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A RAND GRADUATE SCHOOL DISSERTATION

Analyzing Environmental Policies for Chlorinated Solvents with a Model of Markets and Regulations

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Analyzing Environmental Policies for Chlorinated Solvents with a Model of Markets and Regulations

David Pekelney

The original version of this study was prepared as a dissertation in November 1990 in partial fulfillment of the requirements of the doctoral degree in public policy analysis at the RAND Graduate School. The faculty committee that supervised and approved the dissertation consisted of Frank Camm (Chairman), Bart Bennett, and Katy Wolf.

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PREFACE

This analysis concerns the regulation of five chlorinated solvents employed ubiquitously in the economy. These chemicals have many known negative health and environmental effects. The economic model developed in this document, by simulating markets that use chlorinated solvents, can facilitate the design of more coordinated regulations. As such, this research should be of interest to officials in government and industry who make policies that control chlorinated or other hazardous solvents.

This document fulfills requirements for the degree of Doctor of Philosophy in Policy Analysis from the RAND Graduate School. Funding was provided by the National Science Foundation sponsored UCLA Engineering Research Center for Hazardous Substances Control and the RAND Graduate School.

SUMMARY

Chlorinated solvents are a class of chemicals facing government regulation because they are hazardous to health and to the environment. Public and private policymakers face major difficulties in responding to these hazards because regulation of each chemical is separate from the others and separate for land, water, and air media, even though their environmental consequences are interdependent. Furthermore, substitutes for these chemicals are often unsafe, costly, or hard to find. Major industries, such as electronics, aerospace, fabricated metal products, and dry cleaning depend heavily on chlorinated solvents in their production processes.

For example, regulations on trichloroethylene (TCE) have developed over the past twenty years due to its suspect carcinogenicity, toxicity, and contributions to photochemical smog. Although it appeared that TCE regulations reduced overall hazards to health and the environment, we have since discovered that they shifted hazards from the troposphere to the stratosphere. The reason is that the primary substitute for TCE, 1,1,1-trichloroethane (TCA), contributes to stratospheric ozone depletion. TCA is now being regulated more stringently, and one of the major substitute solvents contains d-limonene, which is combustible and has shown positive carcinogenicity in male rats. This case illustrates how government and industry officials face the difficult task of designing environmental policies to *reduce* overall environmental hazards rather than to *change* from one environmental hazard to another.

New regulations on chlorinated solvents cause large-scale substitutions to alternative solvents and cleaning methods. Some alternative solvents remain untested for their health and environmental effects. Without a characterization of solvent substitutions induced by environmental policies, government officials cannot design regulations that consider the relative risks of those substitutions. Hence, we are more likely to repeat the pattern of substituting one environmental hazard for another.

The model described in this document is capable of accounting for solvent substitutions and suggesting the direction and magnitude of those substitutions; it can aid in developing public policy by simulating regulations and their effects on chlorinated solvent markets. Before a solvent policy analysis is complete, additional consideration is needed of the health and environmental consequences, institutional questions, and political concerns.

The first component of the model is a list that accounts for all of the substitute solvents in the major chlorinated solvent cleaning applications. The applications included in the model are metal parts cleaning, electronics parts cleaning, dry cleaning, and paint removal. For each solvent, there is a list of inputs, such as labor, assets, and solvent. These inputs substitute partially for one another in production processes. The second of the model's components is a group of economic equations that represents all of the solvent substitutions in mathematical form. The third component is a large group of parameters that numerically specifies the degree of substitution represented by the economic equations. The final component is a group of quantity constraints and taxes that simulates regulations and environmental policies.

The greatest difficulty in implementing this model is collecting and preparing data that are commensurate with the economic parameters. Substitution parameters are problematic because there are no data available for econometric estimation and because historical information is of little use for rapidly changing technology. Instead, the process for numerically specifying the substitution parameters involves eliciting expert judgments and then normalizing the parameters to assure the equations are consistent with economic theory. Sensitivity tests analyze the results with respect to the method of normalizing parameters, among other sources of uncertainty. In addition, the expert examines results to determine the extent to which the model alters the character of the original judgments.

With the model fully specified, a computer program finds a general equilibrium solution to the system of equations by finding the point where supply equals demand for each solvent and input. The program solves a nonlinear optimization problem where the objective function is the sum of squared differences between supply and demand, and constraints are regulatory measures restricting solvent use.

A numerical example highlights the type of results generated by the model and demonstrates how the model analyzes environmental policies. Under the original Montreal Protocol, an international agreement to reduce stratospheric ozone depletion, the production of Chlorofluorocarbon 113 (CFC-113) is being reduced to 80 percent of the 1986 level by the year 1993. In this case, constraints and taxes on solvent supply in the model represent these new regulations. The results show a reduction of regulated solvents and an increase in solvent substitutes, including chlorinated solvents, nonchlorinated solvents, and nonchemical methods. In electronics cleaning applications, for example, the substitution is away from CFC-113 and to aqueous-based solvents, terpene solvents, and new fluxes that require no cleaning.

ACKNOWLEDGMENTS

I am indebted to my colleagues, friends, and family for their assistance with this project. Katy Wolf showed me the importance of interdisciplinary research to environmental policy, and her commitment and guidance have been invaluable throughout the dissertation process. Frank Camm skillfully directed me through the world of production theory and the development of the applied economic model. Tom Chesnutt, in his role as *de facto* committee member, helped me jump hurdles in computing and mathematics. Without Bart Bennett's assistance, the optimization program might still be running; he offered thoughtful advice on numerical analysis and mathematical programming. Joe Bolten worked hard at the bureaucratic politics needed to keep the funding of this project intact and to ensure its management and completion. Special thanks to Dennis Eckart, who introduced me to policy analysis and the importance of critical independent thinking. Many other friends and family members supported me through the entire doctoral program.

All remaining errors are my own.

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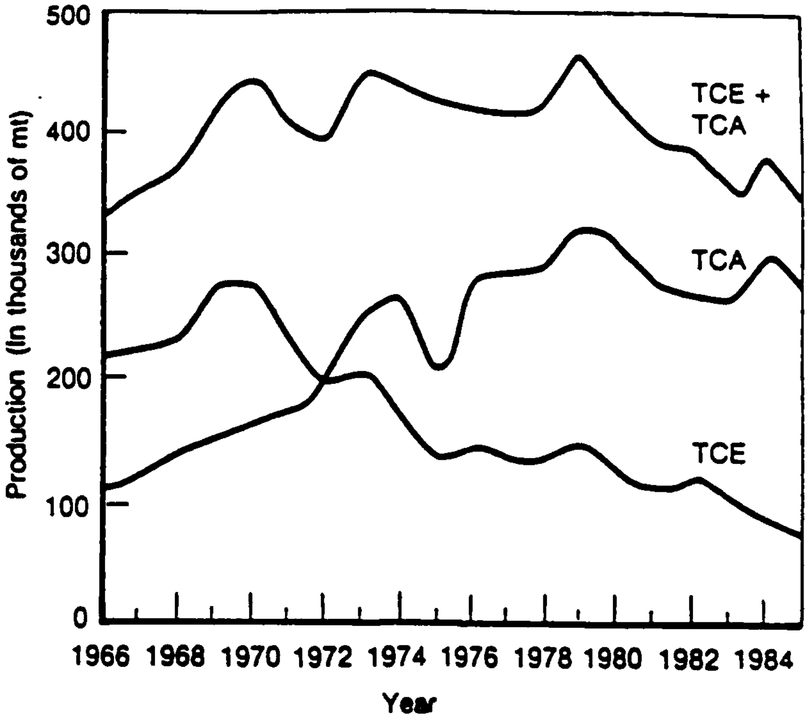
I. INTRODUCTION

POLICY PROBLEM

Chlorinated solvents comprise a family of chemicals that pose three problems for public and private policymakers: (1) They are harmful to health and the environment; (2) governments regulate each chemical separately from the others and separately for land, water, and air media, even though their environmental consequences are interdependent; (3) substitutes for these chemicals are often unsafe, costly, or hard to find. Government regulators have made limited efforts to integrate chlorinated solvent policy, yet regulation remains uncoordinated and has often led to outcomes that merely *change* hazards rather than *reduce* them.

Consider the case of trichloroethylene (TCE), which federal, state, and local agencies regulate heavily because it is toxic, a suspect carcinogen, and it contributes to photochemical smog. The major alternative is 1,1,1-trichloroethane (TCA), which is not highly toxic, carcinogenic, or a smog contributor. Figure 1.1 shows how the production of these two chemicals has responded to the regulatory regime. Although the combined production of these chemicals has remained about the same, TCA has replaced TCE to a large extent. The problem is that TCA contributes to stratospheric ozone depletion.

The potential for ozone depletion by chemicals, such as TCA, was not even suggested until 1974 and was not firmly established by the scientific community until recently. Although it appeared that TCE regulations reduced overall environmental hazards, we have since discovered that they shifted hazards from the troposphere to the stratosphere. Now that TCA is regulated more stringently, one major group of substitutes is terpene solvents. Terpene solvents are combustible, and one ingredient of most cleaning formulations, d-limonene, has generated positive carcinogenicity results in male rats.



SOURCE: Wolf and Camm, 1987.

Fig. 1.1--Substitution of TCA for TCE

The example of TCE solvent substitutions shows why it is difficult to design regulations. In some cases, regulators do not know which solvents will replace the regulated chemical. Even with known substitutes, their hazards may not be established. Only with known substitutes and known hazards is there the possibility of well-informed decisions, and, for these cases, analyzing policies may improve outcomes.

RESEARCH QUESTIONS

Both industry and government are calling for a systematic method to analyze how environmental policies affect specific outcomes, such as solvent demand, air emissions, and changes to production processes.[1] In their efforts to make decisions that are not unnecessarily costly in economic, health, or environmental terms, the following questions arise:

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[1] For example, DuPont, Motorola, AT&T, Chemical Manufacturer's Association, General Dynamics, IBM, California Department of Health Services, and the Environmental Protection Agency (UCLA Engineering

- *How much change will there be in overall levels of solvent demand, air emissions, and hazardous waste generation for each of the chlorinated solvents?* For example, TCA is in high demand because it is a less hazardous substitute for TCE and several other solvents that are under increasing scrutiny.
- *How much substitution will there be to solvents that are less regulated, but may have equal or unknown hazards?* For example, new hydrocarbon solvents may replace chlorinated solvents in metal cleaning and paint removal applications; however, these chemicals have had little testing for carcinogenicity and they contribute to photochemical smog.
- *How much substitution will there be from chemical solvents to nonchemical cleaning processes?* For example, an emerging alternative for removing paint from commercial and military aircraft is plastic media blasting, which generates less hazardous waste.
- *How much will solvent-consuming industries change their production processes to enhance recycling and recovery?* For example, solvent reclamation equipment can reduce the quantity of spent solvent in need of disposal in electronics parts cleaning and dry cleaning.

With information addressing these questions, policymakers in government and industry have the opportunity to make informed decisions.

SIMULATING CHLORINATED SOLVENT MARKETS AND REGULATIONS

Chlorinated solvent applications and substitutions are numerous and diverse, so the question arises, "How can we summarize and analyze all of the information about solvent substitutions to shed light on these research questions?" This is the purpose of the simulation model developed in this analysis.

Research Center for Hazardous Substances Control, Industry Process Substitution-Modification Meeting, UCLA, February 10, 1988).

The simulation model is a detailed mathematical representation of chlorinated solvent substitutions analogous to the process of regulation and substitution described above. Simulated regulations can be designed, coded in the model, and analyzed according to proposed environmental policies.

What are the components of this simulation model? First of all, there is a list or "catalog" of the chlorinated solvents and all of the substitute solvents and substitute processes for a number of important production applications. For each solvent and substitute, there is a list of inputs--such as assets, labor, and solvent--that are needed to make use of solvents in each application. Second, economic equations represent substitutions in mathematical form. The equations allow the degree of substitution between alternatives to be different for each case, as they are in industry. Third, parameter values numerically specify the equations to represent the degree of substitution between competing alternatives. Fourth, simulated regulations, also in mathematical form, represent proposed policies. These simulated regulations can include quantity constraints or taxes similar to what regulators promulgate.

HOW IS THIS MODEL USEFUL?

The simulation model of chlorinated solvent markets and regulations presents summary outcomes of specific policy designs. These results are useful to anyone involved in the policymaking process by:

- accounting for all solvent substitutions;
- suggesting the direction and magnitude of those substitutions;
- comparing explicitly the tradeoffs implicit in solvent regulations.

The model is a search tool for potential problems.[2] This document describes the components of the simulation model and demonstrates how it can aid thinking about new regulations.

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[2] This list of model uses is adapted from Hodges (1989).

ORGANIZATION OF THIS NOTE

The next section introduces the five major chlorinated solvents, as well as their production applications and regulations. Section III describes the structure of the general equilibrium model of chlorinated solvent markets, as well as the form of its equations. Section IV outlines the method of numerical specification for all of the model's parameters and for the benchmark equilibrium data set. Section V tests the model for sensitivity to key assumptions and presents selected results for a relevant policy scenario; and Section VI draws conclusions that are relevant to policy and modeling methodology. Appendix A derives the functional form of the equations in the economic model; and Appendix B includes a complete set of the solution algorithm equations. Appendix C explains details of a subset of cost share parameters. Appendix D shows tables that compare different ways to normalize data for the model. Appendix E is a complete set of results from the model for a specific policy scenario.

II. CHLORINATED SOLVENTS, REGULATIONS, AND PRODUCTION APPLICATIONS

INTRODUCTION TO CHLORINATED SOLVENTS

Chlorinated solvents perform cleaning services in a vast range of industrial and commercial activities and they contributed greatly to economic development. They also end up everywhere from groundwater reservoirs to the stratosphere and contribute to a number of health and environmental problems. The first part of this section describes the five most widely used chlorinated solvents, including their end uses, health effects, and environmental effects. The second part reviews the regulatory regime of each environmental medium. The last part describes the primary production applications that employ these solvents. In essence, this section lays out the "catalog" of chlorinated solvents, their regulations, and their production applications.

The analysis focuses on the five most widely used and emitted chlorinated solvents: trichloroethylene (TCE), methylene chloride (METH), perchloroethylene (PERC), 1,1,1-trichloroethane (TCA), and chlorofluorocarbon 113 (CFC-113)[1] (see Table 2.1). These five have been used throughout the economy for many years in applications such as metal cleaning, paint removal, dry cleaning, and electronics parts cleaning.[2] Together, they make up the vast majority of chlorinated solvent demand in *solvent* applications. Solvent applications in this analysis are applications where solvent dissolves or removes certain constituents. Chlorinated solvents that claim a very small share of the market or perform nonsolvent tasks do not appear in this study.[3]

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[1] Chlorinated solvents are also known as halogenated solvents because they contain one or more of the four halogens: chlorine, fluorine, bromine, and iodine. Another broad term is chlorocarbons (fluorocarbons), which indicates the chlorinated (fluorinated) hydrocarbons.

[2] For a historical perspective on chlorinated solvents see Chesnutt (1988).

[3] Chlorinated solvents not considered in this analysis include carbon tetrachloride, chlorobenzene, ortho-dichlorobenzene, and trichlorofluoromethane (CFC-11) (Wolf and Camm, 1987). Examples of nonsolvent tasks include aerosols, foam blowing, refrigeration, adhesives, pharmaceuticals, and chemical production.

Table 2.1

MAJOR CHLORINATED SOLVENTS

Chemical	Abbreviation
Trichloroethylene	TCE
Methylene Chloride (Dichloromethane, Methylene Dichloride, Methylene Bichloride)	METH
Perchloroethylene (Tetrachloroethylene, Tetrachloroethene, Ethylene Tetrachloride)	PERC
Methyl Chloroform (1,1,1-trichloroethane, Chlorothene)	TCA
Chlorofluorocarbon 113 (1,1,2-trichloro-1,2,2-trifluoroethane, Freon 113)	CFC-113

DESCRIPTION OF CHLORINATED SOLVENTS

TCE

TCE is both nonflammable and volatile, making it very useful in a wide range of applications. It is, arguably, the most effective metal-cleaning solvent available (Kirk-Othmer, 1985, 1979).

Cleaning fabricated metal parts in industries, such as aerospace, electronics, and automobiles, accounts for roughly 70 percent of TCE production. Most metal cleaning is vapor degreasing, where heated solvent vapor condenses on metal parts and carries away contaminants. Cold cleaning, the alternative to vapor degreasing, includes wiping, immersing, or spraying parts with liquid solvent. A total of 20 percent of domestic TCE production is exported, and the remaining 10 percent performs miscellaneous functions, such as chemical intermediates, fabric scouring, fumigants, adhesives, and paints (Kirk-Othmer, 1985, 1979; Chemical Marketing Reporter (CMR), 1989; U.S. EPA, 1981; Wolf and Camm, 1987).

Domestic demand for TCE over the past ten years has been in decline at 5.6 percent per year. The decrease in demand is due primarily to smog regulations. Air regulations control TCE more stringently than the alternatives, so it is more costly in most applications. The slight decrease in production (Table 2.2) would have been more significant; however, from 1984 to 1988, imports decreased by one half and exports increased threefold. Industry sources expect the demand for TCE to decline at 2 to 3 percent annually over the next five years (CMR, 1989).

Table 2.3 summarizes the health and environmental effects of each of the five chlorinated solvents. TCE is a nervous system depressant and produces symptoms similar to those of alcoholic inebriation, in moderate amounts, and narcotic effects, in larger amounts. After heavy

Table 2.2

ANNUAL DOMESTIC PRODUCTION OF CHLORINATED SOLVENTS
(IN THOUSAND METRIC TONS)

Year	TCE	METH	PERC	TCA	CFC-113
1984	86	275	260	306	68
1985	73	263	224	268	73
1986	82	257	188	296	73
1987	82	234	215	315	78
1988	82	229	226	328	78

SOURCES: METH, PERC, and TCA (U.S. International Trade Commission, 1984-1988); TCE and CFC-113 (Wolf, 1990).

Table 2.3

HEALTH AND ENVIRONMENTAL EFFECTS

Solvent	Toxicity	Carcinogenicity	Smog Regulated	Ozone Depletion
TCE	High	Suspect	Yes	No
METH	Medium	Suspect	No	No
PERC	High	Suspect	Yes	No
TCA	Medium	In Progress	No	Yes
CFC-113	Low	Negative	No	Yes

SOURCES: Kirk-Othmer, 1985, 1979; CMR, 1989; U.S.EPA, 1981; Wolf and Camm, 1987.

inhalation, symptoms include headaches, vertigo, tremors, nausea, vomiting, fatigue, intoxication, unconsciousness, and death attributable to ventricular fibrillation. Ingestion may cause liver damage, kidney malfunction, cardiac arrhythmia, and coma. TCE is a possible human carcinogen, according to EPA, based on rat and mouse studies (Kirk-Othmer, 1985, 1979; Wolf and Camm, 1987).

TCE rapidly oxidizes and degrades in the troposphere. Because these processes accelerate in higher temperatures and ultraviolet radiation, this solvent contributes significantly to the formation of photochemical smog. The half-life of TCE (on the order of days) is too short for it to migrate to the stratosphere and deplete the ozone layer (Kirk-Othmer, 1985, 1979; Wolf and Camm, 1987).

METH

METH has excellent solvent properties with waxes, resins, and fats, and it is extremely effective in paint removal. This solvent is nonflammable, very stable, and it does not decompose when exposed to water or metals below boiling point. At higher temperatures and in contact with water, METH corrodes certain metals, such as stainless steel and copper (Kirk-Othmer, 1985, 1979).

Paint removal, aerosols, and chemical processing are the three biggest end uses of METH, consuming 28 percent, 18 percent, and 11 percent of production, respectively. In paint removal, workers either brush or spray METH on painted surfaces and leave it there until the paint blisters. Until recently, aerosol manufacturers combined METH with hydrocarbon propellants to depress vapor-pressure in products, such as cosmetics, carburetor cleaners, and waxes. For chemical processing, METH is a solvent in the production of antibiotics and vitamins. Other METH uses include exports (15 percent), urethane foam blowing (9 percent), metal degreasing (8 percent), electronics (7 percent), and other (4 percent). "Other" includes caffeine extraction from coffee, beer flavoring extraction from hops, and the production of photographic film (Kirk-Othmer, 1985, 1979; CMR, 1989; U.S.EPA, 1981; Wolf and Camm, 1987).

Production of METH has decreased by 2.7 percent per year since 1979. If predictions hold true, METH will decrease more rapidly--in the range of 3 to 5 percent annually--over the next five years. The reason for decline in metal cleaning applications is increased recycling and recovery. In aerosol applications, cancer labeling requirements have reduced demand for consumer goods that contain METH. Chemical producers have shifted production to METH's coproduct, chloroform, to keep prices from falling dramatically. On the other hand, the move away from CFC-11 to METH in urethane foam blowing has mitigated the drop in demand, and there are still few or poor substitutes for METH in paint stripping (Kirk-Othmer, 1985, 1979; CMR, 1989).

METH is one of the least toxic of the chlorinated solvents. It has anesthetic properties and was used medicinally in Europe. For moderate exposures, METH causes nausea, lightheadedness, dizziness, tingling in extremities, and physical coordination can be impaired. In high exposures, it can cause unconsciousness or death, which has happened when unprotected workers have entered tanks with high vapor concentrations. The chemical causes serious damage to the eyes and dermatitis to the skin. The recent study by the National Toxicology Program indicates that METH is carcinogenic to rats and mice, and EPA considers METH a possible human carcinogen. Scientists do not consider METH a contributor to photochemical smog or ozone layer depletion (Kirk-Othmer, 1985, 1979; Wolf and Camm, 1987).

PERC

PERC is the most stable of the chlorinated solvents, so it requires only small amounts of stabilizers. This is a great advantage for the small businesses that use it because there is little need to monitor the solvent and adjust the stabilizing compound. PERC does not corrode common construction metals up to 140° C, even when in contact with air, water, and light. The chemical's solvent properties are excellent, dissolving many substances including fats, oils, tars, and resins. Without light, oxygen does not affect PERC, but it readily oxidizes the same chemical under ultraviolet radiation (Kirk-Othmer, 1985, 1979).

The dry cleaning and commercial textile processing industries consume 50 percent of PERC production. Other uses include chemical intermediates primarily for CFC-113 (28 percent), exports (10 percent), metal cleaning (9 percent), and other (3 percent) (CMR, 1989).

Since 1979, the production of PERC has decreased on average 4.9 percent per year, but its production is expected to be stable at current levels through 1993. The biggest reason for the drop in demand is that dry cleaners are switching over to more efficient machines, largely due to photochemical smog and hazardous waste regulations. This trend may accelerate with OSHA's new occupational exposure limits (25 ppm). Furthermore, production of CFC-113 is being curtailed, causing further decreases in demand for PERC. Factors that increase the demand for PERC are rising exports, falling imports, and its potential as a precursor in the production of chemical substitutes for CFC-113. The net result is an oversupply of PERC in the next five years, exacerbated by co-production facilities switching from carbon tetrachloride (CFC precursor) to PERC (also CFC precursor, but with other major uses) (CMR, 1989).

PERC is a central nervous system depressant with strong anesthetic effects. Most occupational exposure is inhalation, which causes headaches, vertigo, tremors, nausea, vomiting, fatigue, unconsciousness, and death. Unconsciousness is caused by moderate concentrations (1500ppm) after only 30 minutes. Although PERC has a pleasant ethereal odor, the smell is not a good indicator of exposure because the anesthetic effects dull olfactory sensation. Deaths have been reported for workers who entered tanks without protection. PERC ingestion of small quantities is not serious, and repeated exposure to the skin causes dermatitis (Kirk-Othmer, 1985, 1979).

PERC's life span in the atmosphere (on the order of months) is considerably longer than TCE, but not long enough to contribute to stratospheric ozone depletion.[4] Although EPA regulates PERC as a

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[4] These chemicals are unlikely to be contributors to both photochemical smog *and* stratospheric ozone depletion because molecular decomposition occurs either in the troposphere (short atmospheric life span--such as TCE), in the stratosphere (long atmospheric life span--

precursor to photochemical smog, it is probably not a smog contributor. Rather, it is regulated because of its other harmful properties. PERC is one of the chemicals most often found in groundwater contaminated by landfills and sewer discharge, a legacy of past waste management practices when PERC was routinely disposed in municipal landfills or discharged without treatment into sewers (Wolf and Camm, 1987).

TCA

TCA has some corrosive properties with metals and requires inhibitors in many applications. However, it has excellent solvent properties, dissolving fats, greases, waxes, and a range of organic materials. Moreover, TCA is nonflammable and has a relatively low toxicity (Kirk-Othmer, 1985, 1979).

The use of TCA is dominated by commercial metal cleaning operations split between vapor degreasing (34 percent) and cold cleaning (12 percent). Other large uses include aerosol formulations (10 percent), adhesives (8 percent), chemical intermediates (7 percent), paints and coatings (5 percent), electronics (4 percent), miscellaneous applications (5 percent), and exports (15 percent) (CMR, 1989).

The production of TCA has increased only slightly in recent years. The reason for the increase is that TCA is less toxic and contributes less to smog than substitutes, such as TCE. The reason that the increase has been small is that users have been conserving solvent. Stratospheric ozone depletion regulations will sharply curtail TCA supply.

TCA is among the least toxic of the chlorinated solvents. Tests on rats indicate that respiration eliminates 99 percent of injected tracer solvents. Respiratory equipment is still needed for work with moderate or high concentrations, such as tank entry. The chemical is a central nervous system depressant when inhaled, and also causes narcotic effects. Skin exposure to TCA can cause blisters and burning, and eye exposures produce irritation (Kirk-Othmer, 1985, 1979).

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such as CFC-113), or somewhere in between (medium atmospheric life span--such as PERC).

TCA is relatively stable in the lower atmosphere with an atmospheric lifetime (6.5 years) that is significantly longer than either TCE or PERC. Thus, it is not a contributor to photochemical smog. TCA is a contributor to stratospheric ozone depletion, but with only one-eighth the effect as CFC-113 (Wolf and Camm, 1987).

CFC-113

CFC-113, like other chlorofluorocarbons, is an unusually stable compound with low surface tension and viscosity properties. The latter properties make CFC-113 particularly good for cleaning applications that involve small clearance spaces and holes, such as printed circuit board defluxing. Stability allows the chemical to migrate to the upper atmosphere before it decomposes; photolytic conditions break the bond between carbon and chlorine and produce chlorine radicals. This reaction is the first of a series that leads to ozone depletion. The half-life of CFC-113 is about 86 years, which is why it contributes so heavily to stratospheric ozone depletion but does not contribute to tropospheric photochemical smog (Kirk-Othmer, 1979; Wolf, 1990).

