CFA Emission Models for the Reinforced Plastics Industries

by

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Forward

An earlier version of this report was issued on September 18, 1997, and was originally entitled "*Derivation and Verification of the CFA Emission Models*." Many helpful comments and corrections were offered by Environmental Protection Agency (EPA) staff and reinforced plastics industries (RPI) reviewers since the earlier version of this report was released. In order to incorporate these comments and corrections, two addenda to the original report were issued on October 8, 1997 and December 6, 1997. The first addendum amended the data set used to perform the manual resin application regression analysis. The second addendum revised the approach used to estimate the vapor suppressant factor for manual resin application and corrected the data set used to perform the mechanical resin application regression analysis.

The earlier version of this report was the first of two reports created as technical support documents for the proposed Composites Fabricators Association (CFA) Maximum Achievable Control Technology (MACT) approach for existing open molding sources in the RPI. The emission models discussed therein were essential to the proposed CFA MACT approach. The second companion report was entitled "*Analysis of the Open Molding Database*." This second report compared the CFA Emission Model estimates with the EPA emission estimates contained in the EPA's April 1997 Open Molding database.

In late December 1997, the EPA Emissions Monitoring and Analysis Division, Emission Factor and Inventory Group, requested reproducible copies of the original report and addenda as part of a planned update to the AP-42 emission factors for the RPI. However, instead of merely providing the earlier version of the report and associated addenda, which focused on the MACT proposal for the RPI, this revised report was prepared to incorporate the comments and corrections in one document and to provide a more general focus on the models.

The title of this revised report was also changed slightly to prevent confusion with the earlier version.

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Executive Summary

The Environmental Protection Agency (EPA) maintains an official set of predictive emissions factors, known as the AP-42 emission factors. In the past, these factors were used by most of the industry and state regulatory agencies to estimate the styrene emission rates from the various reinforced plastics lamination processes. However, several recent independent styrene source tests indicated that the AP-42 emission factors may significantly under-predict styrene emissions from some reinforced plastics sources.

To investigate this indicated discrepancy, the Composites Fabricators Association (CFA) conducted an extensive two-phase study of the styrene emissions from the major lamination processes and the effects of the available control techniques. These processes and techniques included hand lay-up, spray lay-up, gelcoat spraying. controlled spraying, non-atomized resin application (flow coating and pressure-fed rollers), and vapor suppressants.

This analysis derives simple mathematical expressions of the CFA test data for these processes and techniques. These expressions are called CFA Models, and consist of linear equations based on the amount-of-resin-consumed and simple numerical control factors. The amount-of-resin-consumed basis is selected because it results in the best statistical fit with the data. This analysis also verifies the accuracy of the CFA Models by comparing the model outputs to the available EPA data on styrene emissions. The available data includes EPA emission equations and a Research Triangle Institute (RTI) emission study.

The EPA developed several predictive equations and control factors for estimating baseline and reduced Maximum Achievable Control Technology (MACT) styrene emission rates. These equations appear in the EPA's April 1997 Open Molding database for the reinforced plastics industries (RPI). Although no supporting information was included with this database, these EPA equations are presumably based upon valid styrene emissions data. A comparison of the EPA equations with the CFA Models shows some differences and some similarities. The EPA equations are based upon the amount-of-available-styrene-consumed, which tends to overestimate the effect of styrene content on emissions, especially at higher content levels. The EPA equations also differentiate between filled and unfilled resin emissions, which is not supported by the CFA study. In spite of these differences, the EPA equations generally agree with the CFA Models. In some cases, the EPA equations are nearly identical to, or closely match, the corresponding CFA Model.

The RTI, an EPA technical consultant, also conducted styrene emission testing of the spray lay-up process. The RTI study also investigated the effects of controlled spraying, non-atomized resin application (flow coating and pressure-fed rollers), and vapor suppressants A comparison of the results of this RTI study to the CFA Spray Lay-up Model shows a remarkable, near-perfect agreement between the RTI study and the CFA Model.

Section 1 - Introduction

The purpose of this report is to derive styrene emission models from emission test data for the open molding processes used by the reinforced plastics industry. This derivation consists of the following three steps:

1. Styrene emission data is obtained through extensive emission testing for the various lamination processes.
2. Simple linear emission equations are developed from this emission data using standard linear regression techniques.
3. A matrix of feasible control options, which are both significant and practically enforceable, is created from components of these emission models.

The matrix both describes and defines the CFA Models. The CFA Models discussed herein represent the simplest expressions of the available CFA and Dow test data. However, the following five cautions should be observed when applying these emission models to such a diverse industry as the RPI:

Only styrene vapor emissions are modeled - styrene is the major VOC and HAP contained in the resin and gelcoat formulations used by the RPI, and was the only HAP tested by the CFA. However, other VOC or HAP constituents may be present in some resin or gelcoat formulations. The CFA Models only apply to styrene vapor emissions.

The range of tested monomer levels is limited - the CFA tested resin formulations with styrene contents between 34% and 49%, and gelcoat formulations with styrene contents between 35% and 40%. Other resin and gelcoat formulations may be available with styrene contents above or below these tested ranges. The effect of styrene contents outside the tested ranges is not known, and will be investigated further by the CFA in 1998.

Some control technique combinations are not yet tested - some of the control techniques investigated by the CFA have not been tested together in concert, and the effect of these combinations may be less than or greater than a simple linear combination of the individual control factors. The CFA is conducting further tests on these combinations, and the results of this testing should be available by May 15, 1998.

Individual source emissions may deviate from the average - the CFA models predict average emission rates and are not designed to predict an exact emission rate for each individual source.

Vapor-suppressant performance may be affected by filler loading or resin type - the CFA is currently developing a standard test methodology to measure and adjust the effect of vapor-suppressant for specific resin formulations (including filler loading). This test methodology should be available by May 15, 1998.

Section 2 - Derivation of the CFA Emission Models

This section describes the derivation of four CFA Emission Models, one model for each lamination process used in open molding, including manual resin application (hand lay-up), mechanical resin application (spray lay-up), gelcoat spraying and filament winding.

2.1 - Background

The EPA maintains an official set of predictive emissions factors, known as the AP-42 emission factors. In the past, these factors were used by most of the industry and state regulatory agencies to estimate the styrene emission rates from the various reinforced plastics lamination processes. However, several recent independent styrene source tests indicated that the AP-42 emission factors may significantly under-predict styrene emissions from some reinforced plastics sources. To investigate this indicated discrepancy, the CFA conducted an extensive two-phase study of the styrene emissions from the major lamination processes and the effects of the available control techniques. This study is described below.

2.2 - CFA Emission Study

Phase I

The Phase I study consisted of a total of 60 experimental runs (including run replicates), which explored the effect of various process variables that may affect emissions. The experimental plans for both the mechanical resin application (spray lay-up) and gelcoat spraying processes were blocked, five-variable, two-level, half factorial, “screening” designs for estimating the relative magnitude of each variable response. The experimental plan for the manual resin application (hand lay-up) process was a blocked, four-variable, two-level, full factorial, “screening” design.

The five experimental variables investigated in the CFA emission study of the mechanical resin application process (spray lay-up) and gelcoat spraying process were:

Laminate thickness
Styrene content of resin
Gel time
Resin application rate
Air flow

The manual resin application (hand lay-up) study did not include the resin application rate, because it was not applicable to manual application.

Phase II

The Phase II study consisted of a total of 61 additional experimental runs. Phase II focused on the effect of the various emission control methods that could be applied to the lamination processes. For the mechanical resin application (spray lay-up) process, the following emission control methods were explored:

Vapor suppressant
Non-atomizing application equipment (pressure-fed rollers and flow coaters)
Optimized spraying
BPO catalyst

Only optimized spraying was investigated for gelcoat spraying, because vapor suppressant and non-atomizing application equipment are not feasible (or are extremely limited) for gelcoat application. Likewise, only vapor suppressant was considered for the manual resin application (hand lay-up) process, because spray application techniques are obviously not applicable.

2.3 - Dow Filament Winding Emission Study

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Dow conducted laboratory testing of the styrene emissions from the filament winding process. The Dow study consisted of a total of 20 individual experimental runs, and the test data from this study was provided by Dow in spreadsheet format [e-mail file transmittal from L.Craigie to R. Haberlein, July 2, 1997]. The first ten runs investigated the effect of the following three experimental variables:

Styrene content of resin (% styrene by weight)
Temperature (°F)
Part size (square feet)

These variables were given two different values to assess their corresponding impact on the styrene emission rate. The last ten runs investigated the effect of vapor suppressant combined with the prior experimental variables.

2.4 - Test Results

Compilations of all test data used in this analysis are provided in the appendices the end of this report. These compilations identify every test run, list the independent variable values, and express the associated styrene emission results as both a percentage of the available styrene weight and as a percentage of the neat resin weight. The CFA emission test data is listed in **Appendix A** and the Dow emission test data is listed in **Appendix B**.

CFA Test Results

The contribution of each variable to the total response, or emission rate, was calculated by the Dow researchers as the normalized F-ratio for each statistic. Assuming a styrene emission rate based upon the total weight of neat resin or gelcoat consumed, the relative contributions of the open molding variables are listed in **Table 2.1** below [from Craigie, L., Dow; phone communication with R. Haberlein; 7/15/97]. The sum of the variable responses listed above deviated slightly from a total of 100% due to some slight rounding errors.

Table 2.1 - CFA Test Variable Contributions to Emissions (% resin/gelcoat)

Manual resin application: (hand lay-up)	Thickness	50%
	Styrene Content	39%
	Gel Time	11%
	Air Flow	0%
Mechanical resin application: (spray lay-up)	Styrene Content	88%
	Application Rate	10%
	Thickness	1.3%
	Gel Time	0.3%
	Air Flow	0.1%
Gelcoat Spraying:	Styrene Content	67%
	Thickness	29%
	Air Flow	1.5%
	Gel Time	1.3%
	Application Rate	0.23%

For the three processes investigated in the CFA testing, the filler content and air flow over the wet surface had no significant effect. Therefore, these variables were not considered further in the development of the CFA Emission Models. For manual resin application (hand lay-up), the applied thickness and styrene monomer had the greatest effect. Gel time only had a minor effect. For spray lay-up, the styrene content was the predominate effect at 88%. The application rate variable only had a minor effect (10% of total response), and the laminate thickness and gel time variables had no significant effect. For gelcoat spraying, the styrene content was again the predominate effect at 67%. The applied thickness was a minor effect (29% of total response), and the application rate and gel time variables had no significant effect.

Dow Test Results

According to the Dow researchers, the styrene content of the resin has the most significant effect on the styrene emission rate from filament winding. Vapor suppressants also have a significant effect, with more effect shown for high styrene contents resins than on low styrene content resins. Neither temperature nor mandrel size has a significant effect on emissions.

2.5 - Linear Regressions and Emission Control Factors

In all of the following cases, the linear regression fits are significantly better when the styrene emissions are expressed as a percentage of consumed resin instead of as a percentage of available styrene monomer. For example, the r^2 values for the different regression fits of the styrene emissions as consumed resin and styrene emissions as percentage available styrene monomer are:

	r^2 (as % resin)	r^2 (as % styrene)
Manual Application (one variable)	0.5034	0.2035
Mechanical Application (one variable)	0.7145	0.3983
Gelcoat Spraying (one variable)	0.6539	0.3282
Filament Winding (one variable)	0.7396	0.2026

The styrene emission estimates using the percentage-of-resin-consumed basis have significantly better fits, so the CFA emission factor equations are calculated using the percentage-of-resin-consumed basis instead of the percentage-of-available-styrene basis.

2.5.1 - Manual Resin Application (Hand Lay-up)

Emission Factor

The linear regression fit for all four of the Phase I variables (as a function of consumed resin) is shown in **Table 2.2**. The corresponding equation for estimating styrene emissions is:

$$\begin{aligned} \textit{emissions (as \% resin)} \;=\; & -\,0.46365 \times \textit{thickness} + 0.00265 \times \textit{\% styrene} \\ & + 0.00068 \times \textit{gel time} + 0.00003 \times \textit{air flow} - 0.0320 \end{aligned} \qquad \text{[eq 1]}$$

The overall fit is very good ($r^2 = 0.9697$) and the standard error of the equation is only 0.0034. However, the coefficients for gel time and air flow have relatively large standard error values, and the coefficient for air flow is nearly zero. This suggests that these variables are not good descriptors for the styrene emissions from manual resin application (hand lay-up).

