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The Need for PFC Abatement in Semiconductor Manufacturing

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THE NEED FOR PFC ABATEMENT IN SEMICONDUCTOR MANUFACTURING

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Abstract:

Perfluorocompounds (PFCs) are highly stable chemical compounds used in two integral steps of semiconductor manufacturing: chemical vapor deposition (CVD) chambers and etch chambers. Unfortunately, PFCs are also greenhouse gases linked to global warming. This, combined with their long atmospheric lifetimes gives them global warming potentials much higher than CO_2, the principal greenhouse gas. In a series of voluntary agreements with the United States and other national governments, the worldwide semiconductor industry has set a goal of reducing PFC emissions to 90% of their 1995 levels. To reach this goal, researchers have explored four main methods of reduction: substitution of PFCs, recovery and recycling of PFCs, tool optimization, and exhaust abatement. While the first three methods have successfully reduced emissions in the CVD chambers, they have proven too costly for or inapplicable to etch chambers. Therefore, it has become apparent that further reductions must be achieved through the abatement of etch chamber exhaust.

Herein, we compare three commercially available abatement systems representative of the three techniques currently used to abate PFCs. All three systems are categorized as either downstream systems, which receive diluted exhaust from multiple etch chambers, or point-of-use (POU) systems, which receive concentrated exhaust from a single etch chamber. Though both downstream and POU configurations are equally effective in destroying PFCs, they differ in cost depending on the number of etch chambers in use and the dilution rate per chamber. Given these numbers, our Microsoft Excel-based cost model computes the total cost of each of the three commercial systems, allowing the user to determine which system is most economical for a specific factory setting.

Introduction:

Perfluorocompounds (PFCs) are a group of highly stable chemical compounds used in two integral steps of semiconductor manufacturing: chemical vapor deposition (CVD) chambers and plasma etch chambers. Unfortunately, PFCs also are greenhouse gases linked to global warming. Emissions of greenhouse gases are commonly reported in comparison to CO_2, the principal greenhouse gas, which accounts for 81.4% of greenhouse gas emissions. Although annual emissions are relatively small, PFCs have a much higher global warming potential (GWP) than CO_2 (see Figure 1[1]). For example, SF_6 has a GWP of 23,900. This means that a given volume of SF_6 will absorb 23,900 times as much heat from the sun as that same volume of CO_2 over a period of 100 years.[2] Moreover, since SF_6 and other PFCs have such long lifetimes, once in the atmosphere, they will practically "live" there forever.

Motivated by such international conventions as the 1992 Rio Summit and the 1998 Kyoto Convention, the World Semiconductor Council in April 1999 set an industry-wide goal to reduce year 2010 PFC emissions to 90% of 1995 emissions. Given that the annual growth rate of the industry is approximately 17%, this reduction is like a 90% reduction on a per-chamber basis.[2, 3] Twenty-two U.S.-based semiconductor manufacturers reiterated their commitment to this goal by signing the Memorandum of Understanding with the Environmental Protection Agency in February 1998.[4] Similar industry-government agreements have been signed in Taiwan, Japan, Korea, and Europe.[5] Further motivation to reduce emissions was provided by Dupont, the major supplier of PFCs, which threatened to curtail the sale of C_2F_6, the most widely used PFC, to semiconductor manufacturers if emission controls were not addressed.[2]

Since the signing of the Memorandum of Understanding and Dupont's threat, the semiconductor manufacturing industry has actively sought methods to achieve this level of reduction. Thus far, four main methods have been examined: substitution of PFCs, recovery/recycling of PFCs, tool optimization, and exhaust abatement. While the first three methods have effectively reduced emissions in the CVD chambers, they have proven too costly for or inapplicable to the etching process,[6] which accounts for 10%-30% of the semiconductor industry's PFC emissions.[3] Tool optimization and substitution of PFCs with alternate chemistries have been unsuccessful due to the anisotropy, polymerization, and the precision necessary in etch applications and the recovery and recycling of PFCs has been shown to be economically infeasible.[2] Therefore, to achieve further reductions, it has become necessary to explore methods of effective PFC abatement of etch chamber exhaust, a task not easily accomplished given PFCs' stable chemical structure.