CFC-113 use is as follows: 52 percent vapor-phase cleaning, 15 percent liquid-phase cleaning, 5 percent drying, 6 percent government, 3 percent dry cleaning, 12 percent for plastic foams, refrigeration, other uses, and 7 percent exports (Wolf and Camm, 1987).

Production and demand for CFC-113 have been high in recent years. Growth in production has been 2.9 percent since 1979. The Montreal Protocol already limits production of CFC-113, and future production will depend on how rapidly EPA implements the phase-out.

Tests of CFC-113's cancer-causing properties have been negative, and evidence suggests it is less toxic than the other chlorinated solvents.

REGULATIONS

Hazardous Waste Regulations

RCRA with Amendments. The 1984 Hazardous and Solid Waste Amendments to the existing hazardous waste legislation, the Resource Conservation and Recovery Act of 1976 (RCRA), initiated a step-by-step process to prohibit land disposal of hazardous wastes. All five chlorinated solvents in this analysis were restricted from land disposal in November 1986. Waste treated to specific standards is exempt from land disposal restrictions; the EPA developed treatment standards using the criterion of Best Demonstrated Achievable Technology (BDAT).[5]

The land disposal restrictions have caused major changes in disposal practices and technology. Recycling and recovery has dramatically increased, as has innovation in methods to reduce the amount of hazardous waste generated at its source.

CERCLA with Amendments. The Comprehensive Environmental Response Compensation, and Liability Act (CERCLA) designates funding and cleanup regulations for uncontrolled hazardous waste sites. The Superfund Amendments and Reauthorization Act of 1986 (SARA), among other things, codifies EPA's off-site disposal policy for CERCLA waste and CERCLA compliance with other environmental laws. All of the chlorinated solvents are considered hazardous substances under section 101(14) of this legislation.

California Land Disposal Legislation. This is an example of state legislation enacted before, which goes beyond, federal standards. Promulgated regulations include restrictions of liquid chlorinated solvent wastes with concentrations ≥ 1000 ppm (California Code of Regulations, 1989).

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[5] The EPA conducted a study of the available treatment technologies for the chlorinated solvents. The BDAT standards are those that can be achieved with the best of the alternative treatment methods. Chlorinated solvent waste treated to levels equivalent to BDAT is also exempt, mg/l: TCE, .062; PERC, .079; TCA, 1.05; METH, .2; CFC-113, 1.05.

Table 2.4

SELECTED REGULATIONS ON CHLORINATED SOLVENTS

Solvent	OSHA*	CAA: 111	CAA: 112	Montreal Protocol
TCE	50	Yes	Intent	No
METH	500	No	Intent	No
PERC	25	Yes	Intent	No
TCA	350	No	No	Yes
CFC-113	1000	No	No	Yes

SOURCES: Kirk-Othmer, 1985; CMR, 1989; U.S.EPA, 1981; Wolf and Camm, 1987.

*Permissible exposure level.

Water Regulations

The Clean Water Act. The Clean Water Act requires that standards be set for designated chemicals, including TCE, METH, PERC, and TCA. These standards limit the solvent concentration in water effluent streams.

Proposition 65. California voters approved this proposition in November 1988. It is an example of state restrictions that augment federal water and air regulations. TCE, PERC, and METH fall under Proposition 65, but not TCA or CFC-113. Businesses must provide a clear and reasonable warning to consumers and workers if substances pose a "significant risk" of causing cancer or reproductive toxicity.

Air Regulations

Table 2.4 summarizes the provisions of the major federal air pollution and occupational exposure regulations.

The Clean Air Act: Photochemical Smog. The Clean Air Act (CAA) provides authority to regulate air contaminants based on their contribution to photochemical smog and toxicity. Section 111 of the CAA sets standards for volatile organic compounds (VOCs), which limit the amount of solvent that can be emitted to the atmosphere. VOC standards apply to TCE and PERC, but not to METH, TCA, and CFC-113, because they do not contribute to photochemical smog in the troposphere.

The Clean Air Act: Hazardous Air Pollution. More recent amendments to the Clean Air Act include Section 112, designed to control hazardous substances in the air. EPA sets emissions standards only for those substances defined as hazardous air pollutants. Both TCE and PERC have an "intent to list" as hazardous air pollutants. Listed chemicals undergo further regulatory review, including exposure analysis and control requirements.

The Montreal Protocol. Under the agreement, CFC-113 production dropped to 1986 levels starting July 1, 1989, and then reduces to 50 percent of the 1986 levels in 1995, and by a further 35 percent of the 1986 levels in 1997. A complete phase-out of CFC-113 is scheduled for the year 2000. The first meeting of the parties to the Montreal Protocol was in Helsinki in May 1989. At the June 1990 meeting, participating nations added TCA to the list of regulated chemicals; TCA will be phased out by 2005.

Global Warming. Legislation to mitigate the effect of global warming is now under consideration by Congress as a result of a Bush Administration proposal. CFC-113 and TCA may be included in the plan, although they are already being phased out under stratospheric ozone depletion regulations. The other chlorinated solvents are not directly affected by this legislation, because they are not significant contributors to global warming.

Rule 66. As an example of stringent air regulations at the local level (South Coast Air Quality Management District, Los Angeles), Rule 66 stands out as an early example. The 1968 rule restricted emissions of TCE because of its suspected contributions to photochemical smog, which scientists later confirmed.

Other Regulations

TSCA. Congress passed the Toxic Substances Control Act (TSCA) in 1976 to develop health and environmental data on chemicals and to regulate those chemicals that pose unreasonable risks. The restriction of chlorofluorocarbon propellants in aerosol applications is one of four times the full provisions of TSCA have been invoked. Regulators banned CFC propellants from aerosol products in December 1978.

OSHA. The Occupational Safety and Health Administration (OSHA) regulates the permissible level of occupational exposure for all of the chlorinated solvents. The threshold limit values listed in Table 2.4 indicate acceptable levels of occupational exposure, measured in an eight-hour day, time-weighted average concentration. OSHA will soon regulate METH at either 25 or 10 ppm.

Department of Transportation. All of the solvents are regulated when transported as chemical stock or hazardous waste.

Food and Drug Administration. The FDA defined METH as a decaffeinating agent rather than a food additive to prevent it from being regulated under the Delaney Clause, which prohibits food additives that are known animal carcinogens.

PRODUCTION APPLICATIONS OF CHLORINATED SOLVENTS

This subsection describes the seven most important cleaning applications of chlorinated solvents. Each application's description includes the cleaning process, as well as sources of air emissions, hazardous waste generation, and worker exposure. A discussion of the options to reduce air emissions and hazardous waste generation follows each description: *Product substitutes* are options to reduce the need for the production application to begin with. *Chemical substitutes* and *process substitutes* are alternative means to perform the same cleaning task--presumably to move away from one of the hazardous chemicals. *Recycling and recovery* methods can reduce solvent demand and emissions.

Dry Cleaning

Description. The purpose of dry cleaning is the removal of soils and stains from clothing. The advantages over water laundering are that dry cleaning will not shrink sensitive fabrics and that it has aggressive cleaning capabilities without additional abrasion. Dry cleaning differs from water laundering in that chemical solvents are used to clean clothes in combination with water and detergent rather than water and detergent alone. The process of dry cleaning is similar to household laundering in that there are three steps: washing, extraction, and drying. Washing takes place when the machine adds the solvent-water-detergent blend and agitates, before extraction with a spin cycle. Dry cleaning machines are either transfer machines, which require transfer of clothes from the washing machine to a drying machine, or dry-to-dry machines, which wash, extract, and dry. Extraction and drying remove only 85 to 95 percent of the solvent from clothes, so an aeration process is needed where the solvent can evaporate into a stream of fresh air. During the cleaning process, the solvent mixture is filtered to remove soils with either a regenerative filter of diatomaceous earth or a replaceable cartridge filter with paper elements (Yazdani, Wolf, and Yates, 1990b).

Facilities for these services are most commonly retail cleaners, but also include large-scale industrial plants, specialty plants for fur and leather goods, and a relatively small number of self-service machines in laundromats (Yazdani, Wolf, and Yates, 1990b).

Emissions and Waste. Most of the vapor emissions occur in the aeration phase and during transfer from washer to dryer in transfer machines. Small amounts of fugitive emissions in vapor or liquid form occur from leaking pumps, valves, flanges, seals, and storage vessels. Hazardous waste generation is in the form of filter waste, used filter cartridges, and still bottoms from distillation processes that recover solvent for reuse. Air concentrations can be significant for workers unless adequate ventilation systems are in place (Yazdani, Wolf, and Yates, 1990b).

Chemical Substitutes. Roughly 50 percent of dry cleaning relies on PERC, and most of the rest--primarily in industrial facilities--employs petroleum solvents. CFC-113 and TCA perform a small fraction of dry cleaning (Yazdani, Wolf, and Yates, 1990b).

The chemical alternatives to PERC have significant drawbacks that limit their acceptance as substitutes. CFC-113 is not an adequately aggressive solvent for general use, and supply is being severely constrained by stratospheric ozone depletion regulations. TCA is being used at 150 sites in the United States; however, the solvent requires careful regulation of stabilizers that are highly toxic and more expensive machines to resist corrosion. TCA supply is also constrained by ozone depletion regulations. Petroleum solvents are an excellent alternative, although fire codes may prohibit these solvents or make conversion of existing facilities expensive. A specially designed petroleum solvent with a higher flash point is available, but it is more expensive and takes longer to dry. New chemical substitutes include HCFC-141b, evaluated as technically suitable by the International Fabricare Institute, and HCFC-123, which remains untested. The exposure limits on HCFC-141b make it unacceptable for use in existing PERC equipment (Yazdani, Wolf, and Yates, 1990b).

Process and Product Substitutes. Process substitutes for dry cleaning include water laundering for fabrics that are not damaged by the process. Product substitutes include increased use of fabric treatments that prevent shrinking in water laundering (Yazdani, Wolf, and Yates, 1990b).

Recycling and Recovery. Recovery and recycling is already widespread in the dry cleaning industry. Carbon adsorption units are used in 35 percent of all commercial and industrial facilities. In this process, vapors with relatively low solvent density (e.g., from the shop floor during transfers) pass through a bed of activated carbon, and then later desorb with steam. All dryers use water-cooled condensers to recover vapors, and refrigerated condensation can significantly enhance vapor recovery. Refrigerated condensers are effective at recovery of any high density vapor source, including emissions from the aeration process. A survey indicated that in Southern California, 67 percent of PERC plants used refrigerated condensers or carbon adsorption, and that 100 percent of CFC-113 plants and 33 percent of petroleum solvent plants used refrigerated condensers. A recent innovation is the solvation process, where evaporation of solvent may be enhanced (Yazdani, Wolf, and Yates, 1990b).

Most dry cleaning facilities will purify solvent and recover solvent from filter muck by distillation. This recovery and recycling can be in on-site stills and/or off-site with the services of a commercial reclaimer.

Metal Cleaning: Cold Cleaning

Description. Cold cleaning takes place at room temperature or at higher temperatures that do not approach the boiling point. Solvent cleaning action removes the following from metal surfaces: drawing compounds, cutting and grinding fluids, polishing and buffing compounds, and miscellaneous contaminants, such as metal chips. Solvent application takes place by spraying, immersion, brushing, or wiping. Mechanical agitation can promote cleaning by releasing air bubbles in the solvent tank below the part or by moving a rack of parts up and down. Ultrasonic frequency vibrations can also be used to break down soil films by causing the rapid formation and collapse of gas bubbles. Simple cold cleaning tanks have trays to hold the parts and a spray hose for solvent. In high volume cold cleaning, conveyorized machines transport parts automatically through a solvent bath or through a solvent spray (Yazdani, Wolf, and Yates, 1990a).

Industries that employ extensive cold cleaning include fabricated metal products (e.g., cutlery, hand tools, and structural products), metal furniture, machinery, transportation equipment, instruments, auto repair, and air transportation maintenance (Yazdani, Wolf, and Yates, 1990a).

Emissions and Waste. Cold cleaning emissions are difficult to control and make up 55 percent of solvent emissions in metal cleaning (U.S. EPA, 1977). Hence, the bulk of solvent losses are vapor emissions, and the rest is hazardous waste generation. Emissions occur from cold cleaning tanks through evaporation of the bath, spray vapor losses, waste evaporation, and solvent evaporation from parts after they exit the cold cleaner. Waste generation is in the form of sludge that accumulates in the bottom of the solvent bath, contaminated solvent, and still bottoms from recycling. Cement kilns incinerate the residual of the distillation process (Yazdani, Wolf, and Yates, 1990a).

Chemical Substitutes. All five of the major chlorinated solvents clean metal products in cold cleaning, and a number of nonchlorinated chemical solvent substitutes exist. The group of flammable (low molecular weight) hydrocarbon solvents includes alcohols, aliphatic hydrocarbons, and aromatic hydrocarbons. These solvents are simple to substitute for chlorinated solvents with existing machinery and are effective for many applications; however, they cannot substitute in conveyorized degreasers because they are flammable and they contribute to photochemical smog. Combustible (high molecular weight) hydrocarbon solvents include terpenes, N-Methyl-2-Pyrrolidone (NMP), and Dibasic Esters (DBE). Terpenes are already being tested in cleaning applications, but NMP and DBE remain untested for cold cleaning. All three are biodegradable, but they need to be treated to remove contaminants before sewer release. High combustibility when spraying complicates the conversion process and requires extensive fire protection equipment. These solvents also contribute to photochemical smog (Yazdani, Wolf, and Yates, 1990a).

Aqueous cleaning methods apply to many cold cleaning applications, such as metal furniture, fabricated products, and transportation equipment. Usually, a water blend with additives cleans in conjunction with mechanical, electrical, or ultrasonic energy. Water has disadvantages because it evaporates slowly, it has high surface tension, it causes rusting or staining of metals, and it leaves a residual on the cleaned item. Emulsion cleaning processes use a solvent that is dispersed in water with emulsifying agents. Widely used now, this method is a good substitute where a final residue is acceptable (Yazdani, Wolf, and Yates, 1990a).

Process and Product Substitutes. A replacement for chemical solvent processes is abrasive blasting, which typically uses a high pressure stream of air carrying blasting media, such as sand or nut shells. This process is suitable for cleaning automobile parts, bridge structures, and construction equipment (Yazdani, Wolf, and Yates, 1990a).

Recycling and Recovery. Distillation, the most popular method of waste recycling, can take place on-site or off-site by a commercial reclaimer. In this process, the unit heats contaminated solvent until the more volatile components are boiled off, then separates and condenses the solvent back into liquid form. Solvent recycling off-site is limited in part because there are no widely accepted quality standards for reclaimed solvent, and purity may vary. Improved operating practices and equipment to enhance recovery of solvent vapor include slow dragout speeds and drying tunnels, tank controls, such as floating roofs, solvent segregation, covers, drainage racks, limits on spray and agitation, monitoring, and other improved operating processes (Yazdani, Wolf, and Yates, 1990a).

Carbon adsorption (described for dry cleaning above) is an existing technology that can reduce solvent emissions 50 to 65 percent in applications with low-density vapors. Complex formulations may complicate the process because water soluble components of the solvent blend, such as stabilizers, separate with water in the separation process. Emerging alternatives that might be suitable for capturing vapors are membrane technology and Brayton cycle technology (Yazdani, Wolf, and Yates, 1990a).

Filtration processes remove insoluble solid particles in fluids which can prolong the purity of solvent. Microfiltration systems are capable of keeping solvent very clean by removing extremely small particles. Electrostatic liquid cleaning systems can remove soluble as well as insoluble components of contaminated solvent (Yazdani, Wolf, and Yates, 1990a).

Metal Cleaning: Vapor Degreasing

Description. Vapor degreasing is a process where heated solvent vapor condenses onto the object to be cleaned. The advantages of vapor degreasing are that the solvent condensing on the part is free of contaminants and that cleaning action is faster because of higher temperatures (Yazdani, Wolf, and Yates, 1990a).

Vapor degreasing tanks include a solvent bath heated to form a zone of vapor above the surface of liquid solvent. The part stays in the vapor zone until solvent condenses on its surface and cleaning takes place. Cooling coils above the vapor zone condense solvent and recover it to the solvent bath. Vapor degreasers are either open top or conveyorized. The open top machines have cooling coils that border the upper rim of the tank above the vapor zone, and the top of the tank may be open or have a lid. A conveyorized machine has a closed top and a mechanism to transport parts through the vapor zone and out the other end of the machine. Conveyorized degreasers are more efficient for continuous cleaning rather than batch cleaning, and also for large volume applications (Yazdani, Wolf, and Yates, 1990a).

Emissions and Waste. Emissions from vapor degreasers are easier to control than for cold cleaning. Cooling condensers are effective at recovering the solvent from vapor form back into the solvent bath. Conveyorized degreasers have flaps to cover the entrance and exit of the machine and a fixed top. Total emissions are higher for an average conveyorized degreaser than for an average open top degreaser. This is because the air flow is greater through a conveyorized degreaser, and because the volume of cleaning is greater so more solvent drags out with the parts. Waste generation is in the form of contaminated solvent, sludge that accumulates at the bottom of the solvent bath, and still bottoms from distillation. The residual sludge from distillation processes is typically incinerated at off-site facilities (Yazdani, Wolf, and Yates, 1990a).

Chemical Substitutes. Generally, vapor degreasers use only chlorinated solvents because their vapors are heavier than air and therefore easier to contain, and because other solvents are flammable. HCFC-123 and HCFC-141b are promising chemical substitutes in vapor degreasing applications because they are stable and aggressive solvents and also because they have low ozone depleting potential, low flammability, and no photochemical reactivity. A disadvantage of the HCFCs is their low boiling point. The toxicity of the HCFCs has not yet been determined. Low exposure limits on HCFC-141b make it unacceptable for use in existing equipment (Yazdani, Wolf, and Yates, 1990a).

Process and Product Substitutes. Aqueous and emulsion cleaning processes are substitutes for vapor degreasing in some applications. The subsection on cold cleaning discussed these processes (Yazdani, Wolf, and Yates, 1990a).

Recycling and Recovery. An existing method to control emissions from vapor degreasers employs refrigerated chillers to condense vapors before they escape to the atmosphere. Refrigerated freeboard chillers are secondary cooling coils that condense vapors that escape beyond the primary cooling coils. Water separators are standard equipment on all vapor degreasing machines; these devices separate the liquid condensed on cooling coils into solvent and water components. Carbon adsorption, permeable membranes, filtration, microfiltration, electrostatic cleaning, and on-site and off-site distillation are all applicable to vapor degreasing. Some improved operating practices that are applicable to vapor degreasing (in addition to the methods mentioned in cold cleaning) are raised freeboards and safety vapor thermostats to control abnormal temperatures of solvent baths (Yazdani, Wolf, and Yates, 1990a).

Electronics: Printed Circuit Board Defluxing

Description. The electronics industry uses chlorinated solvents widely in semiconductor wafer fabrication and assembly, printed circuit board fabrication and assembly, other precision cleaning applications, and in-situ generation of etchants. In this study, we include only the assembly of printed circuit boards, because this operation consumes much more chlorinated solvent than any of the others in electronics. The major use of chlorinated solvents in printed circuit board assembly is defluxing, which is the process of removing flux residuals that remain after soldering of components to the board (Wolf, Yazdani, and Yates, 1990a).

In the assembly of printed circuit boards for such products as computers, communications equipment, and military components, electrical components attach through holes or on the surface of the board and then get soldered in place. Flux applied before soldering reduces surface tension so that the solder flows evenly and prevents oxidation. Solder is applied in one method by wave soldering, where the board passes through a wave of molten solder that sticks only to the metal leads of the components. The flux types in use today are rosin flux, synthetically activated flux, and organic acid flux. Rosin or synthetically activated flux require solvent removal. Aqueous solutions can remove organic acid flux or rosin flux with a surfactant (Wolf, Yazdani, and Yates, 1990a).

Emissions and Waste. Emissions to the atmosphere are caused by solvent dragout as the boards exit the defluxer. Because TCA is more acutely toxic than CFC-113, workers need more protection in occupational exposures (Wolf, Yazdani, and Yates, 1990a).

Chemical Substitutes. The primary solvents used in defluxing are CFC-113 and TCA, and to a lesser extent aqueous blends. Chemical substitutes for chlorinated solvents in printed circuit board defluxing include flammables, combustibles, and chlorinated solvent blends. Flammable solvents, such as methyl alcohol, ethyl alcohol, and isopropyl alcohol are problematic at elevated temperatures and cannot alone remove nonpolar[6] contaminants, such as grease and flux residue. CFC-113 solvents blended with flammable solvents enhance effectiveness at dissolving both polar and nonpolar contaminants. The proportion of flammable solvent could increase; however, this would complicate the recovery process because the solutions would no longer be azeotropes (constant boiling blends) (Wolf, Yazdani, and Yates, 1990a).

The combustible hydrocarbon solvents, including terpenes, NMP, and DBE offer greater potential, but not without their own set of difficulties. Terpenes are excellent at dissolving nonpolar contaminants including flux residues and they can be incinerated easily. However, these solvents need water to dissolve polar contaminants and air knife drying to remove excess solvent and water. Other disadvantages of terpenes are that they require expensive fire protection equipment, they contribute to photochemical smog, they have shown positive carcinogenicity in the kidneys of male rats, they generate water waste that will require treatment in most municipalities, and they do not meet military specifications. NMP and DBE are

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[6] The terms "polar" and "nonpolar" refer to the electrical charge of the solvent and contaminant molecules. Polar solvents dissolve polar contaminants and nonpolar solvents dissolve nonpolar contaminants.

technically suitable for defluxing, but they have many of the same problems as terpenes (Wolf, Yazdani, and Yates, 1990a).

Process and Product Substitutes. Two product substitutes can reduce dependence on chlorinated solvents. The first is boardless electronics. This process entails printing the circuit on a surface within the product, which requires less material to clean and fewer solder contacts. The other alternative is to simply accept lower reliability printed circuit boards for applications where it is not critical, such as many consumer products (Wolf, Yazdani, and Yates, 1990a).

One option for process substitution is aqueous cleaning, which involves water soluble organic acid fluxes or water cleaning of rosin fluxes with saponifiers and detergent additives. With past technology in water defluxing there have been problems with residues left after the drying process. Some of these problems are mitigated with new organic acid fluxes. A problem with any water defluxing technique is that the trend in printed circuit boards is toward surface mount technologies, which have small spacings that some people say *cannot* be cleaned with water. Of course, with appropriate design, even these boards could have spacing big enough for water defluxing. A very promising alternative is "no clean" flux, which leaves very little residue. This technology eliminates the need for defluxing altogether because residues are inconsequential for many applications. Still another emerging technology is inert gas soldering (Wolf, Yazdani, and Yates, 1990a).

Recycling and Recovery. Carbon adsorption, described above in dry cleaning and metal cleaning, can also recover vapors in electronics applications. Emerging technologies include membrane technology and Brayton cycle technology. For waste streams of chlorinated solvents, the options include microfiltration, on-site and off-site recycling, and improved equipment and operating practices described for metal cleaning (Wolf, Yazdani, and Yates, 1990a).

Paint Removal: Original Equipment Manufacturing

Description. In the original production of manufactured goods, paint removal is needed to clean painting equipment and to strip defective products that need reworking. A large portion of industrial painting takes place in closed booths designed to capture excess spray. The spray booth walls and floor, as well as the spray guns and lines, need cleaning when paint color changes or periodically when excess paint builds up. The major industries that use paint removal are manufacturing of automobiles, metal furniture and fixtures, electronic and electric equipment, and wood flatstock and furniture. Automobile plants usually clean spray booths daily, but in other industries cleaning is less frequent (Wolf, Yazdani, and Yates, 1990b).

Chemical paint strippers work by applying a solvent mixture with a brush or spray gun, waiting for the chemical action to lift paint from the surface, then removing the paint and solvent mechanically with a scraper or water rinse. Another method of paint removal--typically for smaller parts--is immersion, where parts soak in chemical stripper baths. Formulated METH is the best chemical stripper because its low molecular weight allows it to penetrate paint coatings and expand its volume three or four times. This forces the interstitial structures to expand so that the paint cracks and lifts from the surface (Wolf, Yazdani, and Yates, 1990b).

Emissions and Waste. Emissions to the atmosphere account for 80 percent of the METH use in these applications. The remaining 20 percent is split between hazardous waste containing solvent and paint, and water from the rinse process that also contains solvent and paint (Wolf, Yazdani, and Yates, 1990b).

Chemical Substitutes. There are several chemical strippers that can, in some applications, substitute for METH. Examples include phosphoric and nitric acid. These strippers work best when heated and are therefore most suitable for immersion tank paint removal. Because acid strippers are relatively corrosive to metals, they need corrosion inhibitors in their formulation. Alkali strippers also remove paint--typically in immersion applications at elevated temperatures like acid strippers. These strippers are not as effective at removing all of the paint coating and usually include additives to make them more effective (Wolf, Yazdani, and Yates, 1990b).

In addition to the acid and alkali strippers, hydrocarbon chemical alternatives exist that are either combustible or flammable depending on their flash point. An example of a combustible hydrocarbon is NMP, which strips significantly slower than METH for cured coatings. NMP is less volatile, and therefore less solvent is needed to maintain contact with the paint surface. Although NMP is readily biodegradable, paint may contain hazardous components, so treatment or hazardous waste disposal is probably necessary. DBE is another combustible alternative that is biodegradable. Formulations of DBE for paint booth stripping may include NMP and additives (Wolf, Yazdani, and Yates, 1990b).

Flammable hydrocarbon alternatives include furfuryl alcohol, methyl amyl ketone (MAK), and paint thinners. Furfuryl alcohol blends already find extensive use in automobile booth cleaning because they work well on uncured paint. MAK is also more effective in uncured compared to cured paint, although it still takes longer than METH formulations. MAK has low volatility and therefore low VOC emissions. Paint thinners are effective at stripping uncured paints in paint booths, guns, and lines. Thinners include active solvents (e.g., methyl ethyl ketone), latent solvents (e.g., methyl alcohol), and dilutents (e.g., toulene) (Wolf, Yazdani, and Yates, 1990b).

Process and Product Substitutes. Options for product substitutions include unpainted or precolored products. Several process modifications can serve as alternatives to METH or other chemical strippers for selected applications. One example in paint booth cleaning is water blasting. In this method, a high pressure stream of water removes paint from booth surfaces. This method is successful in the automobile industry where paint is stripped before it has a chance to cure. Precautions to protect workers are needed with high pressure sprays, and water waste containing paint needs filtration before release to public sewer systems (Wolf, Yazdani, and Yates, 1990b). Other alternatives to chemical paint stripping include strippable coatings, high temperature ovens and salt baths, physical methods, such as chiseling, cryogenic methods, and sodium bicarbonate abrasive blasting (Wolf, Yazdani, and Yates, 1990b).

Recycling and Recovery. There are several options for recovery and reuse of vapor emissions of METH strippers. A layer of water on top of the solvent or a cover on the tank can reduce emissions from immersion tanks (Wolf, Yazdani, and Yates, 1990b).

