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Regional Center for Environmental Information
US EPA Region III
1650 Arch St
Philadelphia, PA 19103

U.S. EPA Region III
Regional Center for Environmental
Information
1650 Arch Street (3PM52)
Philadelphia, PA 19103

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VOLATILE ORGANIC COMPOUND EMISSION CONTROLS
FOR WITCO CHEMICAL CORPORATION PLANT
IN TRAINER, PENNSYLVANIA

by

PEDCo Environmental, Inc
1006 N. Bowen Road
Arlington, Texas 76012

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Eileen Glen

U.S. ENVIRONMENTAL PROTECTION AGENCY
REGION III
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SUMMARY

The Witco Chemical Corporation plant in Trainer, Pennsylvania, produces oil-soluble sulfonic acids and sulfonate salts by treating hydrocarbons and phenols with oleum (a solution of sulfur trioxide in 100 percent sulfuric acid) and neutralizing the acid. The reactions take place in a proprietary solvent solution. Although most of the solvent that evaporates is recovered via a system that includes refrigeration and a condenser, a material balance indicates that the plant emits 1200 tons of VOC per year.

Five systems were evaluated for additional VOC control at this plant:

- ° Incineration without heat recovery
- ° Incineration with heat recovery
- ° Carbon adsorption
- ° Refrigeration
- ° Refrigeration combined with carbon adsorption

All of these systems are technically feasible. The nonincineration systems also offer the possibility of recovery and reuse of nitrogen in the process for additional cost savings. Table 1 presents the comparative costs of the five systems. Except for the first option (incineration without heat recovery), all of the systems would result in a net annual savings to the company.

The absence of any significant fugitive VOC sources at the plant should be verified, as no costs for controlling fugitive emissions are included in the estimates. Compliance can be monitored via solvent purchases and inventory.

TABLE 1. COST COMPARISON OF VOC CONTROL SYSTEMS
FOR WITCO CHEMICAL
(September 1982 dollars)

Cost	VOC Control System				
	Incineration	Incineration with heat recovery	Carbon adsorption	Refrigeration	Refrigeration with carbon adsorption
Capital investment	120,000	320,000	180,000	1,290,000	141,000
Annual cost	28,100	74,900	74,800	427,200	50,800
VOC recovery credit	-	(127,300)	(360,700)	(360,700)	(360,700)
Net annual cost (credit) w/o nitrogen credit	28,100	(52,400)	(285,900)	66,500	(309,900)
Nitrogen recovery credit	-	-	(424,900)	(424,900)	(424,900)
Net annual cost (credit)	28,100	(52,400)	(710,800)	(358,400)	(734,800)

SECTION 1

INTRODUCTION

Over the past several years the U.S. Environmental Protection Agency's (EPA's) Office of Air Quality Planning and Standards (OAQPS) has developed a series of Control Techniques Guidelines (CTGs) for volatile organic compounds (VOC) to assist state and local agencies in developing regulations for VOC control. Although the CTGs cover major VOC source categories from an overall nationwide perspective, several VOC source categories that are not covered by CTG documents are major contributors to the ozone problem within given areas.

Air pollution control agencies in the Philadelphia Air Quality Control Region (AQCR) have requested guidance in determining whether VOC controls are available for these non-CTG sources. The agencies have requested information for use in the development of appropriate regulations. This evaluation of potential VOC controls for the Witco Chemical Corporation plant at Trainer, Pennsylvania, is in response to that request.

1.1 SOURCE DESCRIPTION AND TYPES OF VOC EMISSIONS

Witco produces oil-soluble calcium, magnesium, and sodium sulfonates¹ for use as lubricant additives. The process has two steps. In the first step, the sulfonic acid is made by reacting a high-molecular-weight aromatic hydrocarbon or phenol with oleum (a solution of sulfur trioxide in 100 percent sulfuric acid). After the sulfonation reaction has taken place, the solvent is removed by distillation and condensation. In the second step, the sulfonic acid is reacted with the appropriate base (calcium, magnesium, or sodium hydroxide) and then dried to produce sulfonate salt. The reaction takes place in a volatile organic compound solution; most of the VOCs from this process are routed through the condenser system (S01), and the rest are vented through a separate stack (S08). A flow diagram of this process is presented in Figure 1. Witco considers the identity of this solvent to be proprietary; it is