POU versus Downstream Abatement

Given that abatement is requisite, this study will analyze the costs associated with the three principal methods of PFC abatement for etch chambers: thermal abatement, catalytic destruction, and plasma abatement. Abatement systems can be applied in two basic configurations: point-of-use systems and downstream systems. Point-of-use (POU) systems are placed in the foreline directly after the etch chamber and before the rough pump, such as the four POU units in Figure 2. Downstream systems are located after the rough pump where the exhaust gas is diluted, usually with nitrogen. In this arrangement, downstream units can receive exhaust from multiple etch chambers (see Figure 3). POU abatement systems treat a concentrated PFC stream rather than a nitrogen-diluted stream thus requiring less power.[3, 8] In contrast, the downstream units take in much higher volumes of gas, and therefore, require much more power. However, given their configuration, one downstream unit can receive exhaust from multiple chambers, whereas the POU systems are required one per chamber. The project hypothesis is that at some number of etch chambers, the downstream systems will be more economical than multiple POU units. To put it differently, as the number of etch chambers increases, the price of multiple POU systems will increase more rapidly than the price of a downstream system. Alternately, at some level of nitrogen dilution, POU systems will be more economical than downstream systems. That is, as the nitrogen dilution rate increases, the price of multiple downstream units will increase more rapidly than that of multiple POU systems. Both hypotheses are illustrated in Figures 4 and 5, respectively. A cost model was be used to estimate the costs of specific POU and downstream systems as well as to test the project hypotheses.

Etch Chamber Exhaust and Nitrogen Dilution:

To properly evaluate the abatement of etch chamber exhaust, the etch exhaust itself must be analyzed. For this study, etch exhaust will be considered on a per chamber basis rather than a per tool basis, to avoid the complication presented in multi-chamber tools. Etch chamber exhaust varies depending on the type of etch being performed and the recipe being used. Typical exhaust rates are far less than 1 standard liter per minute (sLm) per chamber, usually less than 300 standard cubic centimeters per minute (sccm) per chamber. PFCs usually constitute less than 100 sccm of this exhaust.[9]

Like the etch exhaust, the nitrogen dilution rate necessary for downstream systems, too, varies with the type of etch being performed. According to Joe Van Gompel of BOC Edwards, a "clean process" such as oxide etching requires as little as 10 sLm of nitrogen dilution at the rough pump, whereas a "dirty process" such as nitrogen etch must be diluted with 40-50 sLm. Typical nitrogen dilution rates are around 50 sLm. Nitrogen dilution rates are so large that when using a downstream system, the volume of exhaust directly from an etch chamber is, in comparison, negligible.

To analyze the costs associated with the abatement systems, the number of chambers and the maximum dilution rate per chamber must be provided by the user to the cost model.

Three Abatement Systems:

Three systems, each representative of the three main abatement methods, were chosen for this cost analysis. These units are commercially available and have been tested and proven effective in abating PFCs. The capital, utility, accessory, and installation costs were assembled from a variety of sources ranging from company sales representatives to studies performed with the equipment. The sources for each system are cited here, and the costs are summarized in Figure 6.

Litmas LB1200 and LB3000

The Litmus LB1200 and LB3000 are POU plasma abatement systems located in the foreline between the etch chamber and rough pump. Theses units produce a plasma discharge which decomposes PFCs into carbon and fluorine atoms that are then combined with an additive gas (typically water vapor) to convert them into the less harmful gases HF and CO_2. The destruction and reduction efficiency (DRE) of the Litmas systems has been found to be >96% for CF_4 and >99% for CHF_3 in common etch recipes.[10] The costs of the two units were provided by Jerry Pearson, Vice-President of Litmas Incorporated and sources [3], [7], and [10].

BOC Edwards Thermal Processing Unit (TPU)

The TPU is a downstream thermal abatement system located after the rough pump. The unit combines a burner with a water scrubber to destroy PFCs and a variety of other gases. When PFCs are not present in the exhaust, the TPU works in "low-fire" mode, burning at 650∞C. When PFCs are detected, it switches into "high-fire" mode, burning at 850∞C - 1000∞C.[11] The stable chemical structure of PFCs requires this high temperature to decompose. The TPU uses 6 gallons of water per minute, so a water recirculation module is recommended for each unit. Experimental DRE rates for PFCs are >90%.[12, 13] The costs associated with the TPU were provided by Joe Van Gompel, Product Specialist at BOC Edwards Phone and sources [11] and [12].

Hitachi Super Catalytic Destruction System (SCDS) CD-60, CD-120 and CD-200

The SCDS is a downstream abatement system located after the rough pump. It exploits chemical reactions enhanced by a catalyst, converting PFCs into CO_2 and HF. The catalysts require replacement every 24 months, and the old catalyst can be recycled as a steel additive. Its built-in water recirculation module uses only 1 gallon per minute. Experimental PFC DRE rates for this system are > 99%.[14]

Hitachi Limited was contacted but would not divulge the price of the SCDS units. Jim Manos, Sales Representative at Hitachi, did say that they are "competitively priced with the BOC Edwards TPU." Therefore, the prices of the SCDS systems are estimated. Additional annual operational costs were gathered from source [14].

