The Effects of Environmental Regulation on Technology Diffusion: The Case of Chlorine Manufacturing

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2003

RPP-2003-02

Regulatory Policy Program

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Citation

This paper may be cited as: Miller, Nolan, Lori Snyder, and Robert Stavins. 2003. “The Effects of Environmental Regulation on Technology Diffusion: The Case of Chlorine Manufacturing.” Regulatory Policy Program Working Paper RPP-2003-02. Cambridge, MA: Center for Business and Government, John F. Kennedy School of Government, Harvard University. Comments may be directed to the authors.

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THE EFFECTS OF ENVIRONMENTAL REGULATION ON TECHNOLOGY DIFFUSION: THE CASE OF CHLORINE MANUFACTURING

by

Nolan Miller, Lori Snyder, and Robert Stavins*

1. Introduction

There is increasing interest within the environmental policy community in assessing the factors that affect technological change. This interest is linked with two realities: first, the costs of compliance with environmental regulations are determined, in part, by the cost and availability of alternative production and abatement technologies; and second, regulations themselves can affect the nature and rate of technological change (Jaffe, Newell, and Stavins 2002). Consequently, environmental regulations may play a role in speeding the obsolescence of older technologies and in determining which alternative production processes are chosen to replace them and when such replacement occurs.

We examine the effect of regulation on technological change in the chlorine manufacturing industry by focusing on the *diffusion* of membrane cell technology, widely viewed as environmentally superior to the both the mercury cell and to a third technology, known as the diaphragm cell.

Technological diffusion is the aggregation of technology adoption decisions by firms or individuals (David 1966, Griliches 1957, Stoneman 1983, Kerr and Newell 2000, Keohane 2002).[1] In the chlorine manufacturing industry, there has been a substantial shift over time towards cleaner technologies, but only a relatively small fraction of this change has come about through adoption (retrofitting) of cleaner technologies at existing

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[1] Schumpeter (1942) distinguished three stages in the process by which a new, superior technology permeates the marketplace. First, *invention* consists of the development of a scientifically or technically new product or process. Second, *innovation* occurs when a new product or process is commercialized, that is, made available on the market. Third, a successful innovation gradually comes to be widely available for use in relevant applications through adoption by firms or individuals, a process labeled *diffusion*. See Jaffe, Newell, and Stavins (2002) for a comprehensive summary of the literature on the effect of environmental policy on technology diffusion.

plants. We find that most of the change has been due to the adoption of cleaner technologies by newly constructed facilities (entry) and the closing of facilities with inferior technologies (exit). Therefore, we think of diffusion as a combination of retrofit, entry, and exit decisions. We examine two of these — retrofitting and exit — econometrically to assess the effects of environmental regulation.[2] We employ plant-level data on technology choice, economic variables, and regulatory variables from 1976 to 2001, and examine the retrofit and exit decisions with a hazard model. We consider the effects of both direct regulation of chlorine manufacturing and regulation of downstream users of chlorine.

We find that environmental regulation had significant effects on technological change, but not in the way that many advocates would argue. Rather than encouraging the adoption of cleaner technologies by existing facilities, regulations had the effect of encouraging the shutdown of facilities using environmentally-inferior chlorine-manufacturing techniques. In this way, regulations tended to increase over time the share of plants using the cleaner, membrane technology. This pattern in which environmental regulations have their greatest influence on technology diffusion through systematic effects on exit (and effects on adoption at time of entry), rather than effects on retrofitting, is consistent with previous findings with regard to technology *innovation*.[3]

2. The Chlorine Manufacturing Industry

Over 95 percent of the world's chlorine is produced by an electrolytic process in which electric current is introduced to a salt-water brine, resulting in the separation of chlorine, hydrogen gas and caustic soda (sodium hydroxide). Three different types of cells have been employed in this electrolytic process: mercury cell, diaphragm cell, and membrane cell.

