Evaluation of a Litmas "Blue" Point-of-Use (POU) Plasma Abatement Device for Perfluorocompound (PFC) Destruction

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Abstract: This report describes preliminary experiments to reduce perfluorocompound (PFC) and hydrofluorocompound (HFC) emissions with a beta version of a Litmas “Blue” point-of-use (POU) plasma abatement device on an Applied Materials Centura 5200 MxP+ oxide etch chamber. Using Fourier transform infrared spectrometry (FTIR) and quadrupole mass spectrometry (QMS) as diagnostic tools, the destruction and removal efficiency (DRE) of PFCs from the etch chamber exhaust stream was measured as a function of abatement system input power, feed composition, etch tool parameters, and abatement gas flow rate. In particular, water vapor and oxygen as abatement additive gases were compared. Preliminary cost of ownership (COO) calculations determine fixed capital and installation costs as well as yearly operating and maintenance costs.

Keywords: Perfluorocompounds, Pollution Control Equipment, Emissions Reduction, Point of Use Abatement, Fourier Transform Infrared Spectroscopy, Cost of Ownership, Plasma Etching, Dielectric Etching

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1 EXECUTIVE SUMMARY

This report describes a screening evaluation of a beta version of the Litmas model "Blue" point-of-use (POU) plasma abatement system to determine its ability to reduce perfluorocompound (PFC) emissions from dielectric etch processes. The Litmas device is an inductively-coupled, high-density radio-frequency (RF) plasma source with integrated variable-frequency power supply and solid state matching network. It is among the first commercially available systems specifically designed for POU abatement of PFCs and hydrofluorocompounds (HFCs). One device is needed for each chamber of an etch tool, assuming that each uses a PFC etch recipe.

1.1 Experimental Description

To evaluate the performance of the Litmas device, experiments were conducted with the system installed on a 3-inch diameter branch off the main 4-inch diameter foreline of an Applied Materials Centura 5200 MxP+ oxide etcher to allow "slipstream" operation. Using Fourier transform infrared spectroscopy (FTIR) and quadrupole mass spectrometry (QMS) as diagnostic tools, the performance of the Litmas device was measured as a function of chamber pressure, source power, magnetic field, and etch gas flows along with abatement system parameters such as input power and additive gas identity and flow. The etch tool parameters were selected based on standard Applied Materials centerpoint recipes.

1.2 Data Summary

Table 1 illustrates the efficacy of the Litmas system in reducing the amount of global warming gases emitted from the etcher. As can be seen, the Litmas system consistently reduced emissions from the etcher by more than 97%, particularly when using water vapor as an additive gas. It has been shown for the first time that water vapor is at least as effective and less costly than using O_2 and/or H_2, which have previously been studied as possible additive gases.

Table 1 Emissions Reduction Summary

Abatement Test Description	Additive Gas Used	Reduction in Global Warming Emissions
Unprocessed Feed Gas	Oxygen	> 98%
Etch Exhaust	Oxygen	> 97%
Unprocessed Feed Gas	Water Vapor	> 99%
Etch Exhaust	Water Vapor	> 99%

Where: unprocessed feed gas = operation with tool plasma off
etch exhaust = operation with tool plasma on

1.3 Cost of Ownership

Litmas Inc. estimates the capital cost of the device to be approximately $15,000, assuming large volume orders. Based on the limited evaluation of the device at Motorola, the cost of ownership (COO) is on the order of $5000/year over a 5-year life.

1.4 Conclusions

The Litmas “Blue” POU plasma abatement system represents a promising technology for reducing PFC and HFC emissions from dielectric etch tools in the semiconductor industry. In particular, it has been shown that water vapor is effective as an additive gas for PFC abatement, resulting in less toxic byproducts than those generated when using oxygen. The Litmas system’s high PFC destruction efficiency, no detectable process impact, small footprint, and relatively low COO justifies a long-term trial of the system in a manufacturing environment.

While the initial “slipstream” evaluation was encouraging, unresolved issues with the device require a longer-term evaluation in a manufacturing environment. To evaluate the effect of reduced conductance, additive gas injection, and increased plasma-induced molar gas loads on foreline pressure, the device needs to be installed directly above the chamber roughing pump and integrated into the tool control software. Areas that need further evaluation are the effect of water injection on process performance; foreline degradation due to particulate generation; ISO-KF flange O-ring seal reliability due to exposure to plasma and elevated hydrofluoric acid (HF) levels; effects of particulates or corrosive species on dry pump performance; and device reliability over an extended period of consistent operation.

2 BACKGROUND

A current environmental concern in semiconductor manufacturing is the emission of PFCs and HFCs during plasma etching and plasma-assisted chamber cleaning processes in metal and dielectric film chemical vapor deposition (CVD) systems [1]. PFCs and HFCs have been identified as potential global warming gases because of their strong infrared (IR) absorption cross sections and long atmospheric lifetimes, which can be as long as 50,000 years for CF_4 [2–4]. Because of their potential long-term impact on the global climate, PFCs, HFCs, and SF_6 have been included in international efforts such as the Kyoto Protocol, which aims to significantly reduce the rate of global warming gas emissions into the atmosphere [5]. Within the U.S. semiconductor industry, efforts to reduce PFC emissions have followed the framework of a Memorandum of Understanding (MOU) signed with the U.S. Environmental Protection Agency (EPA) in the spring of 1996. The MOU represents a commitment from industry members to voluntarily reduce PFC emissions. Emissions reduction efforts have followed four primary strategies: 1) alternative chemistries, 2) process optimization, 3) capture/recycle, and 4) abatement. While process optimization and alternative chemistry strategies have resulted in significant progress for reducing emissions from CVD chamber clean processes, the stringent requirements of etch processes have limited their impact in this area [6].

A method for emissions reduction from etch tools that has recently shown promise for high destruction removal efficiencies (DREs) of PFCs and HFCs is the POU plasma abatement system [7, 8]. A POU plasma abatement system uses a small plasma source located in the foreline of an etch tool. A flow of additive reaction gas such as H_2, O_2, H_2O, or CH_4 is added upstream of the POU abatement plasma, which, when dissociated and combined with PFC and/or HFC radicals produced in the plasma, results in byproducts that can be removed using wet scrubbers.

Plasma abatement differs significantly from the more familiar thermal abatement methods (e.g., Edwards TPU, [9]) because it treats the exhaust stream before it is significantly diluted with nitrogen in the dry pump, resulting in significantly lower energy and resource consumption. In addition, treatment of the effluent stream before the dry pump greatly reduces the production of harmful thermal combustion byproducts such as NO and NO_2.

One of the first POU plasma abatement systems to enter the market specifically for PFCs is the Litmas “Blue.” Unlike other commercial plasma-based abatement devices, the Litmas device uses a high-density inductively-coupled source that generates intense plasmas with densities that have been estimated as high as 5.0×10^{12} cm^{-1} [10]. It is postulated that a high density plasma is necessary to effectively dissociate all of the PFC entering the device and to prevent downstream reformation.

A beta unit of the Litmas “Blue” has been successfully tested on the effluent of an Applied Materials Centura 5200 MxP+ medium density oxide etcher in the Advanced Products Research and Development Laboratory (APRDL) at Motorola in Austin, Texas. This report presents an initial performance evaluation of the Litmas system based on these experiments along with a preliminary analysis of the device’s expected cost of ownership.

3 EXPERIMENTAL

3.1 Litmas “Blue” POU Plasma Abatement System

3.1.1 System Specifications

The Litmas “Blue” is a high-density, inductively-coupled plasma source and integrated power supply that is designed to mount directly in the foreline of a process tool. The system specifications are as follows: (as supplied by Litmas):

Size:	35 cm x 31 cm x 14 cm; foreline tube 1.235” ID x 9” length
Weight:	23 kg
Power:	1200 W RF power in 75 W steps
Frequency:	1.8–2.0 MHz variable. Frequency is automatically adjusted to achieve the best load match
Vacuum Connections:	KF50
Tuning Time:	25 ms nominal, 100 ms maximum
Cooling Water:	Industrial cooling water (ICW), 5–35°C, 1 gpm, 100 psi max pressure
Ambient Air Temperature:	5–35°C operating, -40–90°C non-operational
Input Power:	90–130 V AC, 1800 watts or 188–253 V AC, 1800 watts Single phase plus ground Automatic line voltage selection
User Interface:	15-pin sub-D digital interface – allows full remote control of device –OR- 5-pin dip switch control on front panel

Display:	Row of 16 LEDs on front panel indicates the status of the system – Power ON – Interlock OK – Temperature OK – Plasma detect – RF ON – Setpoint OK – Power delivered (10 LEDs each representing 10% of max)

3.1.2 Tuning Mechanism

The Litmas plasma abatement system is based on an integrated, solid state power supply, match, and source. In a traditional RF plasma system, an external power supply is designed to deliver power to a standard 50 Ω RF cable. The matching network then matches the load of the source to the 50 Ω cable. This is generally accomplished through variable capacitors or variable inductors that often require unreliable mechanical tuning mechanisms and algorithms.

By contrast, the Litmas system has eliminated the intermediate RF cable, which allows the power supply to be designed specifically for the loads of the source plasma. Any mismatch between the power supply and the plasma source is handled using a bank of fixed capacitors and frequency tuning of the power supply. By eliminating the overhead associated with matching the power supply to the cable and then re-matching it to the source load, significant cost savings and reliability gains have been realized over traditional plasma sources.

3.1.3 Safety Features/Failure Analysis

Several safety features of the Litmas “Blue” deserve mention. First, the system has been designed for the Canadian Standards Association (CSA) electronics device compliance. (CSA compliance supercedes CE compliance.) Compliance has yet to be certified, but the process for certification is slated to begin during Fall 1998. Examples of CSA compliance include minimum clearances between high voltage components and case ground and installation of cooling water and input power receptacles on opposite faces of the unit. Several other safety features of the Litmas “Blue” include a user interlock to the 15 pin Sub-D user port, a temperature interlock that will turn the system off in case of cooling water failure and a circuit breaker that will trip in case of an internal short.

