

Source Reduction Research Partnership

Metropolitan Water District of Southern California
Environmental Defense Fund

**Source Reduction of
Chlorinated Solvents**

Flexible Foam Manufacture



Prepared for

Alternative Technology Division
Toxic Substances Control Program
California Department of
Toxic Substances Control

and

Pollution Prevention Research Branch
Risk Reduction Engineering Laboratory
Office of Research and Development
U.S. Environmental Protection Agency

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P.O. Box 806
Sacramento, CA 95812-0806**

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TABLE OF CONTENTS

I.	ACKNOWLEDGMENT	i
II.	DISCLAIMER	ii
III.	PREFACE	iii
I.	INTRODUCTION	1
II.	BACKGROUND	6
	FOAM PRODUCTION PROCESS	7
	FOAM AND BLOWING AGENT USE	13
	FOAM INDUSTRY CHARACTERIZATION	16
	RESULTS OF VISITS/SURVEYS	22
	FUTURE INDUSTRY TRENDS	23
III.	SOURCE REDUCTION OPTIONS FOR SLABSTOCK FOAM BLOWING	36
	PRODUCT SUBSTITUTION	36
	CHEMICAL SUBSTITUTION	39
	EQUIPMENT MODIFICATION	47
	PROCESS MODIFICATION	49
	"AB" PROCESS	49
	RECOVERY AND RECYCLE	52
IV.	SOURCE REDUCTION OPTIONS FOR SOLVENT APPLICATIONS	60
	RECOVERY AND REUSE	60
V.	ANALYSIS OF SOURCE REDUCTION OPTIONS FOR FOAM BLOWING APPLICATIONS	62
	SELECTION OF BLOWING AGENT OPTIONS	62
	"NO FURTHER ANALYSIS" OPTIONS	62
	"LIMITED ANALYSIS" OPTIONS	64
	FULL ANALYSIS OPTIONS	73
VI.	ANALYSIS OF SOURCE REDUCTION OPTIONS FOR SOLVENT APPLICATION IN FOAM PLANTS	88
	SELECTION OF SOLVENT OPTIONS	88
VII.	ANALYSIS OF SOURCE REDUCTION OPTIONS FOR SOLVENT APPLICATIONS	91
	SELECTION OF SOLVENT OPTIONS	91
	OFF-SITE RECYCLING	91
	SUMMARY OF RECYCLING	92
VIII.	SUMMARY AND CONCLUSIONS	95
	SUMMARY OF SOLVENT CLEANING OPTIONS POTENTIAL	96
IX.	BIBLIOGRAPHY	100

LIST OF FIGURES

2.1	CHEMICAL REACTIONS INVOLVED IN FOAM PRODUCTION	8
2.2	TYPICAL FOAM LINE	12
2.3	PRODUCT MIX OF A TYPICAL SLABSTOCK PLANT	24
2.4	PRODUCT MIX FOR PLANT #1	25
2.5	PRODUCT MIX FOR PLANT #2	26
2.6	PRODUCT MIX FOR PLANT #3	27

LIST OF TABLES

1.1	QUALITATIVE POTENTIAL OF SOURCE REDUCTION OPTIONS FOR BLOWING AGENTS	3
1.2	QUALITATIVE POTENTIAL OF SOURCE REDUCTION OPTIONS FOR SOLVENT CLEANING	6
2.1	TYPICAL SLABSTOCK FOAM FORMULATIONS	9
2.2	HISTORICAL FLEXIBLE FOAM PRODUCTION	14
2.3	SLABSTOCK FOAM USE BY APPLICATION - 1985	15
2.4	U.S. FLEXIBLE POLYURETHANE SLABSTOCK PLANTS	16
2.5	SOUTHERN CALIFORNIA FLEXIBLE POLYURETHANE SLABSTOCK PLANTS	19
2.6	PROFILE OF SURVEYED PLANTS	20
2.7	FOAM MARKETS OF SURVEYED PLANTS	21
2.8	PROJECTED STATUS OF FOAM INDUSTRY - 1991	34
2.9	CURRENT AND FUTURE BLOWING AGENT USE	35
3.1	PROPERTIES OF CURRENT AND PROPOSED BLOWING AGENTS	37
3.2	HEALTH AND ENVIRONMENTAL CHARACTERISTICS OF CURRENT AND PROPOSED BLOWING AGENTS	41
5.1	CLASSIFICATION OF BLOWING AGENT OPTIONS	63
5.2	ANNUAL COST INCREASE AND METH EMISSIONS	65
5.3	ANNUAL COST INCREASE AND METH EMISSIONS REDUCTION FOR TCA SUBSTITUTION	66
5.4	ANNUAL COST INCREASE AND METH EMISSION REDUCTION FOR POLYURETHANE MODIFICATION	70
5.5	ANNUAL COST INCREASE AND METH EMISSION REDUCTION FOR LIQUID ABSORPTION	71
5.6	ANNUAL COST INCREASE AND METH EMISSION	72
5.7	SUMMARY OF ANNUAL COST AND BLOWING AGENT USE REDUCTIONS FOR "LIMITED ANALYSIS" OPTIONS - U.S.	74
5.8	SUMMARY OF ANNUAL COST AND BLOWING AGENT	75
5.9	CHARACTERISTICS OF SMALL, MEDIUM AND LARGE PLANTS	76
5.10	CAPITAL COSTS FOR CARBON ADSORPTION SYSTEM	79
5.11	ANNUALIZED OPERATING COST FOR CARBON ADSORPTION	80

5.12	ANNUAL COST AND METH EMISSION REDUCTION FOR CARBON ADSORPTION SYSTEM	82
5.13	ANNUAL COST AND METH EMISSION REDUCTION FOR MINIMUM DENSITY SPECIFICATION	87
6.1	CLASSIFICATION OF SOURCE REDUCTION OPTIONS FOR SOLVENT CLEANING USES	89
6.2	ANNUAL COST AND METH USE REDUCTION FROM RECYCLING	93
7.1	SUMMARY OF SOURCE REDUCTION OPTIONS IN THE FLEXIBLE FOAM INDUSTRY	96

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DISCLAIMER

The statements and conclusions of this report do not necessarily represent those of the State of California, the U.S. Environmental Protection Agency or any other contributors. The mention of any commercial products, their source or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products.

PREFACE

This report is one of twelve reports that evaluate the opportunities for source reduction of chlorinated solvents in twelve specific industries. The twelve reports are part of a large-scale study sponsored by the Source Reduction Research Partnership (SRRP), a joint venture by the Metropolitan Water District of Southern California and the Environmental Defense Fund. The reports cover the following industries and industrial practices:

1. Aerosols Manufacture
2. Adhesives Manufacture
3. Chemical Intermediates Manufacture
4. Dry Cleaning of Fabrics
5. Electronic Products Manufacture
6. Flexible Foam Manufacture
7. Food Products Manufacture
8. Paint Removal
9. Pesticides Formulating
10. Pharmaceuticals Manufacture
11. Solvent Cleaning
12. Textiles Manufacture

The objectives of the SRRP study include a survey and evaluation of existing and potential techniques for reducing the generation of halogenated solvent wastes, and thus their potential release into the environment, across a wide range of the industrial users of these solvents.

Each of the industry-specific reports begins with a description of the industry and processes where halogenated and solvents are used. Sources and causes of releases are described and regulatory regime discussed for waste streams of concern.

Subsequent sections focus on source reduction opportunities through chemical substitution, process modification, product substitution and recovery/reuse. For major solvent using industries, select source reduction options were analyzed for their economic feasibility.

The information in the reports was compiled and analyzed by the SRRP project staff, employed by the Partnership to carry out the project research. Each report was reviewed by industry representatives and/or other experts familiar with the specific industry and the relevant technologies and issues, and then reviewed and edited by an additional expert consultant.

The intent of the sponsors is to provide all interested parties with useful information on available and potentially available methods for source reduction of halogenated solvents, in the context of specific industries and processes, and an evaluation in context of the various source reduction options.

I. INTRODUCTION

The five major chlorinated solvents most widely used in commerce today include trichloroethylene (TCE), perchloroethylene (PERC), 1,1,1-trichloroethane (TCA), methylene chloride (METH), and 1,1,2-trichloro-1,2,2-trifluoroethane (CFC-113). Two of these--METH and TCA--are employed in the production of flexible polyurethane slabstock foam, which is used in a diverse range of applications including furniture cushioning, carpet underlay and packaging applications. Carbon dioxide is the primary blowing agent for flexible slabstock foam. METH and TCA function as auxiliary blowing agents that expand the cells of the foam.

The flexible foam industry uses about 18 thousand metric tons (mt) of METH annually as an auxiliary blowing agent; an additional 5 thousand mt of METH is employed for various solvent cleaning purposes in the slabstock and molded foam industries. A few foam plants have recently adopted TCA as an auxiliary blowing agent and its current use probably does not exceed 3 thousand mt. By the end of 1990, however, its use is likely to amount to 17 thousand mt. Because TCA has been adopted so recently, most of the analysis presented here focuses on METH. It does include a discussion, where appropriate, of differences between the two blowing agents that would change the applicability of the source reduction options.

It is possible that METH and TCA use in foam blowing operations may increase in the next few years because of regulations and a tax on the major alternative, CFC-11. Production of this latter chemical will be restricted because it is part of a family of chemical--the chlorofluorocarbons (CFCs)--that are suspected of depleting the stratospheric ozone layer. Congress placed a tax on the chemical that became effective in January, 1990. METH is currently under intense

regulatory scrutiny as well. The Occupational Safety and Health Administration (OSHA) is expected to lower the permissible workplace exposure level significantly in the near future. METH is on the California Proposition 65 list and the state has recently announced that it will regulate the chemical as a toxic air contaminant. TCA contributes to ozone depletion as well but its ozone depletion potential is only about one-tenth that of CFC-11. Its production may be restricted in the future.

Table 1.1 summarizes the source reduction options evaluated in this study for foam blowing operations along with their advantage and disadvantages.

This study includes a full cost and METH emissions reduction analysis of two blowing agent options; a minimum density specification for foam and use of carbon adsorption for vapor recovery. The results suggest that a minimum density foam specification would be cost-effective at a blowing agent price of \$1.03 per kilogram which can be compared with current prices for METH and TCA of \$0.64 and \$0.91 per kilogram respectively. Carbon adsorption alone would be cost-effective at a blowing agent price of \$0.34 per kilogram but the analysis does not apply for TCA. A minimum density foam specification followed by adoption of carbon adsorption would be cost-effective at a blowing agent price of \$4.26 per kilogram.

CFC-11 will be phased out by the end of the century and will no longer be available for use as a blowing agent. The Congressionally mandated tax that became effective in January 1990 approximately doubled the price of CFC-11. The foamers still using CFC-11 will increasingly attempt to adopt METH and TCA which are much less costly to use. State and local governments are discouraging the use of METH and some may require foamers using METH to install vapor recovery. For this reason, the study includes a full analysis of the recovery option. METH recovery has never been demonstrated and recovery is unlikely to lead to more than about a 30 percent reduction in METH use. A more promising option for the foam industry is

- 3 -
Table 1.1

QUALITATIVE POTENTIAL OF SOURCE REDUCTION OPTIONS
FOR BLOWING AGENTS

Option	Use Reduction ^a	Time Frame ^b
Product Substitution		
Non-polyurethane Alternatives	Small	Short
Specify Minimum Density Foam	Medium	Short
Chemical Substitution		
Acetone	Medium	Short
CFC-11	Large	Short
HCFC-123	Large	Long
HCFC-141b	Large	Long
Equipment Modification		
Max-Foam Process	Small	Short
Vertifoam Process	Small	Medium
Process Modification		
AB Process	Medium	Medium
Polyurethane Modification/ Additives	Large	Medium
Recovery and Recycle		
Liquid Absorption	Medium	Medium
Vapor Condensation	Medium	Medium
Carbon Adsorption	Medium	Medium
Brayton Cycle	Medium	Medium
Membrane System	Medium	Medium
Polymeric Adsorption System	Medium	Medium

^aLow indicates none to 10 percent; medium indicates 10 to 40 percent; large indicates more than 40 percent.

^bShort indicates immediate; medium indicates an immediate to three year implementation long indicates more than a three year implementation.

polyurethane modification and development of additives. This option is likely to become available over the next five years and it would be capable of eliminating auxiliary blowing agent use altogether. Currently, there are some additives available that can reduce--but not completely eliminate--blowing agent use. If foamers were required to install recovery, a much less promising option, industry resources would be diverted from R&D funds for investigating additives which over the long-term offer the best solution.

Table 1.2 summarizes the source reduction options evaluated in this study for solvent cleaning uses. Again, it also presents a qualitative estimate of the METH use reduction that could be realized and the time frame over which the option could be adopted.

The balance of this document discusses the state of the flexible slabstock foam industry. Section II focuses on the slabstock foam production process and provides characteristics of the industry structure. Section III describes the source reduction options that might be used to reduce the use of METH as a blowing agent in slabstock foam production. Section IV presents the results of the use reduction and cost analysis of the blowing agent options. Section V identifies and discusses the source reduction options for reducing METH use as a cleaning solvent in flexible slabstock and molded foam operations. Section VI presents the analysis of the cleaning options. Finally, Section VII summarizes the findings.

Table 1.2

QUALITATIVE POTENTIAL OF SOURCE REDUCTION OPTIONS
FOR SOLVENT CLEANING

OPTION	USE REDUCTION	TIME FRAME ^a
Chemical Substitution		
DBE	Large	Short
NMP	Large	Short
Recovery and Recycle of Waste		
On-Site Distillation	Small	Short
Off-Site Distillation	Small	Short

^a

Short indicates immediate to two year implementation.

II. BACKGROUND

In the United States, flexible foam manufacture began in the 1950s. These foams are important for their cushioning characteristics in the manufacture of furniture, bedding, carpet underlay, automobile seats and various other applications. Flexible foams can be molded into their final shape as in automobile seats, for instance--or they can be produced as slabstock, a large continuous bun that can be sawed into pieces with desired dimensions.

Blowing agents are used to form the cells in the foam, imparting flexibility. Carbon dioxide is the primary blowing agent in all flexible foams. In some high density, firmer foams--so called water blown foams--carbon dioxide is the sole blowing agent. In less firm, softer foams, two auxiliary blowing agents, trichlorofluoromethane (CFC-11) and METH, have traditionally been employed. Another auxiliary blowing agent--TCA--has recently been tested successfully. Slabstock foam can be solely water blown or it can be blown with CFC-11, METH or TCA as auxiliary blowing agents. Molded foam can be water blown or it can be blown with CFC-11 as an auxiliary blowing agent; METH is not used in the production of molded foam.

The remainder of this section is divided into four parts. The first subsection summarizes urethane chemistry and the foam production process. The second subsection presents estimates of the use of blowing agents. The third subsection provides information on plant location and industry characteristics. The fourth subsection summarizes the results of the surveys. The fifth subsection discusses the future of this dynamic industry in the light of impending regulatory changes.

FOAM PRODUCTION PROCESS

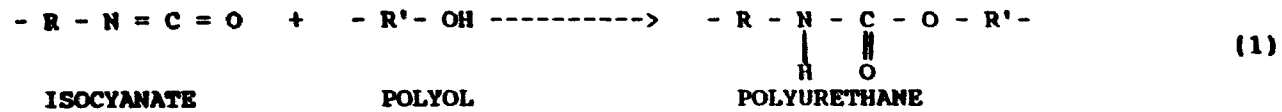
The major chemical reactions that place in foam manufacture are shown in Figure 2.1. The urethane polymer is formed as shown in equation (1) through the reaction of an isocyanate (-NCO) with a polyol (-OH). In the second set of reactions the isocyanate (-NCO) reacts with water to form a urea, evolving carbon dioxide gas. The carbon dioxide produced in the reaction produced in the reaction functions as the primary blowing agent. The disubstituted areas formed in the next reaction are rigid linkages that impart the polymer its strength.

The more water used in the foam formula, the greater the urea formation and the more rigid the foam. The more water, the more carbon dioxide is liberated, giving a less dense foam. Thus, increasing the water which forms the primary blowing agent, leads to a less dense foam but also one that is more rigid. As discussed below, auxiliary blowing agents--like CFC-11 or METH--are used to reduce foam density further without simultaneously increasing the rigidity and for control of the reaction temperature.

The isocyanate used in slabstock production is toluence diisocyanate (TDI), a mixture of two different diisocyanate isomers. The polyols most widely used are based on diols or triols, and are in the molecular weight range of 3,000 to 6,000. Other ingredients that are necessary in the foam formulations include catalysts, surfactants, fillers, flame retardants, colorants, and auxiliary blowing agents.

Table 2.1 shows several typical formulations that employ METH and CFC-11 as auxiliary blowing agents. It is conventional to present the components of various formulations in parts per hundred of polyol (php). Thus, in Table 2.1, levels of all ingredients are given in terms. The amine catalyst, ranging from 0.1 to 1.0 php in Table 2.1 increases the rate of the isocyanate/water reaction which forms carbon dioxide, the primary blowing agent. The tin (stannous octoate) catalyst speeds up the polyol/isocyanate reaction in the formation of the polyurethane.