The linear regression fit for just the styrene content variable is shown in **Table 2.3** below. The corresponding equation for estimating styrene emissions for manual resin application (hand lay-up) is:

$$\textit{emissions (as \% resin)} = 0.00286 \times \textit{\% styrene} - 0.0529 \qquad \text{[eq 2]}$$

The data for both Phase I and Phase II (30 data sets) is used. The overall fit is not as good as the fit for all four variables using just the Phase I data set ($r^2 = 0.50343$), but the standard error of the equation is still only 0.01278, which is acceptable.

Table 2.2 - Four-Variable Linear Regression for Manual Application

No.	ID	(in.)	(%)	(min.)	(fpm)	(%)	(% resin wt)	(% styrene)
1	100295B	0.041	35	30	100	0	6.2%	17.7%
2	100295C	0.088	42	15	50	0	4.9%	11.7%
3A	092095A	0.041	42	15	50	0	7.2%	16.7%
3B	092695B	0.041	42	15	50	0	7.6%	17.7%
4A	100395A	0.088	35	30	100	0	4.2%	11.7%
4B	092695C	0.088	35	30	100	0	4.6%	13.1%
5	092595A	0.041	42	30	50	0	8.1%	19.2%
6	092695A	0.088	35	15	100	0	3.6%	10.1%
7	092795A	0.041	35	15	100	0	5.3%	14.7%
8	092795B	0.088	42	30	50	0	5.7%	13.5%
9	092795C	0.041	35	15	50	0	5.0%	14.0%
10	092895A	0.088	42	30	100	0	6.0%	14.3%
11A	092895B	0.041	42	30	100	0	8.9%	21.2%
11B	092995C	0.041	42	30	100	0	8.9%	21.0%
12A	092895C	0.088	35	15	50	0	3.4%	9.6%
12B	100295A	0.088	35	15	50	0	3.6%	10.1%
13	092995A	0.088	35	30	50	0	4.2%	11.9%
14	092995B	0.041	42	15	100	0	7.1%	17.1%
15	091995A	0.041	35	30	50	0	6.3%	17.6%
16	091995B	0.088	42	15	100	0	4.9%	11.5%

Phase I runs - emissions as % resin

Regression Output:				
Constant		-0.0320		
Std Err of Y Est		0.0034		
R Squared		0.969750		
No. of Observations		20		
Degrees of Freedom		15		
	(in.)	(%)	(min.)	(fpm)
X Coefficient(s)	-0.46365	0.00265	0.00068	3.333E-05
Std Err of Coef.	0.03274	0.00022	0.00010	3.078E-05

Table 2.3 - One-Variable (Styrene) Linear Regression for Manual Application

No.	ID	(in.)	(%)	(min.)	(fpm)	(%)	(% resin wt)	(% styrene)
1	100295B	0.041	35	30	100	0	6.2%	17.7%
2	100295C	0.088	42	15	50	0	4.9%	11.7%
3A	092095A	0.041	42	15	50	0	7.2%	16.7%
3B	092695B	0.041	42	15	50	0	7.6%	17.7%
4A	100395A	0.088	35	30	100	0	4.2%	11.7%
4B	092695C	0.088	35	30	100	0	4.6%	13.1%
5	092595A	0.041	42	30	50	0	8.1%	19.2%
6	092695A	0.088	35	15	100	0	3.6%	10.1%
7	092795A	0.041	35	15	100	0	5.3%	14.7%
8	092795B	0.088	42	30	50	0	5.7%	13.5%
9	092795C	0.041	35	15	50	0	5.0%	14.0%
10	092895A	0.088	42	30	100	0	6.0%	14.3%
11A	092895B	0.041	42	30	100	0	8.9%	21.2%
11B	092995C	0.041	42	30	100	0	8.9%	21.0%
12A	092895C	0.088	35	15	50	0	3.4%	9.6%
12B	100295A	0.088	35	15	50	0	3.6%	10.1%
13	092995A	0.088	35	30	50	0	4.2%	11.9%
14	092995B	0.041	42	15	100	0	7.1%	17.1%
15	091995A	0.041	35	30	50	0	6.3%	17.6%
16	091995B	0.088	42	15	100	0	4.9%	11.5%
	052996B	0.176	44.4			0	7.2%	16.1%
	080196A	0.120	44.4			0	4.9%	11.0%
	060596A	0.088	33.2			0	4.6%	13.8%
	052996A	0.088	44.4			0	6.6%	15.0%
	053096B	0.088	44.4			0	8.4%	18.8%
	060396B	0.088	48.8			0	9.3%	19.0%
	060496B	0.088	33.2			1.5	2.9%	8.7%
	060596B	0.088	33.2			1.5	2.7%	8.1%
	053096A	0.088	44.4			1.5	3.1%	7.0%
	060496A	0.088	48.8			1.5	3.6%	7.4%

Regression Output		(% resin)
Constant		-0.05292
Std Err of Y Est		0.01278
R Squared		0.50343
No. of Observation		26
Degrees of Freedom		24
X Coefficient(s)	0.00286	
Std Err of Coef.	0.00058	

Regression Output		(% styrene)
Constant		0.00941
Std Err of Y Est		0.03144
R Squared		0.20351
No. of Observation		26
Degrees of Freedom		24
X Coefficient(s)	0.00353	
Std Err of Coef.	0.00143	

Note that the shaded Phase II values shown in Table 2.3 above incorporate the effect of vapor suppressant, so these shaded values are not included in the one-variable regression analysis.

Suppressant Control Factor

Using a regression approach recommended by the EPA, a separate equation for "vapor suppressed" manual resin application is developed from the vapor-suppressed data. This EPA approach appears to be more suitable for the vapor-suppressed manual application emissions because the available data (although limited) suggests a highly linear effect between vapor-suppressed emissions and styrene content. The available data values for the various mechanical (spray lay-up) control options are more scattered, so the EPA approach does not appear to be appropriate for the mechanical (spray lay-up) control options.

A linear regression is performed using the four available data points for vapor-suppressed manual application (hand lay-up). The linear regression analysis is shown in **Table 2-4** below. Based upon this regression analysis, the equation for vapor-suppressed manual application (hand lay-up) emissions, expressed as a percentage of resin weight is:

$$\textit{Styrene emissions (\% of resin wt.)} = 0.0004476 \times \textit{\% styrene} + 0.01289 \qquad \text{[eq 3-A]}$$

In order to remain consistent with the control matrix format used for the other CFA models, this vapor-suppressed equation is converted into an equivalent control factor, which is then applied to the non-vapor-suppressed manual equation:

$$\textit{Vapor-Suppressed Control Factor} = \frac{0.0004476 \times \textit{\% styrene} + 0.01289}{0.00286 \times \textit{\% styrene} - 0.0529} \qquad \text{[eq 3-B]}$$

Note that this control factor is only valid for resins with styrene contents greater than 28%.

Table 2.4 - Suppressant Control Factor for Manual Application

run	thickness	styrene content (% resin)	suppressant level (% resin)	styrene emissions (% resin)	styrene emissions (% styrene)
060496B	0.088	33.2	1.5	2.9%	8.7%
060596B	0.088	33.2	1.5	2.7%	8.1%
053096A	0.088	44.4	1.5	3.1%	7.0%
060496A	0.088	48.8	1.5	3.6%	7.4%

Regression Output:

Constant	0.012892
Std Err of Y Est	0.001849
R Squared	0.847151
No. of Observations	4
Degrees of Freedom	2
X Coefficient(s)	0.0004476
Std Err of Coef.	0.0001344

2.5.2 - Mechanical Resin Application (Spray Lay-up)

Emission Factor

The linear regression fit for all five of the Phase I variables (as a function of consumed resin) is shown in **Table 2.5** below. The equation for estimating styrene emissions is:

$$\begin{aligned} \textit{emissions (as \% resin)} = & -0.19881 \times \textit{thickness} + 0.00827 \times \textit{\% styrene} \\ & + 0.00038 \times \textit{gel time} - 0.00854 \times \textit{resin flow} \\ & + 0.00003 \times \textit{air flow} - 0.1941 \end{aligned} \qquad \text{[eq 4]}$$

The overall fit is very good ($r^2 = 0.8698$) and the standard error of the equation is only 0.0143. However, the coefficients for thickness, gel time, resin flow, and air flow have relatively large standard error values, and the coefficients for the air flow and gel time are nearly zero. This suggests that these variables are not good descriptors for the styrene emissions from spray lay-up.

The linear regression fit for just the styrene monomer content variable is shown in **Table 2.6** below. The corresponding equation for estimating styrene emissions is:

$$\textit{emissions (as \% resin)} = 0.00714 \times \textit{\% styrene} - 0.180 \qquad \text{[eq 5]}$$

The data for both Phase I and Phase II (26 data sets) is used. The overall fit is not as good as for all five variables using just the Phase I data set ($r^2 = 0.71447$), but the standard error of the equation is still only 0.01818, which is acceptable.

Suppressant Control Factor

The calculation of the suppressant control factor, which is the emissions factor with suppressant divided by the emissions factor without suppressant, is shown in **Table 2.7** below. Thirteen data sets (including one Phase I data set) are compared to investigate the effect of suppressant on emissions at three different monomer content levels. No obvious relationship between styrene monomer content and suppressant effect is observed for this data. The suppressant factor varies from 0.54 to 0.69, with an average value of **0.62**.

Controlled-Spraying Factor

The calculation of the controlled-spraying reduction factor, which is the emissions factor with controlled-spraying divided by the emissions factor without controlled-spraying, is shown in **Table 2.8** below. Twelve data sets are compared to investigate the effect of controlled-spraying on emissions at two different monomer content levels. No obvious relationship between styrene monomer content and controlled-spraying effect is observed for this data. The controlled-spraying factor varies from 0.64 to 0.83, with an average value of **0.77**.

Table 2.5 - Five-Variable Linear Regression for Mechanical Application

Run No.	Data ID	Laminate Thickness (in.)	Styrene Content (%)	Gel Time (min.)	Resin Flow (lb/min)	Air Flow (fpm)	Suppressant Content (%)	Styrene Emissions (% resin wt)	Styrene Emissions (% monomer)
1	111595B	0.040	35	30	4	100		6.6%	18.8%
2	111695A	0.080	42	15	2	50		13.9%	33.1%
3A	111695B	0.040	42	15	2	50		13.0%	31.0%
3B	113095A	0.040	42	15	2	50		14.2%	33.9%
4A	112895A	0.080	35	30	4	100		6.7%	19.0%
4B	112995B	0.080	35	30	4	100		6.9%	19.6%
5	112895B	0.040	42	30	2	100		15.0%	35.8%
6	112995A	0.080	35	15	4	50		6.4%	18.2%
7	120495A	0.040	35	15	4	50		8.2%	23.3%
8	120595B	0.080	42	30	2	100		16.0%	38.0%
9	120695A	0.040	35	15	2	100		8.0%	22.9%
10	120695B	0.080	42	30	4	50		9.4%	22.4%
11A	120795A	0.040	42	30	4	50		12.1%	28.7%
11B	121195B	0.040	42	30	4	50		12.8%	30.4%
12A	120895A	0.080	35	15	2	100		6.3%	18.1%
12B	121295A	0.080	35	15	2	100		5.6%	16.1%
13	120895B	0.080	35	30	2	50		6.5%	18.6%
14	121495B	0.040	42	15	4	100		10.4%	24.8%
15	121295B	0.040	35	30	2	50		7.2%	20.6%
16	121495A	0.080	42	15	4	100		10.7%	25.4%

Phase I runs - emissions as % resin:

Regression Output:

Constant		-0.1941			
Std Err of Y Est		0.0143			
R Squared		0.8698			
No. of Observations		20			
Degrees of Freedom		14			
	Thickness	% Styrene	Gel Time	Resin Flow	Air Flow
X Coefficient(s)	-0.19881	0.00827	0.00038	-0.00854	0.00003
Std Err of Coef.	0.16587	0.00095	0.00044	0.00327	0.00013

