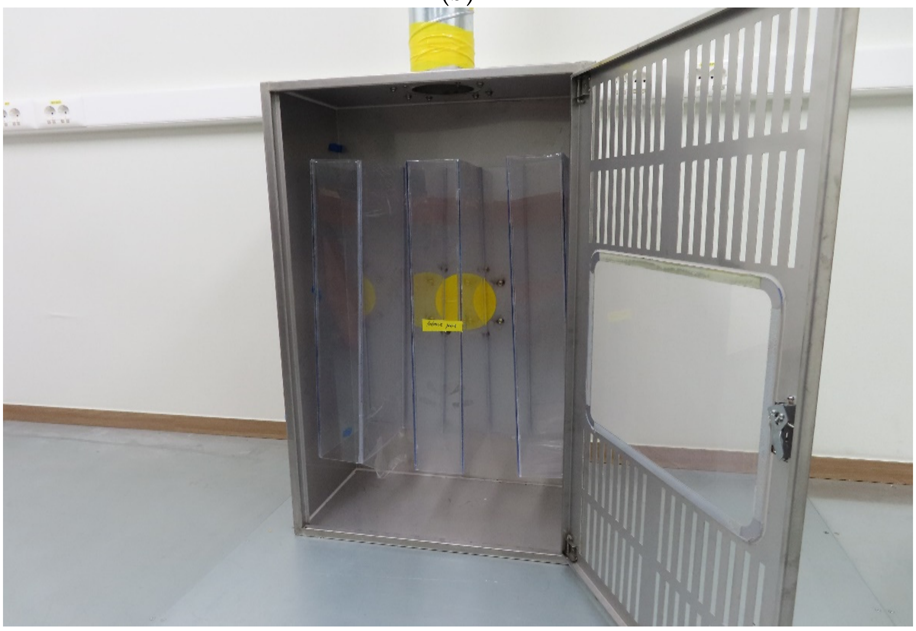
The gas box used in this study had the same shape and form as those used in the etching process. Specifically, the size of the gas box was 600 mm (0.6 m) × 350 mm (0.35 m) × 1000 mm (1 m), and an air intake port with a width of 10 mm (0.01 m) and a height of 125 mm (0.125 m) was installed on the front of the gas box. Additionally, to analyze the gas flow obstruction caused by the pipes inside the gas box, three obstructions with a width of 100 mm (0.1 m) and a height of 250 mm (0.25 m) were manufactured and installed vertically. This is illustrated in Figure 4. In Figure 4, (a) is a modeling of the gas box, and (b) is a picture of the gas box exterior. (c) is a picture of the gas box interior.



(a)

Figure 4. *Cont.*

(**b**)