ISOCYANATE/POLYOL REACTION TO FORM POLYURETHANES



ISOCYANATE/WATER REACTION TO FORM DISUBSTITUTED UREAS

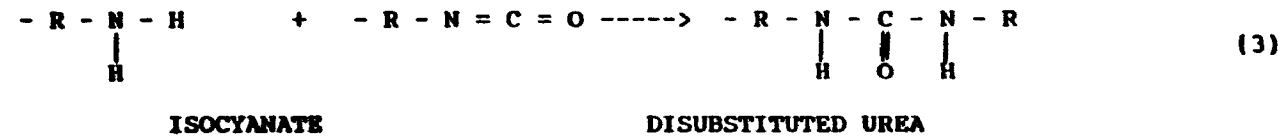
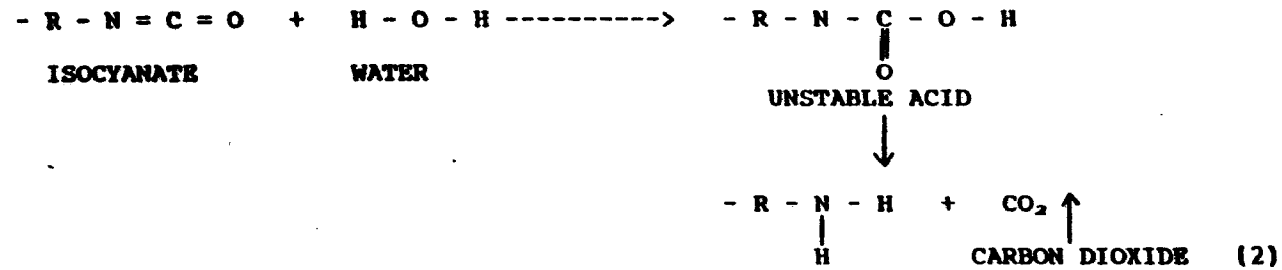


Figure 2.1. CHEMICAL REACTIONS INVOLVED IN FOAM PRODUCTION

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I

TABLE 2.1. TYPICAL SLABSTOCK FOAM FORMULATIONS

FORMULATION	PARTS PER HUNDRED POLYOL (php)					
	1 ^a	2 ^a	3 ^a	4 ^a	5 ^b	6 ^a
POLYOL	100	100	100	100 ^c	100	100
ISOCYANATE (TDI)	NA	45.0	46.0	NA	42.5	NA
AMINE CATALYST	0.15	0.2	0.2	0.1	1.0	0.3
STANNOUS OCTOATE CATALYST	0.8	0.65	0.3	0.275	1.75	0.38
SURFACTANT	1.2	1.5	1.2	1.0	2.0	1.4
WATER	3.5	3.4	2.6	4.3	3.5	3.5
METH	25	20	10	4	-	-
CFC-11	-	-	-	-	13.5	25

PROPERTIES						
DENSITY (lb/ft ³)	0.98	1.0	1.6	1.27	1.4	1.0
25% IFD (lbs) ^d	10	13	19	33	NA	13
65% IFD (lbs)	19	24	34	60	NA	23

^a Polymer with molecular weight 3010.

^b Polymer with molecular weight 3040.

^c NA Means not available.

^d IFD (Indentation Force Deflection) is a measure of foam firmness.

Sources: U.S. EPA (1988); Sayad and Williams (1979a); Sayad and Williams (1979b).

The surfactant is used to control the size of the cells and to stabilize the foam as it rises. The IFD or Indentation Force Deflection given in Table 2.1 is a measure of the firmness of the foam. It is the force required to compress the original foam height by 25 percent or 65 percent. The higher the IFD, the firmer the foam. The softest foams have IFDs less than 18 whereas the firmest foams have IFDs of more than 40.

In comparing columns 3 and 4 of Table 2.1, foam density decreases with increasing water; greater use of water also increases firmness (IFD). A rule of thumb in evaluating blowing agents is that 1 php of water is roughly equivalent to 10 php CFC-11 or 8.5 php methylene chloride (Oertel et al, 1985). This source suggest that because of it lower molecular weight, about 15 percent less METH is required to produce the same amount of foam produced with CFC-11. An industry representative indicates that, in practice, 5 to 10 percent less METH is required.

Slabstock foam is produced on a conveyor belt that can be a variety of lengths, called a foam line. The process is depicted in Figure 2.2. The foam producing reactions occur in the foam tunnel which is surrounded by plastic or metal curtains. The reactants are pumped to the mixing head and discharged through a nozzle where they pur onto the belt. In the foam tunnel, the reactants form a "bun" which reaches its maximum height within two to four minutes. Roughly half the auxiliary blowing agent is lost in the foam tunnel and the balance is lost within 24 hours. The foam leaves the tunnel ready to be sawed into buns from which the finished products can be cut. The bunstock is sawed and the cut sections are transported by the conveyor to the curing and storage area.

The slabstock line must be heavily ventilated. The exhaust vapors contain TDI, a hazardous chemical which has a Permissible Exposure Level (PEL) of 0.005 ppm and Short Term Exposure Level (STEL) of 0.02 ppm. There are generally one or

more large ducts along the foam line which circulate ambient plant air through the conveyor. By the time the foam has left the tunnel, most of the reactions have taken place. The foam then goes to the curing area which generally has much lower ventilation levels because most of the TDI has already been consumed in the foam reactions.

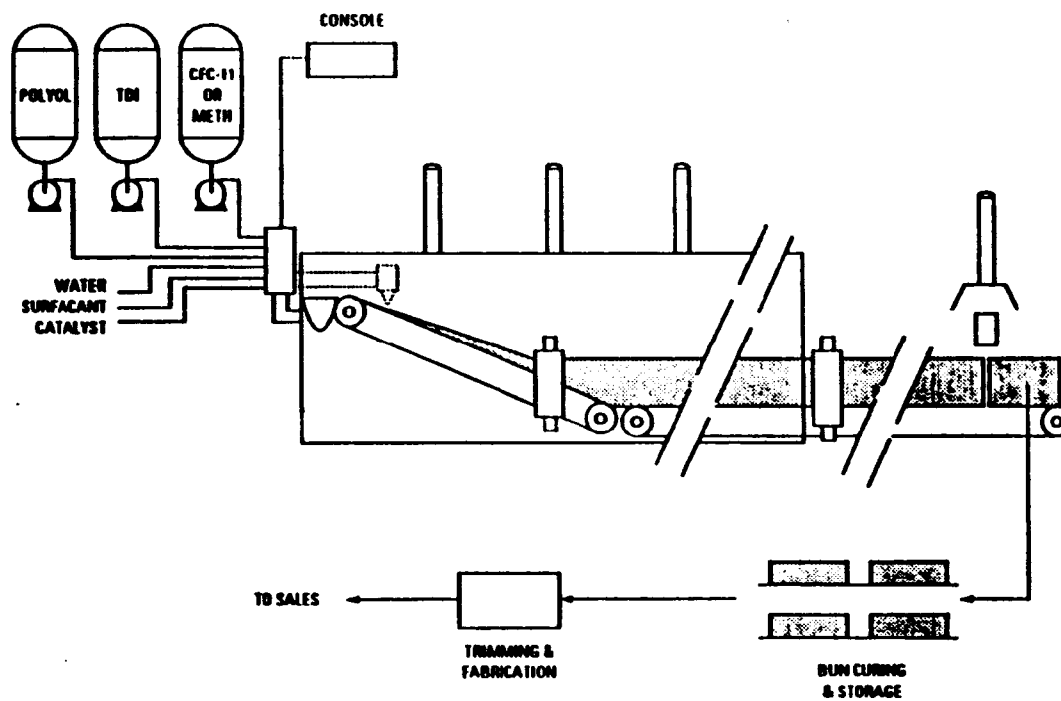


FIGURE 2.2
TYPICAL FOAM LINE

SOURCE FARMER et al. 1987

FOAM AND BLOWING AGENT USE

Table 2.2 shows the historical nationwide production of flexible slabstock and molded foam combined. Table 2.3 specifies the use of slabstock foam in a variety of applications for 1985. Furniture and carpet underlay applications together accounted for roughly two-thirds of the total slabstock production.

CFC-11 use in slabstock foam amounted to 11.4 thousand mt in 1985 (Hammitt et al, 1986). Use of METH in slabstock foam in 1984 is estimated at 10.1 thousand mt (Pandullo and Nash, 1986). In 1989, about 18 thousand mt of METH was employed in foam production. CFC-11 use in slabstock foam manufacture has declined and was lower, at 6.8 thousand mt. Until the early 1980s, most slabstock was produced with CFC-11. Because of improved economics in the METH process, there was a switch to METH. Developments in better amine catalysts have allowed increased METH use, even in the lower density foams where CFC-11 has been traditionally used (Modern Plastics, 1982; Sayad and Williams, 1979a; Sayad and Williams, 1979b; Moore, 1982).

In 1987, production of flexible foam amounted to about 700 thousand mt. Slabstock represented roughly 570 thousand mt and molded foam accounted for about 130 thousand mt. About 60 percent of the slabstock foam produced today is made using CFC-11 or METH as auxiliary blowing agents; the remaining 40 percent is blown with only water, the primary blowing agent. Much of the molded foam is made with only a primary blowing agent. CFC-11 is the sole auxiliary blowing agent used in molded foam applications. METH has not been used as a blowing agent in molded foam production because it has a greater tendency to be retained in the mold which can cause foam collapse or surface defects. Although the METH does not function as a blowing agent, it is apparently used to clean the molds and the foam mixing heads. Such cleaning uses of METH in both slabstock and molded operations are estimated at 5.2 thousand mt currently.

Table 2.2

HISTORICAL FLEXIBLE FOAM PRODUCTION

YEAR	PRODUCTION ^a (thousand metric tons)
1960	38
1965	108
1970	276
1975	435
1980	675
1985	675
1986	NA ^b
1987	700

^a Includes slabstock and molded foams.

^b NA means not available.

Sources: Mooz and Quinn (1980); Hammitt et al (1986); Industry Sources.

Table 2.3

SLABSTOCK FOAM USE BY APPLICATION - 1985

APPLICATION	USE (thousands of metric tons)
Furniture	225
Carpet Underlay	150
Transportation	85
Bedding	70
Textiles	15
Packaging	15
Scrap	5
Miscellaneous	5
TOTAL	570

Source: U.S. EPA (1988); Industry Sources.

FOAM INDUSTRY CHARACTERIZATION

There were 47 firms located throughout the U.S. operating 106 plants involved in the production of flexible slabstock foam in 1985. Significant consolidation has occurred over the last few years and there are now 26 firms with 81 U.S. plants. The firms and their plant locations are listed in Table 2.4. The plants using METH in 1989 in Table 2.4 are those with an asterick next to the name (Industry Sources). METH was used by 50 plants or 62 percent of the foam plants operating in 1989. TCA is presently employed by seven U.S. plants or about 9 percent of the plants. The remaining plants exclusively use CFC-11.

Table 2.5 summarizes the plants operating in Southern California. Of these six Southern California plants, four use METH, and until recently, the two others used CC-11. These plants have now converted to TCA. One of the plants using METH also uses TCA.

Slabstock foam is a low value, low-density product. Since transportation costs of the foam can be significant, foamers generally locate near their markets. A number of the foam plants listed in Table 2.4 are located in the Southeastern U.S. where there is a large concentration of major furniture manufacturers. Slabstock foam is not especially capital intensive so that entrance into the business is relatively easy. On the other hand, small producers, who are dependent on narrow profit margins, can go out of business easily as well.

Several of the foam producers, as indicated in Table 2.4, are large companies with multiple plants across the U.S. These large firms produce between about 4.5 and 13.6 thousand mt of foam annually and use between about 200 and 590 mt of blowing agent.¹ Medium sized firms produce between 2.3 and 4.5

¹ A rule of thumb is that, on average, blowing agent

Table 2.4

U.S. FLEXIBLE POLYURETHANE SLABSTOCK PLANTS

<u>Company</u>	<u>Facility Location</u> ^a	<u>Company</u>	<u>Facility Location</u> ^a
American Foam	Miami FL*	Foamex Products	Auburn IN*
Austin Urethane	Americus GA*		Conyers GA*
Crain Industries	Compton CA*		Cornelius NC*
	Conover NC*		Corry PA*
	Elkhart IN		Dallas TX
	Ft. Smith AZ*		Eddystone PA
	Kent WA*		Elkhart IN*
	Newman GA*		Fort Wayne IN*
	San Leandro CA		Mesquite TX
	Tupelo MS		Milan TN*
Easton	Easton PA*		Orlando FL*
E.R. Carpenter	Conover NC*		San Bernardino CA*
	Elkhart IN*		Santa Teresa NM
	Richmond VA*		Verona MS*
	Lathrop CA		
	Riverside CA*	Future Foam	Anaheim CA
	Russellville KY*		Beaumont TX
	Temple TX*		Council Bluffs IA*
	Tupelo MS*		Middleton WI*
			Newton KS*
			Northglenn CO*
			Omaha NB
Flexible Foam	Cairo IL*	General Foam	Bridgeview IL*
Products (Ohio	Chattanooga TN*		E. Rutherford NJ*
Decorative)	Elkhart IN		West Hazelton PA*
	Houston TX		Paramus NJ
	Mansfield TX		
	Spencerville OH*	General Foam of	St. Paul MN*
		Minnesota	
Florifoam	Miami FL	Great Western	Orange CA
		Hickory Springs	Americus GA*
			Commerce CA*
			Cookeville TN
			Ft. Smith AR*
			Hayward CA
			Hickory NC*
			Portland OR
			Verona MS*

Table 2.4 (Cont'd.)

U.S. FLEXIBLE POLYURETHANE SLABSTOCK PLANTS

<u>Company</u>	<u>Facility Location</u> ^a	<u>Company</u>	<u>Facility Location</u> ^a
Lear Siegler	West Chicago IL*	Trinity Foam of North Carolina	High Point NC*
Leggett & Platt	Brenham TX* Cold Water MS* High Point NC* Moonachie NJ Newburyport MA Tupelo MS*	Woodbridge	Chattanooga TN*
		W.T. Burnett & Co.	Baltimore MD Jessup MD
NC Foam	Mt. Airy NC*		
Olympic Products (Cone Mills)	Greensboro NC Tupelo Ms		
Penn Foam	Raubsville PA ^b		
Plastaner	Livonia MI		
Prestige	Ashboro NC*		
Rectical Foam	Leroy NY LaPorte IN* Morristown TN*		
Scottdell, Inc.	Swanton OH		
Superior Products	Plantersville MS		

^a

* indicates the plant employs METH as a blowing agent.

^b

There was a fire in this plant and it is currently not operating.

Sources: U.S. EPA (1988); Panullo and Nash (1986); Industry Sources.

- 19 -
Table 2.5

SOUTHERN CALIFORNIA FLEXIBLE POLYURETHANE
SLABSTOCK PLANTS

<u>Company</u>	<u>Facility Location</u> ^a
Crain Industries	Compton, CA*
E.R. Carpenter	Riverside, CA*†
Foamex	San Bernardino, CA*
Future Foam	Anaheim, CA†
Great Western	Orange, CA†
Hickory Springs	Commerce, CA*

a* indicates the plant employs METH as a blowing agent.

† indicates the plant employs TCA as a blowing agent.

Table 2.6

PROFILE OF SURVEYED PLANTS

PLANT	ANNUAL FOAM PRODUCTION (thousand mt)	ANNUAL BLOWING AGENT USE (mt)
#1	4,500	272
#2	9,000	454
#3	4,500	272

Table 2.7
FOAM MARKETS OF SURVEYED PLANTS

MARKET	PLANT #1	PLANT #2	PLANT #3
		PERCENT	
Furniture	70	50	40
Carpet Underlay	-	20	15
Bedding	10	10	35
Transportation	-	15	-
Miscellaneous ^a	20	5	10

^aIncludes medical pads, packaging and quilting.

thousand mt of foam and use between about 100 and 200 mt of blowing agent each year. Small firms produce less than 2.3 thousand mt of foam or 100 mt of blowing agent annually. The three plants surveyed are in the large size range.

Equipment used by small and large foamers is similar because the buns are all of the same size. The difference is that the small foamer may operate the plant for only an hour each day for three or four days a week whereas a very large foamer may operate a full 8-hour shift or a full five days a week (Palmer et al, 1980; Industry Source). Many foam plants cannot operate eight hours per day because of space limitations in the curing and storage area.

RESULTS OF VISITS/SURVEYS

SRRP staff visited or surveyed in-depth three slabstock foam plants, tow of them in California and one in North Carolina. All three plants used CFC-11 as an auxiliary blowing agent. Table 2.6 shows the profile for these plants--the amount of foam produced and the level of blowing agent use. These plants together account for about 3 percent of the nationwide slabstock foam production and about 4 percent of the blowing agent use. The two California plants represent one-third of those located in Southern California.

Table 2.7 illustrates the product lines for each of the three foam plants. Each plant sells a significant fraction of foam to the furniture industry, the largest use indicated in Table 2.3. Only two of the plants sell to the carpet underlay market--the second largest foam end use in Table 2.3.