Table 2.6 - One-Variable (Styrene) Linear Regression for Mechanical Application

Run No.	Data ID	Laminate Thickness (in.)	Styrene Content (%)	Gel Time (min.)	Resin Flow (lb/min)	Air Flow (fpm)	Styrene Emissions (% resin wt)	Styrene Emissions (% monomer)
1	111595B	0.040	35	30	4	100	6.6%	18.8%
2	111695A	0.080	42	15	2	50	13.9%	33.1%
3A	111695B	0.040	42	15	2	50	13.0%	31.0%
3B	113095A	0.040	42	15	2	50	14.2%	33.9%
4A	112895A	0.080	35	30	4	100	6.7%	19.0%
4B	112995B	0.080	35	30	4	100	6.9%	19.6%
5	112895B	0.040	42	30	2	100	15.0%	35.8%
6	112995A	0.080	35	15	4	50	6.4%	18.2%
7	120495A	0.040	35	15	4	50	8.2%	23.3%
8	120595B	0.080	42	30	2	100	16.0%	38.0%
9	120695A	0.040	35	15	2	100	8.0%	22.9%
10	120695B	0.080	42	30	4	50	9.4%	22.4%
11A	120795A	0.040	42	30	4	50	12.1%	28.7%
11B	121195B	0.040	42	30	4	50	12.8%	30.4%
12A	120895A	0.080	35	15	2	100	6.3%	18.1%
12B	121295A	0.080	35	15	2	100	5.6%	16.1%
13	120895B	0.080	35	30	2	50	6.5%	18.6%
14	121495B	0.040	42	15	4	100	10.4%	24.8%
15	121295B	0.040	35	30	2	50	7.2%	20.6%
16	121495A	0.080	42	15	4	100	10.7%	25.4%
1 (& 10)	022296A	0.080	42	30	4	100	9.1%	21.7%
lg female	092596B		44.4				12.1%	27.3%
lg male	101796B		44.4				13.4%	30.2%
thick lam	061296B	0.187	44.4				10.6%	23.9%
lg female	092696A		44.4				12.5%	28.2%
	120595A	0.080	44.4				16.0%	36.0%

Regression Output:		
Constant		-0.18023
Std Err of Y Est		0.01818
R Squared		0.71447
No. of Observations		26
Degrees of Freedom		24
	X Coefficient(s)	0.00714
	Std Err of Coef.	0.00092

Table 2.7 - Suppressant Control Factor for Spray Lay-up Emissions

run	styrene content (% resin)	resin flow	suppressant level (% resin)	styrene emissions (% resin)	styrene emissions (% styrene)	
080896A	33.8	2	0	8.3%	24.6%	
080896B	33.8	4	0	8.4%	25.0%	24.2%
081296B	33.8	4	0	7.9%	23.3%	
080696A	44.4	2	0	13.1%	29.5%	
061396A	44.4	4	0	9.9%	22.3%	
081596A	48.8	2	0	15.5%	31.8%	
081696A	48.8	4	0	12.6%	25.7%	
081396B	33.8	2	1.5	6.3%	18.6%	
081396A	33.8	4	1.5	4.2%	12.4%	
080796A	44.4	2	1.5	10.1%	22.9%	
061396B	44.4	4	1.5	5.8%	13.2%	
082796A	48.8	2	1.5	9.2%	18.9%	
081696B	48.8	4	1.5	6.0%	12.4%	

% styrene	flow	control factor	control factor
33.8	2	0.759	0.640
33.8	4	0.515	
44.4	2	0.771	0.691
44.4	4	0.586	
48.8	2	0.594	0.541
48.8	4	0.476	
		average	**0.617**

Table 2.8 - Control Factor for Controlled Spraying of Spray Lay-up Emissions

Data ID	Thickness (in.)	Content (%)	Time (min.)	Flow (lb/min)	Flow (fpm)		styrene emissions (% resin)	styrene emissions (% styrene)	
120695B	0.080	42	30	4	50		9.4%	22.4%	
022296A	0.080	42	30	4	100		9.1%	21.7%	
022196A	0.080	42	30	4	100	Controlled	7.3%	17.4%	
022196B	0.080	42	30	4	100	Controlled	7.4%	17.6%	
022196C	0.080	42	30	4	100	Controlled	7.2%	17.1%	0.789
061296B	0.187	44.4					10.6%	23.9%	
061296A	0.187	44.4				Controlled	7.5%	17.0%	
080196B	0.187	44.4				Controlled	6.1%	13.8%	0.642
092596B		44.4					12.1%	27.3%	
092596A		44.4				Controlled	10.0%	22.5%	0.826
101796B		44.4					13.4%	30.2%	
101796A		44.4				Controlled	10.9%	24.6%	0.813
								average	***0.768***

Non-Atomized Application Factor

The calculation of the non-atomized application reduction factor, which is the emission factor with non-atomized application equipment divided by the emissions factor with typical spray application equipment, is shown in **Table 2.9** below. Six data sets are compared to investigate the effect of non-atomized application equipment on emissions at one monomer content (44.4% styrene). The average control factor for non-atomized application equipment is **0.51**.

Table 2.9 - Non-Spray Equipment Control Factor for Mechanical Application

Data ID	Styrene Content (%)	Resin Flow (lb/min)		styrene emissions (% resin)	styrene emissions (% styrene)
080696A	44.4	2	0% suppressant	13.1%	29.5%
061396A	44.4	4	0% suppressant	9.9%	22.3%
022697B	44.4			7.9%	17.9%
022797A	44.4		flow coater	5.0%	11.4%
022797B	44.4		flow coater	5.1%	11.6%
022797C	44.4		pressure-fed roller	5.7%	12.9%
				average	***0.511***

2.5.3 - Gelcoat Spraying

Emission Factor

The linear regression fit for all five of the Phase I experimental variables (as a function of consumed resin) is shown in **Table 2.10** below. The corresponding equation for estimating styrene emissions is:

$$\textit{emissions (\% resin)} = -5.34119 \times \textit{thickness} + 0.00897 \times \textit{\% styrene} + 0.00083 \times \textit{gel time} - 0.00018 \times \textit{resin flow} + 0.00004 \times \textit{air flow} - 0.0476 \quad \text{[eq 6]}$$

The overall fit is relatively good ($r^2 = 0.8999$) and the standard error of the equation is only 0.012. However, the coefficients for gel time, resin flow, and air flow have relatively large standard error values, and the coefficients for the gelcoat resin flow and air flow are nearly zero. This suggests that these variables are not good descriptors for the styrene emissions from gelcoat spraying. Furthermore, the gelcoat thickness, gel time, resin flow and air flow variables would be practically impossible to effectively regulate as part of any plant permit.

The linear regression fit for just the styrene content factor is shown in **Table 2.11** below. The corresponding equation for estimating styrene emissions is:

$$\textit{emissions (as \% resin)} = 0.01036 \times \textit{\% styrene} - 0.1950 \quad \text{[eq 7]}$$

Table 2.10 - Five-Variable Linear Regression for Gelcoat Emissions

Run #	ID	(in.)	(%)	(min.)	(lb/min)	(fpm)	(% resin wt)
1	101195A	0.018	35	20	4	100	18.8%
2	101195B	0.024	40	10	2	50	18.3%
3A	101295A	0.018	40	10	2	50	21.3%
3B	101695B	0.018	40	10	2	50	23.2%
4A	101295B	0.024	35	20	4	100	15.9%
4B	101695A	0.024	35	20	4	100	14.6%
5	101395A	0.024	40	20	2	100	19.6%
6	101395B	0.024	35	10	4	50	15.2%
7	101695C	0.018	35	10	4	50	17.7%
8	101795A	0.018	40	20	2	100	24.3%
9	101795B	0.018	35	10	2	100	20.3%
10	101895A	0.024	40	20	4	50	21.0%
11A	101895B	0.018	40	20	4	50	24.7%
11B	102395A	0.018	40	20	4	50	24.8%
12A	101995A	0.024	35	10	2	100	15.9%
12B	102395B	0.024	35	10	2	100	15.7%
13	101995B	0.024	35	20	2	50	15.9%
14	101995C	0.018	40	10	4	100	22.4%
15	102495A	0.018	35	20	2	50	17.5%
16	102495B	0.024	40	10	4	100	20.5%
1 (& 14)	030596A	0.018	40	10	4	100	21.1%

Phase I runs - emissions as % resin:

Regression Output:					
Constant		-0.0476			
Std Err of Y Est		0.0120			
R Squared		0.8999			
No. of Observations		21			
Degrees of Freedom		15			
	(in.)	(%)	(min.)	(lb/min)	(fpm)
X Coefficient(s)	-5.34119	0.00897	0.00083	0.00018	4.3E-05
Std Err of Coef.	0.90498	0.00109	0.00053	0.00265	0.00011

Table 2.11 - One-Variable (Styrene) Linear Regression for Gelcoat Emissions

Phase I runs - emissions as % resin weight:

Regression Output:		
Constant		-0.1950
Std Err of Y Est		0.0198
R Squared		0.6539
No. of Observations		21
Degrees of Freedom		19
X Coefficient(s)	0.01036	
Std Err of Coef.	0.00173	

Table 2.12 - Control Factor for Controlled Spraying of Gelcoat

	Data ID	Laminate Thickness (in.)	Styrene Content (%)	Gel Time (min.)	Resin Flow (lb/min)	Air Flow (fpm)		styrene emissions (% resin)	(% styrene)	
14	101995C	0.018	40	10	4	100		22.4%	56.0%	
1	030596A	0.018	40	10	4	100		21.1%	52.7%	
2	030796A	0.018	40	10	4	100	Controlled	12.7%	31.9%	
4A	030796B	0.018	40	10	4	100	Controlled	12.7%	31.7%	
4B	030796D	0.018	40	10	4	100	Controlled	12.5%	31.3%	0.581
lg female	091796A		35					13.0%	37.4%	
lg female	091896A		35				Controlled	10.8%	31.0%	0.831
lg male	101596A		35					18.5%	52.8%	
lg male	101696A		35				Controlled	14.3%	41.6%	0.773
									average	**0.728**

The data for both Phase I and Phase II (21 data sets) is used. The overall fit is not as good as for all five factors using just the Phase I data set ($r^2 = 0.6539$), but the standard error of the equation is still only 0.0198, which is acceptable.

Controlled-Spraying Factor

The calculation of the controlled-spraying reduction factor for gelcoat spraying, which is the emissions factor for controlled-spraying divided by the emissions factor for conventional spraying, is shown in **Table 2.12** below. Nine data sets are compared to investigate the effect of controlled-spraying on gelcoat emissions at two different monomer content levels. A possible relationship between styrene monomer content and controlled-spraying effect is observed for this data - the factor is less at the higher styrene content level. The controlled-spraying factor for gelcoat spraying varies from 0.58 to 0.83, with an average value of **0.73**.

2.5.4 - Filament Winding

The Dow Study of filament winding had a total of 20 experimental runs - ten runs with suppressed resin and ten runs with non-suppressed resin.

Emission Factor

The linear regression fit for the ten data points for non-suppressed resin emissions in the Dow Study, using all three of the experimental variables (styrene content, part size, and temperature), is shown in **Table 2.13**. The corresponding equation for estimating styrene emissions is:

$$\textit{emissions (\% resin)} = (0.002532 \times \%\ \textit{styrene}) - (0.00013 \times \textit{temp}) + (0.000773 \times \textit{size}) - 0.02716 \qquad \text{[eq 8]}$$

The overall fit is good ($r^2 = 0.9214$) and the standard error of the equation is only 0.00849. However, the coefficients for part size and temperature have relatively large standard error values and relatively insignificant coefficients. This suggests that these variables are not good descriptors for the styrene emissions from filament winding. Furthermore, both the part size and temperature variables would be practically impossible to effectively regulate as part of any plant permit.

