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Performance evaluation of a water mist system in semiconductor wet bench fires

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ARTICLE INFO

Article history:
Received 7 July 2007
Accepted 26 September 2007

Keywords:
Water mist
Wet bench
Semiconductor
Fire

ABSTRACT

Wet benches are typically utilized in semiconductor facilities for wafer and parts cleaning. Heaters and some flammable liquids, such as acetone and isopropyl alcohol (IPA), are employed during the cleaning process. Wet bench fires have caused serious losses in the semiconductor industry. To assess the fire protection performance, several field tests were performed using a water mist system installed in the wet bench. In this study, acetone pan fuel was used as fire source. The test parameters were operational pressure, pan size, nozzle location, cylinder obstruction and degree of door closure. An appropriate design for operating pressure and the location of water mist nozzles extinguished wet bench fires effectively in the early fire stages. The nozzles are suggested to be fixed above or on the each side of the pan, ensuring that mist can completely cover a pan surface with sufficient momentum. With this suggested design, fires can be extinguished in the pan and do not spread over the wet bench.

1. Introduction

Taiwan has roughly 1000 semiconductor facilities, with a total output value of approximately US$ 23 billion in 2006, ranking the Taiwanese industry as third largest worldwide. A polypropylene (PP)/polyvinyl chloride (PVC) wet bench is typically utilized in clean room environments. Hundreds of chemicals are used during manufacturing, some of which evaporate easily and have a wide flammability range (Chelton et al., 1991; Hirano, 2004). FM Global has estimated that 1 in 10 manufacturing plants experience a fire loss annually. Fires involving wet benches have caused significant losses in the semiconductor industry in past years. At the start of the 1990s, FM focused on replacing materials or protecting existing plastic wet benches in the semiconductor industry. Numerous companies simply accepted the recommendations, following the FM7-7 guidelines (2003) and installed carbon dioxide or fine water mist fire suppression systems in wet benches. This study analyzes the performance of water mist fire suppression systems utilized for wet bench protection. According to NFPA750 (2000), water mist is defined as spray in which 99% of spray droplets, by flow-weighted cumulative distribution, have diameters <1000 μm as the minimum design operating pressure of water mist nozzles. Due to the large surface-to-volume ratio and long suspension time, water mist has very effective fire extinguishing characteristics. The dominant mechanisms for fire suppression with water mist are flame cooling, oxygen displacement, radiant attenuation, dilution of flammable vapors, and direct impingement wetting and cooling of combustible materials (Braidech et al., 1955; Mawhinney et al., 1994). Water mist has the advantages of being non-toxic and non-corrosive and causes no environmental problems, which is characteristics important to maintaining clean room environments.

Previous studies indicated that wet bench fires should be suppressed in the early fire stage (Fisher et al., 1986; Wu et al., 1995). Wu et al. (1996) experimentally analyzed simulated wet bench fires using fine water spray. A polypropylene pool fire was placed in the middle of working surface with two 7 in. cylinders on each side to block direct impingement with water

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0957-5820/$ – see front matter
doi:10.1016/j.psep.2007.10.013

mist. Two nozzles on the each end wall extinguished all polypropylene pool fires in 10 s. Mawhinney and Solomon (1997) utilized a twin-fluid nozzle to generate a fine spray to extinguish liquid pool fires. Mawhinney demonstrated that spraying downward directly at the flames is the most effective means of extinguishing a fire. Obstructions in the spray path reduce spray momentum and the amount of water suspended in air as mist, resulting in reduced ability to extinguish a fire.

2. Experimental apparatus

To control experimental conditions, fire tests were conducted in a field test facility 25 m long, 9 m wide and 7 m high. All tests were considered open-air tests; that is, air was supplied naturally. The test facility consists of a test compartment, water mist systems and instruments for data collection.

2.1. Experimental layout

Fig. 1 shows the schematic configuration of the experimental apparatuses. The wet bench is 2.3 m long, 0.64 m wide and 1.61 m high, based on FM 5560 approval standard (2005). Five square pans were placed isometrically in the working surface. Mist nozzles were fixed on the top of the wet bench wall based on test scenarios. The mist nozzle was connected to an electric high-pressure pump via a soft hose. Mist operating pressure was adjusted via the pump pressure valve. The high-pressure pump produced 130 bar pressure and a flow rate up to 13 L/min. A commercially available high-pressure water mist nozzle was used. The nozzle K factor was 1.42 L/min/bar$^{1/2}$ and flow rate was 11.65 L/min at 100 bar. The volume mean diameter of droplet is about 100 μm at 100 bar, which was measured by an image processing technique. The spray angle is 60°. There are 21 jet holes in the nozzle, 3 of them in the inner ring and the rest of 18 holes in the outer one. Pressure was monitored using a pressure gauge attached behind the nozzle. Temperature was measured using a thermocouple tree, arranged at the pan center line. The radiometer was employed to measure the radiant attenuation effects of the mist. All measured data were transferred to a disk storage system using a PC-controlled data recording system.