As mentioned earlier, about 40 percent of the foam produced today is blown solely with water. Plants #1 and #2 produce 15 and 20 percent of their foam respectively only with water, whereas plant #3 produces much more--60 percent--with water alone. This variation is likely due to the difference in product mix (see Table 2.7) since plants #1 and #3 produce identical amounts of foam and use the same amount of auxiliary blowing agent.

Figure 2.3 shows the product mix for a typical slabstock plant. It indicates the percent of a particular plant output devoted to the production of foam with various IFDs at 25 percent compression. In effect, it shows the distribution of foams in terms of firmness. Traditionally, some foamers used pure METH for certain grades of foam and pure CFC-11 for certain other grades. Whereas some foamers used METH for foams down to 15 IFD, others use it for foams no softer than 30 IFD. Some foamers use a 50-50 blend of CFC-11 and METH supplied by the chemical producers (Mooz et al, 1982).

Figures 2.4, 2.5 and 2.6 display the product mix for the three surveyed plants. The distribution of Plant #1 is very like that of the typical plant shown in Figure 2.2. More than three-fourths of the plant output is in the range of 20 to 40 IFD. In contrast, Plant #2's product output is more diverse; only 55 percent of the plant output is between 20 and 40 IFD. Plant #3 has a reasonably diverse output as well.

FUTURE INDUSTRY TRENDS

As mentioned earlier, 18 thousand mt of METH and 6.8 thousand mt of CFC-11 were used in 1989 as auxiliary blowing agents in the production of slabstock foam. 5.2 thousand mt of METH is also used in the foam industry as a solvent to clean foam mixing heads and for other cleaning purposes in both slabstock and molded foam operations.

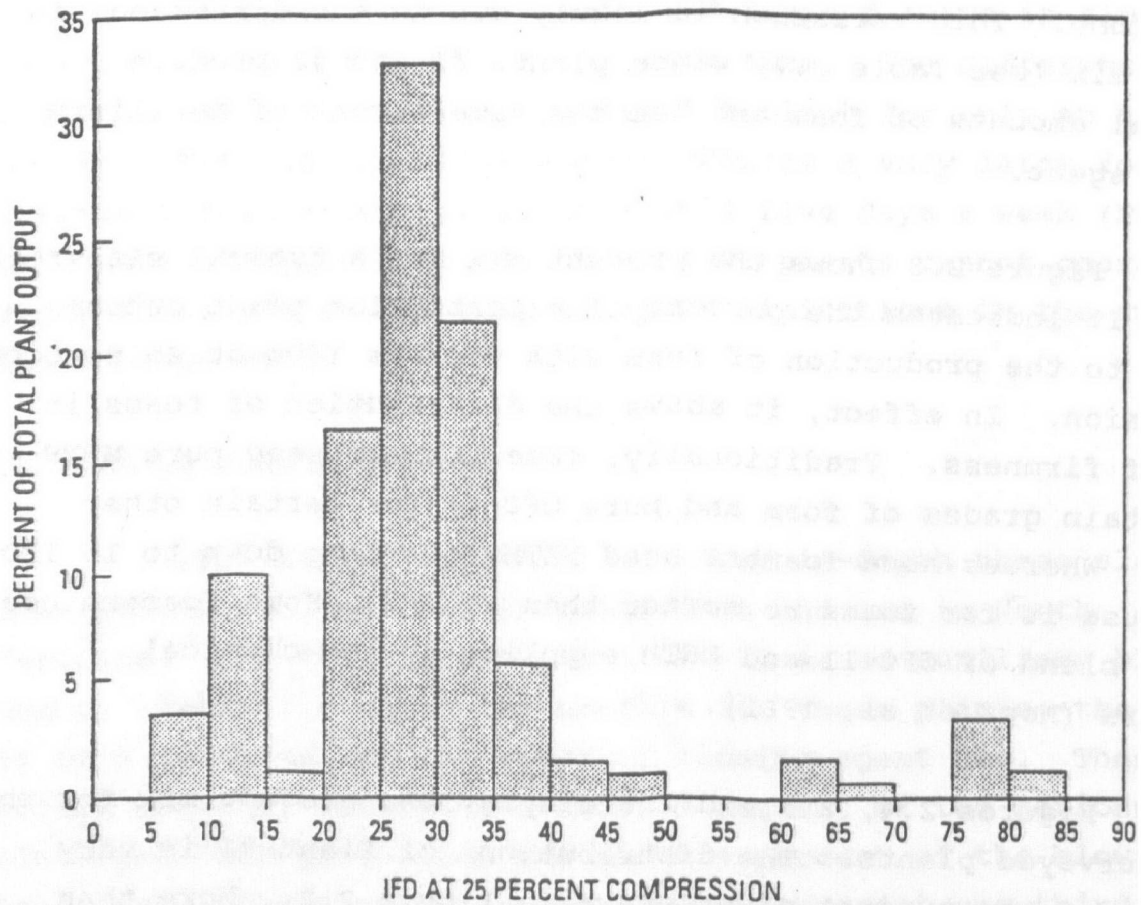
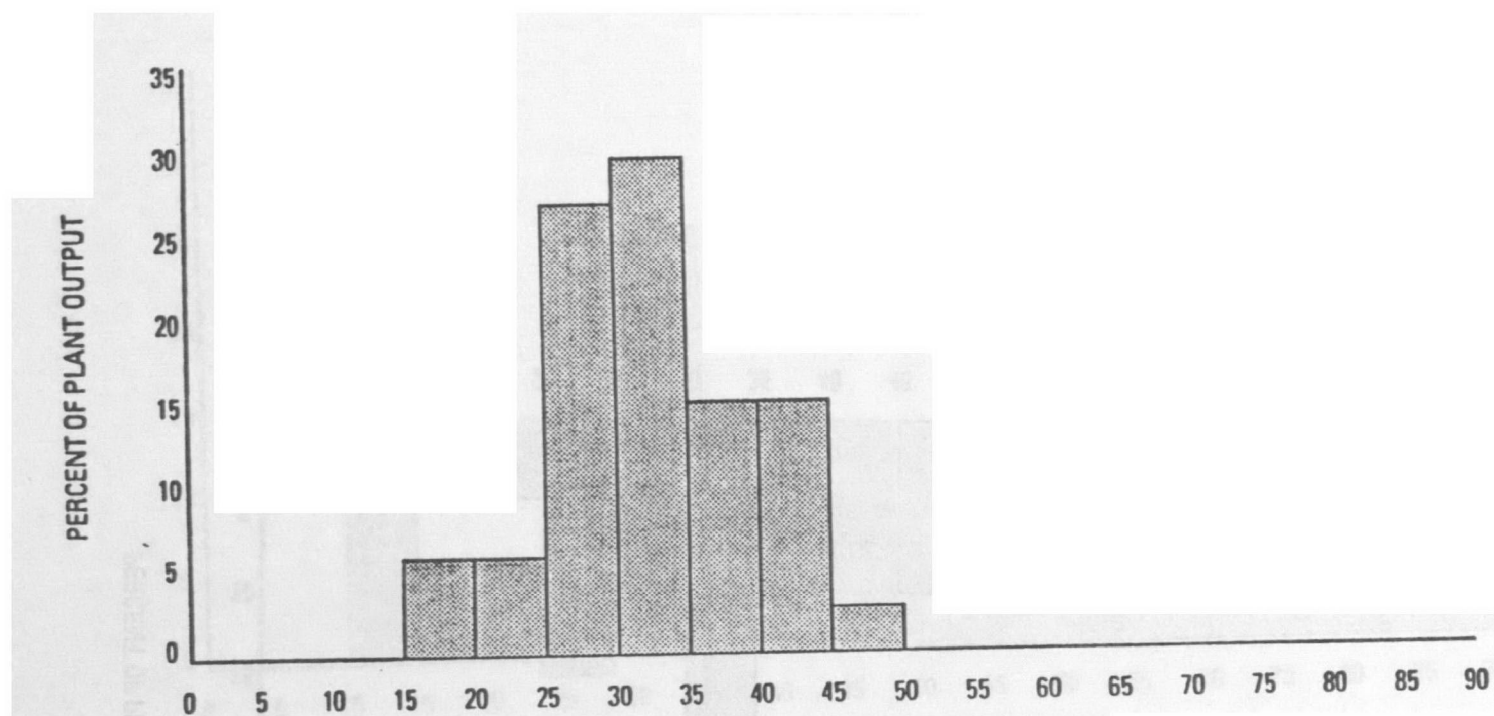


FIGURE 23
PRODUCT MIX OF A TYPICAL SLABSTOCK PLANT

SOURCE: MOOZ et al, 1982



IFD AT 25 PERCENT COMPRESSION

FIGURE 2.4
PRODUCT MIX FOR PLANT #1

SOURCE: S. R. R. P. SITE VISIT

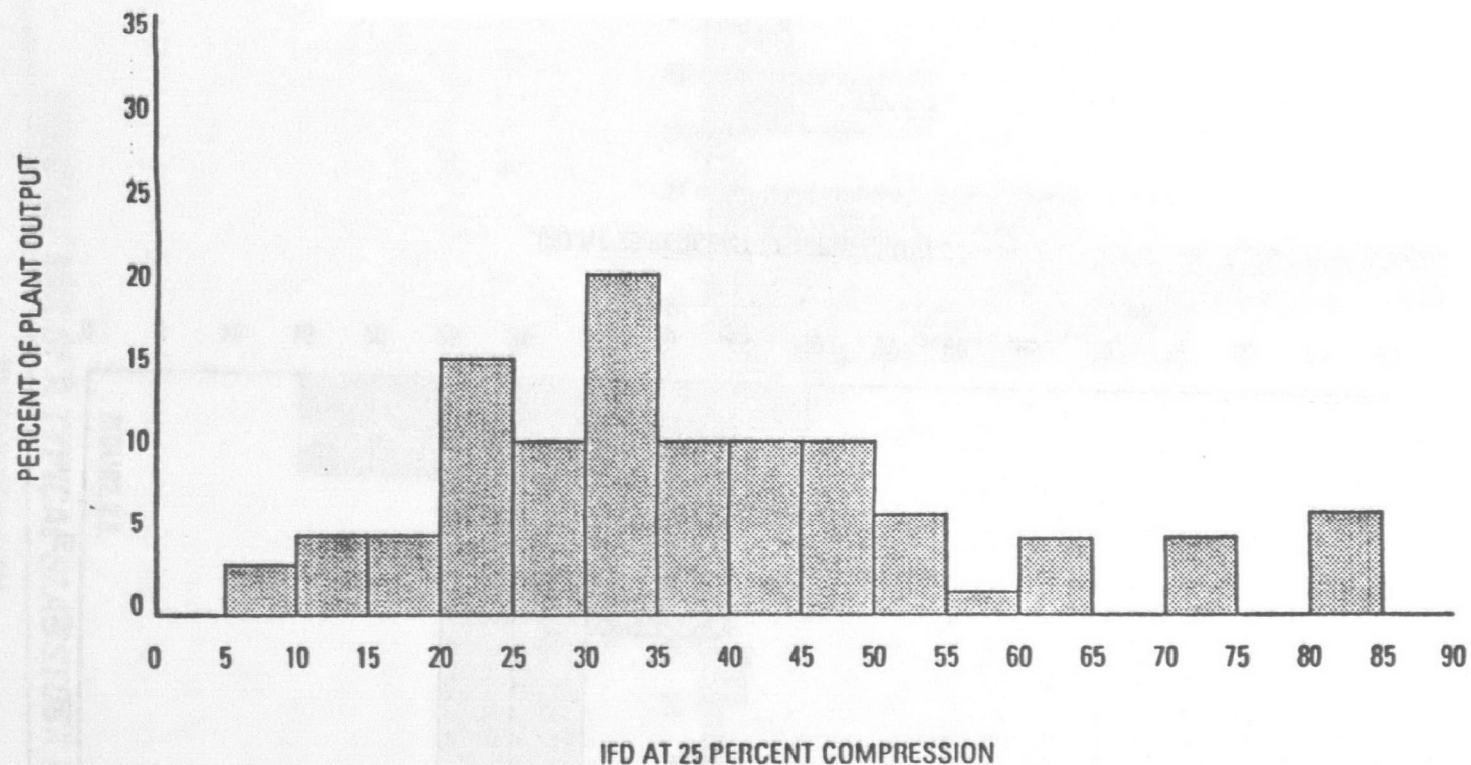


FIGURE 2.5
PRODUCT MIX FOR PLANT #2

SOURCE: S.R.R.P. SITE VISIT

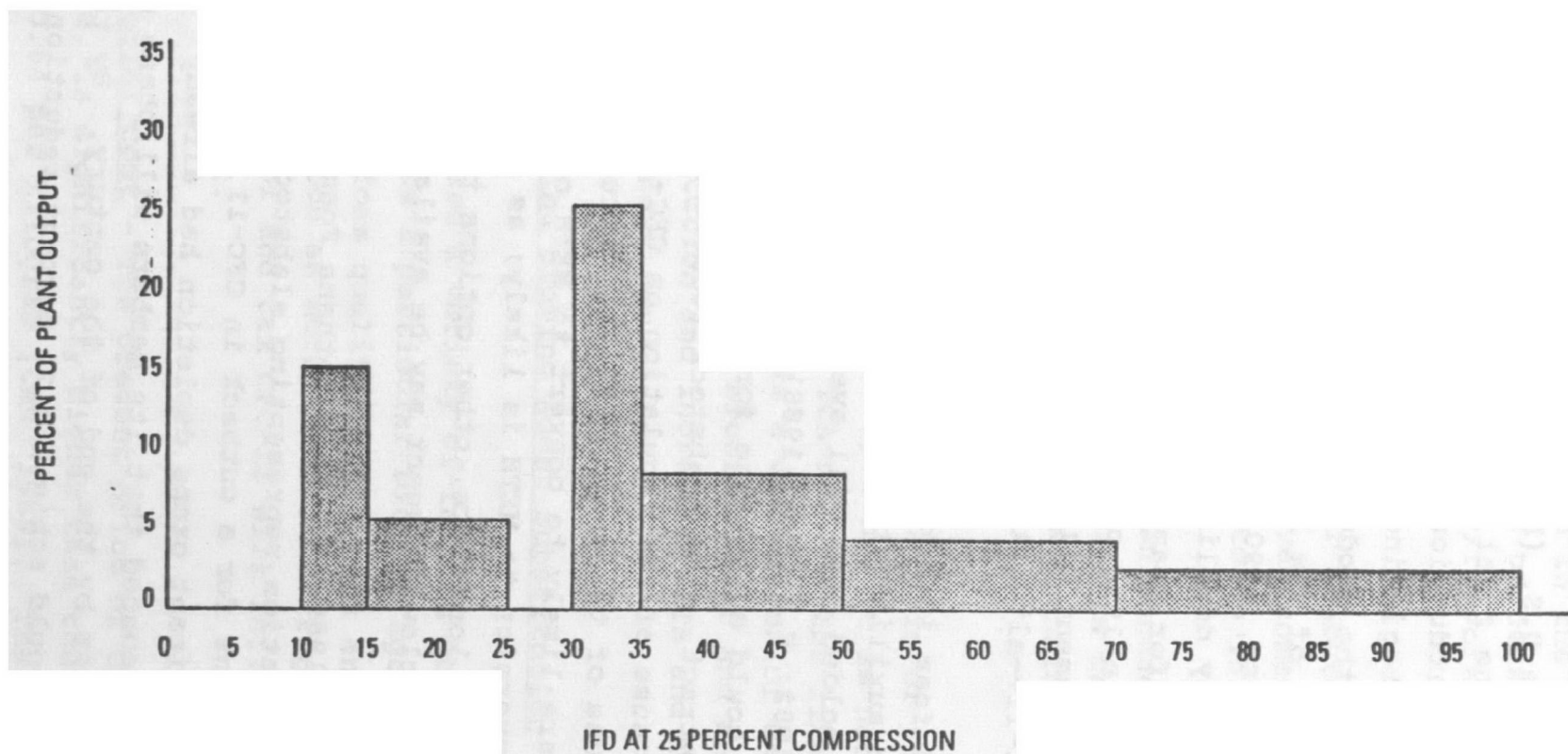


FIGURE 2.6
PRODUCT MIX FOR PLANT #3

SOURCE: S.R.R.P. SITE VISIT

In September of 1987, the U.S. signed the Montreal Protocol, an international agreement to limit production of ozone depleting substances (Montreal Protocol, 1987). On December 14, 1987, EPA proposed a domestic regulation that would implement the Montreal Protocol in the U.S. (Fed Reg, 1987). In August of 1988, EPA promulgated the final regulation (Fed Reg, 1988). This regulation capped the production of CFC-11, a fully halogenated CFC, at the 1986 level beginning in July, 1989. It specifies that in 1993 and 1998, the production level will be reduced to eighty percent and half of the 1986 production level respectively. In January, 1990, a Congressional tax was placed on CFC-11, approximately doubling its price. This has made it increasingly expensive for foamers to use CFC-11. At an international meeting in 1990 on ozone depleting substances, it is likely that an agreement will be reached to phase out CFCs--including CFC-11--altogether by the end of the century.