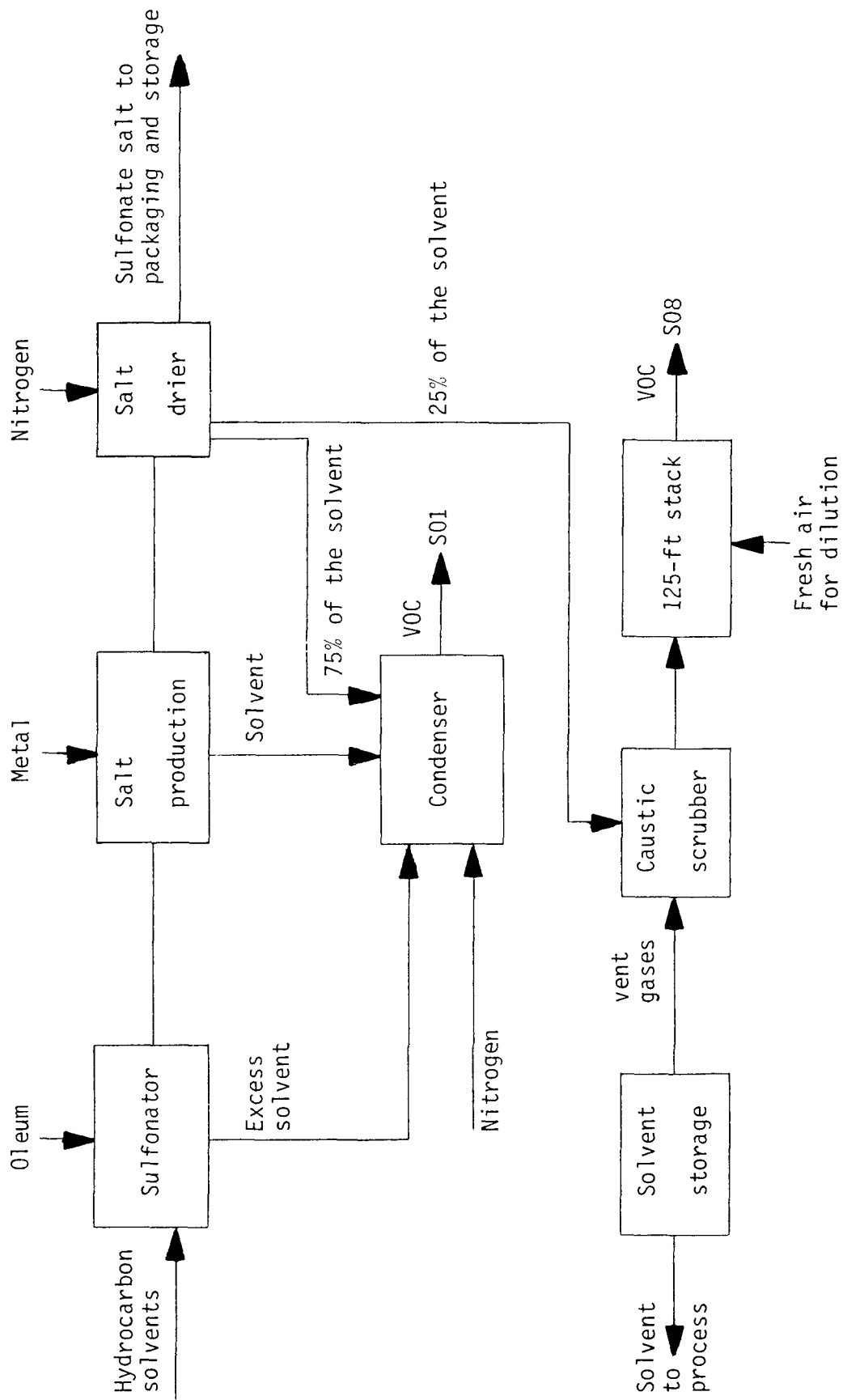


Figure 1. Flow diagram for the Witco plant.

a water-insoluble, flammable VOC with a density of about six pounds per gallon.

Reactions that form sulfonate salts also take place in this solvent medium. The bulk of the VOC from this process is routed to the condenser, which is used in sulfonic acid manufacturing. After the sulfonic acid has been manufactured, most of the solvent is removed by distillation.

Total VOC emissions amount to about 400 pounds per hour or 1200 tons per year. Because the solvent is flammable, all distillation and evaporation takes place in a nitrogen atmosphere. The nitrogen flow rate is about 1425 scfm.