Recyclers take contaminated solvent with a high METH content, then sell reclaimed METH back on the market and dispose of distillation residues. Formulators separate components of contaminated solvent and then reblend the components into formulated stripper. Distillation units perform on-site recycling in some operations. METH evaporates from waste water, and a treatment process needs to remove paint before sewer discharge. Reclaiming METH from water streams is expensive because of the small solvent concentration (Wolf, Yazdani, and Yates, 1990b).

Paint Removal: Maintenance

Description. In maintenance applications, most paint stripping is for planes, tanks, automobiles, and ships that are undergoing periodic servicing. Military use accounts for two-thirds of METH's maintenance applications, and commercial airlines, automobile repair, and other industries account for the rest (Wolf, Yazdani, and Yates, 1990b).

The typical process of removing paint from these vehicles starts with applying chemical stripper with spray guns. After the stripper lifts paint from the surface, workers remove the paint-solvent mixture with rubber scrapers. Finally, a water rinse washes residual paint and stripper from the vehicle. Maintenance paint removal also includes immersion tanks for stripping paint from small parts. In automobile body repair, chemical stripper and sanding work together to remove paint (Wolf, Yazdani, and Yates, 1990b).

Emissions and Waste. The mixture of stripper and paint scraped from vehicles is hazardous waste and requires proper disposal. The water rinse needs treatment before release into public sewer systems.

Workers need to use protective measures for respiration and skin exposures. The stripping operation usually takes place in an enclosed garage or hangar (Wolf, Yazdani, and Yates, 1990b).

Chemical and Product Substitutes. There are no chemical and few product substitutes that are appropriate for the major maintenance applications, such as military vehicles and commercial airplanes. American Airlines uses a polished metal skin on their aircraft, which needs polishing but not repainting (Wolf, Yazdani, and Yates, 1990b).

Process Substitutes. Most of the process modifications are abrasive methods that make use of an abrasive media, such as plastic pellets, sand, walnut shells, rice hulls, aluminum oxide pellets, and steel shot, and an air or water stream to propel the media at high velocity. Perhaps the most extensively developed abrasive method is plastic media blasting, which makes use of plastic pellets that are hard and angular enough to remove paint, but soft enough not to damage the skin of the aircraft; in fact, it is still controversial whether plastic media blasting significantly damages the skin of the aircraft. For smaller parts, the blasting takes place in an enclosed cabinet, and for larger parts or vehicles, an enclosed room or hangar is needed. The plastic media blasting system requires a hopper for the plastic media, a system for recovering the plastic media and sorting it from paint and other contaminants, a compressor for the pneumatic nozzle, and a dust control system for protecting workers and reducing atmospheric emissions. The dust collected and sorted from the media contains paint with chromium, cadmium, and lead in military applications and is thus hazardous waste (Wolf, Yazdani, and Yates, 1990b).

Other process modification methods include cryogenic stripping, laser paint stripping, flash lamps, carbon dioxide pellets, and sodium bicarbonate. Cryogenic methods have potential for small parts only, which excludes military and commercial vehicles. Laser paint stripping uses a pulsed ultraviolet eximer laser to break chemical bonds in the paint material without damaging the underlying painted surface. This method is not fully developed--remaining problems include controls for curved surfaces and determination of the residual paint material, which is of unknown molecular structure after the laser bond-breaking process. Another new technology is the tubular quartz flash lamp filled with xenon gas. The light pulse causes the paint material to sublime, pyrolyze, or chemically dissociate. Carbon dioxide paint removal works by spraying compressed dry ice pellets, which sublime several minutes after the blasting process and leave only the paint residue behind. Sodium bicarbonate blasting, as described for original equipment is a proven and viable alternative for some maintenance applications (Wolf, Yazdani, and Yates, 1990b).

Recycling and Recovery. Recycling and recovery methods are technically applicable to maintenance paint removal, but they are unlikely to be economically viable (Wolf, Yazdani, and Yates, 1990b).

Paint Removal: Consumer

Description. Consumer paint removal is 95 percent furniture paint stripping, although it is also door, door frame, porch, and deck stripping. Often, the consumer will do the paint stripping themselves in their garage or back yard. The alternative is to pay a commercial paint stripper (Wolf, Yazdani, and Yates, 1990b).

The do-it-yourself style paint stripper will usually apply the solvent by brush and remove it with a scraper. Commercial paint strippers use immersion tanks or flow-over tanks. With immersion tanks, the solvent coats items when they are dipped in a tank. In flow-over tanks, the solvent feeds through a line with a brush at the end--the furniture piece sits on a flow-over table that collects the solvent as it runs off the furniture. With either immersion tank or flow-over tank application, scrapers or water spraying remove the bulk of the paint and solvent. Aside from furniture strippers, commercial paint removal operations include general painters and floor refinishers. For individual use, consumers buy standard formulations from hardware stores, but commercial users may do their own chemical formulation (Wolf, Yazdani, and Yates, 1990b).

Emissions and Waste. In commercial use, approximately 80 percent of all METH solvent is emitted to the atmosphere. The remaining METH is in the mixture of stripper and paint that collects in the bottom of soak tanks. Water from the rinse operation, contaminated with METH and paint, needs treatment before release to a sewer system, or if concentrations are great enough, it may need hazardous waste disposal. For "do-it-yourself" operations, nearly 100 percent of the METH is emitted to the atmosphere (Wolf, Yazdani, and Yates, 1990b).

Chemical Substitutes. Chemical substitutes are the primary opportunities to move away from METH in consumer applications. One consumer paint solvent included NMP, but later withdrew from the market--reportedly because it was poorly formulated and did not work well. Although NMP is fairly toxic, an effective formulation is possible according to GAF, an NMP producer. Paint stripping with NMP takes considerably longer than with METH. A water-based DBE product recently introduced claims to have no harmful fumes and will not burn exposed skin. Although the DBE formulation is also slower than METH, it is less volatile and remains active for 10 hours--long after a METH-based product would have evaporated. DBE products may also require scrubbing and sanding before repainting. Flammable hydrocarbon strippers are available to remove mostly shellacs, varnishes, and lacquers (Wolf, Yazdani, and Yates, 1990b).

Process Substitutes. The only process modifications that are available for consumer paint stripping are cryogenic methods and heat guns. The cryogenic equipment is expensive and unlikely to be cost effective for small commercial paint strippers, although it could loosen paint before removal with one of the alternative chemical strippers, such as NMP or DBE. There are heat guns available that blow air at 800 degrees F that blisters paint off the surface; however, these products are dangerous and may damage furniture (Wolf, Yazdani, and Yates, 1990b).

Product Substitutes, Recycling, and Recovery. Although product substitutes are not promising, recovery and recycling of vapors from commercial paint stripping operations is feasible (Wolf, Yazdani, and Yates, 1990b).

CONCLUSIONS

Because chlorinated solvent applications and substitutions are diverse, simple tools are not adequate for analyzing market changes and regulations. To describe the effects of regulations, we need a method to summarize all of the information in the catalog of solvent substitutions presented in this section. The next section defines a market structure and economic equations that can represent numerous substitution opportunities in mathematical form.

III. DESIGN AND IMPLEMENTATION OF THE ECONOMIC MODEL

The last chapter described an array of chemical substitutes and process substitutes that perform cleaning tasks in each of the major chlorinated solvent applications. Recovery and recycling technologies reduce solvent use, emissions, and hazardous waste generation for many of these chemical and process substitutes. Some product substitutes reduce the need for cleaning tasks altogether. The first part of this section defines the structure of chlorinated solvent markets in the context of a general equilibrium model. The second part specifies these markets in economic terms and defines a set of equations to represent markets in mathematical form. The last part of this section describes the method of implementing the model to generate numerical results.

THE CHLORINATED SOLVENT MARKETS MODEL

Structure of Chlorinated Solvent Markets

Wolf and Camm (1987) developed an exploratory model of chlorinated solvent markets structured in four levels: production applications, solvent services, factors of production, and waste disposal options. This Note extends the work of Wolf and Camm in the following four ways:

(1) Expanded detail of substitutions. This analysis models and collects data on each of the solvent service and factor of production substitutions individually. The expanded detail of substitutions and regulatory policies is apparent in the description of second order parameters in this section and the description of the numerical specification in the next section.

(2) Explicit modeling of regulatory policies. The regulatory policies represented in the model are analogous to specific regulatory provisions and take the form of supply constraints as well as taxes.

(3) Expanded range of production applications. As described in Section II, the model includes three paint removal applications, which means that nearly all of the cleaning applications of chlorinated solvents are in the model.

(4) Revised waste disposal options. Since the promulgation of the RCRA land disposal restrictions, solvent users have little choice among waste disposal options for the chlorinated solvents. Important policy questions now focus on source reduction instead. Thus, the present model has only one option for waste disposal and greater detail in factors of production and solvent services--where source reduction takes place.

The market structure in *this* model represents all of the product substitutes, chemical substitutes, process substitutes, and recycling and recovery methods for each of the chlorinated solvent applications described in Section II. At the top of the structure are markets for each of the *production applications*, which include dry cleaning, two categories of metal cleaning, electronics, and three categories of paint removal.

The middle level includes a range of markets for *solvent services* that can perform cleaning in the production applications. Solvent service markets exist for each of the chemical substitutes and for each of the process substitutes described in Section II. For example, in vapor degreasing, the range of solvent services includes the chemical substitutes TCE, METH, PERC, and TCA, as well as the process substitutes aqueous cleaning and emulsion cleaning.

The bottom level of the market structure includes *factors of production* that are needed to provide each of the solvent services. When recycling and recovery technologies change, changes occur in factors of production, such as solvent, energy, fixed assets, labor, and waste disposal. Increasing emissions control equipment, for example, typically involves increasing the assets factor of production and decreasing the solvent factor of production.

A Numerically Computable General Equilibrium Model

Each level of the market structure and all of the production applications are inextricably linked to one another. For example, regulations on methylene chloride affect paint removal in original manufacturing, maintenance, and consumer applications, as well as cold clean[illegible] and vapor degreasing. Limiting the model to fewer markets would ignore the system-wide consequences. For this reason, we need to model all of these markets at the same time and to make explicit links between them. This is the function of a general equilibrium model.

Economists use applied general equilibrium models extensively to analyze policy changes that affect broad sectors of a nation's economy.[1] Typical policy changes include changes in federal income or energy taxation, and the sectors of the economy affected include groups of manufactured goods and various groups of consumers. In the model described in this analysis, the "economy" is where chlorinated solvents perform cleaning in production applications. Examples of market sectors in the model's economy are the market for cleaning printed circuit boards and the market for CFC-113 solvent. The model analyzes policy changes in environmental regulations affecting supply, use, and disposal of chlorinated solvents.

Table 3.1 shows the economy's hierarchical structure, with production applications at the top, solvent services in the middle, and factors of production at the bottom. A computer program solves a large number of equations that represent supply and demand in each market sector. The program finds a general equilibrium where supply equals demand in each market.

A common technique in general equilibrium analysis is to approximate nonlinear functions with linear forms by totally differentiating supply and demand equations. In differential form, models represent local equilibria that can compare the relative effects of policy changes, but they cannot compute numerically the absolute effects of policy changes. The advantage of this technique is that it is easier to solve a system of linear equations than a system of nonlinear equations; however, linear approximations are appropriate only when the approximated function is linear or when the changes are

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[1] See Scarf and Shoven (1984) for examples of applied general equilibrium models as well as articles on methods of computing equilibrium prices, numerical specification, econometric estimation methods, and model structure.

Table 3.1

STRUCTURE OF GENERAL EQUILIBRIUM MODEL
(NUMBER OF EQUATIONS)

Market Levels	Supply Equations	Demand Equations
Production Applications	7	7
Solvent Services	37	37
Factors of Production	220	220

incremental. Neither of these conditions exist in this case.[2] Hence, the model of chlorinated solvent markets is a numerically computable general equilibrium rather than a linear approximation.

FORMAL SPECIFICATION OF ECONOMIC MARKETS

Supply and Demand for Production Applications

Production applications include dry cleaning, cold cleaning, vapor degreasing, electronics, original equipment paint removal, maintenance paint removal, and consumer paint removal. This level of the market structure represents the final outputs in the chlorinated solvent markets model. In dry cleaning, for example, the final outputs are cleaned garments. In electronics, the final outputs are cleaned printed circuit boards. The supply function for a production application is its marginal cost function, which is a function only of solvent service prices (p_{ij}, where i represents production applications and j represents solvent services) that go into its production, and not the level of output. This follows from the assumption of constant returns to scale, which implies that the cost function is independent of output level.[3] In other words, the supply curve for a production application is flat,

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[2] See Solow (1983) for a demonstration of the divergence between local and general equilibrium approaches in a model of energy tax incidence.

[3] Samuelson's nonsubstitution theorem states that with constant returns to scale production, output price is independent of output demand. Hence, output prices can be computed from the input prices only, and the supply curve is flat (Samuelson, 1951; Varian, 1984).

and any level is produced at the same cost per unit.[*] In equilibrium, the price of each production application (P_i) is equal to its marginal cost (MC_i), because all consumers and producers are price takers. The demand (Q_i^d) for a production application depends on the price of that application (P_i):

$$\text{Supply: } P_i = MC_i = g(p_{ij}) \tag{3.1}$$

$$\text{Demand: } Q_i^d = f(P_i) \tag{3.2}$$

Table 3.2

SOLVENT SERVICES FOR EACH PRODUCTION APPLICATION

				Paint Removal		
Dry Cleaning	Cold Cleaning	Vapor Degreasing	Electronics	Original	Maintenance	Consumer
PERC	TCE	TCE	TCA	METH	METH	METH
TCA	METH	METH	CFC-113	H_2OBlast	PMB	Flamm
CFC-113	PERC	PERC	H_2O	Flamm	Bicarb	Comb
Flamm	TCA	TCA	Comb	Comb	Laser	Heat Gun
HCFC	CFC-113	CFC-113	No Clean	Immersion		
	H_2O	H_2O	HCFC			
	Flamm					
	Comb					

TCE = Trichloroethylene; METH = Methylene Chloride; PERC = Perchloroethylene; TCA = 1,1,1-trichloroethane; CFC-113 = Chlorofluorocarbon-113; Flamm = Flammables; H_2O = Aqueous; Comb = Combustibles; No Clean = Low residue solder flux; Immersion = Acid Stripper Immersion.

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[*] These assumptions imply a long-run planning horizon and apply to solvent services and factors of production as well as production applications. We specified data for a three-to five-year planning horizon because existing technology will probably change thereafter, even though this is short for a long-run model. A later part of this section discusses this issue in the context of second order parameters.

Supply and Demand for Solvent Services

A number of solvent services can perform each of the production applications. The model represents the level of solvent services as the number of units cleaned using a particular solvent service. Using dry cleaning as an example once again, the demand for PERC solvent services is the total quantity of garment cleaning with PERC.[5] In electronics, the demand for CFC-113 solvent services is the quantity of printed circuit boards cleaned with CFC-113. The marginal cost function (MC_{ij}) depends only on the prices of the factors of production that go into its provision (p_{ijk}, where i represents production applications, j represents solvent services, and k represents factors of production), following again from the constant returns to scale assumption. All producers and consumers are price takers, so the price of solvent services (P_{ij}) is equal to marginal cost. The demand ($Q_{ij}{}^{d}$) schedule for these solvent services depends on the price of the solvent services (P_{ij} and P_{in} with $j \neq n$) and the level of production applications (Q_i):

$$\text{Supply: } P_{ij} = MC_{ij} = g(p_{ijk}) \qquad (3.3)$$

$$\text{Demand: } Q_{ij}{}^{d} = f(P_{ij}, P_{in}, Q_i) \quad j \neq n \qquad (3.4)$$

Table 3.2 shows the solvent services for each of the production applications. There is one column for each of the production applications, and the rows show the list of available solvent services.

Supply and Demand of Factors of Production

Factors of production include solvent, energy, fixed assets, waste disposal, labor, pollution costs, and water disposal. Waste disposal represents the cost of hazardous waste disposal of spent solvent. Water disposal is the cost of treatment and disposal of rinse water where applicable. Pollution cost is the cost, not borne by the solvent user,

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[5] The units of measure are garments cleaned, with "garment" defined as the amount of cleaning performed for one dollar at the benchmark equilibrium.

of employing a particular solvent service in an application--that is, the external cost, which is proportional to the overall level of health and environmental hazards.

The model assumes factors of production are the same across all solvent services and production applications. That is, a pound of PERC solvent is the same for dry cleaning as for cold cleaning, and all of the PERC solvent factors of production add together to get total demand for this solvent.

The model also assumes the marginal cost of a factor of production is constant and exogenous. Producers and consumers are price takers, and at the benchmark equilibrium, prices of all factors of production are equal to their marginal costs. Factor prices may be above marginal costs when a new regulation constrains supply.

Total demand for a factor of production (Q_k^d) is the sum of the demand for that factor (Q_{ijk}^d, where k represents factors of production) over all solvent services (j) and production applications (i). The demand for factors depends on the price of those factors (P_k and P_o with $k \neq o$, where k and o are factors of production) and the output of solvent services (Q_{ij}):

$$\text{Supply: } P_k = MC_k = \text{Constant} \tag{3.5}$$

$$\text{Demand: } Q_k^d = \sum_{ij} Q_{ijk}^d = \sum_{ij} f_{ij}(P_k, P_o, Q_{ij}) \tag{3.6}$$

FUNCTIONAL FORM OF THE ECONOMIC MODEL

From the description of chlorinated solvent applications presented in the previous section, we see the need for a mathematical form that will capture varied and complex production technologies. Forms such as Cobb-Douglas are not adequate for the task because they treat substitution opportunities in a simplistic fashion. For this reason, translog functional form models production technologies that involve chlorinated solvents in this analysis.

Translog Production and Cost Functions

A "transcendental logarithmic" or "translog" production function is one that is transcendental[6] logarithmic in its input and output variables (Christensen, Jorgenson, and Lau, 1971). For example, lnY = f($\ln X_1$, $\ln X_2$, $\ln X_3$) is such a function, where Y is an output and the X_i are inputs. A translog function is a "second order approximation" to a general production function because its mathematical form is a Taylor's series expansion to the second order of the Taylor polynomial. Appendix A derives translog functional form from a Taylor's series expansion.

The advantage of translog functional form is that it is "flexible." Flexible functional forms have fewer restrictions on the technology they represent than Cobb-Douglas, Leontief, or constant elasticity of substitution (CES) forms, which are all first order approximations.

Restrictions on technology often have to do with the opportunities for substitution between inputs in a production process, so it is interesting to compare the difference in elasticities of substitution for the Cobb-Douglas, CES, and translog production functions. The Allen-Uzawa partial elasticity of substitution (σ) is a measure of how difficult or easy it is to substitute one input, say labor, for another input such as capital.[7] The Cobb-Douglas function restricts σ between inputs to be constant, identical for all pairs of inputs, and always one. The CES function restricts σ to be constant and identical for all pairs of inputs, but does not restrict its value to one. The difference in the translog form is that it does not restrict σ to be constant, identical for all pairs, or one. Until the advent of flexible functional forms, the possibilities for representing production

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[6] A transcendental function is one that cannot be defined algebraically by a finite number of terms. Examples include ln(x), e^x, and sin(x).

[7] More precisely, Allen-Uzawa partial elasticities of substitution are share weighted cross-price elasticities of demand. These measures of substitution tell us how the ratio of inputs j and n responds to the changes in relative price of j and n, holding output constant, just like ordinary elasticities of substitution in the two input case. The difference is that for more than two inputs, other input prices are held constant and the other input quantities will adjust optimally (Varian, 1984).

technology were limited and included restrictions that are not likely to exist empirically.[8]

With this understanding of the properties of the translog functional form, it is clear why it is appropriate for modeling the economic behavior of chlorinated solvent consuming industries. The main thrust of the argument is that the technologies in these industries do not exhibit constant, identical, and unitary substitution opportunities. Thus, a second order nonlinear approximation, such as translog functional form, is appropriate.

The product substitutes, chemical substitutes, process substitutes, and recycling and recovery methods discussed in Section II provide numerous examples of how substitution opportunities vary between and within the production applications. For example, it is considerably easier for a metal cleaning operation to substitute hydrocarbon cleaners in place of perchloroethylene than it is for a dry cleaning operation to substitute hydrocarbon cleaners in place of perchloroethylene. At the same time, it may be substantially easier for dry cleaners to increase recycling by expanding route service pickup of spent solvent than it is for metal cleaners who already recycle extensively on-site.

Supply Equations for Production Applications and Solvent Services

For every translog production function there is a corresponding translog cost function that is dual and contains all of the economically relevant aspects of the production technology. For example, all of the supply equations in the model are in the form of translog marginal cost equations. When all costs are variable, the marginal cost curve is the supply curve as long as marginal costs exceed average costs. A translog cost function is as follows:

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[8] Flexible functional forms do not have the ability to approximate any arbitrary production function because they still require restrictions to be well-behaved economically. Furthermore, these forms are still approximations--albeit better approximations than the first order approximations--and therefore they can not be interpreted globally (Chambers, 1988).

$$\ln P = \ln MC = \sum_j \alpha_j \ln p_j + \frac{1}{2} \sum_j \sum_n \beta_{jn} \ln p_j \ln p_n \qquad (3.7)$$

In this equation, P is the price of the production output, MC is the marginal cost of the production output, and p_j and p_n (with $j \neq n$) are the prices of inputs to the production process. The chlorinated solvent model uses this cost function to represent supply of production applications and solvent services. When MC is the marginal cost of a solvent service, the inputs are factor of production prices. When MC is the marginal cost of a production application, the inputs are solvent service prices.

By the principle of duality, these cost equations embody all of the relevant technological information (e.g., returns to scale, substitutability) about the production processes that employ chlorinated solvents.[9] The technological information is in the form of restrictions on the parameters in the cost functions. For example, the cost function is independent of output level because it assumes constant returns to scale in production. Hence, output cost depends only on prices of inputs, and the parameter value for output is zero. Likewise, if the cost function is quasiconvex in prices,[10] a condition that depends on its second order parameters, then the production function isoquants are convex to the origin. Duality is significant because it allows representation of production technology with only cost data. This proves to be of great value when the production variables are not easily observable, but the cost variables are observable. In these cases, cost functions can represent production technology instead of production functions.

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[9] See Chambers (1988) for a discussion of the dual approach.

[10] If the function maps out a convex set on the x-axis for all values of $f(x) \leq b$, it is quasiconvex. Formally, a function $f(x)$ is quasiconvex iff the sets, $\{x \in X \mid f(x) \leq b\}$ are convex, for any real number b, where X is a convex set of real numbers (Intriligator, 1971).

Input Demand Equations

Another useful result of the duality between cost and production functions is that the first derivative of the cost function equals the cost minimizing demand for inputs to the production process. By Shepherd's Lemma, the logarithmic derivative of equation 3.7 with respect to input prices is as follows (Varian, 1984):

$$s_j = \alpha_j + \sum_n \beta_{jn} \ln p_n \tag{3.8}$$

In the logarithmic case, Shepherd's Lemma gives us input shares (s_j) rather than quantities for derived input demand. However, the shares still represent the cost minimizing demand for inputs. These are the type of equations used to represent the demand for solvent services and factors of production in this analysis.

The First Order Translog Parameters

When $p_n = 1$ in equation (3.8), it is apparent that the first order parameters from a translog cost function are input cost shares. An input cost share is the portion of the total cost of production that is attributable to a particular input. The convenient feature of using a cost function of this form is that engineering cost data can specify these parameters. That is, we can use shares from engineering cost studies in the model.

First order translog parameters need restrictions so the equations behave consistently with economic theory. The first restriction is that the cost function must be monotonic because cost must increase or at least stay the same when prices increase. Hence, the first order translog parameters must be nonnegative. Furthermore, if the price of an input increases by one dollar, the cost of the output should increase by one dollar (times the number of inputs) when all other things are held constant. In other terms, the cost functions must be linear homogeneous in prices, which implies that the cost shares sum to one.[11]

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[11] That is, $\alpha_j \geq 0$, $\sum_j \alpha_j = 1$

The Second Order Translog Parameters

The second order translog parameters represent technical substitution opportunities within a given industry as well as the nontechnical behavioral aspects of substitution choices. Factor of production substitutions and solvent service substitutions depend on engineering considerations, cost considerations, and institutional considerations, such as regulations and industry preferences.

More formally, the second order parameters are elasticities of input cost share with respect to input price.[12] That is, they are measures of how the cost share for one input changes when the price of that input changes *or* when the price of another input changes. The second order parameters are also known as *constant share elasticities* (CSEs) because they are constant with respect to input price (Jorgenson, 1984).

Like the first order parameters, the second order parameters need constraints for the cost function to be consistent with neoclassical economic theory. The cost function must be linear homogeneous in prices, which means the row sums of the CSE matrices must be zero in addition to the first order parameter restrictions discussed above. A well-behaved cost function is also postulated to be continuously differentiable. As a result, the matrix of CSEs must be symmetric as well (Fuss, McFadden, and Mundlak, 1978).[13]

The second order parameters in the translog cost function, β, are related to the Allen-Uzawa partial elasticities of substitution, as shown by Uzawa (1962):

$$\sigma_{jn} = \frac{\beta_{jn} + s_j s_n}{s_j s_n} \qquad (3.9)$$

$$\sigma_{jj} = \frac{\beta_{jj} + s_j^2 - s_j}{s_j^2} \qquad (3.10)$$

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[12] That is, $\beta_{jn} = \partial \ln s_j / \partial \ln p_n$

[13] $\sum_n \beta_{jn} = 0$, $\beta_{jn} = \beta_{nj}$

In these equations, σ_{jn} is the change in input j with respect to a change in the price of n; σ_{jj} is the change in input j with respect to a change in the price of j; and s_j, s_n, s_{jn}, β_{jj}, and β_{jn} are the same parameters defined above. Uzawa's transformations show how technological characteristics (σ) are determined from cost equation parameters--a restatement of the dual approach.

When the restrictions on the first and second order parameters are in place, the model's equations are monotonic, continuous, and differentiable functions. This means there are no "threshold" effects in the model. Incremental changes in one of the markets generate incremental changes in the outcomes of the model and not a discontinuous large change beyond a certain threshold. The question then arises, "Is it reasonable to represent chlorinated solvent markets as smooth functions?"

The regulated solvents will not disappear overnight, but rather step by step as industry adopts additional control technologies, recycling, and substitutes. Hence, it is reasonable to assume there will be a smooth response to regulations within the time frame of the model. An example is the regulation of METH in occupational exposures. Regulations are becoming more stringent by lowering the maximum level of daily exposure. As industry adds more equipment to control worker exposures, METH demand declines.

