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EVALUATION OF DOWNWARD DESMOKE SYSTEM IN A CLEANROOM

Chen-Wei Chiu, Chun-Chieh Wang and Chiun-Hsun Chen
Department of Mechanical Engineering, National Chiao Tung University, HsinChu 30056, Taiwan

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ABSTRACT

This study adopts the SFPE performance-based design procedure to evaluate the performance of upwards and downwards desmoke systems, respectively, in a wafer fabrication zone. The tools used for this purpose include Fire Dynamics Simulator (FDS) and Simulex. The design fires are 800 kW (scenario 1) and 3 MW (scenario 2), respectively. Both desmoke systems in scenarios 1, 2 and 4 meet the performance criteria, whereas the downward system in scenario 3 cannot satisfy the property protection requirement. However, the downward desmoke system can still be utilized, provided it complies with some restrictions in fire protection design, for example materials used and the provision of an acceptable emergency plan. For occupant evacuation, the Simulex result shows that the total evacuation time is 191 s. FDS simulations involving the installation of smoke curtain confirm that the evacuation time is less than the smoke layer descending time, indicating that the occupants can safely evacuate in the event of a fire.

1. INTRODUCTION

1.1 Background

Recently, the technical development of the Taiwanese semiconductor industry has accelerated significantly, creating substantial profits. However, the 24-hour operating process of semiconductor manufacturing represents a significant potential liability to the owner, operator and general public in terms of life safety and preservation of assets, due to heavy use of hazardous production materials (HPM). Additionally, the wafers and process tools are highly sensitive to smoke, particulates and water. Therefore, a cleanroom is needed to maintain the required air quality, along with the necessary humidity and particulate number to prevent the wafers from suffering pollutant contamination. These factors raised the risks involved in operating such factories, particularly the fire incident. In the event of a fire, the resultant damage and property loss is much higher than in conflagrations in other types of buildings. For example, the cleanroom fire at Winbond Electronics Corporation [1] caused significant property losses of approximately 6 billion NT, although nobody was injured, as listed in Table 1 [1]. Table 1 also lists the losses associated with another two severe fires in wafer fabs.

However, the fire protection designs and the corresponding equipment of these factories fully complied with the local building [2] and fire codes [3], regarded as the minimum requirements for fire safety. Apparently, the requirements by law enforcement cannot fully meet the real needs for the fire safety design of the semi-conductor industry or the other so-called advanced technology industries, such as TFT-LCD and LED. Therefore, these industries have expended tremendous attention and effort on developing an advanced calamity strategy to reduce the risk of fire.

Some special features of cleanroom now used in advanced technology factories include the following.

- Semiconductor manufacturing uses numerous toxic and explosive chemicals, as listed in Table 2. Most of these chemicals are so active that they can easily cause fires or other severe damage in the event of accidental leakage.

- The flow field in a cleanroom differs from that in other buildings. The conditioned air flow is drawn downwards vertically from the Filter Fan Unit (FFU) to the fabrication area, through the perforated raised floor, and eventually to the subfab, as illustrated in Fig. 1. In the event of a fire, the movement of smoke in a cleanroom is expected to differ from that in other buildings. Additionally, cleanrooms contain no vertical and horizontal fire-endurance compartments because of production line allocation and the air flow design mentioned previously.

- Process tools inside cleanrooms are highly sensitive to contamination from smoke/ particulates and water.

- The zone area of cleanroom for such factories is very large, but the occupant density is low due to high automation. Furthermore, the distribution of production lines has become increasingly complicated owing to space limitations. Therefore, occupant evacuation plans become extremely important and it may change occasionally due to the retrofit and renovation of facilities.

Because the structure of cleanroom is regarded as an enclosure, where there are no openings under normal operating condition, it is required to equip with the Desmoke System on the ceiling by the prescriptive fire code of Taiwan [3]. According to the code, the minimum desmoke capacity is set to be 2 m^3/min per m^2 floor area. From the descriptions of the special features of cleanroom mentioned previously, it is easy to understand that fire safety design for semiconductor factories, and particularly for cleanrooms, has considerable difficulty in fully complying with the prescriptive codes [2,3]. Therefore, this study introduces the fire safety engineering (FSE) design methodology to provide a so-called substituted design equivalency, and this methodology usually is superior to that required by the prescriptive codes to resolve the fire protection situation.

Therefore, engineering tools, such as CFD models, are applied to design and evaluate the calamity system used in a cleanroom in an advanced technology facility. This study evaluates a new concept of downward desmoke system, incorporating a decrease of FFU air supply rate in fire zone, the appropriate distribution of sprinklers and an intensive trained evacuation plan, etc., to check whether such a design can achieve equivalent performance to the traditional upward desmoke system in meeting the local fire code. The calamity system is described in detail later.

Table 1: Accident fires of semiconductor factories in Hsinchu, ROC

	Winbond Electronics Corp. [1]	United Integrated Circuits Corp. [1]	Advanced Microelectronic Products Inc. [1]
Time	1996/10/14	1997/10/03	1997/11/11
Casualty	N/A	N/A	One man injured
Loss Property	6 billion NT	12 billion NT	3 billion NT
Fire Occasion	Wet bench	Fume exhaust system	Wet bench

Table 2: Semiconductor manufacturing process gases

Manufacturing Process	Using Gases
Epitaxy	SiH_4, $SiHCl_3$, SiH_2Cl_2, $SiCl_4$, AsH_3, $AsCl_3$, PH_3, B_3H_6, H_2, N_2
Diffusion	AsH_3, $AsCl_3$, PH_3, $POCl_3$, B_2H_6, BCl_3, BBr_3, $SiCl_4$, SiH_2Cl_2, Ar, NH_3, N_2
Chemical Vapor Deposition	SiH_4, $SiHCl_3$, SiH_2Cl_2, NF_3, CF_4, CHF_3, $C_2F_6PH_3$, B_2H_6, NH_3, N_2O, O_2, SiF_4, H_2, N_2
Etching	HF, HCl, CF_4, CHF_3, $CClF_3$, C_2F_6, PH_3, B_2H_6 SiH_4, C_3F_8, SiF_4, SiF_6, $CBrF_3$, C_2ClF_5, Cl_2, PH_5, $CClF_2$, C_2ClF_2, $C_2Cl_2F_4$, CCl_4, C_3H_8, CH_4NF_3, Ar, He
Sputtering	Ar, O_2, NH_3
Implant	PH_3, PF_3, PF_5, SiF_4, AsH_3, B_2H_6, BF_3, BCl_3

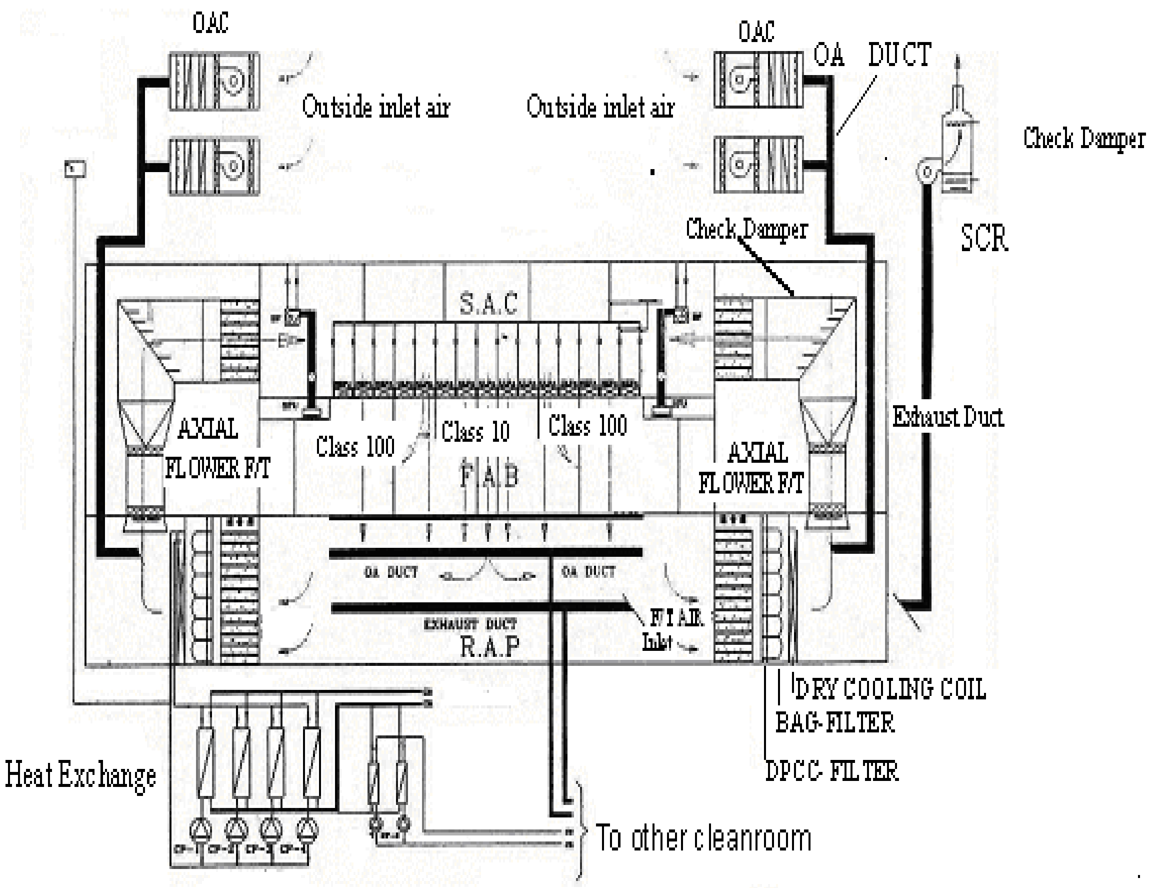

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Fig. 1: The construction of cleanroom