The VOC emission rates were obtained from a report that Witco submitted to the Pennsylvania Department of Environmental Resources, and they are based on a material balance.² All the solvent from sulfonation and salt production and about 75 percent of the solvent from salt drying is sent first to the condenser, and then through a 100-ft stack (emission point S01). The other 25 percent of the solvent from salt drying is routed through a caustic scrubber to the 125-ft dryer stack (emission point S08) for uncontrolled emissions. It is assumed that no fugitive emissions occur and that all VOC emissions come from one of the two identified emission points.

The plant uses natural gas and fuel oil with a 0.5 percent maximum sulfur content to provide process heat and steam. Natural gas is sold to Witco on an interruptible service basis. It is the cheaper of the two fuels and thus is used whenever available. Heat produced by combustion of the VOC used in the plant process could replace fuel as a source of process heat and steam. This would be equivalent to about 10 per cent of the output from one of the process boilers.

SECTION 2

EMISSION CONTROL TECHNIQUES

2.1 CURRENT WITCO PRACTICES

The VOC emissions from the process reactor are controlled first by a chilled-water condenser that operates at a maximum temperature of 35° to 40°F (2° to 4°C). The water is chilled by cooling towers and a refrigeration system. The gas stream from the condenser, which contains about 98 percent nitrogen and 2 percent VOC, then passes through a refrigeration system, where it is cooled to below 10°F (-12°C). Most of the solvent from the sulfonate salt dryers is routed through the condenser system, but about 25 percent is vented through a separate stack.

2.2 PROPOSED CONTROL SYSTEMS

Improved VOC control can be achieved by incineration, incineration with heat recovery, additional refrigeration, or a combination of refrigeration and carbon adsorption, all of which are technically feasible. Each of these systems is evaluated in the following subsections.

2.2.1 Incineration

Incineration of the gas streams from the condenser and dryer is technically feasible. The solvent concentration in the gas stream appears to be large enough so that supplemental fuel would not be required for incineration. Because the stream contains very little oxygen, however, combustion air would have to be added.

2.2.2 Incineration With Heat Recovery

It is estimated that about 65 percent of the heat content of the solvent could be recovered for use in the plant.

2.2.3 Carbon Adsorption

Additional VOC emission control could be obtained by routing the gas streams from the condenser and dryer through a bed of activated carbon. Because solvent is insoluble in water, it can be recovered from the carbon by steam stripping and then reused in the plant. The adsorber would have two carbon beds; this allows one bed to be regenerated while the other one is on line.

2.2.4 Refrigeration

Additional refrigeration of the gas stream could further reduce emissions. Cooling to -110°F (-79°C) should achieve at least a 90 percent reduction in VOC emissions (E. Pijanowski, Trane Thermal, Inc., personal communication, February 23, 1983). A large refrigeration unit would be required to handle the volume of nitrogen that would have to be cooled.

2.2.5 Combined Refrigeration and Carbon Adsorption

A combination system that incorporates both refrigeration and carbon adsorption is less expensive to install than a system that uses only one control device. Both components in such a system are much smaller than would be required for a single corresponding control system capable of achieving the same overall control efficiency.

2.2.6 Other Control Methods Considered

Catalytic incineration is not feasible because sulfonate metal salts are formed in the plant process.³ Metal compounds tend to deposit on the catalyst surface and render it inactive. Although the same problem might apply to a carbon adsorber, replacement of all or part of the carbon is relatively easy and inexpensive.

The use of the gas stream as fuel for an existing process boiler is also impractical. The large volume of inert gas (nitrogen) that would have to be routed through the boiler could adversely affect the operation of the burner by causing incomplete combustion, deposition of tars and resins on heat transfer surfaces, and tube fouling.⁴

SECTION 3

COST ANALYSIS

Some of the data presented in this section has been combined or is approximated to avoid revealing information that Witco considers confidential. Calculations performed with these approximations represent actual plant conditions reasonably well and do not materially affect the conclusions of this study.

3.1 PLANT PARAMETERS

The combined flow rate from the sulfonic acid and sulfonate salt units is 90,000 scf per hour; most of the flow comes from the sulfonic acid unit. About 1600 scf per hour of the stream is solvent, and the balance is nitrogen. The 400 pounds of solvent per hour has a recovery value of \$67 (16.7 cents per pound) as solvent and it has a heat content of 8×10^6 Btu/h.

