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TITLE: # Cost Effectiveness of Silent Discharge Plasma for Point-of-Use VOC Emissions Control in Semiconductor Fabrication

AUTHOR(S): Mark Cummings
Steven R. Booth

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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Cost Effectiveness of Silent Discharge Plasma for Point-of-Use VOC Emissions Control in Semiconductor Fabrication

Prepared for:

John Coogan
Los Alamos National Laboratory

by:
Mark Cummings
Steven R. Booth
Environmental Technology Cost-Savings Analysis Project (ETCAP)
Energy and Environmental Analysis Group
Technology and Safety Assessment Division
Los Alamos National Laboratory

Project Manager: Steven R. Booth
ph: (505)667-9422
fax: (505)665-5125
email: sbooth@lanl.gov

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Conclusions

Silent Discharge Plasma (SDP):

- is an innovative technology for destroying VOCs by directing the exhaust gas stream through an electrically created low-temperature plasma
- destroys VOCs at near ambient temperature and pressure
- can be engineered to attain very high destruction removal efficiencies (DREs)
- has a small footprint relative to other VOC treatment technologies
- effectively treated PGMEA and HMDS in tests on lithography tool exhaust streams without fouling at typical influent concentrations
- costs are independent of VOC concentration, but highly dependent on the specific target compound, desired DRE, and inlet flow rate

Summary

Extensive research into the treatment and control of Volatile Organic Compounds (VOCs) from semiconductor industry manufacturing processes has identified the need for alternatives to existing combustion devices. Specifically, semiconductor manufacturing design is moving toward the application of effective, small-scale, abatement control technologies for specific point-of-use (POU) waste streams associated with a particular component or manufacturing tool. The consortium of companies involved in semiconductor precompetitive research and development known collectively as SEMATECH recently evaluated eleven emerging environmental technologies designed to treat POU process emissions of VOCs specific to the semiconductor industry. After rigorous technical review only one technology, the Silent Discharge Plasma (SDP) developed at Los Alamos National Laboratory, was considered to successfully meet the required technical performance standards and potential cost effectiveness necessary for continued consideration by SEMATECH in their point-of-use emissions control plans.

Proponents of POU control argue that replacing a single large emissions control system with smaller, distributed systems designed for very specific waste streams will increase manufacturing flexibility, minimize waste generation, and reduce environmental impact. Cost of ownership of the SDP technology was evaluated for use in a fabrication facility. The results of cost analysis showed that SDP performance and cost-effectiveness are quite compound-specific; costs for treatment of methanol and acetone are prohibitive at the high flow rates (3000-4000 scfm) associated with solvent bench exhaust streams. However, the SDP technology may be a cost effective alternative for treating POU exhaust gases at the lower flow rates (100-500 scfm) associated with individual lithography tools or, and because lithography tool target exhaust compounds are particularly conducive to destruction via SDP.

Introduction

The current approach to air pollution control for the semiconductor industry combines all exhausts from process tools, cleaning tools, and fume hoods into a single large stream. Typically, exhaust gases are piped to a concentrator wheel where the organic constituents are concentrated prior to being fed to a regenerative thermal oxidizer (RTO). Concentration of the stream enhances the performance and cost effectiveness of the RTO by increasing the thermal capacity of the feed stream, thereby decreasing reliance on an external fuel source.

The advantage of RTO is that it is a well-understood and thoroughly tested technology that can handle the high air flow rates associated with the combined exhaust streams generated in manufacturing. The disadvantages of RTO are high operating and maintenance (O&M) costs, decreased flexibility, and fouling of the equipment by particular exhaust stream constituents. O&M costs are relatively high because RTO is labor- and utility-intensive. Fouling of the system by exhaust gas constituents, primarily hexamethyldisilazane (HMDS) increases maintenance, leading to an increase in downtime and expense. The lack of flexibility inherent in a single, large air emissions system is significant within the semiconductor industry because products change rapidly and have a relatively short commercial life.

To increase manufacturing flexibility, reduce operating expenses, and provide a higher level of pollution control the industry is moving toward a point-of-use (POU) pollution control philosophy. In a POU environment, smaller distributed pollution control systems are integrated into individual tools, replacing the centralized air emissions system currently in use. Whereas current plenum exhaust is high flow, low concentration, and extremely variable, POU exhaust is low flow, high concentration, and specific to the particular tool.