Inputs into the Cost Model:

The cost model was developed in Microsoft Excel. It requires four inputs: the number of etch chambers in use in the factory, the maximum exhaust from a chamber before the rough pump (in sccm), the maximum nitrogen dilution necessary at the rough pump (in sLm) per chamber, and an interest rate for all time value of money calculations.

The maximum exhaust flow from the etch chamber only affects usage of the Litmas LB1200. The cost model provides two options, ">100" sccm or "<100" sccm. Should the user select the maximum exhaust flow to be ">100" sccm, the Litmas LB1200 will be eliminated as a possibility since it can handle a maximum of only 100 sccm. In the case that the user selects "<100", both the Litmas LB1200 and LB3000 will be considered, though the latter will never be optimal as it is more expensive. If the user does not know what the maximum exhaust flow will be, it is recommended that it be left at ">100." This ensures that the LB1200 is not used when it is inapplicable.

The model asks for the maximum nitrogen dilution per chamber to avoid the complication of different dilution rates for different etch recipes. Of course, this input only affects the downstream systems. It is limited to a minimum of 1 sLm and a maximum 60 sLm. If the user is unsure what nitrogen dilution rate is necessary, it is recommended that it be set at 50 sLm. Fifty sLm is the typical rate, and a higher than necessary rate will ensure proper abatement while a lower than necessary rate will not.

Outputs of the Cost Model:

The cost model first determines how many units of each system are necessary to handle the exhaust given by the user's inputs. The POU units are required one per chamber. Therefore, the number of POU units necessary is equal to the number of chambers given by the user. The number of downstream units required is determined by the total downstream exhaust, which is defined as:

*Total Downstream Exhaust = Number of Chambers in Use * Dilution Rate Per Chamber*

The TPU can handle at maximum 200 sLm of total downstream exhaust. As the total downstream exhaust exceeds 200 sLm, 400 sLm, and 600 sLm, a second, third, and fourth TPU are required. For the Hitachi SCDS, the model calculates the optimal combination of CD60, CD120, and CD200 units to handle the total downstream exhaust. A sample output is shown in Figure 7.

The initial and annual costs of each system are defined as

*Initial Cost = (Cost of each Unit + Cost of any Required Additional Accessories) * Number of Units Required*

*Annual Cost = Annual Operational Costs per Unit * Number of Units Required*

The annual operational cost includes utility cost, maintenance cost, and any other annually recurring costs. The model includes tables similar to Figure 6, which provide the model with the unit cost, accessory cost, annual utility cost, and maximum exhaust rate for each system. Every output uses the numbers in these tables for its computations. These numbers can be altered should system specifications change, to update prices, or to substitute the specifications of another system. For example, the Hitachi system prices were estimated and can be changed if the actual prices were known. Should the other systems' prices decrease or increase, these too can be reflected in the model.

Having computed the initial and annual costs, the model proceeds to calculate the cost of ownership, using the user-given interest rate, for a period of one to six years. Using this cost allows the user to see which system will be most economical for his planning horizon and how much that system will be in present-value dollars. It assumes that the initial cost is paid up front (i.e., at time 0) and that the annual operational cost is paid at the end of each year. For each abatement system, the present-value cost of ownership is computed for the whole system as well as per chamber. These computations are presented in a table (Figure 8) and corresponding graph (Figure 9).

The model also addresses the two project hypotheses by generating a table and graph of initial cost as a function of the number of etch chambers (Figure 10) and initial cost as a function of the dilution rate (Figure 11). In Figure 10, the user-given nitrogen dilution rate is held constant while the number of chambers is varied to see at what number of chambers the downstream systems are more economical. Conversely, in Figure 11 the user-given number of etch chambers is held constant while the dilution rate is varied to see at what dilution rate the POU units are most economical. Note resemblance of Figure 10 to Figure 4 and Figure 11 to Figure 5.

Finally, the model computes the average capacity of the two downstream units (Figure 12). Capacity for both systems is defined as:

*Capacity = Total Downstream Exhaust / Maximum Exhaust Capacity of the System = (Number of Chambers in Use * Dilution Rate Per Chamber) / Maximum Exhaust Capacity of the System*

Since dilution rates do not affect POU systems, their capacities were not included. The capacity computations allow the user to see which of the two downstream systems would be better utilized and if there is room for increased usage.