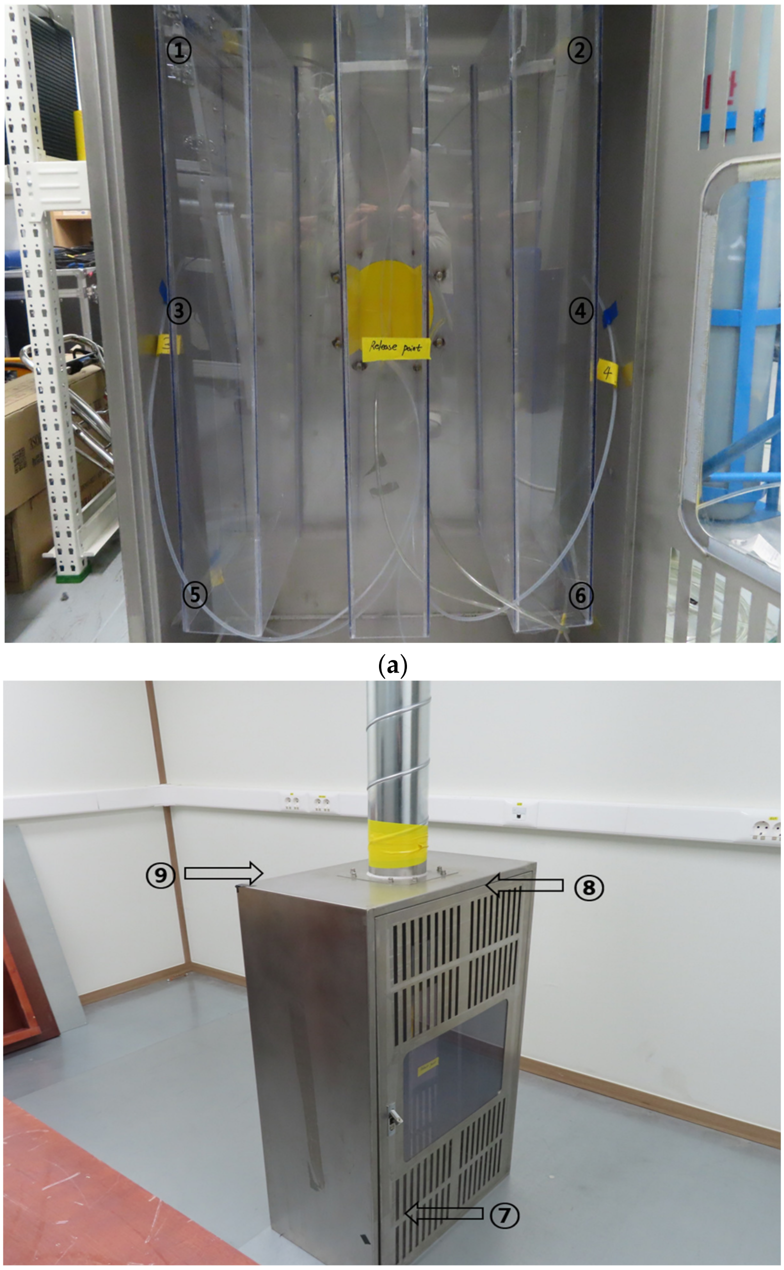


(**c**)

Figure 4. External and Internal View of Gas Box.

2.6. Sampling Point Selection

To check the change in internal and external concentrations after carbon monoxide, a flammable and toxic gas leaked for 10 min, and nine sampling points and release points were selected, as shown in Figure 5. The release and sampling times were determined according to the SEMI standard. According to SEMI S6, the equilibrium time due to the gas release flow must be considered, and the release flow of the tracer gas should be simulated for at least 5 min. Therefore, the concentration was measured 1 min, 10 min (at the end of the leak), and 20 min after the leak (sampling points 1–6). In addition, the toxic concentration must be measured below the TWA in spaces where workers may be exposed to gas leakage from inside the gas box. Therefore, the concentrations were measured at the gas box air intake, south, and north points (sampling points 7–9), and the concentrations inside the box were compared, considering the dilution flow when the gas box door was opened. Figure 5 shows a picture of the location for measuring the tracer gas concentrations. Table 7 summarizes the locations shown in Figure 5. In Figure 5, (a) shows sampling locations 1~6. And (b) shows sampling locations 7~9.



(**b**)

Figure 5. Tracer gas sampling point in gas box (S: sampling point 1–9).

Table 7. Sampling Location List.

Sampling Name	Definition
S1	Location (①) at the upper left side of the gas box in Figure 5.
S2	Location (②) at the upper right side of the gas box in Figure 5.
S3	Location (③) at the center left side of the gas box in Figure 5.
S4	Location (④) at the center-right side of the gas box in Figure 5.
S5	Location (⑤) at the bottom left side of the gas box in Figure 5.
S6	Location (⑥) at the bottom right side of the gas box in Figure 5.
S7	Location (⑦) at the bottom air intake of the gas box in Figure 5.
S8	Location (⑧) at the worker breathing zone in front of the gas box in Figure 5
S9	Location (⑨) at the worker breathing zone at the rear of the gas box in Figure 5.

3. Results

Based on a duct with a diameter of 75 mm (0.075 m), experiments were conducted by opening 0%, 50%, and 100% of the cross-sectional area of the duct. After 15.4 LPM of tracer gas (SF6 1%, 99% N_2) had leaked from inside the gas box, the concentrations inside and outside the box were measured over time. The ERC of carbon monoxide was converted using the tracer gas concentrations measured with a multi gas detector. Concentrations below 25% (125,000 ppm) of the carbon monoxide LEL and less than 50% (12.5 ppm) of the carbon monoxide TWA were considered acceptable. In Tables 12 and 13, the maximum concentrations were measured at 124.00 ppb (Toxic) and 22.61 ppm (Flammable). The ERC was calculated using SEMI S6 Appendix 2, Section A2-4.1, with the measured values as follows:

$$\text{Flammable ERC} = 22.61 \text{ ppm} \times 100/1\% = 2261 \text{ ppm}$$
$$\text{LEL of CO} = 125{,}000 \text{ ppm } (12.5\%)$$
$$\text{ERC } (\%) = 2261 \text{ ppm}/125{,}000 \text{ ppm} \times 100\% = 1.81\%$$
$$\text{Toxic ERC} = 124.00 \text{ ppb} \times 100/1\% = 12{,}400 \text{ ppb}$$
$$\text{TWA of CO} = 25{,}000 \text{ ppb } (25 \text{ ppm})$$
$$\text{ERC } (\%) = 12{,}400 \text{ ppb}/25{,}000 \text{ ppb} \times 100\% = 49.60\%$$

3.1. Results of Gas Box Concentration Analysis with 0% Air Intake Ratio

Before the experiment, it was expected that no hazardous substances would leak if the gas box was completely sealed. However, 10 min after the leak occurred, the internal concentration was measured to be over 25% of the LEL, and the toxic concentration measured externally was over 50% of the TWA value. Theoretically, leakage does not occur if absolute sealing is achieved. However, although the gas boxes used in the actual system and the testing box were sealed as much as possible, it was difficult to achieve a perfect seal. This result can be confirmed through testing and experience, in which the accumulated concentration inevitably results in external exposure. Additionally, when the air intake is blocked, a vacuum is created, causing the airflow to become extremely low and form a small flow rate. Because of this, the leaked gas is treated through the duct at points close to the gas box (sampling points 1, 2, 3, 4), and the points are relatively far away (sampling points 5 and 6) and lack exhaust suction capacity; therefore, even if the sealing was carried out well, it is assumed that the accumulated hazardous substances leak to the outside. The test results for the gas box with an air intake ratio of 0% are shown in Tables 8 and 9. Table 8 compares the LEL concentrations measured in the gas box with an air intake ratio of 0%, and Table 9 compares the TWA concentrations.

Table 8. Flammability Sampling Concentrations (0% opening area).

Sampling Point	Measured Value (ppm)	Equivalent Concentration (ppm)	Reference Concentration (ppm)	% LEL	Pass/Fail
S1 (1 min)	180.09	18,009	125,000	14.41	Pass
S1 (10 min)	216.45	21,645	125,000	17.32	Pass
S1 (20 min—release off)	1.01	101	125,000	0.08	Pass
S2 (1 min)	80.25	8025	125,000	6.42	Pass
S2 (10 min)	137.55	13,755	125,000	11.00	Pass
S2 (20 min—release off)	0.56	56	125,000	0.05	Pass
S3 (1 min)	200.56	20,056	125,000	16.04	Pass
S3 (10 min)	200.16	20,016	125,000	16.01	Pass
S3 (20 min—release off)	0.39	39	125,000	0.03	Pass
S4 (1 min)	283.22	28,322	125,000	22.66	Pass
S4 (10 min)	304.25	30,425	125,000	24.34	Pass
S4 (20 min—release off)	0.27	27	125,000	0.02	Pass
S5 (1 min)	307.02	30,702	125,000	24.56	Pass
S5 (10 min)	315.18	31,518	125,000	25.21	Fail
S5 (20 min—release off)	0.24	24	125,000	0.02	Pass
S6 (1 min)	315.68	31,568	125,000	25.25	Fail
S6 (10 min)	332.36	33,236	125,000	26.59	Fail
S6 (20 min—release off)	0.23	23	125,000	0.02	Pass

Table 9. Toxicity Sampling Concentrations (0% opening area).

Sampling Point	Measured Value (ppb)	Equivalent Concentration (ppb)	Reference Concentration (ppb)	% TWA	Pass/Fail
S1 * (20 min—release off)	1012	101,200	25,000	Over 400	Fail
S2 * (20 min—release off)	564	46,400	25,000	226.00	Fail
S3 * (20 min—release off)	390	39,000	25,000	156.00	Fail
S4 * (20 min—release off)	270	27,000	25,000	108.00	Fail
S5 * (20 min—release off)	238	23,800	25,000	95.20	Fail
S6 * (20 min—release off)	227	22,700	25,000	90.08	Fail
S7 (1 min)	1.35	135	25,000	0.54	Pass
S7 (10 min)	201.19	20,119	25,000	80.48	Fail
S7 (20 min—release off)	212.65	21,265	25,000	85.06	Fail
S8 (1 min)	2.34	234	25,000	0.93	Pass
S8 (10 min)	89.97	8997	25,000	35.99	Pass
S8 (20 min—release off)	178.16	17,816	25,000	71.27	Fail
S9 (1 min)	2.54	254	25,000	1.02	Pass
S9 (10 min)	126.53	12,653	25,000	50.61	Fail
S9 (20 min—release off)	171.50	17,150	25,000	68.60	Fail

* The test was performed inside a gas box.