3.2 NITROGEN CREDIT

The plant currently exhausts a solvent-contaminated nitrogen stream that could be recycled to the process if the solvent were removed. The estimated capital cost for equipment to recycle the nitrogen is \$120,000. The annual cost for operating this equipment would be \$29,600; however, this equipment would produce an annual nitrogen credit of \$454,500, which reduces the annual cost to a credit of \$424,900 (as shown in Table 2). This credit is based on a nitrogen price of \$30 per ton (W. Reiger, Union Carbide Corporation, personal communication, March 3, 1983) and an 80 percent net recovery efficiency (90 percent control device efficiency with 10 percent blowdown to maintain nitrogen quality).

3.3 INCINERATION

The 1500-scfm VOC-nitrogen stream would be burned in 26 percent excess air. No incremental fuel would be required. About 65 percent of the 8×10^6

TABLE 2. NITROGEN RECOVERY
(September 1982 dollars)

CAPITAL COST	
Installed equipment	120,000
ANNUAL COST	
Capital recovery factor	14,100
Operating and maintenance	5,700
Property taxes and insurance	4,800
Utilities	<u>5,000</u>
Total annual cost	29,600
Nitrogen recovery credit	(454,500)
Net annual credit	(424,900)

Btu/h would be recoverable, based on an incineration temperature of 2000°F and a stack exhaust temperature of 400°F. An incinerator without heat recovery would cost about \$60,000. Adding a waste heat boiler would increase the equipment cost by about \$100,000. Installation costs would be about equal to equipment costs. Credits for recovered heat are based on a price of \$4.08/10⁶ Btu paid for natural gas by Pennsylvania utilities in September 1982.⁵ This would be \$127,300 per year. If the recovered heat displaced No. 6 fuel oil, the credit would be \$4.847/10⁶ Btu.⁵

A capital recovery factor of 14.67 percent of the total capital investment (based on a 12-year equipment life and a 10 percent interest rate) was used.⁶ Property taxes and insurance were estimated to be 4 percent of total capital costs and maintenance costs were estimated to be 4.75 percent of total capital costs.

3.4 CARBON ADSORPTION

Vic Manufacturing Company and Hoyt Manufacturing Company provided separate cost estimates for a carbon adsorber to handle the VOC stream at Witco (N. Shaw, Vic Manufacturing Company, personal communication, March 14, 1982 and V. Nayak, Hoyt Manufacturing Company, personal communication, March 15, 1983). The respective estimated equipment costs from the two vendors were \$95,000 and \$145,000; in both cases, installation costs were estimated to be

an additional 50 percent. Equipment and installation costs are site-specific, but it was estimated that the cost of the necessary duct work and blowers would amount to 50 percent of the carbon adsorber equipment cost. The two estimates were averaged together to obtain an estimate \$120,000 for the equipment cost and \$180,000 for the installed equipment cost.

The capital recovery factor for carbon adsorber systems is based on a 20-year life and a 10 percent interest rate. The capital recovery factor, nonvariable operating and maintenance costs (estimated at 4.75 percent), and property taxes and insurance (estimated at 4.0 percent) add up to 20.5 percent of the total capital cost. Low pressure steam is estimated to cost \$3.50 per thousand pounds. (L. Nisbet, PEDCo, Inc., personal communication, December 1, 1982). Vic estimated that 5 pounds of steam would be required to strip 1 pound of solvent (N. Shaw, Vic Manufacturing Company, personal communication, March 14, 1982). Properties and prices of the solvent were obtained from standard references.^{7,8}

The sulfonic acid manufacturing process operates 5940 hours per year, and the sulfonate salt manufacturing process operates 6720 hours per year.² The carbon adsorber was assumed to operate an equivalent of 6000 hours per year because sulfonic acid manufacturing produces most of the VOC emissions. Solvent credits are based on 90 percent recovery of 400 pounds per hour and a price of 16.7 cents per pound.

Annual costs include a capital recovery charge of 11.75 percent of the capital investment, based on a 20-year life and a 10 percent interest rate; operating and maintenance costs are estimated to be 4.75 percent of capital costs; and property taxes and insurance charges are estimated to be 4 percent of capital costs.