1.2 Literature Review

Kathy and William [4] conducted full-scale measurements in an aircraft hangar with a nominal 30.4 m (100 ft) ceiling height. Gas temperatures resulting from an approximately 8250 kW isopropyl alcohol pool fire were measured both above the fire and on the ceiling. They found that the detector on the 30.4 m ceiling could not respond to the high HRR, 8250 KW, from the ground pool fire from 0.75 m^2 fuel pan. It is verified by comparing the predictions from the DETACT-QS, FPETOOL, LAVENT and FLOW3D models with the experimental data. The field fire model used the volume heat source (VHS) and the k-ε turbulent model. However, Kathy and William concluded that the LAVENT model corresponding to temperature and flow fields provides a better agreement with the experiment data.

Hu [5] measured flow field and turbulence characters, such as velocity vectors, turbulence intensity and turbulence kinetic energy, by using an ultrasonic anemometer in the cleanroom. He investigated the turbulent intensity near the workstation, where the surrounding fluid is from vertical FFU flow. Hu suggested that turbulent intensity effect should be considered in simulating the flow field when the processing tools are set up.

Heskestad and Lutton [6] experimentally investigated the reduced scale cleanroom fire (the room size is 4.8 m x 6.0 m x 2.44 m in height). Specifically, Heskestad and Lutton measured ceiling temperature when using a CH4 burner (600 kW) to simulate a cleanroom fire.

Cheng et al. [7] applied the commercial code of STAR-CD to study cleanroom airflow uniformity. The k-ε turbulent model was adopted, and a perforated raised floor was simulated as a porous medium. The parameters were the height of the subfab and the permeability coefficients of the porous floor, respectively. Cheng et al. found that increased subfab height (0.6 m – 1.5 m) and decreased permeability coefficients (0.1 or 0.25) of the porous floor can optimize airflow uniformity.

Nam [8] used the CFD program REFLEQS developed from NASA to forecast the extent the smoke cloud from a cleanroom fire. The CO_2

concentration (34.5 ppm) was used as a marker for smoke concentration. Nam also used the volume heat source (VHS), 250 or 500 kW, and altered the flow rate (0.1 ~ 0.91 ms^{-1}) of FFU to make a comparison with the experimental data of Heskestad and Lutton [6]. Nam claimed that the analytical results are accurate with the experimental data on a cleanroom fire.

Huang [9] used the CFD software FLUENT to compare different combustion models, and confirmed the model accuracy through comparison with the measurements of Heskestad and Lutton [6]. He adopted three combustion models, including the volume heat source (VHS), eddy break-up and presumed probability density function (prePDF) model. Additionally, Huang considered the radiation effect on global radiative heat exchange via the discrete transfer method (DTRM).

Chang [10] used the CFD software PHOENICS to confirm the efficiency of the calamity strategy. The conceptual method of modifying the airflow rate (0.26 ms^{-1}) of FFU to increase the pressure difference between the fire-endurance zones was proposed to limit smoke spread. Chang found that the upward smoke exhaust strategy appears more effective than the downwards one for fire accidents occurring in the FAB (fabrication) zone. On the other hand, the downwards exhaust strategy is more effective for SUBFAB fires. Therefore, Chang recommended that the semiconductor industry should prepare two calamity strategies. However, this recommendation is unworkable in real situations.

Chen [11] examined the characteristics of fires and explosions in semiconductor fabrication processes, and illustrated their common and peculiar features of fire and explosion in the semiconductor fabrication processes. Particularly, this study discussed and collated the fire risk via the exhaust system, which generally contained large quantities of flammable and corrosive gases and vapors.

From the perspective of fire safety codes in Taiwan, Chiu [1] surveyed and investigated air-tight cleanroom fires, which cause severe damage to life and property. Chiu intensively discussed how to combine smoke control systems, fire (smoke) zones, fire protection equipment, tool layout and space distribution to control fire and smoke movement.

Acorn [12] conducted an intensive review, entitled "Code Compliance for Advanced Technology Facilities". This review described and discussed the various code requirements for advanced facilities in terms of HPM storage, mechanical venting, air conditioning systems, fire suppression, electrical power and evacuation alarm systems. The main codes adopted include Uniform Building Code (UBC) and Uniform Fire Code (UFC).

1.3 Scope of Present Study

This study is based on Fire Safety Engineering (FSE) guidelines to design calamity strategies for high technology facilities. The main purpose is to meet the requirements for preservation of life and property via performance-based design, based on the assumption that present building and fire codes are difficult to completely comply with. The basic design tool adopted is Fire Dynamics Simulator (FDS), a CFD program devised by National Institute of Standards and Technology (NIST) [13]. This tool is used to simulate design cleanroom fires and thus obtain the corresponding fire and smoke developments. An egress model, SIMULEX software [14], then is used to evaluate the evacuation time required for each design fire, together with the information on facility layout and population density. Finally, the optimal calamity strategy is deduced from these evaluations.

2. CASE STUDIES

This study evaluates the calamity systems, whose client is a 12" wafer fabrication factory, whose wafer manufacture process diagram is illustrated in Fig. 2. This study uses FDS and Simulex as the engineering tools to simulate the fire and smoke development by assigned scenarios, and subsequently uses the occupant evacuation route and time required to reach the safe zone.

The case studies consider two types of calamity systems, namely the downward desmoke system (Fig. 3) and the upward desmoke system (Fig. 4). The so-called return air shaft desmoke system, which is an inappropriate design because its distance to exhaust is too long and overall exhaust capability is too low. This study emphasizes evaluating the effectiveness and performance for both upward and downward desmoke systems. The procedure for selecting an appropriate calamity system follows the SFPE Engineering Guide to Performance-based Fire Protection Analysis and Design [15]. The performance-based design procedure is detailed as follows.

2.1 Define Project Scope

The first step in performance-based design is to define the project scope. The present project involves smoke exhaust design evaluation in the cleanroom of a 12" wafer fabrication facility.