3.2. Results of Gas Box Concentration Analysis with 50% Air Intake Ratio (One Direction)

By measuring the concentration with an opening area of 50% of the duct cross-sectional area, no point exceeded 25% of the LEL 20 min after the leak; however, the airflow was not constant because the air intake was made in only one direction. Points with high local concentrations (sampling points 4, 5, and 6) were also identified. Some points exceeded 50% of the toxicity standard TWA (25 ppm); therefore, manufacturing the air intake in one direction meant that the gas box was unsafe in the case of carbon monoxide leakage. However, unlike in the completely sealed gas box experiment, there was no carbon monoxide leaking to the outside, which means that the airflow through the air intake led to the leakage of gas into the duct rather than leaking it to the outside. The test results for the gas box with an air intake ratio of 50% (in one direction) are shown in Tables 10 and 11. Table 10 compares the LEL concentrations measured in the gas box with an air intake ratio of 50%, and Table 11 compares the TWA concentrations.

Table 10. Flammability Sampling Concentrations (50% opening area, one direction).

Sampling Point	Measured Value (ppm)	Equivalent Concentration (ppm)	Reference Concentration (ppm)	% LEL	Pass/Fail
S1 (1 min)	5.88	588	125,000	0.47	Pass
S1 (10 min)	6.36	636	125,000	0.51	Pass
S1 (20 min—release off)	0.19	19	125,000	0.02	Pass
S2 (1 min)	17.03	1703	125,000	1.36	Pass
S2 (10 min)	17.72	1772	125,000	1.42	Pass
S2 (20 min—release off)	0.15	15	125,000	0.01	Pass
S3 (1 min)	10.88	1088	125,000	0.87	Pass
S3 (10 min)	12.96	1296	125,000	1.04	Pass
S3 (20 min—release off)	0.14	14	125,000	0.01	Pass
S4 (1 min)	15.99	1599	125,000	1.28	Pass
S4 (10 min)	16.38	1638	125,000	1.31	Pass
S4 (20 min—release off)	17.84	1784	125,000	1.43	Pass
S5 (1 min)	16.76	1676	125,000	1.34	Pass
S5 (10 min)	10.13	1013	125,000	0.81	Pass
S5 (20 min—release off)	14.42	1442	125,000	1.15	Pass
S6 (1 min)	57.92	5792	125,000	4.63	Pass
S6 (10 min)	72.04	7204	125,000	5.76	Pass
S6 (20 min—release off)	6.87	687	125,000	0.55	Pass

Table 11. Toxicity Sampling Concentrations (50% opening area, one direction).

Sampling Point	Measured Value (ppb)	Equivalent Concentration (ppb)	Reference Concentration (ppb)	% TWA	Pass/Fail
S1 * (20 min—release off)	193	19,300	25,000	77.20	Pass
S2 * (20 min—release off)	153	15,300	25,000	61.20	Pass
S3 * (20 min—release off)	139	13,900	25,000	55.60	Pass
S4 * (20 min—release off)	17,837	1,783,700	25,000	Over 400	Fail
S5 * (20 min—release off)	14,415	1,441,500	25,000	Over 400	Fail

Table 11. *Cont.*

Sampling Point	Measured Value (ppb)	Equivalent Concentration (ppb)	Reference Concentration (ppb)	% TWA	Pass/Fail
S6 * (20 min—release off)	6873	687,300	25,000	Over 400	Fail
S7 (1 min)	51.43	5143	25,000	20.57	Pass
S7 (10 min)	61.23	6123	25,000	24.49	Pass
S7 (20 min—release off)	59.85	5985	25,000	23.94	Pass
S8 (1 min)	33.84	3384	25,000	13.54	Pass
S8 (10 min)	54.24	5424	25,000	22.10	Pass
S8 (20 min—release off)	41.77	4177	25,000	16.71	Pass
S9 (1 min)	30.89	3089	25,000	12.36	Pass
S9 (10 min)	42.45	4245	25,000	16.98	Pass
S9 (20 min—release off)	52.68	5268	25,000	21.07	Pass

* The test was performed inside a gas box.