The mercury cell— the oldest technology— is widely viewed as having the greatest potential for environmental damage, due to the use and release of mercury, a highly persistent and bio-accumulative toxin. The diaphragm cell technology, which accounts for two-thirds of chlorine produced in the United States, is considered to be more environmentally benign than the mercury cell, although not without its own environmental risks. This is because the diaphragm is composed of layers of asbestos. The newer membrane process — the most environmentally benign — accounts for less than one-third of chlorine produced in the United States (Chlorine Institute 2001).

Over the past 25 years, there has been a gradual movement from mercury and diaphragm cells to membrane technology. In 1975, plants using mercury cells accounted

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[2] The entry aspect, while important, is empirically difficult to estimate because one only has data on facilities that choose to enter and cannot observe or infer all the possible firms that considered entering in a period and decided not to. This makes probabilistic empirical analysis of the entry decision infeasible.

[3] Newell, Jaffe, and Stavins (1999) find this pattern in the effects of regulation on the innovation of energy-efficiency attributes of a variety of home appliances.

for about 22 percent of total chlorine capacity, plants using diaphragm cells accounted for 73 percent, and membrane cell plant capacity was less than one percent of the total.[4] By 2001, mercury cell capacity had fallen to about 10 percent, diaphragm cells accounted for 67 percent, and membrane cells accounted for 20 percent (Chlorine Institute 2001).[5] Some of the significant increase in membrane cell capacity has come from retrofitting of cell technologies at existing facilities, but the bulk of the diffusion of membrane cell technology has taken place through entry and exit of facilities. Figure 1 provides a summary of diffusion of membrane technology from 1976 through 2001.

3. The Regulation of Chlorine Manufacturing

In 1972, a widely publicized incident of mercury poisoning in Minamata Bay, Japan led the Japanese government to prohibit the use of mercury cells for chlorine production. The United States did not follow suit, but it did impose more stringent environmental constraints on mercury cell units during the early 1970s. Subsequently, chlorine manufacturing became subject to increased regulation under the Clean Air Act, the Clean Water Act, the Resource Conservation and Recovery Act (RCRA), and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), popularly known as Superfund. In addition, chlorine manufacturing became subject to public disclosure requirements under the Toxics Release Inventory (TRI), which has required large manufacturing facilities to make public their annual releases of over 300 different toxic chemicals since 1986. Nearly all chlorine manufacturing plants meet the reporting thresholds for the TRI, and are thus required to disclose their release levels.[6]

In addition to regulation of the chlorine manufacturing process, there has also been increased environmental pressure on industries that use chlorine as an input. This indirect regulation is potentially important for chlorine manufacturing technology choices because a large share of chlorine is manufactured for captive use, i.e., manufactured for on-site use in the production of other products. In our sample, nearly all chlorine facilities are co-located with other manufacturing units, the most frequently observed pairings being with organic chemical and plastics plants and pulp and paper mills. Changes in regulations in these downstream industries can have substantial impacts on the demand for chlorine and can affect the rate of entry and exit of chlorine production plants.

Two major (indirect) regulations may have altered the demand for chlorine. One is the Montreal Protocol, which regulates the production of ozone-depleting chemicals,

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[4] The remaining four percent of chlorine was produced at facilities that used a method other than electrolysis.

[5] The remaining 2.35 percent of chlorine was produced at facilities that use a method other than electrolysis.

[6] Large manufacturing facilities are defined as having 10 or more employees and using/processing 25,000 pounds per year or manufacturing 10,000 pounds per year of a listed chemical.

such as chloroflorocarbons (CFCs), for which chlorine is a key ingredient. In 1987, the Montreal Protocol imposed a timeline for phasing out CFC production in the United States and other industrialized countries. The other potentially important indirect regulation is the so-called “Cluster Rule” regulation of releases from pulp and paper mills. Finalized in 1998, the Cluster Rule , tightened restrictions on the release of chlorinated compounds to both water and air. This led to increased interest by the industry in non-chlorine bleaching agents, which in turn may have affected the economic viability of some chlorine plants.