The SDP technology is well-suited to fit the needs of POU emissions control for the several reasons. First, the technology is capable of oxidizing a wide range of intractable exhaust compounds at ambient temperatures and pressures and at very high destruction removal efficiencies (DREs). Second, the electrical power levels required for destruction of target compounds can be finely tuned and adjusted in order to optimize operating expenses. In addition, the SDP equipment can cycle on and off to take advantage of the periodic nature of exhaust gas release. Third, the SDP system has a small footprint relative to other VOC abatement technologies. Fourth, HMDS is readily destroyed by SDP at low concentrations without reducing removal rates for other target compounds.

Caveats

SDP shows optimal performance under a high concentration, low flow regime. It is not particularly sensitive to influent exhaust stream concentration, but is sensitive to flow rate, specific exhaust compound(s), and the target DRE. Cost of ownership calculations depend these latter three parameters. This results in both advantages and disadvantages to the system. If the target compounds are favorable to destruction via SDP such as those emitted by lithography tool exhaust (i.e., PGMEA, HMDS), and if flow rates are relatively low (i.e., ranging from approximately 100-500 scfm), then the cost of ownership is relatively small. If, on the other hand, target compounds are unfavorable to SDP treatment such as those emitted by solvent benches (i.e., acetone and methanol), then cost of ownership becomes relatively high, particularly at the high flow rates (3000-4000 scfm) associated with solvent bench exhaust output. Cost is also dependent on the specific target DRE. For purposes of this report we assume a DRE of 99% applies. As will be shown, increasing the DRE to 99.9% or greater is achievable, but operating costs increase accordingly.

The SDP technology has not yet been demonstrated at full-scale over a long-term period. For this reason, there is necessarily some uncertainty associated with O&M. Costs for O&M are based upon past experience and vendor recommendations. Costs provided for the SDP power supply and related equipment are based upon retail prices and do not take into consideration discounts that may apply for quantity. Finally, it is commonplace for

RTOs to present unit costs in $/1000 scfm because it is economically favorable to do so for systems that treat small concentrations of contaminants in large volumes of air. However, as POU emissions control takes the opposite approach, we believe that unit costs in $/lb VOC treated are a more appropriate way to judge SDP cost of ownership.