Strictly speaking, the time frame of the model is shorter than usually considered in a long run neoclassical economics model. However, because we expect changes in technology beyond 3-5 years, we cannot define a long run model in the strict sense. This is a compromise of convenience to implement a model of technologies and regulatory policies that are rapidly evolving. Without such compromise, the important policy issues in chlorinated solvent markets would be impossible to analyze rigorously.

With monotonic continuous differentiable functions, we can reason *a priori* that the model will not display threshold properties from errors in the second order parameters. However, we still do not know how much the results change if these errors occur. Section V tests for sensitivity to errors in parameters and gives an idea of the magnitude of changes in results that are caused by parameter errors.

Global Properties of the Translog Functional Form

The Allen-Uzawa partial elasticities of substitution (AUES) are not constant at data points other than the benchmark equilibrium. As we move away from the benchmark equilibrium to new values of price and demand, the cost shares of inputs change and hence the AUESs, which are share weighted, also change. In contrast, the second order translog parameters remain constant at all data points and input shares, which is, again, why they are also known as constant share elasticities (CSEs).

A drawback of the translog and other flexible functional forms is that it is possible that the production function does not behave regularly beyond limited departures from the initial given data point of approximation--the benchmark equilibrium. The conditions of regularity are defined as monotonicity[14] and quasiconcavity,[15] which are needed to conform with neoclassical economics. The tests of global regularity in the literature have been only for simplified cases of two or three variables.[16] Irregular global behavior of the translog production function has been demonstrated only for small or large base point Allen-Uzawa partial elasticities of substitution. The ultimate test of global properties is on the particular data set in question, and Section IV tests parameter matrices of data used in this analysis.

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[14] *Monotonicity* is the quality of a production function that, "if you have at least as much of both inputs, it should be possible to produce at least as much output" (Varian, 1987). This means that the marginal products (first derivatives) of an increasing monotonic production function are positive.

[15] *Quasiconcavity* requires that if some level of two inputs can produce some level of output, then any weighted average combination of these inputs can also produce that level of output. That is, the production isoquants will be convex to the origin.

[16] See Wales (1977); Guilkey and Lovell (1980); Guilkey, Lovell, and Sickles (1983); Caves and Christensen (1980); and Barnett and Lee (1985).

Functional Form of the Output Demand Equations

The output demand equations represent how demand for production applications changes when their price changes. For example, if the price of electronics parts cleaning increases because of solvent regulations, then the demand for cleaning services will probably decrease. In production applications where cost effective product substitutes exist, an increase in price is more likely to stimulate a drop in demand. As discussed in Section II, product substitutes in electronics include printing circuits on surfaces other than printed circuit boards and simply cleaning boards less thoroughly.

An elasticity of demand parameter determines output demand--one parameter for each of the seven production applications (η_i). These parameters are the percentage change in the demand for a one percent change in price. The following equations determine the demand (Q_i) from the initial demand (Q_i^o) and a given output price (P_i):

$$Q_i = Q_i^o P_i^{\eta_i} \tag{3.11}$$

It is important to distinguish what these parameters mean in the case of each production application. For example, in the case of dry cleaning, the output demand elasticity represents the degree to which consumers will change from dry cleaning to water laundering and treated fabrics or simply clean their clothing less often. In electronics, the elasticity represents the degree to which less cleaning will become acceptable and the degree to which boardless electronics substitute when the price of this application increases. For original equipment paint removal, the elasticity represents the degree to which unpainted and precolored products will substitute for painted products.

Now that the market structure has been specified, and equations defined to represent those markets, we can move on to the method of implementing the model to generate numerical results. Appendix B contains the complete set of equations in the model.

IMPLEMENTATION OF THE MODEL

Solution Algorithm

The procedure for computing the solution is summarized in Figure 3.1. The algorithm starts with prices of factors of production and computes prices of solvent services and prices of production applications. Then, the program computes demand for production applications, solvent services, and finally factors of production. The following steps provide more detail of the solution algorithm:

(1) Calculate Output Prices. The initial set of prices [**A**] for factors of production are entered in the translog cost equation (3.7) to compute the price of solvent services [**B**]. Then the prices of solvent services, again with equation (3.7), compute the prices of production applications [**C**].

(2) Calculate Demand for Production Applications. With the prices of production applications from step (1), the program computes production application demand with equation (3.11) [**D**].

(3) Calculate Demand for Solvent Services. First, the program calculates the total consumer spending on each of the production applications by multiplying the demand from step (2) times the price from step (1). These values then multiply by the cost share of each solvent service--which equation (3.8) determines with the prices of solvent services found in step (1). This product is the portion of the total cost of a production application that is attributable to a solvent

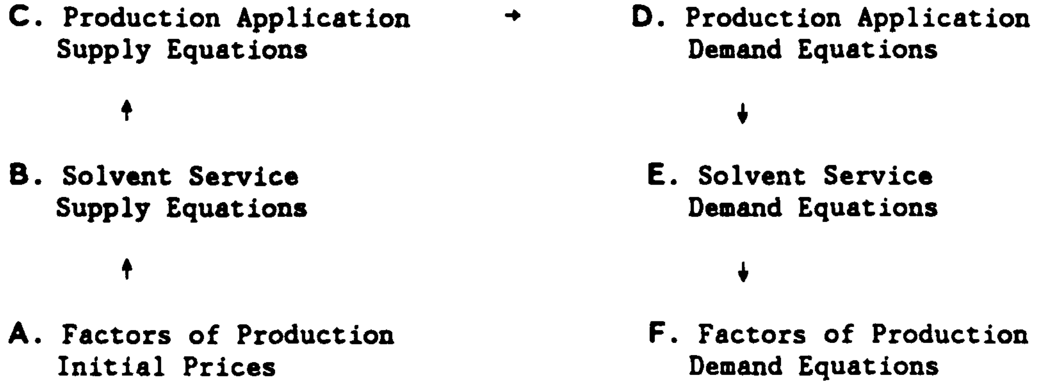

Fig. 3.1--Solution algorithm flow diagram

service. Finally, the program divides by the price of each solvent service to get each solvent service demand [E].

(4) Calculate Demand for Factors of Production. Calculate the cost shares for each of the factors of production using equation (3.8) and the prices of factors of production found in step (1). Multiply these shares by the cost attributable to each of the solvent services calculated in step (3) to get the cost attributable to each of the factors of production. Divide these costs by the factor prices to get demand for factors of production [F].

With no constraints on the model, the program computes demand for inputs and outputs from the initial factor of production prices as described in steps (1-4). There is no simultaneity between the supply and demand equations, so the program solves the equations in a sequential fashion. In this case, the program finds the equilibrium prices and quantities after one pass through the solution algorithm.

When regulations introduce supply constraints, the value of demand computed with steps (1-4) may exceed the bound of a supply constraint. When this happens, the prices of the constrained factors of production change and steps (1-4) repeat iteratively until demand is within the bounds of the supply constraint.

Programming and Computing

The model formulation is an optimization problem with a nonlinear objective function and linear constraints. The objective function is the sum of squared differences between supply and demand, and the constraints represent regulatory supply constraints. The prices of factors of production change iteratively until the objective function is minimized, which occurs when supply equals demand in all markets.

CONCLUSIONS

This section described the economic model and its implementation, including the market structure, economic equations, and solution algorithm. The next section describes the numerical specification of the model.

IV. NUMERICAL SPECIFICATION OF MODEL PARAMETERS

Section III described equations that represent chlorinated solvent substitutions in mathematical form. The description included definitions of the parameters in these equations, including restrictions to assure the equations are consistent with economic theory. This section describes the numerical specification of those *parameter values* as well as the *benchmark equilibrium data set* containing the initial values of the model's variables.

Because there is no single source of data on chlorinated solvent markets, I use an eclectic approach to data collection. The sources span a diverse range from the literature on empirical estimation to solvent waste manifests, solvent production figures, and expert judgments.

Compared to other applied general equilibrium models, the numerical specification of this model relies heavily on expertise in chlorinated solvent process engineering. The role of solvent process expertise is twofold, involving reconciliation of different types of engineering and cost data, as well as subjectively judging economic parameter values.

Estimating substitution parameters for general equilibrium models such as this often encounters difficult estimation of a large number of equations or strong assumptions (e.g., second order parameters are all zero). This chapter contains an innovation designed to get around these difficulties, albeit not without problems of its own: a method of numerically specifying substitution parameters with expert judgments.

The first subsection below compares the most commonly used methods of numerically specifying general equilibrium models. A sequence of four more subsections follow, one to describe the specification of each of the four major data requirements of the model: (1) first order translog parameters, (2) the benchmark equilibrium, (3) second order translog parameters, and finally, (4) output demand parameters.

METHODS OF NUMERICAL SPECIFICATION

Stochastic Estimation Compared to Deterministic Calibration

Mansur and Whalley (1984) describe two methods of numerically specifying applied general equilibrium models for "counterfactual"[1] policy analysis. The first method involves stochastic estimation of parameters with an econometric model. This usually involves estimation of a large number of simultaneous equations with a large number of observations. The second method is to select a single observation of variables deterministically, adjust them to comply with equilibrium conditions, and thereafter call this set of variables the "benchmark equilibrium data set." Along with the data are parameter values that are either computed from the benchmark equilibrium data, drawn from the literature of empirical estimation, or chosen subjectively. The second method needs "calibration," a process of restricting parameters so that the model finds the benchmark equilibrium observation as its solution.

Stochastic estimation is often preferred to deterministic calibration because, given certain conditions, it lends more confidence in the results of a counterfactual policy analysis. Econometric methods can test the fit of model to data as well as other formalized ways to deal with uncertainty. Alternatively, deterministic calibration methods have usually relied on sensitivity analysis to test the robustness of results. Despite the advantages of econometric estimation, most applications employ deterministic calibration for a number of reasons that the model of chlorinated solvent markets shares: (1) The number of parameters is often so large that a large number of observations is needed to assure adequate degrees of freedom in estimation. (2) When the policy changes have been profound, historical data are of limited use. (3) It takes less time and computational cost. (4) The data required to use statistical estimation do not exist and would be extraordinarily expensive and difficult to collect.

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[1] "Policy evaluation proceeds by comparing a 'benchmark' equilibrium under existing policies to a new equilibrium under new policies. As the new policy alternatives considered are usually hypothetical, such an equilibrium is termed 'counterfactual.'" In effect, counterfactual policy analysis is the "numerical analog" to comparative statics analysis (Mansur and Whalley, 1984).

Equations (3.7), (3.8), and (3.11) have three types of parameters that need numerical specification: The *First Order Translog Parameters* (α) are input cost shares when prices are one. The *Second Order Translog Parameters* (β) are partial elasticities of input cost share with respect to input price. The *Output Demand Parameters* (η) are elasticities of outputs with respect to output prices. Furthermore, the *Data Set* variables need numerical specification, including price of both inputs (p) and outputs (P) and the demand for outputs (Q^o).

FIRST ORDER TRANSLOG PARAMETERS

The difficulty in specifying the first order parameters is that data exist only in small bits and pieces that are not necessarily commensurate with one another. The process of specifying these parameter values involves substantial interpretation and extrapolation, relying heavily on process engineering experts. A single "integrating" expert plays a major role in this process by tapping the expert's own knowledge base and by collecting large amounts of information from numerous other process specialists.[2]

This is the complete set of first order translog parameters needed to specify the model:

- α_{ij} are the cost shares attributable to solvent services j for production applications i,
- α_{ijk} are the cost shares attributable to factors of production k for solvent services j for production applications i.

The first order translog parameters are observable empirically if we redefine physical units so all prices are one and assume that the empirical observation represents an economic equilibrium. Under these

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[2] The "integrating expert" was Dr. K. Wolf of the Institute for Research and Technical Assistance. The other experts who contributed information included representatives from government agencies, chemical producers, solvent reclaimers, hazardous waste haulers, as well as from industries that employ chlorinated solvents for dry cleaning, metal cleaning, electronics parts cleaning, and paint removal.

conditions, the parameter values are observed industrial cost data. The strategy for estimating these parameters is to specify the α_{ijk} parameters and the benchmark equilibrium data set and then to compute α_{ij}. The procedure for specifying α_{ijk} is to: (1) update the subset of cost shares that exist in observed industrial cost data (the "reference cost shares"), (2) compute cost shares for those applications for which no reference data exist, (3) add a cost share for pollution and other external costs, and (4) normalize all of the revised cost shares to sum to unity.

Updating Reference Cost Shares. Wolf and Camm (1987) present cost shares from an engineering cost study (GCA, 1983), adjusted to include waste disposal costs, for a small subset of the values in Table 4.1. These cost shares form the reference cost shares, which this section updates and uses to estimate similar cost shares for production applications, solvent services, and factors of production that were not estimated in the earlier work by GCA (1983). That is, the reference cost shares are the subset from which the complete set of cost shares are extrapolated. Appendix C contains more details of the cost share adjustments.

To get a subset of cost shares in Table 4.1, the reference cost shares need adjusting to compensate for changes in market conditions and regulation since GCA estimated the earlier values. One of the largest changes has been in the cost of waste disposal. EPA has banned most forms of land disposal of chlorinated solvents, increasing the cost of waste disposal dramatically. At the same time, industry has developed recycling capacity and markets for all of the chlorinated solvents, especially those that are expensive in virgin form. The higher the price of virgin solvent, the more value the spent solvent has to a reclaimer, who charges less for disposal than for solvents that are lower in price. These adjustments involve increasing the waste disposal cost share and then multiplying the waste disposal cost share by a factor proportional to the value of the solvent, which indicates the degree of recycling. Table 4.2 shows virgin solvent prices and recycling adjustments. Each of the updated waste disposal figures

Table 4.1

FACTORS OF PRODUCTION COST SHARES

	Factors of Production						
Solvent Service for Production Application	Solvent	Energy	Assets	Waste Disposal	Labor	Pol- Cost	Water Disposal
Dry Cleaning							
PERC	.17	.02	.47	.04	.22	.08	.00
TCA	.14	.02	.51	.06	.24	.03	.00
CFC-113	.14	.02	.48	.04	.23	.08	.00
Flammables	.07	.04	.45	.03	.31	.10	.00
HCFC	.26	.02	.44	.02	.21	.04	.00
Cold Cleaning							
TCE	.28	.05	.12	.10	.34	.11	.00
METH	.24	.06	.14	.15	.38	.04	.00
PERC	.23	.05	.13	.14	.35	.10	.00
TCA	.31	.05	.13	.11	.36	.04	.00
CFC-113	.56	.03	.08	.03	.23	.06	.00
Aqueous	.30	.21	.15	.00	.19	.05	.10
Flammables	.22	.06	.15	.03	.42	.12	.00
Combustibles	.55	.03	.08	.03	.24	.04	.03
Vapor Degreasing							
TCE	.25	.09	.17	.09	.30	.10	.00
METH	.21	.10	.19	.13	.33	.04	.00
PERC	.20	.09	.18	.13	.31	.09	.00
TCA	.28	.10	.18	.09	.32	.03	.00
CFC-113	.52	.06	.12	.02	.21	.06	.00
Aqueous	.23	.33	.18	.00	.14	.04	.08
Electronics							
TCA	.28	.10	.21	.10	.29	.03	.00
CFC-113	.52	.06	.14	.02	.19	.06	.00
Aqueous	.30	.13	.28	.00	.15	.05	.10
Combustibles	.68	.04	.09	.02	.13	.02	.03
Noclean	1.00	.00	.00	.00	.00	.00	.00
HCFC	.70	.04	.10	.01	.13	.02	.00
Original Equipment							
METH	.22	.05	.07	.14	.40	.05	.05
Flammables	.28	.05	.07	.01	.41	.12	.05
Combustibles	.62	.03	.04	.07	.19	.03	.03
Water Blasting	.00	.15	.24	.08	.46	.01	.06
Non-METH Immersion	.22	.08	.14	.15	.38	.03	.00
Maintenance							
METH	.23	.08	.13	.10	.36	.05	.05
Plastic Media Blasting	.05	.05	.41	.05	.37	.01	.05
Sodium Bicarbonate	.05	.05	.40	.07	.36	.00	.07
Laser	.00	.10	.70	.05	.10	.05	.00
Consumer							
METH	.48	.00	.08	.00	.41	.03	.00
Flammables	.40	.00	.08	.00	.42	.10	.00
Combustibles	.52	.00	.07	.00	.37	.04	.00
Heat Gun	.00	.05	.48	.00	.43	.04	.00

replaces the old waste disposal cost share and all of the shares are normalized to sum to unity.

From the Updated Subset of Reference Cost Shares to the Full Set of Cost Shares. The reference cost shares were available only for PERC and hydrocarbon dry cleaning, and for TCA and aqueous vapor degreasing. For the other solvent services and production applications, we estimate the cost shares by starting with the updated reference cost shares and adjusting for differences in solvent volatility and the relative cost of waste disposal.

Just like the waste disposal costs needed to be adjusted to update the reference cost shares, they need to be adjusted to extrapolate to solvents not in the reference cost shares. Again, the higher the price of virgin solvent the more extensive the recycling. Table 4.2 shows the rest of the recycling adjustments, which the program multiplies by the waste disposal share to get a share that is adjusted to a particular solvent.

Differences in volatility and price determine solvent cost share adjustments. Each of the solvents not in the reference cost shares is adjusted accordingly. Table 4.3 shows the solvent emissions as a proportion of demand, which reflects the relative volatility of the solvents in question.

Adding Pollution Cost Adjustments to the Full Set of Cost Shares. The pollution cost adjustments in Table 4.4 are representative of the costs to society not included in the other factors of production. For example, fugitive emissions from vapor degreasing into the atmosphere in vapor form or into the sewer in liquid form represent a cost to society in terms of health and the environment that is not borne by the solvent user. These pollution costs reflect the state of knowledge and regulation before this year's METH regulation to reduce further occupational exposures and before this year's CFC-113 and TCA regulations for ozone depletion.

The values in Table 4.4 adjust pollution costs for different solvent services and production applications. These factors are all relative to the reference cost share values for pollution costs, so the

Table 4.2

SOLVENT PRICES AND RECYCLING ADJUSTMENT

Solvent	Price (in dollars) per lb.	Price (in dollars) per kg.	Recycling Adjustment (pTCE/p*)
TCE	.39[a]	.85	1.00
METH	.29[a]	.64	1.33
PERC	.29[a]	.64	1.33
TCA	.41[a]	.89	.99
CFC-113	1.12[a]	2.47	.34
Aqueous	.35[b]	.77	
All Flammables	.24[b]	.53	
Combustibles			
Metal Cleaning	1.88[d]	4.14	
Paint Stripping	1.88[b]	4.14	
Electronics	3.76[d]	8.28	
Nonchemical			
Plastic Blasting Media	2.40[c]	5.28	
Sodium Bicarbonate	.18[a]	.40	
Non-METH Immersion	.27[a,b]	.59	
HCFC	2.24[e]	4.94	.17

[a] Chemical Marketing Reporter: June 5, 1989; 2.20462 lbs./kg.

[b] Expert Estimate

[c] Fusco Abrasive Systems, for (10) 250lb. drums.

[d] Petroferm Inc.

[e] The HCFCs are not yet on the market; industry sources indicate they will be approximately 100 percent higher in price than CFC-113.

Table 4.3

SOLVENT EMISSIONS AS A PROPORTION OF DEMAND

Production Application	Solvent Service									
							Hydrocarbons			
	TCE	PERC	METH	TCA	CFC-113	Aqueous	Flam.	Combust.	Non-METH	HCFC
Cold Cleaning	.85	.85	.85	.85	.85	.70	.85	.45		
Vapor Deg.	.85	.85	.85	.85	.85	.70				
Electronics				.85	.85	.70		.45		.85
Dry Cleaning		.88		.85	.85					.85
Original Eqpt.			.85			.0	.85	.45	.45[a]	
Maintenance			.85							
Consumer			.85				.85	.45		

SOURCE: (Wolf, 1989).

[a] Non-METH stripping methods (e.g., phosphoric acid).

Table 4.4

POLLUTION COST ADJUSTMENTS

Production Application	Solvent Service									
							Hydrocarbons			
	TCE	PERC	METH	TCA	CFC-113	Aqueous	Flam.	Combust.	Non-chem.	HCFC
Cold Cleaning	1.1	.9	.35	.35	.9	.4	.98	.50		
Vapor Deg.	1.1	.9	.35	.35	.9	.4				
Electronics				.35	.9	.4		.50	.0	.5
Dry Cleaning		.9		.35	.9		.98			.5
Original Eqpt.			.5			.10	1.13	.65	.3	
Maintenance			.5						.11[a] .05[a] .3[a]	
Consumer			.35				.98	.5	.4	

[a] Plastic media blasting/sodium bicarbonate/flash lamp and laser, respectively. These values are factors to multiply by reference cost shares (Wolf, 1989).

program multiplies values in Table 4.4 by the relevant reference cost shares.

Normalizing the Complete Set of Cost Shares to Sum to Unity. After the program adds pollution cost shares to the other cost shares, it normalizes all of the shares to sum to one. As discussed in the last section, the first order parameters need to be nonnegative and sum to one if the cost functions are to be monotonic and linear homogeneous in prices. Table 4.1 is the complete set of factors of production cost shares for all of the solvent services and all of the production applications, all normalized to sum to unity.

BENCHMARK EQUILIBRIUM DATA SET

The benchmark equilibrium data set is in the form of "transaction matrices," which have inputs for rows and outputs for columns. Each element of a transaction matrix is the value (price times quantity) of the output that can be attributed to a given input.

The benchmark equilibrium specifies all prices as one. This means that the physical units are redefined such that one unit will generate a return of one dollar. In this way, the model does not need the price of the conventional unit of measurement for every commodity. Empirical cost data can then specify cost share values because the first order translog parameters are identical to input cost shares when prices are one. The following equilibrium conditions must be met for the data set to define the benchmark equilibrium:

- Demand equals supply for all quantities.
- The sum of input payments equals output revenues.

The first condition is necessary for a general equilibrium. We meet this condition at the benchmark equilibrium by specifying one transaction matrix defined as the initial supply transaction matrix as well as the initial demand transaction matrix. The second condition reflects the assumption of constant returns to scale.[3] The program meets

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[3] As discussed in the last section, constant returns to scale

this condition by choosing one transaction value and then computing the other transaction values with the help of the first order translog parameters so the sum of input payments is equal to output revenue in each case.

The following transaction matrices make up the benchmark equilibrium data set:

- T_i are the transaction values of production applications i.
- T_{ij} are the transaction values attributable to solvent services j for production applications i.
- T_{ijk} are the transaction values attributable to factors of production k for solvent services j for production applications i.

Computing the Benchmark Equilibrium Data Set

To compute the transaction values of the benchmark equilibrium data set, the only data needed are the parameters α_{ijk} and a subset of transaction values--in this case, the transaction values of solvent in each of the solvent services for each of the production applications (that is, T_{ijk} for k = solvent factor of production). With this data, the program computes transaction values for nonsolvent factors of production and for production applications, after which the program computes the last of the first order translog parameters.[*] In this way, the program computes all of the transaction values from the first order translog parameters and the transaction values of virgin solvent demand.

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implies that marginal cost is a function of input prices only and not level of output.

[*] Compute solvent service transaction values:

$$T_{ij} = \sum_{k} T_{ijk} = T_{ijk}[k=\mathrm{solvent}] \;/\; \alpha_{ijk}[k=\mathrm{solvent}]$$

Compute nonsolvent factor of production transaction values:

$$T_{ijk}[k\neq \mathrm{solvent}] = T_{ij} * \alpha_{ijk}[k\neq \mathrm{solvent}]$$

Compute production application transaction values:

$$T_i = \sum_{j} T_{ij}$$

Compute first order translog parameters for solvent services:

$$\alpha_{ij} = T_{ij} \;/\; T_i$$

To specify the solvent factor of production transaction matrices, the respective demand and price values are needed. Table 4.5 shows demand for the solvent factor of production for all of the solvent services and all of the production applications. Table 4.2 shows the prices of various solvent compounds drawn from market reports and solvent vendors. The price and demand values above are then multiplied to get the transaction values of solvent demand in Table 4.6.[5]

One of the nice features of having the benchmark equilibrium data set is that it can test the computer model. If the problem is formulated, specified, and coded properly, the solution set should be equal to the benchmark data. That is, when the model runs without regulatory constraints or price changes, the solution should be identical to the benchmark equilibrium values of price and quantity.

SECOND ORDER TRANSLOG PARAMETERS

The complete set of CSE matrices that needs specification in the model of chlorinated solvent markets is as follows:

> β_{ijn} are the solvent service j,n CSEs for each of the production applications i.
>
> β_{ijko} are the factor of production k,o CSEs for each of the solvent services j for each of the production applications i.

As described in Section III, the second order translog parameters represent the degree of substitution between inputs to a production process. This subsection describes how these parameters are numerically specified in the model. The role of the expert is more than one of interpreting and reconciling data as for the benchmark equilibrium; instead, the expert subjectively judges the value of the second order parameters.

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[5] There are four exceptions to this method of computing transaction values. These are cases where the solvent service does not employ chemical solvent or where the method is very new or experimental. In these cases, the transaction values specify the labor factor of production and expert judgments for the portion of market share.

Table 4.5

SOLVENT DEMAND FOR 1988
(IN THOUSAND METRIC TONS)

	Solvent Service									
							Hydrocarbons			
Production Application	TCE	PERC	METH	TCA	CFC-113	Aqueous	Flam.	Combust.	Non-chem.	HCFC
Dry Cleaning		107.2[e]		1.1[f]	2.0[f]		101.0[g]			1.1[f]
Metal Cleaning										
Total	60.0[a]	20.0[b]	18.1[c]	146.0[d]	23.0[f]					
Cold Clean.	13.7[f]	1.6[f]	13.4[f]	38.0[d]	17.0[f]	236.0[g]	334.0[f]	42.0[f]		
Vapor Deg.	46.3[f]	18.4[f]	4.7[f]	108.0[d]	6.0[f]	219.0[g]				
Electronics				3.6[d]	24.0[f]	30.0[g]		.7[f]		0.7[f]
Original Eqpt.			10.0[f]				7.0[f]	.3[f]	5.0[f]	
Maintenance			20.0[f]						.17[h] .1f[h]	
Consumer			20.0[f]				3.0[f]	.1[f]		

[a] Chemical Marketing Reporter, January 23, 1989.

[b] Chemical Marketing Reporter, February 6, 1989.

[c] Chemical Marketing Reporter, February 20, 1989.

[d] Chemical Marketing Reporter, January 30, 1989.

[e] (b) minus 5000 mt. for textile processing (Expert Estimate).

[f] Expert Estimates.

[g] Wolf and Camm (1987).

[h] Plastic media blasting/sodium bicarbonate, respectively.