The linear regression fit for just the styrene content variable is shown in **Table 2.14** below. The corresponding one-variable equation for estimating styrene emissions for filament winding is:

$$\textit{emissions (\% resin)} = (0.002746 \times \%\ \textit{styrene}) - 0.02980 \qquad \text{[eq 9]}$$

The overall fit is still quite good ($r^2 = 0.7396$), and the standard error of the equation is only 0.03065, which is quite acceptable.

Table 2.13 - Four-Variable Linear Regression for Filament Winding

	Filament Winding tests				Emissions	Emissions	Emissions
					Based on	Based on	Based on
Run	%Sty	Supp	Temp	Size	% Resin	% Styrene	% Resin wt
9	33	0	85	6	5.9	17.9%	5.9%
7	48	0	73	33	11.8	24.5%	11.8%
16	33	0	85	33	6.3	19.1%	6.3%
13	48	0	73	6	8.3	17.4%	8.3%
14	33	0	73	33	7.2	21.8%	7.2%
6	48	0	85	33	10.3	21.4%	10.3%
19	48	0	85	33	10.3	21.4%	10.3%
2	48	0	85	6	8.6	17.9%	8.6%
18	48	0	85	33	12.0	24.9%	12.0%
1	33	0	73	6	4.9	14.9%	4.9%
15	48	1.5	85	33	5.0	10.3%	5.0%
17	33	1.5	73	6	3.7	11.2%	3.7%
20	33	1.5	73	6	3.7	11.2%	3.7%
5	33	1.5	85	6	5.4	16.5%	5.4%
4	33	1.5	73	33	4.8	14.4%	4.8%
3	48	1.5	85	33	4.0	8.4%	4.0%
8	48	1.5	73	6	4.9	10.3%	4.9%
12	48	1.5	73	33	4.6	9.6%	4.6%
11	48	1.5	85	6	6.6	13.8%	6.6%
10	33	1.5	73	6	3.9	11.8%	3.9%

Regression Output:

Constant		-0.02716	
Std Err of Y Est		0.008491	
R Squared		0.921438	
No. of Observations		10	
Degrees of Freedon		6	
	%Sty	**Temp**	**Size**
X Coefficient(s)	0.002532	-0.00013	0.000773
Std Err of Coef.	0.000374	0.000468	0.000208

Table 2.14 - One-Variable (Styrene) Linear Regression for Filament Winding

Filament Winding Tests					**Emissions**	Emissions	Emissions
Non-Suppressed Only					**Based on**	Based on	Based on
Run	**%Sty**	**Supp**	**Temp**	**Size**	**% Resin**	% Styrene	% Resin
14	**33**	**0**	**73**	**33**	**7.21**	21.8%	7.2%
1	**33**	**0**	**73**	**6**	**4.93**	14.9%	4.9%
16	**33**	**0**	**85**	**33**	**6.29**	19.1%	6.3%
9	**33**	**0**	**85**	**6**	**5.9**	17.9%	5.9%
2	**48**	**0**	**85**	**6**	**8.58**	17.9%	8.6%
18	**48**	**0**	**85**	**33**	**11.96**	24.9%	12.0%
19	**48**	**0**	**85**	**33**	**10.28**	21.4%	10.3%
13	**48**	**0**	**73**	**6**	**8.34**	17.4%	8.3%
7	**48**	**0**	**73**	**33**	**11.77**	24.5%	11.8%
6	**48**	**0**	**85**	**33**	**10.28**	21.4%	10.3%

Regression Output:		**% Resin**
Constant		-0.02980
Std Err of Y Est		0.01339
R Squared		0.73963
No. of Observations		10
Degrees of Freedom		8
	%Sty	
X Coefficient(s)	0.002746	
Std Err of Coef.	0.000576	

Table 2.15 - Control Factor for Filament Winding with Suppressed Resin

Non-Suppressed versus Suppressed Resin

Run	**%Sty**	**Supp**	**Temp**	**Size**	**% Resin**	% Styrene	% Resin wt	0.001443 x %Sty	Factor
Small Part									
1	**33**	**0**	**73**	**6**	**4.93**	14.9%	4.9%		
9	**33**	**0**	**85**	**6**	**5.9**	17.9%	5.9%		
13	**48**	**0**	**73**	**6**	**8.34**	17.4%	8.3%		
2	**48**	**0**	**85**	**6**	**8.58**	17.9%	8.6%		
17	**33**	**1.5**	**73**	**6**	**3.68**	11.2%	3.7%		
20	**33**	**1.5**	**73**	**6**	**3.68**	11.2%	3.7%	3.7%	0.76
10	**33**	**1.5**	**73**	**6**	**3.88**	11.8%	3.9%		
5	**33**	**1.5**	**85**	**6**	**5.44**	16.5%	5.4%		0.92
8	**48**	**1.5**	**73**	**6**	**4.92**	10.3%	4.9%		0.59
11	**48**	**1.5**	**85**	**6**	**6.6**	13.8%	6.6%		0.77
Large Part								Small Part AVG:	0.76
14	**33**	**0**	**73**	**33**	**7.21**	21.8%	7.2%	6.8%	
16	**33**	**0**	**85**	**33**	**6.29**	19.1%	6.3%		
7	**48**	**0**	**73**	**33**	**11.77**	24.5%	11.8%		
6	**48**	**0**	**85**	**33**	**10.28**	21.4%	10.3%		
18	**48**	**0**	**85**	**33**	**11.96**	24.9%	12.0%	10.8%	
19	**48**	**0**	**85**	**33**	**10.28**	21.4%	10.3%		
4	**33**	**1.5**	**73/85**	**33**	**4.75**	14.4%	4.8%		0.70
12	**48**	**1.5**	**73**	**33**	**4.62**	9.6%	4.6%		0.39
15	**48**	**1.5**	**85**	**33**	**4.95**	10.3%	5.0%	4.5%	0.41
3	**48**	**1.5**	**85**	**33**	**4.03**	8.4%	4.0%		
								Large Part AVG:	0.50
								Overall AVG:	**0.65**
								CFA Predicted:	**0.62**

Suppressant Control Factor

The calculation of the suppressant control factor for filament winding, which is the emission factor for resin with suppressant divided by the emission factor for resin without suppressant, is shown in **Table 2.15** on the previous page. Ten data sets (suppressed and non-suppressed) are compared to investigate the effect of suppressant on emissions at two different styrene monomer content. No obvious relationship is observed between the styrene monomer content and suppressant effect for this data. The suppressant factor varies widely from 0.39 to 0.92, with an average value of **0.65**.

2.6 - CFA Emission Models

The results of the CFA emission testing discussed in the previous sections are now converted into algebraic expressions, henceforth referred to as "Emission Models." A separate CFA Emission Model is developed for manual resin application (hand lay-up), mechanical resin application (spray lay-up), and gelcoat spraying. Each Emission Model estimates the styrene emission rate for the corresponding process. The manual resin application (hand lay-up), mechanical resin application (spray lay-up) and gelcoat spraying models are based upon the responses to the chief process variables measured in the Phase I CFA testing and the effects of the emission reduction techniques measured in the Phase II CFA testing. No distinction between the emission rates from filled and unfilled resin systems was observed during the CFA testing, so the effect of filler was not incorporated into any model. Resin fillers appear to merely extend the amount of resin used to manufacture a part, and do not significantly affect an emission rate based upon the consumption of neat (unfilled) resin or available styrene monomer.

The results of the Dow study of filament winding emissions also discussed in the previous section are converted into an algebraic expression, henceforth referred to as the "Filament Winding Model." This model is based upon the experimental responses to the chief process variables and the effects of resin suppressant measured in the Dow testing.

Both the multi-variable and the single variable models are presented below for completeness. As discussed earlier, the multi-variable models are not suitable for regulatory purposes. However, the one-variable (styrene content) models are suitable and have acceptable scatter for the purpose of characterizing styrene emissions across an entire industry such as reinforced plastics. The CFA Emission Models for non-suppressed resins and gel coat are plotted in **Figure 2.1** at the end of this section. The CFA Emission Models for vapor-suppressed resins are shown in **Figure 2.2**. The emission factors are also listed in a handy tabular format in **Table 2.16**.

2.6.1 - Manual Resin Application (Hand Lay-up) Model

The general emission model for manual resin application (hand lay-up) is:

$$\textit{Emission Rate} = \textit{Resin Usage} \times \textit{Emission Factor} \times \textit{Suppressant Factor} \qquad \text{[eq 10]}$$

The four-variable emission model is:

$$\begin{aligned}\textit{Emission Rate} = \textit{Resin Usage} \times (&-0.46365 \times \textit{thickness} + 0.00265 \times \textit{\%styrene} \\ &+ 0.00068 \times \textit{gel time} + 0.00003 \times \textit{air flow} - 0.0320)\end{aligned} \qquad \text{[eq 11]}$$

And the one-variable emission model, which is also one of the CFA matrix elements, is:

$$\begin{aligned}\textit{Emission Rate} = \textit{Resin Usage} \times (0.00286 \times \textit{\% styrene} - 0.0529) \\ \times \left[1.00 \text{ <or> } \frac{0.0004476 \times \textit{\% styrene} + 0.01289}{0.00286 \times \textit{\% styrene} - 0.0529}\right]\end{aligned} \qquad \text{[eq 12]}$$

2.6.2 - Mechanical Resin Application (Spray Lay-up) Model

The general emission model for mechanical resin application (spray lay-up) for both filled and unfilled resins is:

$$\begin{aligned}\textit{Emission Rate} = \textit{Resin Usage} \times \textit{Emission Factor} \times \textit{Suppressant Factor} \\ \times [\textit{Controlled Spray Factor} \text{ <or> } \textit{Non-Spray Factor}]\end{aligned} \qquad \text{[eq 13]}$$

The five-variable emission model is:

$$\begin{aligned}\textit{Emission Rate} = \textit{Resin Usage} \times (&-0.19881 \times \textit{thickness} + 0.00827 \times \textit{\% styrene} \\ &+ 0.00038 \times \textit{gel time} - 0.00854 \times \textit{resin flow} \\ &+ 0.00003 \times \textit{air flow} - 0.1941) \times [1.00 \text{ <or> } 0.62] \\ &\times [1.00 \text{ <or> } 0.77] \text{ <or> } [1.00 \text{ <or> } 0.51]\end{aligned} \qquad \text{[eq 14]}$$

And the one-variable emission model, which is also one of the CFA matrix elements, is:

$$\begin{aligned}\textit{Emission Rate} = \textit{Resin Usage} \times (0.00714 \times \textit{\% styrene} - 0.180) \times [1.00 \text{ <or> } 0.62] \\ \times [1.00 \text{ <or> } 0.77] \text{ <or> } [1.00 \text{ <or> } 0.51]\end{aligned} \qquad \text{[eq 15]}$$

2.6.3 - Gelcoat Spraying Model

The general emission model for gelcoat spraying is:

Emission Rate = Resin Usage x Emission Factor x Controlled Spray Factor [eq 16]

The five-variable emission model is:

Emission Rate = Resin Usage x (-5.34119 x thickness + 0.00897 x % styrene
+ 0.00083 x gel time - 0.00018 x resin flow
+ 0.00004 x air flow - 0.0476) x [1.00 <or> 0.73] [eq 17]

And the one-variable emission model, which is also one of the CFA matrix elements, is:

Emission Rate = Resin Usage x (0.01036 x % styrene - 0.1950)
x [1.00 <or> 0.73] [eq 18]

2.6.4 - Filament Winding Model

The general emission model for filament winding is:

Emission Rate = Resin Usage x Emission Factor x Suppressant Factor [eq 19]

The four-variable emission model (including suppressant as a variable) is:

Emission Rate = Resin Usage x ((0.002532 x % styrene) - (0.00013 x temp)
+ (0.000773 x size) - 0.02716)) x [1.00 <or> 0.65] [eq 20]

And the one-variable emission model, which is also one of the CFA matrix elements, is:

Emission Rate = Resin Usage x ((0.002746 x % styrene) - 0.02980)
x [1.00 <or> 0.65] [eq 21]

Figure 2.1 - Plot of the CFA Emission Models for Non-Suppressed Resin (emissions versus % styrene)