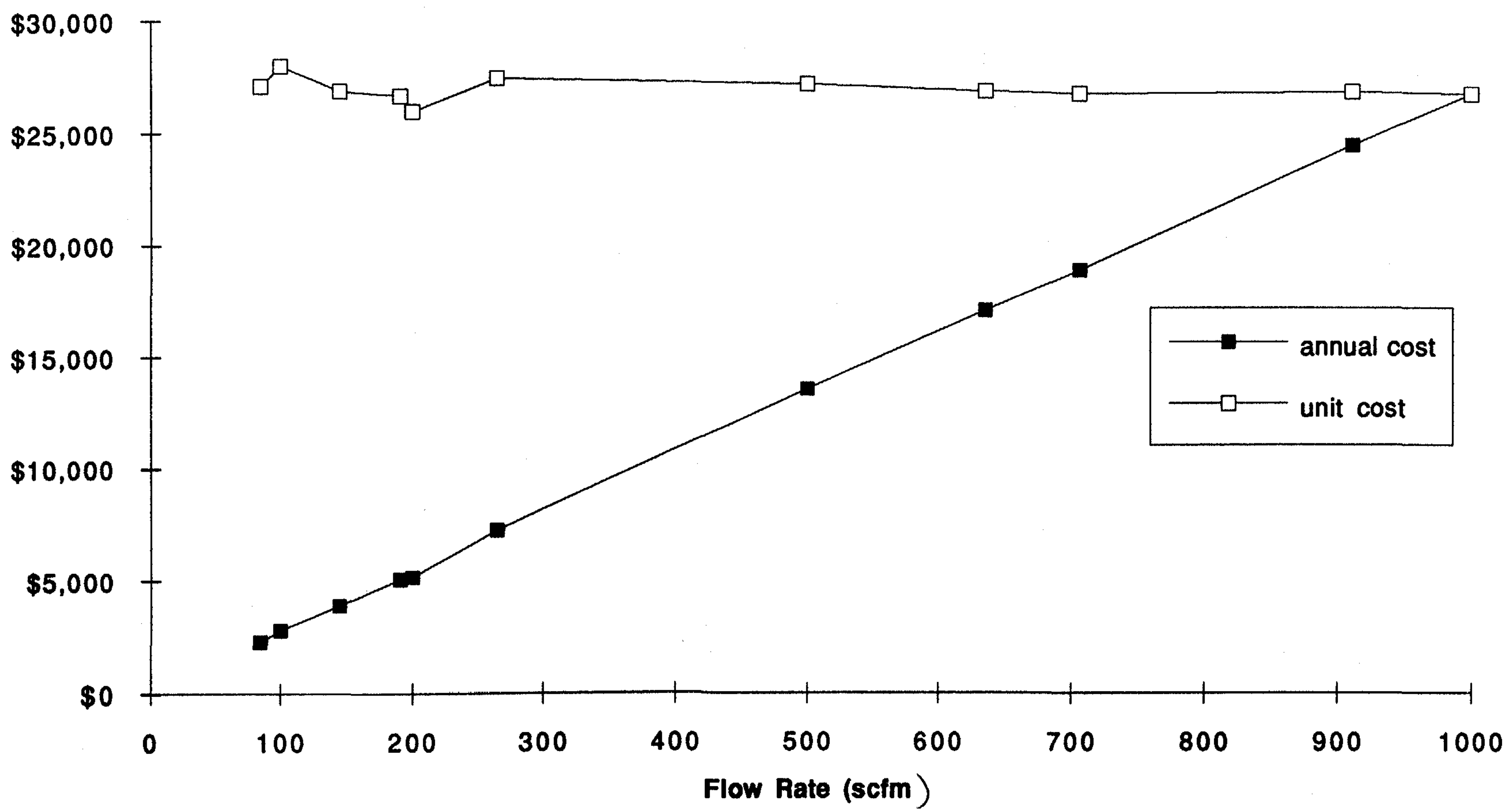
Cost of Ownership Assumptions

Table 1 presents the cost of ownership for SDP in terms of unit costs in both $/lb VOCs destroyed and $/1,000 scfm treated. Unit costs are based on average values for the important parameters of flow rate [2], energy density requirement for a particular compound [1], exhaust stream duty cycle, and the desired DRE. We assume a DRE of 99% is a reasonable target for the effluent stream. A duty cycle of 25% is assumed. Because of the influence of the above four parameters on the cost of ownership, a sensitivity analysis is presented showing their relationship to cost. Figures 1 - 4 show the cost of ownership in $/1,000 scfm as a function of flow rate, energy density requirement, target DRE, and duty cycle, respectively, for treatment of PGMEA from lithography tool exhaust output. Data points given for flow rate are based on actual flows from coaters at 4 different fabs [2]. Following these figures is the basis of cost for Table 1.