3.3. Results of Gas Box Concentration Analysis with 50% Air Intake Ratio (Both Directions)

The opening area was 50% of the cross-sectional area of the duct, and air intakes were placed on both sides to ensure a smooth airflow inside the gas box. As a result of measuring the concentration, there was no point exceeding 25% of the LEL 20 min after leakage, and there were no points that exceeded 50% of the toxicity standard TWA (25 ppm). No external carbon monoxide (CO) leakage was observed. This means that the more appropriate and smoother the airflow through the air intake port, the more quickly carbon monoxide can be drawn through the duct and moved to the treatment facility, even if it leaks. The test results for the gas box with an air intake ratio of 50% (both directions) are shown in Tables 12 and 13. Table 12 compares the LEL concentrations measured in the gas box with an air intake ratio of 50%, and Table 13 compares the TWA concentrations.

Table 12. Flammability Sampling Concentrations (50% opening area, both directions).

Sampling Point	Measured Value (ppm)	Equivalent Concentration (ppm)	Reference Concentration (ppm)	% LEL	Pass/Fail
S1 (1 min)	22.61	2261	125,000	1.81	Pass
S1 (10 min)	20.18	2018	125,000	1.61	Pass
S1 (20 min—release off)	0.11	11	125,000	0.01	Pass
S2 (1 min)	20.81	2081	125,000	1.66	Pass
S2 (10 min)	19.65	1965	125,000	1.57	Pass
S2 (20 min—release off)	0.11	11	125,000	0.01	Pass
S3 (1 min)	22.03	2203	125,000	1.76	Pass
S3 (10 min)	20.36	2036	125,000	1.63	Pass
S3 (20 min—release off)	0.11	11	125,000	0.01	Pass
S4 (1 min)	21.87	2187	125,000	1.75	Pass
S4 (10 min)	20.92	2092	125,000	1.67	Pass
S4 (20 min—release off)	0.12	12	125,000	0.01	Pass
S5 (1 min)	20.37	2037	125,000	1.63	Pass

Table 12. *Cont.*

Sampling Point	Measured Value (ppm)	Equivalent Concentration (ppm)	Reference Concentration (ppm)	% LEL	Pass/Fail
S5 (10 min)	21.85	2185	125,000	1.75	Pass
S5 (20 min—release off)	0.12	12	125,000	0.01	Pass
S6 (1 min)	20.03	2003	125,000	1.60	Pass
S6 (10 min)	19.39	1939	125,000	1.55	Pass
S6 (20 min—release off)	0.12	12	125,000	0.01	Pass

Table 13. Toxicity Sampling Concentrations (50% opening area, both directions).

Sampling Point	Measured Value (ppb)	Equivalent Concentration (ppb)	Reference Concentration (ppb)	% TWA	Pass/Fail
S1 * (20 min—release off)	110	11,000	25,000	44.00	Pass
S2 * (20 min—release off)	110	11,000	25,000	44.00	Pass
S3 * (20 min—release off)	110	11,000	25,000	44.00	Pass
S4 * (20 min—release off)	124	12,400	25,000	49.60	Pass
S5 * (20 min—release off)	122	12,200	25,000	48.80	Pass
S6 * (20 min—release off)	116	11,600	25,000	46.40	Pass
S7 (1 min)	52.91	5291	25,000	21.16	Pass
S7 (10 min)	58.12	5812	25,000	23.25	Pass
S7 (20 min—release off)	28.37	2837	25,000	11.35	Pass
S8 (1 min)	25.44	2544	25,000	10.18	Pass
S8 (10 min)	31.32	2132	25,000	12.53	Pass
S8 (20 min—release off)	35.43	3543	25,000	14.17	Pass
S9 (1 min)	27.44	2744	25,000	10.98	Pass
S9 (10 min)	61.24	6124	25,000	24.49	Pass
S9 (20 min—release off)	53.45	5345	25,000	21.38	Pass

* The test was performed inside a gas box.