3.5 REFRIGERATION

Capital and operating costs for VOC control by refrigeration were obtained from a published report⁹ and updated to September 1982 dollars by use of cost indices published in Chemical Engineering. To achieve 90 percent control would require cooling to about -110°F (-79°C).⁹ The installed cost for a refrigeration system would be \$1.29 million.

The capital recovery charge is 14.67 percent of the total capital investment; this is based on a 10 percent interest rate and a 12-year equipment life.⁶ Operating and maintenance costs are estimated to be 2.4 percent of capital costs, and property taxes and insurance are estimated to be 4 percent of capital costs. Estimated annual power requirements are 3.21 million kilowatt-hours (E. Pijanowski, Trane Thermal, Inc., personal communication, February 23, 1982). At a cost of \$0.0484/kWh, this would be \$155,400 per year. As in the case of the carbon adsorber, refrigeration would recover the solvent and possibly enable the plant to recycle the nitrogen to the process.

3.6 COMBINED REFRIGERATION AND CARBON ADSORPTION

A combination of refrigeration and carbon adsorption seems to be the most economical VOC control method. Refrigeration would lower the VOC vapor pressure and condense out much of the VOC. This would reduce the VOC loading on the carbon adsorber and allow the use of a smaller unit. The prospect of using sufficient refrigeration to halve the VOC pressure and halve the size of the carbon adsorber was analyzed. This approach would reduce capital costs and related annual costs. It would also reduce overall utility costs because the reduction in steam requirements to strip the carbon adsorber would more than offset the cost of electricity for the refrigeration unit.

Actual costs would be site-specific; optimization of the trade-off between increased refrigeration and decreased carbon adsorption would require a more detailed engineering evaluation of the Witco facility. Capital costs would be \$22,200 for incremental refrigeration (E. Pijanowski, Trane Thermal, Inc., personal communication, February 23, 1983) and \$118,800 for a carbon adsorber, for a total installed equipment cost of \$141,000. Annual costs are estimated to be \$50,800. With a VOC recovery credit of \$360,700, the net annual credit would be \$309,900. This amount, plus an annual nitrogen credit of \$454,500, yields a net credit of \$764,400 for this system.

3.7 COST-EFFECTIVENESS

Table 3 summarizes capital cost, annual cost, and cost-effectiveness determinations for carbon adsorption, incineration, refrigeration, and combined refrigeration-carbon adsorption. Incineration with heat recovery would

TABLE 3. CAPITAL COSTS, ANNUAL COSTS, AND COST-EFFECTIVENESS OF VARIOUS VOC CONTROL SYSTEMS
(September 1982 dollars)

	Incineration	Incineration with heat recovery	Carbon adsorption	Refrigeration	Combined refrigeration adsorption
CAPITAL COST					
Installed equipment	120,000	320,000	180,000	1,290,000	141,000
ANNUAL COST					
Capital recovery factor	17,600	46,900	21,200	189,200	17,200
Operating and maintenance	5,700	15,200	8,600	31,000	6,700
Property taxes and insurance	4,800	12,800	7,200	51,600	5,600
Steam and utilities	<u>0</u>	<u>0</u>	<u>37,800</u>	<u>155,400</u>	<u>21,300</u>
Total annual cost	28,100	74,900	74,800	427,200	50,800
VOC or heat recovery credit ^a	-	(127,300) ^b	(360,700) ^c	(360,700) ^c	(360,700) ^c
Net annual cost (credit) ^a	28,100	(52,400)	(285,900)	66,500	(309,900)
Nitrogen recovery credit ^d	-	-	(424,900)	(424,900)	(424,900)
Net annual cost (credit) ^d	28,100	(52,400)	(710,800)	(358,400)	(734,800)
Tons of VOC controlled	1,080	1,080	1,080	1,080	1,080
Cost (credit) per ton of VOC controlled	26	(49)	(658)	(332)	(680)

^aIncludes VOC or heat recovery credit.

^bHeat recovery credit.

^cVOC recovery credit.

^dIncludes VOC or heat and nitrogen recovery credit.

result in an annual credit of \$89,800 on a \$160,000 capital investment. Carbon adsorption would result in an annual credit of \$285,900 on a \$180,000 capital investment. The refrigeration-carbon adsorption combination would result in an annual credit of \$309,900 on a \$141,000 capital investment. All of these control options appear to be attractive investments, with credits ranging from \$83 to \$287 per ton on VOC controlled. Incineration without heat recovery would cost \$13 per ton of VOC controlled, and vapor recovery would cost \$62 per ton of VOC controlled.