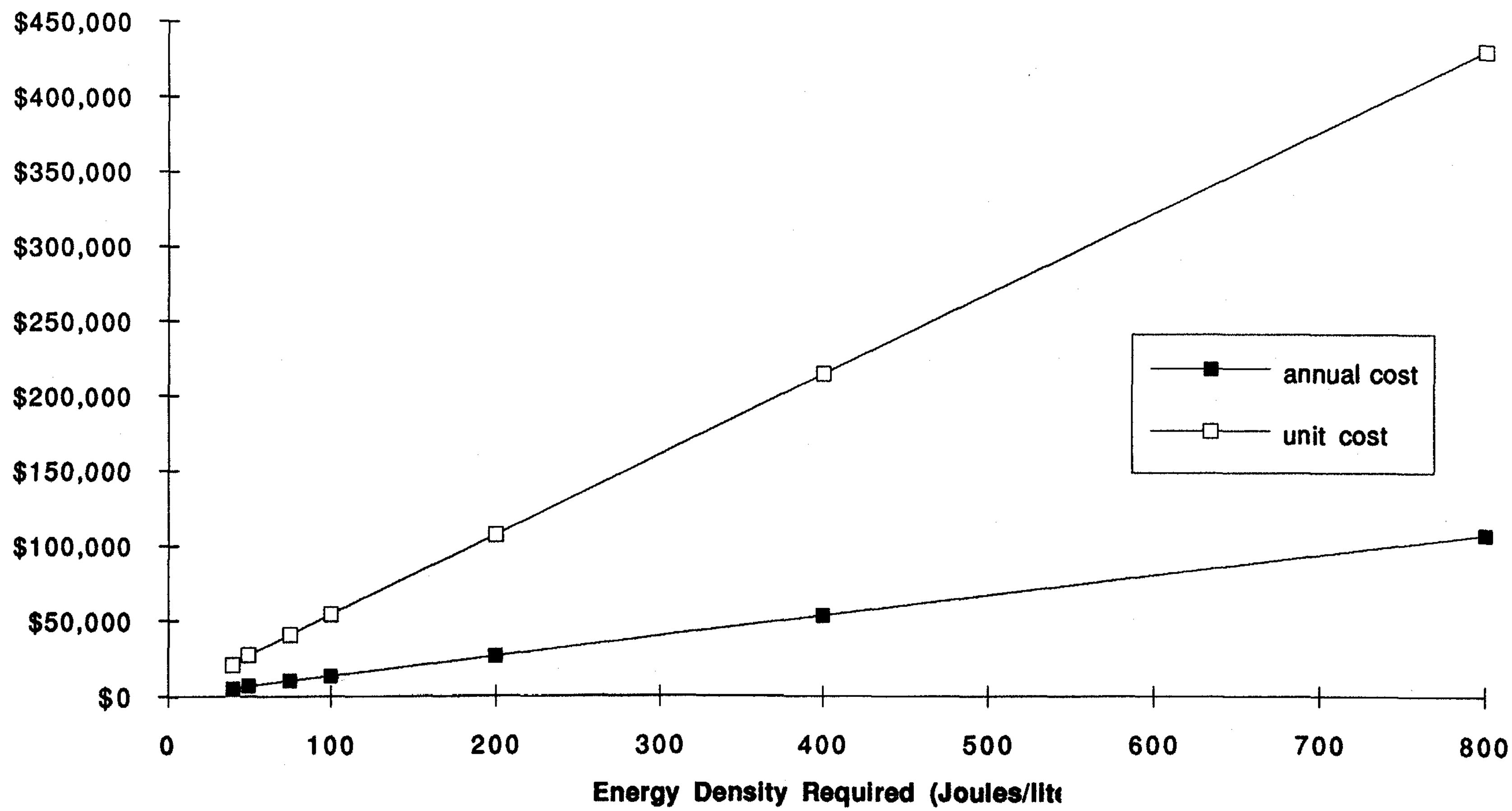
	A	B	C	D
1	Cost of Ownership Calculation for SDP			12/11/96
2	Operational Component	Solvent Bench	Dryer	Litho Tool
3	Target Compound	Acetone	IPA	PGMEA
4	Molecular Weight	58.08	60.10	132.16
5	Influent Concentration (ppm)	200	200	200
6	Allowable Effluent Conc. (ppm)	2	2	2
7	Target DRE	99%	99%	99%
8	Nine-factor (based on Target DRE)	2	2	2
9	Peak Flow Rate (scfm)	4000	400	500
10	Energy Density Required (J/liter)	1500	200	50
11	Power Requirement (kW)	5662	75	24
12	VOC Loading (lb/hr)	7.8	0.8	2.2
13				
14	Equipment Cost			
15	Power Supply Size Factor ($/W)	$0.75	$1.00	$1.00
16	Power Supply	$4,246,500	$75,000	$24,000
17	Cells and Support Equipment	$566,200	$7,500	$2,400
18	Sales tax (3%)	$144,381	$2,475	$792
19	Freight (5%)	$240,635	$4,125	$1,320
20	Total Equipment Cost (TEC)	$5,197,716	$89,100	$28,512
21	Indirect Costs (0.25 x TEC)	$1,299,429	$22,275	$7,128
22	(incl. piping, elec., installation)			
23	Total Capital Cost (TCC)	$6,497,145	$111,375	$35,640
24				
25	Operating & Maintenance Costs			
26	Operating Labor (0.02 x TCC)	$129,943	$2,228	$713
27	Maintenance Labor	$905,978	$12,080	$3,775
28	Maintenance Materials (0.04 x TCC)	$259,886	$4,455	$1,426
29	Footprint (total equip sq. ft.)	3397	30	12
30	Floor Space Unit Cost ($/sq.ft.)	$75	$75	$75
31	Floor Space Annual Cost	$254,806	$2,250	$900
32	Total O&M	$1,550,613	$21,012	$6,813
33				
34	Utilities			
35	Electricity Unit Cost ($/kWh)	$0.05	$0.05	$0.05
36	Duty Cycle	25%	25%	25%
37	Electricity Usage (kWh/yr)	12,400,568	165,341	51,669
38	Annual Electricity Cost ($/yr)	$620,028	$8,267	$2,583
39				
40	Annual Capital			
41	(@ 7.0%, 10 yr term)	$924,544	$15,849	$5,072
42	Annual Operating Cost	$129,943	$2,228	$713
43	Annual Maintenance	$1,165,863	$16,535	$5,201
44	Annual Utilities	$620,028	$8,267	$2,583
45	Total Annual Cost	$2,840,400	$42,900	$13,600
46	PV 10 yr O&M Cost (at 2.8%)	$16,510,664	$232,938	$73,225
47	Total PV Cost (TCC + 10 yr O&M)	$23,007,800	$344,300	$108,900
48	Annual VOCs Destroyed (lb/yr)	68,034	7,040	19,351
49	COO ($/lb VOC)	$42	$6	$1
50	COO ($/1,000 scfm)	$710,100	$107,300	$27,200