Litmas Inc. speculates that the most probable failure mechanisms for the Litmas “Blue” are dielectric tube failure and electrical failure within the power supply. Many of the power supply failure mechanisms have been addressed by adherence to CSA safety requirements. Because dielectric tube failure would expose the tool foreline to atmosphere, specific attention has been devoted to reduce the likelihood of this failure mode. A proprietary, doubly-contained cooling configuration has been developed that provides cooling to the entire length of the dielectric tube, thus preventing the large temperature gradients that would lead to dielectric tube failure. In addition, the double containment prevents any cooling fluid from being introduced to the foreline upon dielectric failure.

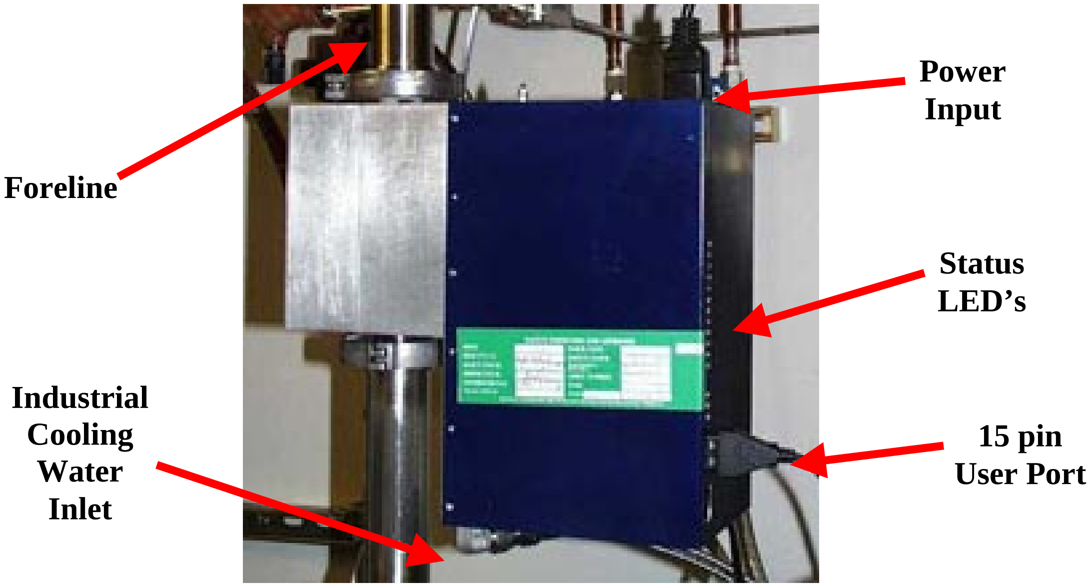


Figure 1 Litmas "Blue" POU Plasma Abatement Device

3.2 Installation

3.2.1 Abatement System Installation

For these experiments, the Litmas system was installed on a secondary foreline on an Applied Materials Centura 5200 MxP+ medium density oxide etcher located in APRDL. The secondary foreline was originally envisioned as a means of diverting a percentage of the tool effluent to the abatement system for testing while still protecting the tool in case of an abatement system failure. Preliminary experiments indicated that this method was not suitable for testing the Litmas system because changes in the pressure of the secondary foreline resulted in changes in the percentage of tool exhaust diverted to the abatement system. In all experiments, the primary foreline was completely isolated and all exhaust was diverted through the abatement system.

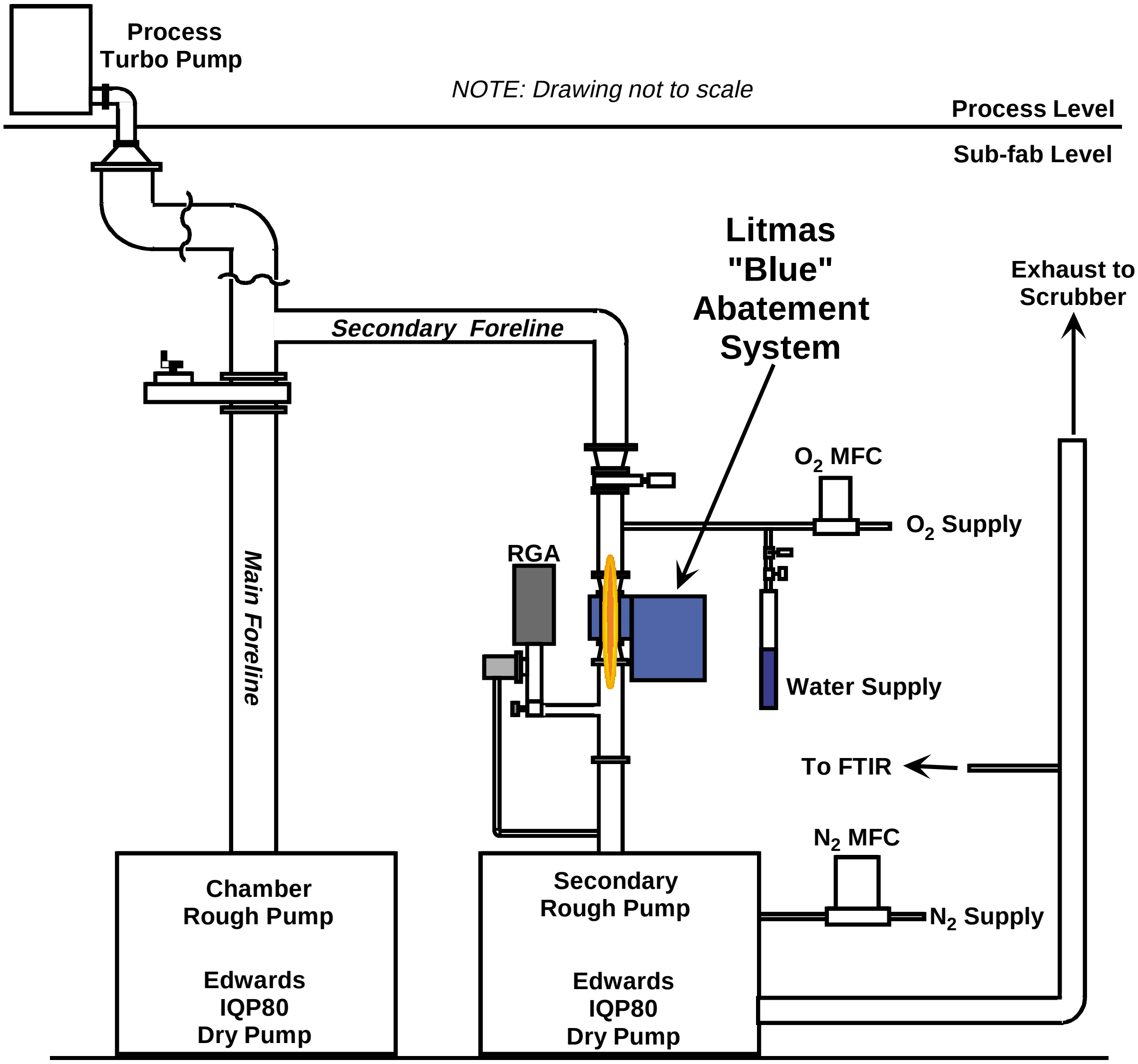


Figure 2 Abatement System Installation Schematic

3.2.2 Oxygen Addition System

Oxygen was added to the foreline by installing a 2000 sccm Unit Instruments model 1661 metal seal digital mass flow controller (MFC) on a line joining the foreline immediately upstream of the abatement system (see Figure 3). The MFC was controlled digitally using a laptop computer and RS232 serial interface.

3.2.3 Water Vapor Addition System

Besides using O_2 as an additive reaction gas, experiments were designed to investigate the use of water vapor as a suitable reaction gas. Since water has the advantage of low cost and ease of handling and is by itself a source of both oxygen and hydrogen, its use as an additive gas could provide significant cost savings over oxygen and/or hydrogen gas. A simple and inexpensive water delivery system was constructed that would tee into the pre-existing O_2 delivery line. This was done by suspending a small length (~ one foot) of 1-inch O.D. stainless steel tubing capped at the bottom by a ISO-KF25 blank. The tube was filled approximately two-thirds full with deionized (DI) water and capped at the top by a ISO-KF25 to 3/8-inch Swagelock reducing flange. Heating tape was wrapped along the length of the tube to maintain the water at a slightly elevated temperature (~ 40°C). A diaphragm shut-off valve and a metering valve (Nupro model SS-MGVR4-MH) controlled the flow of water vapor into the foreline. To prevent condensation, heating tape was placed along the entire length of the delivery line from the water container to the foreline junction. The temperature of the line was maintained between 60°C and 90°C.

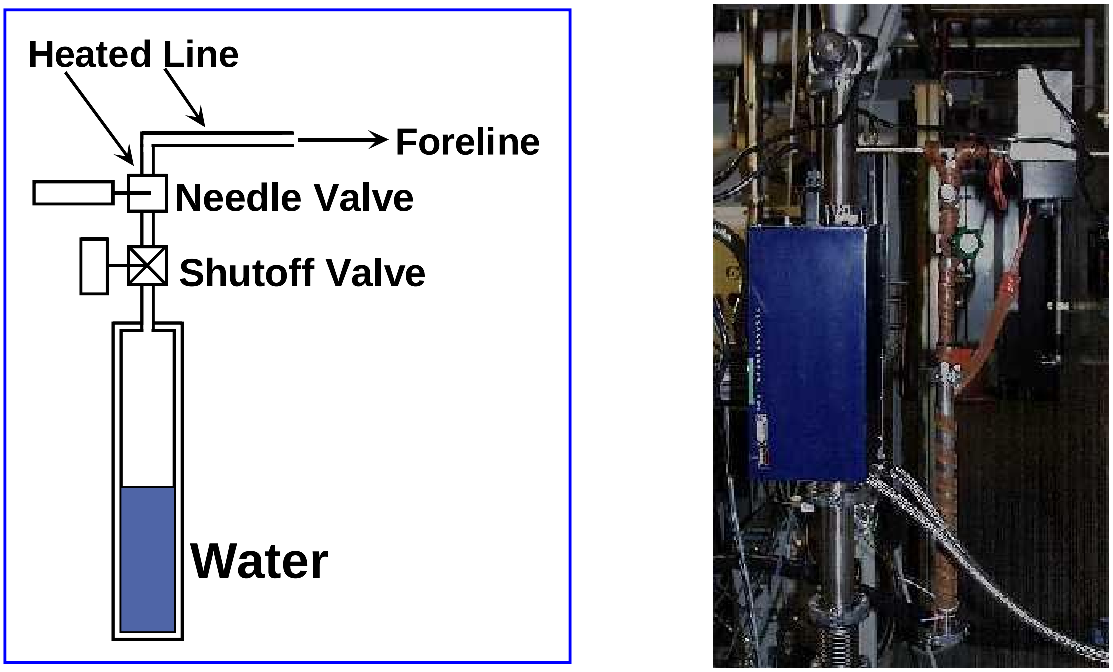


Figure 3 Additive Gas Delivery System

3.2.4 Foreline Pump N_2 Purge Control

To allow quantitative conversion of byproduct concentrations in the post-pump exhaust to fluxes through the foreline, the N_2 purge to the roughing pump was controlled by a 50 slm Tylan 2920 MFC. For all experiments, the exhaust N_2 purge was set at a constant 45 slm.