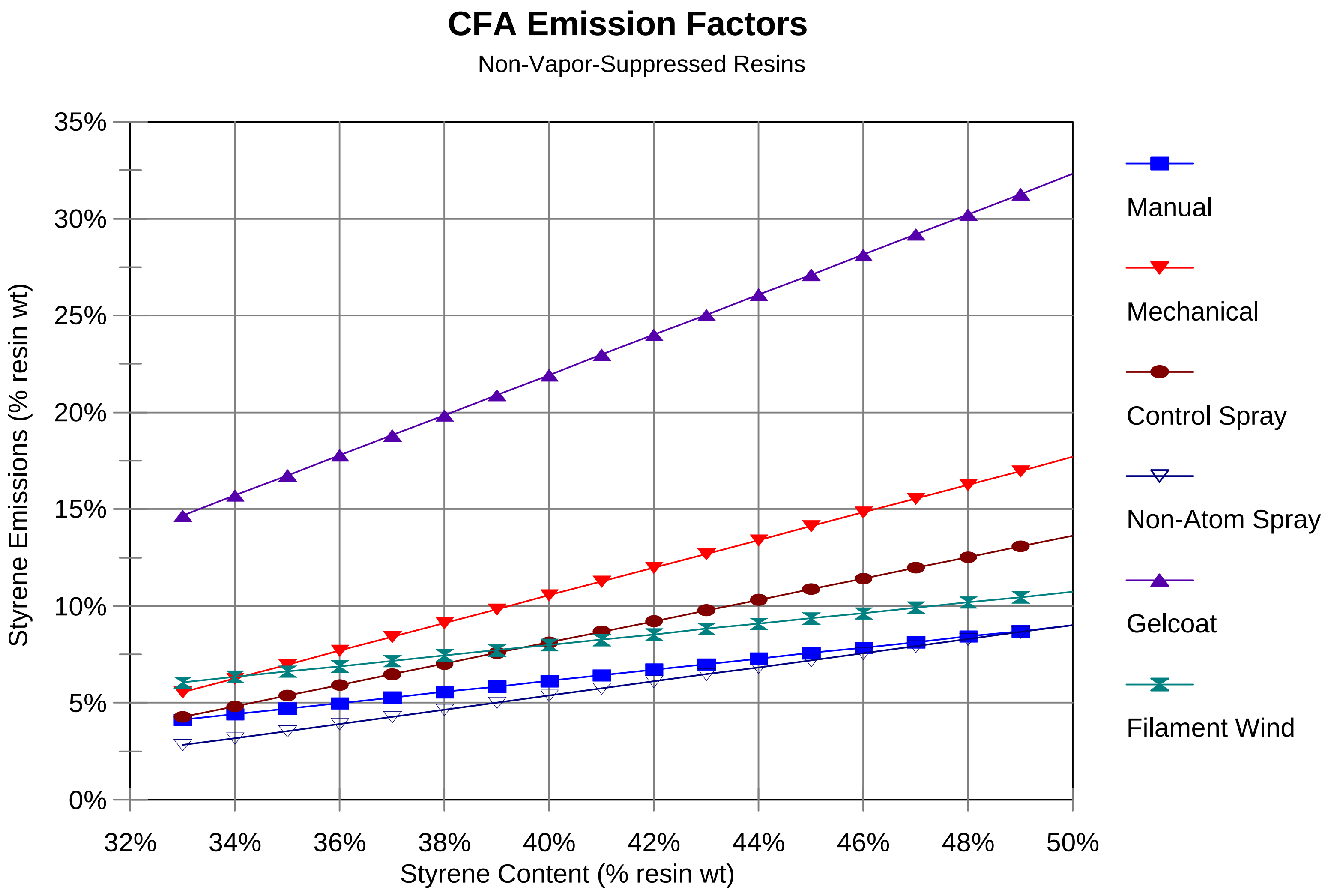

Figure 2.2 - Plot of the CFA Emission Models for Vapor-Suppressed Resin (emissions versus % styrene)

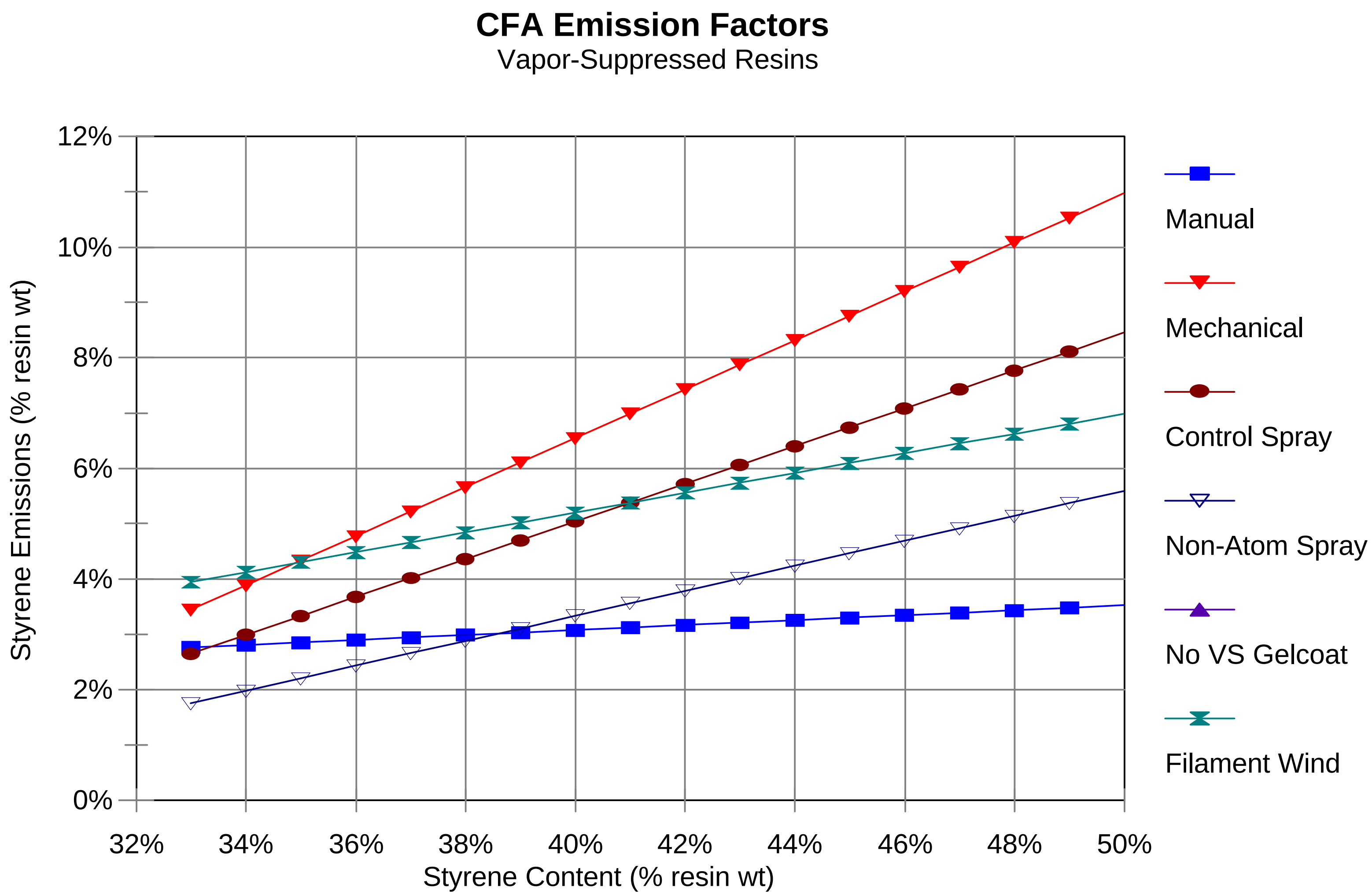

Table 2.16 - Emission Factors for the CFA Emission Models

CFA EMISSION FACTORS

(Styrene Emission Rates listed as % of Neat Resin Weight as applied)

Styrene Content % wt	Manual Resin Application		Mechanical Resin Application						Gelcoat Application		Filament Winding	
	Bucket & Tool		Uncontrolled Spray		Controlled Spray		Non-Atomized Application		Uncontrolled Spray	Controlled Spray		
	Non-Vapor Suppressed	Vapor-Suppressed	Non-Vapor Suppressed	Vapor-Suppressed	Non-Vapor Suppressed	Vapor-Suppressed	Non-Vapor Suppressed	Vapor-Suppressed			Non-Vapor Suppressed	Vapor-Suppressed
33%	4.1%	2.8%	5.6%	3.4%	4.3%	*	**	*	14.7%	10.7%	6.1%	4.0%
34%	4.4%	2.8%	6.3%	3.9%	4.8%	*	**	*	15.7%	11.5%	6.4%	4.1%
35%	4.7%	2.9%	7.0%	4.3%	5.4%	*	**	*	16.8%	12.2%	6.6%	4.3%
36%	5.0%	2.9%	7.7%	4.8%	5.9%	*	**	*	17.8%	13.0%	6.9%	4.5%
37%	5.3%	2.9%	8.4%	5.2%	6.5%	*	**	*	18.8%	13.7%	7.2%	4.7%
38%	5.6%	3.0%	9.1%	5.7%	7.0%	to	**	to	19.9%	14.5%	7.5%	4.8%
39%	5.9%	3.0%	9.8%	6.1%	7.6%	be	**	be	20.9%	15.3%	7.7%	5.0%
40%	6.2%	3.1%	10.6%	6.5%	8.1%	determined	**	determined	21.9%	16.0%	8.0%	5.2%
41%	6.4%	3.1%	11.3%	7.0%	8.7%	by	**	by	23.0%	16.8%	8.3%	5.4%
42%	6.7%	3.2%	12.0%	7.4%	9.2%	05/15/98	6.1%	05/15/98	24.0%	17.5%	8.6%	5.6%
43%	7.0%	3.2%	12.7%	7.9%	9.8%	*	6.5%	*	25.0%	18.3%	8.8%	5.7%
44%	7.3%	3.3%	13.4%	8.3%	10.3%	*	6.8%	*	26.1%	19.0%	9.1%	5.9%
45%	7.6%	3.3%	14.1%	8.8%	10.9%	*	7.2%	*	27.1%	19.8%	9.4%	6.1%
46%	7.9%	3.3%	14.8%	9.2%	11.4%	*	7.6%	*	28.2%	20.6%	9.7%	6.3%
47%	8.2%	3.4%	15.6%	9.6%	12.0%	*	**	*	29.2%	21.3%	9.9%	6.5%
48%	8.4%	3.4%	16.3%	10.1%	12.5%	*	**	*	30.2%	22.1%	10.2%	6.6%
49%	8.7%	3.5%	17.0%	10.5%	13.1%	*	**	*	31.3%	22.8%	10.5%	6.8%
50%	9.0%	3.5%	17.7%	11.0%	13.6%	*	**	*	32.3%	23.6%	10.8%	7.0%

prepared on 1/15/98 - emission rates based on revised 12/8/97 CFA Matrix Models
** outside the tested range

Section 3 - Verification of CFA Emission Models

3.1 - Available Emissions Data

The following two sources of existing available data for estimating the styrene emissions from the reinforced plastics industry have been provided by the EPA:

EPA April 1997 Open Molding Database styrene emission equations
RTI Emissions Study

Discussions of each source of data, and comparisons of the emission data to the RTI Emission Models, are provided in the next two sections. The purpose of these comparisons is to gauge the relative agreement between the CFA Emission Models and the existing EPA emissions data.