Table 1. SDP Cost of Ownership is presented in $/lb VOCs destroyed and in $/1,000 scfm.

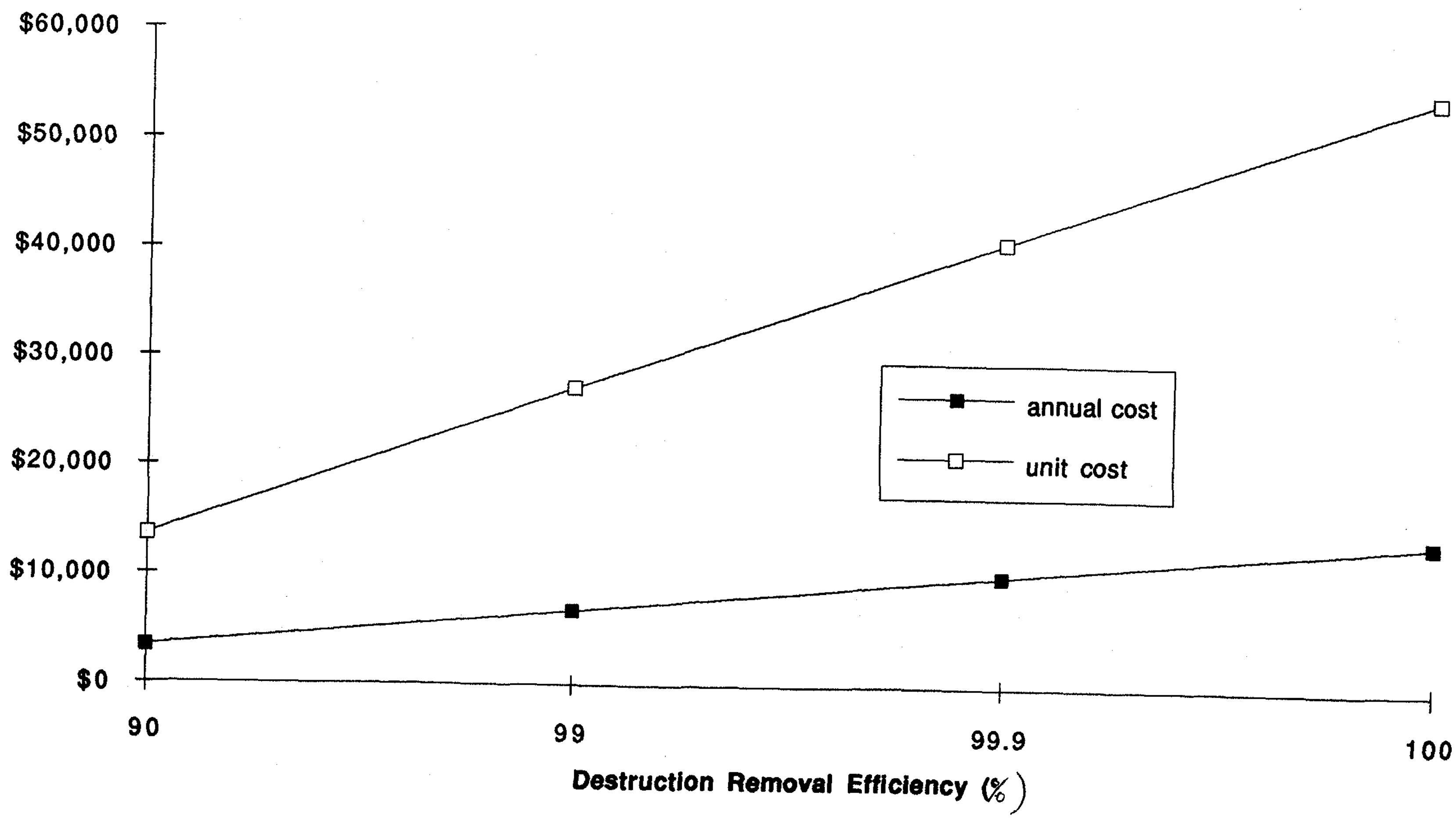
SDP sensitivity to flow rate. Energy requirement is 100 J/liter for 99% DRE