3.3 Diagnostics

3.3.1 Midac I2000 FTIR

The primary diagnostic used for these experiments was a Midac I2000 FTIR with ZnSe optics, a 10 cm stainless steel gas cell, and liquid N_2-cooled mercury cadmium telluride (MCT) detector. The exhaust gas was sampled downstream of the secondary roughing pump and drawn through a 25-ft. heated PTFE- grade Teflon sampling line maintained at 121°C. The elevated temperature reduced adsorption of species such as HF and H_2O onto the sampling line. Downstream of the line, the sample entered the FTIR cell, which was also maintained at 121°C. The sample was pumped through the cell at approximately 5 slm, past a pressure control valve, and into a separate house acid gas exhaust line using a small diaphragm pump. For all experiments, the pressure in the FTIR cell was maintained at 600 Torr, which ensured a steady, high rate of flow from the sampling line.

For all data points collected, the FTIR was operated at a resolution of 0.5 $cm^{-1}$with four scan signal averaging. Under these settings, the FTIR was able to obtain spectra approximately every seven seconds. Background spectra were collected about every two hours or as necessary to maintain a linear baseline in the absorbance spectrum.

Data was analyzed using Midac AutoQuant 3.0, a program that calculates gas concentrations from FTIR spectra given a set of reference spectra for each species. Using a multi-point regression routine, a sample spectrum is analyzed to determine the best fit of a linear combination of reference spectra. A comparison of the scaling factor used to fit each of the sample spectra with the concentrations of the reference spectra allows the species' concentrations within the gas stream to be calculated.

Reference spectra using GRAMS 32 Version 4.0 (Galactic Industries Corp.) were generated using a dynamic dilution system and certified gas standards. Up to nine separate references were generated, which spanned three orders of concentration magnitude from 0.01% to 1%. Non-linearities and saturation effects in the references were accounted for within the non-linear AutoQuant regression routines.

The Midac I2000 FTIR with 10 cm path length cell and MCT detector is capable of maintaining linear responses up to approximately 300 ppm (0.03%) for CF_4. Calculations shown in Appendix A indicate a limit of detection of approximately 1.91 ppm for a minimum S/N of 3-1. Thus, a 98–99% DRE is measurable for an initial CF_4 concentration of 100–200 ppm.

3.3.2 MKS PPT 300 AMU Open Source RGA (QMS)

In addition to FTIR, a MKS PPT 300 AMU residual gas analyzer (RGA) was also used as a diagnostic. The RGA was installed directly on the secondary foreline immediately downstream of the abatement system. Using a small turbo-molecular pump, samples were extracted through a needle valve into the RGA itself.

Since the RGA could not be calibrated for fluorine in Motorola's sub-fab, quantitative determinations of foreline flows could not be made. The tool, however, was useful for observing the presence of F_2 in the exhaust of the abatement device.

3.4 Experimental Design

Two main types of abatement experiments were conducted: additive oxygen and additive water vapor. Each of the experiments had a similar structure and execution with only a few minor differences.

3.4.1 Abatement using Oxygen as Additive Gas

Preliminary experiments were conducted to determine the optimum oxygen flow for maximum abatement efficiency in subsequent experiments. By flowing a mix of gases that would be representative of the majority of the experiments conducted and operating the abatement system at near-maximum power, the optimum oxygen flow was found to be on the order of 70–90 sccm. This represents an O_2/PFC ratio of approximately 1.27–1.63. Because of pumping limitations, the lower end of this optimum was chosen to avoid foreline overpressure. For all subsequent experiments, the O_2 flow was maintained at a constant 70 sccm.

Using a standard Applied Materials centerpoint recipe, a set of experiments was designed to explore the effect of the following parameters on abatement performance: etch tool source power, chamber pressure, magnetic field, abatement input power, input gas composition, and gas flow. From these parameters, a 17-point experiment was devised that would investigate these effects. During each run, a series of abatement input powers were applied to both the unprocessed (feed flow experiments) and processed (etch exhaust experiments) gas flows.

Table 2 Experimental Design Matrix

Run #	Etch Power (W)	Etch Pressure (mTorr)	B Field (Gauss)	CHF_3 Flow (sccm)	CF_4 Flow (sccm)	Ar Flow (sccm)
1	1000	200	15	40	4	50
2	1000	200	15	60	6	70
3	1000	200	45	40	6	70
4	1000	200	45	60	4	50
5	1000	250	15	40	6	50
6	1000	250	15	60	4	70
7	1000	250	45	40	4	70
8	1000	250	45	60	6	50
9	1153	200	15	40	4	70
10	1153	200	15	60	6	50
11	1153	200	45	40	6	50
12	1153	200	45	60	4	70
13	1153	250	15	40	6	70
14	1153	250	15	60	4	50
15	1153	200	45	40	4	50
16	1153	250	45	60	6	70
17	1100	225	30	50	5	60

3.4.2 Abatement Using Water Vapor as Additive Gas

Several preliminary experiments were conducted to determine both the magnitudes of flows necessary to achieve high DREs and the optimum methods for delivery of water vapor into the foreline. Water is generally difficult to introduce to vacuum systems because of its low vapor pressure at room temperature and because it is a very strong adsorber on vacuum chamber walls. A simple water delivery system (described in Section 3.2.3) was constructed for these experiments, which allowed for control of water vapor delivery into the system. Because an MFC or mass flow meter (MFM) was not available, the absolute flows of water vapor into the system were not quantifiable at the time of experimental data acquisition.

Early experiments using water indicated that, in general, the higher the water vapor flow, the better the abatement efficiency. Therefore, the water vapor flow was set such that abatement efficiency was maximized while still keeping foreline pressure under 1.0 Torr. Post-experiment analysis of the FTIR spectra showed that for all water vapor-based abatement experiments, the flow was approximately 250 sccm.

It was observed throughout the course of the oxygen abatement experiments that the performance of the abatement system was insensitive to the etch parameters. Therefore, a set of simplified experiments was devised that eliminated etch parameters such as source power, magnetic field strength, and chamber pressure as variables. What remained was a set of nine experiments that explored the effects of input power and feed gas composition on destruction efficiency. Once again, abatement efficiency was determined for both processed etch exhaust and unprocessed feed gas flows.

3.4.3 Process Impact Experiments

Two experiments were conducted to verify that there were no negative impacts on etch process performance as a result of the installation and operation of the abatement system. Using the standard chamber qualifying recipes for TEOS and Si_3N_4, patterned wafers were etched both before the abatement system was installed and during its operation. Etch rates and etch uniformity across the wafer were compared with baseline measures to determine if the abatement system induced any process shifts. Particle counts were compared to baseline performance by etching bare silicon wafers during abatement system operation.

4 RESULTS

Sections 4.1 through 4.3 report the effectiveness of the Litmas system in destroying CHF_3 and CF_4. All destruction efficiencies are calculated on the basis of the flow of PFCs to the abatement system, which is not necessarily the feed rates of PFC to the etch chamber. In addition to maximum destruction efficiencies of both CHF_3 and CF_4, the net reduction in global warming emissions has been calculated on the basis of gCE, a unit that normalizes the global warming impact of a gas to that of CO_2 over a 100-year period. PFC flows are converted to grams of carbon equivalent using Eq. [1] (calculation of global warming emissions).

$$gCE = \sum_{PFCs} (F_{PFC})(4.46x10^{-5})(M.W._{PFC})\left(12/44\right)(GWP_{100,PFC}) \qquad \textbf{Eq. [1]}$$

Where:

F_{PFC} = Flow of PFC in sccm

4.46 x 10^{-5} = moles/sccm (conversion factor)

12/44 = carbon atomic weight to CO_2 molecular weight conversion

$M.W._{PFC}$ = molecular weight of PFC molecule in g/mol

$GWP_{100,PFC}$ = Global Warming Potential of PFC (100 year time horizon)

Table 3 summarizes the GWP_{100} values for various PFCs and HFCs used in the semiconductor industry [4].

Table 3 Global Warming Potentials (GWP's) of PFCs and HFCs Used in the Semiconductor Industry (100 year time horizon)

PFC/HFC	GWP100
CF_4	6,300
CHF_3	12,100
CH_2F_2	580
C_2F_6	12,500
C_4F_8	9,100
SF_6	24,900

4.1 Abatement Using Oxygen as Additive Gas

4.1.1 Feed Flow Experiments (O_2 Additive)

Table 4 and Figure 4 report the results of abatement of unprocessed PFC gases using O_2 as an additive gas. In these experiments with etch plasma off, process gases flowed directly to the abatement device. Because gas is not consumed in the etch chamber, the PFC load is higher in these experiments than in the subsequent etch exhaust abatement experiments.