Project and Research Conclusions:

In the course of researching and developing the equations used by the cost model, some particular aspects of abatement systems became apparent. The number of POU systems required is a function of the number of etch chambers. The number of downstream units required is a function of the product of the number of etch chambers and the nitrogen dilution rate, more specifically the total downstream exhaust. That is to say, the price of an abatement system can be determined using only the number of etch chambers and the maximum nitrogen dilution rate necessary per chamber. This function could be graphically represented in a three-dimensional graph. Such a graph is simulated in the sample outputs Figure 10 and Figure 11.

The utility of this research is in illuminating and simplifying the obscure, complicated field of PFC exhaust gas abatement. Based on two simple factors, a factory manager, who may know relatively little about abatement, could use the model to determine what type of abatement is least expensive and as an estimate of its expense. With the model's per-chamber approach, complications arising from considering multi-chamber tools are avoided. Similarly, by using the maximum dilution rate, the effect that changing the etch recipe can have on the dilution rate is ignored. Simplifying these complexities, the model allows the user to determine which abatement system is most economical. Providing economically feasible solutions encourages industry to make ecologically friendly decisions, which benefits everyone. Though the cost model does not solve the problem of PFC emissions and global warming, it can help factory managers and the semiconductor industry as a whole take a step in that direction.

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Figure 1: Atmospheric Lifetimes and Global Warming Potentials of PFCs with respect to CO_2

Atmospheric Lifetimes and Global Warming Potentials of PFCs with respect to CO_2

Gas:	Atmospheric Half-life (Years):	GWP (over 100 years):
Carbon Dioxide - CO_2	50-200	1
Halocarbon 14 - CF_4	50,000	6,500
Halocarbon 116 - C_2F_6	10,000	9,200
Halocarbon 218 - C_3F_8	2,600	7,000
Octafluorocyclobutane - C_4F_8	3,200	8,700
Octafluorocyclopentene - C_5F_8	1	90
Halocarbon 23 - CHF_3	264	11,700
Nitrogen trifluoride - NF_3	740	11,700
Sulfur hexafluoride - SF_6	3,200	23,900