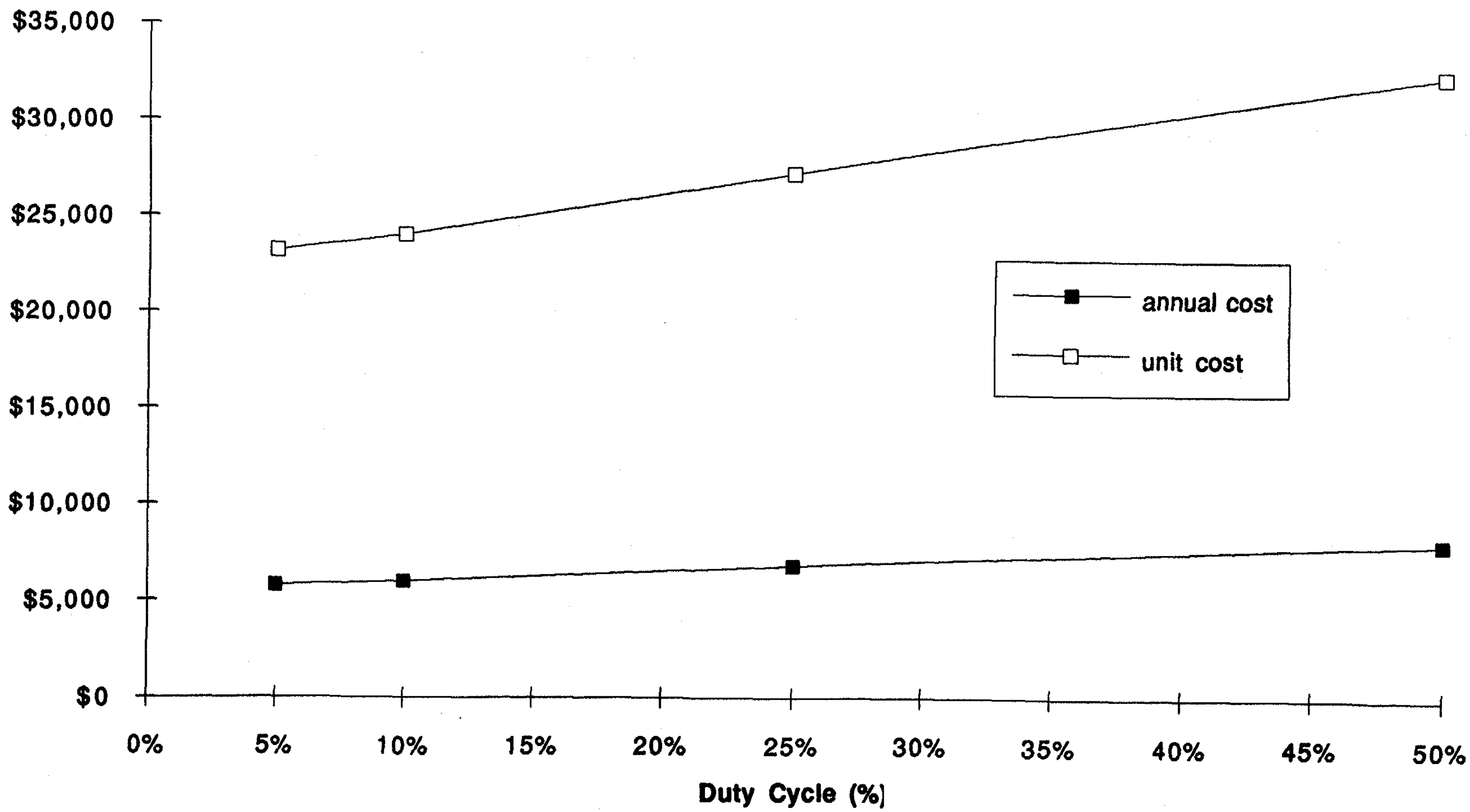
SDP sensitivity to Energy Density. Flow rate is 250 sc