Table 4 Maximum DREs of PFCs Using O_2 (unprocessed gas flows)

Run #	CHF_3 Flow (sccm)	CF_4 Flow (sccm)	Ar Flow (sccm)	CF_4 DRE (max)	CHF_3 DRE (max)
1	40	4	50	92%	~ 100%
2	60	6	70	88%	~ 100%
3	40	6	70	94%	~ 100%
4	60	4	50	85%	~ 100%
5	40	6	50	94%	~ 100%
6	60	4	70	85%	~ 100%
7	40	4	70	93%	~ 100%
8	60	6	50	89%	~ 100%
9	50	5	60	91%	~ 100%

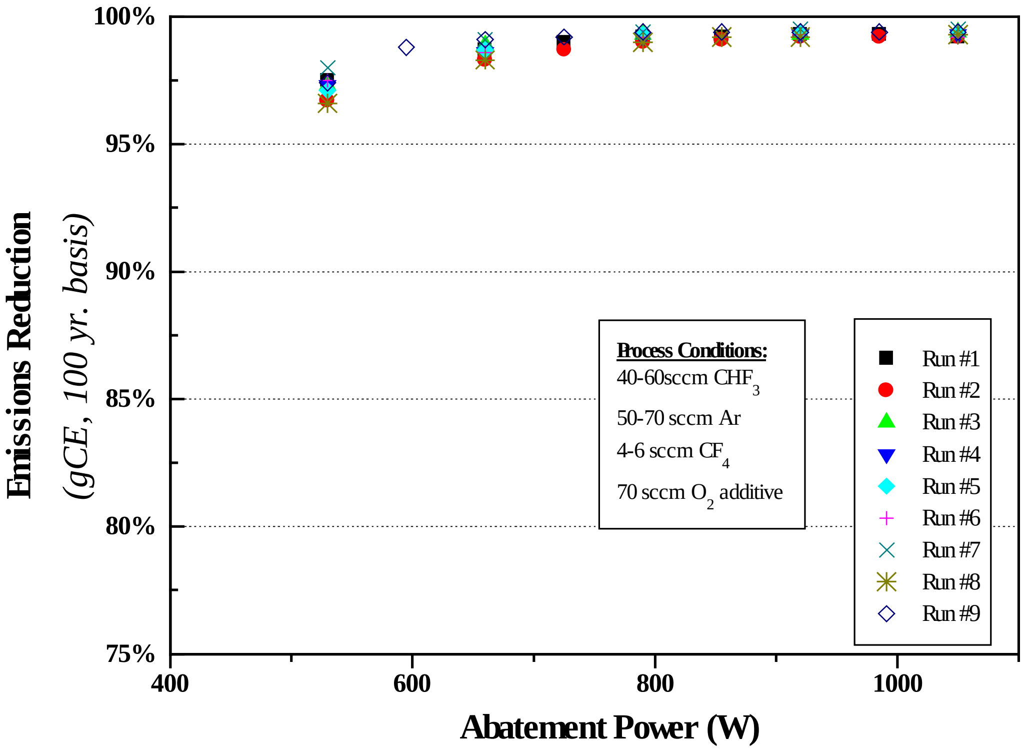


Figure 4 Net PFC Emissions Reduction Using O_2 (etch plasma off, unprocessed gas flow)

4.1.2 Etch Experiments (with O_2)

Table 5 and Figure 5 report the results of abatement of processed PFC gases (etch plasma on) using O_2 as an additive gas. In these experiments, the etch pressure, etch power, etch pressure, and magnetic field were varied according to the 17-point experimental matrix (see Table 2).

Table 5 Maximum DREs of PFCs Using O_2 (during etching)

Run #	Etch Power (W)	Etch Pressure (mTorr)	B Field (Gauss)	CHF_3 Flow (sccm)	CF_4 Flow (sccm)	Ar Flow (sccm)	CF_4 DRE (max)	CHF_3 DRE (sccm)
1	1000	200	15	40	4	50	97%	~ 100%
2	1000	200	15	60	6	70	93%	~ 100%
3	1000	200	45	40	6	70	96%	~ 100%
4	1000	200	45	60	4	50	94%	~ 100%
5	1000	250	15	40	6	50	97%	~ 100%
6	1000	250	15	60	4	70	95%	~ 100%
7	1000	250	45	40	4	70	97%	~ 100%
8	1000	250	45	60	6	50	93%	~ 100%
9	1153	200	15	40	4	70	97%	~ 100%
10	1153	200	15	60	6	50	93%	~ 100%
11	1153	200	45	40	6	50	97%	~ 100%
12	1153	200	45	60	4	70	95%	~ 100%
13	1153	250	15	40	6	70	97%	~ 100%
14	1153	250	15	60	4	50	95%	~ 100%
15	1153	200	45	40	4	50	*	*
16	1153	250	45	60	6	70	95%	~ 100%
17	1100	225	30	50	5	60	96%	~ 100%

* Because of etch tool RF matching difficulties, this data point was not completed.

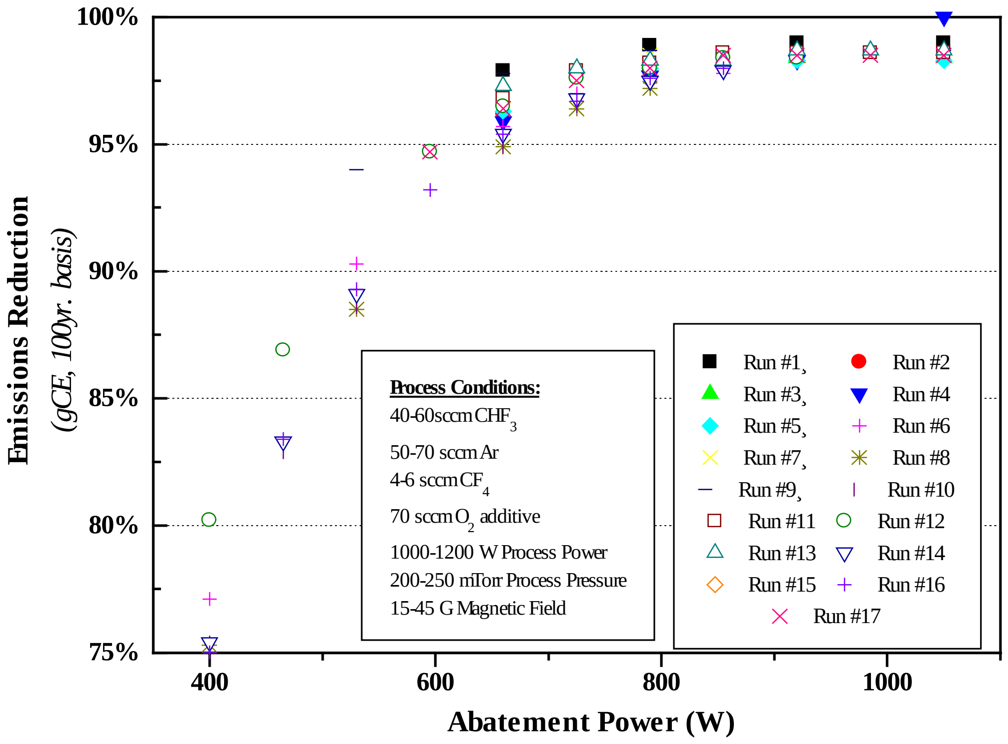


Figure 5 **Net PFC Emissions Reduction Using O_2 (etch plasma on)**

4.1.3 Byproduct Distributions and Mass Balance Results

As a check of the consistency of the FTIR results, carbon and fluorine mass balances were verified to account for all of the gas species fed to the chamber. During process flow experiments with the etch plasma off, the carbon mass balance (carbon out/carbon in * 100%) closed to within 5% for all experiments. This was not the case for the etch plasma-on experiments in which only about 60–70% of the carbon fed to the chamber was accounted for within the exhaust. It is believed that this absent carbon can be accounted for in the form of chamber wall deposits.

Because atomic and molecular fluorine is not detectable with FTIR techniques, the fluorine mass balance is more difficult to close. For both etch exhaust and process flow experiments, approximately 50–60% of the fluorine was accounted for. The missing fluorine is believed to be present in the etch tool chamber wall deposits, molecular fluorine, and HF, which is more difficult to quantify by FTIR at 121°C because of surface adsorption.

Using O_2 as an additive gas resulted in primarily CO_2, COF_2, F_2, and HF as abatement byproducts. The presence of F_2, which is undetectable to the FTIR, was verified using the RGA; however, it was not quantified. In addition, small amounts of NO_2 were also produced in the system because of the presence of N_2, which is used in small quantities as a turbomolecular pump purge gas. An example FTIR spectrum (for O_2 DOE Run #5) showing this byproduct distribution appears in Figure 6.