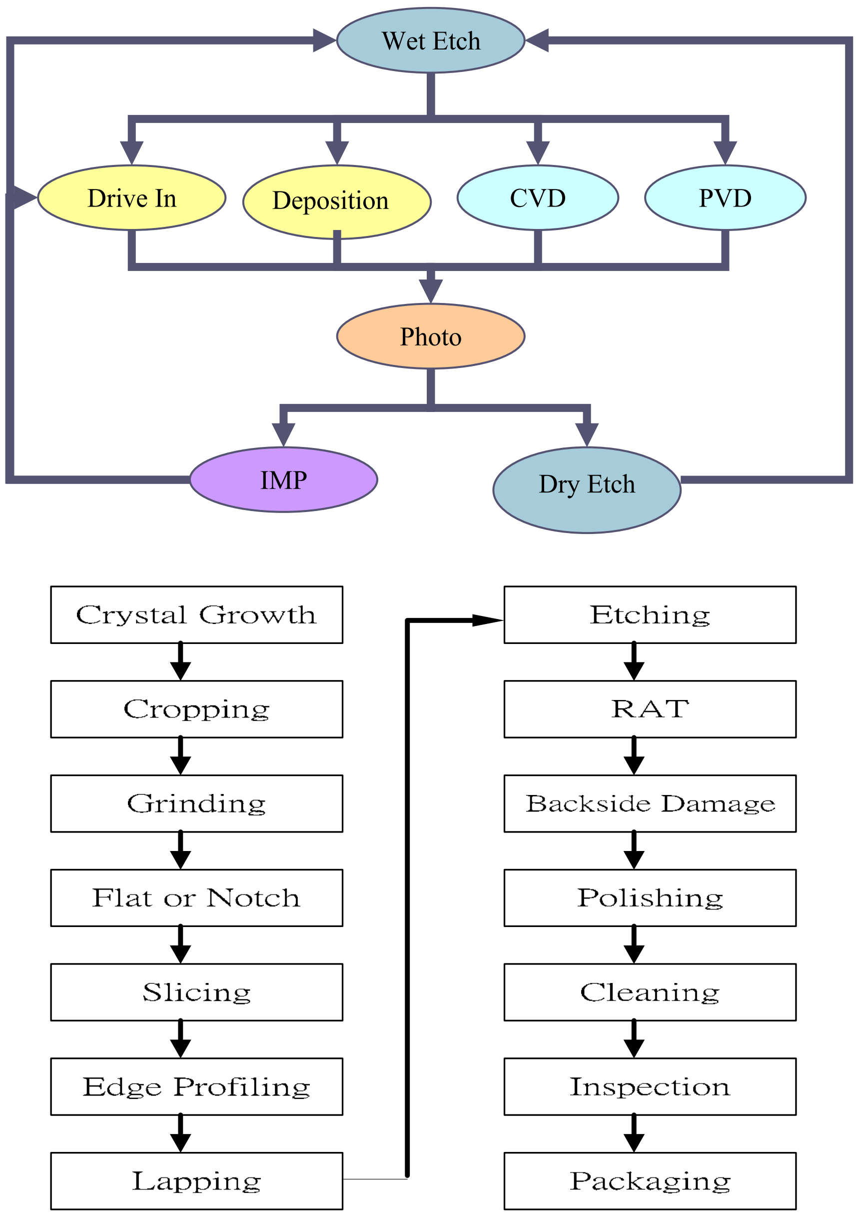

Fig. 2: Diagram of wafer manufacture

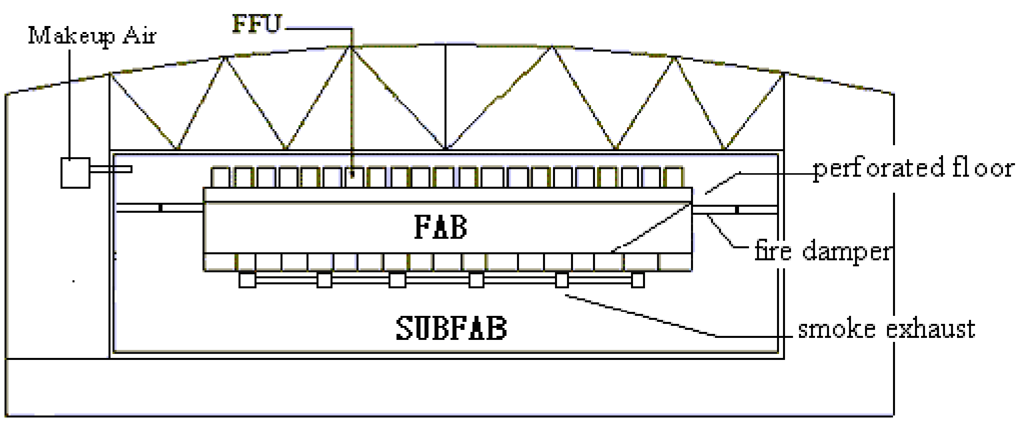

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Fig. 3: The downward desmoke system

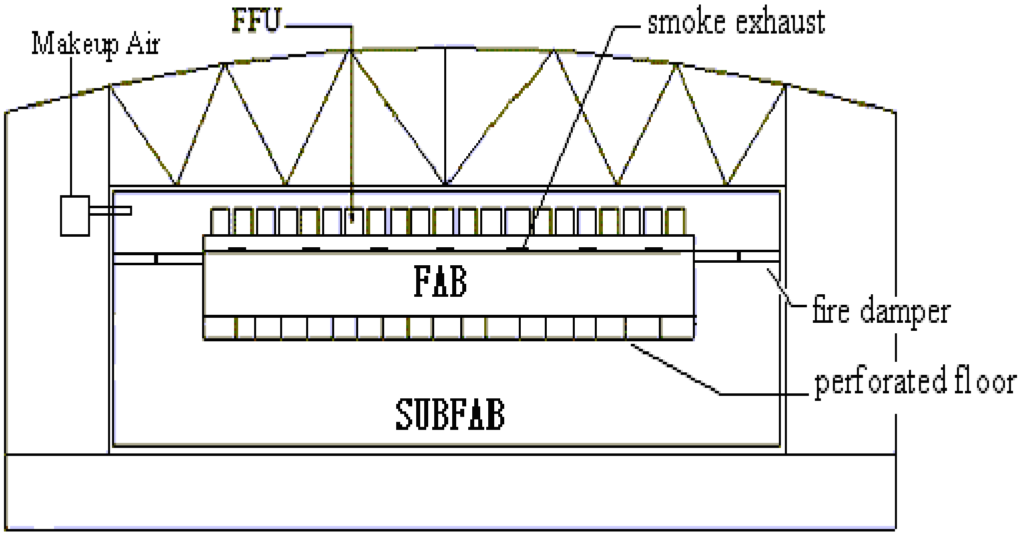

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Fig. 4: The upward desmoke system

Employing an upward desmoke system enables wafer fabrication to comply with local fire codes. However, such a fire protection system will cause problems for the production line design. Since wafer sizes grow due to advanced manufacturing technology, wafers now are transported by machines, for example Automated Guided Vehicle (AGV), rather than manpower. An AGV system suspended beneath the ceiling is now extremely common in 12” wafer fabrication facilities for transporting wafers among workstations. Apparently, this transportation facility will intervene in the upward desmoke system and penetrate the fire/smoke curtain/barrier and/or compartments. Therefore, the code-complied desmoke system must be evaluated, and a substitute/equivalence design may be required for conflict resolution.

To prevent the above problems interfering with the performance of the upward desmoke system, a downward desmoke system was considered by the 12” wafer fabrication facility. Therefore, this project was set up to evaluate its feasibility, determine the corresponding emergency operating procedure and demonstrate its equivalency to the code-complied system, with this last being the key issue.

However, it is very difficult to quantify the prescriptive codes, particularly for making a comparison with the performance design. Therefore, this project adopts an occupant evacuation time to provide a comparison basis. Since no standard procedure exists for the evacuation, the time is commonly adopted as the required evacuation for a smoke layer descended to 1.8 m by shutting down all of the FFU. However, shutting down FFU without any action of the desmoke system in an emergency can be refused by the management of a wafer fab. Therefore, designing an acceptable evacuation plan is extremely challenging.

2.2 Identify Goals

The next step is to identify the fire safety goals, including levels of protection:

(a) Protect life: ensure all of the occupants can escape from the cleanroom without being harmed by the fire.

(b) Protect property: restrict the spread of fire and smoke to adjacent compartments, and reduce the damage in the zone of origin of the fire as much as possible.

2.3 Develop Performance Criteria

The performance criteria are the further refinement of design objectives, and take the form of numerical values with which the expected performance of the trial designs can be compared. Performance criteria may include two parts:

(a) Life safety criteria: life safety criteria address the survivability of individuals exposed to fire and its by-products. Tables 3 and 4 indicate the life safety criteria, which are specified so that the occupants have sufficient time to safely escape. This project adopts the restrictions that along the evacuation route, the temperature at the height of 1.8 m does not exceed 80°C, and the concentration of the toxic carbon monoxide gas does not exceed 1400 ppm at the same location [16].

(b) Non life-safety criteria: in semiconductor factories, wafers and process tools are highly sensitive to smoke contamination, and thus the project selects the proper criteria, for example FM7-7/17-12 [17], a loss prevention data of semiconductor fabrication facilities in cleanroom, as the fire protection requirements. In the fire-origin zone, the fire does not reach the flashover [18], whose ceiling temperature exceeds 600°C. For smoke damage criterion, the smoke particles are not allowed to enter the neighboring zones.

2.4 Develop Fire Scenarios and Design Fire

This step involves describing possible fire events, and involves fire, building and occupant characteristics. Next, several assumptions are made regarding these fire scenarios:

- no arson is considered.
- no explosion is considered.
- no destruction of building is considered.
- no human extinguishing of the fire is considered.

The cleanroom fire scenario is designed in accordance with the above restrictions. The F.M. statistical data [17] on the cleanroom fires in America from 1977 to 1997 identify two primary causes of cleanroom fires. The first cause is wetbench fires in the fab-zone, while the second cause is fume exhaust duct fire. A wetbench fire in the fab-zone is adopted as the fire scenario here.

The fire scenario in the Fab-zone is a wetbench fire, and this fire is assumed not to spread to other workstations. FDS simulation divides the fabrication area into eight compartments, each of which has an area of 450 m^2 and a height of 5 m. Additionally, the fire simulation should include the perforated raised floor (2 m high) and the subfab (5 m high), as illustrated in Fig. 1. Therefore, the total height is 12 m. The selected cubic grid size is 0.125 m^3 and the total grid number is 379,000. The wetbench, which has a combustible area of 6 × 12 m, is made of PP (Polypropylene) and is located at the center of the fire-origin zone. The floor is nonflammable steel and the ceiling is nonflammable material, except for the FFU frame. Fig. 4 illustrates the configuration of the cleanroom. Sprinkler installation complies with NFPA 13 [19], and the sprinkler is selected as an early suppression fast response with RTI (Response Time Index) of 45. The default activation temperature of the sprinklers is 68°C.

According to the FM test results [20] for different fire simulations on a wetbench, the CO_2 extinguishment system fitted inside the wetbench can effectively reduce the heat release rate. However, this work neglects these effects by assuming that the system fails, one of the worst conditions.