3.2 - EPA Emission Equations

The EPA listed the following four equations for estimating the styrene emission factor as a first-order (or linear) function of the available styrene monomer for the corresponding subcategories in open molding:

Corrosion Hand Lay-up and Non-Corrosion Hand Lay-up (Filled & Unfilled):

$$\textit{Emission Factor (\% styrene)} = 15.7\% - (0.31 \times (42\% - \% \textit{ styrene})) \quad \text{[eq 22]}$$

Corrosion Spray Lay-up and Non-Corrosion Spray Lay-up (Unfilled):

$$\textit{Emission Factor (\% styrene)} = 30.2\% - (1.47 \times (42\% - \% \textit{ styrene})) \quad \text{[eq 23]}$$

Non-Corrosion Spray Lay-up (Filled):

$$\textit{Emission Factor (\% styrene)} = 17.7\% - (0.66 \times (36.8\% - \% \textit{ styrene})) \quad \text{[eq 24]}$$

Filament Winding:

$$\textit{Emission Factor (\% styrene)} = 20.37\% - (0.14 \times (48\% - \% \textit{ styrene})) \quad \text{[eq 25]}$$

Plots of these EPA emission equations are provided in **Figure 3.1**. The emission values are reexpressed as a percentage of the resin weight to correspond with the CFA Models. This mathematical expression does not change the basic nature of the EPA equations.

The EPA emission equations are not actual data sets, because the data values used by the EPA to establish these relationships were not included with the Open Molding Database. Presumably, the EPA based these emission equations upon valid emission data, so the equations are included as representative of an, as yet unrevealed, set of emission data.

An equation for gelcoat spraying was not provided by the EPA, so no comparison can be made with the CFA Gelcoat Model. Moreover, the Open Molding database does not include any data on gelcoat styrene monomer content for non-corrosion sources, and only limited data for some corrosion sources. Therefore, any gelcoat equation considered by the EPA would not have the necessary input data to be useful. This fundamental problem is discussed in detail in the companion report entitled the "Analysis of the Open Molding Database."

The EPA also listed the following styrene emission control factors, which were used to adjust the styrene emissions for the different emission control techniques reported by the reinforced plastics sources in the Open Molding Database:

vapor suppressed resin, unfilled -	40% reduction	60% control factor
vapor suppressed resin, filled -	13% reduction	87% control factor
vacuum bagging -	45% reduction	55% control factor
thermal oxidation -	95% reduction	5% control factor

Again, the EPA control factors are not reported with supporting data, but are merely listed in the Open Molding database. As above, the EPA presumably based these styrene emission control factors upon valid emission test data, so the controls factors are included as representative of an, as yet unrevealed, set of emission data.

The EPA equations are compared with the CFA Emission Models across a full range of styrene monomer contents. As shown in **Figure 3.2**, the EPA hand lay-up equation closely agrees with the CFA Manual Resin Application (Hand Lay-up) Model, although the equation slightly over-estimates the effect of styrene emissions at higher styrene monomer contents. The curve for the CFA Mechanical Resin Application (Spray Lay-up) Model lies between the EPA spray lay-up equations for unfilled and filled resins, as shown in **Figure 3.3**. However, the CFA Mechanical Resin Application (Spray Lay-up) Model closely agrees with the merged, aggregate curve formed by merging the data points for the EPA equations for filled and unfilled resin with the corresponding data points for the CFA Mechanical Resin Application (Spray Lay-up) Model. The aggregate curve is developed by creating an equally-weighted, merged data set including the filled equation data points (weighted once), the unfilled equation data points (weighted once), and the CFA model data points (weighted twice to represent both filled and unfilled resins). A plot of the CFA Filament Winding Model is compared to the EPA equation in **Figure 3.4**.

A linear regression of the merged data point set, shown in **Table 3.1**, determines the slope and intercept of the aggregate spray lay-up curve. A comparison of the EPA control factors and CFA Model control factors is also listed in **Table 3.2**.

Figure 3.1 - Plots of the EPA's Emission Equations (emissions vs % styrene)

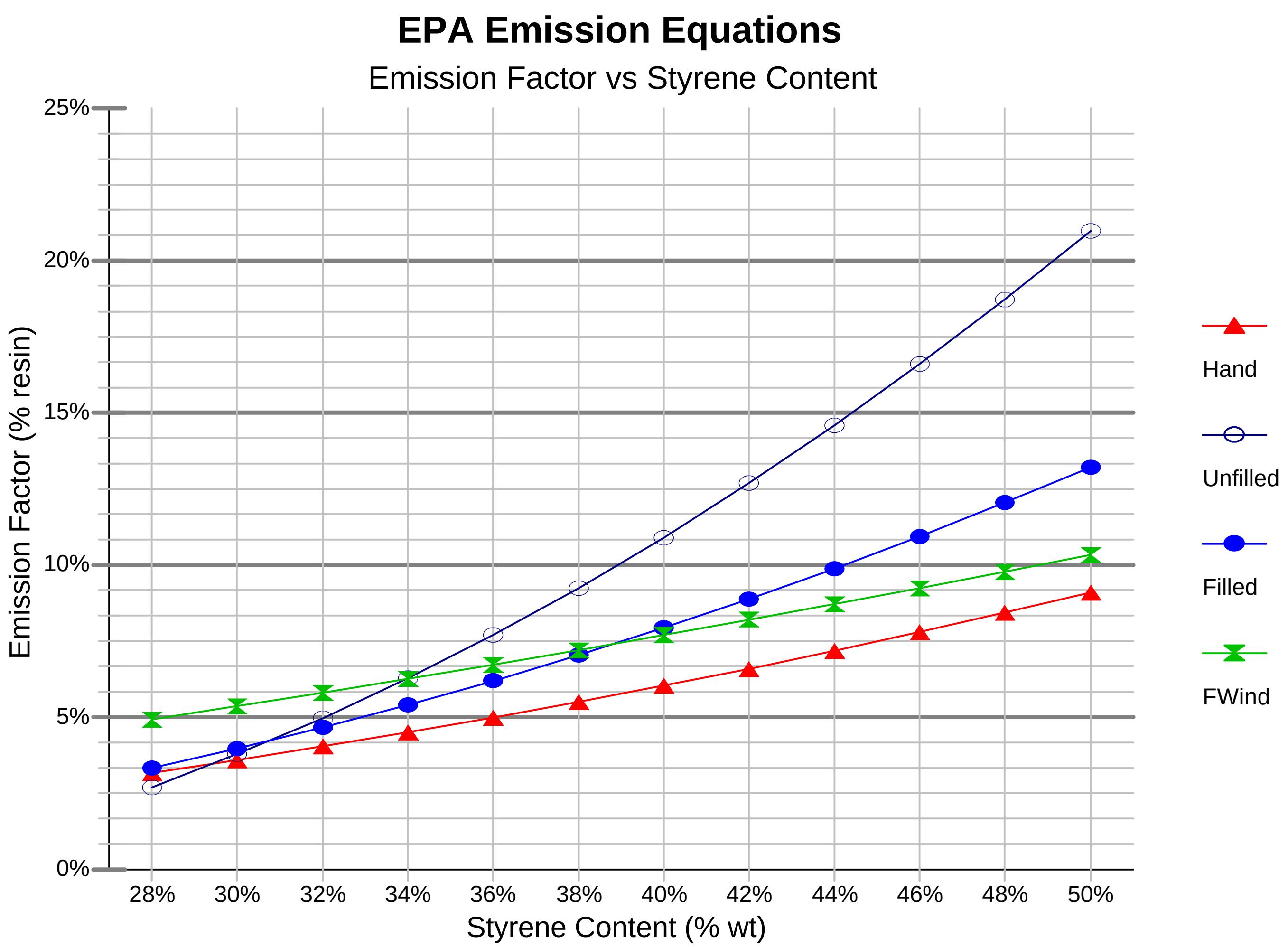

Figure 3.2 - Plot of the EPA Equation versus the CFA Model for Manual (Hand Lay-up)