Figure 2: Basic Configuration of POU system

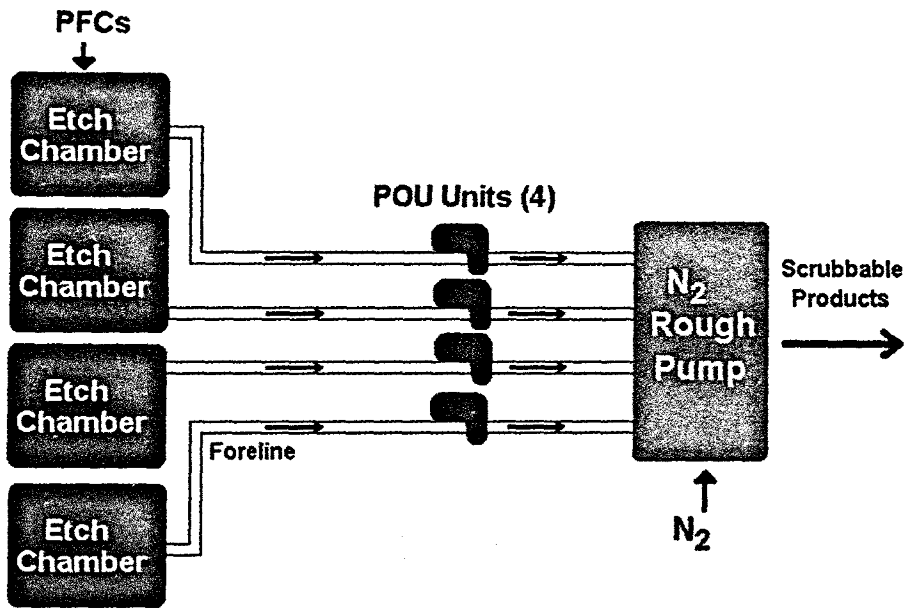


Figure 3: Basic Configuration of a Downstream system

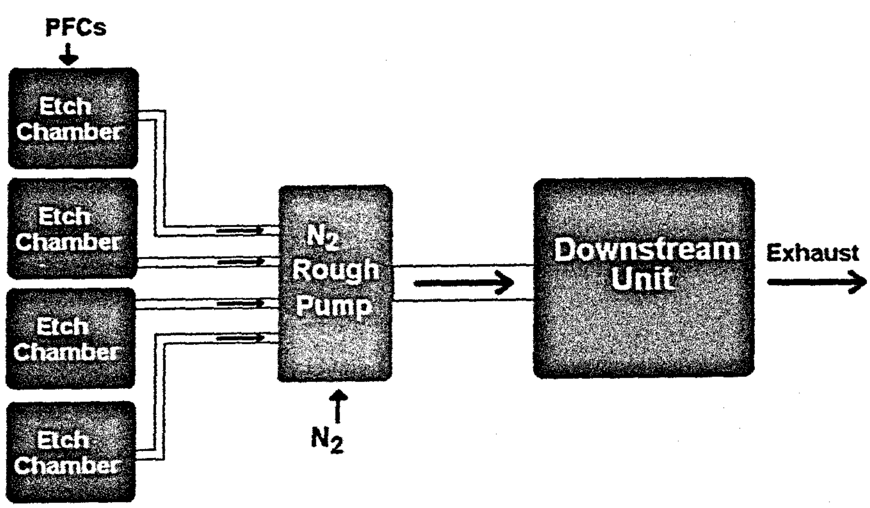


Figure 4: Hypothethical Graph 1

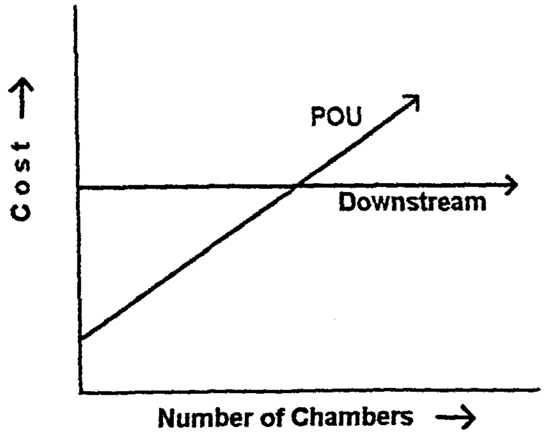


Figure 5: Hypothetical Graph 2

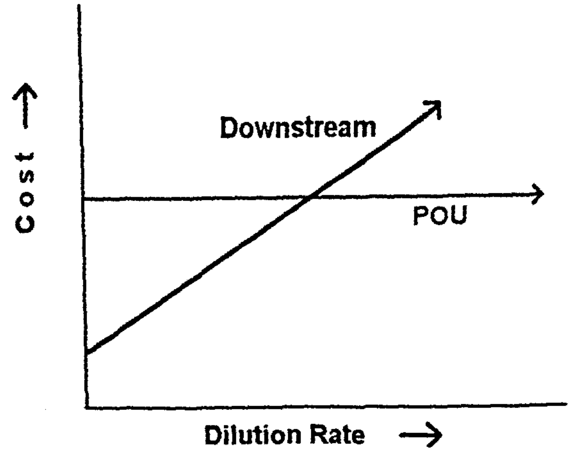


Figure 6: Summary of Costs

	POU or Downstream?	Maximum Exhaust Flow per Chamber (sccm)	Maximum Total Downstream Exhaust (sLm)	Unit Price	Required Accessory Price	Annual Operational Costs
Litmas LB1200	POU	100	N/A	$25,000	$5,800	$300
Litmas LB3000	POU	300	N/A	$32,000	$5,800	$350
BOC Edwards TPU	Downstream	N/A	200	$120,000	$10,000	$6,500
Hitachi SCDS CD60	Downstream	N/A	60	$50,000	N/A	$6,000
Hitachi SCDS CD120	Downstream	N/A	120	$90,000	N/A	$6,000
Hitachi SCDS CD200	Downstream	N/A	200	$130,000	N/A	$6,000

Figure 7: Output - Units Required, Initial costs, and Annual Costs

	Number of Units Required	Initial Cost	Annual Costs
Litmas LB1200	Not Applicable	N/A	N/A
Litmas LB3000	6	$226,800	$2,100
BOC Edwards	2	$260,000	$13,000
Hitachi CD60	0	$0	$0
Hitachi CD120	1	$90,000	$6,000
Hitachi CD200	1	$130,000	$6,000
Hitachi System		$220,000	$12,000

Figure 8: Output - Present Value Cost of Ownership Table

†	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Litmas LB1200	N/A	N/A	N/A	N/A	N/A	N/A
Litmas LB3000	$228,744.44	$230,544.86	$232,211.90	$233,755.47	$235,184.69	$236,508.05
BOC Edwards	$272,037.04	$283,182.44	$293,502.26	$303,057.65	$311,905.23	$320,097.44
Hitachi CD60	†	†	†	†	†	†
Hitachi CD120	†	†	†	†	†	†
Hitachi CD200	†	†	†	†	†	†
Hitachi System	$231,111.11	$241,399.18	$250,925.16	$259,745.52	$267,912.52	$275,474.56