2.2. Fire source

The wet bench fire source, using acetone as the fuel, was contained in a square iron pan 20 cm × 20 cm or 30 cm × 30 cm, both pans were 15 cm deep. The water mist system was manually activated after 60 s pre-burn to reach a steady-state burning condition.

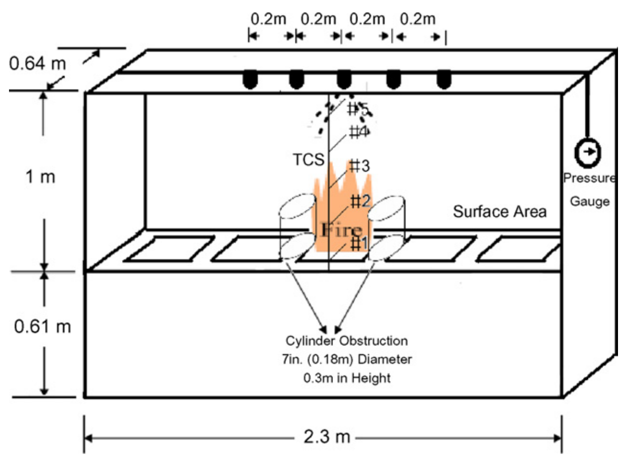

Fig. 1 – Experiment layout of wet bench fire tests.

2.3. Data collection

Five *k*-type thermocouples were set above the pan center as in Fig. 1. The thermocouples were marked #1, #2, #3, #4, #5 and located at 15 cm, 35 cm, 55 cm, 75 cm and 95 cm, respectively, arranged in the pan center line above the fuel surface to measure temperature history.

2.4. Test parameters

The fire tests parameters utilized were operating pressure, nozzle location, pan size, cylinder obstruction and degree of door closure. Each fire test was repeated at least three times to achieve data consistency.

Table 1 shows the water (mist) volume flow rate at different operating pressures in 1 min.

3. Results and discussion

Generally, water-based fire protection systems should not be applied to Class B fires as most fuel would splash over the pan. Therefore, cooling the fuel surface with water evaporation is difficult and can produce a 'running liquid fire.' However, water mist systems do not have sufficient water for a fuel to float—water accounts for only 1/10 of the content in conventional sprinkler systems. Water mist system may therefore suppress wet bench fires effectively with appropriate design and operation.

3.1. Single nozzle tests with different pan sizes and operating pressures

The pan sizes used were 20 cm × 20 cm square and 30 cm × 30 cm, both pans were 15 cm deep. In these tests, one water mist nozzle was fixed 1 m above the pan center. Each pan was filled with 400 cm^3 or 900 cm^3 acetone such that the same fuel surface level (1 cm high) was maintained. After 60 s of pre-burning, the water mist system was activated manually. The mist operating pressure was changed from 15 bar to 55 bar in series of tests to identify the critical pressure. Table 2 shows the time required to extinguish the fires in different pan sizes and at different operating pressures. When the nozzle was installed just above the pans, fires were extinguished in seconds at most operating pressures. The water mist system effectively extinguished the acetone pan fires. During each pan size test, there was a critical pressure. Below the critical pressure, the mist took more than 10 s to extinguish the fires or even did not extinguish the fires. For the 20 cm and 30 cm pan fires, the critical pressure was the same 15 bar. Under that pressure, mist density (flux) and jet

Table 1 – Volume flow rates of water mist nozzle (L/min)

Nozzle type	Pressure (bar)			
	55	45	35	25
One nozzle	10.6	9.4	8.4	7.2
	K factor = 1.42			

Table 2 – Fuel pan size and corresponding extinction time (s) under different operating pressure

Fuel size test		
Pressure (bar)	Fuel pan size	
	30 cm × 30 cm	20 cm × 20 cm
55	2	1
45	3	1
35	3	1
25	5	1
15	Fail	Fail

Fail: cannot be extinguished.

momentum was insufficient to extinguish the fires. According to Table 2, the time to extinguish a small pan fire was shorter than that for a large fire. For the 30 cm × 30 cm pan, when operating pressure decreased, time to extinguish the fire increased; however, this phenomenon was not obvious for the 20 cm pan. For different pan sizes, flux and momentum of water mist have significant roles in fire suppression. For the 20 cm pan, the mist totally covered the pan during tests and fires were extinguished instantly. However, for the 30 cm pan with larger fuel surface, additional mist and at an increased momentum was needed to extinguish the fires. That is, the 30 cm pan fires needed additional time to be extinguished.