The economics of VOC emission control by carbon adsorption, vapor recovery, and the refrigeration-carbon adsorption combination are improved greatly if all or part of the nitrogen can be recovered and recycled. An annual credit of \$424,900 on a \$120,000 capital investment is obtainable, based on recycling 80 percent of the nitrogen and a nitrogen cost of \$30 per ton (W. Reiger, Union Carbide, personal communication, March 3, 1983). Costs and credits for nitrogen recycling are shown in Table 1 (in the Summary).

Witco's emissions are based on a material balance and on the assumption that all VOCs are emitted through the two stacks (no fugitive emissions). Some plant testing may be necessary to verify this assumption.

4. REGULATORY ANALYSIS

This section contains a draft regulation, applicable compliance and monitoring techniques, and a discussion of potential problem areas.

4.1 DRAFT REGULATION

A. Definitions

1. For the purpose of this regulation, the general definitions apply.
2. For the purpose of this regulation, the following definitions also apply.
 - a. "Control system" means any number of control devices that are designed and operated to reduce the quantity of VOC emitted to the atmosphere.
 - b. "Carbon adsorber" means a device that adsorbs VOC on activated carbon in such a manner that at least a 90 percent reduction in VOC emissions to the atmosphere is achieved.
 - c. "Incinerator" means a device that burns VOC in such a manner that at least a 90 percent reduction in VOC emissions to the atmosphere is achieved.
 - d. "Vapor recovery unit" means a device that removes VOC from gas streams by any combination of refrigeration and compression in such a manner that at least a 90 percent reduction in VOC emissions to the atmosphere is achieved.
 - e. "Refrigeration" means cooling of a VOC-containing gas in such a manner as to lower the partial vapor pressure of the VOC.
 - f. Equipment normally used in manufacturing (e.g., condensers) shall not be considered to be part of any "control system" and shall not be used to claim credits for VOC emission reductions.

B. Applicability

1. This regulation applies to manufacturers of surface active agents, finishing agents, sulfonated oils, and assistants as defined by Standard Industrial Classification 2843. This includes, but is not limited to, the manufacture of sulfonic acids, metal sulfonate salts, sulfonated phenols, and metal phenate salts.
2. This regulation applies to the control of VOC emissions in manufacturing processes in which VOC can be employed as a solvent, reactant, product, or intermediate.
3. VOC sources that emit less than 10 tons (9091 kilograms) per year or 55 pounds (25 kilograms) per day shall be exempt from this regulation. The most stringent requirement will apply.

C. Provision for Specific Processes

1. Carbon adsorbers, vapor recovery units, incinerators, refrigeration, or any combination of these controls shall be used.
2. Equivalent controls may be used, but they must reduce VOC emissions by at least as much as the control devices cited in C-1.
3. The owner or operator of a facility subject to this regulation shall reduce the VOC emissions from all process equipment:
 - a. By at least 90 percent if VOC emissions are equal to or more than 550 pounds (250 kilograms) per day; or
 - b. To 55 pounds (25 kilograms) per day or less if VOC emissions are less than 550 pounds (250 kilograms) per day.

D. Compliance Schedules

1. The owner or operator of a facility subject to this regulation must meet the applicable increments of progress shown in the following schedule:
 - a. Submit final plans for all emission control systems and process equipment within 5 months after this regulation is in effect.
 - b. Award contracts or purchase orders for all emission control systems and process equipment within 8 months after this regulation is in effect.
 - c. Initiate onsite construction or installation of all emission control and process equipment within 12 months after this regulation is in effect.

- d. Complete onsite construction or installation of the emission control and process equipment within 18 months after this regulation is in effect.
 - e. Achieve final compliance, demonstrated as specified in Section E, within 24 months after this regulation is in effect.
2. The owner or operator of a facility subject to this regulation may submit to the Director a proposed alternative compliance schedule, and the Director may approve such a schedule, provided:
- a. The proposed alternative compliance schedule is submitted within 3 months after this regulation is in effect.
 - b. The owner or operator provides information showing the need for an alternative schedule.
 - c. The alternative compliance schedule contains increments of progress.
 - d. The owner or operator of the facility submits sufficient documentation and certification from appropriate suppliers, contractors, manufacturers, or fabricators to justify the dates proposed for the increments of progress.
 - e. Final compliance is achieved as expeditiously as possible and before the photochemical oxidant attainment date.
3. The owner or operator of a facility subject to a compliance schedule of this section shall certify to the Director within five days after the deadline for each increment of progress whether the required increment of progress has been met.