Table 3: Limiting conditions for tenability caused by toxic products of combustion

Chemical products	5 minutes exposure		30 minutes exposure	
	Incapacitation	Death	Incapacitation	Death
Carbon monoxide Low oxygen Carbon dioxide	6000 ppm < 13% > 7%	12000 ppm < 5% > 10%	1400 ppm < 12% > 6%	2500 ppm < 7% > 9%

Table 4: Limiting conditions for tenability caused by heat

	Symptom	Exposure level
Radiation	Severe skin pain	2.5 kWm^{-2}
Conduction	Skin burns 1 s contact (metal)	60°C
Convection	Skin/lungs affected by hot gas in > 60 s	120°C
Convection	Skin/lungs affected by hot gas in < 60 s	190°C

Two fire scenarios are chosen for the Fab-zone fire. In one scenario the fire is ignited from combustible vapors, evaporated from the wafer-cleaning liquid IPA (Isopropyl Alcohol), in a wetbench in the etching area. The heat release rate of PP is measured using a cone calorimeter test [21]. The heat release rate reaches 400 kWm^{-2} after 50 s and 800 kWm^{-2} after 217 s for this material. Notably, the burning area of the wetbench is limited to 1 × 1 m^2 at the floor surface. The total simulation time is 300 s.

To further verify the exhaust capability of downward desmoke system, a higher fire-load is also chosen. This fire scenario results from a tool fire caused by the careless usage of photoresist stripper in the photolithography zone. Because photoresist stripper is a flammable chemical liquid, the corresponding maximum heat release rate is set as 3 MW. The fire growth adopts a t-squared model [22,23] and is assigned ultra-fast, and the heat release rate reaches 1 MW at 75 s. Table 5 summarizes the fire scenarios and the two desmoke systems.

2.5 Develop Trial Design

For the operation parameters, the initial condition is for all of the FFU air streams to be flowing downward at a velocity of 0.5 ms^{-1}. The desmoke system manually activates 30 s after a fire is confirmed. The two smoke management strategies are specified as follows:

(a) Downward desmoke system: reduce the FFU air velocity to 0.1 ms^{-1} in the fire-origin compartment and increase the velocity to 0.6 ms^{-1} in the neighboring compartments. The exhaust capacity of the desmoke system in the fire-origin compartment is 26.88 m^3s^{-1}, and the system is not activated in other compartments.

(b) Upward desmoke system: shut down the FFU air flow in the fire-origin compartment and increase the velocity to 0.6 ms^{-1} in the neighboring compartments. The exhaust capacity is 20 m^3s^{-1}.

2.6 Evaluate Trial Designs

For each trial design, the fire/smoke development is simulated using FDS developed by NIST. The life and property criteria then are examined to determine whether they meet the specified requirement. Finally, the evacuation times, subject to the former simulation conditions, are calculated using the SIMULEX program.

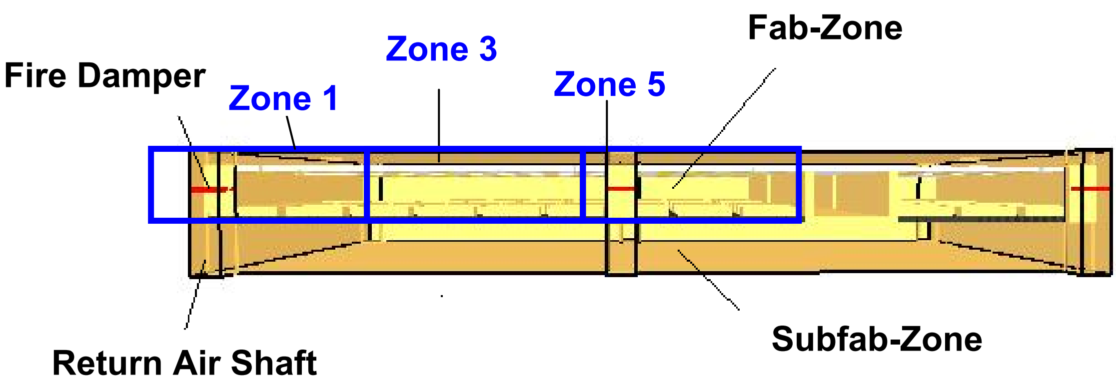


Fig. 5: The simulation layout of cleanroom structure

Table 5: Trial designs

	Number of Scenarios	Fire Growth Model	Calamity Strategy	Fire Location
Trial Design 1	S1	800 kW (cone)	Downward	Wetbench fire in zone 3
	S2	800 kW (cone)	Upward	
Trial Design 2	S3	3MW (t-squared model)	Downward	Photoresist stripper fire in zone 7
	S4	3MW (t-squared model)	Upward	

3. SIMULATION RESULTS

3.1 FDS Simulation Results

The FDS simulations comprise four scenarios involving both downward and upward desmoke systems. The respective scenarios are evaluated based on whether they can meet the performance criteria of both life safety and property protection. To compare the scenarios with the life safety criteria, three different points at the height of 1.8 m in the fire-origin compartment are selected to obtain the corresponding temperature and CO concentration. These three points are located at the center of the fire source (point 1), and at 3 m (point 2) and 5 m (point 3) from the center, respectively. The last two points provide reference points for checking the life safety criteria on the evacuation route. Finally, smoke movement is visualized using Smokeview, one of the FDS functions.

Trial Design 1

For Trial design 1, the fire-origin source is situated in Zone 3. A fire was started at the center of the wetbench by simulation when t = 0, and the environmental temperature was fixed at 24°C. The air-conditioning continued to operate normally, and the desmoke system was closed after the fire. Fig. 6 shows that the smoke particles in the simulation started to descend at 21 s. At t = 30 s, the desmoke system was manually activated. The FFU in the fire zone decreased to 0.1 ms^{-1}, and those in the other zones increased to 0.6 ms^{-1}. The smoke particles were found to be restricted to the fire-origin zone when the desmoke system was manually activated 28 s later. At t = 110 s, the smoke particles were brought downward near the smoke exhaust vent. The sprinklers were activated at about t = 158 s. At t = 300 s, the smoke particles were almost completely extracted by the desmoke system. Also, no flashover occurred.

In this scenario, Fig. 7a shows the temperature history at point 1. Initially, the temperature rise is almost linear with time, and begins to become oscillatory after t = 80 s. However, the trend is rising. The oscillation phenomenon results from the interaction among the rising fire plume, downward air stream from FFU and suction of the desmoke system. The highest temperature, 200°C, occurs just before the sprinkler takes action at t = 158 s. After that, the temperature drops suddenly as expected, then quickly recovers and subsequently levels off. Apparently, the fire is not extinguished but is controlled by the action of sprinkler system. On the other hand, the temperatures at points 2 and 3 are maintained at a constant 24°C.

The variation of CO concentration at point 1 shown in Fig. 7a almost synchronizes with that of temperature. The variation initially increases monotonically with time until the sprinkler is activated. However, the maximum CO concentration, 113 ppm, occurs at t = 159 s, one second behind the activation of the sprinkler. This value is significantly lower than the unattainable toxic criterion of 1400 ppm, indicating that the combustion is more complete. This occurs because the air is still supplied from FFU even if the fire occurs in this scenario.

Apparently, the activation of the downward desmoke system in Scenario 1 can meet the required performance criteria specified in section 2.3. To further insure that the fire and smoke in fire zone (zone 3) do not spread out to the neighboring zones, such as zone 1 and 5, by the fire control method mentioned above, the corresponding temperatures and CO concentrations at the height near the ceiling for these zones are presented in Fig. 7b. It clearly shows that both the temperatures and CO concentrations beneath the ceiling in zone 1 and 5 are maintained at their original values, indicating that the fire and smoke indeed are restrained in the fire zone.

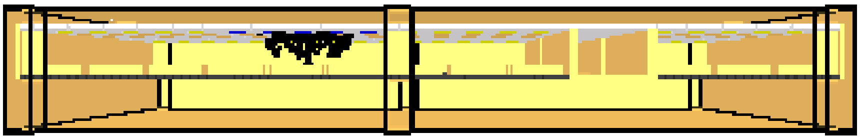
Scenario 2 involves the case of a wafer fabrication area equipped with the upward desmoke system. Notably, the FFU is switched off in the fire-origin zone because the fire is confirmed to occur in this scenario. Therefore, the sprinkler is expected to activate earlier than that in Scenario 1. In Fig. 8a, the highest temperature at point 1 reaches about 157°C, lower than the corresponding one in Scenario 1. This difference occurs because the fire plume rises directly to the ceiling without encountering any incoming flow. The temperatures in points 2 and 3 are maintained at around 24°C.

In Fig. 8a, the highest CO concentration at point 1 is about 82 ppm, lower than the relative one in scenario 1, owing to the local temperature being lower than criteria temperature. The temperature and toxicity do not exceed the life safety criteria. Fig. 8b shows the temperatures and CO concentrations at the height near the ceiling for the fire zone (zone 3) and its neighboring zones (zone 1 and zone 5). Similar to the last scenario, the fire and smoke do not spread out of the fire zone, in other words, the neighboring zones are not affected by the fire occurrence.

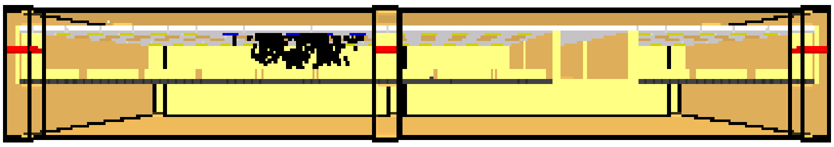
Regarding property protection, since the desmoke system is manually activated after 30 s with the pressure difference resulting from different downward air velocities restraining the smoke particles to remain within the fire-origin zone. At t = 70 s, the upward desmoke system completely exhausted the smoke particles. The sprinklers were activated at approximately 149 s. By 180 s, the device has effectively controlled the fire situation and no flashover happened.