3.4. Results of Gas Box Concentration Analysis with 100% Air Intake Ratio (Both Directions)

The opening area was 100% of the cross-sectional area of the duct, and air intakes were placed on both sides to ensure smooth airflow inside the gas box. As a result of measuring the concentration, no point exceeded 25% of the LEL 20 min after leakage. However, there was a point where the concentration exceeded 50% of the toxicity standard TWA (25 ppm). The point where the concentration exceeded 50% occurred externally, indicating that the leaked gas flowed through the intake hole. Therefore, if an excessively large intake hole is selected, workers may be exposed to the danger of toxic gas leakage. The test results for the gas box with an air intake ratio of 100% (both directions) are shown in Tables 14 and 15. Table 14 compares the LEL concentrations measured in the gas box with an air intake ratio of 100%, and Table 15 compares the TWA concentrations.

Table 14. Flammability Sampling Concentrations (100% opening area, both directions).

Sampling Point	Measured Value (ppm)	Equivalent Concentration (ppm)	Reference Concentration (ppm)	% LEL	Pass/Fail
S1 (1 min)	3.36	336	125,000	0.27	Pass
S1 (10 min)	4.36	436	125,000	0.35	Pass
S1 (20 min—release off)	0.10	10	125,000	0.01	Pass
S2 (1 min)	7.10	710	125,000	0.57	Pass
S2 (10 min)	6.83	683	125,000	0.55	Pass
S2 (20 min—release off)	0.11	110	125,000	0.01	Pass
S3 (1 min)	5.59	559	125,000	0.45	Pass
S3 (10 min)	5.53	553	125,000	0.44	Pass
S3 (20 min—release off)	0.10	100	125,000	0.01	Pass
S4 (1 min)	11.31	1131	125,000	0.90	Pass
S4 (10 min)	10.26	1026	125,000	0.82	Pass
S4 (20 min—release off)	0.11	110	125,000	0.01	Pass
S5 (1 min)	5.60	560	125,000	0.45	Pass
S5 (10 min)	4.94	494	125,000	0.40	Pass
S5 (20 min—release off)	0.10	100	125,000	0.01	Pass
S6 (1 min)	8.89	889	125,000	0.71	Pass
S6 (10 min)	9.13	913	125,000	0.73	Pass
S6 (20 min—release off)	0.10	100	125,000	0.01	Pass

Table 15. Toxicity Sampling Concentrations (100% opening area, both directions).

Sampling Point	Measured Value (ppb)	Equivalent Concentration (ppb)	Reference Concentration (ppb)	% TWA	Pass/Fail
S1 * (20 min—release off)	100	10,000	25,000	40.00	Pass
S2 * (20 min—release off)	110	11,000	25,000	44.00	Pass
S3 * (20 min—release off)	100	10,000	25,000	40.00	Pass
S4 * (20 min—release off)	110	11,000	25,000	44.00	Pass
S5 * (20 min—release off)	100	10,000	25,000	40.00	Pass
S6 * (20 min—release off)	100	10,000	25,000	40.00	Pass
S7 (1 min)	149	14,900	25,000	59.60	Fail
S7 (10 min)	145	14,500	25,000	58.00	Fail
S7 (20 min—release off)	55.53	5553	25,000	22.21	Pass
S8 (1 min)	38.72	3872	25,000	15.49	Pass
S8 (10 min)	59.53	5953	25,000	23.81	Pass
S8 (20 min—release off)	152	15,200	25,000	60.08	Fail
S9 (1 min)	42.21	4221	25,000	16.88	Pass
S9 (10 min)	152	15,200	25,000	60.08	Fail
S9 (20 min—release off)	156	15,600	25,000	62.40	Fail

* The test was performed inside a gas box.

3.5. Summary of Test Results

In this study, the location and size of the air intake in the gas box used in the semiconductor process were changed based on the exhaust duct size.

The results obtained from the tests are summarized in Table 16. Table 16 presents the fail results for air intake ratios of 0%, 50% (one direction), and 100%. In particular, the flammable concentration exhibited fail results only when there was no air intake, whereas the toxic concentration exhibited fail results under other conditions.

Table 16. Summary of Flammable and Toxicity Test Results.