Table 4.6

SOLVENT TRANSACTION VALUES (IN MILLIONS OF DOLLARS)

	Solvent Service									
							Hydrocarbons			
Production Application	TCE	METH	PERC	TCA	CFC-113	Aqueous	Flam.	Combust.	Non-chem.	HCFC
Dry Cleaning			68.6	1.0	4.9		53.5			4.1
Cold Cleaning	11.7	8.6	1.0	33.8	42.0	181.7	177.0	173.8		
Vapor Deg.	39.4	3.0	11.8	96.1	14.8	168.6				
Electronics				3.2	59.3	23.1		2.9		.3
Original Eqpt.		6.4					3.7	1.2	3.0	
Maintenance		12.8							.9/ .04[a]	
Consumer		12.8					1.6	.4		

[a] Plastic media blasting/sodium bicarbonate, respectively.

The difficulty of numerically specifying the CSE substitution parameters with expert judgments is that the value of these parameters is difficult to grasp intuitively. For example, a pair of inputs to a production process that are substitutes can have a CSE substitution parameter that is either positive or negative depending on the relative cost shares. By the same argument, the absolute value of the CSE parameter is not necessarily consistent with the magnitude of the substitution of inputs it represents.

An alternative parameter form is the compensated *Allen partial elasticity of demand* (AED) (also known as cross-elasticity of demand), which is the notion of how much the demand for an input changes for a change in the price of another input. This is simply the own-price elasticity of demand when referring to the change in demand for a change in the price of the same input (Allen, 1938; Kang and Brown, 1981). The AED substitution parameter is intuitive because its sign indicates whether two inputs are substitutes or complements, and because the absolute value indicates the magnitude of the substitution. For this reason, it is far more intuitive to solicit expert judgments of AED parameters. The AED parameters can be transformed into CSE parameters with cost shares, such as the first order translog parameters described above:[6]

$$\beta_{jn} = \eta_{jn}s_j - s_j s_n \qquad (4.1)$$

$$\beta_{jj} = \eta_{jj} - s_j^2 + s_j \qquad (4.2)$$

Where: s_j and s_n are cost shares, η are AEDs, and β are CSEs.

Formal Methods of Eliciting Expert Judgments

Several formalized methods for eliciting subjective judgments, such as the Delphi Method, the Analytic Hierarchy Process, and Expert Systems, inform the method of specifying the CSE parameters.

The Delphi and related methods refer to a number of experts working in a "group communication process" to specify the same set of parameters (Linstone and Turoff, 1975; Press, 1979). Using this method for the substitution parameters would be extremely expensive and time-consuming because of the large number of parameters. However, parts of the Delphi process--which involves eliciting subjective opinions of experts, compiling the group opinion, and revising the subjective opinions in an iterative fashion--apply to this study. For example, the expert revises parameter judgments in light of the complete set of parameter estimates. Although it is beyond the scope of the present research, a full Delphi process could reevaluate the most important parameters in the model.

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[6] These transformations are derived from Uzawa's transformations (equations 3.9 and 3.10) and the definition of the Allen-Uzawa partial elasticity of demand (Allen, 1938; Kang and Brown, 1981):

$$\sigma_{jn} = (\partial \ln q_j / \partial \ln p_n)/s_n$$

Where: σ is the AUES; q is input demand; p is input price; and j and n are inputs, and s_n are cost shares; $\partial \ln q_j/\partial \ln p_n$ is defined holding output constant.

Saaty's (1980) Analytic Hierarchy Process and variants thereof (Crawford and Williams, 1985) provide formal quantitative methods to analyze subjective judgments of experts. The methods rely on subjective scales constructed by making pairwise comparisons and arranging them in a "judgment matrix." These matrices are pairwise comparisons of comparable alternatives according to particular criteria. They are not the same form as the matrices of translog second order parameters--which are representations of economic behavior.

An expert system is a computer system that can simulate the judgments of human experts with programmed sets of facts and heuristics (Bowerman and Glover, 1988). Expert systems sometimes make use of a formal equation with expert specified parameters as part of a decision rule. Often, one expert will specify the knowledge in the expert system because that expert is the only source of a particular field of knowledge *or* so that the judgments of many experts are integrated and as consistent as possible.[7] Because each matrix of CSE parameters embodies many expert judgments, the model is, in a sense, a stylized expert system. The "integrating expert" judged the CSE parameters by referring to the expert's own specialty areas and by referring to numerous other experts when needed.

Method of Eliciting Expert Judgments of Substitution Parameters

The method of soliciting the subjective valuations from the expert is as follows:

Define the AED substitution parameters. In this task, the integrating expert learns what the parameters mean in a variety of ways so that the expert understands the concept well enough to make informed judgments about their values. The parameter definitions need explanation in economic terms and in lay terms. To mitigate bias, we framed selection decisions numerically and graphically.[8] When a substitution parameter is being explained, for example, the expert sees

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[7] A classic example is the "Aldo in a Box" expert system developed by Campbell Soup to save the knowledge of a retiring rotary sterilizer debugging expert (Bowerman and Glover, 1988).

[8] Any method of expert specification of parameters can be biased by

how an input's price change affects change in input demand by observing changes in a numerical table. At the same time, the expert is able to see the shifts in inputs on a bar graph. Repeating this process for different values of the substitution parameters makes their meaning and definition as clear as possible.

Specify parameter values. The expert makes judgments of the values of each the AED substitution parameters. Typically, the expert specifies the sign of each of the elements first--with the own price AEDs always negative, substitute inputs positive, and complementary inputs negative. Then, the expert specifies whether the shift away from an affected input is large or small for a given price change by choosing a value on the measurement scale of AEDs (discussed below).

The expert does not consciously constrain the AED matrices in terms of symmetry or row sums when making judgments of AED values. It is too complex to do so because the transpose elements in the AED matrices are symmetric only when divided by their cost shares. Also, row sum restrictions are nonintuitive because it is hard to imagine the effects of all of the inputs changing at one time. More intuitive is the effect of one price change on all of the demand changes; however, the requirement of cost share weighting (i.e., the columns sum to zero only when the AEDs are divided by cost shares) clouds an intuitive vision of column restrictions. Since the expert does not constrain the parameter matrices, the data are normalized to conform to row sum and symmetry restrictions (described below).

Measurement Scale

The expert chooses parameter values on a numerical scale defined by examining a range of empirical estimates from the literature. Table 4.7 shows the empirical estimates from four studies of elasticities of input demand--each estimated with a translog model. To develop a scale for the chlorinated solvent markets model, I consider these empirical estimates and the extent of changes in market conditions taking place in

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the framing of the selection decisions as demonstrated by Tversky and Kahneman (1981).

chlorinated solvent industries. Regulation of chlorinated solvents induces very specific and sometimes large substitution opportunities, so the scale is extended slightly beyond the range of the empirical values.[9] The scale of own-price AEDs ranged from -1.0 to 0, and the scale of cross-price AEDs ranged from -.7 to +.7.

Converting AED to CSE Parameters

Three steps are needed to convert the parameters that the expert judged (AEDs) to the parameters used in the model's economic equations (CSEs): (1) The first step converts the parameters from price elasticities to share elasticities. (2) Then the parameters are normalized so that they are consistent with economic theory and well-behaved in the optimization procedure. (3) Finally, the parameters need testing for concavity to assure that their global properties are also consistent with economic theory. With these restrictions fulfilled, the cost function is consistent with the assumed differentiability, monotonicity, and homogeneity in input prices. Equations (4.1) and

Table 4.7

ALLEN ELASTICITIES OF DEMAND

	Capital-energy		Capital-labor		Own Elasticities		
Study	E_{KE}	E_{EK}	E_{KL}	E_{LK}	E_{KK}	E_{LL}	E_{EE}
Griffin/Gregory	.13	.15	.05	.01	-.18	-.12	-.79
Berndt/Wood	-.14	-.18	.29	.06	-.50	-.46	-.45
Hudson/Jorgenson	-.02	-.18	.29	.14	-.42	-.45	.07
Fuss	-.050	-.004	.198	.198	-.762	-.491	-.486

Note: Table from Kang and Brown, 1981; Griffin and Gregory, 1976; Berndt and Wood, 1975; Hudson and Jorgenson, 1974; Fuss, 1977.

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[9] Another reason to extend the range of the empirical values is that the estimates in Table 4.7 are from much larger sectors of the economy, which implies they will be less extreme than those in chlorinated solvent markets.

(4.2) perform the first step, converting from AEDs to CSEs. The following paragraphs describe the second and third steps.

Parameter Normalization. For the equations to behave properly and to be consistent with economic theory, each parameter matrix needs to be symmetric and to have rows sum to zero. Since the CSE matrix is symmetric (when the cost function is differentiable), the transpose elements of the CSE matrix are really two observations of the same parameter framed in opposite directions. If the expert judgments are perfectly consistent, then they will be identical.[18] The program averages transpose elements judged by the expert to assure symmetry in the economic model.

The row sums cannot be normalized algebraically while maintaining the symmetric properties because there are too many equations and not enough unknowns. To normalize the row sums, a minimization model employs a penalty function for the difference between the original matrix of parameters and a new matrix that is symmetric and has row sums equal to zero.

The program implements several variations of the penalty function in the minimization problem. These include the sum of percent deviations, the sum of absolute deviations, and the sum of absolute deviations squared. Each of these penalty functions suggests a different bias in the values of the normalized matrix. For example, using absolute squared deviations in the penalty function tended to fix larger values, and move smaller values. Alternatively, using percent deviations, moves the values greater than one the most and tends to fix values less than one.

In selecting among these penalty functions, an important criterion is whether or not the signs of the values in the AED matrix change. The signs of the AEDs indicate whether inputs are substitutes or complements. The sum of percent deviations penalty function tends to

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[18] The AED values the expert judges are converted to CSE parameters and a sample of the matrices is examined to see how close they are to the symmetry requirement. For this data set, no gross disparities were found.

keep the signs the same because it fixes small values, and because small values are close to zero they are most likely to change signs. This penalty function does not tend to fix zero values, so the program set zero values to very small nonzero numbers so they would stay close to zero. For the sum of squared deviations penalty function, the minimization procedure runs with and without constraints on the signs of the parameters. (The sign constrained program was very unstable for the other penalty functions.) Section V tests four penalty functions for sensitivity and presents results for the two penalty functions that generate results closest to the expectation of the expert.[11]

Testing for Concavity. The restrictions described above assure the translog cost function will be homogeneous in prices, homothetic, and represent a dual production function that has constant returns to scale. Another important property of a well-behaved cost function is concavity. If the cost function is concave in prices, then the production function is concave (Diewert, 1974). The production function needs to be concave if the production isoquants are to be convex and, hence, represent diminishing marginal rates of technical substitution.

The translog cost function without further restrictions may not be concave. Even when it is concave at the benchmark equilibrium with prices equal to one, it may not be concave with regulatory constraints or taxes. To assure concavity we need to either (1) impose further constraints on the matrix of CSEs to assure *global* concavity, or (2) test for *local* concavity in the regions that are relevant to the model.[12] In this analysis, a computer procedure assures local concavity at the benchmark equilibrium, and then tests for local concavity at the new equilibrium with regulatory constraints or taxes.

The test for local concavity calls for Eigen analysis of the Hessian matrix, $\mathbf{H}$, which is negative semi-definite when the cost function meets the local concavity condition. If the Hessian is not

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[11] Tables D.1 through D.4 in Appendix D show the results of this normalization process for four penalty function configurations.

[12] The following discussion and procedure is from Jorgenson (1984), Lau (1978), Borges (1980), Goulder (1982), and Varian (1984).

Table 4.8

LOCAL CONCAVITY ADJUSTMENTS
(NUMBER OF MATRICES ADJUSTED)

Multiply Matrix By:	Sum of Absolute Deviations	Sum of Squared Deviations	Sum of Percent Deviations	Constrained Sum of Squared Deviations
1.0	30	42	21	25
.9	1	0	9	3
.8	1	0	6	5
.7	4	1	2	6
.6	6	0	0	2
.5	1	0	5	2
.4	0	0	0	1
.3	0	0	0	0
.2	0	1	0	0
.1	0	0	0	0
.0	1	0	1	0
Total	44	44	44	44

negative semi-definite, then the program makes an adjustment in the CSE matrix according to the method used by Borges (1980) and Goulder (1982). The program multiplies the CSE matrix by the scalar .9 and tests the Hessian. If the Hessian is still not negative semi-definite, the program multiplies the original CSE matrix by .8 and so on until the Hessian is finally negative semi-definite--that is, when all of its eigen values are nonpositive. The program tests each of the 44 Hessian matrices for local concavity and adjusts them enough to assure local concavity at benchmark equilibrium prices. Table 4.8 shows the adjustments needed to assure local concavity at the benchmark equilibrium for each of four penalty functions.

Once the program finds new equilibrium prices, it tests the matrices for local concavity once again, but does not make further adjustments. For the case of regulations on ozone depleting substances, all of the matrices of CSEs are locally concave at the new equilibrium with the sum of absolute deviations and sum of squared deviations penalty functions. With the sum of percent deviations penalty function, two matrices are not locally concave,[13] and with the constrained sum of squared deviations penalty function, six matrices are not locally concave at the new equilibrium.[14] All of the matrices that are not locally concave involved the ozone depleting substances that were regulated in the model.

Although the cost functions are not completely consistent with economic theory in this case, the results are consistent with results from cases of similar but slightly smaller policy changes for which the matrices are locally concave at the final equilibrium. The implications of this violation appear to be small for this numerical application; however, future research is needed to be sure.

From the local concavity tests, the sum of squared deviations penalty function is preferable because it needs less adjustment at the initial equilibrium and it stays locally concave at the new equilibrium as well. However, local concavity is only one criterion to judge these methods. Section V compares the four methods of normalizing the data--the four penalty functions--in the context of the model's results and finds that the sum of squared deviations method is not desirable on all counts. The most desirable penalty function, hence, depends on the particular application and data set.

OUTPUT DEMAND PARAMETERS

The expert judged the output demand parameters in a manner similar to that of the CSE parameters. First, I constructed a scale from high to low. Then, the expert made judgments on this scale for each of the production applications. The scale ranges from -1.2 to 0, and the specified values appear in Table 4.9.

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[13] One is for dry cleaning solvent services and the other for factors of production for CFC-113 solvent services in cold cleaning.

[14] Two are the same two not locally concave with the sum of percent deviations penalty function. Two more are for factors of production for TCA solvent services in cold cleaning and vapor degreasing; and the last two are for factors of production for CFC-113 solvent services in cold cleaning and electronics.

Table 4.9

OUTPUT DEMAND ELASTICITIES

Production Application	Output Demand Elasticity
Dry Cleaning	-1.0
Metal Cleaning	
Cold Cleaning	-.5
Vapor Degreasing	-.5
Electronics	-.1
Paint Removal	
Original Equipment	-.5
Maintenance	-.5
Consumer	-.8

We see that the output demand is inelastic for electronics production applications. This parameter reflects the difficulty of achieving an acceptable level of reliability without careful defluxing, and that cleaning costs are a small part of the total costs of producing printed circuit boards. On the other hand, dry cleaning is more elastic in demand because there are better product substitutes for dry cleaning applications--such as water laundering and fabric treatments.

CONCLUSIONS

This section has described the method of numerical specification of the model of chlorinated solvent markets and regulations. Without a single consistent source of data, the numerical specification involved a number of sources and technical expertise for interpretation and reconciliation. In the case of the second order translog parameters, expert information was used to value parameters subjectively. Because of the diversity of the data sources and the varying degrees of reliability, sensitivity testing is an important part of the overall analysis. The next section describes the parametric analysis and presents results that are indicative of how the model analyzes specific regulatory proposals.

V. PARAMETRIC ANALYSIS AND RESULTS

With the numerical specification described in the last section, the economic model generates results for specific policy scenarios. The model needs parametric analysis before we can interpret these results. This section first examines some of the major sources of uncertainty in the model including sensitivity to the method of normalizing substitution parameters, sensitivity to error in parameter values, and sensitivity to functional form. Then, a set of results illustrates the effects of regulations on ozone depleting substances.

PARAMETRIC ANALYSIS

Of all possible sources of uncertainty that are present in the model, the three chosen for closer examination appear *a priori* to have large effects on the results. The method of normalizing the parameters is an important source of uncertainty because each of the alternative methods has different biases; without testing it is unclear how much they alter the expert information. The program also tests substitution parameters for sensitivity to errors because they are all specified using expert judgments. Finally, the program tests functional form to find out if it is really worth the effort of using a translog cost function; although Cobb-Douglas functional form has much stronger assumptions (all of the second order parameters are zero), it is far more efficient to implement.

The next three subsections explain details of these sensitivity tests. In general, these tests show that the method of normalization makes a large difference in the model's results. For this reason, the program performs the other sensitivity tests for each of the normalization methods *and* the expert evaluates all of the results. Testing the effect of errors in parameter values shows that the model's results do not change substantially for all but large errors. In contrast, the functional form of the model makes a substantial difference in some cases.

Although this is not a complete set of tests, it does demonstrate the capabilities and limits of the model. The following sources of uncertainty are appropriate for future analysis: model specification, sensitivity to the benchmark equilibrium, sensitivity to individual parameter values, and comparison with other functional forms aside from Cobb-Douglas and translog.

Sensitivity to Method of Normalizing Substitution Parameters

Section IV described four methods of normalizing the second order translog parameters. Each of these methods transforms the parameters in some way that may diverge from the expert's judgment. To compare the four methods, the expert reviewed the same set of results for each method. The idea is to determine which method is best at maintaining the expert information.

Tables 5.1a through 5.1d show a subset of results generated for a policy scenario that is described in greater detail later in this section. In this case, the supply of CFC-113 and TCA are constrained as part of a program for controlling stratospheric ozone depleting chemicals. The column on the left of each table indicates the method of normalizing the parameters. For example, in Table 5.1a, the "sum of absolute deviations" method normalized the data that generated these results.

The column labeled "Solvent Service" shows the possible solvent services used in the vapor degreasing production application. Section II described vapor degreasing and the other production applications. The column "Before" indicates the level of vapor degreasing for each of the solvent services before the regulations, and the "After" column shows the same set of solvent services after the regulations are imposed. The "Change" column is simply the difference between before and after, and "%Change" is the change in percentage terms. The units of these reported figures are in millions of units cleaned (vapor degreased), where one unit is the cleaning performed for the cost of one dollar at the benchmark equilibrium. For example, one unit of vapor degreasing is one aircraft part cleaned if the cost of cleaning that

Table 5.1

RESULTS OF FOUR METHODS OF PARAMETER NORMALIZATION: THE EFFECTS OF OZONE DEPLETION REGULATIONS ON VAPOR DEGREASING SOLVENT SERVICES

Parameter Normalization	Solvent Service	Before	After	Change	%Change	%Before	%After
(a) Sum of Absolute Deviations	TCE	157.6000	193.7454	36.1454	0.2293	0.1180	0.1389
	METH	14.2857	36.5860	22.3003	1.5610	0.0107	0.0262
	PERC	59.0000	83.0943	24.0943	0.4084	0.0442	0.0596
	TCA	343.2143	331.5897	-11.6246	-0.0339	0.2570	0.2377
	113	28.4615	0.0019	-28.4596	-0.9999	0.0213	0.0000
	H_2O	733.0435	750.2231	17.1796	0.0234	0.5488	0.5377
(b) Sum of Squared Deviations	TCE	157.6000	158.7661	1.1661	0.0074	0.1180	0.1227
	METH	14.2857	15.3315	1.0458	0.0732	0.0107	0.0118
	PERC	59.0000	60.9463	1.9463	0.0330	0.0442	0.0471
	TCA	343.2143	322.9702	-20.2441	-0.0590	0.2570	0.2496
	113	28.4615	0.0019	-28.4596	-0.9999	0.0213	0.0000
	H_2O	733.0435	736.1063	3.0628	0.0042	0.5488	0.5688
(c) Sum of Percent Deviations	TCE	157.6000	157.6780	0.0780	0.0005	0.1180	0.1189
	METH	14.2857	16.0837	1.7980	0.1259	0.0107	0.0121
	PERC	59.0000	62.0184	3.0184	0.0512	0.0442	0.0468
	TCA	343.2143	313.1993	-30.0150	-0.0875	0.2570	0.2363
	113	28.4615	0.0019	-28.4596	-0.9999	0.0213	0.0000
	H_2O	733.0435	776.6246	43.5811	0.0595	0.5488	0.5859
(d) Constrained Sum of Squared Deviations	TCE	157.6000	158.6776	1.0776	0.0068	0.1180	0.1191
	METH	14.2857	15.6691	1.3834	0.0968	0.0107	0.0118
	PERC	59.0000	61.5499	2.5499	0.0432	0.0442	0.0462
	TCA	343.2143	320.7800	-22.4343	-0.0654	0.2570	0.2408
	113	28.4615	0.0019	-28.4596	-0.9999	0.0213	0.0000
	H_2O	733.0435	775.2949	42.2515	0.0576	0.5488	0.5821

TCE = Trichloroethylene; METH = Methylene Chloride; PERC = Perchloroethylene; TCA = 1,1,1-trichloroethane; 113 = Chlorofluorocarbon-113; H20 = Aqueous.

part is one dollar. The last two columns, "%Before" and "%After" show the proportions of all vapor degreasing performed with each of the solvent services before and after the new regulations.

The expert reviewed the complete set of results, and this table is a subset presented because it highlights the strengths and weaknesses in each of the four methods of normalizing parameters. Starting with the parameter normalization in Table 5.1a, the substitution to TCE, METH, and PERC is far too great according to the expert. The most likely situation is for aqueous-based solvents (H_2O) to be the largest substitute, with only small increases in the other chlorinated solvents. To explain this loss of expert information, consider that this normalization method minimizes the sum of absolute deviations and, hence, makes substantial changes in parameters that start out small. The substitutions of TCE, METH, and PERC start out small and are biased upward.

The normalization method in Table 5.1b minimizes the sum of squared deviations, which may change the sign of parameters with small absolute values. Aqueous solvent services increased much less than expected by the expert. An inspection of the parameter matrices before and after the normalization shows sign changes in small values of these parameters. The net effect in the model is enough to generate results that do not hold up to expert scrutiny.[1]

In Table 5.1c, the sum of percent deviations normalizes the data and this method does not change small values much at all; none of the signs of the parameters changed. The direction of change in the results is consistent with what the expert expects. Since the larger values change the most with this normalization method, the overall level of the parameters is reduced and the substitutions in the model should be reduced in magnitude. However, the expert's opinion is that these values are not biased downward. Aqueous solvents substitute for much of the ozone depleting chemicals as expected. All of the other substitutions are of expected proportions and magnitudes as well.

With the normalization in Table 5.1d, all of the signs of the parameters are constrained to stay the same as the original values judged by the expert. The substitutions with this method are also intuitively consistent to the expert. The expert is indifferent whether this method or that in 5.1c is closer to the expert information in the original parameters.

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[1] See Appendix D, which shows actual AED parameters before and after they were normalized by each of the four methods.

Sensitivity to Error in the Parameter Values

How sensitive are the model's results to error in the model's parameters? Section III explained that the equations in the model are monotonic, continuous, and differentiable functions, so there should not be any "threshold" effects where small changes in parameter values will cause drastic changes in results. However, this reasoning does not tell us *how much* the results change if there are errors in the parameters.

To test the effects of errors in the expert's judgments, the model runs over and over, each time with a different error term added to the parameters. The concept is to vary the parameters by adding different error terms and to observe how much the results of the model change. For example, an error term is added to the CSE parameters as follows:

$$\beta_{ijr} = \hat{\beta}_{ij} + \varepsilon_r$$

In this expression, $\hat{\beta}_{ij}$ are the parameter values estimated by the expert, ε_r is the error term that has r replicates, and β_{ijr} are the new values of the parameters that run in the model for the *rth* replicate. This expression also shows the same error value adds to all of the elements in one matrix of parameters, β_{ij}. Since the model contains a large number of parameters,[2] the same error term is added to one of three whole groups of parameter matrices to test one of these groups at a time. The three levels in the model define these three groups: output demand elasticities (η), substitution elasticities (β^S) for solvent services, and substitution elasticities (β^F) for factors of production.

The program draws replicates of the error term from a normal distribution with mean zero and a standard deviation that takes on increasing values. The standard deviation of this normal distribution increases until the standard error of the model's results is as large as

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[2] The number of *independent* parameters is as follows: 7 output demand parameters, 128 solvent substitution parameters, and 776 parameters for factors of production. When transpose elements of symmetric matrices are considered separate parameters, the numbers are higher: 7 output demand parameters, 218 substitution parameters for solvent services, and 1332 parameters for factors of production.

the mean of the results. In other words, the parameter error term increases until the noise (standard error of results) is as loud as the signal (mean of the results). If a very large error term is needed to make the noise in the results as big as the signal, we conclude the model's results are robust for errors in the parameters.

Table 5.2 shows the results of this sensitivity analysis for each of the four methods of normalizing the second order parameters. The left column indicates which method normalizes the data, and the value of total METH demand when the parameters are at their expert estimated (mean) values. METH is the regulated solvent in this scenario, so it is particularly sensitive to changes in parameters and it highlights properties of the model. The "Error S.D." column is the standard deviation of the normal distribution from which the error terms are drawn. The "S.E." column is the standard error of total METH demand as computed for each of 100 different sets of parameters formed by adding 100 different error terms drawn from the normal distribution. "Mean/S.E." is the mean of total METH demand divided by the standard error of METH demand computed for the 100 draws. The labels η, β^S, and β^F indicate which group of parameters is being tested while the other groups are constant.

The most general conclusion to draw from Table 5.2 is that the parameters need to have errors as high as +-.4 to +-.5 before the noise in the results will approach the size of the signal. In other terms, the model's parameters are robust for errors in the parameters estimated by the expert. The closest the noise gets to the mean value of total METH demand is for the CSE parameters for factors of production β^F when the sum of squared deviations method normalized the data. The ratio of the mean to the standard error is 1.60 when the standard deviation of the error is .5. This is a strong result considering the expert judged that a 90 percent confidence interval would be +- .1. When the standard deviation of the error distribution is .1, the ratio of the mean to the standard error is 8.3 in the worst case.