Trial Design 2

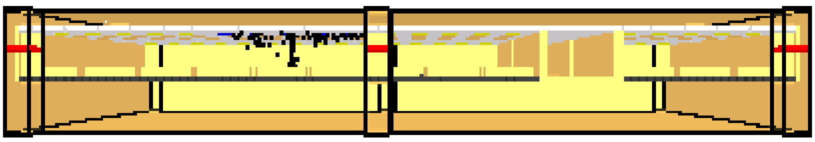
Trial design 2 chooses a significantly stronger fire of 3 MW in heat release rate. In scenario 3, using the downward desmoke strategy, the highest temperature at point 1 is about 257°C (see Fig. 8) at t = 60 s and then the sprinklers were activated at about 73 s. Meanwhile, the temperature maximum at points 2 and 3 are around 29°C and 27°C, respectively. The highest CO concentration at point 1 is 281 ppm (see Fig. 9a), which is still below the unattainable one of 1400 ppm. Apparently, both CO concentration and temperature meet the criteria for protecting human life. From Fig. 9b, which is the temperatures and CO concentrations at the height near the ceiling for zone 1, 3 and 5, it indicates that the neighboring zones, zone 1 and zone 5, are not attacked by the fire occurred in zone 3.



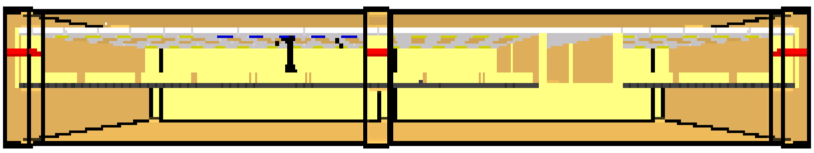
t = 24 sec



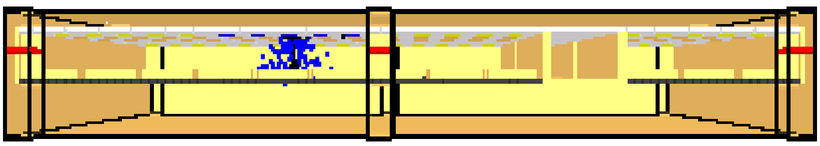
t = 30 s



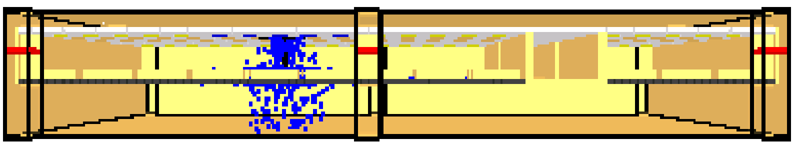
t = 58 s



t = 110 s



t = 159 s



t = 300 s

Fig. 6: The smoke particles profiles (scenario 1)

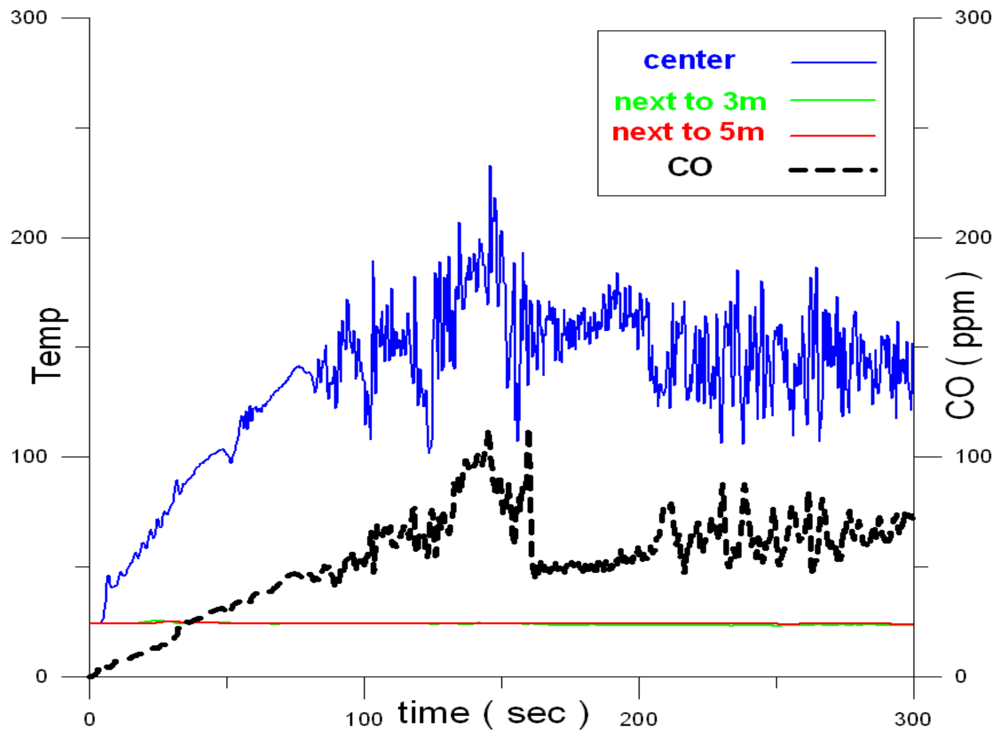


Fig. 7a: The temperature and CO concentration measured variation at 1.8 m (scenario 1)

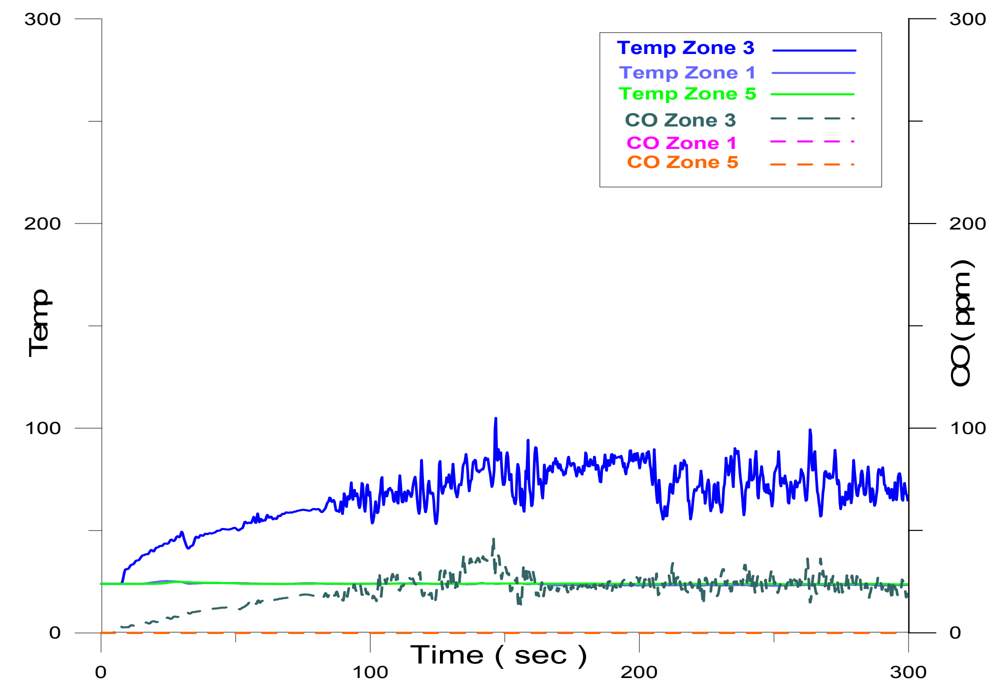


Fig. 7b: The temperature and CO concentration measured variation at the height near ceiling (scenario 1)

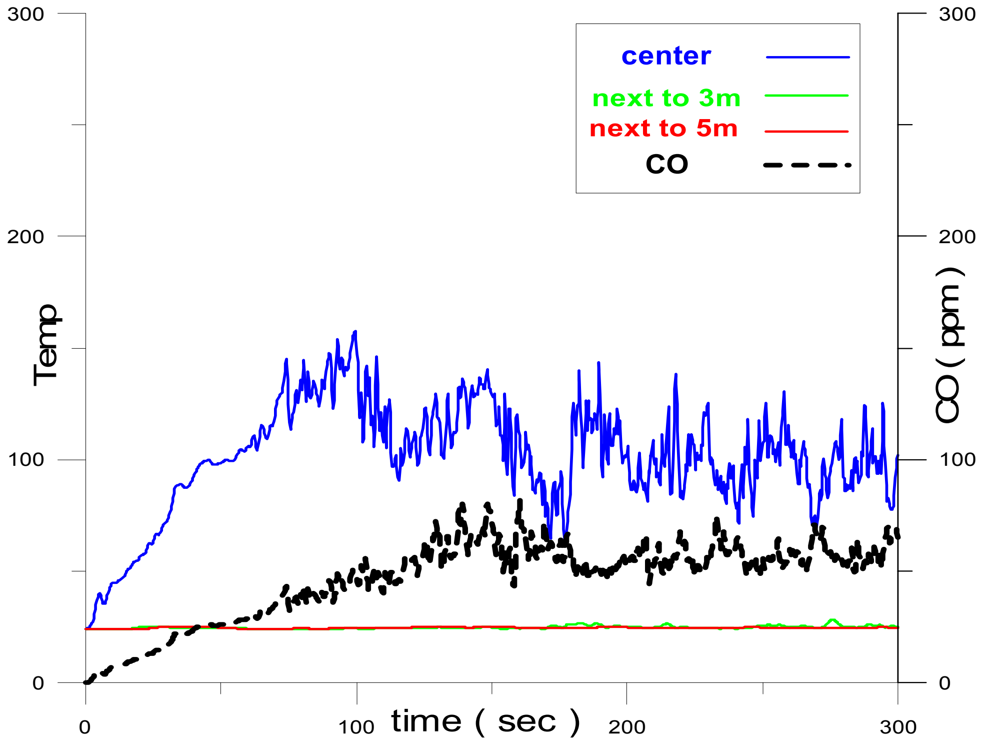


Fig. 8a: The temperature and CO concentration measured variation at 1.8 m (scenario 2)