Test Condition	Definition of Value	Inside of Gas Box				Outside of Gas Box	
		Flammable Concentration (LEL)		Toxicity Concentration (TWA)		Toxicity Concentration (TWA)	
0% of opening area	Concentration Location Concentration Location	FAIL	Min.: 6.42% S2 (1 min) Max.: 26.59% S6 (10 min)	FAIL	Min.: 90.08% S6 Max.: >400% S1	FAIL	Min.: 0.54% Intake (1 min) Max.: 85.06% Intake (20 min)
50% of opening area (one direction)	Concentration Location Concentration Location	PASS	Min.: 0.47% S1 (1 min) Max.: 5.76% S6 (10 min)	FAIL	Min.: 55.60% S3 Max.: >400% S4	PASS	Min.: 12.36% North (1 min) Max.: 24.49% Intake (10 min)
50% of opening area (both directions)	Concentration Location Concentration Location	PASS	Min.: 1.55% S6 (10 min) Max.: 1.81% S1 (1 min)	PASS	Min.: 44.00% S1 Max.: 49.60% S4	PASS	Min.: 10.18% South (1 min) Max.: 24.49% North (10 min)
100% of opening area (both directions)	Concentration Location Concentration Location	PASS	Min.: 0.27% S1 (1 min) Max.: 0.90% S4 (1 min)	PASS	Min.: 40.00% S1, 3, 5, 6 Max.: 44.00% S2, 4	FAIL	Min.: 15.49% South (1 min) Max.: 62.40% North (20 min)

The results obtained through the tests are presented in the following graphs: Figures 6 and 7. Figure 6 shows a graph comparing the measured concentrations for each air intake ratio, calculated as a percentage of the LEL. The sampling locations for each table are shown in Figure 5.

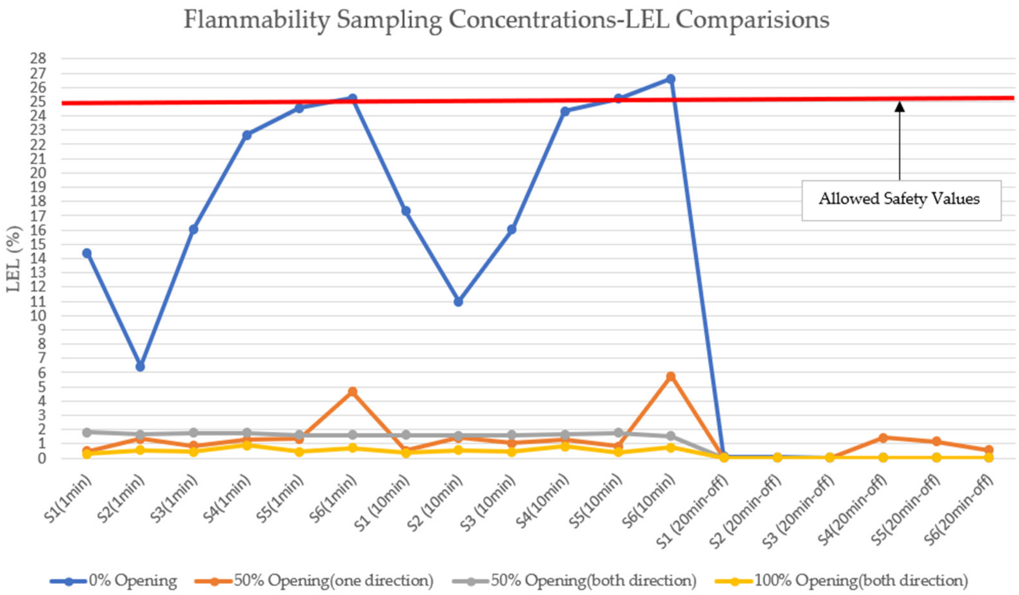


Figure 6. Flammable Sampling Concentration–LEL Comparisons.