Table 5.2

SENSITIVITY TO PARAMETERS: TOTAL METH DEMAND

Parameter	Error	η		β^S		β^F	
Normalization	S.D.	S.E.	Mean/S.E.	S.E.	Mean/S.E.	S.E.	Mean/S.E.
Sum of	.1	0.2325	(170.9028)	1.8277	(21.7391)	4.7856	(8.3024)
Absolute	.2	0.4199	(94.6310)	3.5374	(11.2321)	8.3255	(4.7723)
Deviations	.3	0.6867	(57.8584)	5.3970	(7.3619)	12.3230	(3.2242)
	.4	0.9601	(41.3829)	8.0987	(4.9060)	18.5878	(2.1375)
Mean = 39.7322	.5	1.1297	(35.1718)	8.6047	(4.6175)	23.4823	(1.6920)
Sum of	.1	0.2039	(173.2839)	0.7189	(49.1499)	3.7353	(9.4594)
Squared	.2	0.4779	(73.9336)	1.7864	(19.7791)	8.3711	(4.2209)
Deviations	.3	0.6761	(52.2601)	2.3269	(15.1847)	11.1784	(3.1609)
	.4	0.8266	(42.7449)	3.3911	(10.4195)	16.8136	(2.1015)
Mean = 35.3340	.5	1.1970	(29.5178)	3.5917	(9.8376)	21.9723	(1.6081)
Sum of	.1	0.2704	(210.6492)	6.5382	(8.7109)	5.3257	(10.6941)
Percent	.2	0.5691	(100.0739)	14.1711	(4.0190)	9.9519	(5.7229)
Deviations	.3	0.8313	(68.5143)	20.6678	(2.7557)	14.1123	(4.0357)
	.4	1.0453	(54.4830)	27.1277	(2.0994)	22.3404	(2.5493)
Mean = 56.9532	.5	1.4244	(39.9834)	33.4426	(1.7030)	28.8673	(1.9729)
Constrained	.1	0.3105	(171.9851)	6.1124	(8.7376)	4.4225	(12.0762)
Sum of	.2	0.6206	(86.0557)	12.5353	(4.2606)	9.4210	(5.6689)
Squared	.3	0.7594	(70.3299)	17.5964	(3.0351)	13.0090	(4.1054)
Deviations	.4	1.0271	(52.0003)	26.6380	(2.0049)	19.8509	(2.6904)
Mean = 53.4072	.5	1.5028	(35.5379)	26.6813	(2.0017)	21.7119	(2.4598)

η = Output demand parameters; β^S = CSE parameters for solvent services; β^F = CSE parameters for factors of production.

For the output demand parameters (η) the ratio of the mean to the standard error never dips below 29.5 (sum of squared deviations), which indicates the results are not very sensitive to error in these parameters at all. For the CSE parameters for solvent services (β^S), the ratio of the mean to standard error is in the 1 to 2 range only when the error S.D. is in the range of .4 to .5, and only for the sum of percent deviations normalization method and the constrained sum of squared deviations normalization method. For the CSE parameters for factors of production (β^F), the ratio of the mean to the standard error is in the 1 to 2 range when the error S.D. is in the .4 to .5 range for all of the methods of parameter normalization.

These tests of sensitivity show that the expert has to be wrong by a large margin before the results of the model are substantially different. Since many of these are substitution parameters from translog functional form, the question arises, "How much difference does the functional form make?"

Sensitivity to Functional Form

The tests for sensitivity to functional form compares translog and Cobb-Douglas equations. This test is straightforward to implement because the translog collapses to Cobb-Douglas when the second order parameters are all zero. In general, the expectation is that the two functional forms will be close to each other for small changes, but less so for larger changes. This is because the translog is a second order approximation to a general cost function, where the Cobb-Douglas is a first order approximation.

In Table 5.3, taxes of 20, 40, and 100 percent represent three levels of regulation in the model. These taxes are on the solvent factor of production to reflect increasing regulatory scrutiny. The column labeled "Cobb-Douglas" shows the percent decrease in total METH demand that results from taxing the METH solvent factor of production using Cobb-Douglas functional form. The four columns labeled "Translog A B C D" contain the percent decrease in total METH demand when translog functional form is used with data that have been normalized by each of the four methods reported in Tables 5.1 and 5.2.

The first and second of the translog columns labeled A and B show the percent decrease in total METH demand when the sum of absolute deviations and the sum of squared deviations methods normalize the data. For columns A and B, the decrease in METH demand is 31.6 percent and 38.6 percent, respectively, with a 20 percent tax--more than twice the decrease than for Cobb-Douglas functional form. The decrease in METH demand shown in C and D (sum of percent deviations and constrained sum of squared deviations) is much closer to the results for Cobb-Douglas functional form. In all but the last case, the difference between the Cobb-Douglas and translog results increases as the tax increases. That is, translog functional form makes more difference for larger taxes. The last case, column D, is very close to the Cobb-Douglas results due to the normalization procedure, which reduces the absolute value of the CSE parameters to be closer to zero, which is identically the Cobb-Douglas case.

These results show that translog and Cobb-Douglas functional forms are consistent in terms of the direction of the results they generate. However, with three out of the four normalization methods, translog form generates sizeable differences in magnitude of the results compared to Cobb-Douglas, especially for larger taxes. When the data are normalized with the constrained sum of squared deviations method, the results are nearly the same for both functional forms.

Parametric Analysis Conclusions

The results of the model are robust to errors in the parameters. Parameter errors need to be in the range of +-.4 to +-.5 before the standard error in the model results approaches the mean of the results.

Table 5.3

SENSITIVITY TO FUNCTIONAL FORM: PERCENTAGE DECREASE IN TOTAL METH DEMAND

		Translog			
Tax	Cobb-Douglas	A	B	C	D
0.2000	-15.7987	-31.6115	-38.5770	-11.6496	-15.5571
0.4000	-27.1901	-49.5930	-55.5193	-20.6025	-26.8185
1.0000	-47.9801	-77.3350	-99.2758	-38.3681	-47.4781

A = Sum of Absolute Deviations; B = Sum of Squared Deviations; C = Sum of Percent Deviations; D = Constrained Sum of Squared Deviations.

Translog and Cobb-Douglas functional form results are considerably different for the normalization methods that did not constrain the sign of the parameters, but very similar when the signs are constrained. Perhaps with another method of normalizing the parameters, there could be a way to preserve more of the information in the original translog parameters and still avoid sign changes.

Among the sources of uncertainty examined in this parametric analysis, the method of normalizing the CSE parameters is the most important. Each normalization method has a particular bias that shows up in the results of the model. Of the four methods, only two of them give results that are clearly sensible to the expert. The tables that follow present results for these two methods: the sum of percent deviations and the constrained sum of squared deviations.

RESULTS

This subsection provides the results of the model for simulated regulations that promise important changes in markets where chlorinated solvents are employed. The case involves a cap on CFC-113 and TCA production and a tax on CFC-113 designed to reduce the atmospheric emissions of these ozone depleting substances. This scenario is important because it involves a set of regulations that is currently being developed and that affects important domestic industries. It also highlights the type of results generated by the model and demonstrates how the model helps analyze environmental policies. The first part of this subsection describes the model's representation of ozone depletion regulations. The second part shows selected results and interprets them for their policy significance. Detailed tables of results for this policy scenario are in Appendix E.

Model Representation of Ozone Depletion Regulations

Figure 5.1 shows the effects of a cap on the production of an ozone depleting chemical, such as CFC-113. This series of diagrams shows how the effects of regulations are traced throughout the entire system of markets. The top diagram, Figure 5.1a, shows the market for a

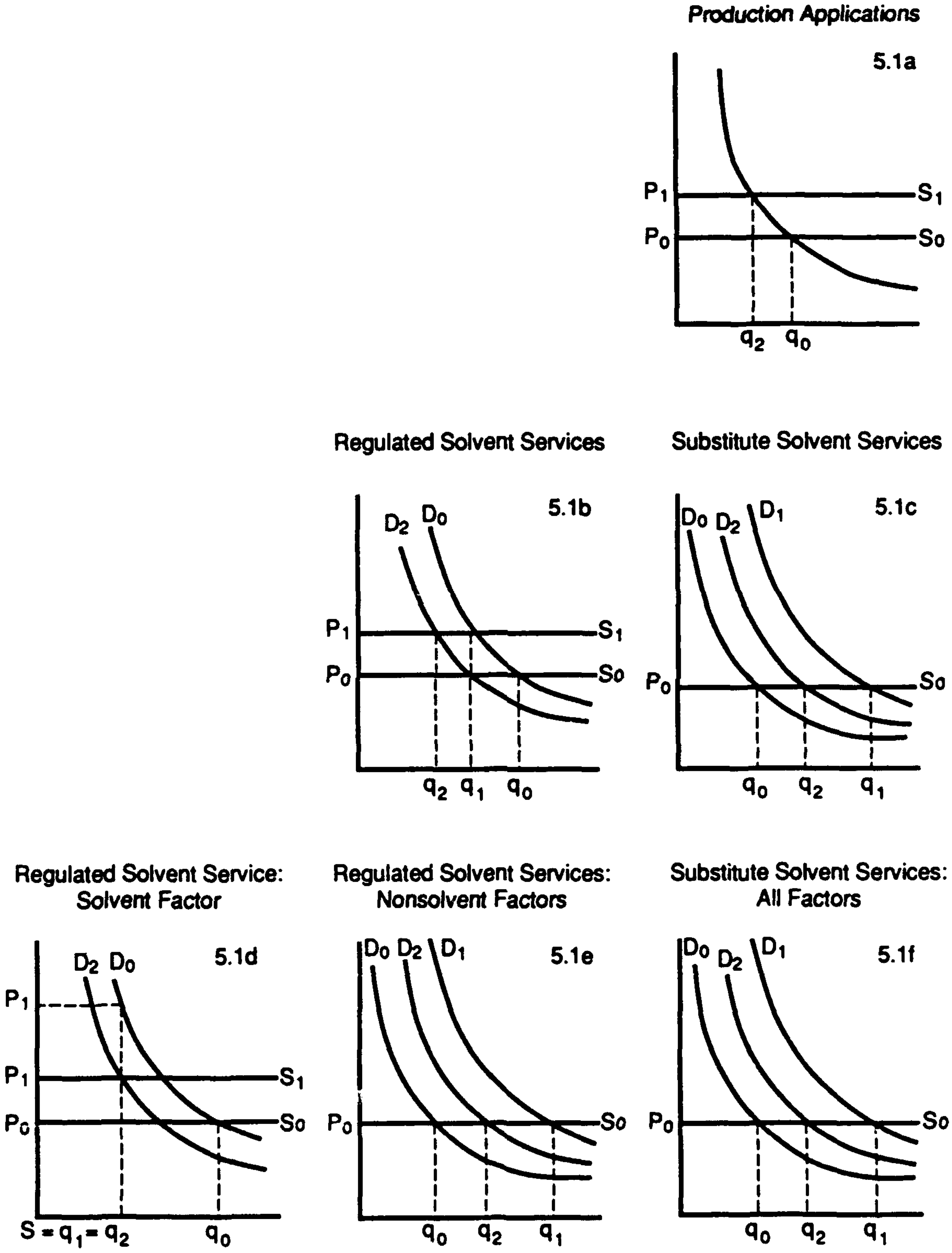

Fig. 5.1—Diagram of ozone depletion regulations

production application provided with a number of solvent services, two of which are in the middle diagrams 5.1b and 5.1c. The bottom row shows factors of production needed to provide the solvent services. Taken together, these diagrams illustrate the structure of the model described in Section III.

In this case, a supply constraint on the solvent factor of production, shown as S in Figure 5.1d, represents an ozone depletion regulation. We follow the effects of this regulation up through the system, and then follow the scale effects back down through the same system of markets.

The constraint in Figure 5.1d causes an increase in price of solvent from p_o to p_1 by sliding up the demand curve D_o. Figure 5.1e shows the outward shift in demand for the nonsolvent (substitute) factors of production to D_1. The increase in the supply curve in Figure 5.1b from S_o to S_1 shows the increase in cost of providing solvent services with the regulated chemical. This causes a decrease in demand for the regulated solvent service from q_0 to q_1 and an outward shift in the demand for substitute solvent services as shown in Figure 5.1c.

Figure 5.1a shows that the increase in the cost of solvent services causes an increase in the cost of the production applications and a decrease in demand. This shift in the scale of production applications has effects that are followed back down through the system of markets. Figures 5.1b and 5.1c show downward shifts in demand to D_2. The new equilibrium in both cases is q_2. For the regulated solvent service (5.1b), the substitution effect and the scale effect act in the same direction to decrease the demand for the regulated solvent service. For the substitute solvent services, the substitution effect and the scale effects act in opposite directions, and Figure 5.1c shows the case where the substitution effect outweighs the scale effect for a net increase in demand at q_2.

Figures 5.1d, 5.1e, and 5.1f show inward shifts in demand to D_2. The scale effect for the regulated solvent factor (Figure 5.1d) causes the inward shift, and hence the new equilibrium price of p_2 rather than p_1. That is, the scale effects offset some of the constraint's effect on price. For the nonsolvent factors of the regulated solvent service, the scale effects are less than the substitution effects with an equilibrium value of q_2 (Figure 5.1e). Figure 5.1f shows that the demand for all of the factors of production for the substitute solvent services increases on net after accounting for the substitution and scale effects. In some cases, the scale effect may outweigh the substitution effect causing a net decrease in factors of production.

This set of diagrams is the "road map" that traces the system-wide effects of solvent regulations through the model. The regulation influences the demand for the regulated solvent directly when its supply is constrained and indirectly due to changes in the demand for solvent services and production applications. The tables that follow show model results of the demand for solvent, solvent services, and factors of production.

Total Solvent Demand

The numerical results presented below are from the scenario where the supplies of TCA and CFC-113 are constrained to be 20 percent less than the supplies specified in the benchmark equilibrium. Twenty percent is the constraint that is being imposed under the first phase of the Montreal Protocol mentioned in Section II. In addition, there is an 86 percent tax on CFC-113, which is equivalent to the $1.10 per pound tax recently imposed by Congress.

The sum of demand for the solvent factor of production for each of the solvent services for all of the production applications is total solvent demand. For example, the total solvent demand for TCA is the sum of all of the TCA solvent factor of production demand in the model. Because roughly 98 percent of solvent demand is ultimately emitted to the atmosphere, the figures for total solvent demand reveal the impact on air quality, as well as on solvent sales.[3]

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[3] See Pekelney (1990) for a detailed description of how the demand for virgin solvent relates to atmospheric emissions for the chlorinated solvents.

Table 5.4 shows how the ozone depletion regulations affect total solvent demand for each of the solvents. The first column indicates which method normalized the data used to generate these results. The second column indicates the name of the solvent. The third and fourth columns show the total solvent demand before and after the regulatory changes represented in the model. The last column shows the percentage of change between before and after.

Both of the regulated solvents decrease dramatically as a result of the constraints and taxes as shown in Table 5.4a, which is computed with data normalized with the constrained sum of squared deviations method. For TCA, the decrease in total solvent demand of 20.0 percent (30.1 thousand metric tons) is exactly as expected with the 20 percent

Table 5.4

THE EFFECTS OF OZONE DEPLETION REGULATIONS ON TOTAL SOLVENT DEMAND (IN THOUSAND METRIC TONS)

Parameter Normalization	Solvent	Before	After	Change	%Change
(a)	TCE	60.1176	61.0919	0.9743	0.0162
Constrained	METH	68.1250	69.3635	1.2385	0.0182
Sum of	PERC	127.1875	128.8117	1.6242	0.0128
Squared	TCA	150.6742	120.5619	-30.1123	-0.1999
Deviations	113	48.9879	19.1591	-29.8288	-0.6089
	FLAM	444.9057	448.9707	4.0650	0.0091
	COMB	43.0676	44.3551	1.2875	0.0299
	HCFC	0.8907	0.7948	-0.0959	-0.1077
(b)	TCE	60.1176	60.2884	0.1708	0.0028
Sum of	METH	68.1250	68.8593	0.7343	0.0108
Percent	PERC	127.1875	128.2116	1.0241	0.0081
Deviations	TCA	150.6742	120.5618	-30.1124	-0.1999
	113	48.9879	21.4241	-27.5638	-0.5627
	FLAM	444.9057	447.8332	2.9276	0.0066
	COMB	43.0676	53.2644	10.1967	0.2368
	HCFC	0.8907	0.6103	-0.2804	-0.3148

TCE = Trichloroethylene; METH = Methylene Chloride; PERC = Perchloroethylene; TCA = 1,1,1-trichloroethane; 113 = Chlorofluorocarbon-113; FLAM = Flammables; COMB = Combustibles; HCFC = Hydrochlorofluorocarbons.

constraint and no taxes. For CFC-113, the decrease in total solvent demand is 61.1 percent (29.8 thousand metric tons), which is well beyond the 20 percent supply constraint. This indicates that the supply constraint is not binding. That is, the tax on CFC-113 reduced the demand for that solvent below that of the supply constraint. Table 5.4b shows the same set of results computed with data normalized with the sum of percent deviations method. The figures are similar for all of the solvents except the combustibles, which increase quite a bit more in Table 5.4b. Combustible solvents are not likely to increase as much as shown in Table 5.4b within the time frame of the model. This is because of complications involved in fire suppression, water treatment, and sewer disposal in the various production applications.

In essence, the figures for total solvent demand show us where the regulatory constraints come into play. The regulations reduce the emissions of ozone depleting substances, so total solvent demand--because it so closely linked with total solvent emissions--gives us an indicator of the major objective of this regulatory policy. The next table shows us the change in one solvent's demand for each of the production applications where it is employed.

Solvent Allocation

Solvent allocation is the breakdown of solvent demand by production application for one solvent at a time. This shows which applications experience the greatest change in solvent consumption as a result of the regulations.

Table 5.5 is similar in format to Table 5.4 with the addition of the last two columns, which indicate the proportions of solvent allocation before and after the imposition of the ozone depletion regulations. The second column indicates which production application employs CFC-113. For example, in Table 5.5a and 5.5b, the proportion of CFC-113 employed in vapor degreasing drops from 12.2 percent to 0 percent of total CFC-113 solvent demand. The two normalization methods are similar in results for vapor degreasing, but in electronics CFC-113 demand increased by a higher percentage than dry cleaning and cold cleaning in 5.5b and by a lower percentage in 5.5a.

Table 5.5

THE EFFECTS OF OZONE DEPLETION REGULATIONS ON CFC-113 ALLOCATION (IN THOUSAND METRIC TONS)

Parameter Normalization	Applications	Before	After	Change	%Change	%Before	%After
(a)							
Constrained	DRY	1.9838	0.7804	-1.2034	-0.6066	0.0405	0.0407
Sum of	COLD	17.0040	0.8000	-16.2040	-0.9530	0.3471	0.0418
Squared	VAPOR	5.9919	0.0004	-5.9915	-0.9999	0.1223	0.0000
Deviations	ELEC	24.0081	17.5783	-6.4298	-0.2678	0.4901	0.9175
(b)	DRY	1.9838	1.2817	-0.7021	-0.3539	0.0405	0.0598
Sum of	COLD	17.0040	9.9915	-7.0125	-0.4124	0.3471	0.4664
Percent	VAPOR	5.9919	0.0004	-5.9915	-0.9999	0.1223	0.0000
Deviations	ELEC	24.0081	10.1505	-13.8576	-0.5772	0.4901	0.4738

DRY = Dry Cleaning; COLD = Cold Cleaning; VAPOR = Vapor Degreasing; ELEC = Electronics.

Changes in solvent allocation illustrate the relative difficulty of reducing solvent consumption for each of the production applications. In both cases, a huge drop occurs in CFC-113 vapor degreasing demand. This reflects the high costs and volatility of CFC-113, which make it particularly expensive to use, and the availability of substitute solvents that are cheaper to use in this production application. In the case of electronics, it is difficult to move away from CFC-113 because of the reluctance to use recycled solvent if its purity cannot be guaranteed, and also because of military specifications. The decrease in CFC-113 demand in dry cleaning is expected to be small because this solvent is used now in a very small market for specialty dry cleaning for which no good substitutes are available at this time.

Solvent allocation gives us more information on the environmental bottom line--solvent demand and emissions--for a given solvent. It also gives us a means to compare the effects of the regulations across a number of production applications and their related industries. The next set of results reflect how one of these industries responds by substituting among solvent services.

Solvent Services

These results show substitution from one solvent service to other solvent services for one particular production application. The alternative solvent services for a production application represent the chemical substitutes and process substitutes described in Section II that can perform the same cleaning function.

Table 5.6 shows the changes in solvent services for the electronics production application. The demand for solvent services that employ the regulated solvents decreased as expected. In Table 5.6a, there is a drop of 1.0 percent (.09 million units cleaned)* for TCA and 12.0 percent (13.7 million units cleaned) for CFC-113 in solvent services demanded. At the same time, the demand for aqueous (water-based) solvent services increased by 6.9 percent (5.3 million units cleaned).

Table 5.6

THE EFFECTS OF OZONE DEPLETION REGULATIONS ON ELECTRONICS SOLVENT SERVICES (IN MILLION UNITS CLEANED)

Parameter Normalization	Solvent Service	Before	After	Change	%Change
(a)	TCA	11.4286	11.3399	-0.0887	-0.0078
Constrained	113	114.0385	100.3458	-13.6927	-0.1201
Sum of	H_2O	77.0000	82.2953	5.2953	0.0688
Squared	COMB	4.2647	7.4488	3.1841	0.7466
Deviations	NOCLEAN	1.0000	3.8554	2.8554	2.8554
	HCFC	0.4286	0.6926	0.2640	0.6161
(b)	TCA	11.4286	10.3225	-1.1061	-0.0968
Sum of	113	114.0385	56.9105	-57.1279	-0.5010
Percent	H_2O	77.0000	80.8609	3.8609	0.0501
Deviations	COMB	4.2647	63.5998	59.3351	13.9131
	NOCLEAN	1.0000	3.7288	2.7288	2.7288
	HCFC	0.4286	0.6631	0.2345	0.5471

TCE = Trichloroethylene; METH = Methylene Chloride; PERC = Perchloroethylene; TCA = 1,1,1-trichloroethane; 113 = Chlorofluorocarbon-113.

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*Unit in this case is the quantity of solvent service that is provided for one dollar at the benchmark equilibrium.

The increase in aqueous-based solvent services reflects an increase in the use of organic acid fluxes, which are water soluble. As mentioned in Section II, some of the problems with residues left after the drying process are being mitigated with new organic acid fluxes and therefore aqueous solvent services are relatively large substitutes for TCA and CFC-113.

Table 5.6b shows results that are similar except in the magnitude of the decrease in CFC-113 solvent services and increase in combustible solvent services. These figures are computed with data normalized by the sum of percent deviations method. Both CFC-113's decrease and the combustibles' increase are substantially larger than computed with the constrained sum of squared deviations normalization method in Table 5.6a. The increase in combustibles for electronics is unlikely to be as large as shown in Table 5.5b because of the difficulties of using combustibles for cleaning printed circuit boards, in the judgment of the expert.

The substitution of solvent services reflects the technical opportunities for alternative methods of solvent cleaning. Another set of responses to the ozone depletion regulations is the change in the factors of production that go into the provision of solvent services. The next subsection describes the changes in factors of production for CFC-113 solvent services in electronics that reduce the amount of solvent needed to perform cleaning tasks.

Factors of Production Shares

The change in factor shares shows how the change in solvent use is achieved by altering the mix of inputs to the production process. These changes represent reduction of emissions or hazardous waste at the source of its generation.

Table 5.7a shows that the solvent, waste, and pollution factors of production all decrease in factor shares. The two righthand columns show the share of solvent decreased from 52.0 percent to 41.8 percent of factors needed in the provision of the CFC-113 solvent service. Likewise waste decreases from 2.0 to 1.1 percent, and pollution

Table 5.7

THE EFFECTS OF OZONE DEPLETION REGULATIONS ON FACTORS OF PRODUCTION FOR CFC-113 SOLVENT SERVICES IN ELECTRONICS

Parameter Normalization	Factor of Production	Before*	After	Change	%Change	%Before	%After
(a)	SOLVENT	59.3000	43.4183	-15.8817	-0.2678	0.5200	0.4176
Constrained	ENERGY	6.8423	8.0811	1.2388	0.1810	0.0600	0.0777
Sum of	ASSETS	15.9654	21.3028	5.3374	0.3343	0.1400	0.2049
Squared	WASTE	2.2808	1.1272	-1.1535	-0.5058	0.0200	0.0108
Deviations	LABOR	22.8077	29.3225	6.5148	0.2856	0.2000	0.2820
	POLLUTION	6.8423	0.7300	-6.1123	-0.8933	0.0600	0.0070
(b)	SOLVENT	59.3000	25.0717	-34.2283	-0.5772	0.5200	0.4269
Sum of	ENERGY	6.8423	4.5500	-2.2923	-0.3350	0.0600	0.0775
Percent	ASSETS	15.9654	11.4835	-4.4819	-0.2807	0.1400	0.1955
Deviations	WASTE	2.2808	0.7915	-1.4892	-0.6530	0.0200	0.0135
	LABOR	22.8077	15.6993	-7.1084	-0.3117	0.2000	0.2673
	POLLUTION	6.8423	1.1340	-5.7083	-0.8343	0.0600	0.0193

*Units in this case are the quantity of the factor of production that is provided for one dollar at the benchmark equilibrium.

decreased from 6.0 to 0.7 percent of factors of production. These three factors of production are complements in that the reduction of solvent use means that less waste is generated and less hazardous material is emitted that causes environmental harm.

If reduction of hazardous waste generation is a result of improved processes that can do the same cleaning task with less solvent, then we expect a larger percentage decrease in waste and pollution than for solvent. These results substantiate this notion. In percentage terms, solvent decreased by 27.8 percent, waste decreased by 50.6 percent, and pollution decreased by 89.3 percent.

At the same time, energy, assets, and labor increased by 18.1, 33.4, and 28.6 percent, respectively. In the electronics production application, changes in these factors of production represent increased on-site recycling capacity and some measures to reduce emissions, such as additional freeboard chillers to capture more fugitive solvent. Because CFC-113 is going to be phased out altogether, solvent users are not going to invest in technology that has long payback periods; rather, for their long run solvent needs, they will invest in other solvent services. Although CFC-113 is still in use, it makes sense to invest in solvent-saving equipment only with relatively short payback periods.

CONCLUSIONS

As mentioned at the beginning of this document, the purpose of the model of chlorinated solvent markets and regulations is to develop a tool to help make better policy decisions by: (1) accounting for all solvent substitutions, (2) suggesting the direction and magnitude of those substitutions, and (3) comparing explicitly the tradeoffs implicit in solvent regulations. This section described the results from a policy scenario that demonstrates how the model accounts for solvent substitutions and suggests their direction and magnitude. However, the model's results provide only a partial comparison of the tradeoffs involved in solvent regulations. Clearly, additional consideration is needed of the health and environmental consequences, institutional questions, and political concerns.

VI. CONCLUSIONS

This study's analysis of chlorinated solvent technology and markets leads to a series of policy relevant conclusions. In addition, the development and demonstration of the economic model leads to conclusions that concern modeling methodology.

POLICY CONCLUSIONS

To design regulations as effectively as possible, policymakers need to compare explicitly the tradeoffs implicit in solvent regulations. The effects of solvent regulations spread well beyond the particular environmental hazards they are designed to address. Hence, officials need to assess and account for a wide range of interconnected markets. The hope is that regulatory decisions can be based on the hazards of the solvent substitutes, rather than focused on only one solvent and one environmental medium at a time. The case of TCE illustrates the substitution of hazards from the troposphere to the stratosphere. In reviewing all of the solvents and their substitutes, it is apparent that similar substitutions take place in many other applications.