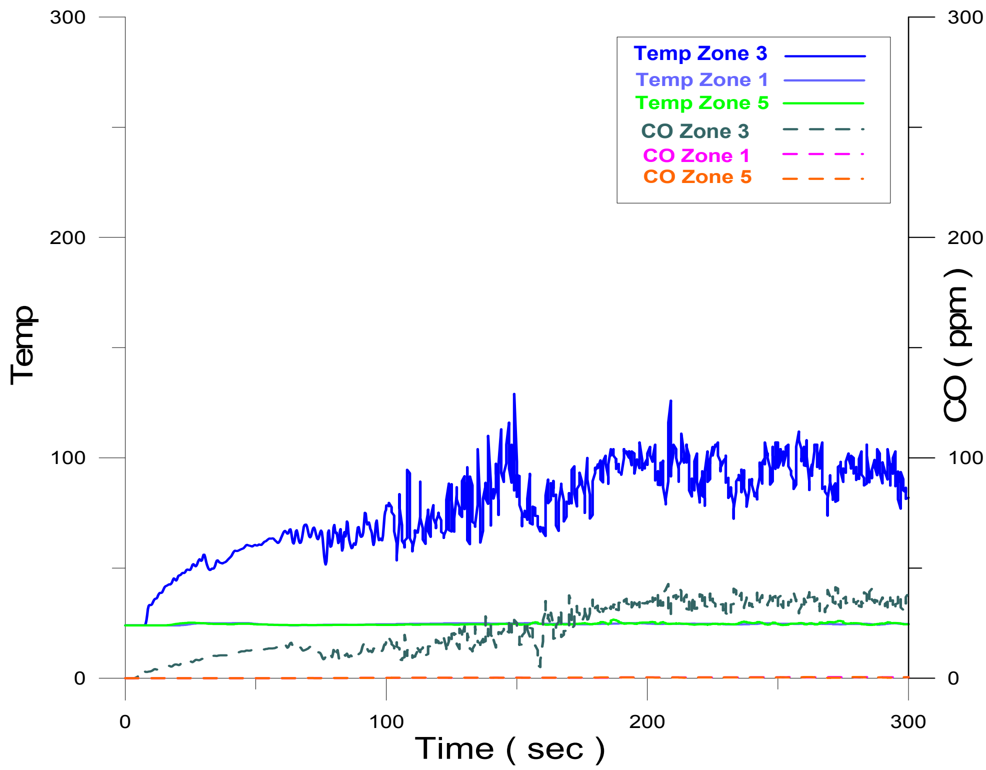


Fig. 8b: The temperature and CO concentration measured variation at the height near ceiling (scenario 2)

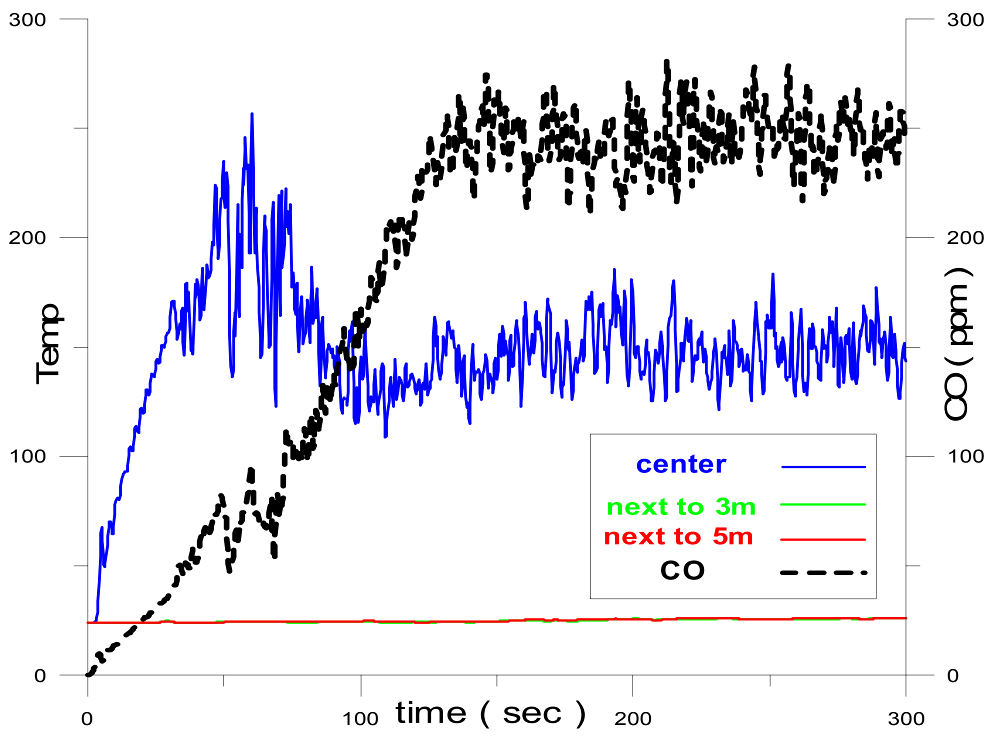


Fig. 9a: The temperature and CO concentration measured variation at 1.8 m (scenario 3)

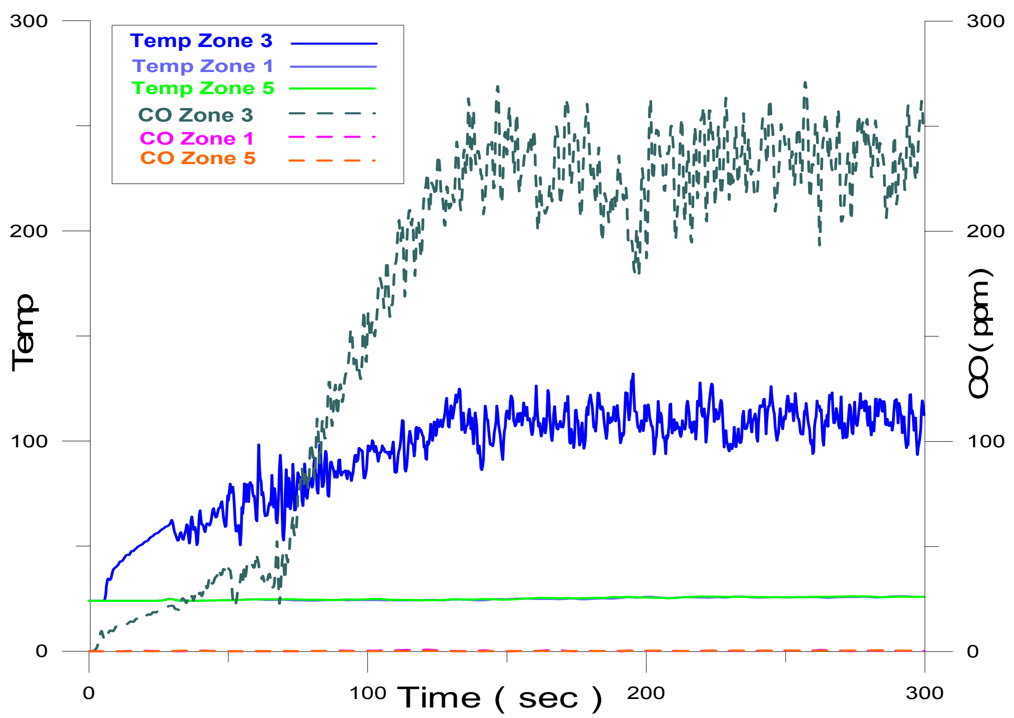


Fig. 9b: The temperature and CO concentration measured variation at the height near ceiling (scenario 3)

However, Fig. 10 shows that the smoke particles are restricted in the fire-origin zone within 50 s after the fire, and then pass across the boundary lines to enter the neighboring zones. Eventually, the smoke particles are full of the fabrication zone. Consequently, the smoke control strategy in scenario 3 apparently fails to meet the property protection requirement.