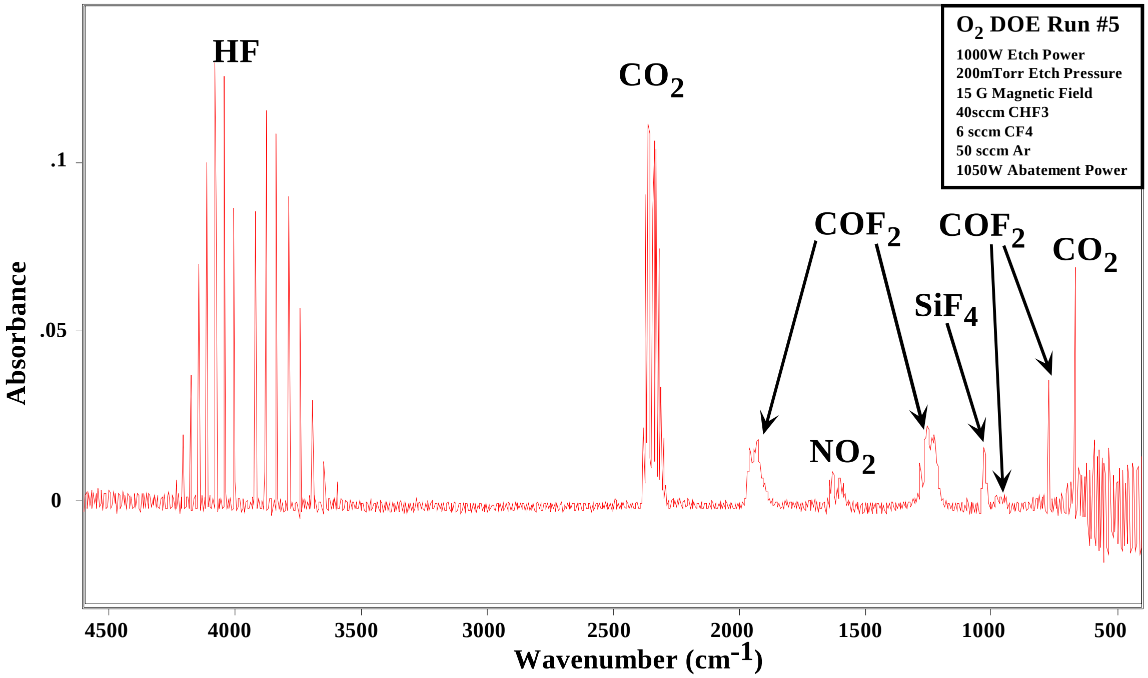
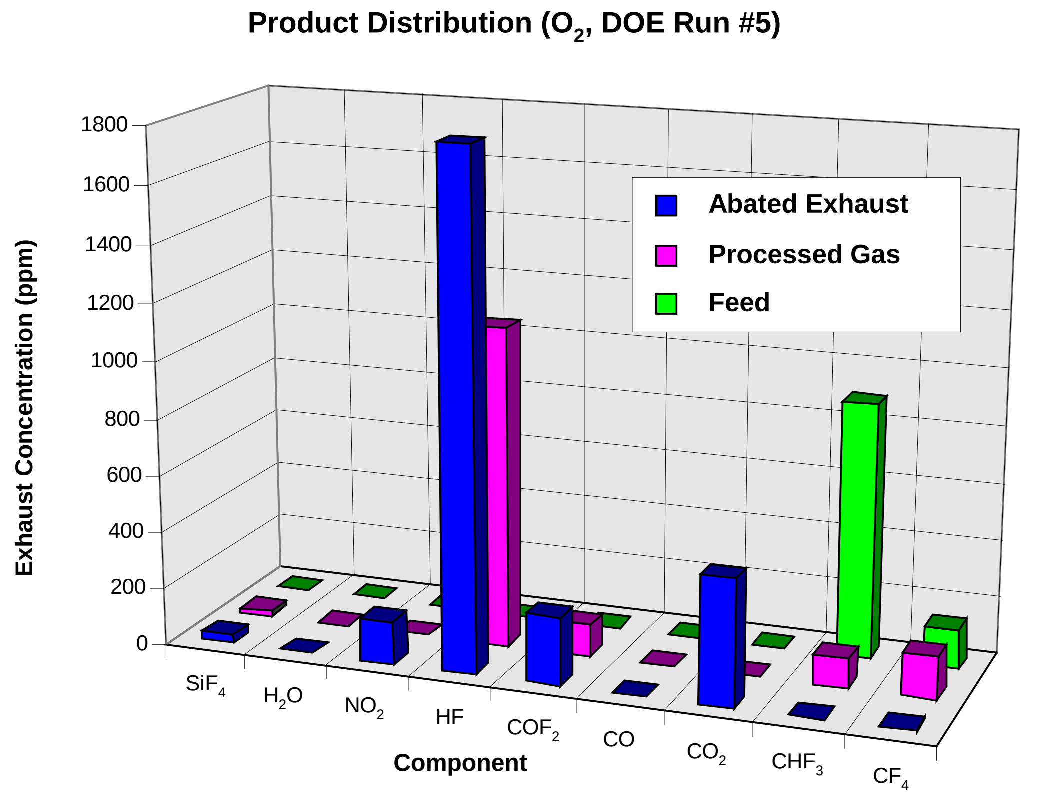


Figure 6 **Example FTIR Spectrum for PFC Abatement Using O_2**

Figure 7 represents the byproduct distribution for a representative experiment (O_2 DOE Run #5, conditions are given in the figure). It tracks the composition of the gas as it enters the chamber, is used by the etch tool, and is abated by the Litmas device. While the particular byproduct concentrations varied from run to run depending on the feed gas composition and etch tool parameters, the general distribution was consistent. HF, CO_2, COF_2, and F_2 are the primary byproducts of abating PFCs with O_2 as the additive gas.



	SiF_4	H_2O	NO_2	HF	COF_2	CO	CO_2	CHF_3	CF_4
🟦 Abated Exhaust	29	0	148	1792	238	0	440	0	5
🟪 Processed Gas	16	0	0	1121	110	0	5	106	149
🟩 Feed	0	0	0	0	0	0	0	891	138

Figure 7 Byproduct Distribution for Abatement Using O_2

4.2 Abatement Using Water Vapor as Additive Gas

4.2.1 Feed Flow Experiments (H_2O Vapor Addition)

Table 6 and Figure 8 report the results of abatement of unprocessed PFC gases using water vapor as an additive gas. In these experiments with etch plasma off, process gases flowed directly to the abatement device.

Table 6 Maximum DREs of PFCs Using H_2O Vapor (unprocessed gas flows)

Run #	CHF_3 Flow (sccm)	CF_4 Flow (sccm)	Ar Flow (sccm)	CF_4 DRE (max)	CHF_3 DRE (max)
1	40	4	50	99%	~ 100%
2	60	6	70	98%	~ 100%
3	40	6	70	99%	~ 100%
4	60	4	50	97%	~ 100%
5	40	6	50	99%	~ 100%
6	60	4	70	98%	~ 100%
7	40	4	70	99%	~ 100%
8	60	6	50	97%	~ 100%
9	50	5	60	97%	~ 100%

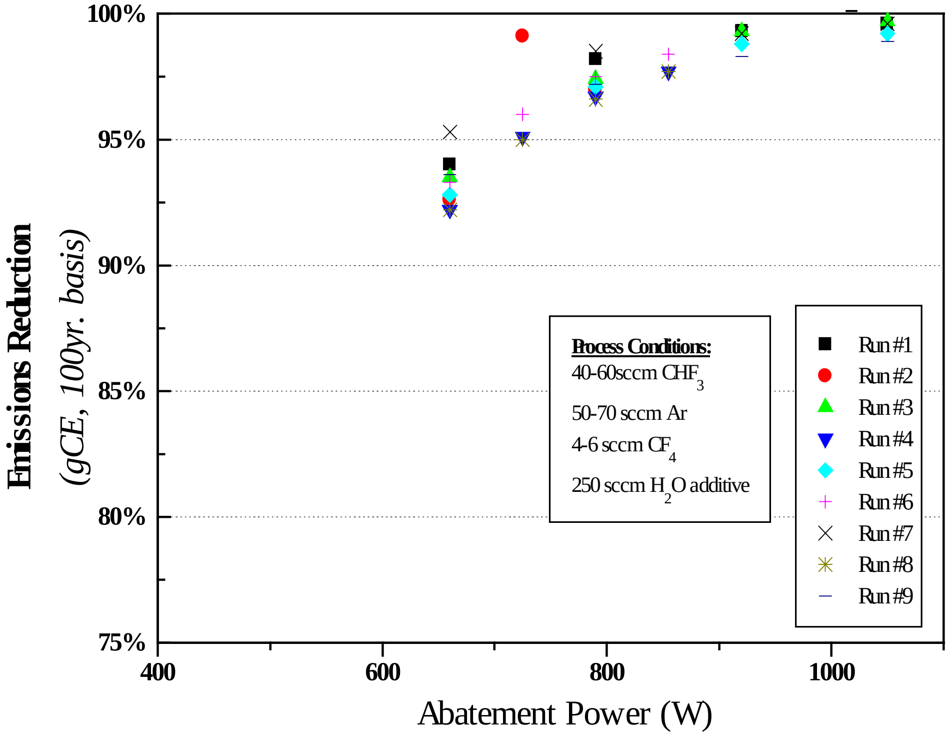


Figure 8 Net PFC Emissions Reduction Using H_2O Vapor (unprocessed gas flows)

4.2.2 Etch Experiments (with H_2O Vapor)

Table 7 and Figure 9 report the results of abatement of etch exhaust using water vapor as an additive gas. The etch tool pressure, power, and magnetic field were held constant in these experiments at the Run #17 centerpoint values while the composition of the feed gas was varied according to a nine-point factorial matrix.

Table 7 Maximum DREs of PFCs Using H_2O Vapor (during etching)

Run #	Etch Power (W)	Etch Pressure (mTorr)	B Field (Gauss)	CHF_3 Flow (sccm)	CF_4 Flow (sccm)	Ar Flow (sccm)	CF_4 DRE (max)	CHF_3 DRE (sccm)
1	1100	225	30	40	4	50	99%	~ 100%
2	1100	225	30	60	6	70	~ 100%	99%
3	1100	225	30	40	6	70	99%	~ 100%
4	1100	225	30	60	4	50	96%	99%
5	1100	225	30	40	6	50	99%	99%
6	1100	225	30	60	4	70	96%	~ 100%
7	1100	225	30	40	4	70	99%	~ 100%
8	1100	225	30	60	6	50	96%	99%
9	1100	225	30	50	5	60	99%	99%

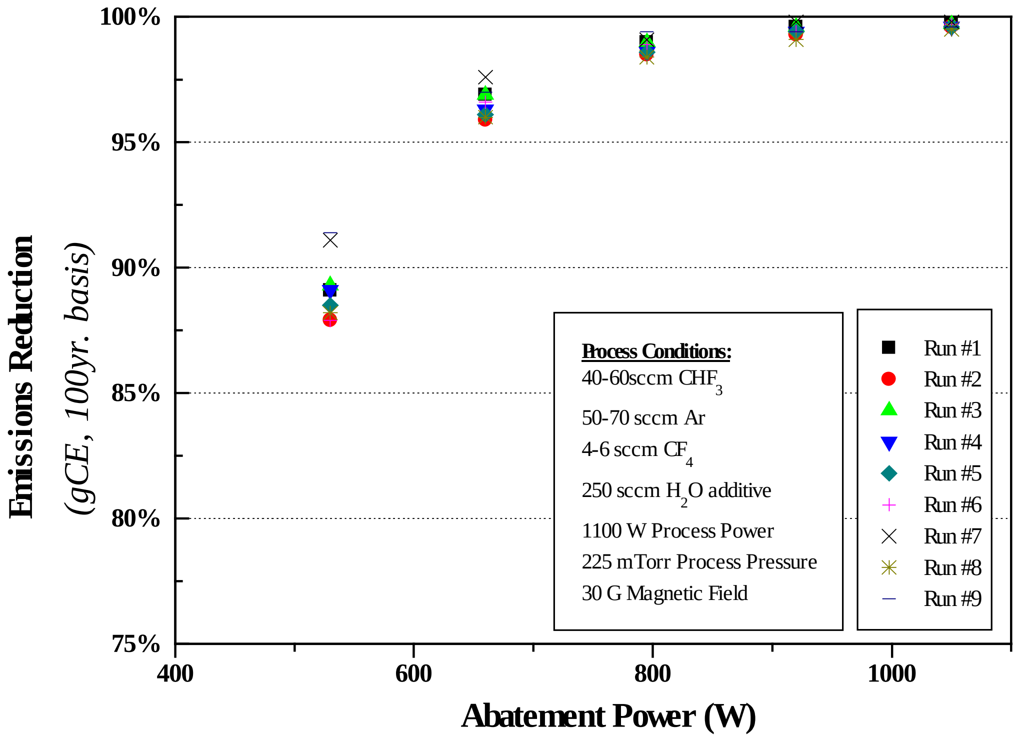


Figure 9 Net PFC Emissions Reduction Using H_2O Vapor (etch plasma on)

4.2.3 Byproduct Distribution and Mass Balance Results

Carbon and fluorine mass balances were also determined for water vapor addition experiments. Carbon balances closed to within 10% for flow experiments, but again fell short for etch exhaust experiments at about 70–80% of total. The 10% discrepancy in carbon mass balance numbers between O_2-based and H_2O-based etch experiments is not understood; however, it is believed that etch tool chamber wall deposition is again responsible for the closure shortfall.