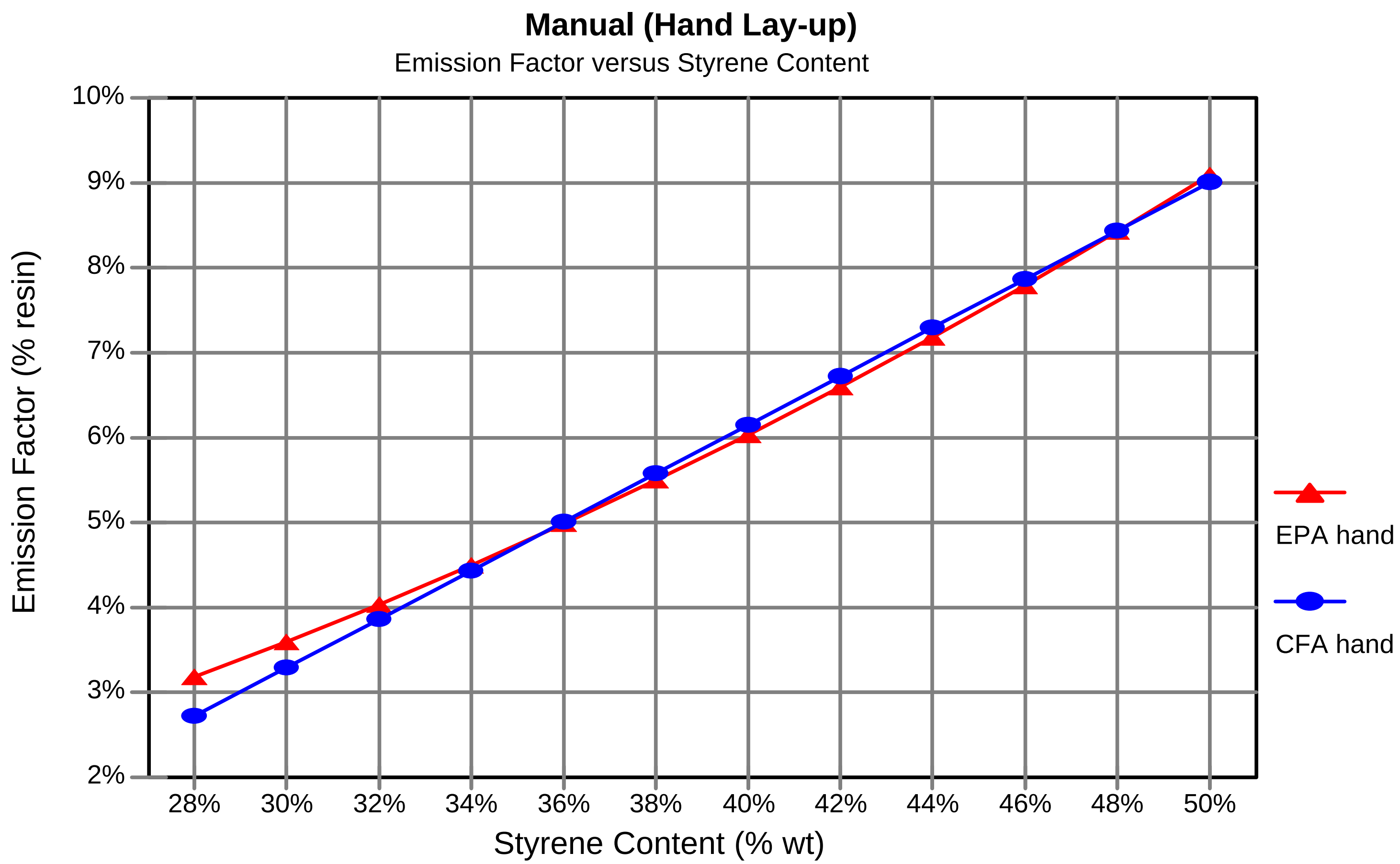

Figure 3.3 - Plots of the EPA Equations vs the CFA Model for Spray Lay-up

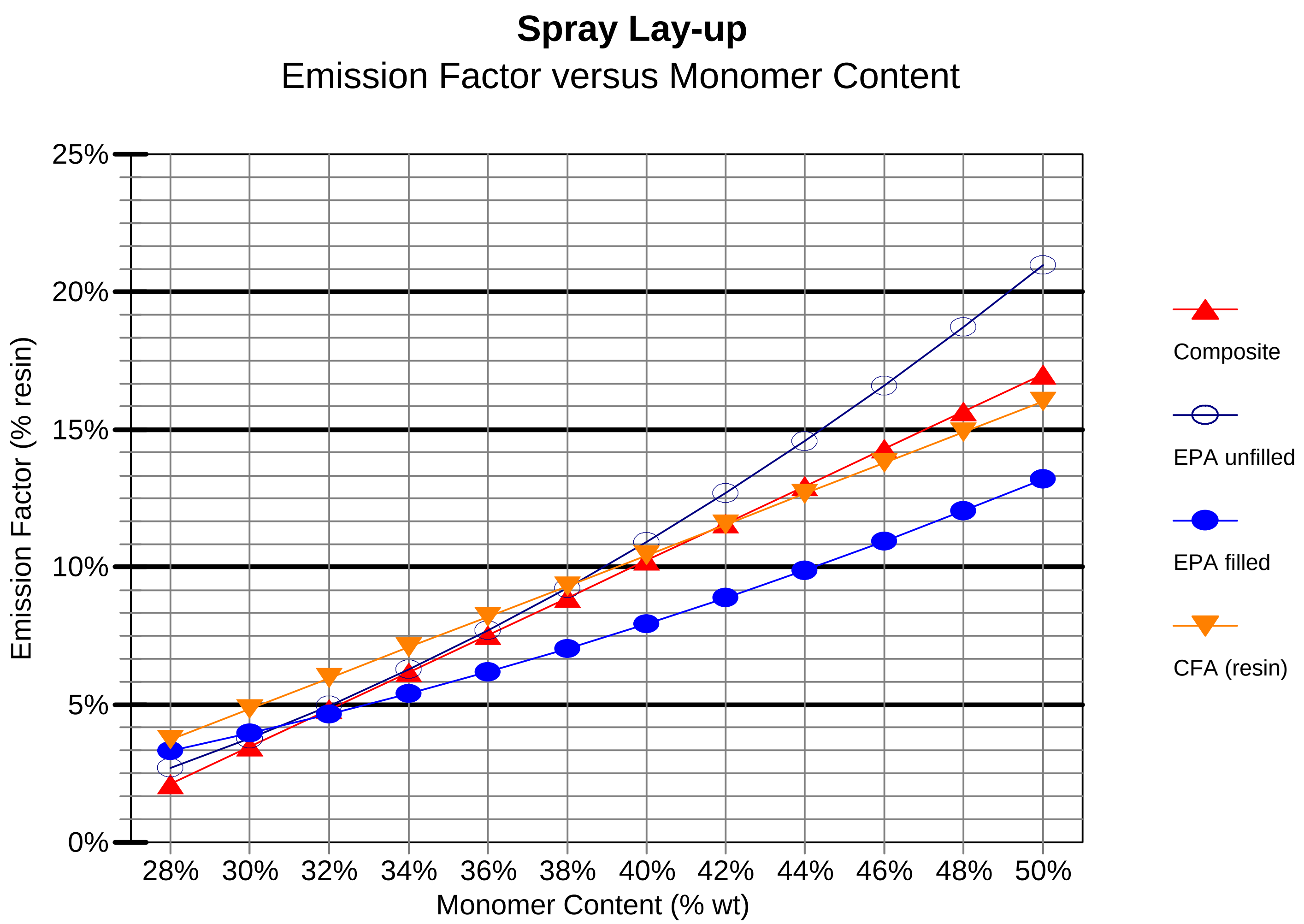

Figure 3.4 - Plot of the EPA Equation vs the CFA Model for Filament Winding

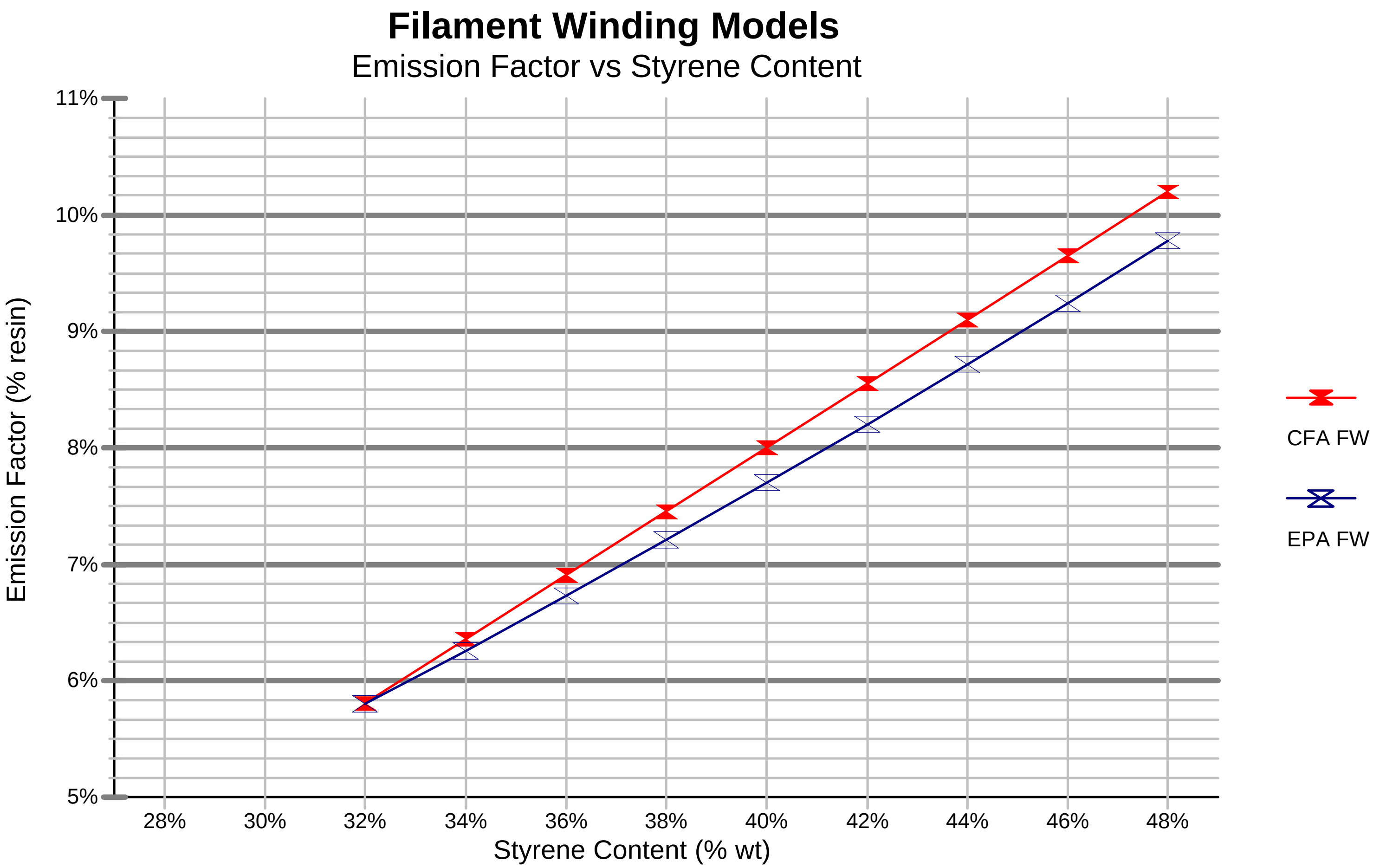

Table 3.1 - Linear Regression of the Composite Curve for Spray Lay-up

(CFA x 2 + EPA filled x 1+ EPA unfilled x1)

CFA Resin (filled & unfilled)				EPA filled		EPA unfilled	
% sty	% resin	% sty	% resin	% sty	% resin	% sty	% resin
28%	2.0%	28%	2.0%	28%	2.7%	28%	3.3%
30%	3.4%	30%	3.4%	30%	3.8%	30%	4.0%
32%	4.8%	32%	4.8%	32%	5.0%	32%	4.7%
34%	6.3%	34%	6.3%	34%	6.3%	34%	5.4%
36%	7.7%	36%	7.7%	36%	7.7%	36%	6.2%
38%	9.1%	38%	9.1%	38%	9.2%	38%	7.0%
40%	10.6%	40%	10.6%	40%	10.9%	40%	7.9%
42%	12.0%	42%	12.0%	42%	12.7%	42%	8.9%
44%	13.4%	44%	13.4%	44%	14.6%	44%	9.9%
46%	14.8%	46%	14.8%	46%	16.6%	46%	10.9%
48%	16.3%	48%	16.3%	48%	18.7%	48%	12.0%
50%	17.7%	50%	17.7%	50%	21.0%	50%	13.2%

Regression Output:		
Constant		-0.16846
Std Err of Y Est		0.015289
R Squared		0.907003
No. of Observations		48
Degrees of Freedom		46
X Coefficient(s)	0.67703	
Std Err of Coef.	0.031964	

Table 3.2 - Comparisons of the EPA & CFA Control Factors

	EPA Database Control Factor	RTI Control Factor	CFA Control Factor	Absolute Difference CFA vs RTI	Percentage Difference CFA vs RTI
Vapor Suppressant	0.60	0.62	0.62	0.00	0.0%
Controlled Spraying	not listed	0.70	0.77	0.07	10.0%
Non-Atomizing Application (flow coater & pressure-fed roller)	not listed	0.49 average	0.51	0.02	4.1%

3.3 - RTI Emissions Study

The summary of the test results for the RTI Emission Study are listed in **Table 3.3**. Based upon this summary, the RTI test results are compared to the CFA Emission Models for mechanical resin application (spray lay-up) and gelcoat spraying, with the following observations:

Near-perfect agreement with the emission factor for spray application of gelcoat (21.7% versus CFA's factor of 20.2% for 38.7% styrene content gelcoat).

Close agreement with the uncontrolled emission factor for spray lay-up application of resin (a more conservative 10.4% versus CFA's factor of 9.35% for 38.3% monomer).

Near-perfect agreement (a more generous 48% versus CFA's factor of 51%) with the reduced emission factor for non-atomizing application of resin (i.e., pressure-fed rollers and flow coating).

Perfect agreement (62.0% versus CFA's factor of 62%) with the reduced emission factor for spray application of vapor-suppressed resin.

Close agreement (a more generous 70% versus CFA's factor of 77%) with the reduced emission factor for controlled spray application of resin.

The results of the RTI Emission Study strongly verify the accuracy of the CFA Emission Models. It is remarkable that two independent test programs, conducted by different personnel at different times and places using different testing protocols would result in such near-perfect agreement.

Table 3.3 - Summary of RTI Test Results

Emission Results, Sept 1995 draft - pages 36 & 4
55 Test Runs

Description	Test Runs	Resin Formula	Styrene Content	Styrene Emission Factor	Styrene Emission Factor
			lb/lb	% styrene	% resin/gel
GELCOAT					
Regular	9	GF-1	38.7%	56.0%	21.7%
Low-VOC	9	GF-2	25.4%	54.2%	13.8%
RESIN					
Low-profile (normal spray)	2	RF-1	38.3%	27.1%	10.4%
Low-profile (controlled spray)	5	RF-1	38.3%	17.5%	6.7%
Low-styrene	3	RF-2	35.3%	17.3%	6.1%
Styrene-suppressed	3	RF-3 sup	43.5%	10.6%	4.6%
Styrene-suppressed + wax	3	RF-6 sup	43.3%	10.6%	4.6%
Neat BPO	2	RF-4 BPO	42.6%	26.2%	11.2%
BPO + thickener	2	RF-4 BPO	42.6%	21.3%	9.1%

REDUCED EMISSION FACTORS

Sept 1995 draft - page 60
emissions expressed in g/m2

Description	Styrene Content	Emission Reduction	Reduced Emission Factor
	lb/lb	%	%
Baseline - Normal Spray	38.3%	0.0%	100.0%
Controlled Spray		29.9%	70.1%
Flowcoater		52.0%	48.0%
Pressure-fed Roller		53.0%	47.0%
Suppressed Resin (w and w/o wax)		38.0%	62.0%
Lower Monomer	35.3%	11.0%	89.0%

Section 4 - Appendices

Appendix A - CFA Test Data (Phase I and Phase II)