In scenario 4, using an upward desmoke system, the highest temperature at point 1 is about 250°C (see Fig. 11a). Meanwhile, the highest temperatures at points 2 and 3 are 27°C and 26°C, respectively. The highest CO concentration at point 1 is about 266 ppm (see Fig. 11a). Apparently, scenario 4 complies with the life safety criteria. The smoke particles are continuously restricted in the fire-origin zone because the upward desmoke strategy can bring the high temperature smoke away directly. Also, Fig. 11b shows that the temperatures and CO concentrations near the ceiling at zone 1 and 5 are still maintained at their original values and not affected by the fire taken place in zone 3. Apparently, the fire is constrained in the fire zone and it does not spread out of the zone 3. Therefore, Scenario 4 successfully meets the performance requirements.

3.2 Evacuation Results

From the above discussion, there appears to be no problems in the safe evacuation of the occupants of the fabrication area in the event of a fire in the assigned fire scenario. However, the fire simulations do not consider the installation of the smoke curtain as explained in section 2.1. Nevertheless, the local fire code requires that a smoke curtain be installed. Therefore, this part of the simulation must prove that the evacuation time can still meet the provision in such design.

The fabrication area contains 351 occupants, and has eight exits. The width of these exits is 1.2 m. Fig. 12 shows the production line configuration and the distribution of occupants in the wafer fabrication area.

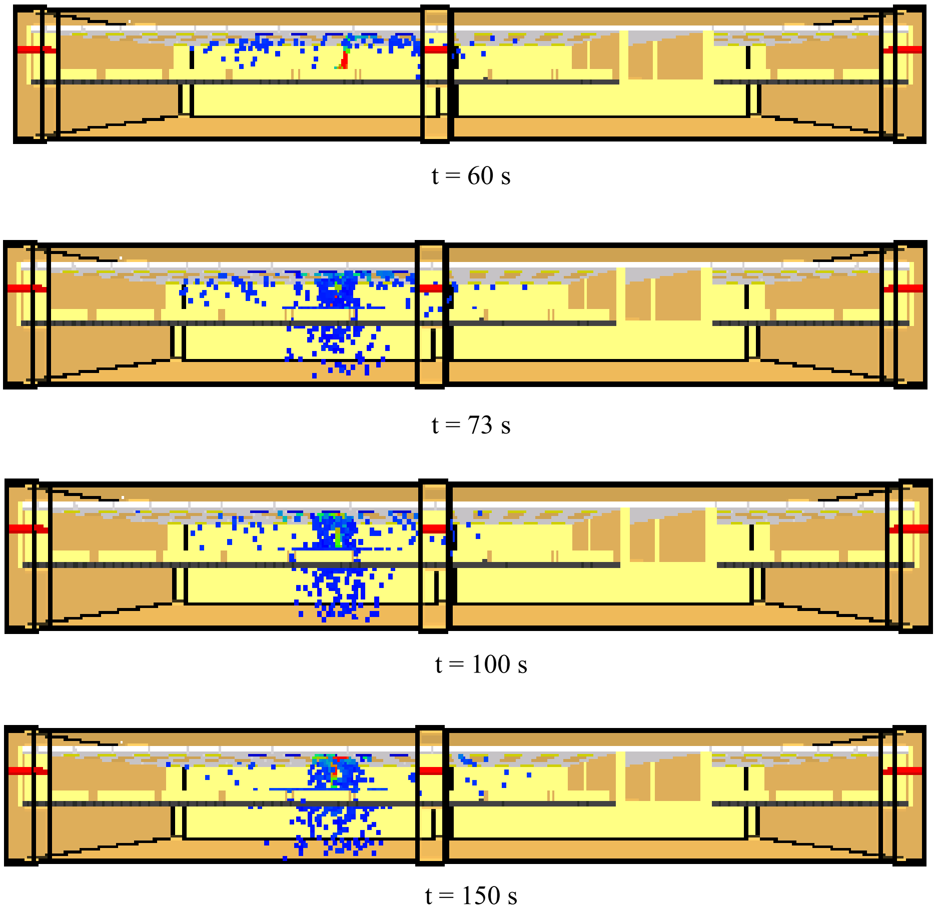


Fig. 10: The smoke particles profiles within temperature (scenario 3)

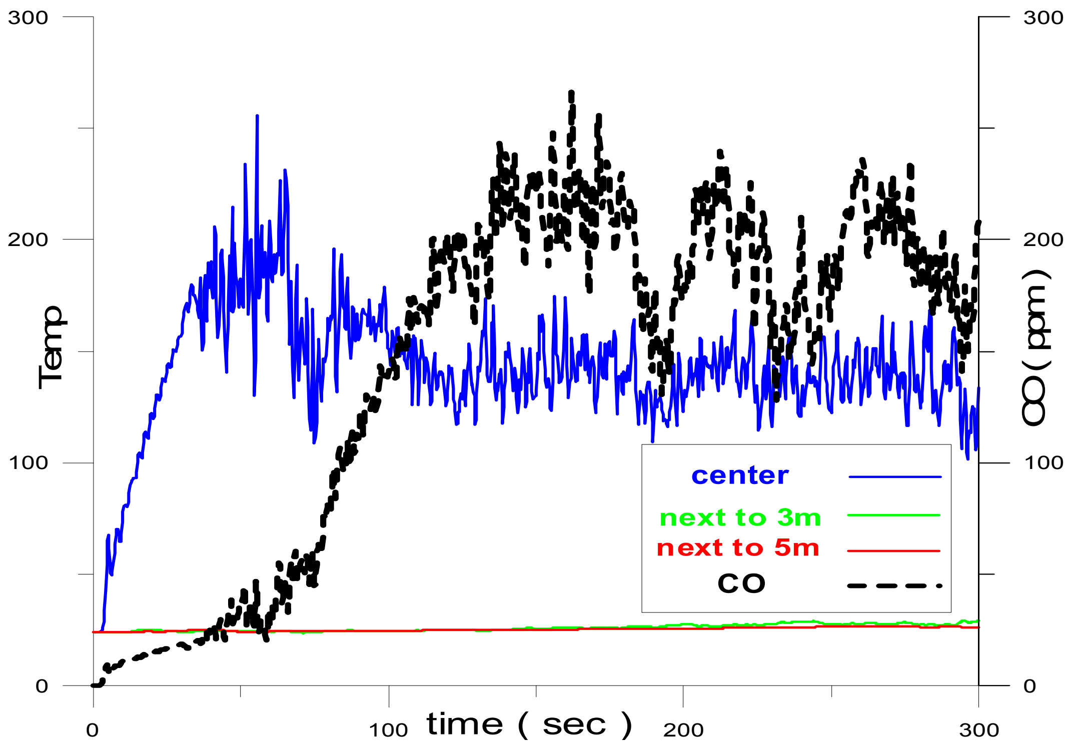


Fig. 11a: The temperature and CO concentration measured variation at 1.8 m (scenario 4)

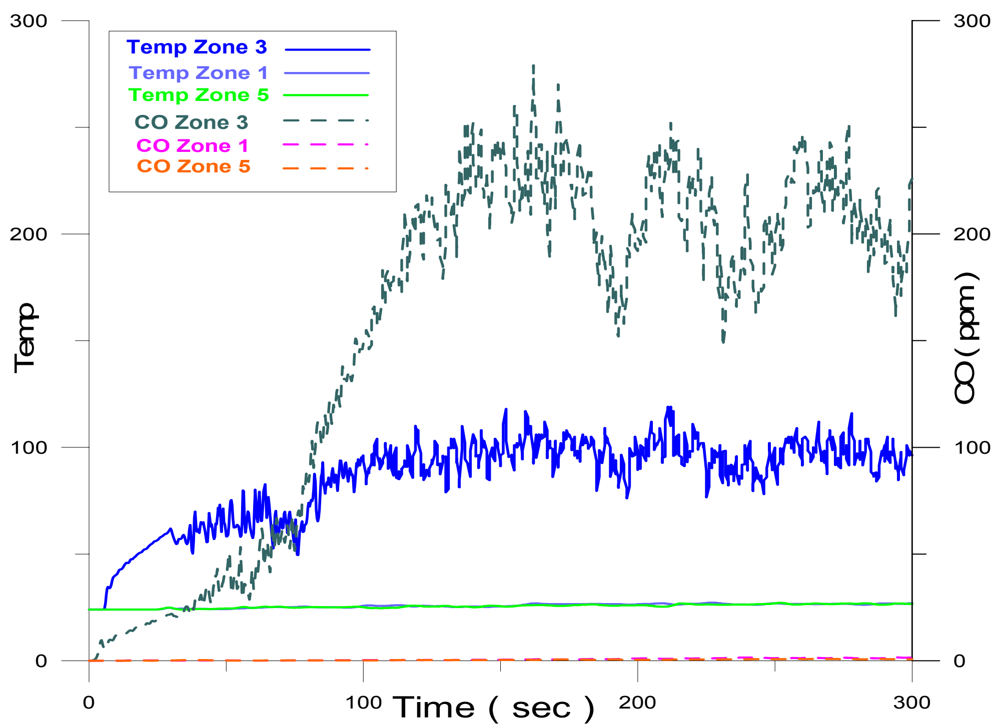


Fig. 11b: The temperature and CO concentration measured variation at the height near ceiling (scenario 4)

The resultant evacuation time is 67 seconds using SIMULEX. Notably, the dynamic evacuation time should be multiplied by a safety factor of 1.5, which is a requirement of the Fire Administration. The evacuation time then is 101 s. Importantly, 90 s more must be added to consider the activation time (30 s) for starting the smoke control system and the occupant response time (60 s). The total evacuation time is calculated as 191 s (see Table 6).