Policy outcomes need to be compared industry by industry, because the direction and magnitude of solvent substitutions and changes in production processes varies widely. When the model analyzes current ozone depletion regulations, the demand for CFC-113 drops by 100 percent in vapor degreasing applications, but only by 27 percent in the electronics industry.

Changes in production processes, represented as substitutions of other factors of production for solvent, are apparent for each regulation. Investment in recycling and recovery equipment, and processes that reduce the generation of hazardous wastes and air emissions at their source, are examples of production process changes. Ozone depletion regulations shifted CFC-113 solvent in electronics from 52 percent to 42 percent of production inputs. While solvent demand decreased, the demand for hazardous waste disposal and pollution costs also decreased. Energy, assets, and labor all increased at the same time, representing solvent-saving strategies, such as additional freeboard chillers.

Many new regulations are restricting chlorinated solvents. Looking at the whole group of chlorinated solvents in each environmental medium, it is apparent that they are coming under increasing scrutiny under a number of stringent regulatory regimes. As a result of these simultaneous regulatory forces and their cumulative effects, there are large and rapid dislocations in the whole range of applications that employ chlorinated solvents.

The effects of many regulations on a group of solvents need to be assessed simultaneously. If only one regulation is examined at a time, it is easy to draw erroneous conclusions. The regulation of CFC-113 and TCA is a good example. These two chemicals are substitutes in a number of applications, so if we examine only one regulation it appears there will be a great deal of substitution to the other solvent. However, since they are *both* being regulated more stringently, the substitutions will be to other alternatives.

The results show large-scale substitution to alternative solvents, even though some of these substitutes are not tested for their harmful effects. The net outcome is a shift from the more tested solvents to the less tested solvents. TSCA authorized regulations require testing of very few chemicals before they enter the market. As a result, the health effects are not well known for quite a while after exposure in industry and commerce. In the case of cancer or other long latency diseases, the exposure may be quite extensive before the hazards become apparent and are tested formally.

The model in this analysis describes solvent substitutions; however, risk-risk analysis is also needed for a complete comparison of health and environmental effects. The results from the simulation model can make explicit the substitutions induced by proposed regulations, but this does not imply that the new hazards are greater or less than the hazards they replace. Some sort of risk-risk analysis is the only way to compare relative hazards.

METHODOLOGY CONCLUSIONS

The results of the model are not precise in a predictive sense, but rather generally indicative of the direction and magnitude of solvent and process substitutions. Precise predictions are possible only with extensive data collection. Not only would such an effort be difficult and expensive, but historical data are not relevant because of recent large-scale changes in solvent technology and regulation. The method of using subjective judgments has the advantage that the model is easily updated as technologies develop.

The difficulty of using expert data is that they need to be normalized to be consistent with the economic theory of well-behaved cost functions. In making these normalizations with the methods used in this analysis, striking tradeoffs are apparent about how the parameter normalization biases the original expert values.

Comparing these methods further and developing others would be a fruitful area of future research. Perhaps another method of normalizing the parameters would preserve more of the expert information and still be consistent with the economic model? Analyzing the uncertainty in the model is also an area that could use more research, including model specification, sensitivity to the benchmark equilibrium, sensitivity to individual parameter values, and comparison of other functional forms aside from Cobb-Douglas and translog.

Appendix A

DERIVING A TRANSLOG FUNCTION FROM TAYLOR'S SERIES

TAYLOR'S SERIES APPROXIMATION

Taylor's multivariate approximation to the second order without a remainder is defined by:

$$f(a + x) = f(a) + \sum_i f'_i(a)X_i + \frac{1}{2}\sum_i \sum_j f''_{ij}(a)X_iX_j \qquad (A.1)$$

where: $a = \{a_1,\ldots,a_n\}$ is the point of expansion around which the function is to be evaluated, $x = \{x_1,\ldots,x_i\}$ is the offset from the expansion point, f, f', and f" are the function value, first partial with respect to X_i, and the second partial with respect to X_i and X_j.

DERIVING THE TRANSLOG PRODUCTION FUNCTION FROM TAYLOR'S SERIES

The translog production function is simply a second order Taylor's Series approximation of a general natural logarithmic production function. Start with a general natural logarithmic production function with the natural logarithm of the output equal to a function of the natural logarithms of the inputs:

$$\ln Y = f(\ln Z_1,\ldots,\ln Z_n) \qquad (A.2)$$

Taylor's expansion of lnY around a fixed point $a = \{a_1,\ldots,a_n\}$ simply uses equation (A.1) for $X = \{X_1,\ldots,X_i\}$ and $X_i = \ln Z_i$ from equation (A.2). Thus,

$$\ln Y = f(a) + \sum_i f'_i(a)\ln Z_i + \frac{1}{2}\sum_i \sum_j f''_{ij}(a)\ln Z_i \ln Z_j$$

For convenience, this equation is rewritten with parameters α and β:

$$\ln Y = \alpha_o + \sum_i \alpha_i \ln Z_i + \frac{1}{2} \sum_i \sum_j \beta_{ij} \ln Z_i \ln Z_j$$

where $\alpha_o = f(a)$, $\alpha_i = f'_i(a)$, and $\beta_{ij} = f''_{ij}(a)$ are the functions and the partial logarithmic derivatives.

Appendix B

SOLUTION ALGORITHM EQUATIONS

The following notation is used in the equations below:

Variable and Parameter Subscripts:

i = production applications

j,n = solvent services

k,o = factors of production

Variable Superscripts:

o = initial value from the transaction matrix that does not change

$'$ = initial value on the first iteration and changed by the solution algorithm on subsequent iterations

s = supply

no superscript = value computed on the latest iteration

Where:

T_{ij} is the transaction value attributable to a given solvent service in provision of a given production application,

T_{ijk} is the transaction value attributable to a given factor of production in the provision of a given solvent service for a given production application,

R is the residual excess supply,

Ω is the sum of squared residuals,

Σ_{jn} is the summation over all j and n.

(1) Compute Benchmark Equilibrium.

$$T^{o}_{ij} = \sum_{k} T^{o}_{ijk} = T^{o}_{ijk}[k = \text{solvent}] \;/\; \alpha_{ijk}[k = \text{solvent}]$$

$$T^{o}_{ijk}[k \neq \text{solvent}] = T^{o}_{ij} * \alpha_{ijk}[k \neq \text{solvent}]$$

$$T^{o}_{i} = \sum_{j} T^{o}_{ij}$$

$$\alpha_{ij} = T^{o}_{ij} \;/\; T^{o}_{i}$$

(2) Calculate Output Prices.

$$\ln p_{ij} = \sum_{k} \alpha_{ijk} \ln p'_{k} + \frac{1}{2} \sum_{ko} \beta_{ijko} \ln p'_{k} \ln p'_{o}$$

$$\ln p_{i} = \sum_{j} \alpha_{ij} \ln p_{ij} + \frac{1}{2} \sum_{jn} \beta_{ijn} \ln p_{ij} \ln p_{in}$$

(3) Calculate Demand for Production Applications.

$$Q_{i} = (Q_{i}^{o})(P_{i}^{\eta_{i}})$$

(4) Calculate Demand for Solvent Services.

$$T_{ij} = (P_{i}Q_{i})(\alpha_{ij} + \sum_{n} \beta_{ijn} \ln p_{in})$$

$$Q_{ij} = \frac{T_{ij}}{P_{ij}}$$

(5) Calculate Demand for Factors of Production.

$$Q_{ijk} = \frac{(T_{ij})(\alpha_{ijk} + \sum_{o} \beta_{ijko} \ln p_{o})}{P_{k}}$$

(6) Calculate Excess Supply.

$$R_{i} = Q_{i}^{s} - Q_{i}$$

$$R_{ij} = Q_{ij}^{s} - Q_{ij}$$

$$R_{ijk} = Q_{ijk}^{s} - Q_{ijk}$$

(7) Solve for the Minimum Excess Supply.

$$\Omega = \sum_{i}(R_{i}^{2}) + \sum_{ji} (R_{ij}^{2}) + \sum_{kji} (R_{ijk}^{2})$$

Appendix C

DETAILS OF COST SHARE ADJUSTMENTS

Dry Cleaning. For CFC-113, TCA, and HCFC dry cleaning, we start with the reference cost share of solvent for PERC dry cleaning and multiply it by the ratio of the price of the given solvent to the price of PERC [e.g., pCFC-113/pPERC = 3.86] to get the solvent cost shares. The energy, assets, and labor cost shares for each of these solvent services were assumed to be similar to PERC dry cleaning. The waste disposal cost share for each of these solvent services was estimated by starting with the cost share for PERC that has been doubled, but before it has been adjusted for recycling. Then each waste disposal cost share is adjusted for recycling according to its value in virgin form.

Vapor Degreasing. We have assumed that the GCA data are based on TCA as the primary solvent used for vapor degreasing. For the other solvents used in vapor degreasing (except for aqueous solution, for which GCA cost shares are available), we adjust proportionally to the relative prices of virgin solvent, as we did for other solvents in dry cleaning, to get the solvent cost share. Energy, assets, and labor cost shares are assumed the same as for TCA. Waste disposal is adjusted for recycling for each of the solvent services as described above.

Cold Cleaning. For cold cleaning solvents other than flammables and combustibles, we start with the cost shares that were computed for vapor degreasing, and decrease energy and assets to one-half and two-thirds of their original values, respectively, and leave the other cost shares unchanged. The flammable and combustible cold cleaning application cost shares are derived by starting with the reference cost shares for TCA vapor degreasing, and decreasing the energy and assets in the same manner as for the chlorinated solvents. Then we adjust the solvent cost share for flammables and combustibles by the relative price of flammables and combustibles to the price of TCA. For combustibles only, we then multiply by .6, because combustibles emit much less than the chlorinated solvents due to their lower vapor pressure, resulting in total demand that is 40 percent less.[1] Table 4.1 shows the proportions of emissions (emissions = 1 - waste) for all of the solvents for all of the applications. Flammables waste disposal is assumed to be a small share, as in the case of flammable waste disposal in dry cleaning. Combustible waste disposal and water disposal are assumed to be one-third and two-thirds of waste disposal for TCE vapor degreasing. Labor cost is the same as that for TCA for all but aqueous solvent service cleaning.

Electronics. In electronics, we start with the cost shares for TCA vapor degreasing and adjust solvent cost shares according to their price as we did in cold cleaning. For all solvent services, the cost shares for labor in electronics was lowered by 3 percent and the cost share for assets was raised by the same percent to indicate the high level of mechanization in the electronics industry compared to cold cleaning and vapor degreasing. For the combustibles, the cost shares for energy assets and labor were set equal to those of TCA. The solvent cost share for combustibles is the cost share of solvent for TCA multiplied by the ratio of the price of combustibles to the price of TCA, multiplied by .6 to indicate lower emissions. The waste disposal cost share for combustibles was set equal to that of TCA, but with waste disposal split up into one-third for waste disposal and two-thirds water disposal. The waste disposal cost share for the other chlorinated solvents is computed as described above with the recycling adjustment for each solvent. The only "solvent service" cost for noclean flux is the additional cost of the noclean flux compared to standard flux.

Original Paint Removal. For METH original paint removal, we start with the cost shares from METH cold cleaning and make assets lower, labor higher, and add water disposal costs. For combustibles, the

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[1] This is 40 percent less in absolute terms. If demand is 100 lbs. of chlorinated solvents, then 85 lbs. is emitted and 15 lbs. ends up as waste. For the combustibles, we are saying that demand is only 60 lbs., of which 45 lbs. is emitted. In relative terms, as is shown in Table 4.1, the emissions are 85 percent for the chlorinated solvents and 45 percent for the combustibles. Flammables are roughly as volatile as the chlorinated solvents, so we do not adjust relative to TCA.

solvent share is also raised by the ratio of the price of combustibles to the price of METH, but the share is multiplied by .6 to account for lower emissions, and then by 1.5 to account for the reduced effectiveness. (Nothing works as well as METH for paint removal, so you have to use much more solvent for the same task.) For flammables, we start with original application METH and change the solvent share to be proportional to the ratio of the prices of flammables and METH, and then multiply by 1.5 to account for reduced performance. For water blasting, we also start with METH cost shares, then change the solvent cost share to zero, and assign its cost shares one-third to energy and two-thirds to assets. Water blasting waste disposal is one-half of METH waste disposal. For immersion, we use the cold cleaning METH shares with energy increased slightly, no water disposal, and the solvent cost share adjusted by the ratio of the price of non-METH solvents used in this application to the price of METH.

Maintenance Paint Removal. For maintenance paint removal, the METH shares are the same as cold cleaning with METH, but with energy slightly higher and an added cost of water disposal. For plastic media blasting, the assets are very high, there is water and waste disposal, and labor is high. Bicarb blasting is like plastic media blasting, but with a higher water disposal cost and a higher waste disposal cost. For laser and slash lamp, labor is reduced almost entirely, assets are increased substantially, there is no solvent, and energy is a large share of cost.

Consumer Paint Removal. For consumer METH use, assets are small--about half the cost is the solvent itself--and there is no energy or waste disposal cost. For combustibles, we use the same as METH, but with higher solvent costs. Flammables are like METH but with lower solvent cost shares. Heat guns costs are all assets, labor, and energy.

Appendix D

TABLES OF NORMALIZED PARAMETER COMPARISONS: FACTORS OF PRODUCTION FOR CFC-113 SOLVENT SERVICES IN ELECTRONICS

Table D.1

MINIMIZE SUM OF ABSOLUTE DEVIATIONS: NEAR 0 = .01
NORMALIZED PARAMETER MATRIX

Original CSEs

-1.0504	-0.0196	-0.0072	-0.0384	-0.0414	-0.1702
-0.0196	0.0464	-0.0074	0.0019	-0.0107	0.0027
-0.0072	-0.0074	0.1104	0.0183	-0.0263	0.0479
-0.0384	0.0019	0.0183	-0.1804	-0.0029	-0.0052
-0.0414	-0.0107	-0.0263	-0.0029	0.1500	0.0483
-0.1702	0.0027	0.0479	-0.0052	0.0483	-0.9436

Normalized CSEs

-0.9023	-0.0196	-0.0072	0.1380	-0.0414	0.8325
-0.0196	0.0395	-0.0087	0.0019	-0.0158	0.0027
-0.0072	-0.0087	0.0752	0.0183	-0.1255	0.0479
0.1380	0.0019	0.0183	-0.1521	-0.0029	-0.0031
-0.0414	-0.0158	-0.1255	-0.0029	0.1374	0.0483
0.8325	0.0027	0.0479	-0.0031	0.0483	-0.9282

Original AEDs

-1.3000	0.0223	0.1262	-0.0538	0.1204	-0.2673
0.1933	-0.0100	0.0167	0.0517	0.0217	0.1050
0.4686	0.0071	-0.0100	0.1507	0.0121	0.4021
-1.4000	0.1550	1.0550	-0.2000	0.0550	-0.2000
0.3130	0.0065	0.0085	0.0055	-0.0100	0.3015
-2.3167	0.1050	0.9383	-0.0667	1.0050	-1.0000

Normalized AEDs

-1.1519	0.0223	0.1262	0.2853	0.1204	1.6610
0.1933	-0.0169	-0.0044	0.0517	-0.0639	0.1050
0.4686	-0.0019	-0.0452	0.1507	-0.6965	0.4021
7.4190	0.1550	1.0550	-0.1717	0.0550	-0.0968
0.3130	-0.0192	-0.4876	0.0055	-0.0226	0.3014
14.3949	0.1050	0.9383	-0.0323	1.0047	-0.9846

Table D.2

MINIMIZE SUM OF SQUARED ABSOLUTE DEVIATIONS: NEAR 0 = .01
NORMALIZED PARAMETER MATRIX

Original CSEs					
-1.0504	-0.0196	-0.0072	-0.0384	-0.0414	-0.1702
-0.0196	0.0464	-0.0074	0.0019	-0.0107	0.0027
-0.0072	-0.0074	0.1104	0.0183	-0.0263	0.0479
-0.0384	0.0019	0.0183	-0.1804	-0.0029	-0.0052
-0.0414	-0.0107	-0.0263	-0.0029	0.1500	0.0483
-0.1702	0.0027	0.0479	-0.0052	0.0483	-0.9436
Normalized CSEs					
-0.6716	0.1358	0.1278	0.1537	0.0967	0.1575
0.1358	-0.0216	-0.0958	-0.0294	-0.0960	0.1069
0.1278	-0.0958	0.0016	-0.0334	-0.1320	0.1317
0.1537	-0.0294	-0.0334	-0.1751	-0.0515	0.1357
0.0967	-0.0960	-0.1320	-0.0515	0.0475	0.1352
0.1575	0.1069	0.1317	0.1357	0.1352	-0.6671
Original AEDs					
-1.3000	0.0223	0.1262	-0.0538	0.1204	-0.2673
0.1933	-0.0100	0.0167	0.0517	0.0217	0.1050
0.4686	0.0071	-0.0100	0.1507	0.0121	0.4021
-1.4000	0.1550	1.0550	-0.2000	0.0550	-0.2000
0.3130	0.0065	0.0085	0.0055	-0.0100	0.3015
-2.3167	0.1050	0.9383	-0.0667	1.0050	-1.0000
Normalized AEDs					
-0.9212	0.3212	0.3858	0.3156	0.3860	0.3628
2.7838	-0.0780	-1.4565	-0.4704	-1.3995	1.8424
1.4331	-0.6242	-0.1188	-0.2187	-0.7427	1.0010
8.2047	-1.4111	-1.5311	-0.1947	-2.3753	6.8456
1.0037	-0.4199	-0.5199	-0.2375	-0.1125	0.7362
3.1444	1.8424	2.3357	2.2819	2.4541	-0.7235

Table D.3

MINIMIZE SUM OF PERCENT DEVIATIONS: NEAR 0 = .01
NORMALIZED PARAMETER MATRIX

Original CSEs

-1.0504	-0.0196	-0.0072	-0.0384	-0.0414	-0.1702
-0.0196	0.0464	-0.0074	0.0019	-0.0107	0.0027
-0.0072	-0.0074	0.1104	0.0183	-0.0263	0.0479
-0.0384	0.0019	0.0183	-0.1804	-0.0029	-0.0052
-0.0414	-0.0107	-0.0263	-0.0029	0.1500	0.0483
-0.1702	0.0027	0.0479	-0.0052	0.0483	-0.9436

Normalized CSEs

0.2768	-0.0196	-0.0072	-0.0384	-0.0414	-0.1702
-0.0196	0.0331	-0.0074	0.0019	-0.0107	0.0027
-0.0072	-0.0074	-0.0253	0.0183	-0.0263	0.0479
-0.0384	0.0019	0.0183	0.0263	-0.0029	-0.0052
-0.0414	-0.0107	-0.0263	-0.0029	0.0330	0.0483
-0.1702	0.0027	0.0479	-0.0052	0.0483	0.0765

Original AEDs

-1.3000	0.0223	0.1262	-0.0538	0.1204	-0.2673
0.1933	-0.0100	0.0167	0.0517	0.0217	0.1050
0.4686	0.0071	-0.0100	0.1507	0.0121	0.4021
-1.4000	0.1550	1.0550	-0.2000	0.0550	-0.2000
0.3130	0.0065	0.0085	0.0055	-0.0100	0.3015
-2.3167	0.1050	0.9383	-0.0667	1.0050	-1.0000

Normalized AEDs

0.0272	0.0223	0.1262	-0.0538	0.1204	-0.2673
0.1933	-0.0233	0.0167	0.0517	0.0217	0.1050
0.4686	0.0071	-0.1457	0.1507	0.0121	0.4021
-1.4000	0.1550	1.0550	0.0067	0.0550	-0.2000
0.3130	0.0065	0.0085	0.0055	-0.1270	0.3015
-2.3167	0.1050	0.9383	-0.0667	1.0049	0.0201

Table D.4

MINIMIZE CONSTRAINED SUM OF SQUARED ABSOLUTE DEVIATIONS: NEAR 0 = .01
NORMALIZED PARAMETER MATRIX

Original CSEs

-1.0504	-0.0196	-0.0072	-0.0384	-0.0414	-0.1702
-0.0196	0.0464	-0.0074	0.0019	-0.0107	0.0027
-0.0072	-0.0074	0.1104	0.0183	-0.0263	0.0479
-0.0384	0.0019	0.0183	-0.1804	-0.0029	-0.0052
-0.0414	-0.0107	-0.0263	-0.0029	0.1500	0.0483
-0.1702	0.0027	0.0479	-0.0052	0.0483	-0.9436

Normalized CSEs

0.2000	-0.0151	0.0127	-0.0356	-0.0034	-0.1586
-0.0151	0.0245	-0.0078	0.0041	-0.0112	0.0055
0.0127	-0.0078	-0.0496	0.0206	-0.0280	0.0520
-0.0356	0.0041	0.0206	0.0196	-0.0006	-0.0081
-0.0034	-0.0112	-0.0280	-0.0006	-0.0097	0.0528
-0.1586	0.0055	0.0520	-0.0081	0.0528	0.0564

Original AEDs

-1.3000	0.0223	0.1262	-0.0538	0.1204	-0.2673
0.1933	-0.0100	0.0167	0.0517	0.0217	0.1050
0.4686	0.0071	-0.0100	0.1507	0.0121	0.4021
-1.4000	0.1550	1.0550	-0.2000	0.0550	-0.2000
0.3130	0.0065	0.0085	0.0055	-0.0100	0.3015
-2.3167	0.1050	0.9383	-0.0667	1.0050	-1.0000

Normalized AEDs

-0.0496	0.0310	0.1645	-0.0486	0.1935	-0.2450
0.2686	-0.0319	0.0097	0.0881	0.0141	0.1512
0.6110	0.0041	-0.1700	0.1672	0.0000	0.4316
-1.2624	0.2643	1.1704	0.0000	0.1716	-0.3438
0.5030	0.0042	0.0000	0.0172	-0.1697	0.3239
-2.1235	0.1512	1.0071	-0.1146	1.0798	0.0000

Appendix E

COMPLETE RESULTS FOR OZONE DEPLETION REGULATIONS

TOTAL SOLVENT DEMAND

Solvent	Before	After	Change	%Change	%Before	%After
TCE	60.1176	61.0919	0.9743	0.0162	0.0641	0.0684
METH	68.1250	69.3635	1.2385	0.0182	0.0726	0.0777
PERC	127.1875	128.8117	1.6242	0.0128	0.1356	0.1442
TCA	150.6742	120.5619	-30.1123	-0.1999	0.1606	0.1350
113	42.9964	19.1591	-23.8372	-0.5544	0.0458	0.0215
FLAM	444.9057	448.9707	4.0650	0.0091	0.4743	0.5027
COMB	43.0676	44.3551	1.2875	0.0299	0.0459	0.0497
HCFC	0.8907	0.7948	-0.0959	-0.1077	0.0009	0.0009

TCE ALLOCATION

Application	Before	After	Change	%Change	%Before	%After
COLD	13.7647	14.4221	0.6574	0.0478	0.2290	0.2361
VAPOR	46.3529	46.6699	0.3169	0.0068	0.7710	0.7639

METH ALLOCATION

Application	Before	After	Change	%Change	%Before	%After
COLD	13.4375	14.2221	0.7846	0.0584	0.1972	0.2050
VAPOR	4.6875	5.1414	0.4539	0.0968	0.0688	0.0741
ORIG	10.0000	10.0000	0.0000	0.0000	0.1468	0.1442
MAINT	20.0000	20.0000	0.0000	0.0000	0.2936	0.2883
CONS	20.0000	20.0000	0.0000	0.0000	0.2936	0.2883

PERC ALLOCATION

Application	Before	After	Change	%Change	%Before	%After
DRY	107.1875	107.5122	0.3247	0.0030	0.8428	0.8346
COLD	1.5625	2.0652	0.5027	0.3217	0.0123	0.0160
VAPOR	18.4375	19.2343	0.7968	0.0432	0.1450	0.1493

TCA ALLOCATION

Application	Before	After	Change	%Change	%Before	%After
DRY	1.1236	0.4360	-0.6876	-0.6119	0.0075	0.0036
COLD	37.9775	31.1966	-6.7810	-0.1786	0.2521	0.2588
VAPOR	107.9775	85.8950	-22.0826	-0.2045	0.7166	0.7125
ELEC	3.5955	3.0343	-0.5612	-0.1561	0.0239	0.0252

CFC-113 ALLOCATION

Application	Before	After	Change	%Change	%Before	%After
DRY	1.9838	0.7804	-1.2034	-0.6066	0.0461	0.0407
COLD	17.0040	0.8000	-16.2040	-0.9530	0.3955	0.0418
VAPOR	0.0004	0.0004	0.0000	0.0000	0.0000	0.0000
ELEC	24.0081	17.5783	-6.4298	-0.2678	0.5584	0.9175

Flammables ALLOCATION

Application	Before	After	Change	%Change	%Before	%After
DRY	100.9434	100.5520	-0.3914	-0.0039	0.2269	0.2240
COLD	333.9623	338.4187	4.4564	0.0133	0.7506	0.7538
ORIG	6.9811	6.9811	0.0000	0.0000	0.0157	0.0155
CONS	3.0189	3.0189	0.0000	0.0000	0.0068	0.0067

Combustibles ALLOCATION

Application	Before	After	Change	%Change	%Before	%After
COLD	41.9807	42.7452	0.7645	0.0182	0.9828	0.9772
ELEC	0.3502	0.6117	0.2615	0.7466	0.0082	0.0140
ORIG	0.2899	0.2899	0.0000	0.0000	0.0068	0.0066
CONS	0.0966	0.0966	0.0000	0.0000	0.0023	0.0022

HCFC ALLOCATION

Application	Before	After	Change	%Change	%Before	%After
DRY	0.8300	0.6966	-0.1333	-0.1606	0.9318	0.8765
ELEC	0.0607	0.0981	0.0374	0.6161	0.0682	0.1235

DRY CLEANING SOLVENT SERVICES

Application	Before	After	Change	%Change	%Before	%After
PERC	1715.0000	1720.1955	5.1955	0.0030	0.6734	0.6763
TCA	16.6667	11.9280	-4.7386	-0.2843	0.0065	0.0047
113	35.0000	36.7432	1.7432	0.0498	0.0137	0.0144
FLAM	764.2857	761.3221	-2.9636	-0.0039	0.3001	0.2993
HCFC	15.7692	13.2363	-2.5329	-0.1606	0.0062	0.0052