The fluorine mass balance for the H_2O-based experiments reflects the absence of F_2 as an abatement byproduct (as indicated in the RGA data) with measured values actually exceeding input values by approximately 20%. It is thought that this discrepancy may be because of fluorine extraction from the surface of the foreline downstream of the abatement system.

Using water vapor as an abatement gas resulted in a significantly different byproduct distribution compared to oxygen as an additive gas because of the greater availability of hydrogen radicals and the reduced availability of oxygen radicals that participate in the reactions. The primary byproducts included HF, CO, and CO_2, with no evidence of significant COF_2 or F_2 formation (as indicated in the RGA spectra). An FTIR spectrum illustrating this distribution is shown in Figure 10.

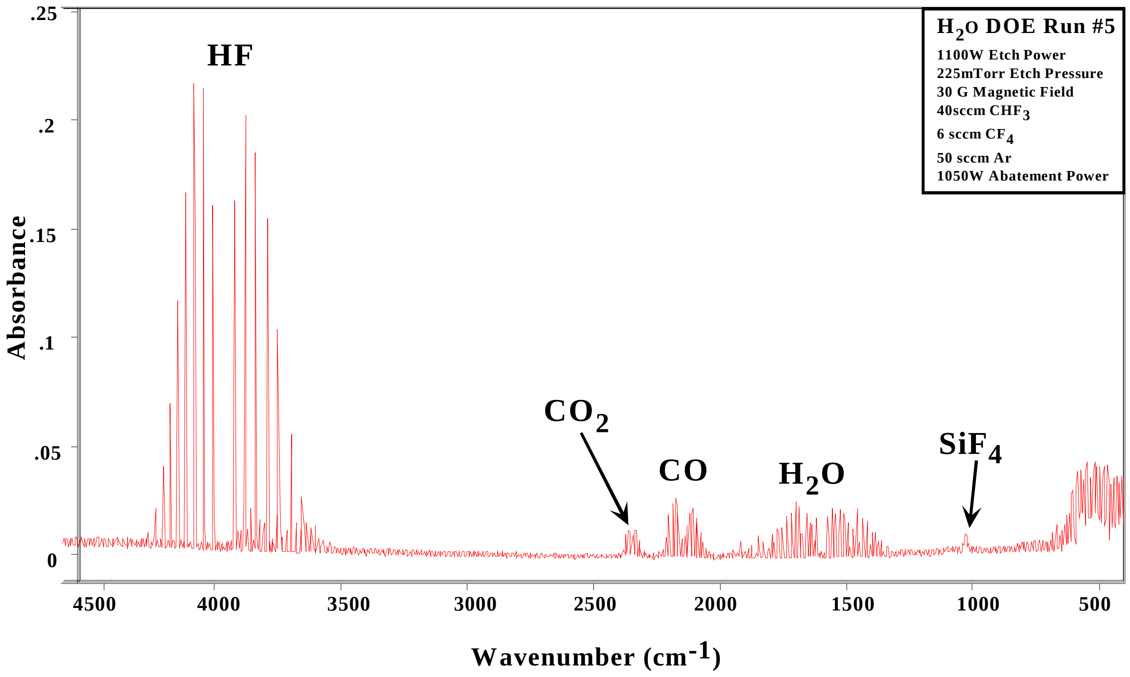
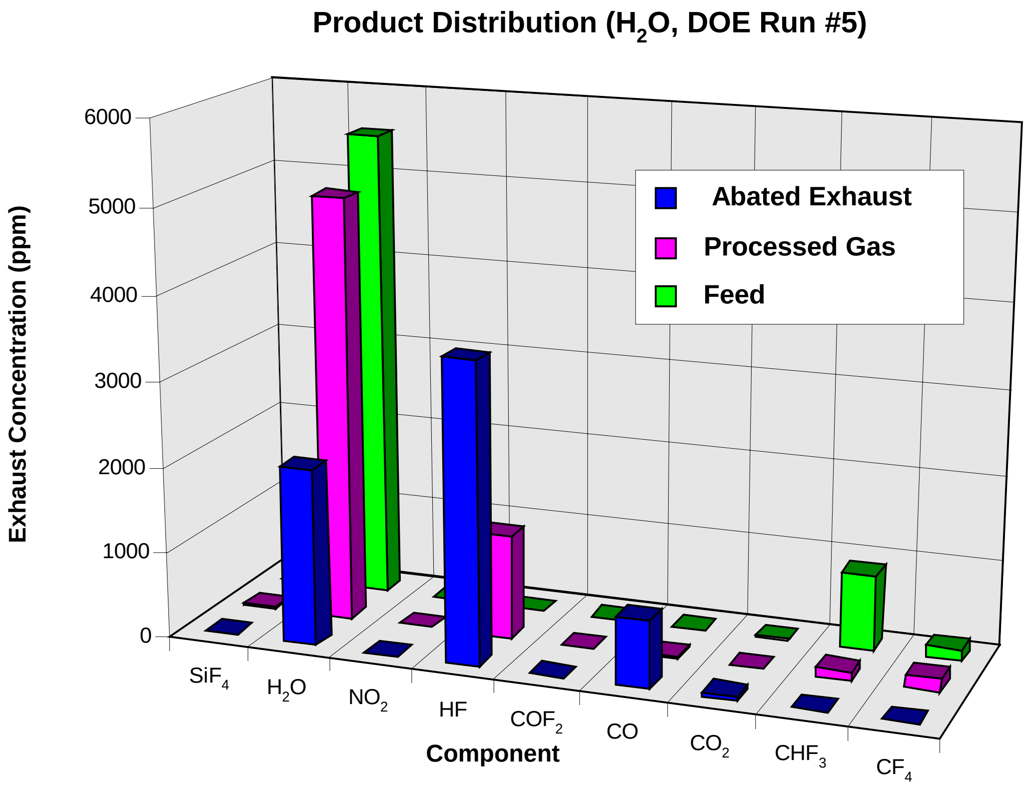


Figure 10 Example FTIR Spectrum for PFC Abatement Using H_2O Vapor

The significant differences in byproduct distribution when using water vapor are illustrated in Figure 11, which follows the composition of the gas stream as it is feeds into the chamber, leaves the chamber, and exits the abatement system. As can be seen, the primary byproducts for water vapor-based abatement are CO and HF with no evidence of the formation of F_2, COF_2, or NO_2. Carbon dioxide (CO_2) is also produced as a minor byproduct, but represents only a few percent of the distribution.



	SiF_4	H_2O	NO_2	HF	COF_2	CO	CO_2	CHF_3	CF_4
🟦 Abated Exhaust	10	2077	0	3521	0	787	48	1	1
🟪 Processed Gas	14	4985	0	1224	0	28	9	103	143
🟩 Feed	0	5518	0	0	0	0	10	894	140

Figure 11 Byproduct Distribution for Abatement Using H_2O Vapor

4.3 Process Impact Experiments

Table 8 presents the results of the experiments dedicated to determining possible etch process impacts resulting from the abatement system. These experiments consisted of comparing the metrics of etched patterned TEOS and Si_3N_4 wafers before the abatement system was installed (primary foreline in use) and with it running. In addition, particles were counted on a pair of bare silicon wafers etched with and without the abatement system running.

Table 8 Process Impact Results

Wafer	Abatement Status	Normalized Etch Rate	Particle Count
TEOS	Off	1.0000	N/A
	On	0.9969	N/A
Si_3N_4	Off	1.0000	N/A
	On	0.984	N/A
Bare Si	Off	N/A	70*
	On	N/A	8

*Particle count somewhat high because of previous chamber inactivity.
Note: N/A denotes that no measurement was taken for the given metric.

The etch rates observed for both TEOS etch and Si_3N_4 patterned wafers indicated no statistically significant shift because of the addition of the abatement system to the etch tool foreline. Particle measurements obtained from bare silicon wafers showed no significant increase in contamination because of the abatement device.

4.4 Uncertainty of Measurements

It is estimated that uncertainties in PFC destruction efficiency measurements are quite low (on the order of ± 1% DRE) because mass balance calculations indicate that measured levels of unprocessed and unabated PFCs in the pump exhaust agree with PFC feed gas flows into the chamber by the tool MFCs. Uncertainties of byproduct species will be somewhat higher because of lower infrared absorption cross sections, narrowed spectral features, higher likelihood of adsorption onto extraction line surfaces (especially with H_2O and HF), and greater likelihood of chemical reactivity.

5 DISCUSSION OF EXPERIMENTAL RESULTS

The Litmas “Blue” abatement system was effective at abating both CHF_3 and CF_4 from etch processes using either O_2 or H_2O vapor as additive gases. Both abatement chemistries resulted in greater than 97% reductions in global warming gas emissions at maximum applied abatement power.

Each experiment in which the effect of input abatement power was examined resulted in approximately the same saturation behavior with power. Most experiments indicated significant gains in abatement efficiency at lower applied RF power (400–700 W) with diminished returns at higher input powers (700–1050 W).