Figure 9: Output - Present Value Cost of Ownership Graph

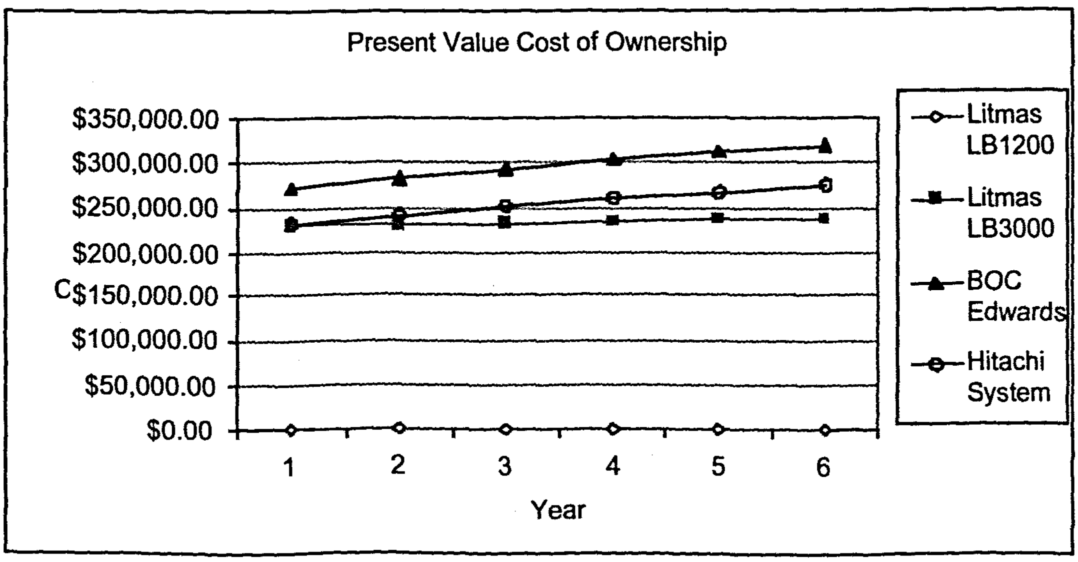


Figure 10: Output - Chamber Analysis Graph

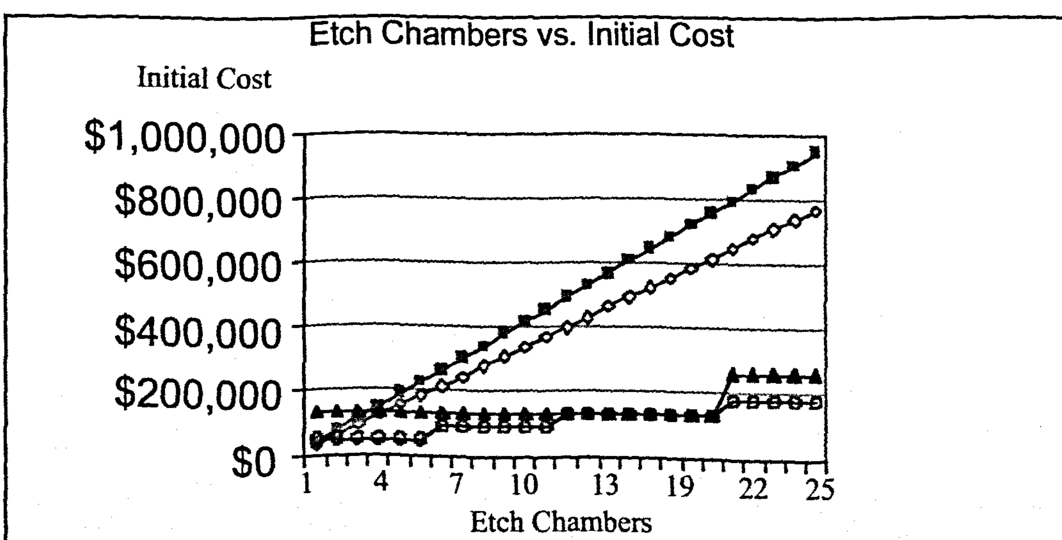


Figure 11: Output - Dilution Analysis Graph

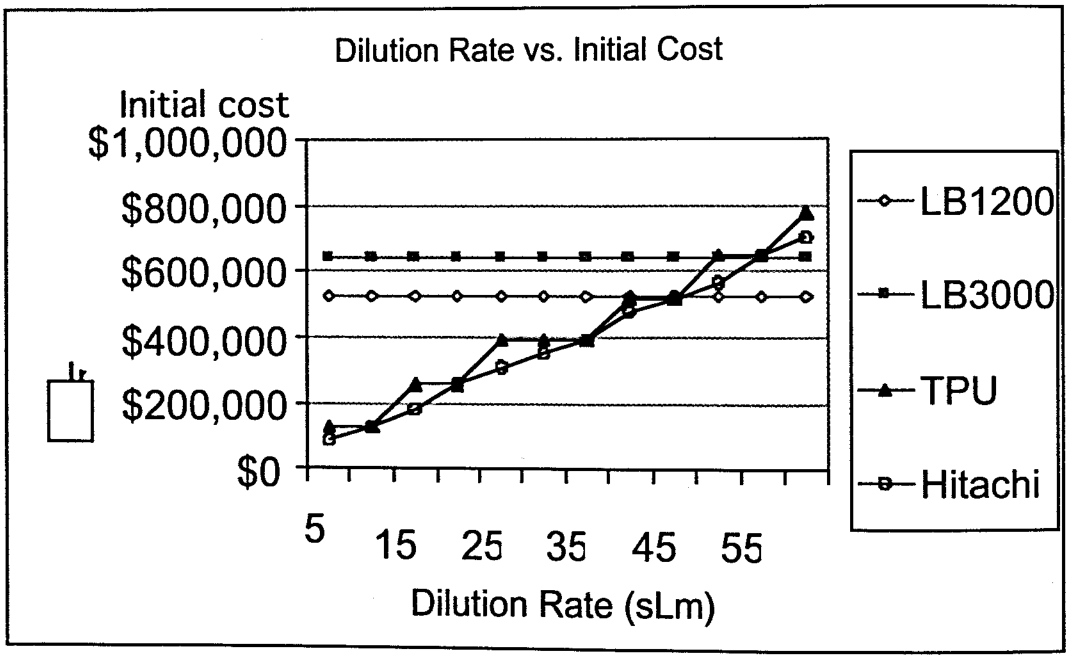
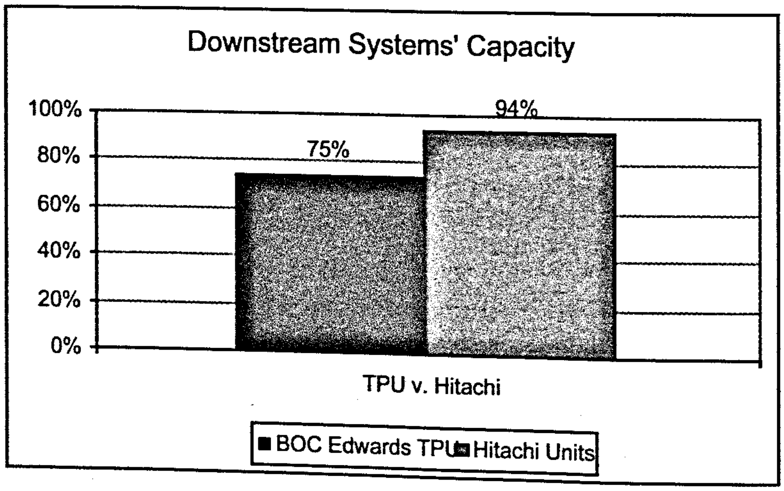


Figure 12: Output - Capacity Analysis Graph



WORKS CITED:

[1] "Inventory of US Greenhouse Gas Emissions and Sinks", U.S. Environmental Protection Agency (2000). *http://www.epa.gov/globalwarming/publications /emissions/us2000/index.html*

[2] Van Gompel, Joe. (2000). "PFCs in the Semiconductor Industry: A Primer", *Semiconductor International*, Vol. 23, Issue 8.

[3] Vartanian, V., Beu, L., Lii, T., Graves, D., et. al. (2000). "Plasma abatement reduces PFC emission", *Semiconductor International*, Vol. 23, Issue 6.

[4] Peters, Laura. (1998). "Decreasing the release of PFCs", *Semiconductor International*, Vol. 21, Issue8.

[5] Lewis, Mark and Huang, Jennifer. (1999, July 29). "Taiwan: Semiconductor Industrial Pollution Plan", *International Market Insight Reports*.

[6] Lester, Maria A. (2000). "No more PFC emissions in Plasma Chamber Cleaning?", *Semiconductor International*, Vol. 23, Issue 1.