COLD CLEANING SOLVENT SERVICES

Application	Before	After	Change	%Change	%Before	%After
TCE	41.7857	43.7813	1.9956	0.0478	0.0210	0.0219
METH	35.8333	37.9256	2.0923	0.0584	0.0180	0.0190
PERC	4.3478	5.7466	1.3987	0.3217	0.0022	0.0029
TCA	109.0323	102.6729	-6.3593	-0.0583	0.0547	0.0515
113	75.0000	4.1142	-70.8858	-0.9451	0.0376	0.0021
H_2O	605.6667	663.3316	57.6650	0.0952	0.3040	0.3326
FLAM	804.5455	815.2814	10.7360	0.0133	0.4038	0.4087
COMB	316.0000	321.7548	5.7548	0.0182	0.1586	0.1613

VAPOR DEGREASING SOLVENT SERVICES

Application	Before	After	Change	%Change	%Before	%After
TCE	157.6000	158.6776	1.0776	0.0068	0.1206	0.1191
METH	14.2857	15.6691	1.3834	0.0968	0.0109	0.0118
PERC	59.0000	61.5499	2.5499	0.0432	0.0451	0.0462
TCA	343.2143	320.7800	-22.4343	-0.0654	0.2626	0.2408
113	0.0019	0.0019	0.0000	0.0000	0.0000	0.0000
H_2O	733.0435	775.2949	42.2515	0.0576	0.5608	0.5821

ELECTRONICS SOLVENT SERVICES

Application	Before	After	Change	%Change	%Before	%After
TCA	11.4286	11.3399	-0.0887	-0.0078	0.0549	0.0551
113	114.0385	100.3458	-13.6927	-0.1201	0.5478	0.4872
H_2O	77.0000	82.2953	5.2953	0.0688	0.3699	0.3995
COMB	4.2647	7.4488	3.1841	0.7466	0.0205	0.0362
NOCLEAN	1.0000	3.8554	2.8554	2.8554	0.0048	0.0187
HCFC	0.4286	0.6926	0.2640	0.6161	0.0021	0.0034

ORIGINAL SOLVENT SERVICES

Application	Before	After	Change	%Change	%Before	%After
METH	29.0909	29.0909	0.0000	0.0000	0.4956	0.4956
H_2OBLAST	13.2143	13.2143	0.0000	0.0000	0.2251	0.2251
FLAMM	1.9355	1.9355	0.0000	0.0000	0.0330	0.0330
COMB	0.8261	0.8261	0.0000	0.0000	0.0141	0.0141
IMMERSION	13.6364	13.6364	0.0000	0.0000	0.2323	0.2323

MAINTENANCE SOLVENT SERVICES

Application	Before	After	Change	%Change	%Before	%After
METH	55.6522	55.6522	0.0000	0.0000	0.7405	0.7405
PMB	18.0000	18.0000	0.0000	0.0000	0.2395	0.2395
BICARB	0.8000	0.8000	0.0000	0.0000	0.0106	0.0106
LASER	0.7000	0.7000	0.0000	0.0000	0.0093	0.0093

CONSUMER SOLVENT SERVICES

Application	Before	After	Change	%Change	%Before	%After
METH	26.6667	26.6667	0.0000	0.0000	0.8239	0.8239
FLAM	4.0000	4.0000	0.0000	0.0000	0.1236	0.1236
COMB	0.7692	0.7692	0.0000	0.0000	0.0238	0.0238
GUN	0.9302	0.9302	0.0000	0.0000	0.0287	0.0287

DRY CLEANING FACTORS OF PRODUCTION
PERC Solvent Services:

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	68.6000	68.8078	0.2078	0.0030	0.0400	0.0400
ENERGY	34.3000	34.4039	0.1039	0.0030	0.0200	0.0200
ASSETS	806.0500	808.4919	2.4419	0.0030	0.4700	0.4700
WASTE	291.5500	292.4332	0.8832	0.0030	0.1700	0.1700
LABOR	377.3000	378.4430	1.1430	0.0030	0.2200	0.2200
POLLUTION	137.2000	137.6156	0.4156	0.0030	0.0800	0.0800

DRY CLEANING FACTORS OF PRODUCTION
TCA Solvent Services:

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	1.0000	0.3881	-0.6119	-0.6119	0.0600	0.0324
ENERGY	0.3333	0.2508	-0.0826	-0.2477	0.0200	0.0210
ASSETS	8.5000	6.4746	-2.0254	-0.2383	0.5100	0.5409
WASTE	2.3333	1.6611	-0.6722	-0.2881	0.1400	0.1388
LABOR	4.0000	2.8626	-1.1374	-0.2843	0.2400	0.2392
POLLUTION	0.5000	0.3320	-0.1680	-0.3360	0.0300	0.0277

DRY CLEANING FACTORS OF PRODUCTION
CFC-113 Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	4.9000	1.9276	-2.9724	-0.6066	0.1400	0.0508
ENERGY	0.7000	0.9612	0.2612	0.3731	0.0200	0.0253
ASSETS	16.8000	22.6448	5.8448	0.3479	0.4800	0.5966
WASTE	1.4000	1.3464	-0.0536	-0.0383	0.0400	0.0355
LABOR	8.4000	8.8204	0.4204	0.0501	0.2400	0.2324
POLLUTION	2.8000	2.2580	-0.5420	-0.1936	0.0800	0.0595

DRY CLEANING FACTORS OF PRODUCTION
Flammable Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	53.5000	53.2925	-0.2075	-0.0039	0.0700	0.0700
ENERGY	30.5714	30.4529	-0.1185	-0.0039	0.0400	0.0400
ASSETS	343.9286	342.5949	-1.3336	-0.0039	0.4500	0.4500
WASTE	22.9286	22.8397	-0.0889	-0.0039	0.0300	0.0300
LABOR	236.9286	236.0099	-0.9187	-0.0039	0.3100	0.3100
POLLUTION	76.4286	76.1322	-0.2964	-0.0039	0.1000	0.1000

DRY CLEANING FACTORS OF PRODUCTION
HCFC Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	4.1000	3.4414	-0.6586	-0.1606	0.2600	0.2600
ENERGY	0.3154	0.2647	-0.0507	-0.1606	0.0200	0.0200
ASSETS	6.9385	5.8240	-1.1145	-0.1606	0.4400	0.4400
WASTE	0.3154	0.2647	-0.0507	-0.1606	0.0200	0.0200
LABOR	3.4692	2.9120	-0.5572	-0.1606	0.2200	0.2200
POLLUTION	0.6308	0.5295	-0.1013	-0.1606	0.0400	0.0400

COLD CLEANING FACTORS OF PRODUCTION
TCE Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	11.7000	12.2588	0.5588	0.0478	0.2800	0.2800
ENERGY	2.0893	2.1891	0.0998	0.0478	0.0500	0.0500
ASSETS	5.0143	5.2538	0.2395	0.0478	0.1200	0.1200
WASTE	4.1786	4.3781	0.1996	0.0478	0.1000	0.1000
LABOR	14.2071	14.8856	0.6785	0.0478	0.3400	0.3400
POLLUTION	4.5964	4.8159	0.2195	0.0478	0.1100	0.1100
H_2ODISP	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000

COLD CLEANING FACTORS OF PRODUCTION
METH Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	8.6000	9.1021	0.5021	0.0584	0.2400	0.2400
ENERGY	2.1500	2.2755	0.1255	0.0584	0.0600	0.0600
ASSETS	5.0167	5.3096	0.2929	0.0584	0.1400	0.1400
WASTE	5.3750	5.6888	0.3138	0.0584	0.1500	0.1500
LABOR	13.2583	14.0325	0.7741	0.0584	0.3700	0.3700
POLLUTION	1.4333	1.5170	0.0837	0.0584	0.0400	0.0400
H_2ODISP	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000

COLD CLEANING FACTORS OF PRODUCTION
PERC Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	1.0000	1.3217	0.3217	0.3217	0.2300	0.2300
ENERGY	0.2174	0.2873	0.0699	0.3217	0.0500	0.0500
ASSETS	0.5652	0.7471	0.1818	0.3217	0.1300	0.1300
WASTE	0.6087	0.8045	0.1958	0.3217	0.1400	0.1400
LABOR	1.5217	2.0113	0.4896	0.3217	0.3500	0.3500
POLLUTION	0.4348	0.5747	0.1399	0.3217	0.1000	0.1000
H_2ODISP	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000

COLD CLEANING FACTORS OF PRODUCTION
TCA Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	33.8000	27.7649	-6.0351	-0.1786	0.3100	0.2690
ENERGY	5.4516	5.4796	0.0280	0.0051	0.0500	0.0531
ASSETS	14.1742	15.0780	0.9038	0.0638	0.1200	0.1461
WASTE	11.9935	11.3828	-0.6108	-0.0509	0.1100	0.1103
LABOR	39.2516	40.8309	1.5793	0.0402	0.3600	0.3956
POLLUTION	4.3613	2.6671	-1.6942	-0.3885	0.0400	0.0258
H_2ODISP	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000

COLD CLEANING FACTORS OF PRODUCTION
CFC-113 Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	42.0000	1.9761	-40.0239	-0.9530	0.5600	0.4651
ENERGY	2.2500	0.1687	-2.0813	-0.9250	0.0300	0.0397
ASSETS	6.0000	0.5014	-5.4986	-0.9164	0.0800	0.1180
WASTE	2.2500	0.0995	-2.1505	-0.9558	0.0300	0.0234
LABOR	18.0000	1.4778	-16.5222	-0.9179	0.2400	0.3478
POLLUTION	4[illegible]00	0.0256	-4.4744	-0.9943	0.0600	0.0060
H_2ODISP	0.0[illegible]	0.0000	0.0000	-NAN	0.0000	0.0000

COLD CLEANING FACTORS OF PRODUCTION
H_2O Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	1[illegible].7000	198.9995	17.2995	0.0952	0.3000	0.3000
ENERGY	127.1900	139.2996	12.1096	0.0952	0.2100	0.2100
ASSETS	90.8500	99.4997	8.6497	0.0952	0.1500	0.1500
WASTE	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000
LABOR	115.0767	126.0330	10.9563	0.0952	0.1900	0.1900
POLLUTION	30.2833	33.1666	2.8832	0.0952	0.0500	0.0500
H_2ODISP	60.5667	66.3332	5.7665	0.0952	0.1000	0.1000

COLD CLEANING FACTORS OF PRODUCTION
Flammable Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	177.0000	179.3619	2.3619	0.0133	0.2200	0.2200
ENERGY	48.2727	48.9169	0.6442	0.0133	0.0600	0.0600
ASSETS	120.6818	122.2922	1.6104	0.0133	0.1500	0.1500
WASTE	24.1364	24.4584	0.3221	0.0133	0.0300	0.0300
LABOR	337.9091	342.4182	4.5091	0.0133	0.4200	0.4200
POLLUTION	96.5455	97.8338	1.2883	0.0133	0.1200	0.1200
H_2ODISP	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000

COLD CLEANING FACTORS OF PRODUCTION
Combustible Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	173.8000	176.9651	3.1651	0.0182	0.5500	0.5500
ENERGY	9.4800	9.6526	0.1726	0.0182	0.0300	0.0300
ASSETS	25.2800	25.7404	0.4604	0.0182	0.0800	0.0800
WASTE	9.4800	9.6526	0.1726	0.0182	0.0300	0.0300
LABOR	75.8400	77.2211	1.3811	0.0182	0.2400	0.2400
POLLUTION	12.6400	12.8702	0.2302	0.0182	0.0400	0.0400
H_2ODISP	9.4800	9.6526	0.1726	0.0182	0.0300	0.0300

VAPOR DEGREASING FACTORS OF PRODUCTION
TCE Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	39.4000	39.6694	0.2694	0.0068	0.2500	0.2500
ENERGY	14.1840	14.2810	0.0970	0.0068	0.0900	0.0900
ASSETS	26.7920	26.9752	0.1832	0.0068	0.1700	0.1700
WASTE	14.1840	14.2810	0.0970	0.0068	0.0900	0.0900
LABOR	47.2800	47.6033	0.3233	0.0068	0.3000	0.3000
POLLUTION	15.7600	15.8678	0.1078	0.0068	0.1000	0.1000
H_2ODISP	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000

VAPOR DEGREASING FACTORS OF PRODUCTION
METH Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	3.0000	3.2905	0.2905	0.0968	0.2100	0.2100
ENERGY	1.4286	1.5669	0.1383	0.0968	0.1000	0.1000
ASSETS	2.7143	2.9771	0.2628	0.0968	0.1900	0.1900
WASTE	1.8571	2.0370	0.1798	0.0968	0.1300	0.1300
LABOR	4.7143	5.1708	0.4565	0.0968	0.3300	0.3300
POLLUTION	0.5714	0.6268	0.0553	0.0968	0.0400	0.0400
H_2ODISP	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000

VAPOR DEGREASING FACTORS OF PRODUCTION
PERC Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	11.8000	12.3100	0.5100	0.0432	0.2000	0.2000
ENERGY	5.3100	5.5395	0.2295	0.0432	0.0900	0.0900
ASSETS	10.6200	11.0790	0.4590	0.0432	0.1800	0.1800
WASTE	7.6700	8.0015	0.3315	0.0432	0.1300	0.1300
LABOR	18.2900	19.0805	0.7905	0.0432	0.3100	0.3100
POLLUTION	5.3100	5.5395	0.2295	0.0432	0.0900	0.0900
H_2ODISP	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000

VAPOR DEGREASING FACTORS OF PRODUCTION
TCA Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	96.1000	76.4465	-19.6535	-0.2045	0.2800	0.2370
ENERGY	34.3214	34.2942	-0.0272	-0.0008	0.1000	0.1063
ASSETS	61.7786	65.5060	3.7274	0.0603	0.1800	0.2031
WASTE	30.8893	28.1955	-2.6937	-0.0872	0.0900	0.0874
LABOR	109.8286	113.2586	3.4301	0.0312	0.3200	0.3512
POLLUTION	10.2964	4.8269	-5.4695	-0.5312	0.0300	0.0150
H_2ODISP	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000

VAPOR DEGREASING FACTORS OF PRODUCTION
CFC-113 Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	0.0010	0.0010	0.0000	0.0000	0.5200	0.5589
ENERGY	0.0001	0.0001	-0.0000	-0.0868	0.0600	0.0589
ASSETS	0.0002	0.0002	0.0000	0.0272	0.1200	0.1325
WASTE	0.0000	0.0000	-0.0000	-0.6074	0.0200	0.0084
LABOR	0.0004	0.0004	-0.0000	-0.0028	0.2200	0.2358
POLLUTION	0.0001	0.0000	-0.0001	-0.9152	0.0600	0.0055
H_2ODISP	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000

VAPOR DEGREASING FACTORS OF PRODUCTION
H_2O Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	168.6000	178.3178	9.7178	0.0576	0.2300	0.2300
ENERGY	241.9043	255.8473	13.9430	0.0576	0.3300	0.3300
ASSETS	131.9478	139.5531	7.6053	0.0576	0.1800	0.1800
WASTE	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000
LABOR	102.6261	108.5413	5.9152	0.0576	0.1400	0.1400
POLLUTION	29.3217	31.0118	1.6901	0.0576	0.0400	0.0400
H_2ODISP	58.6435	62.0236	3.3801	0.0576	0.0800	0.0800

ELECTRONICS FACTORS OF PRODUCTION
TCA Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	3.2000	2.7005	-0.4995	-0.1561	0.2800	0.2369
ENERGY	1.1429	1.2126	0.0697	0.0610	0.1000	0.1064
ASSETS	2.4000	2.7019	0.3019	0.1258	0.2100	0.2370
WASTE	1.1429	1.1090	-0.0339	-0.0296	0.1000	0.0973
LABOR	3.2000	3.5070	0.3070	0.0959	0.2800	0.3076
POLLUTION	0.3429	0.1706	-0.1722	-0.5023	0.0300	0.0150
H_2ODISP	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000

ELECTRONICS FACTORS OF PRODUCTION
CFC-113 Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	59.3000	43.4183	-15.8817	-0.2678	0.5200	0.4176
ENERGY	6.8423	8.0811	1.2388	0.1810	0.0600	0.0777
ASSETS	15.9654	21.3028	5.3374	0.3343	0.1400	0.2049
WASTE	2.2808	1.1272	-1.1535	-0.5058	0.0200	0.0108
LABOR	22.8077	29.3225	6.5148	0.2856	0.2000	0.2820
POLLUTION	6.8423	0.7300	-6.1123	-0.8933	0.0600	0.0070
H_2ODISP	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000

ELECTRONICS FACTORS OF PRODUCTION
H_2O Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	23.1000	24.6886	1.5886	0.0688	0.3000	0.3000
ENERGY	10.0100	10.6984	0.6884	0.0688	0.1300	0.1300
ASSETS	21.5600	23.0427	1.4827	0.0688	0.2800	0.2800
WASTE	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000
LABOR	10.7800	11.5213	0.7413	0.0688	0.1400	0.1400
POLLUTION	3.8500	4.1148	0.2648	0.0688	0.0500	0.0500
H_2ODISP	7.7000	8.2295	0.5295	0.0688	0.1000	0.1000

ELECTRONICS FACTORS OF PRODUCTION
Combustible Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	2.9000	5.0652	2.1652	0.7466	0.6800	0.6800
ENERGY	0.1706	0.2980	0.1274	0.7466	0.0400	0.0400
ASSETS	0.3838	0.6704	0.2866	0.7466	0.0900	0.0900
WASTE	0.0853	0.1490	0.0637	0.7466	0.0200	0.0200
LABOR	0.5118	0.8939	0.3821	0.7466	0.1200	0.1200
POLLUTION	0.0853	0.1490	0.0637	0.7466	0.0200	0.0200
H_2ODISP	0.1279	0.2235	0.0955	0.7466	0.0300	0.0300

ELECTRONICS FACTORS OF PRODUCTION
No Clean Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	1.0000	1.0000	0.0000	0.0000	1.0000	1.0000
ENERGY	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000
ASSETS	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000
WASTE	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000
LABOR	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000
POLLUTION	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000
H_2ODISP	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000

ELECTRONICS FACTORS OF PRODUCTION
HCFC Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	0.3000	0.4848	0.1848	0.6161	0.7000	0.7000
ENERGY	0.0171	0.0277	0.0106	0.6161	0.0400	0.0400
ASSETS	0.0429	0.0693	0.0264	0.6161	0.1000	0.1000
WASTE	0.0043	0.0069	0.0026	0.6161	0.0100	0.0100
LABOR	0.0557	0.0900	0.0343	0.6161	0.1300	0.1300
POLLUTION	0.0086	0.0139	0.0053	0.6161	0.0200	0.0200
H_2ODISP	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000

ORIGINAL FACTORS OF PRODUCTION
METH Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	6.4000	6.4000	0.0000	0.0000	0.2200	0.2200
ENERGY	1.4545	1.4545	0.0000	0.0000	0.0500	0.0500
ASSETS	2.0364	2.0364	0.0000	0.0000	0.0700	0.0700
WASTE	4.0727	4.0727	0.0000	0.0000	0.1400	0.1400
LABOR	12.2182	12.2182	0.0000	0.0000	0.4200	0.4200
POLLUTION	1.4545	1.4545	0.0000	0.0000	0.0500	0.0500
H_2ODISP	1.4545	1.4545	0.0000	0.0000	0.0500	0.0500

ORIGINAL FACTORS OF PRODUCTION
H_2O Blast Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000
ENERGY	0.1239	0.1239	0.0000	0.0000	0.1500	0.1500
ASSETS	0.1983	0.1983	0.0000	0.0000	0.2400	0.2400
WASTE	0.0661	0.0661	0.0000	0.0000	0.0800	0.0800
LABOR	0.3800	0.3800	0.0000	0.0000	0.4600	0.4600
POLLUTION	0.0083	0.0083	0.0000	0.0000	0.0100	0.0100
H_2ODISP	0.0496	0.0496	0.0000	0.0000	0.0600	0.0600

ORIGINAL FACTORS OF PRODUCTION
Flammable Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	3.7000	3.7000	0.0000	0.0000	0.2800	0.2800
ENERGY	0.6607	0.6607	0.0000	0.0000	0.0500	0.0500
ASSETS	0.9250	0.9250	0.0000	0.0000	0.0700	0.0700
WASTE	0.1321	0.1321	0.0000	0.0000	0.0100	0.0100
LABOR	5.5500	5.5500	0.0000	0.0000	0.4200	0.4200
POLLUTION	1.5857	1.5857	0.0000	0.0000	0.1200	0.1200
H_2ODISP	0.6607	0.6607	0.0000	0.0000	0.0500	0.0500

ORIGINAL FACTORS OF PRODUCTION
Combustible Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	1.2000	1.2000	0.0000	0.0000	0.6200	0.6200
ENERGY	0.0581	0.0581	0.0000	0.0000	0.0300	0.0300
ASSETS	0.0774	0.0774	0.0000	0.0000	0.0400	0.0400
WASTE	0.1355	0.1355	0.0000	0.0000	0.0700	0.0700
LABOR	0.3484	0.3484	0.0000	0.0000	0.1800	0.1800
POLLUTION	0.0581	0.0581	0.0000	0.0000	0.0300	0.0300
H_2ODISP	0.0581	0.0581	0.0000	0.0000	0.0300	0.0300

ORIGINAL FACTORS OF PRODUCTION
Immersion Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	3.0000	3.0000	0.0000	0.0000	0.2200	0.2200
ENERGY	1.0909	1.0909	0.0000	0.0000	0.0800	0.0800
ASSETS	1.9091	1.9091	0.0000	0.0000	0.1400	0.1400
WASTE	2.0455	2.0455	0.0000	0.0000	0.1500	0.1500
LABOR	5.1818	5.1818	0.0000	0.0000	0.3800	0.3800
POLLUTION	0.4091	0.4091	0.0000	0.0000	0.0300	0.0300
H_2ODISP	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000

MAINTENANCE FACTORS OF PRODUCTION
METH Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	12.8000	12.8000	0.0000	0.0000	0.2300	0.2300
ENERGY	4.4522	4.4522	0.0000	0.0000	0.0800	0.0800
ASSETS	7.2348	7.2348	0.0000	0.0000	0.1300	0.1300
WASTE	5.5652	5.5652	0.0000	0.0000	0.1000	0.1000
LABOR	20.0348	20.0348	0.0000	0.0000	0.3600	0.3600
POLLUTION	2.7826	2.7826	0.0000	0.0000	0.0500	0.0500
H_2ODISP	2.7826	2.7826	0.0000	0.0000	0.0500	0.0500

MAINTENANCE FACTORS OF PRODUCTION
PMB Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	0.9000	0.9000	0.0000	0.0000	0.0500	0.0500
ENERGY	0.9000	0.9000	0.0000	0.0000	0.0500	0.0500
ASSETS	7.3800	7.3800	0.0000	0.0000	0.4100	0.4100
WASTE	0.9000	0.9000	0.0000	0.0000	0.0500	0.0500
LABOR	6.8400	6.8400	0.0000	0.0000	0.3800	0.3800
POLLUTION	0.1800	0.1800	0.0000	0.0000	0.0100	0.0100
H_2ODISP	0.9000	0.9000	0.0000	0.0000	0.0500	0.0500

MAINTENANCE FACTORS OF PRODUCTION
Bicarb Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	0.0400	0.0400	0.0000	0.0000	0.0500	0.0500
ENERGY	0.0400	0.0400	0.0000	0.0000	0.0500	0.0500
ASSETS	0.3200	0.3200	0.0000	0.0000	0.4000	0.4000
WASTE	0.0560	0.0560	0.0000	0.0000	0.0700	0.0700
LABOR	0.2880	0.2880	0.0000	0.0000	0.3600	0.3600
POLLUTION	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000
H_2ODISP	0.0560	0.0560	0.0000	0.0000	0.0700	0.0700

MAINTENANCE FACTORS OF PRODUCTION
Laser Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000
ENERGY	0.0700	0.0700	0.0000	0.0000	0.1000	0.1000
ASSETS	0.4900	0.4900	0.0000	0.0000	0.7000	0.7000
WASTE	0.0350	0.0350	0.0000	0.0000	0.0500	0.0500
LABOR	0.0700	0.0700	0.0000	0.0000	0.1000	0.1000
POLLUTION	0.0350	0.0350	0.0000	0.0000	0.0500	0.0500
H_2ODISP	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000

CONSUMER FACTORS OF PRODUCTION
METH Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	12.8000	12.8000	0.0000	0.0000	0.4800	0.4800
ENERGY	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000
ASSETS	2.1333	2.1333	0.0000	0.0000	0.0800	0.0800
LABOR	10.9333	10.9333	0.0000	0.0000	0.4100	0.4100
POLLUTION	0.8000	0.8000	0.0000	0.0000	0.0300	0.0300

CONSUMER FACTORS OF PRODUCTION
Flammable Solvent Services

Factor	Before	After	Change	%Change	%Before	%After
SOLVENT	1.6000	1.6000	0.0000	0.0000	0.4000	0.4000
ENERGY	0.0000	0.0000	0.0000	-NAN	0.0000	0.0000
ASSETS	0.3200	0.3200	0.0000	0.0000	0.0800	0.0800
LABOR	1.6800	1.6800	0.0000	0.0000	0.4200	0.4200
POLLUTION	0.4000	0.4000	0.0000	0.0000	0.1000	0.1000

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                     CONSUMER FACTORS OF PRODUCTION
                           Combustible Solvent Services
Factor        Before       After    Change   %Change   %Before    %After
SOLVENT       0.4000      0.4000    0.0000    0.0000    0.5200    0.5200
ENERGY        0.0000      0.0000    0.0000      -NAN    0.0000    0.0000
ASSETS        0.0538      0.0538    0.0000    0.0000    0.0700    0.0700
LABOR         0.2846      0.2846    0.0000    0.0000    0.3700    0.3700
POLLUTION     0.0308      0.0308    0.0000    0.0000    0.0400    0.0400

                     CONSUMER FACTORS OF PRODUCTION
                            Heat Gun Solvent Services
Factor        Before       After    Change   %Change   %Before    %After
SOLVENT       0.0000      0.0000    0.0000      -NAN    0.0000    0.0000
ENERGY        0.0465      0.0465    0.0000    0.0000    0.0500    0.0500
ASSETS        0.4465      0.4465    0.0000    0.0000    0.4800    0.4800
LABOR         0.4000      0.4000    0.0000    0.0000    0.4300    0.4300
POLLUTION     0.0372      0.0372    0.0000    0.0000    0.0400    0.0400

                      PRODUCTION APPLICATIONS
Application   Before       After    Change   %Change   %Before    %After
DRY        2546.7216   2543.4676   -3.2541   -0.0013    0.4094    0.4110
COLD       1992.2113   1979.5765  -12.6348   -0.0063    0.3203    0.3199
VAPOR      1307.1454   1295.3119  -11.8335   -0.0091    0.2101    0.2093
ELEC        208.1603    203.6129   -4.5474   -0.0218    0.0335    0.0329
ORIG         58.7031     58.7031    0.0000    0.0000    0.0094    0.0095
MAIN         75.1522     75.1522    0.0000    0.0000    0.0121    0.0121
CONS         32.3661     32.3661    0.0000    0.0000    0.0052    0.0052
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