Another important aspect of the data is that over the conditions tested, changing input conditions from the etch tool had only a small effect on the performance of the abatement system. Remarkably, the abatement efficiency for etch tool exhaust and for process feed flow experiments was very similar even though the PFC load on the abatement system was quite different. Feed flow experiments placed a PFC load on the abatement system that was up to five times the load placed upon the system during etching because of the use of PFCs within the tool. This result suggests that abatement with the Litmas “Blue” at high efficiencies may be possible at significantly higher PFC flow rates than those used in these studies.

Although O_2-based abatement and H_2O-based abatement resulted in similar overall reductions in global warming emissions, the associated abatement mechanisms and byproducts varied significantly.

As can be seen by comparing Figure 7 and Figure 11, O_2 abatement results in highly oxidized byproducts such as CO_2, COF_2, and NO_2 while H_2O abatement results in less-oxidized byproducts such as CO and HF. It is believed that the significant presence of fluorine-scavenging H atoms within the water-based abatement plasma explains why so little CF_4 is formed and so much HF produced in these experiments. (The preferential formation of HF can be attributed to the high bond strength of the H-F bond, which is on the order of 5.7eV, while the C-F bond strength in CF_4 is approximately 5.0 eV.) Likewise, the lower concentration of H atoms in O_2-based abatement plasmas results in higher CF_4 reformation rates, but better DREs for CHF_3.

A trend that is less clear but may have important implications is the impact of Ar dilution on the abatement efficiency of the device. As can be seen in Figure 12, the average emissions savings tend to increase with argon (Ar) dilution ratio. While this effect is coupled somewhat to the total load of PFCs sent to the abatement system, it does still appear that the smaller expected residence time because of the Ar dilution is offset by the added plasma density gains induced by the shift to a more electropositive gas mixture.

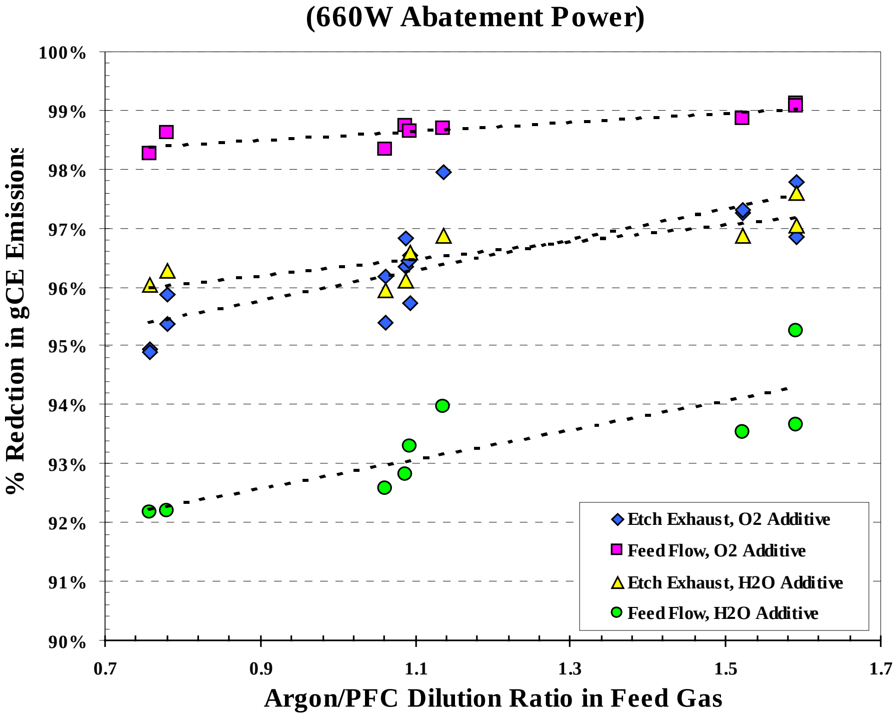


Figure 12 Effect of Argon Dilution on Abatement Efficiency

The relative transparency of the abatement device to the process itself was not surprising because of the long foreline and large turbo-molecular pump between the abatement device and the processing chamber. For any species to back-diffuse into the chamber and induce a process shift, the Peclet number ((Pe) = ratio of convective transport rate to diffusive transport rate) would need to be on the order of one. For conditions encountered in a typical foreline (200 mTorr, 4” diameter, 40’ length, 298 K, 200 sccm flow), the actual Peclet number has been estimated on the order of $3x10^4$ (see Appendix C). This is obviously much higher than one and indicates a strictly convective flow that will prevent any back diffusion of abatement byproducts to the process chamber.

6 COST OF OWNERSHIP ESTIMATE

Cost of installation and ownership of the Litmas "Blue" abatement system is roughly estimated based on the experience of recent experiments and estimates provided by maintenance and facilities personnel at Motorola. Cost can be divided into fixed capital and installation, operating, and maintenance costs.

6.1 Fixed Costs

6.1.1 Capital Cost

The initial capital cost of the Litmas "Blue" will be somewhat variable, with the final price dependent upon the size of the order, optional equipment, and other factors. A single device purchase will likely be approximately $25,000 with significant discounts for larger orders. Litmas has set a target, high volume price of $15,000 per unit once production capacity ramps. One such device would be required for each chamber of an etch tool, assuming they all required PFC abatement.

6.1.2 Installation Costs

Installation costs will be somewhat variable depending on the particular installation circumstances. On all systems, installation will require the following:

- Power Input (1 phase, 90–230 V, 1800 V-Amps)
- ICW (1 gpm)
- Foreline modification to accept the abatement unit

Rough estimates from facilities indicate installation will likely cost $5,000–$8,000 per unit depending upon foreline and utility accessibility within the sub-fab.

In addition, a means of introducing water vapor or oxygen to the foreline will be necessary. Because the recent experiments with water have been successful, Litmas is considering integrating a water delivery system with the abatement system in future models. However, current models do not include this option. Depending on the desired control of flow, water delivery may cost as little as $300 per unit or as much as $6,000 per unit (for a liquid delivery MFC). If O_2 is used as an abatement gas, the installation of an O_2 MFC and delivery line could add as much as $3,000 per system to the already indicated per unit installation cost.

6.2 Operating Costs

6.2.1 Direct Utility Costs

The small power and water requirements of the Litmas "Blue" mean that operating costs are low compared to capital and installation costs.

Power ($0.05/kWh × 1.2kW) = **$0.06/hour** (operating time)

Industrial Cooling Water (1 gpm × $0.0065/gal) = **$0.39/hour** (operating time)

Oxygen (if used) (00247cfm (70 sccm) × $0.0045/cf) = **$0.00067/hour** (operating time)

Water Delivery System Heaters (if water is used) ($0.05/kWh × 0.1 kW) = **$0.005/hour** (total time)

Given a hypothetical etch time/tool of 650 hours/year and automatic software control of the abatement device, the total utility costs per abatement unit are approximately $296, which is significantly lower than capital and installation costs. This cost could be reduced yet further by using cooling water that has been used by the dry roughing pumps.

6.2.2 Maintenance/Consumables Costs

Because marathon trials of the Litmas system have yet to be conducted, maintenance costs are difficult to estimate. The system itself has no scheduled maintenance requirements or consumables and is designed for long-term, maintenance-free operation[1]. Long-term trials are necessary to determine the reliability of production units.

Periodic maintenance may be required for a water delivery system if it is designed for batch delivery. Given a 1 gallon water reservoir and 250 sccm (0.2 g/min) H_2O additive flow, refills of the system may be necessary every 315 operation hours (~ six months assuming 650 hours/year etch tool use). For the sake of cost calculations, assume 2 hours of maintenance per year at $40/hour for water delivery system fills. This results in approximately $80/year in maintenance costs.

6.2.3 Labor Costs

Because the Litmas system is designed to be controlled by the etch tool itself, no direct labor costs are incurred during normal operation.

6.3 Preliminary Cost of Ownership Analysis

Although the unit was not evaluated long enough to determine typical cost of ownership (COO) parameters, a preliminary analysis illustrates the cost effectiveness of the device compared to other approaches for PFC abatement. Assuming the unit operates without failure, it has been estimated that the first year COO is approximately $21,876 (using water as an additive gas), of which approximately $15,000 is the capital cost of the device itself[2]. The remaining cost is primarily due to utility usage and foreline modifications that are necessary for device installation. Maintenance and operating costs are expected to be very small compared to the capital expenditure. A five-year COO estimate indicates annualized costs of approximately $4,676 (using water as an additive gas).

Table 9 COO Summary (first year cost)

Capital Cost	$15,000
Installation Cost	$6,500 (+ $3,000 using O_2)
Operating Expenses	$296/year
Maintenance Expenses	$80/year
Total First Year Cost Estimate	**$21,876 ($H_2O$), $24,876 ($O_2$)**

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[1] The beta unit in these experiments ran trouble free for approximately 40 hours over the span of 2 weeks

[2] This quote is representative of the purchase price of the Litmas "Blue" abatement device for large volume orders. Small volume orders will necessarily have larger per unit purchase prices.

Table 10 COO Summary (5-year annualized)

Capital Cost	\$15,000
Installation Cost	\$6,500 (+ \$3,000 using O_2)
Operating Expenses	\$5,990 (\$296/year × 5 years)
Maintenance Expenses	\$400 (\$80/year × 5 years)
Total 5-Year Cost Estimate	**\$23,380 (H_2O), \$26,380 (O_2)**
Annualized COO	**\$4,676/year (H_2O), \$5,276/year (O_2)**

7 UNRESOLVED ISSUES

Although the Litmas plasma abatement system performed satisfactorily in the short screening evaluation, it must be located directly on the tool foreline and operated under tool software control for an extended period of time to evaluate the long-term effects of operation in a true manufacturing environment. A marathon should be conducted to evaluate the following long-term concerns: effect of increased molar gas loads and additive gas flows on foreline pressures as a result of the decreased conductance through the abatement device, possible particle or film deposition in the foreline and in the pump (on rotor and stator, reducing vacuum performance), O-ring reliability issues because of long-term exposure to plasma and HF, corrosion because of the simultaneous presence of HF and water vapor, and long-term effects on pump bearings because of possible particulate formation. In addition, the device itself should be evaluated for long-term performance and COO.