4. Empirical Model

We utilize a proportional hazard model to analyze the effect of economic and regulatory variables on retrofit and exit decisions by chlorine manufacturing plants from 1976 to 2001.[7] The hazard model is appropriate because our focus is on the *timing* of technology decisions. Plants face different anticipated returns to adoption of membrane technology. Those with higher anticipated returns are expected to adopt earlier, if adoption cost is falling over time. Economic and regulatory conditions can affect expected costs and returns, and, hence, affect the timing of adoption.

The hazard function is defined as the probability of adopting membrane technology, given that the facility has not yet adopted:

$$h(t) = \frac{f(t)}{1 - F(t)}$$

where f(t) is the probability density function for adoption and F(t) is the cumulative distribution function. To measure the effects of explanatory variables on the hazard rate, a conventional approach is the proportional hazard model, which separates the hazard rate into two components: a baseline hazard rate which is a function of time, $h_0(t)$; and a function of the covariates, usually defined as exp(X′β), where β is a vector of parameters that weight the explanatory variables X. Combining these, the hazard rate h(t) is written:

$$h(t) = h_0(t)\exp(X'\beta)$$

In a proportional hazard model, the explanatory variables have the effect of shifting the baseline hazard. The baseline hazard function can be left unspecified, as in a Cox proportional hazard model, or parameterized by specifying a particular distribution for f(t). While the Cox proportional hazard model has the advantage of not requiring assumptions about the form of the underlying hazard function, it also has a major shortcoming for this analysis: the effects of any pure time series variables cannot be estimated.

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[7] See Kiefer (1988) for a discussion of the use of hazard models in economics.

Use of a parameterized baseline hazard model requires a choice of specification. An exponential density function yields a constant baseline hazard function. Other specifications yield baseline hazard functions that are functions of time, allowing for the possibility that the baseline hazard increases or decreases over time. Commonly used distributions that yield monotonically increasing or decreasing hazard functions are the Weibull and the Gompertz density functions (Kennedy 1998).

Without strong *a priori* notions regarding the shape of the underlying baseline hazard, we begin by assuming an exponential density function and estimate the hazard model for the retrofit and exit decisions. By assuming an exponential density function we are assuming that the hazard function is constant and that the probability of adopting does not increase or decrease over time. We then conduct sensitivity analyses to determine the robustness of the results.

5. Data

5.1 Dependent Variables

Data on cell technology use at U.S. chlorine manufacturing plants were obtained from the Chlorine Institute (2002) and from the Directory of Chemical Producers (SRI 1976-2001). One of our two dependent variables, RETRO, is an indicator of membrane retrofitting at an existing plant, and takes a value of one in the last year a facility used the old technology.[8] The other dependent variable, SHUTDOWN, takes a value of one if a facility closed during a given year.

5.2 Explanatory Variables

Size: While there is no clear theoretical relationship between the size of a plant and its likelihood to retrofit or exit, empirical research on technology diffusion has frequently found that larger plants are more likely to adopt new technologies or adopt more quickly (David 1966, Griliches 1957, Kerr and Newell 2000). We employ two measures of size — plant capacity and net sales of parent company.[9] These measures reflect two different notions of size. Plant capacity refers to the share of the individual plant in the chlorine market. In contrast, net sales are measured at the parent company, not the individual production unit, and hence serves as a proxy for access to capital, risk aversion, and other firm-specific factors.

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[8] Defining the variable RETRO to take a value of one in the last year in which a facility used the old technology was done for technical reasons. STATA implements the hazard function estimation by assuming that any event variables, such as RETRO, that take a value of 1, indicate that the event occured at the end of the period. So if a facility uses the membrane technology in 2000 and mercury cells in 1999, then we assume the change ocurred at the end of 1999.

[9] Table 1 provides summary statistics for the variables used in the analysis.