The molded foam industry has almost completely moved away from use of an auxiliary blowing agent. It is estimated that virtually all molded foam will eventually be "water blown" (Carroll and Ziv, 1982; U.S. EPA, 1988). In any case, it is unlikely that METH could substitute for CFC-11 in molded foam production. In contrast, some slabstock foamers have converted to METH and TCA because of the regulation on CFC-11. In the next year, largely because of the tax on CFC-11, virtually all slabstock foamers are likely to convert to METH or TCA. In the short-term some conversion to METH is likely; as discussed in the next section, over the long-term, other options that reduce the need for an auxiliary blowing agent may be available.

In February, 1989, the Polyurethane Foam Association (PFA)--a trade organization representing slabstock foamers--announced plans for a cutback in CFC-11 use in the light of reports that significant ozone depletion had already occurred. The PFA announced that its members will phase out the use of CFC-11 altogether by the end of the century. By the end of 1989, the members would achieve a 20 percent reduction from

1986 levels (PFA, 1989). The PFA said that elimination of CFC-11 would be achieved through adoption of alternative HCFC blowing agents (see chemical substitution in the next section), alternative foam chemistries (see process modification/additives in the next section) and recovery/recycle (see recovery and recycle in the next section).

Another blowing agent for slabstock foam, TCA, has been recently tested and adopted by seven commercial plants. By the end of 1990, there are projected to be 15 to 20 plants using TCA.

One foam producer has been conducting trials with acetone as a blowing agent. Acetone is cheaper than the other blowing agents and the producer is planning to patent and adopt this process in several plants.

In order to perform an analysis of the potential offered by various source reduction options, it is necessary to know the present level of METH and TCA use and the likely use in the next few years. What follows is a discussion of the factors that influence the choice of a blowing agent and an estimate of the level of substitution and increased METH and TCA use that could occur over the next few years.

Factor Influencing Blowing Agent Substitution

There are a variety of factors that have influenced foamers to choose a particular blowing agent. These include raw material cost, foam quality, scrap rate and ventilation levels. Other factors such as more restrictive regulations on METH and the regulation of and tax CFC-11 will influence the future choice of blowing agent.

Raw Material Cost - The present price of CFC-11, about \$1.76 per kilogram, is significantly higher than the price of METH, at about \$0.64 per kilogram (CMR, 1989). The Congressional tax raises the price of CFC-11 even higher, to \$4.78 per kilogram.

Because METH has a lower molecular weight than CFC-11, only 90 to 95 percent of the blowing agent is required to accomplish the same foam expansion. Roughly the same amount of TCA and CFC-11 are required because their molecular weights are nearly equal.

Since the blowing agent accounts for 5 to 15 percent of the total raw material costs in slabstock production, there has traditionally been a significant cost advantage to using METH in place of CFC-11. This is offset to some extent by an increase in the catalyst requirement with METH. In Table 2.1, for instance, formulations 2 and 6 have essentially identical densities and IFDs. Only 20 php METH is necessary in formulation 2, compared with 25 php CFC-11 in formulation 6. Although slightly more amine catalyst is required in the CFC-11 formulation, significantly more stannous octoate catalyst is required for the methylene chloride formulation. Because the blowing agent volumes are much higher than the catalyst volumes, however, on balance the raw material cost for the METH formulation would be lower. Although actual cost savings would depend on the foam grade, estimates of the savings with METH are estimated to 2 to 4 percent (Mooz et al, 1982) and 6 to 12 percent (Industry Source). In the last several years, many foamers have converted from CFC-11 METH.

The current price of TCA is \$0.91 per kilogram. TCA will be a more expensive blowing agent to use because of its higher price and because of its higher molecular weight somewhat more TCA than METH will be required to produce an equivalent amount of foam. If cost were the only determining factor, foamers would choose METH over TCA as a blowing agent. Because of the new tax on CFC-11, all foamers will convert as quickly as possible from CFC-11 to METH or TCA.

Foam Quality - Many foamers claim that a better quality foam can be produced using CFC-11 even though there have been substantial improvements in catalyst and polyol technology for use specifically with METH. In particular, the softer low density foams have traditionally been made with CFC-11.

Scrap Rate - It is not clear whether there is actually a higher scrap rate with METH, although some foamers insist this is the case. Foam production rates may amount to as much 1,000 pounds per minute. The cost for increased scrap production could be prohibitive but probably would not be a factor with experience.

Ventilation Levels - The Permissible Exposure Level (PEL) in the workplace of CFC-11 is 1,000 ppm. In contrast, the PEL for METH set by law is 500 ppm. The Occupational Safety and Health Administration (OSHA) will shortly issue a new standard for METH and it is expected to be in the 25 to 50 ppm range. The PEL of TCA is 350 ppm.

The lower PEL requirement for METH will not make a difference on the foam line itself where ventilation levels are already high to dilute the TDI in the foam formulation. As indicated earlier, this chemical has a PEL of 0.005 ppm. One estimate suggests that between one-third and half of the blowing agent is emitted during bun curing and storage in the curing area. The curing area in many foam facilities may not presently have sufficient ventilation to accommodate a conversion from CFC-11 to METH, particularly with the expected lower PEL. Providing additional ventilation could be costly. A conversion to TCA which has a higher PEL would require less ventilation, but would impose additional raw material costs. Many Southern California producers cure and store the buns outside.

Other Regulations - The Consumer Product Safety Commission (CPSC) has required certain consumer products containing METH to carry a label. The chemical has shown increased tumor incidence in some animal tests (NTP, 1986), although the validity of the results remain controversial. EPA is considering listing METH under Section 112 of the Clean Air Act as a hazardous air pollutant. California lists METH under Proposition 65 and has recently classified the material as a toxic air contaminant.

In Southern California, the South Coast Air Quality Management District (SCAQMD) recently passed a rule requiring foamers to reduce their blowing agent use by 40 percent by the end of 1992 (SCAQMD, 1989). This reduction can be accomplished through vapor recovery or through use of an exempt blowing agent.

Many other states across the nation are examining whether to list METH as a toxic air contaminant. In New Jersey, for example, a tough law capping the emissions at a specific level is in place. Texas is trying to discourage emissions of METH. According to one industry source, virtually all foamers in Texas and New Jersey are converting or have converted from METH to CFC-11. In Table 2.6, there are 7 foam plants in Texas, and only two of which use METH. There are two plants in Texas, Jersey and both use CFC-11. In California, the recent listing of METH as a toxic air contaminant will likely cause foamers to convert away from METH. In these three states, because of regulatory pressure on METH and federal regulatory pressure and tax on CFC-11, foamers are likely to convert to TCA.

Estimate of Future Blowing Agent Use

All of the factors discussed here have influenced the choice of blowing agent in the past and will influence the choice in the future. During the 1970s, virtually all foamers used CFC-11. In the late 1970s and early 1980s, many foamers converted to METH. Catalyst packages for use with METH were improved so that foam quality was high and there was a slight raw materials cost advantage to using METH.

In 1987, the Montreal Protocol was signed and in 1988, EPA passed a regulation that capped the production level of CFC-11 at the 1986 level in July of 1989. About that time, TCA was found to be an adequate blowing agent and successful commercial trials were conducted. In January of 1990, Congress placed a heavy tax on CFC-11 and later in the year, it was expected that an agreement would be reached to phase out CFC-11 altogether by the end of the century.

The tax made CFC-11 more expensive and 11 foamers using it either have converted to other blowing agents or will convert by the end of 1990. The first choice of most foamers would be METH. The chemical is less costly than TCA and somewhat less of it is required to produce an equivalent amount of foam. In many states, however, local government agencies will not grant permits to use METH. In such cases, the foamers will convert to TCA. As mentioned earlier, one foam producer is using acetone in one plant. The substance is photochemically reactive and many states would not be likely to grant a permit for its use without air emission controls. It is less expensive than other blowing agents, however, and this producer will probably eventually convert five plants. In the light of all these factors, Table 2.8 presents SRRP staff estimates of the status of the foam industry by the beginning of 1991.

The values show that there will be 57 plants using METH nationwide, 19 plants using TCA and 5 using acetone. In Southern California there are presently four plants using METH and the other two have or will convert to TCA.

Table 2.9 compares current blowing agent use with the SRRP staff estimates of the blowing agent use in the beginning of 1991. Total blowing agent use in the beginning of 1991. Total blowing agent use will decline slightly because some CFC-11 foamers will convert to METH; the latter blowing agent is more efficient. The values of Table 2.9 demonstrate that Southern California blowing agent use in early 1991 will account for about 8 percent use. This represents 7 percent of nationwide METH use and 13 percent of nationwide TCA use.

Table 2.8

PROJECTED STATUS OF FOAM INDUSTRY - 1991

Blowing Agent	NUMBER OF PLANTS	
	In U.S.	In Southern California
METH	57	^a 4
TCA	20	2
CFC-11	0	0
Acetone	5	0
Total	82	6

^a

One of the Southern California plants uses both METH and TCA. It is categorized in the METH column.

Table 2.9

CURRENT AND FUTURE BLOWING AGENT USE

	BLOWING AGENT USE (thousand mt)				
	CFC-11	METH	TCA	Acetone	Total
U.S.					
1989	6.8	18 ^a	0 ^b	0 ^c	24.8
1991	0	19.53	5.89	1.23	26.65
Southern California					
1989	0.541	1.38	0	0	1.92
1991	0	1.38	0.71	0	2.09

^a

Assumes an average CFC-11 plant use and that the METH requirement will be 90 percent of that for CFC-11.

^b

Assumes requirement for TCA is 30 percent more than that of CFC-11.

^c

Assumes requirement for acetone is 42 percent that of CFC-11 and 68 percent that of METH.

Source: SRRP staff estimates.

III. SOURCE REDUCTION OPTIONS FOR SLABSTOCK FOAM BLOWING

This section discusses five classes of source reduction options: product substitution; chemical substitution; equipment modification; process modification and recovery and reuse of chlorinated solvents. Most of the chlorinated solvent losses in foam production are in the form of atmospheric emissions and all losses occur before the foam leaves the plant. All source reduction options, therefore, focus on reducing emissions (or use) of the chlorinated solvent with the exception of the recovery options, no options that involve liquid or solid waste are examined.

PRODUCT SUBSTITUTION

Two options for product substitution are analyzed. They include substitution of non-polyurethane foam alternatives and implementation of a requirement for minimum foam density. Each of these options changes the form or type of product that is ultimately produced.

Non-polyurethane Alternatives

There are a variety of products that have been used in the past or are used today in place of flexible slabstock foam. They include substitutes like cotton batting, coil springs, and rubberized horsehair that were used before flexible foam was developed. Other options like natural or synthetic fiberfill and latex or rubber foams are in use today to some extent. There is only one producer of latex and rubber foams in the U.S. and one industry source indicates the process is very costly and it generates large volumes of contaminated effluents. Still other products, like porous plastic or semiflexible foams are not yet in development (U.S. EPA, 1988).

Some of these products are competitive with flexible foams in certain markets. Natural and synthetic fiberglass and latex foam, for instance, are competitive with flexible foam in

the rough underlay sector. One source estimates that the introduction of non-flexible foam cushioning material might reduce emissions of CFC-11 blown foam by 5 to 15 percent (U.S. EPA, 1988). However, because of flexible foam advantages, a significant substitution is likely to occur only if a regulation requiring it is passed.

Minimum Density Foam

Generally, more blowing agent is required to produce low density foams than high density foams. This is apparent from a comparison of columns two and three or columns five and six of Table 3.1. Even in high density foams, however, significant levels of auxiliary blowing agent are required to make soft foams. Specifying a minimum density foam limit would reduce the amount of auxiliary blowing agent required in the production process. The reduction achievable would depend on the density limit that was chosen. As mentioned earlier, the regulatory pressure may cause foamers to reduce their blowing agent use. To do this, most of them may simply stop producing the lower density foams altogether. This would primarily affect CFC-11 which has historically been used for low density soft foams, but would almost certainly affect METH and TCA as well.

This strategy offers advantages and disadvantages. In the furniture market, for example, higher density foams frequently are of better quality and are more durable. Indeed, the lowest density foams in this application area are used in lower priced furniture. Higher density foam would be more costly because more polyol and isocyanate catalyst would be required per unit volume of foam output. Thus, although the foam would have greater durability, it would be more expensive as well. In furniture, however, the cost of the foam itself does not significantly influence the price of the final product. In this market, the requirement for minimum foam density would result in a more expensive, but more durable piece of furniture.

Table 3.1

PROPERTIES OF CURRENT AND PROPOSED BLOWING AGENTS

Chemical	Molecular Weight	Boiling Point (degrees C)	Vapor Pressure at 25 degrees C (mm Hg)	Gas Efficiency ^a (Percent)	Solvent Strength
METH	84.9	39.8	400	38-50 ^b	High
CFC-11	137.4	23.8	792	55	Low
HCFC-123	153.0	28.7	685	50	Low to Moderate
HCFC-141b	116.9	32.0	600	45	Low to High
HCFC-133a	118.5	6.1	NA ^c	40	High
TCA	133.5	74.1	135	NA	High
Acetone	58.08	56.2	227	NA	NA

^a Percent of total theoretical vapor converted to foam cell void volume.

^b Use of appropriate catalysts increases this value to nearly 50.

^c NA is not available.

Sources: DuPont (1980); DuPont (1986); Ostrowski (1989).

One source estimates that 30 to 50 percent of the CFC-11 emitted from slabstock foam production could be eliminated through specifying a minimum density standard (U.S. EPA, 1988). An industry source believes the number is much lower--perhaps 10 to 20 percent. Since much less METH than CFC-11 is used in the lower density formulations, the reduction in METH that is possible would be significantly smaller. Again the reduction that could be achieved would depend on the density level that was chosen.

CHEMICAL SUBSTITUTION

There are several substitutes that have been proposed to replace METH as the auxiliary blowing agent in slabstock foam. One of these--CFC-11--will be banned by the end of the century. Two others--TCA and acetone--have recently been adopted by a few foamers. Others, discussed below, would not be available for several years.

Certain properties of these other chemicals are compared with those of METH and CFC-11 in Table 3.1. In general, to be a viable candidate for substitution, a blowing agent must have certain characteristics. It must not react with foam ingredients and it must not dissolve the polymer. Its boiling point should fall within a certain range and it must have adequate gas efficiency (ability to create open cell volume). Other desirable qualities are that the substitute pose minimal damage to human health and the environment.

CFC-11

The current regulatory status of CFC-11 was discussed in the previous section. In principle, CFC-11 could completely replace METH and TCA in flexible slabstock foams applications. A number of previous studies have looked at the cost and technical feasibility of substituting METH for CFC-11 as the auxiliary blowing agent (Palmer et al, 1980; Mooz et al, 1982; Hammitt et

al, 1986; Camm et al, 1986; U.S. EPA, 1988; U.S. EPA 1987). Such studies implicitly contain the analysis of the reverse substitution--CFC-11 for METH. There is now a consensus that CFC-11 depletes the ozone layer and the chemical will be phased out by the end of the century. CFC-11 substitution is therefore not a good option for reducing or eliminating emissions of METH and TCA and it is mentioned here only for completeness.

Acetone

This blowing agent was investigated by a chemical producer in the past. It is now undergoing a commercial trial and the foam producer plans to license it. Apparently acetone is a technically suitable blowing agent.

There are some disadvantages to its use, however. It is flammable and this could pose a problem in the curing and storage area because about half the blowing agent remains in the foam at that stage. The facility would have to be made explosion proof and insurance costs would almost certainly be higher. Acetone is also photochemically reactive and some air districts might not allow its use without air emission controls.

The molecular weight of acetone at 58.08 is much lower than that of METH. Only about 70 percent as much acetone as METH would be required to blow an equivalent amount of foam. The price of acetone--\$0.64 per kilogram--is identical to that of METH.

Hydrochlorofluorocarbons (HCFCs)

Because CFC-11 is under intense regulatory scrutiny, there have been significant resources devoted to identifying potential alternative blowing agents. The CFC producers have been and are particularly active in this regard and they have identified three HCFCs that have properties suitable for a blowing agent (DuPont, 1986; DuPont, 1980). In addition to the

required technical characteristics, alternatives should have low acute toxicity, low chronic toxicity, low or no flammability, they must not contribute to ozone depletion in the upper atmosphere, and they must not contribute to ozone depletion in the upper atmosphere, and they must not contribute significantly to photochemical smog formation in the lower atmosphere. The CFC producers have identified two chemicals that hold promise as future substitutes for CFC-11 and, by extension, METH and TCA. Work on a third candidate was discontinued because it was embryotoxic. Table 3.2 compares the health and environmental characteristics of METH, CFC-11, TCA, acetone and the HCFC blowing agents.

HCFC-123 - This chemical, HCFC-123 or 1,1-dichloro-2,2,2-trifluoroethane, contains chlorine but is not fully halogenated. CFCs that are not fully halogenated contain hydrogen which makes them less stable. As a consequence, they have shorter atmospheric lifetimes and break down more readily in the lower atmosphere. HCFC-123, because it is not fully halogenated, probably does not cause significant ozone depletion and recent estimates place the ozone depletion potential at 2 percent that of CFC-11 (DuPont, 1988).