7.1 Excess Pumping Load

Over the course of these experiments, it was discovered that for the abatement system to operate at its greatest effectiveness, some over-capacity has to be built into the pumping system. Elevating neutral gas temperatures and fragmenting PFC molecules into simpler byproducts increase the demand on the pumping system. Based on calculations of conductance for each component in the experimental set-up (see Appendix B—Foreline Conductance Calculations), it was determined that had the Litmas abatement system been installed on the main 4-inch foreline rather than a long 3-inch secondary foreline, the system could have been operated at increased applied abatement power and dilution flow rates without overpressure limitations. (This would have resulted in slightly higher destruction efficiency levels than are reported here.)

The Litmas device does represent a flow constriction to the 4-inch foreline of the etch tool; however, the 1.235” I.D. of the device is similar to the standard inlet size of most pumping systems. Based on calculations shown in Appendix A, the addition of the Litmas tool to the foreline represents the equivalent of approximately 80 feet of 4-inch diameter foreline (25-feet of 3-inch diameter foreline).

Litmas is currently experimenting with a larger diameter plasma tube device (2.0 and 2.375-inch I.D.) that will help reduce the pumping constriction currently placed on the foreline. This should help reduce the conductance loss, but will not affect the additional loading on the pump because of the breaking up of large molecules into small ones. In addition, some issues related to the lower plasma density at similar input powers can be expected when using an abatement system with a larger power deposition volume (and therefore lower power deposition density.) Any loss in destruction efficiency because of lower plasma density may be offset by the longer residence time experienced by the exhaust within the larger diameter abatement device. Further study in this area will be necessary to determine the optimum tube diameter, input power, and device configuration.

7.2 Foreline Deposition

The condition of the foreline downstream of the abatement system is of obvious concern from a long-term reliability standpoint. Because of the almost complete lack of understanding of the processes taking place within a water vapor/PFC plasma, there is some concern about deposits in a system operating under these conditions. Water vapor represents an ambiguous situation where both hydrogen-based deposition of fluorocarbon films and simultaneous oxygen-based etching of those films might be expected.

Throughout the preliminary experiments, no appreciable deposition was observed on the foreline downstream of the abatement device. However, significant deposition would have been unlikely in these experiments because of the intermittent use of oxygen as an additive gas. Even if deposition were to occur during water vapor addition, it would have been removed during the oxygen addition experiments.

In a subsequent marathon, the foreline near the plasma device will need to be inspected periodically to evaluate whether particulate deposition occurs. In case deposition is a long-term problem with the water vapor additive gas technique, it may eventually prove necessary to operate the unit during oxygen-based chamber clean steps to clean the foreline walls of any fluorocarbon film deposition.

7.3 O-Ring Reliability

Because of prolonged exposure to a reactive plasma and to elevated HF concentrations, the long-term reliability of the ISO-KF O-ring gaskets immediately upstream and downstream of the abatement device is under question. Standard Viton O-rings were used in these experiments with no visible degradation in seal or O-ring condition. Long-term trials will be necessary to determine the effect of HF exposure. If O-ring degradation is found to be significant, alternative O-ring material (e.g., Kalrez) may be necessary.

7.4 Effects of Particulate Generation and Deposits on Internal Pump Components

Another unresolved issue requiring further study before large scale integration of plasma abatement systems into the manufacturing environment is the possibility of particle generation or deposit build-up within the abatement device. Although dry pumps are designed to pass small levels of particulates, long-term particulate abrasion or deposition of the pump rotor and stator would lead to a gradual reduction in pump performance. The long-term effect of elevated levels of corrosive species in internal pump components is also of concern. In addition, the dry pump silencer should be inspected during a marathon trial to evaluate particulate contamination.

8 CONCLUSIONS

The results of preliminary testing of the Litmas POU plasma abatement device have been encouraging. The device has been shown to reduce emissions from a representative dielectric etch process by more than 95% under all tested conditions.

Using O_2 as an abatement additive gas, the Litmas “Blue” reduced global warming emissions from a standard Applied Materials etch recipe by 98.5% using 1050W of abatement input power (O_2 DOE Run #17). CF_4, which is considered the most difficult PFC to abate, was destroyed with an efficiency of 96% while CHF_3 was abated to below detectable levels (>99.5% abatement). Similar reductions in global warming emissions were observed for etch processes with varying etch process parameters, feed gas compositions, and gas flow rates. The primary byproducts of abatement using O_2 include CO_2, COF_2, and HF with the formation of a trace of F_2 and NO_2.

It has also been shown that water vapor is a viable alternative to O_2 and/or H_2 as an abatement additive gas. While offering significant advantages from a safety and cost standpoint, water vapor-based abatement reduced greenhouse gas emissions from the standard etch recipe by 99.6% (H_2O DOE Run #9). CF_4 destruction efficiency was 99.3%, while CHF_3 was destroyed with a 98.6% efficiency. Similar reductions were observed for other related recipes. The primary byproducts of water vapor-based abatement included HF and CO with trace formation of CO_2 and negligible formations of COF_2, NO_2, and F_2.

Initial testing also showed that the Litmas device induced no discernable processing impacts, with etch rates and particle counts all falling within acceptable ranges during operation. This is as expected based upon a calculation that shows it is highly unlikely that any species produced by the abatement system will back-diffuse to the process chamber (see Appendix C—Calculation of Peclet Number).

A preliminary COO analysis revealed that the Litmas device is economically favorable. It has been estimated that the first-year COO will be approximately $21,876 with the bulk of that being capital and installation costs. Because of the low cooling and power requirements, utility costs are expected to account for only a few hundred dollars per year. A five-year annualized COO estimate resulted in an annual expense of approximately $4,676.

While issues, such as device reliability, O-ring degradation, particle formation, foreline deposition, and added pumping load, still must be resolved during a long-term marathon trial, the plasma abatement represents a significant step forward towards solving the PFC emissions problem. Assuming positive results of long-term testing, the high abatement efficiency, small footprint, process transparency, low COO, and simplicity of use make plasma abatement with a device such as the Litmas “Blue” a viable technology for reducing PFC emissions from etch tools.

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APPENDIX A
Minimum FTIR Detection Limit

Average noise peak height in the region of the CF_4 peak from a 0.01% (100 ppm) CF_4 standard is approximately 0.00143 absorbance units. The CF_4 signal peak height for the same standard is approximately 0.224 absorbance units. For a 3-to-1 S/N minimum limit of detection:

$$\frac{100\,\text{ppm}}{0.224/0.00143\,\text{S/N}} = \frac{x\,\text{ppm}}{3/1\,\text{S/N}}$$

$$x = 1.91\text{ ppm}$$

APPENDIX B
Foreline Conductance Calculations

Using the following equation for the conductance of a long tube, the conductances of the various sections of foreline were calculated for a representative flow of 400 sccm.

Conductance Calculation Equation (from Leybold Vacuum Products Inc. “Vacuum Technology: Its Foundations, Formulae and Tables”)[3]

$$C = 135\frac{d^4}{l}\overline{P} + 12.1\frac{d^3}{l}\left(\frac{1+192\overline{P}d}{1+237\overline{P}d}\right) [=]\ \mathrm{l} * \mathrm{s}^{-1} \qquad \textbf{Eq. [2]}$$

where: d = pipe diameter (cm)
l = pipe length (cm)
$\overline{P}$ = Average pressure along length of tube (mBar)

Foreline Section	Est. Length	Diameter	Conductance
Pump Inlet to POU	2 ft.	2 in.	360 l/s
POU Abatement System	9 in.	1.235 in.	162 l/s
POU to Iso Valve	9 in.	2 in.	1172 l/s
Iso Valve to Tee	20 ft.	3 in.	232 l/s
Main Foreline from Tee to Tool	40 ft.	4 in.	391 l/s

As can be seen, the combination of the narrow secondary foreline along with the abatement system resulted in a significant loss in overall pipe conductance.

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[3] This is an empirical equation designed to be accurate for both molecular and viscous flow of air. For the conditions encountered during these experiments, the flow was generally viscous.

APPENDIX C
Calculation of Peclet Number

Calculation of the Peclet number follows from its definition as the ratio or the rate of convective transport to the rate of diffusive transport:

$$Pe = \frac{vl}{D} \quad \textbf{Eq. [3]}$$

Where:

v = convective velocity
l = tube length
D = Diffusivity of gas

Estimation of this transport parameter provides an estimate of the dominant transport property within the tube.

The convective velocity of the gas is estimated via a simple relation of pressure, molar flow rate, temperature, and tube diameter.

$$v = \frac{F}{nA} = \frac{FRT}{PA} \quad \textbf{Eq. [4]}$$

Where: F = molar flow rate (mol/s)
R = Universal gas constant
A = Cross-sectional area of the foreline (m^2)
T = Temperature of the gas (K)

The diffusivity can be estimated from basic kinetic theory. By assuming a worst case scenario (smallest and lightest gas) of hydrogen gas within the foreline, a lower bound to the Peclet number can be determined. An estimate for the self-diffusivity of an ideal gas is given by the relation:

$$D_{ii} = \frac{1}{3n\sigma}\left(\frac{8kT}{\pi m_i}\right)^{1/2} \quad \textbf{Eq. [5]}$$

Where: n = number density of the gas ($\#/m^3$)
m_I = mass of gas molecule (kg)
k = Boltzmann’s constant = 1.23×10^{-23}
σ = Collisional cross section of gas molecule (m^2)

The collisional cross section for H_2 can be roughly estimated according to the relation:

$$\sigma = \sqrt{2}\pi a^2 \quad \textbf{Eq. [6]}$$

Where: a = molecular radius (m^2)

As a rough estimate, assume the molecular radius of H_2 to be approximately equal to twice the (5.29×10^{-11} m) Bohr radius. Also assume the following parameters as representative of foreline conditions:

P = 200 mTorr = 26.7 Pa

T = 298 K

F = 400 sccm = 1.07 mol/s

l = 40 ft. = 12.2 m

A = 8.1×10^{-3} m^2 (corresponds to a 4-inch diameter foreline)

Using these assumed representative values, the minimum Peclet number for the foreline is on the order of $\mathbf{5.8 \times 10^{4}}$, which is much larger than one and is evidence of the convective nature of transport within the foreline. It is therefore a valid assumption that gas species produced or added to the foreline near the rough pump inlet will not back-diffuse into the process chamber, thus not affect process performance.

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