[7] *http://www.litmas.com/products.html*

[8] Brown, R.S., Rossin, J.A., Thomas, C.J. (2001). "Catalytic process for control of PFC Emission", *Semiconductor International*, Vol. 24, Issue 6.

[9] Seely, Andrew, et. al. (2000). "Effective PFC gas abatement in a production environment." *Semiconductor FabTech*, 10th edition.

[10] Vartanian, V., et. al. (2000). "Long term evalutaion of a Litmas Blue point of use plasma abatement device for PFC destruction." *SEMATECH report 99123865A-ENG.*

[11] Walling, T., Tran, A., and Ridgeway, B. (1997). "Evaluation of an Edwards TPU 4214 and an Ecosys Phoenix IV for CF4 Abatement." *SEMATECH report 97073319A-TR.*

[12] Beu, Laure, et. al. (1998). "Current State of Technology: PFC EmissionsReduction." *SEMATECH report 98053508A-TR.*

[13] Van Gompel, Joe. (1997). "A new way to treat process exhaust to remove CF4.", *Semiconductor International*, Vol. 20, Issue 10.

[14] Decker, T., Cox, J., Koenigseder, S. (2001) "PFC Abatement for the SC Industry: Results from a Catalytic Method." *Future Fab*, Vol. 11.

Faculty Comments:

The research mentor for the Manesh/Kendrick study was Scott Mason who serves the Industrial Engineering Department as Graduate Studies Chair. He made these remarks about the work of his two undergraduate researchers:

> Mohsen Manesh and Brian Kendrick were the only two undergraduates registered in my graduate level "Modeling and Analysis of Semiconductor Manufacturing" course in the Fall 2001 semester. The course, which both students took as a technical elective for their Bachelor of Science in Industrial Engineering degree, requires students (either as an individual or in a team of two) to complete both a literature review on a topic of their choosing, as well as a final project. Both the literature review and final project are presented orally to the class.
>
> First, Mr. Manech and Mr. Kendrick reviewed the open literature pertaining to the caustic emissions produced by semiconductor manufacturers and the Memorandum of Understanding signed by the Semiconductor Industry Association and the Environmental Protection Agency in 1996 to reduce PFC emissions worldwide. This literature review was completed professionally and accurately, surpassing most of the graduate students' own literature reviews in my course.
>
> Taking their learnings on PFC emissions in the semiconductor industry to heart, they developed an "Etch Chamber PFC Exhaust Abatement Cost Model" in Microsoft Excel for their class project. This cost model performed a capacitated, present value analysis of seven different abatement solutions available to the semiconductor industry today in terms of total number of etch chambers, exhaust flow per chamber, and nitrogen dilution rate. These two students took the initiative to contact leading abatement system vendors to conduct their research, again showing a motivation level rarely matched by their classmates.
>
> As graduate studies chair, I review the applications of all incoming graduate students to our program. I feel Mr. Manech and Mr. Kendrick have already demonstrated a level of excellence that surpasses many of the graduate applicants that I have reviewed.

Mr. Kendrick and Mr. Manesh's undergraduate faculty advisor, Terry R. Collins, is familiar with the research of the two students. He also knows them well because of the contributions they have made to the Industrial Engineering Department. He had this to say about them:

> Mr. Manech and Mr. Kendrick have submitted a research article to the Undergraduate Research Awards Selection Committee for consideration toward publication in the University of Arkansas Journal of Undergraduate Research. Their research contribution in the development of this article is scholarly for it includes genuine research methodologies and applicability in the area of environmental abatement for perflourocompounds (PFC's).
>
> I have known Mr. Manech and Mr. Kendrick since they joined our Industrial Engineering undergraduate program three years ago. I currently serve as their undergraduate faculty advisor. Both are exemplary students, which is evidenced by their exceptional overall GPA (Brian Kendrick 3.64/4.0, Mohsen Manech 3.91/4.0), and their Chancellor's Scholar status. They are also very active in university, department and student chapter functions and activities. Mr. Manech unselfishly volunteers his spare time to tutor underclassmen in our prestigious Students Helping Undergraduate Students (SHUR) program. Other tutors in the SHUR program are compensated for their time, but Mr. Manech felt that it is more of a privilege than a job to work with first year industrial engineering students. He is also a freshman orientation leader for the University of Arkansas. Mr. Kendrick devoted countless hours in assisting with the coordination of the Ergonomics Symposium last year. This symposium was a fund-raising activity for the IE student chapter, which cleared an amazing $25,000 for the chapter. As you can see, these two students are overachievers in all endeavors.