A shorter atmospheric lifetime suggest that HCFC-123 could contribute to the formation of photochemical smog in the lower atmosphere. However, the available data suggest that the lifetime is long enough that photochemical reactivity will not be a problem. In fact, EPA has published a rule exempting the chemical as a smog contributor (Fed Reg, 1989).

HCFC-123 does not appear to be acutely toxic but DuPont suggest an internal exposure level of 100 ppm for the chemical which is fairly low. The CFC producers worldwide have, together, initiated lifetime animal studies to determine if the chemical poses chronic problems. The results of these tests will not be available for three to four years.

Table 3.2

**HEALTH AND ENVIRONMENTAL CHARACTERISTICS OF
CURRENT AND PROPOSED BLOWING AGENTS**

Chemical	Ozone Depletion Potential ^a	Photochemical Smog	Flammable	Toxicity
METH	No	No	No	Under Evaluation
CFC-11	1.0	No	No	Low
HCFC-123	0.02	No	No	In Progress ^b
HCFC-141b	0.08	No	No	Weak Mutagen, In Progress
HCFC-133a	^c NA	NA	No	Embryotoxic
TCA	0.10	No	No	Low
Acetone	No	Yes	Yes	Low

^a Ozone Depletion Potential (ODP) is the capability of depleting ozone of one kilogram of the substance relative to a kilogram of CFC-11 which has a defined ODP of 1.0.

^b HCFC-123 and HCFC-141b are undergoing lifetime animal tests jointly sponsored by domestic and foreign CFC producers.

^c NA means not available.

Sources: DuPont (1980); DuPont (1986).

The properties of HCFC-123 are shown in Table 3.1. The boiling point is midway between those of CFC-11 and METH. Its vapor pressure also lies between that of CFC-11 and METH. Its solvent power is greater than that of CFC-11 but less than that of METH. HCFC-123 has been successfully tested in flexible foam production. The test results suggest that the alternative could be used in formulations containing CFC-11 today with only minor changes. One producer is building a commercial production plant for HCFC-123 and if the lifetime animal tests identify no problems, HCFC-123 will be produced on a commercial scale.

DuPont, the largest CFC producer, estimates a bulk price for the chemical of \$1.00 to \$2.00 per pound or \$2.20 to \$4.40 per kilogram (U.S. EPA, 1988). This can be compared with bulk prices for CFC-11 and METH of \$4.78, and \$0.64 per kilogram respectively (CMR, 1989).² The molecular weight of HCFC-123 is 153--higher than that of CFC-11 (137.4) and of METH (84.9). This indicates that, in principle, about 80 percent more HCFC-123 than METH would be required as an auxiliary blowing agent for a given amount of foam. In field trials, it has been found that up to 25 percent more HCFC-123 than theoretically expected was required to make foam with equivalent properties to that blown with CFC-11. The solvency of HCFC-123 is somewhat higher than that of CFC-11 and this is likely to be the reason for the higher requirement (Plastics Technology, 1989). This would increase the cost of using this expensive alternative even further.

EPA is considering a restriction or ban on 1,1,1-trichloroethane (TCA) because it contributes to ozone depletion. This latter chemical has an ozone depletion potential only one-tenth that of CFC-11 but its production level is very high. EPA may ultimately regulate other minor contributors to ozone depletion like HCFC-123 if they achieve widespread use.

² The CFC-11 bulk price includes the Congressionally mandated tax of \$1.37 per pound or \$3.02 per kilogram that became effective in January, 1990.

HCFC-123 like nearly all other halogenated chemicals, also contributes to global warming. The regulatory future of HCFC-123--which does contribute to ozone depletion and global warming to a small extent--is therefore in question before it has even been produced commercially. Because of the uncertainty of EPA's future actions on modest ozone depleters, the foam industry cannot look to HCFC-123 as a permanent solution.

Although HCFC-123 holds short-term promise as a substitute blowing agent, it probably will not be available for three or four years until animal testing is complete. Even if commercial production begins, the chemical will almost certainly be much more expensive than METH and it may also eventually be regulated. In spite of these drawbacks, the alternative could potentially reduce METH use and emissions in slabstock foam production by 100 percent.

HCFC-141b - This HCFC, 1,1-dichloro-1-fluoroethane, is not fully halogenated. It has a short atmospheric lifetime, indicating it will break down in the lower atmosphere. Like HCFC-123, HCFC-141b has been exempted as a smog contributor by EPA (Fed Reg, 1989). However, its ozone depletion potential is still relatively high--about 8 percent that of CFC-11--and, as mentioned earlier, EPA may eventually regulate it as an ozone depleter.

As indicated in Table 3.1, the boiling point and vapor pressure of HCFC-141b lie between those of METH and CFC-11. Although its solvency for polyurethane is higher than that of CFC-11, it is probably no more than that of METH. The molecular weight of HCFC-141b is higher than that of METH suggesting that roughly 40 percent more blowing agent would be required to produce the same amount of foam. In field trials, however, 17 percent less HCFC-141b was required than theoretically expected to make foam having equivalent properties to that blown with conventional blowing agents (Plastics Technology, 1989). One of the plants SRRP staff surveyed--Plant #2--has tried HCFC-141b in foam formulations and it apparently performed well.

One drawback of HCFC-141b is that its flammability limit is lower than that of METH and it is somewhat toxic. Flammability can impose additional dangers in the workplace and can increase costs for fire protection. The CFC producers are now sponsoring chronic tests on the chemical and results should be available in three to four years. Other problems are that it does deplete the ozone layer to a small extent and it has global warming potential. These two factors again suggest that EPA may eventually regulate the chemical.

There is an existing commercial production process for HCFC-141b. HCFC-1442b is produced today by Pennwalt for use as a propellant in perfume formulations. HCFC-141b can be coproduced with HCFC-142b using TCA as a feedstock (see the companion document on Intermediates). A second producer has announced it will build a plant. If the lifetime animal studies reveal no toxicity problems, production of HCFC-141b could be initiated immediately.

The flexible foam industry prefers HCFC-141b over HCFC-123 primarily because it will be cheaper and less of it is required to blow an equivalent amount of foam. The cost of using HCFC-141b will therefore be significantly less than the cost of using HCFC-123.

HCFC-133Aa - At one stage, HCFC-133a appeared to offer some promise as a blowing agent. Its properties, according to Table 3.1, illustrate that it would be an acceptable substitute. Although its boiling point is lower and vapor pressure higher than the other blowing agents, its boiling point is apparently within the acceptable range. In spite of the fact that it could prove to be an appropriate alternative technically, work has been discontinued on HCFC-133a because it is embryotoxic.

TCA - TCA has an ozone depletion factor about one-tenth that of CFC-11. EPA has not yet decided whether to restrict or perhaps ban TCA as an upper atmospheric ozone depleter. Because of its uncertain regulatory future, TCA's viability as an alternative blowing agent is in question.

A technical problem with TCA is its high boiling point, 74.1 degrees C, as indicated in Table 3.1. This is outside the range that is normally acceptable for blowing agents, a range of from 30 to 50 degrees C. In principle, TCA could be used because peak bun temperatures reach between 120 and 170 degrees C, but the higher boiling point can significantly delay volatilization. Dow chemical has done demonstration trials with TCA, foamers have performed commercial trials and all have been successful. In fact, to the surprise of many experienced foam experts, it turns out that the high boiling point does not present a major problem. The amount of catalyst used with METH needs to be changed slightly for use with TCA but the same catalyst that is used with METH is suitable. The chemical has been adopted by a few foamers and one of them reports that it is more difficult to make the low density foams with TCA than with METH. It is likely that adjustments to the polyols used with TCA will solve this problem in the future.

An issue that could arise with the use of TCA is its susceptibility to hydrolysis. If TCA comes in contact with water, it can decompose, forming hydrochloric acid which does corrode carbon steel equipment. Water is an ingredient in foam production (See Figure 2.1) but the water and blowing agent are not premixed so decomposition would not occur during the production process. As discussed later, the susceptibility to

hydrolysis would increase the cost of recovery of TCA vapors with carbon adsorption, if steam were used for desorption.

Because of its higher molecular weight, about 60 percent more TCA than METH is theoretically required to blow an equivalent volume of foam. One foamer indicates that, in practice, the number is lower, at 40 percent. TCA's current price--about \$0.91 per kilogram--is much higher than that of METH which is \$0.64 per kilogram. This would discourage conversion to TCA except in cases where regulatory pressure to reduce METH use is intense.

EQUIPMENT MODIFICATION

There are two equipment changes that might be effective in reducing blowing agent use. They include the Max-Foam process licensed by Unifoam AG and the Vertifoam process developed by Hyman International. As discussed later under the category of vapor recovery, both firms have developed recovery systems using carbon adsorption for use with their equipment.

Max-Foam Process

Max-Foam is a trough-feed process that produces a flat-topped bunstock that minimizes trim waste and increase the gas efficiency of the blowing agent (Edge-Sweets, undated a). Most foamers have apparently adopted this process and it has become the standard feedstock configuration.

One industry source suggest that nearly all foamers have converted to the Max-Foam Process. Another source estimates the number of plants that employ the process at 60 to 80. In fact, all three of the foamers the SRRP staff surveyed have converted to this process. It is probable that all foam plants will adopt the process in the next few years as they purchase new equipment.

One surveyed foamer indicated that the equipment is priced 20 percent higher than other equipment.

The reduction in METH use that could be achieved by the remaining plants adopting the Max-Foam process is very small although there appears to be disagreement on the magnitude of the potential reduction. One foamer surveyed by SRRP staff stated that there was no savings. A second foamer indicated that the savings in blowing agent use were not significant. The third foamer suggested that the savings in blowing agent use amounted to 10 percent. One knowledge industry supplier maintains that the process does not reduce blowing agent use at all.

Vertifoam Process

Forty-one Vertifoam machines had been installed worldwide by 1987 (Webb and Griffiths, 1987). There have been five Vertifoam units installed in the U.S. since 1982 and four of them are operating today. The process takes place in a vertical expansion chamber that is totally enclosed. Premixed feed is introduced at the bottom of this chamber and the rising foam is drawn up through the chamber. As the foam emerges from the top, slabs are cut (Edge-Sweets, Undated a; Edge-Sweets, undated b).

Because the METH emissions pass upward through the forming bun, the gas efficiency in the vertical system is improved over that of a conventional horizontal configuration. This increased efficiency and the fact that the METH emissions are better confined, are the major advantages of the Vertifoam system. Confining the emissions could also lead to better opportunities for recovery and reuse of the blowing agent (see the discussion of recovery below).

Retrofit of the systems in existing facilities is difficult because the equipment is 50 feet high and many facilities may not be able to accommodate that height. Furthermore, capital costs are higher than for conventional systems. One source claims that

raw material savings with the system range from 4 to 11 percent for CFC-11 (U.S. EPA, 1988). However, industry sources claim that the Vertifoam configuration does not reduce METH use at all and that the process is inefficient and ineffective except in small markets.

PROCESS MODIFICATION

There are two process modifications that could be effective in reducing or eliminating the requirement for METH auxiliary blowing agent. The first is a process that uses an alternative blowing agent which reduces the amount of auxiliary blowing agent that is necessary. The second involves modifications in the polyurethane foam and development of additives that could eliminate use of an auxiliary blowing agent.

"AB" PROCESS

This blowing method was developed by a Belgium firm, Kabel-und-Gummiwerke AG, and is licensed by a Swiss Firm, Innochem, S.A. The Alternative Blowing (AB) process employs formic acid (HCOOH) instead of water as the primary blowing agent. Instead of only carbon dioxide (CO_2) liberated in the traditional foam blowing process, in the AB process, the formic acid reacts with an isocyanate to produce equal volumes of carbon dioxide and carbon monoxide (CO) which then function as primary blowing agents. Because twice as much CO CO_2 is produced in the formic acid reaction, there is a lower requirement for an auxiliary blowing agent. A disadvantage is that the CO produced in the process is flammable and toxic posing a danger to workers.

Equipment costs for converting to this process were estimated at between \$5000 and \$10,000 in 1983 by the license (CMR, 1983). One former estimates the cost of conversion at \$10,000 to \$15,000 today for stainless steel equipment that is corrosion resistant. One industry expert believes these reported costs are

significantly underestimated, he estimates the total cost of conversion at \$250,000. Other costs would include operating costs and royalty payments to the licensee. Automatic monitoring equipment for detecting CO would also have to be installed. Raw materials costs would be significantly reduced since one kilogram of formic acid could replace 4 kilograms of METH (CMR, 1983). The current price of formic acid is \$0.88 per kilogram compared to a price of METH at \$0.64 per kilogram (CMR, 1989).

The process developers claim that AB formulations give equivalent density and hardness, but a significant reduction in the silicone surfactant level is required. Otherwise, the cells of the foam are too fine or overstabilized. Apparently, amine catalyst adjustment is also necessary (CMR, 1983). There are reports that the physical properties of the foam produced with this process are inferior. One industry source claims that foams of less than 1.2 pounds per cubic foot cannot be made using the AB process. He also estimates that use of the process might result in a reduction of 50 percent at most in blowing agent use. Another industry source estimates the use reduction at 25 percent.

There are no plants in this country that currently employ the formic acid process. Foamers are reluctant to take on the additional risks that come with use of formic acid and production of CO. The OSHA PELs of the two chemicals are very low--5 and 35 ppm, respectively. Although it could be argued that the presence of the TDI already mandates high ventilation levels, additional precautions would be required. CO emissions in the curing area would likely be high and increased ventilation would almost certainly be necessary. Furthermore, emissions of CO are regulated by EPA and local air districts. A significant investment might be required to tighten up the plant to lower CO emissions and an after burner may be required on the stack to oxidize the CO to CO₂. In addition, because formic acid is corrosive, foamers would have to install stainless steel equipment.

Polyurethane Modifications/Additives

There are a number of chemical modification options being examined that could eliminate the requirement for an auxiliary blowing agent. These include polyol modifications, extended range polyol modifications, and formulation modification/additives.

Polyol Modifications. Extended range HR (High resilience) polyols are being investigated by several firms. The HR technology is used today in the production of molded foam. Historically only about 5 percent of U.S. slabstock production--the higher density foams above 3 lb/ft³--uses HR formulations. This foam is primarily used in higher quality commercial furniture. With process changes, solely water-blown foams might eventually account for a somewhat larger fraction of the foam produced. However, the HR process is not especially promising for most slabstock foam operations since production of low density foams using the process is technically more difficult.

The second formulation modification involves a new polyol system under investigation at Union Carbide and other firms. Union Carbide's process is called Ultracel and it employs higher molecular weight polymers and requires the addition of diethanolamine which reduces the formation of ureas and improves froth viscosity and stability. The process might be capable of producing foams in the medium to high density range (1.5 to 2.5 lb/ft³) that are relatively firm, between 25 and 40 ILD. With this system, it is possible to vary the hardness of the foam by altering the amount of diethanolamine without using an auxiliary blowing agent (U.S. EPA, 1988). The process presently cannot produce the low density softer foams.

BASF has introduced a similar system which whips the chemicals into a froth before they polymerize. It is a water based process for producing foams down to 1.4 lb/ft³ densities (C&EN, 1989).

The third modified formulation is a system under investigation by Montedison S.p.A., an Italian firm. This system uses a special polyol that could produce very soft foams with densities down to 1.3 lb/ft³. Higher density foams with high softness could also be produced with this process without the use of an auxiliary blowing agent. Certain density foams, those below 1.3 lb/ft³, currently made with auxiliary blowing agent, could not be made with this system (Consoli et al, 1981; Consoli et al, 1984).

The fourth system was recently introduced by Union Carbide. An additive called Geolite is put into the foam formulation. It reduces the density and hardness of the foam so that it requires less auxiliary blowing agent. Again, it cannot eliminate auxiliary blowing agent use for all foam grades.

Although modified polyol systems such as those described here could ultimately reduce the use of auxiliary blowing agent significantly, they would probably be more costly. The increased cost of the new polyols would not be entirely offset by the lower blowing agent costs. Furthermore, the new foam chemistries cannot yet produce foams in the lower density range--below about 1.3 lb/ft³. These systems are still in the development stage, and commercialization is probably several years away. They do offer great promise, however, for significantly reducing METH use in flexible foam. In fact, foamers believe that alternate foam chemistries are one of the best alternatives over the long-term. Reformation to water blown foams for densities above about 1.3 lb/ft³ in conjunction with a minimum density limit could eliminate auxiliary blowing agent altogether.

RECOVERY AND RECYCLE

There are a variety of recovery techniques that can be considered for capturing METH from foam operations. These include liquid absorption, vapor condensation and carbon adsorption. The only one of these that has been examined

in-depth for use in flexible foam plants is carbon adsorption. There are two newer vapor recovery techniques that might also be used for recovery of METH. These include the Brayton Cycle Heat Pump technology and a membrane method. Each of these techniques is discussed below.

Liquid Absorption

Liquid absorption has been employed commercially to remove particular substances from gas streams. The soluble component in the gas mixture is transferred into a liquid absorbent. A good absorbent will not react with the sorbent and the boiling points of the absorbent and sorbent should differ significantly so that the two can be separated by distillation.