SDP sensitivity to target DRE. Assume fixed 250 scfm, 50 J/l, 99% DRE



SDP sensitivity to duty cycle. Assume 250 scfm, 50 J/l, 99% DRE



Basis of Cost

Row 1	**Title** and **date** of latest revision
Row 2	Applicable **Operational Component** within semiconductor fab
Row 3	The **Target Compound** dictates the SDP energy density requirement. Some compounds require much greater input power to destroy than others. For solvent benches we assume a mix of IPA, methanol, and acetone. Acetone is the designated target constituent because it requires the highest energy density for destruction. For dryers, IPA is the target. For litho tools, PGMEA is the target compound, but HMDS is also readily destroyed at an equivalent energy density.
Row 4	The **Molecular Weight** of the target compound is presented for calculating the VOC loading and subsequent unit cost in $/lb VOC destroyed.
Row 5	Average **Influent Concentration** to the SDP cells in ppm.
Row 6	The **Allowable Effluent Concentration** as governed by state and federal air emissions regulations
Row 7	**Target DRE** = 1 – (B6/B5) This result gives the desired percent destruction which is used in calculating the power requirement.
Row 8	The **Nine-factor** is the number of orders of magnitude of desired destruction of the target compound; thus 99% DRE is equivalent to a nine-factor of 2.
Row 9	**Peak Flow Rate** is the maximum output air flow rate assumed to apply to the given operational component.
Row 10	**Energy Density Required** is the empirically derived amount of pulsed power necessary to destroy one nine-factor (i.e., 90%) of the target compound.
Row 11	**Power Requirement** = (B10*B9*B8*3.785*7.48)/60/1000 This result yields the necessary size of the power supply that drives the SDP system. It is dependent upon the energy density required, flow rate, and desired DRE [3].
Row 12	**VOC loading** = (((B9/0.1336)*3.785*60*(B5/1000000))/22.4)*B4/454 The loading is a function of influent concentration, flow rate, and the molecular weight of the target compound.
Rows 15–19	**Equipment Cost** **Power Supply Size Factor** is a function of the power requirement. Costs for power supplies under 5kW are assumed to be $2/W; from 5kW up to 15kW costs are $1.50/W; from 15kW to 100kW, $1/W, and >100kW systems are costed at $0.75/W [4].

Power Supply = ROUND(B11,)*1000*B15
This is the single largest cost associated with SDP and dependent upon the power requirement and power supply size factor.
Cells and Support Equipment =ROUND(B11,)*100
include primarily pyrex and aluminum to construct the SDP cells and holding tank; this cost is based on $0.10/W, a percentage of the power requirement.
Sales Tax is assumed to be 3% of power supply and support equipment.
Freight is assume to apply to 5% of power supply and support equipment.

Row 20 **Total Equipment Cost (TEC)** is the sum of the power supply, cells and support equipment, sales tax, and freight.

Row 21 **Indirect Costs** are 25% of TEC and include the piping, electrical, labor, and G&A costs incurred to install the system. Installation requires 2 FTEs 1 one day once piping and electrical hookups are completed.

Row 23 **Total Capital Cost** is the sum of TEC and indirect costs.

Rows 26–31 **O&M Costs**
Operating Labor is considered to be approximately 2% of TCC, as the SDP equipment is self-sustaining and only requires periodic monitoring.
Maintenance Labor = B11*0.1*32*50
Based upon 10% of power requirement. For a 10kW system, it is assumed that SDP cells will need cleaning twice annually, requiring 2 employees 2 days for disassembly, assembly, and cleaning. Larger systems have a greater number of cells; hence the dependence on power requirement.
Maintenance Materials are conservatively costed at 4% of TCC.
Footprint takes into consideration both power supply and the SDP cell holding tank dimensions. Approximate equipment footprints are as follows:

10kW:	2' x 4' tank 2' x 2' power supply	12ft^2
20kW:	3' x 4' tank 2' x 2' power supply	16ft^2
50kW:	6' x 4' tank 3' x 2' power supply	30ft^2
100kW:	6' x 8' tank 4' x 2' power supply	56ft^2

Floor Space Unit Cost is based on $75/sq. ft. [5].
Floor Space Annual Cost is the footprint x floor space unit cost.