During the tests, the single nozzle fixed above the pool extinguished the wet bench fires in seconds with appropriate pressure. When pressure reached 15 bar, the flame became unstable and started to tremble markedly. The fire even spread to other pans located beside the fire pan. At a low operating pressure, the fire had the potential to ignite fuel in another pan and spread over the wet bench.

3.2. *Tests for nozzle distribution*

These experiments addressed the effect of the following two parameters: location tests for a single nozzle; and, using two nozzles at the same time. In the first test, the water mist nozzles were placed at two different locations, 20 cm and 40 cm apart from the original position (pan centerline), 1 m above the pan center. Table 3 shows the times required to extinguish the fire with a single nozzle placed in different locations. For the 20 cm distance, extinguishing times for the 30 cm × 30 cm pan all were 3 s at operating pressures of 55 bar, 45 bar and 35 bar. The extinguishing times for the 20 cm × 20 cm pan were 2 s, 1 s and 1 s at pressures of 55 bar, 45 bar and 35 bar, respectively. The water mist system effectively extinguished the pan fires. However, when the nozzle was placed 40 cm away from the original position, the water mist could not extinguish the pan fires at all operating pressures. For the 40 cm tests, the fire plume drifted to another side of the pan and may ignite adjacent pan. This performance difference resulted from mist coverage. At 40 cm, the mist did not cover all of the pan area, whereas at 20 cm, the mist still covered the whole pan. Due to the low flash point of acetone, the mist needs sufficient momentum and totally covered to extinguish the fires. In 40 cm case showed that the cooling effect of mist was insufficient to extinguish acetone fires.

The second test evaluated extinguishing efficiency of two nozzles on each side of the pan fixed symmetrically on the top of the wet bench. There were two distances, 40 cm and 80 cm used between each nozzle. It means 20 cm and 40 cm from the pan center to each nozzle. The 20 cm × 20 cm pan was utilized

Table 3 – Fuel pan size and corresponding extinction time (s) under different operating pressure and location

Fuel size and nozzle location test						
Pressure (bar)	Fuel pan size (30 cm × 30 cm)			Fuel pan size (20 cm × 20 cm)		
	Center[a]	20 cm[a]	40 cm[a]	Center[a]	20 cm[a]	40 cm[a]
55	2	3	Fail	1	2	Fail
45	3	3	–	1	1	–
35	3	3	–	1	1	–
25	5	us	–	1	us	–
15	Fail	–	–	Fail		–

us: Unstable condition; Fail: cannot be extinguished.
[a] Nozzle location.

Table 4 – Distruibution tests and corresponding extinction time (s) under different operating pressure

Nozzle distribution tests (two nozzles)		
Pressure (bar)	Nozzle distance, 40 cm (20 cm to pan center)	Nozzle distance, 80 cm (40 cm to pan center)
55	1	1
45	1	Fail
35	3	–
25	5	–

Fail: cannot be extinguished.

as the fire source for these nozzle distribution tests. Table 4 shows the times required to extinguish the wet bench fires with 40 cm and 80 cm between the two nozzles. In contrast to the single nozzle tests, the fire plume was suppressed in the pan and the fire did not tremble significantly, not easy to ignite a adjacent pan. The extinguishing times indicated that using the two nozzles was slightly better than using a single nozzle located the same distance from the pan center. When the two nozzles were utilized, density-to-pan-fire ratio was almost double; however, the mist momentum was still insufficient. This experimental finding indicates why the time difference between single nozzle and two nozzles was not obvious. The mist required adequate momentum to extinguish the fire, regardless of whether a single nozzle or two nozzles were used.