One study evaluated a system for recovery of METH in a slabstock plant using 1-hexanol (Farmer et al, 1987). Three cases of liquid absorption for a model plant producing 5,400 mt of foam and using 218 mt of METH annually were evaluated. It was estimated that the emissions (or use) of METH could be reduced by 32 to 45 percent. On this basis the control cost-effectiveness was placed at between \$2,800 to \$3,100 per metric ton of METH emissions avoided.

The disadvantages of this process include reactivity of hexane with the TDI in the stream to form urethanes which could foul the column and increase maintenance costs. Also, captured METH would probably not be directly reusable because the stabilizer additives would be depleted in the process. Liquid absorption has not yet been demonstrated at the pilot or commercial level for slabstock plants.

Vapor Condensation

This method involves refrigerating the gas stream below the dew point of the components. As the stream is cooled, METH and water will condense out. For optimal recovery of METH, the

stream should be chilled to -100 degrees F which would require use of CFC refrigerant. As mentioned earlier, the CFCs are likely to be phased out by the end of the century. The trace components in a flexible foam plant--the TDI and amines, for instance--could be condensed with the water, posing a waste water treatment problem. In contrast, the METH stabilizers may not condense with the METH and reblending would be necessary before the METH could be reused.

Farmer et al (1987) estimated the cost of vapor condensation using a model plant. They assumed a 28.5 percent recovery of the METH used in a plant producing 5,400 mt of foam and using 218 mt of METH annually. The cost-effectiveness considering only the capital cost was estimated at \$5,600 per mt of METH emissions avoided.

Carbon Adsorption

The feasibility of carbon adsorption for recovery of CFC-11 from flexible foam operations has been examined in a number of studies (Palmer et al, 1980; Mooz and Quinn, 1980; Mooz et al, 1982; Urano and Yamamoto, 1985; Camm et al, 1986; U.S. EPA, 1988). There was one pilot demonstration of carbon adsorption for CFC-11 recovery, but not in this country; (Axel Sporon-Fiedler, 1986, Nutt and Skidmore, 1987). In this experiment which took place in Denmark, the maximum blowing agent recovery was 40 percent which was achieved only after improvements to the foam line exhaust system were made. The system was heavily corroded and it was eventually dismantled. A commercial demonstration of CFC-11 was performed (Pauw, 1988). A collection efficiency of 40 percent was achieved, again only with exhaust system modifications. In the U.S., there was reportedly a test at a foam plant in 1968 which resulted in a 33 percent collection efficiency of CFC-11. There are no published data on this test and foam industry representatives are not familiar with the experiment. Various technical problems remain unresolved. No pilot or commercial demonstrations on flexible foam plants using METH have occurred.

Carbon adsorption using granular activated carbon (GAC) has been employed for many years to capture solvents before they are emitted to the atmosphere. GAC preferentially adsorbs organic molecules from a gas stream. When the carbon bed is heated, generally with steam, the organic material is desorbed and retained in the steam. After condensation, the organic molecules can be separated from the water for reuse. Alternatives to steam desorption, such as nitrogen, vacuum or hot air, are sometimes employed. Two carbon beds, one for adsorption and the other for desorption are typically used.

There are several major obstacles to implementing carbon adsorption in foam plants. First, capital costs of the system depend greatly on the volume flow of air in the plant. In flexible foam plants where high air flows are required to dilute the TDI, the cost of carbon adsorption would be substantial. Costs of recovery also depend on the amount of METH that can be captured in the airstream. For foamers who use CFC-11, between 70 and 90 percent of the emissions occur on the line. In contrast less METH, only 55 to 67 percent, is emitted on the line; the balance is emitted in the curing area. Thus, the efficiency of capture for METH would be lower than for CFC-11, and carbon adsorption costs would be correspondingly higher. Estimates of the CFC-11 emissions in foam plants that can be captured range from about 10 to 80 percent (U.S. EPA, 1988; Sporon-Fiedler, 1986; Nutt and Skidmore, 1987). Under pilot plant conditions, the actual percentage of the CFC-11 used that could be recovered was very low--in the 10 to 40 percent range, depending on whether or not the line had been modified for better collection of blowing agent (Sporon-Fiedler, 1986; Nutt and Skidmore, 1987). Because METH emissions are more dispersed throughout the plant, the capture rate for that chemical would probably be much less.

The second problem that arises in evaluating carbon adsorption in foam plants is the presence of TDI and amine catalysts which can deactivate the carbon (Urano and Yamamoto, 1985). These are present in the airstreams and the adsorbed TDI reacts with water to form urea residues that coat the carbon and resist regeneration. In one pilot study on CFC-11, the TDI irreversibly fouled the carbon bed which was projected to have a useful life of only three years (Farmer et al, 1987). One proposed solution is to use a sacrificial carbon bed between the foam tunnel and the main adsorbers to adsorb the TDI. The METH would bypass this bed and adsorb to the main beds and the TDI would remain on the front bed.

A third problem involves the question of whether the METH desorbed from the carbon bed could be reused directly without purification. There would be small amounts of other components like water and amines in the recovered blowing agent. It is necessary to employ a particular high purity METH formulation in foam blowing to guarantee that the foam is processed correctly and is not discolored. Furthermore, a stabilizer should be added to the METH and it would be dangerous for foamers to handle it in concentrated form. Thus, purification and reformulation of the blowing agent might require an expertise that foamers currently do not have.

A fourth problem that arises with carbon adsorption is that there are intermedia transfers--from atmospheric emissions to contaminated water and solid waste. The sacrificial carbon bed contaminated with TDI would require disposal or incineration if regeneration of the carbon were the chosen option. Indeed, these beds would contain insoluble urea residues formed in the reaction of TDI with water in the foam blowing process or from the steam. Waste carbon from foam operations has never been regenerated so it is not clear whether this option would be effective. If it were not, the carbon would pose a solid water disposal problem.

When steam is used for desorption, the water stream resulting from the desorption of the METH bed might contain unreacted ingredients and products. It may require treatment if local regulations prevented its release to the sewer. Regeneration of the carbon with a heated inert gas like air or nitrogen instead of steam is also an option. This would reduce the water contaminated problem.

There are two measures that might be taken in existing foam plants to improve the economics of recovery. First, the foam line could be better enclosed so the efficiency of capture of the METH was higher. Today, foam lines are "leaky" because of the high ventilation levels required to dilute the TDI while workers visually monitor the foam. It is not clear whether this efficiency could be improved by capturing the METH from the curing room as well as from the foam line. Enclosure of the curing area may be difficult, however, because of the presence of overhead cranes. A possible solution is to place the recovery system at floor level where most of the heavier than air METH leaves the buns.

One study estimated the recovery cost using carbon adsorption in a plant producing 5,400 mt of foam using 218 mt of METH annually (Farmer et al, 1987). This analysis assumed that modifications would have to be made in the plant to reduce the exhaust air flow so as to reduce the size of the carbon beds. As mentioned earlier, there are high ventilation levels in foam plants because of the TDI. Large volumes of air are drawn through the foam pouring equipment to dilute and withdraw vapors emitted during foam rise. The opening at the feed trough is frequently left open during production to allow the operator to view the process. Air flows are in the range of 5,000 to 30,000 cubic feet per minute. Ventilation levels in the curing area are lower because very little unreacted TDI is released at this point. The analysis assumed that modifications to the foam line would be made to reduce the exhaust air flow.

Assuming various net METH recovery efficiencies, Farmer et al (1987) estimated the carbon system recovery costs. In one case, which involved treatment of the exhaust from the foam tunnel, it was assumed that a 33 percent net METH recovery could be obtained. The control cost was \$2,900 per mt of METH. In a second case, with recovery of exhaust from both the foam tunnel and the curing area, the net efficiency was 48 percent and the cost was estimated at \$2,770 per mt. In a third case, treatment of the foam tunnel, curing area and bun saw exhaust hood would give a net recovery efficiency of 51 percent at a cost of \$4,290 per mt.

Recovery and reuse of METH using carbon adsorption holds only limited future promise since significant technical issues remain unresolved.

Brayton Cycle Heat Pump (BCHP)

The Department of Energy (DOE) has been supporting the development of the BCHP in conjunction with 3M and Garrett Air Research since 1978. The technique uses a reverse Brayton refrigeration cycle. It cools gas streams to very low temperatures--commonly -80 degrees F--and condenses the components for collection. The technique requires the use of a carbon bed with hot gas regeneration, and according to the manufacturer, the energy savings are significant and efficiencies are better than for other processes. This method has been demonstrated at 3M for solvent recovery on commercial sized magnetic tape manufacturing facilities (Nucon, 1989).

There are two thermodynamic advantages to this method. First, in the Brayton cycle an increased pressure is used. The dew point temperature of a substance in the gas stream increases as the gas pressure increases. This cycle operates more efficiently than other systems which condense the components at atmospheric pressure. Second, the Brayton cycle employed a turboexpander

where most of the work input to the compressor stages is recovered. A disadvantage is that water vapor will be present in the system. This water may react with or solubilize trace components like TDI and urea, remove METH stabilizers and present a wastewater treatment problem.

The BCHP has never been demonstrated in a foam plant for recovery of METH. One study did estimate the cost of this system in a plant producing 5,400 mt of foam and using 218 mt of METH annually (Farmer et al, 1987). The control costs were about \$2,800 per mt of METH recovered assuming a net recovery efficiency of 33 to 46 percent.

Membrane System

Another new system is being proposed to collect vapors from air streams. A semipermeable composite membrane is used to separate the organic solvent from air. The membrane modules allow a large membrane surface area to be picked into a small volume. Organic solvents are preferentially drawn through the membrane by a vacuum pump and the solvent is condensed and removed as a liquid. The firm manufacturing the membranes claims that comparison with carbon adsorption shows that the membrane process is more cost-effective if the solvent concentration is relatively high--0.5 percent or higher--and the airstream to be treated is small--between about 100 and 1,000 standard cubic feet per minute (Wijams et al, undated). This would pose problems in a foam plant where the METH concentration is low and the airflow is high. Capital costs of the systems are in the range of \$400 to 1,000 per standard cubic feet per minute of airflow (MTR, undated).

IV. SOURCE REDUCTION OPTIONS FOR SOLVENT APPLICATIONS

In earlier sections, it was mentioned that a significant amount of METH--5.2 thousand mt--is used annually for various solvent purposes in the flexible foam industry. One major use is to clean the foam heads that deliver the foam formulation ingredients in both slabstock and molded foam production. Another large use is to clean the molds in molded foam production.

SRRP staff surveyed or visited three slabstock manufacturers and one molded foam manufacturer for information on METH use for cleaning. Plant #1, described earlier, purchases 6.8 mt of METH annually for this purpose. The METH, after cleaning, is added to the CFC-11 and used as a blowing agent in the production of the slabstock foam. Plant #2 uses 18.1 mt annually to clean the equipment three times per day. The firm has on-site recovery and generates 4.5 mt of waste which is sent to an out-of-state disposal facility. The waste represents about 25 percent of purchases. Plant #3 uses 36.6 mt of METH for cleaning each year. The plant generates 30 mt of waste each year which costs about \$42,000 to dispose of. This level of waste seems high when compared with METH purchases, particularly since METH is volatile. The molded foam producer uses about one-half mt annually to clean the equipment once per day.

In this section, only recovery and reuse options are discussed. Although many other options could be applicable, the low use level did not warrant their detailed investigation.

RECOVERY AND REUSE

One of the foam plants we surveyed--Plant #2--uses an on-site recovery unit. It is a simple off-the shelf distillation unit with a plastic liner. The METH is separated from the contaminants for reuse in the cleaning process. The contaminated

sludge is sent off-site for disposal. Another foamer claims that the used METH contains polyurethane contaminants that interfere with the recycling process. Nevertheless, it does appear as if on-site distillation would be feasible; the polyurethane residue would simply remain in the sludge.

Another foamer reuses the spent METH directly in the blowing agent formulation. He claims that it works very well and that the contaminants--which would probably be solid polyurethane particles--do not interfere with foam production. Indeed, this technique appears to be a good way to reduce the virgin METH requirement for cleaning. A problem could arise particularly if the foamer used CFC-11 as a blowing agent. The catalyst package would be appropriate for CFC-11 and the presence of high quantities of METH could alter the foam quality or uniformity.

Off-site recycling of the spent METH might also be feasible. The foamer could send the spent solvent to the recycler and could purchase back recycled, instead of virgin solvent. One recycler we contacted was hesitant to take the METH from a foamer because he believed the spent solvent could contain TDI which he did not want to deal with because of its acute toxicity. In fact, however, a subsequent analysis of the spent METH revealed no TDI and, indeed, all of it should be reacted by the time the equipment is cleaned. Because the polyurethane could pose some processing problems, recycling the solvent for reuse in cleaning foam equipment would probably be more expensive than recycling solvent in traditional cleaning processes.

V. ANALYSIS OF SOURCE REDUCTION OPTIONS FOR FOAM BLOWING APPLICATIONS

A significant amount of METH--some 18 thousand mt--is used today as a blowing agent in slabstock foam manufacture. As discussed in the last section, there are a variety of options for reducing the use or release of METH in this process. In this section, the options are classified into three categories and the cost and blowing agent use reduction are estimated.

SELECTION OF BLOWING AGENT OPTIONS

SRRP staff has defined three categories of options as illustrated in Table 5.1. Options in column one are those that are not analyzed further. This category includes options that could achieve only small use reductions, options that have not been demonstrated, options that are either technically or institutionally infeasible, options that are already penetrating the market or options that have known potential or cost. The second column includes options for which a limited analysis was performed. These are options that appear to hold promise but for which the information on cost and blowing agent use reduction is incomplete.

Options in the third category, full analysis, are those that appear promising and for which the information on cost and use reduction is more complete. These options are examined in some detail for small, medium and large foamers. They include recovery and reuse of blowing agent and specification of a minimum density level for foam production.

"NO FURTHER ANALYSIS" OPTIONS

Table 5.1 shows the options that fall into this category. Non-polyurethane alternatives are competitive with foam in some products but greater substitution would change the

Table 5.1
Classification of Blowing Agent Options

NO FURTHER ANALYSIS	LIMITED ANALYSIS	FULL ANALYSIS
Non-polyurethane Alternatives Acetone Substitution		Specify Minimum Density Foam
CFC-11 Substitution	HCFC Substitution	Carbon Adsorption
TCA Substitution	TCA Substitution	
Max-Foam Process	Polyurethane Modifications/ Additives	
Vertifoam Process	Liquid Adsorption	
AB Process	Vapor Condensation	
Brayton Cycle		
Membrane System		
Polymeric Adsorption System		

nature of the product at perhaps a higher cost. Only small use reductions could be achieved. Even though acetone appears to be a promising substitution option, the information that would allow even a limited analysis is not currently available to the SRRP staff. CFC-11 will not be produced after the end of the century so it is not a viable substitution option. The Max-foam process is already used by most foamers and will be adopted by the rest in the next few years. It reduces blowing agent use only to a small extent, if at all. The Vertifoam process requires building modifications and may not reduce blowing agent use. The AB process is unlikely to be used in the U.S. because of the toxicity of formic acid and carbon monoxide. The membrane system and Brayton Cycle are undemonstrated. None of these options will be considered further.

"LIMITED ANALYSIS" OPTIONS

As Table 5.1 indicates, there are four options in this category. Each is separately discussed below.

HCFC Substitution

For purposes of this analysis, it is assumed that both HCFC-123 and HCFC-141b emerge from the lifetime animal tests with low or no toxicity and become available in 1993 to foamers. Further, it is assumed that HCFC's will not be regulated as ozone depleters by EPA and that HCFC-141b's moderate flammability does not pose a problem in flexible slabstock foam production.

As indicated earlier, there are 56 plants in the U.S. that together use 18 thousand mt of METH annually. In the next few years, that value may increase somewhat because of the regulation on CFC-11 but so will the number of plants using METH. There are five plants in Southern California that use METH. Nationwide, the average foamer uses 31 mt of METH each year.

As mentioned previously, because HCFC-123 has a much higher molecular weight than METH, about 80 percent more of the chemical would be required to blow an equivalent amount of foam. About 40 percent more HCFC-141b is required. The average foam plant will use about 580 mt of HCFC-123 and 450 mt of HCFC-141b annually.

The price of HCFC-123 is estimated at between \$2.20 and \$4.40 per kilogram; for analysis the midpoint at \$3.30 can be used. No estimates for the price of HCFC-141b could be obtained. \$2.00 per kilogram was assumed. These prices are much higher than the price of METH which is currently \$0.64 per kilogram.

It is conceivable that a blend of HCFC-123 and HCFC-141b might be employed. The nonflammable HCV-123 would suppress the moderate flammability of HCFC-141b. At the same time, the expected lower price of HCFC-141b would encourage use of as much of this chemical in the blend as possible.

Table 5.2 summarizes the results of substitution of HCFCs for METH. In the case of HCFC-123, the substitution would cost about \$5,300 per mt of METH emissions avoided. For HCFC-141b, the value would be less--about \$2,200 per mt. For the 50/50 mixture by weight of the two HCFCs, the cost is about \$3,700 per mt of METH emissions avoided.

It should be noted that these figures are likely to significantly underestimate the actual cost which would include the costs of reformulation and identification of appropriate catalyst packages. During reformation, the foam industry would experience dislocations and many foam runs could result in unusable foam. Thus, the actual cost for HCFC substitution could be substantially higher than the figures of Table 5.2 indicate.