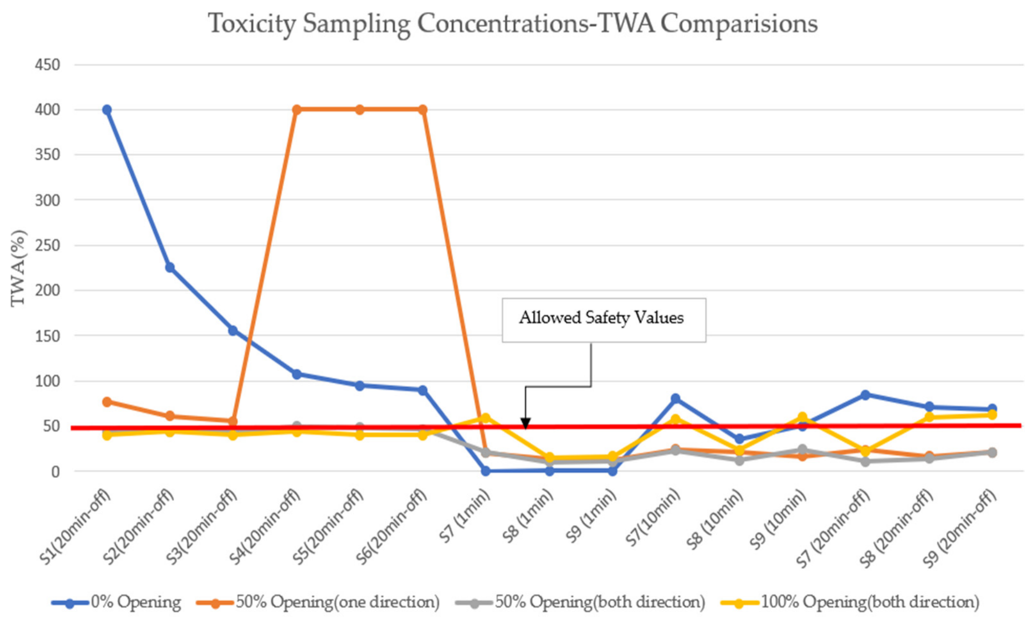


Figure 7. Toxicity Sampling Concentration–TWA Comparisons.

Figure 7 shows a graph comparing the measured concentrations for each air intake ratio, calculated as a percentage of the TWA. The sampling locations for each table are shown in Figure 5.

Figures 6 and 7 confirm through the test results that when the ratio of the air intake to the duct cross-sectional area is 50%, not only the flammable hazardous concentration but also the toxic concentration exposed to the outside can be managed below the dangerous lower limit. As shown in Figure 6, the presence or absence of air intake significantly affects the case of a flammable gas leak. That is, when there is no air intake, a stagnant flow occurs inside, which means that a large explosive atmosphere can form inside. Additionally, as shown in Figure 7, toxic concentrations accumulated in the case of an inappropriate exhaust design and when an air intake was not provided. Notably, it was confirmed that an excessive air intake can cause toxic gasses to leak through the intake.

4. Conclusions

Therefore, in this study, a 0.21 m^3 gas box (size of 600 mm (0.6 m) × 350 mm (0.35 m) × 1000 mm (1 m)) was manufactured to examine the optimal shape of the gas box for semiconductor manufacturing equipment. A duct with the same size (75 mm (0.075 m)) as that used in the current etching process was installed, and 15.4 LPM of tracer gas flowed for 10 min at the release point. The concentration of tracer gas (SF6 1%, 99% N_2) was measured at nine internal and external sampling points: 1 min after the leak, 10 min after the leak (at the end of the leak), and 20 min after the end of the leak. When 15.4 LPM leaked into the gas box without an air inlet, the concentration inside the box reached a maximum of 33,236 ppm. Therefore, it cannot be considered safe because it exceeds 31,250 ppm, which is more than 25% of the LEL. Additionally, the concentration of carbon monoxide, which was more than four times the TWA, was measured inside and outside the gas box. As a result of the experiment, the results of the experiment showed that the air intake was necessary, and when the air was drawn in from only one direction, the carbon monoxide concentration was less than 25% of the LEL, but the TWA was still more than four times the carbon monoxide standard. In other words, there is a dead zone in which the air does not flow smoothly. Additionally, when the air intake was designed to be of the same size as the duct, the internal gas concentration was measured to be less than 25% of the LEL; however, concentrations higher than the CO gas TWA were measured on the air intake side, indicating that there is a risk of external workers being exposed to hazardous gasses in the event of an excessive air intake design or a hazardous gas leak. When the air intake was made in both directions, the concentration was less than 25% of the LEL and less than 50% of the TWA, confirming that the air was safely discharged through the duct. In the previous experiment, the fluid resistance due to internal piping and valves could not be reflected; however, this experiment improved accuracy by installing obstacles inside. This study was conducted to enhance the safety of workers in the field when flammable and toxic substances leak by testing the location and area of the air intake of the gas box exhaust. This study aims to present specific standards for gas box design and help establish legal systems or standardized guidelines.

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