3.3. *Obstruction tests*

In real working process, tools or solvent tanks are sometimes located near the working surface of washing tanks (pan fire

Table 5 – Extinguishing time of obstruction tests under different operating pressure

Obstruction tests (two nozzles)						
Pressure (bar)	Nozzle distance (40 cm)			Nozzle distance (80 cm)		
	0[a]	1[a]	2[a]	0[a]	1[a]	2[a]
55	1	1	1	1	3	3
45	1	1	1	Fail	Fail	Fail
35	3	3	2	–	–	–
25	5	3	2	–	–	–

Fail: cannot be extinguished.
[a] Obstruction number.

Table 6 – Door closure degree and corresponding extinction time (s) under different operating pressure

Pressure (bar)	Door closure test											
	Nozzle distance (20 cm)						Nozzle distance (40 cm)					
	Open[a]		Half closed[a]		Totally closed[a]		Open[a]		Half closed[a]		Totally closed[a]	
	1[b]	2[b]	1[b]	2[b]	1[b]	2[b]	1[b]	2[b]	1[b]	2[b]	1[b]	2[b]
55	2	1	2	1	1	1	Fail	1	Fail	1	2	1
45	1	1	4	1	1	1		Fail	–	3	2	1
35	1	3	9	1	2	1			–	3	6	1
25	us	5	us	1	3	1			–	us	us	1

us: Unstable condition; Fail: cannot be extinguished.
[a] Closure degree.
[b] Nozzle used.

source). These tools or solvent tanks in this study were considered obstructions to a fire extinguishing system. In the following experiments, cylinders 30 cm high and 18 cm in diameter were utilized as obstructions to simulate tools or solvent tanks left on the bench. During the first test, one cylinder was placed 10 cm away from one side of a pan. In the second test, two cylinders were placed 10 cm away on each side of the pan. These obstructions may affect the direct flow of water mist to a fire, thereby changing the performance of the water mist system. However, tests results shows in Table 5, indicate little difference in extinguish capability with and without obstructions. In the 40 cm tests, for the nozzles are fixed above the pan, the mist was partly blocked by one or two cylinders. Obstructions didn't seriously affect the mist to fuel surface. However, for the 80 cm tests, the impinging angle was changed and relatively more mist was blocked. In these scenarios, more time was needed to extinguish the fires than that without obstructions.

3.4. *Tests for degree of closure of the wet bench door*

During manufacturing, the wet bench door is closed and opened repeatedly. When a fire occurs, the door may be open, closed, or partially open. The degree of closure of the wet bench door is a factor that likely affects extinguishing performance. Degree of door closure affects the availability of oxygen in the wet bench. During this test, the door of the wet bench was half closed and totally closed that an iron plate was used to simulate the closure degree of real scenarios. The iron plate could be fixed to cover the upper layer as the partially open (half-closed) status or cover all the open area as totally closed status. In the half-closed status, the upper layer of test area was covered by iron-made plates. Table 6 presents the degree of door closure and the corresponding extinguishing times under different operating pressures. Figs. 2–4 show the temperature history during the extinguishing process for degrees of door closure. Fig. 5 shows the oxygen consumption during the extinguishing process for degrees of door closure. When the door was closed completely, heat was stored on the upper layer of wet bench, making water mist evaporate rapidly and accelerating oxygen consumption, made the fire easy to be extinguished. However, according to Table 6, the extinguishing times for an open door and half-closed door were not significantly different because oxygen could still freely feed the fires in these situations. However, extinguishing times decreased markedly when the door was completely closed because oxygen consumption was near the combustion limit; thus, these fires were more easily extinguished than those when the door was half closed or opened.

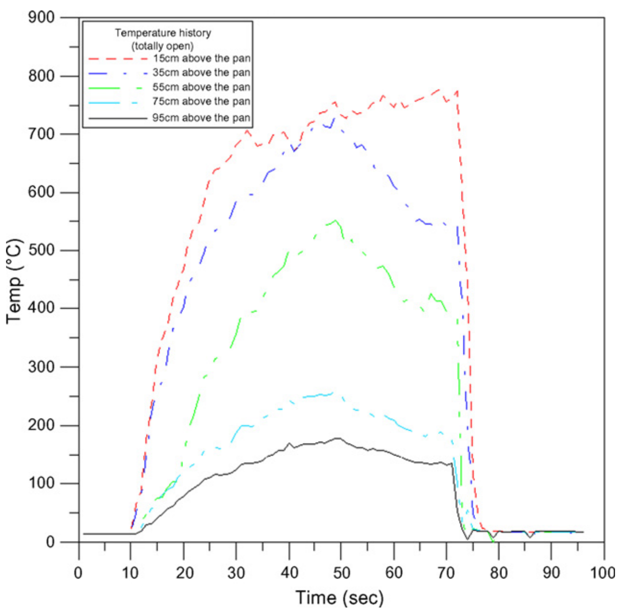

Fig. 2 – Temperature history of totally open door tests.