Table 5.2

ANNUAL COST INCREASE AND METH EMISSIONS REDUCTION FOR HCFC SUBSTITUTION

HCFC	Average Annual Cost (million \$)			Annual METH Emissions Reduction (mt)		
	To Foamer	To Southern California	To Nation	To Foamer	To Southern California	To Nation
HCFC-123	1.7	8.5	95.3	321	1,605	18,000
HCFC-141b	0.7	3.5	38.8	321	1,605	18,000
Combination ^a	1.2	6.0	67.1	321	1,605	18,000

^a

Combination represents a 50/50 mixture by weight of HCFC-123 and HCFC-141b.

TCA Substitution

There is presently no information on the costs of the new TCA catalyst package; for this analysis, these costs can be ignored. The current price of TCA is about \$0.91 per kilogram which can be compared with a METH price of \$0.64 per kilogram (CMR, 1989). The molecular weight of TCA is about 60 percent greater than that of METH so the blowing agent use requirement will be correspondingly larger. Thus 28.8 thousand mt of TCA would be necessary to replace the 18 thousand mt of METH currently used. Nationwide the annual cost would be \$14.7 million or \$0.8 million per metric ton of METH emissions avoided. Table 5.3 summarizes the cost, the avoided METH emissions and the increase in TCA emissions that would accompany a conversion. A comparison of the values of Tables 5.2 and 5.3 demonstrates that TCA substitution is much cheaper than HCFC substitution.

Polyurethane Modification

The modified polyol systems offered by Union Carbide and the Italian firm, Montpolimeri S.p.A. hold promise for producing foams down to about 1.3 pounds per cubic foot without the use of auxiliary blowing agent.

The density range of these new polyol systems tends to be somewhat higher than for traditional systems. This would increase the raw materials cost. The polyols themselves are also more expensive. All of these factors will lead to an increased cost of the foam. Because these new technologies are still in the development stage, the cost of ultimately adopting them is unknown.

Only modest modifications to the feed delivery system would be required so plant equipment conversion costs would be

Table 5.3

ANNUAL COST INCREASE AND METH EMISSIONS REDUCTION FOR TCA SUBSTITUTION

	To Foamer	To Southern California	To U.S.
Average Annual Cost (million \$)	0.3	1.3	14.7
Annual METH Emissions Reduction (mt)	321	1,284	18,000
Annual TCA Emissions Increase (mt)	514	2,568	28,762

small. The major cost would be increased raw material and one source estimates that this cost would be in the range of 10 to 30 percent (Farmer et al, 1987). Using this cost range and assuming that 30 to 60 percent of the METH blown slabstock is affected and a reduction in the METH use per unit of affected foam is 50 to 100 percent, Farmer et al (1987) estimate a control cost-effectiveness of \$4,400 to \$45,000 per metric ton of METH emissions avoided. If one adopts the low estimate of \$4,400 per metric ton of emissions avoided and again assumes that the average plant uses 321 mt of METH annually, the results shown in Table 5.4 are obtained.

Liquid Absorption

Farmer et al (1987) estimated a cost of \$2,800 to \$3,100 per metric ton of METH emissions avoided for a liquid absorption system in a foam plant using 218 mt of METH each year. The average plant uses more METH, 321 mt. There is no reason to expect that the cost per mt would differ significantly in this larger plant. The Farmer et al (1987) analysis assumed a recovery efficiency of 32 to 45 percent, but this range reflected plant improvements to collect more METH. The SRRP staff assumed a lower recovery efficiency of 25 percent (see discussion in next subsection on carbon adsorption). Table 5.5 presents the results for liquid absorption in the average foam plant with 25 percent recovery efficiency and the upper limit to cost in Farmer et al (1987).

Refrigerated Condensation

Farmer et al (1987) estimated the cost of recovery of 218 mt at \$5,600 per mt of METH emissions avoided assuming a recovery efficiency of 28.5 percent. Again, results are applied directly to a larger plant using 321 mt of METH and assume a recovery efficiency of 25 percent, we get the results presented in Table 5.6.

Table 5.4
ANNUAL COST INCREASE AND METH EMISSION REDUCTION FOR POLYURETHANE MODIFICATION

	To Foamer	To Southern California	To U.S.
Average Annual Cost (million \$)	0.4	1.6	23.3
Annual METH Emission Reduction (mt)	69	274	3,910
Cost Increase Per METH Emission Avoided (\$/mt)	5,960	5,960	5,960

Table 5.5

ANNUAL COST INCREASE AND METH EMISSION REDUCTION FOR LIQUID
ABSORPTION

<u>LIQUID ABSORPTION</u>	<u>To Foamer</u>	<u>To Southern California</u>	<u>To U.S.</u>
Average Annual Cost (million \$)	0.2	1.0	13.7
Annual METH Savings (mt)	86	343	4,888
Cost Per METH Emissions Avoided (\$/mt)	2,800	2,800	2,800

Table 5.6

ANNUAL COST INCREASE AND METH EMISSION REDUCTION
FOR VAPOR CONDENSATION

VAPOR CONDENSATION	To Foamer	To Southern California	To U.S.
Average Annual Cost (million \$)	0.5	1.9	27.4
Annual METH Savings (mt)	86	343	4,887
Cost Per METH Emissions Avoided (\$/mt)	5,600	5,600	5,600

Summary of "Limited Analysis" Options

Tables 5.7 and 5.8 summarize the "limited analysis" option results. TCA substitution is the least costly option, followed by HCFC-141b substitution. Substitution of HCFC-123 is a much higher cost option. It's worth noting here that there is a great deal of uncertainty in the cost and emission reduction figures. Another factor that is important to stress is that the chemical substitution options lead to increased use of an alternative chemical that may pose hazards of a different sort than METH. The recovery options also present a different type of risk in the form of water pollution and solid waste. The impact of these issues cannot really be quantified but they must remain part of the consideration of alternatives.

FULL ANALYSIS OPTIONS

As Table 5.1 indicates, two options were selected for full analysis: specification of a minimum density level and carbon adsorption for recovery of METH vapors. Two scenarios were defined to consider and evaluate these options. In Scenario 1, the analysis was made for carbon adsorption alone. In Scenario 2, the analysis includes both minimum density specification and carbon adsorption. In this latter case, the minimum density specification reduces blowing agent use and emissions so that the potential of carbon adsorption for reducing emissions is less.

The minimum density and carbon adsorption options are examined for three plant sizes. As mentioned earlier, large firms produce between 9 and 45 thousand mt of foam and use about 250 to 1,360 mt of METH each year. Roughly one-third of the plants fall into this category (Mooz and Quinn, 1980). The large size plant that we consider produces 12.4 thousand mt of foam and uses about 750 mt of METH annually. Medium sized firms produce in the range of 3 to 9 thousand mt of blowing agent. An estimated

Table 5.7

SUMMARY OF ANNUAL COST AND BLOWING AGENT USE REDUCTIONS
FOR "LIMITED ANALYSIS" OPTIONS - U.S.

Option	Annual Cost (million \$)	Annual Meth Emission Reduction (mt)	Cost Per METH Emissions Avoided (\$/mt)
HCFC-123	117.3	19,530	6,005
HCFC-141b	39.9	19,530	2,004
HCFC Combination	78.6	19,530	4,025
Polyurethane Modification/Additives	23.3	3,910	5,960
Liquid Absorption	13.7	4,888	2,800
Vapor Condensation	27.4	4,887	5,600

a

Parenthesis indicate a cost credit.

Table 5.8

SUMMARY OF ANNUAL COST AND BLOWING AGENT USE REDUCTIONS FOR
"LIMITED ANALYSIS" OPTIONS--SOUTHERN CALIFORNIA

Option	Annual Cost (millions \$)	Annual METH Emission Reduction (mt)	Cost Per METH Emissions Avoided (\$/mt)
HCFC-123	8.2	1,380	6,005
HCFC-141b	2.8	1,380	2,044
HCFC Combination	5.5	1,380	4,025
Polyurethane Modification/ Additives	1.6	274	5,960
Liquid Absorption	1.0	343	2,800
Vapor Condensation	1.9	343	5,600

15 percent of the plants fall into this category (Mooz and Quinn, 1980). A model medium sized plant produces 3.3 thousand mt of foam annually and has a blowing agent use of about 200 mt of METH annually. Small plants produce less than 3 thousand mt of foam and use less than about 115 mt of METH each year. About 50 percent of plants fall into this category. The small plant uses about 100 mt of METH each year. These data are summarized in Table 5.9.

Scenario 1. Carbon Adsorption Along. There have been no carbon adsorption pilot or commercial demonstrations on METH but there have been such demonstrations on CFC-11. As mentioned earlier, these operations had very low recovery efficiencies, in the range of 10 to 40 percent, depending on whether the line had been modified for better collection. For METH, since a smaller percentage is emitted on the foam line, the collection efficiency would be even lower.

One study estimated the cost of a carbon adsorption system for a plant producing 5.4 thousand mt of foam annually operating 200 days per year with a 2 hour pouring period at an average pouring rate of 230 kilograms per minute (Farmer et al, 1987). The study assumed that the foam line was 30 meters long with overhead exhaust stacks. The cost estimates include modification to the foam line--improved conveyor enclosure at the entrance and exit of the foam tunnel and addition of horizontal vapor withdrawal ducts on the line.

Equipment for retrofitting carbon adsorption systems in existing foam plants would be similar. Such systems depend on the pouring rate and the exhaust ventilation rate and this does not vary significantly from plant to plant. The size of the system and its capital cost depends most heavily on the exhaust level rather than on the foam output of the plant. Operating costs, on the other hand, are dependent on the foam output and on the size of the equipment.

Table 5.9

CHARACTERISTICS OF SMALL, MEDIUM AND LARGE PLANTS

PLANT SIZE	ANNUAL FOAM PRODUCTION (thousand mt)	ANNUAL METH USE (mt)
Large	12.6	550
Medium	4.0	175
Small	2.0	90

The Farmer et al (1987) study sized and costed out a carbon adsorption system using 218 thousand mt of METH annually. This is virtually identical to the medium sized foam plant described in Table 5.10. A large plant produces 3.75 times as much foam. The medium sized plant operates 2 hours per day. This suggest that the large plant would operate for 7.5 hours per day at the same pouring rate. The operating time for the small plant is about one hour per day.

The bed chosen in the Farmer et al (1987) analysis to treat tunnel exhaust at 5,000 ppm contained 5,100 kg of carbon and was 0.9 meters deep. This should be adequate for the large plant size under consideration. For this analysis, same size carbon bed is used to treat the tunnel exhaust from small, medium and large plants and in doing so the capital cost of carbon adsorption system may be overestimated for medium and small users.

The cost of the system includes a single pass sacrificial guard bed that will capture the TDI. The system treats 5,000 standard cubic feet per minute (scfm) stream for an 8-hour period for the large plant, a 2-hour period for the medium sized plant and a 1-hour period for the small plant. A steam desorption system is included. In all cases, a regeneration/drying phase would be required to prepare the carbon for the next adsorption phase.

Tables 5.10 and 5.11 present the capital costs and the annualized operating costs respectively for this carbon adsorption system for small, medium and large plants. Note that the capital cost of the unit is much larger than the operating cost so that the variation among small, medium and large foamers is minimal. The annual cost to a foamer to implement the carbon adsorption recovery is in the range of \$250,000.

Table 5.10
CAPITAL COSTS FOR CARBON ADSORPTION SYSTEM

Capital Equipment	Cost (\$1,000)
Adsorbers	256
Other Equipment ^a	69.7
Tunnel Enclosure	17.9
Total Equipment Cost	343.6
Total Installed Direct Costs ^b	566.9
Indirect Capital ^c	295.2
Total Depreciable Capital ^d	862.1
Total Capital Investment ^e	948.3

^a Other equipment includes a guard bed, a condenser, a decanter/condensate storage tank, a storage tank for recovered METH and pumps.

^b Installed direct costs are the total equipment cost plus 65 percent of purchased equipment.

^c Includes engineering and supervision at 10 percent of direct capital, miscellaneous field construction expenses at 5 percent, contractor fees at 10 percent, contingencies at 15 percent, startup expenses at 2 percent and interest during construction at 10 percent.

^d Sum of Total Installed Direct Costs and Indirect Capital.

^e Includes working capital at 10 percent of total depreciable capital.

Table 5.11
ANNUALIZED OPERATING COST FOR CARBON ADSORPTION

COST ITEM	COST (\$1,000)		
	Small	Medium	Large
Direct Operating and Maintenance Costs ^a	21.8	32.8	52.3
Indirect Cost ^b	178.1	179.9	181.6
Total Annual Operating and Maintenance Costs	199.9	212.7	233.9

^a Estimate for medium plant taken from Farmer et al (1987) with 6.3 percent adjustment for inflation. Values for small and large plants adjusted to account for shorter and longer operation respectively.

^b Includes \$154,300 as a capital recovery factor determined by assuming a 10 percent interest rate and a 10-year equipment life. Also includes overhead which is estimated at 30 percent of operating labor and maintenance; administration estimated at 50 percent of operating labor costs; and insurance and property taxes estimated at \$18,900.

Note: Values are from Farmer et al (1987) with costs adjusted for inflation between late 1987 through mid 1989. Bureau of Labor and Statistics indicates that the Producer Price Index for Industrial Commodities, Machinery and Equipment rose 6.3 percent over the period.

Another source estimates the annual recovery cost for a comparable facility to be somewhat higher--at between \$283,000 and \$466,000 (South Coast AQMD, 1989).

The SRRP staff estimate of the net METH recovery through carbon adsorption is 30 percent, with the improvements in the line to facilitate vapor capture. Estimates for CFCD-11 capture range from 10 to 40 percent and since METH emissions on the foam line are lower, a lower value was chosen. The cost and METH emissions avoided for small, medium and large plants are summarized in Table 5.12

It is not clear whether the captured METH could be reused directly in the foam production process without further processing. Although one recycler analyzed the METH used in equipment cleaning at our request (see next section), the METH from the foam blowing process may contain different components.

There are three possibilities for the captured METH. First, it could be reused directly as a blowing agent. Second, it could be sold to an off-site recycle for a net credit. Third, it could be distilled on-site and reused in the foam blowing process. The first option is the most favorable economically for the foamer. If the METH were directly usable in the process, then small, medium and large foamers would get a purchase credit \$19,200, \$38,400 and \$144,000 respectively. These savings provide an impressive offset to the total annualized costs in Table 5.12. In fact, the cost of the process under these circumstances would be \$6.00, \$3.20 and \$0.56 per kilogram of then small, medium and large foamers would get a purchase \$19,200, \$38,400 and \$144,000 respectively. These savings provide an impressive offset to the total annualized costs in Table 5.12. In fact the cost of the process under these circumstances would be \$6.00, \$3.20 and \$0.56 per kilogram of emissions avoided for small, medium and large formers

Table 5.12

**ANNUAL COST AND METH EMISSION REDUCTION FOR
CARBON ADSORPTION SYSTEM**

	Average Annual Cost (million \$)	Annual METH Emission Reduction (mt)
To Foamer		
Small	0.20	27
Medium	0.21	53
Large	0.23	165
Southern California ^a	0.89	436
Nationwide ^b	12.40	5,840

^a

Assumes two medium sized and two large plants.

^b

Assumes 47 percent of the plants are large, 13 percent are medium sized and 40 percent are small.

respectively. The process appears to be cost-effective today for large foamers but only if direct reuse of the blowing agent were possible.

The more likely option is the second one since foamers are unlikely to accept the recovered solvent for direct reuse. Furthermore, if contaminants are present in high concentrations, the catalyst package might no longer be appropriate. These would have to be removed before the blowing agent could be reused. One recycler indicates that he pays \$1.25 per gallon for waste METH disposal. If the solvent is contaminated at the 30 percent level, the foam will get a credit of \$0.50 per gallon or about \$0.10 per kilogram. This would be a net annual credit of \$3,000, \$6,000 and \$22,500 for small, medium and large foamers respectively.

It is worth noting that the carbon adsorption recovery process could be cost-effective today for foamers who employ CFC-11 as a blowing agent. The present price of that chemical is \$1.76 per kilogram, well above the price of METH. Somewhat more CFC-11 could be recovered since more is emitted on the line. For large foams in particular, if the blowing agent could be directly reused, it would be cost-effective today to install a recovery system.

Scenario 2: Specification of Minimum Density Followed by Carbon Adsorption. Detailed information on all flexible foam markets is required for a complete cost and use reduction analysis for a minimum density specification. This information would include data on METH use as a function of ILD and foam density and the levels of use and the end markets for the foam as a function of ILD and foam density. These data are not available and the analysis must, by necessity, incorporate certain assumptions.

Slabstock foam is a low margin product. If higher density foams were produced, larger quantities of raw materials like polyols, catalysts and isocyanates would be required and the cost of producing the foam would increase commensurately. In effect, higher quantities of raw material would be required for a given volume of foam,. For example, if the foam density increased from 1.0 lb/ft³ to 1.2 lb/ft³. then the raw material requirements and their costs would increase by 20 percent. The price of the foam would increase and the fabricators, who are very competitive, might not continue to use slabstock foam, particularly in markets where low cost and low density are important. Thus, in some markets, there would be a shift from low to higher density foams; in other markets, there might be a shift to other products or foam made with other blowing agents like CFC-11, for instance.