E. Determining Compliance

1. The owner or operator of a VOC source subject to this regulation shall demonstrate compliance by:
- a. Certifying that the appropriate control equipment is in place and in use.
 - b. Providing the Director with certified analyses of all VOC in place and in use. Analyses may be provided by the owner-operator of the source, the manufacturer of the VOC, or an independent laboratory acceptable to the Director.
 - c. Maintaining VOC purchasing, inventory, and consumption records in such a manner that the Director can determine compliance.
 - d. Maintaining the appropriate control equipment in a manner consistent with manufacturer's recommendations.

- e. Maintaining operating and maintenance records on the appropriate control equipment in such a manner that the Director can determine compliance.
2. The Director may require that the owner or operator of a VOC source subject to this regulation demonstrate compliance by conducting emission tests in a manner consistent with U.S. EPA standards. All tests shall be made by, or under the direction of, a person qualified by training and/or experience in the field of air pollution testing. The Director shall receive at least 30 days' advance notice of such testing so that the Director and/or his authorized representative(s) may witness the test.

A source emitting 550 pounds per day 365 days per year would be a 100-ton per year source. The regulation would require VOC emission reduction to 55 pounds per day or 10 tons per year.

4.2 REGULATIONS IN OTHER AREAS

No BACT/LAER determinations, New Source Performance Standards, or regulations applicable to this industry were found.

4.3 COMPLIANCE AND MONITORING TECHNIQUES

Emissions can be accurately estimated from solvent inventories and purchasing records, and they can be verified by spot inspections. The plant may also demonstrate compliance by submitting monthly material balances.

4.4 POTENTIAL PROBLEM AREAS

Control equipment has been sized and economic evaluations have been made on the basis of 1980 data Witco submitted to the Pennsylvania Department of Environmental Resources.² The timeliness of this information would have to be verified before any control equipment could be mandated.

If purchasing and inventory records indicate that VOC emissions are still excessive after control equipment has been installed, it may be necessary for the agency to examine production and operating schedules to determine whether the control equipment is adequate to comply with regulations. This will entail obtaining the following information:

1. Operating schedules for all equipment connected to the control device(s).

2. VOC quantities potentially routed to the control device(s).
3. Operating capacity and schedule of the control device(s).

If the question is still unresolved, VOC emission testing may be necessary.

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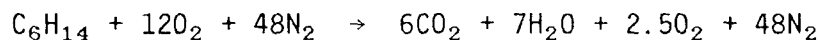
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APPENDIX A

OUTLINE OF CALCULATIONS FOR
INCINERATOR PERFORMANCE AND HEAT RECOVERY

APPENDIX A

OUTLINE OF CALCULATIONS FOR INCINERATOR PERFORMANCE AND HEAT RECOVERY



Hexane = 393 pounds per hour in 26% excess air

Process nitrogen = 1425 scfm = 85,500 scfh = 6309 pounds

$$\text{Carbon dioxide} = \frac{393 \times 6 \times 44}{86} = 1206 \text{ pounds}$$

$$\text{Water} = \frac{393 \times 7 \times 18}{86} = 576 \text{ pounds}$$

$$\text{Oxygen} = \frac{393 \times 2.5 \times 32}{86} = 366 \text{ pounds}$$

$$\text{Nitrogen from air} = \frac{393 \times 48 \times 28}{86} = 6142 \text{ pounds}$$

$$\text{Total nitrogen} = 6309 + 6142 = 12,451 \text{ pounds}$$

$$\begin{aligned} \text{To heat to } 1500^\circ\text{F} &= (1206 \times 377.6) + (576 \times 717.6) + (366 \times 350.8) + \\ &\quad (12,451 \times 378.7) = 5,712,311 \text{ Btu} \end{aligned}$$

$$\begin{aligned} \text{To heat to } 2000^\circ\text{F} &= (1206 \times 531.4) + (576 \times 1003.1) + (366 \times 84.5) + \\ &\quad (12,451 \times 523.0) = 7,761,454 \text{ Btu} \end{aligned}$$

Fuel value of hexane = 20,771 Btu/lb

$$393 \times 20,771 \approx 8.163 \text{ million Btu}$$

2000°F is attainable