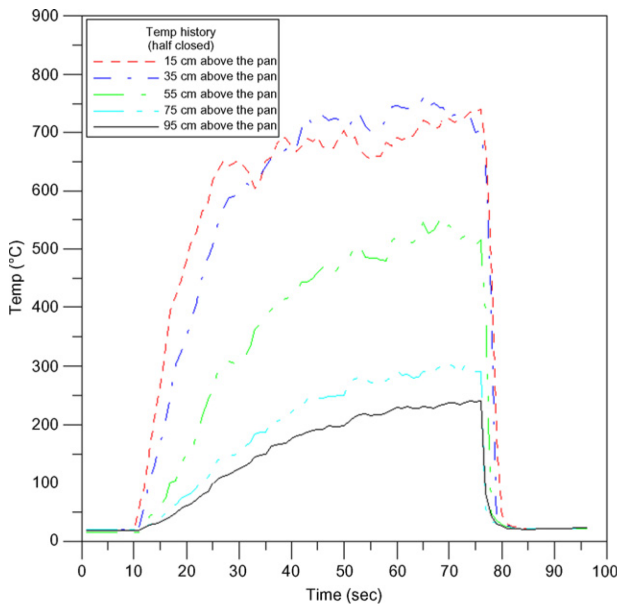

Fig. 3 – Temperature history of half closed door tests.

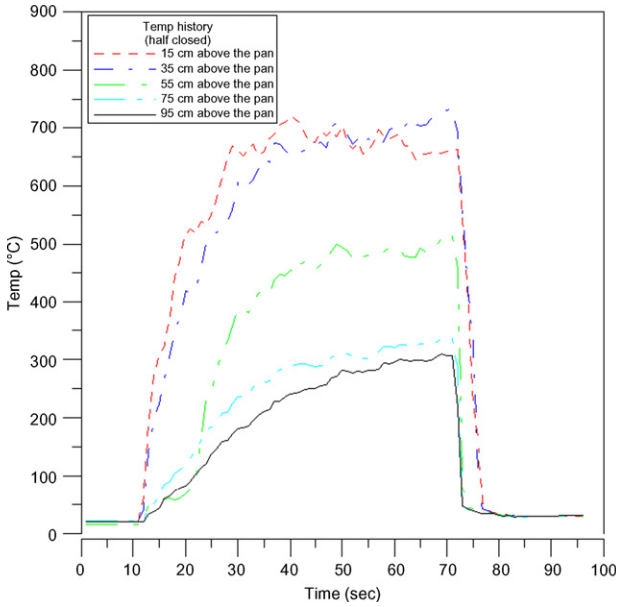

Fig. 4 – Temperature history of totally closed door tests.

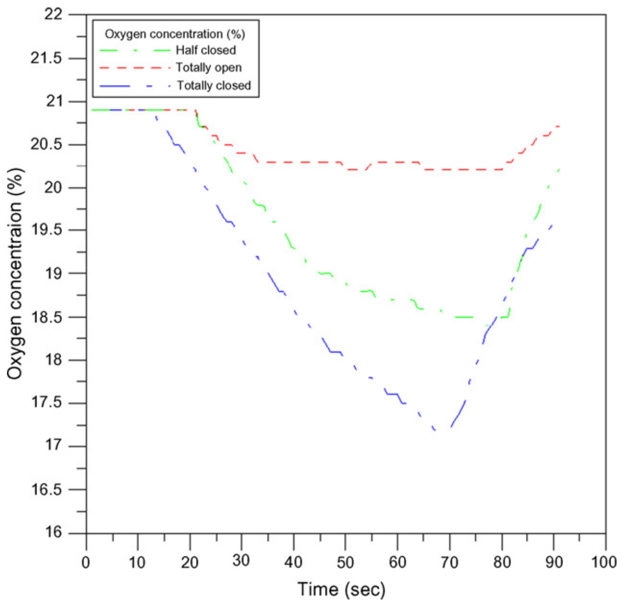

Fig. 5 – Oxygen concentration history for different door closure degree.