Row 32 **Total O&M** =SUM(B26+B27+B28+B31)
This is the sum of O&M labor, maintenance materials, and floor space.

Rows 35–38 **Utilities**
Electricity Unit Cost is the price per kWh for electricity and is assumed to be $0.05

Duty Cycle is the percentage of time that the output exhaust from a particular tool is actually being emitted. 25% is considered a conservative estimate.
Electricity Usage = 8760*B11*B36
This value is dependent upon power requirement and duty cycle, and assumes continuous operation.
Annual Electricity Cost = electricity unit cost x usage.

Row 41 **Annual Capital** = 0.1423*B23
The multiplier is based on amortization of TCC at 7% over a 10-year term.

Row 42 **Annual Operating Cost** is the same as operating labor (Row 26).

Row 43 **Annual Maintenance** is the sum of maintenance labor and materials.

Row 44 **Annual UtilitiesA** is the same as annual electricity cost (Row 38).

Row 45 **Total Annual Cost** is the sum of amortized capital, operating, maintenance, and utilities

Row 46 **Present Value 10-year O&M Cost** = 8.618*(B42+B43+B44)
This value is the total cost of O&M plus utilities over 10 years. The multiplier is based on the current discount rate of 2.8%.

Row 47 **Total Present Value Cost** is the sum of the present value 10-year O&M cost plus the TCC.

Row 48 **Annual VOCs Destroyed** are the pounds per year of target exhaust compounds treated, assuming continuous operation (VOC loading x 8760 hours).

Row 49 **Cost of Ownership** = B45/48
This value is the unit cost in $/lb VOCs destroyed, and is derived by dividing the total annual cost by the annual VOCs destroyed.

Row 50 **Cost of Ownership** = ROUND((B45/B9)*1000,-2)
This is COO in terms of $/1,000 scfm and is calculated by dividing total annual cost by the peak flow rate (Row 9).

Contacts

John Coogan
Los Alamos National Laboratory

Peter Chase
High Mesa Technology

References

[1]. Coogan, J., and A. Jassal, "Non-thermal Plasma for Abatement of VOC Emissions from Semiconductor Manufacturing Processes: Interim Report," presented to SEMATECH, January 1996.

[2]. Bowie, K., personal communication, December 6, 1996.

[3]. Coogan, J., personal communication, December 5, 1996.

[4]. Elgar Power Supply Co., personal communication to John Coogan, December 10, 1996.

[5]. Jassal, A., personal communication, December 3, 1996.

SDP flow rate sensitivity

flow rate	annual cost	unit cost
85	$2,300	$27,100
100	$2,800	$28,000
145	$3,900	$26,900
191	$5,100	$26,700
200	$5,200	$26,000
265	$7,300	$27,500
500	$13,600	$27,200
636	$17,100	$26,900
706	$18,900	$26,800
911	$24,500	$26,900
1000	$26,800	$26,800

ASSUME 50 J/l energy density reqr
ASSUME 99% DRE (=> 100 J/l)
" " 75% duty cycle

SDP energy sensitivity

energy reqmnt	annual cost	unit cost
40	$5,200	$20,800
50	$6,800	$27,200
75	$10,200	$40,800
100	$13,600	$54,400
200	$26,800	$107,200
400	$53,700	$214,800
800	$107,600	$430,400

Assume fixed flow rate of 250 scfm
99% DRE
25% duty cycle

Target DRE (%	annual cost	unit cost
90	$3,400	$13,600
99	$6,800	$27,200
99.9	$10,200	$40,800
99.99	$13,600	$54,400

ASSUME 250 scfm flow
50 J/l E.D. reqt
~~99% DRE~~
25% duty cycle

SDP duty cycle sensitivity

duty cycle	annual cost	unit cost
5%	$5,800	$23,200
10%	$6,000	$24,000
25%	$6,800	$27,200
50%	$8,100	$32,400

ASSUME DRE = 99%
FLOW RATE = 250 scfm
ENERGY DENSITY = 50 J/l