The furniture market accounts for about 40 percent of slabstock flexible foam use as indicated in Table 2.3. Low quality furniture is made with low density foam as cushioning. In the furniture market, the cost of the other furniture components is generally much higher density foam would probably not increase the price of the furniture item significantly. An added benefit would be an increase in the durability of the furniture. In the furniture market, it is likely that a cost increase from adoption of higher density foam would simply be passed on to the consumer.

The structure of the carpet underlay market segment is much different. As the values of Table 2.3 show, this segment represents 26 percent of the slabstock market. As mentioned earlier, alternative materials including synthetic and natural fiberfill and jute are used today in carpet underlay applications and are competitive with slabstock foam. In this case, if higher density foam were used and the cost increased, a significant part of the market could go to the alternatives which would then be cheaper.

The difference between the furniture and rug underlay markets demonstrates the diverse effects a minimum density requirement would have on different markets. Foam producers sell to fabricators who are influenced heavily in the end use markets by competitive pricing. Although the information on market/ILD interrelationships is not available, one can estimate the use reduction and cost of a minimum density requirement.

The analysis, distinguishes among small, medium and large plants and assumes a uniform density distribution from plant to plant. Most foamers tend to sell to a variety of markets and produce a range of foams with various ILDs. It is likely that such plants also produce a range of densities and the impacts of a minimum density requirement are proportional to the amount of foam produced below the cutoff level.

According to Table 2.1, densities as low as 0.9 to 1.0 lb/ft³ are achieved for some foams. If the minimum density cutoff level is set at 1.3 lb/ft³, raw material cost would increase about 18 percent (Farmer et al, 1987). An industry source estimates that raw material costs are about \$0.75 per pound of foam produced or \$1.65 per kilogram of foam produced. An 18 percent increase in raw material cost implies an annual cost increase of about \$300 per mt of affected foam.

The figures of Table 2.2 indicate that 700 thousand mt of flexible foam--including both slabstock and molded foam--was produced in 1987. In 1985, the figure was 603 thousand mt and 440 thousand t of it was slabstock. If the same proportion is assumed to be valid in 1987, then 511 thousand mt of slabstock foam was produced in that year. METH is used by 57 percent of the plants and 18 thousand mt of METH and 10.8 thousand mt of CFC-11 are used today. For this analysis, it is assumed that 60 percent of the slabstock foam or about 300 thousand mt was produced using METH.

One source estimates that the portion of METH blown slabstock output that would be affected by a minimum density specification is 30 to 40 percent. The same source assumes that the reduction in METH use per unit of affected foam is 20 to 40 percent and that the level of METH in the replaced foam is 6 percent. The 6 percent figure corresponds to about 10 parts per hundred polyol (php) which is representative of several typical METH formulations. In Table 2.1, for instance, the weight percent METH and CFC-11 range from 4 to 25 php (Farmer et al, 1987). If the midpoints of the ranges for the affected foam and the reduction in METH use for the affected foam are adopted, then 1,890 mt of METH use (or emission) would be avoided annually.

Table 5.13 summarizes the results for small, medium and large foam plants in Southern California and nationwide. The figures suggest that this option would cost the nation about \$7 million and reduce METH use by 1,440 mt. The price of METH at which this option becomes cost-effective is about \$1 per kilogram. This can be compared with the current METH price of \$0.64 per kilogram.

The values of Table 5.13 show that it would cost the nation \$19.5 million annually to implement a minimum density specification followed by carbon adsorption. Over 5,400 thousand mt of METH emissions are avoided.

Table 5.13

ANNUAL COST AND METH EMISSION REDUCTION FOR MINIMUM DENSITY SPECIFICATION

	Average Annual Cost (million \$)	Annual METH Emission Reduction ^a (mt)
Foamer		
Small	0.04	7
Medium	0.1	14
Large	0.2	45
Southern California	0.6	120
Nationwide	7.1	1,440

^aCalculations assume that there is a minimum density specification of 1.3 lb/ft³; that 20 percent of the METH blown slabstock is affected; that there is a 30 percent reduction in METH use per unit of affected foam; and that the level of METH in the affected foam is 6 percent.

VI. ANALYSIS OF SOURCE REDUCTION OPTIONS FOR SOLVENT APPLICATIONS IN FOAM PLANTS

Approximately 5 thousand mt is used to clean foam heads, equipment and molds in slabstock and molded foam production operations. In this section options were selected for limited and full analysis.

SELECTION OF SOLVENT OPTIONS

Table 6.1 summarizes the source reduction options and classifies them for further analysis. The substitution options--use of DBE or NMP--are "No Analysis" options because of their doubtful feasibility. On-site and off-site recycling was found to be promising and, thus qualifying "Full Analysis" options.

The figures of Table 2.2 indicate that 700 thousand mt of flexible foam--including both slabstock and molded foam--was produced in 1987. In 1985, the figure was 603 thousand mt and 440 thousand mt of it was a slabstock. If the same proportion is assumed to be valid in 1987, then 511 thousand mt of slabstock foam was produced in that year. METH is used by 57 percent of the plants and 18 thousand mt of METH and 10.8 thousand mt of CFC-11 are used today. For this analysis, it is assumed that 60 percent of the slabstock foam or about 300 thousand mt was produce using METH.

One source estimates that the portion of METH blown slabstock output that would be affected by a minimum density specification if 30 to 40 percent. The same source assumes that the reduction in METH use per unit of affected foam is 20 to 40 percent and that the level of METH in the replaced foam is 6 percent. The 6 percent figure corresponds to abut 20 parts per hundred polyol (php) which is representative of several typical METH formulations. In Table 2.1, for instance, the weight

TABLE 6.1

CLASSIFICATION OF SOURCE REDUCTION
OPTIONS FOR SOLVENT CLEANING USES

NO FURTHER ANALYSIS	LIMITED ANALYSIS	FULL ANALYSIS
Substitution of DBE		On-site Distillation
Substitution of NMP		Off-site Distillation

percent METH and CFC-11 range from 4 to 25 php (Farmer et al, 1987). If the midpoints of the ranges for the affected foam and the reduction in METH use for the affected foam are adopted, then 1,890 mt of METH use (or emission) would be avoided annually.

Table 5.12 summarizes the results for small, medium and large foam plants in Southern California and nationwide. The figures suggest that this option would cost the nation about \$7 million and reduce METH use by about 1,440 mt. The price of METH at which this option becomes cost-effective is about \$1 per kilogram. This can be compared with the current METH price of \$0.64 per kilogram.

The values of Table 5.12 show that it would cost the nation 19.5 million annually to implement a minimum density specification followed by carbon adsorption. Just over 5,400 thousand mt of METH emissions are avoided.

VII. ANALYSIS OF SOURCE REDUCTION OPTIONS FOR SOLVENT APPLICATIONS IN FOAM PLANTS

Approximately 5 thousand mt is used to clean foam heads, equipment and molds in slabstock and molded foam production operations. In this section, certain options were selected for limited and full analysis.

SELECTION OF SOLVENT OPTIONS

Table 6.1 summarizes the source reduction options and classifies them for further analysis. The substitution options--use of DBE or NMP--are "No Analysis" options because of their feasibility. On-site and off-site recycling was found to be promising and, thus qualifying. "Full Analysis" options.

If the foamer buys back mt of recycled solvent, the net annual benefit is \$3,600. It is presently cost-effective to use an off-site recycler and purchase recycled rather than virgin solvent for cleaning.

OFF-SITE RECYCLING

One of the plants in the survey cleans equipment three times per day. The other two plants did not report the frequency of cleaning. A plant which uses 32 mt of METH annually to clean the equipment with an operating schedule of 200 days per year, uses 160 kilograms or 32 gallons daily. The foamer could purchase a 10 gallon per hour still and operate it one hour per day plus one hour for warm up. One industry source estimates the electricity costs for the year at \$500. Labor requirements would be one hour per week. At a burdened rate of \$20 per hour, the labor charges would be \$1,000 annually. Total operating and maintenance costs are \$1,500 per year.

A self-contained still capable of processing 10 gallons per hour has a capital cost of about \$9,000. Assuming an interest rate of 10 percent and an equipment lifetime of 10 years, the capital recovery factor is 0.163 and the annual capital charges are \$1,470. Total annual costs are about \$2,970.

This analysis assumes that three-fourths of the METH is emitted and one-fourth or 8 mt of METH is waste. At a distillation efficiency of 90 percent, the foamer must pay for disposal of the sludge from the on-site distillation process, however. The volume of sludge requiring disposal is 0.8 mt of METH annually and 3.4 mt of sludge. This 3.4 mt of sludge arises from the 8 mt of METH which is contaminated to the 30 percent level giving a total waste volume of 11.4 mt. The total volume requiring disposal is 4.2 mt. At a charge of \$1.25 per gallon, the cost will be \$1,160 per year. The net cost to the foamer for purchase of the equipment and waste disposal is \$4,130 annually.

The foamer, because he recycles and reuses the METH on-site can forego purchases of 7.2 mt of the chemical each year. This savings amounts to \$4,608 each year. The foamer can also purchase recycled solvent for the balance of the 24.8 mt of solvent annually. If this solvent is purchased at 3.75 cents per pounds less than virgin solvent, then the saving amounts to \$2,046. The total savings outweighs the cost by \$2,524 annually. This suggests that it is presently cost-effective to adopt on-site distillation.

SUMMARY OF RECYCLING OPTIONS

Table 6.2 summarizes the annual cost savings that could be realized from purchasing solvent that has been recycled off-site and from purchase and use of an on-site still. The figures show that there are cost savings achievable for both options. It is more cost-effective to use an off-site recycler than it is to purchase an on-site still. The still we consider

Table 6.2

ANNUAL COST AND METH USE REDUCTION FROM RECYCLING

	To Foamer	ANNUAL COST (\$ thousands)		To Foamer	ANNUAL VIRGIN METH USE REDUCTION ^a (mt)	
		To Southern California	To Nation		To Southern California	To Nation
Off-Site Recycling	(3.6) ^b	(54.0)	(586.8)	8.0	120.0	1,304.0
On-Site Recycling	(2.5)	(37.5)	(407.5)	7.2	108.0	1,173.6

^a Includes only the recycled solvent purchased in place of the waste solvent.

^b Parentheses indicate a credit.

is capable of processing 10 gallons per hour and would be used only a few hours per day. A smaller cheaper still would probably suffice and equipment at half the cost of the one estimated here would make on-site recycling more cost-effective than off-site recycling.

The values of Table 6.3 show the reduction in METH virgin purchases that either on- or off-site recycling could achieve. The figures do not include credit or for purchases other than those to replace the waste solvent. That is, in the case of off-site recycling, the foamer sends 8 mt of contaminated solvent to the recycler and buys back 8 mt of reclaimed solvent.

VIII. SUMMARY AND CONCLUSIONS

Approximately 18 thousand mt of METH are used as the auxiliary blowing agent in slabstock foam production today. In the next few years, as foamers move away from CFC-11, METH use might increase to about 195 thousand mt. About 5 thousand mt of METH is used to clean foam heads, equipment and molds in slabstock and molded foam production operations.

In the 1970s, CFC-11 was the most widely used auxiliary blowing agent. In the late 1970s, improvements in the catalyst package made METH a technically viable alternative for virtually all grades of foam. Since METH was somewhat less expensive to use, its use increased significantly throughout the 1980s. In the mid 1980s, regulatory pressure increased on CFC-11 because the chemical depletes stratospheric ozone. At about the same time, national and local regulators increased their scrutiny of METH and began taking actions to discourage its use. In 1989, TCA was identified as a suitable blowing agent and a few commercial trials were conducted. In January of 1990, the Congressional tax was levied on CFC-11 and the blowing agent became prohibitively expensive to use. AT this stage, virtually all foamers using CFC-11 made the decision to switch to METH or TCA and they began doing so. METH is the first choice for all foamers because it is less expensive to use than TCA. In some states and localities, however, regulators will not grant permits to use METH because of its perceived toxicity. In these cases, foamers will convert to the more expensive TCA. By the end of 1990, conversion will be complete and CFC-11 will no longer be used as a blowing agent in flexible slabstock foam.

The conversion away from CFC-11 will cause an increase in the use of METH and TCA. In some states and localities, there will be increasing pressure to reduce blowing agent use. In Southern California, for instance, the SCAQMD recently passed a rule requiring a 40 percent reduction in blowing agent use by the

end of 1990. This reduction can be achieved through adoption of exempt blowing agents, which in this case, include TCA and the HCFCs. Since the HCFCs will not be available until the 1993/1994 time frame, this option cannot be presently exercised. Other ways of achieving the reduction are adopting TCA, converting away from production of less dense foams--minimum density concept--and implementing vapor recovery.

The most promising option for the flexible foam industry is the development of new polyols and additives that will entirely eliminate the need for an auxiliary blowing agent. This is the option preferred by the foam industry and it is the one that is preferred from a societal standpoint. Industry experts estimate that within two years, additives will be developed to make foam of all grades at comparable quality without the use of auxiliary blowing agent.

The analysis performed here has focused heavily on a minimum density specification and carbon adsorption recovery because data were available on the cost and use reduction associated with these options and because regulatory agencies are moving toward a requirement for blowing agent use reduction. Recovery presents a dilemma. The high air flows in foam plants will render recovery systems expensive; another drawback is that only a fraction of the blowing agent can be collected. With improvements to the ventilation system on the line and capture of the blowing agent in the curing and storage area, a higher fraction of the blowing agent can be collected.

SUMMARY OF SOLVENT CLEANING OPTIONS POTENTIAL

On- and off-site recycling are promising options that could be implemented immediately. Table 7.1 summarizes the various options.

Table 7.1
Summary of Source Reduction
Options in the Flexible Foam Industry

OPTIONS	ADVANTAGES	DISADVANTAGES
<u>PRODUCT SUBSTITUTION</u>		
Non-Polyurethane alternatives (cotton batting, fiberfill, etc.)	Can reduce emissions from polyurethane foam manufacture	Uncertain environmental and cost tradeoffs, relatively minor reductions
Minimum density foam	Reduction in aux. blowing agent use, greater durability	Higher cost
<u>CHEMICAL SUBSTITUTION</u>		
CFC-11 instead of METH	Less toxic, can be directly substituted	Higher cost, faces elimination as ozone depleter.
Acetone instead of METH	Less toxic, 30% less is needed, less costly	Flammable and photoreactive, controls are required, process not developed
HCFC's instead of METH	Can be directly substituted	Higher cost, more required untested toxicity, some are photoreactive, commercially still unavailable
TCA instead of METH	Non-photchemically, reactive proven performance	Ozone depleter (uncertain regulatory future), susceptibility to hydrolysis, more required, higher cost

Table 7.1 (cont'd)

OPTION	ADVANTAGES	DISADVANTAGES
<u>Equipment Modification</u>		
<u>Max-Foam Process</u>	Minimizes Trimuaste, may increase efficiency of blowing agent	Minimal reduction in blowing agent use
Vertifoam Process	Increased gas efficiency, Emissions are confined allowing gas ecovery, reduces gas use	Retrofit is difficult, higher capital costs, process may be inefficient
<u>Process Modification</u>		
"AB" Process	More CO/CO ₂ produced-reducing need for blowing agent, raw materials cost reduced	CO is toxic and flammable, high conversion costs, additional chemicals required, product quality may be inferior, formic acid is corrosive
<u>Polyurethane Modifications/ Additives</u>		
- HR Process	High quality product	Technically difficult
- Polyol System	Does not need auxiliary blowing agent	Cannot produce low density, soft foams

Table 7.1 (cont'd)

OPTION	ADVANTAGES	DISADVANTAGES
Montedison Process	Produces foams of high, medium, and low densities, high softness foams producible without auxiliary blowing agent	Can't produce foam lower than 1.3 lb/ft, Experimental stage
Geolite Process	Reduces need for auxiliary blowing agent	Cannot eliminate auxiliary agent, Experimental stage
<u>Recycle & Recovery</u> Liquid Absorption	May significantly reduce METH use and emissions, captures METH	Form undesired by products, increase maintenance costs, captured METH not directly usable
Vapour Absorption	Recovers significant METH amounts	Requires CFC refrigerant, waste water problem, METH may lose stabilizers
Carbon Absorption	Recovers 30-40% of the blowing agent (CFC-11)	Potential high capital costs, carbon beds sensitive to deactivation, captured METH may require purification, increased waste water and solids problem, process retrofit may be necessary
Brayton Cycle Heat Pump	Energy savings, High Efficiency, Successful Commercial Demonstration	Water Vapour Contamination, Waste Water Problem
Membrane System	Cost Effective, Low Capital Costs	Requires High Solvent Concentration
<u>Solvent Recovery & Reuse</u> On-site distillation	Reduces hazardous waste	Additional manpower training costs
Direct Reuse	Low costs	Blowing agent may be contaminated
Off-site recycling	Reduces amount of virgin solvent required	More expensive than for cleaners, potentially increased technical and health problems

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