3.5. *Fire spreading in a wet bench*

During the series of tests, several special phenomena should be discussed. The fire spread in some fire tests. In the distribution tests, a single nozzle fixed above the pan can destabilize the flame, making it tremble, jump to another pan and ignite when operating pressure was insufficient. Additionally, when a single nozzle was fixed at the side of the wet bench or at a distance from the center above the pan, it stretched the flame to the other side and easily ignited other fuel pan. To prevent fire spread, nozzles should be fixed above pan fire and have sufficient operating pressure, or fixed on each side of the pan to prevent flame stretching. With proper nozzle locations, fires can be suppressed in the pan and not ignite other pans nearby.

4. Conclusions

In this study, several parameters were examined in acetone wet bench fires. In the single nozzle tests with different pan sizes, water mist extinguished the small pan fire easier than large pan fires. In the nozzle distribution tests, the area covered by the water mist and mist momentum played important roles. The closer the water mist to the center of pan (raised the coverage), the easier the fire can be extinguished. With sufficient coverage, a critical operating pressure exists. Above that pressure, fires were easily extinguished. The critical pressure should be used when designing a water mist system, as insufficient pressure can increase the opportunity of a fire spreading through fuel spread. In this study, the number of the nozzles used also affected the ability of water mist to extinguish a fire. When two nozzles were fixed on either side of the pan, efficiency extinguishing a fire was better than that with a single nozzle. During the obstruction test, there was little difference in extinction time when one cylinder was located on one side or two cylinders were placed on either side of the pan. Additionally, the degree to which the wet bench door was closed markedly affected extinguishing performance of the wet bench fire. We suggest that the door to a wet bench or ventilation should be closed during a wet bench fire. This study identified several issues germane to preventing fire spreading out during wet bench fires. Low operating pressure, unsuitable location of nozzles and improper discharge angle can make fires to spread in a wet bench. An appropriate design with sufficient operating pressure and locations of water mist nozzles can extinguish wet bench fires effectively in early fire stages.

Finally, the possible future extensions are given. It is known that the test results might be affected as the doors are either open or closed if the enclosure is subjected to forced ventilation by, for example, an air or fume extraction system. Therefore, it will be the next research subject to consider the ventilation effect.

Acknowledgments

The authors would like to thank the National Science Council of the Republic of China, Taiwan (Contract No. NSC [95]-[2622]-[E]-[166]-[006]-[CC3]) and the Ministry of Education, Republic of China, Taiwan, for financially supporting this research.

REFERENCES

Braidech, M.M., Neale, J.A., Matson, A.F. and Dufour, R.E., 1955, The Mechanisms of Extinguishment of Fire by Finely Divided Water. NY: Underwriters Laboratories Inc. for the National Board of Fire Underwriters p. 73.

Chelton, C.F., Glowatz, M. and Mosovsky, J.A., 1991, Chemical hazards in the semiconductor industry, IEEE Trans Educ, 34: 269–288.

Fisher, L.F., Williamson, R.B., Toms, G.L. and Grinnion, D.M., 1986, Fire protection of flammable work stations in the clean room environment of a microelectronic fabrication facility, Fire Technol, 22(2).

FM 5560, 2005, Approval Standard for Water Mist Systems, 2005 ed. (FM Global Technologies LLC).

FM Global Loss Prevention Data Sheet 7-7, 2003, Semiconductor Fabrication Facilities.

Hirano, T. 2004, Accidental explosions of semiconductor manufacturing gases in Japan, J Loss Prev Process Ind, 17: 29–34.

Mawhinney, J.R., Dlugogorski, B.Z. and Kim, A.K., 1994, A Closer Look at the Fire Extinguishing Properties of Water Mist, Fire Safety Science—Proceedings of Fourth International Symposium (pp. 47–).

Mawhinney, J.R. and Solomon, R., 1997, Water Mist Fire Suppression Systems, Fire Protection Handbook, 18th ed., pp. 6/216–6/248 (section 6, chapter 15).

NFPA 570, 2000. Standard for the Installation of Water Mist Fire Protection Systems, 2000 ed. (National Fire Protection Association, Quincy, MA).

Wu, P.K., Chaffee, J. and Knaggs, B., 1995, A Wet Bench Free-burn Test Under FMRC Fire Products Collector. (Factory Mutual Research Corporation, Norwood, MA).

Wu, P.K., Taylor, J. and Harriman, R.B., October 1996, Wet Bench Fire Suppression with Fine Water Sprays. (Factory Mutual Research Corporation, Norwood, MA).