Table 6: Total evacuation time

	Simulex Simulation
Time (s)	30* + 60 + 101 (67 ×1.5) = 191

Fig. 13 shows the escaping movements at t = 30 s. The figure reveals that exits 2, 3, 4, 6, 7 and 8 display the slightly crowed condition. In summary, since the wafer fabrication zone is very large, occupant density (331/3600 = 0.09 persons/m^2) is very low, and these works are quite familiar with the environment, the evacuation is expected to proceed smoothly. For example, the three accidental fires mentioned in section 1.1 caused just one injury and no fatalities.

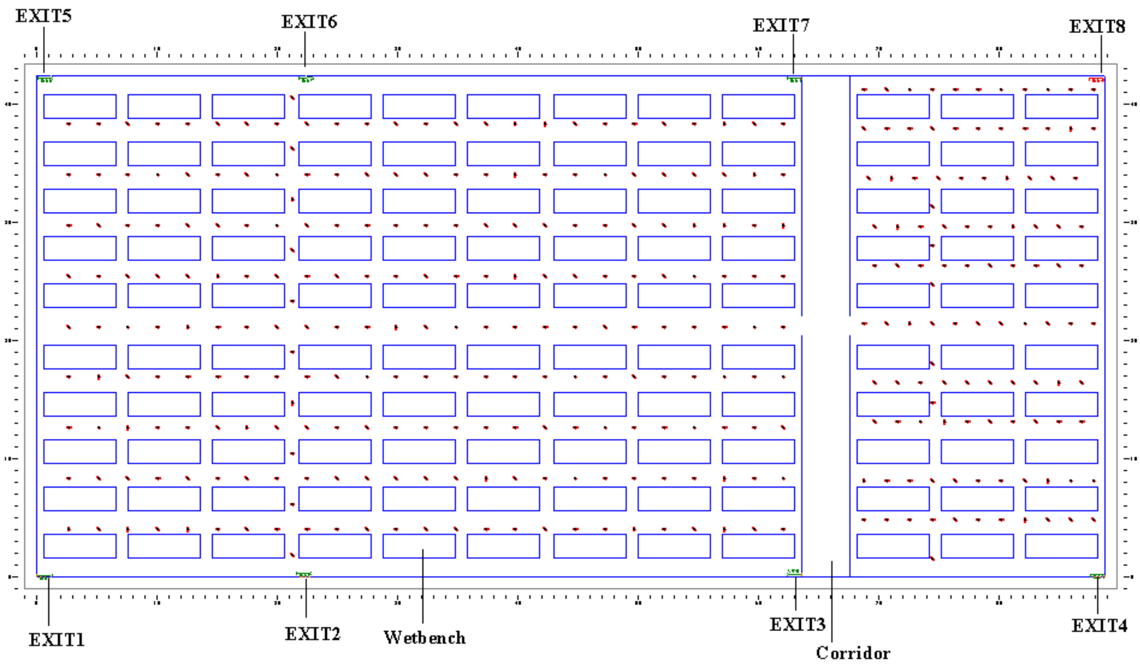


Fig. 12: The facility configuration and occupants displayed in wafer fab

Fig. 13: The occupants escaping movements (t = 30 s)

3.3 Comparison between the Results and the Prescriptive Code

The above simulated results obtained from the performance-based design procedure should be compared with the corresponding results from the local fire code to ensure their equivalence and/or superiority. Since the prescriptive code does not mention any specific evacuation time, the present study divides the Fab-zone into eight smoke compartments according to the fire code, which requires that each 500 m^2 compartment in the building should have at least one hour of fire-resistance, enabling occupants to escape to a safe place unharmed. Based on this regulation, this study uses FDS to further evaluate occupant safety.

The FDS model uses two types of smoke curtain, with heights of 50 cm and 80 cm, respectively, under two conditions, a successful and a failed operation desmoke operation (the worst case), respectively. The designated desmoke capacity is 15 m^3s^{-1} in each smoke compartment, complying with the local fire code (Taiwan). Table 7 lists comparisons of the results from the prescription-based codes and the Performance-based design. The FDS smoke layer interface position is determined by the N-percentage rule and the corresponding value of N is chosen as 80, recommended by NFPA 92B (suggesting N = 80~90) [24]. In the operational case, the smoke descending time is 352 s using the 50-cm smoke curtain and 387 s using the 80-cm smoke curtain. In the failure case (or the worst case), the smoke descending time is 281 s using the 50-cm smoke curtain and 305 s using the 80-cm smoke curtain.

The simulated evacuation time (Simulex) for the downward desmoke system is 191 s, less than the 281 s obtained for the worst case, which complies with the local fire code. It indicates that the downward desmoke system can achieve the safety goal in cases where occupant evacuation are required.

3.4 Selected Design Meets Performance Criteria

Table 8 lists the result of evaluation trial designs. The simulation results confirm that the downward exhaust strategy can tolerate the situation of 800-kW fire, but it fails owing to the fire intensity in the case of 3 MW. Therefore, the amount of HPM in the fabrication area must be controlled. This provision is also suggested by Article 51 of UFC [25], NFPA 318 [26] and FM Loss Prevention Data 7-7/7-12 [17].

Finally, according to the trial design results, several recommendations for fire safety engineering are proposed:

- The wetbench should utilize metal material instead of PP. In the event of a wetbench fire, heat release rate can be significantly reduced, and the downward exhaust strategy then can control the fire.
- The wafer fabrication usually has an AGV wafer transport system to cut across the compartment, and can seek a newly designed smoke curtain, which is hidden in the ceiling normally and can be pulled downwards automatically in the event of a fire.
- It is suggested that the variation range of the FFU flow speed be maximized, to make the resultant pressure difference more effective in restricting the smoke spread.
- In this study, the concentrations and spread of corrosive and toxic gases, which are part of combustion products, are not taken into consideration because the limited available data in FDS itself. Therefore, a new project is proposed recently to measure and evaluate the other combustion products of the materials, especially the plastics, used in semiconductor manufacture workstations by using Cone Calorimeter with FTIR. These data will be applied in the future extension of this study.

Table 7: Simulation differences based on prescription-based codes and the performance-based design case

	Smoke exhaust Venting	Smoke curtain	Descending smoke time (s)	Simulex evacuation time (s)
Prescriptive codes (Taiwan)	Yes	50 cm	352	-
	Yes	80 cm	387	-
	Fail	50 cm	281	-
	Fail	80 cm	305	-
Performance-based design	Exhaust capacity (Downward) 26.88 m^3s^{-1}	-	-	191

Table 8: The evaluating result of trial designs

Performance requirement		Trial Design 1		Trial Design 2	
		Scenario1	Scenario2	Scenario3	Scenario4
Life safety criteria	Temperature < 80°C	O	O	O	O
	CO Concentration < 1400 ppm	O	O	O	O
Non-life safety criteria	Restrict smoke particles in the fire zone	O	O	X	O

"**O**": passed "**X**": failed

4. CONCLUSIONS

This study adopted the SFPE performance-based design procedure to evaluate the desmoke system in a wafer fabrication zone. The tools used are FDS and Simulex, respectively. Upward and downward desmoke systems are set up in the wafer fabrication zone. The design fires are 800 kW and 3 MW. Both desmoke systems in designed fire 1 (800 kW) meet the performance criteria, while the downward desmoke system in a designed fire of 3 MW do not satisfy the required criteria. However, the downward desmoke system can still be utilized, provided there is full compliance with various restrictions in the fire protection design, for example the materials used and the acceptable emergency plan. Although the downward desmoke system cannot completely protect assets, the fire scenario (3 MW) passes the life safety requirements by using the downward desmoke system. The downward desmoke system thus meets the local fire code requirements, but insurance companies do not necessarily agree with the fire protection system.

Regarding occupant evacuation, the simulation result of Simulex shows total evacuation time of 191 s. FDS simulations with smoke curtain installation confirm that the evacuation time is less than the smoke descending time, indicating that the occupants can evacuate safely.

Presently, local fire codes remain inadequate for advanced technology factories because suitable fire protection regulations currently remain unavailable. Therefore, several recommendations are proposed for local fire codes:

- The governmental regulations basically are considered the minimum requirements for fire safety. Unfortunately, these regulations cannot quantify the safety level. Therefore, occupant evacuation time using the criterion, where the evacuation is completed before the time of smoke layer descending to 1.8 m, may serve as a safe quantity for life safety.

- In property protection, insurance companies generally require significantly higher standards of property protection. Advanced technology facilities should consider smoke damage as the first priority in the cleanroom, rather than no flashover in the fire-origin compartment.

- Local fire authorities should establish a special fire code, similar to UFC Article 51, suitable for fire safety requirements for advanced technology factories.

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