Hand Lay-up Test Data

Run No.	Data ID	Laminate Thickness (in)	Resin Styrene (%)	Gel Time (min)	Air Flow (fpm)	Supressant Content (% wt)	Styrene Emissions (% resin wt)	Styrene Emissions % monomer
1	100295B	0.041	35	30	100	0	6.2%	17.7%
2	100295C	0.088	42	15	50	0	4.9%	11.7%
3A	092095A	0.041	42	15	50	0	7.2%	16.7%
3B	092695B	0.041	42	15	50	0	7.6%	17.7%
4A	100395A	0.088	35	30	100	0	4.2%	11.7%
4B	092695C	0.088	35	30	100	0	4.6%	13.1%
5	092595A	0.041	42	30	50	0	8.1%	19.2%
6	092695A	0.088	35	15	100	0	3.6%	10.1%
7	092795A	0.041	35	15	100	0	5.3%	14.7%
8	092795B	0.088	42	30	50	0	5.7%	13.5%
9	092795C	0.041	35	15	50	0	5.0%	14.0%
10	092895A	0.088	42	30	100	0	6.0%	14.3%
11A	092895B	0.041	42	30	100	0	8.9%	21.2%
11B	092995C	0.041	42	30	100	0	8.9%	21.0%
12A	092895C	0.088	35	15	50	0	3.4%	9.6%
12B	100295A	0.088	35	15	50	0	3.6%	10.1%
13	092995A	0.088	35	30	50	0	4.2%	11.9%
14	092995B	0.041	42	15	100	0	7.1%	17.1%
15	091995A	0.041	35	30	50	0	6.3%	17.6%
16	091995B	0.088	42	15	100	0	4.9%	11.5%
thick lam	052996B	0.176	44.4			0	7.2%	16.1%
thick lam	080196A	0.120	44.4			0	4.9%	11.0%
suppress	060596A	0.088	33.2			0	4.6%	13.8%
suppress	060396B	0.088	48.8			0	9.3%	19.0%
suppress	060496B	0.088	33.2			1.5	2.9%	8.7%
suppress	060496A	0.088	48.8			1.5	3.6%	7.4%
suppress	060596B	0.088	33.2			1.5	2.7%	8.1%
suppress	052996A	0.088	44.4			0	6.6%	15.0%
suppress	053096B	0.088	44.4			0	8.4%	18.8%
suppress	053096A	0.088	44.4			1.5	3.1%	7.0%

Spray Lay-up Test Data

Run No.	Data ID	Laminate Thickness (in.)	Styrene Content (%)	Gel Time (min.)	Resin Flow (lb/min)	Air Flow (fpm)		Styrene Emissions (% resin wt)	Styrene Emissions (% monomer)
1	111595B	0.040	35	30	4	100		6.6%	18.8%
2	111695A	0.080	42	15	2	50		13.9%	33.1%
3A	111695B	0.040	42	15	2	50		13.0%	31.0%
3B	113095A	0.040	42	15	2	50		14.2%	33.9%
4A	112895A	0.080	35	30	4	100		6.7%	19.0%
4B	112995B	0.080	35	30	4	100		6.9%	19.6%
5	112895B	0.040	42	30	2	100		15.0%	35.8%
6	112995A	0.080	35	15	4	50		6.4%	18.2%
7	120495A	0.040	35	15	4	50		8.2%	23.3%
8	120595B	0.080	42	30	2	100		16.0%	38.0%
9	120695A	0.040	35	15	2	100		8.0%	22.9%
10	120695B	0.080	42	30	4	50		9.4%	22.4%
11A	120795A	0.040	42	30	4	50		12.1%	28.7%
11B	121195B	0.040	42	30	4	50		12.8%	30.4%
12A	120895A	0.080	35	15	2	100		6.3%	18.1%
12B	121295A	0.080	35	15	2	100		5.6%	16.1%
13	120895B	0.080	35	30	2	50		6.5%	18.6%
14	121495B	0.040	42	15	4	100		10.4%	24.8%
15	121295B	0.040	35	30	2	50		7.2%	20.6%
16	121495A	0.080	42	15	4	100		10.7%	25.4%
1 (& 10)	022296A	0.080	42	30	4	100		9.1%	21.7%
2	022196A	0.080	42	30	4	100	Controlled	7.3%	17.4%
3	022296B	0.080	42	30	4	100	Optimized	8.4%	20.0%
4A	022196B	0.080	42	30	4	100	C & O	7.4%	17.6%
4B	022196C	0.080	42	30	4	100	C & O	7.2%	17.1%
filler test	090596A		45.7				unfilled	9.2%	20.1%
thick lam	061296B	0.187	44.4					10.6%	23.9%
thick lam	061296A	0.187	44.4				Controlled	7.5%	17.0%
thick lam	080196B	0.187	44.4				Controlled	6.1%	13.8%
bpo 2%	103096A		40				Controlled	5.4%	13.3%
bpo 2%	103096B		40				Controlled	5.8%	14.3%
bpo 2.75%	110696A		40				Controlled	5.1%	12.6%
mekp 2%	103096C		40				Controlled	5.5%	13.7%
mekp 2%	103196A		40				Controlled	5.5%	13.7%
mekp 1.25%	103196B		40				Controlled	5.7%	14.3%
lg female	092596A		44.4				Controlled	10.0%	22.5%
lg female	092596B		44.4					12.1%	27.3%
lg male	101796A		44.4				Controlled	10.9%	24.6%
lg male	101796B		44.4					13.4%	30.2%
suppress	080696A		44.4		2		0	13.1%	29.5%
suppress	080796A		44.4		2		1.5	10.1%	22.9%
suppress	061396A		44.4		4		0	9.9%	22.3%
suppress	061396B		44.4		4		1.5	5.8%	13.2%
suppress	080896A		33.8		2		0	8.3%	24.6%
suppress	081396B		33.8		2		1.5	6.3%	18.6%
suppress	080896B		33.8		4		0	8.4%	25.0%
suppress	081296B		33.8		4		0	7.9%	23.3%
suppress	081396A		33.8		4		1.5	4.2%	12.4%
suppress	081596A		48.8		2		0	15.5%	31.8%
suppress	082796A		48.8		2		1.5	9.2%	18.9%
suppress	081696A		48.8		4		0	12.6%	25.7%
suppress	081696B		48.8		4		1.5	6.0%	12.4%
non-spray	022697A		44.4				hand lay	4.3%	9.9%
non-spray	022697B		44.4				spray lay	7.9%	17.9%
non-spray	022797A		44.4				flow coat	5.0%	11.4%
non-spray	022797B		44.4				flow coat	5.1%	11.6%
non-spray	022797C		44.4				pressroller	5.7%	12.9%

Gelcoat Spraying Test Data

Run No.	Data ID	GC Film Thickness (in.)	GC Styrene %	Gel Time (min.)	GC Flow (lb/min)	Air Flow (fpm)		Styrene Emissions (% resin wt)	Styrene Emissions (% monomer)
1	101195A	0.018	35	20	4	100		18.8%	53.8%
2	101195B	0.024	40	10	2	50		18.3%	45.8%
3A	101295A	0.018	40	10	2	50		21.3%	53.2%
3B	101695B	0.018	40	10	2	50		23.2%	57.9%
4A	101295B	0.024	35	20	4	100		15.9%	45.3%
4B	101695A	0.024	35	20	4	100		14.6%	41.8%
5	101395A	0.024	40	20	2	100		19.6%	49.0%
6	101395B	0.024	35	10	4	50		15.2%	43.5%
7	101695C	0.018	35	10	4	50		17.7%	50.5%
8	101795A	0.018	40	20	2	100		24.3%	60.7%
9	101795B	0.018	35	10	2	100		20.3%	58.0%
10	101895A	0.024	40	20	4	50		21.0%	52.4%
11A	101895B	0.018	40	20	4	50		24.7%	61.8%
11B	102395A	0.018	40	20	4	50		24.8%	62.0%
12A	101995A	0.024	35	10	2	100		15.9%	45.4%
12B	102395B	0.024	35	10	2	100		15.7%	44.8%
13	101995B	0.024	35	20	2	50		15.9%	45.4%
14	101995C	0.018	40	10	4	100		22.4%	56.0%
15	102495A	0.018	35	20	2	50		17.5%	49.9%
16	102495B	0.024	40	10	4	100		20.5%	51.3%
1 (& 14)	030596A	0.018	40	10	4	100		21.1%	52.7%
2	030796A	0.018	40	10	4	100	Controlled	12.7%	31.9%
3	030596B	0.018	40	10	4	100	Optimized	17.2%	43.0%
4A	030796B	0.018	40	10	4	100	C & O	12.7%	31.7%
4B	030796D	0.018	40	10	4	100	C & O	12.5%	31.3%
lg female	091896A		35				Controlled	10.8%	31.0%
lg female	091796A		35					13.0%	37.4%
lg male	101696A		35				Controlled	14.3%	41.6%
lg male	101596A		35					18.5%	52.8%

Filled Resin Test Data

Run No.	Data ID	Styrene Content (%) includ. filler	Styrene Content (%) neat resin		Styrene Emissions (% resin wt) includ. filler	Styrene Emissions (% monomer)
non filled	090596A	45.8%	45.8%	0.0%	9.2%	20.1%
low filled	090496B	32.8%	45.8%	13.0%	6.2%	18.9%
high filled	082996A	19.5%	45.8%	26.2%	4.2%	21.5%
high filled	090496A	19.5%	45.8%	26.2%	3.4%	17.4%
high filled	090596B	19.5%	45.8%	26.2%	3.4%	17.6%

Appendix B - Dow Filament Winding Test Data

	Filament Winding tests				**Emissions Based on**	Emissions Based on	Emissions Based on
Run	**%Sty**	**Supp**	**Temp**	**Size**	**% Resin**	% Styrene	% Resin wt
9	**33**	**0**	**85**	**6**	**5.9**	17.9%	5.9%
7	**48**	**0**	**73**	**33**	**11.8**	24.5%	11.8%
16	**33**	**0**	**85**	**33**	**6.3**	19.1%	6.3%
13	**48**	**0**	**73**	**6**	**8.3**	17.4%	8.3%
14	**33**	**0**	**73**	**33**	**7.2**	21.8%	7.2%
6	**48**	**0**	**85**	**33**	**10.3**	21.4%	10.3%
19	**48**	**0**	**85**	**33**	**10.3**	21.4%	10.3%
2	**48**	**0**	**85**	**6**	**8.6**	17.9%	8.6%
18	**48**	**0**	**85**	**33**	**12.0**	24.9%	12.0%
1	**33**	**0**	**73**	**6**	**4.9**	14.9%	4.9%
15	**48**	**1.5**	**85**	**33**	**5.0**	10.3%	5.0%
17	**33**	**1.5**	**73**	**6**	**3.7**	11.2%	3.7%
20	**33**	**1.5**	**73**	**6**	**3.7**	11.2%	3.7%
5	**33**	**1.5**	**85**	**6**	**5.4**	16.5%	5.4%
4	**33**	**1.5**	**73**	**33**	**4.8**	14.4%	4.8%
3	**48**	**1.5**	**85**	**33**	**4.0**	8.4%	4.0%
8	**48**	**1.5**	**73**	**6**	**4.9**	10.3%	4.9%
12	**48**	**1.5**	**73**	**33**	**4.6**	9.6%	4.6%
11	**48**	**1.5**	**85**	**6**	**6.6**	13.8%	6.6%
10	**33**	**1.5**	**73**	**6**	**3.9**	11.8%	3.9%

CFA Emission Model for the Reinforced Plastics Industries - 1 Variable

28-Feb-98

APPLICATION METHOD	Current Monomer Content (%)	New Monomer Content (%)	Monomer Factor (%)		Vapor Suppressant Factor (%)		Controlled Spraying Factor (%)	or	Non-Atom Equipment Factor (%)	Add-on Control Factor (%)	% of Add-on Control (%)	Current Emission Factor (lb/ton)	New Emission Factor (lb/ton)	New Emission Factor (% resin)
Manual Resin	44.0%	44.0%	100.0%	n	100%		n/a		n/a	95%	0%	146	146	7.3%
Mechanical Resin	44.0%	44.0%	100.0%	n	100%	n	100%	n	100%	95%	0%	268	268	13.4%
Gelcoat Spray	44.0%	44.0%	100.0%		n/a	n	100%		n/a	95%	0%	522	522	26.1%
Filament Resin	44.0%	44.0%	100.0%	n	100%		n/a		n/a	95%	0%	182	182	9.1%