Complexity: Chlorine is often produced and used on site as an input in the production of other products. Fifty-four percent of the chlorine manufacturing facilities in our sample were co-located with manufacturing units operating in a different three-digit SIC code, usually other chemical products or pulp and paper. Such "complexity" of operation might affect both the exit and retrofit decisions, because the more integrated is chlorine production with other high value-added goods, the more costly and difficult it might be to shut down a plant either temporarily or permanently. The variable, COMPLEX, is an integer variable that indicates the number of other production processes, as captured in 3-digit SIC codes, that occur at the manufacturing site.[10]

General Economic Conditions: Chlorine production is a pro-cyclical industry. We employ two measures of business activity — lagged values of GDP in the chemical manufacturing industry, and lagged values of the real price of chlorine.

Regulatory Variables: As described above, several regulatory regimes may have affected the rate and direction of technology diffusion in the chlorine industry. We construct dummy variables that capture whether a facility was affected by a specific regulatory regime including: Superfund, the Montreal Protocol, the pulp and paper cluster rule, and the Toxics Release Inventory. We also include a dummy variable that indicates whether the plant uses mercury cells, because these cells have been more heavily regulated under various regulatory regimes.[11]

6. Results

6.1 The Retrofit Decision

We have complete data on 51 facilities, eight of which adopted the membrane technology during the sample period.[12] The earliest observed retrofit was in 1983, and the latest was in 1999. The results of the estimation of the hazard model for the adoption decision are presented in Table 2.

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[10] Other measures of complexity were also constructed, including a binomial dummy reflecting multiple production processes. The signs are the same, but the binomial variable tends to be less statistically powerful in explaining variation in retrofitting and exit decisions.

[11] This will pick up any variation that is common across plants using the same technology, some of which may be regulatory and some of which may not be.

[12] We have data on net sales only for plants owned by publicly traded companies. Restricting our sample to publicly traded companies reduces the sample from 65 facilities to 51 facilities. We also estimated the model with the full sample, and found that the model performed poorly. There are several possible explanations for the difference in results across the two samples. A model of technology adoption that applies well for publicly traded firms may simply not be appropriate for privately-held firms' decision-making. Another possibility is that net sales controls for important differences in adoption timing decisions across companies, because all plants owned by the same company have the same value for net sales in any given year.

A brief note on interpreting the results from the proportional hazard model is required. The results reported in Table 2 are not the estimated values of the coefficients, β, but rather the estimated hazard rates. Thus, an estimated hazard rate greater than 1.0 indicates that an increase in the covariate increases the baseline hazard, while estimated hazard rates less than 1.0 indicate that the respective variable decreases the baseline hazard. The larger the deviation from 1.0, the greater the effect, but in a non-linear fashion.[13]

The analysis shows that larger plants and plants owned by firms with larger sales volumes were more likely to switch to the membrane technology. Complex facilities were substantially less likely to switch. Increases in the lagged real price of chlorine (a proxy for expected future prices) made technology changes less likely, contrary to the notion that large investments in new technology are more likely to occur during economic expansions. On the other hand, the opportunity cost of the downtime necessary to change technologies is greater when real prices are higher.[14] When GDP in the chemical industry was used as an indicator of business activity, the sign and magnitude of the effect was similar, but the results were not statistically significant.

In none of the specifications were the effects of the regulatory variables statistically significant. Mercury plants, which were subject to stringent regulation for water, air, and hazardous waste removal, were no more likely to switch to the membrane technology than diaphragm plants. Similarly, TRI reporting appears to have had no significant effect on retrofitting decisions, whether TRI is measured as a simple indicator variable, by rank of total releases, or by magnitude of reported releases.[15]

6.2 The Exit Decision

We also estimated a hazard model for the exit decision. The publicly-traded sample consisted of 55 facilities, 21 of which ceased operations between 1976 and 2001. We tested a variety of specifications, controlling for economic and regulatory determinants. The results are found in Table 3.

Despite the fact that the results of the exit analysis are not as robust to changes in specification as are the results of the retrofit analysis, some interesting and quite striking patterns emerge. Although the economic covariates seem to have had little effect on the timing of exit decisions (with the exception of facility-level capacity, which retarded shutdown), regulations do explain some of the variation in exit decisions. In particular,

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[13] Standard errors and significance levels are presented in the table, but significance levels are determined by the coefficient estimates and the standard errors, not the estimated hazard rates and the standard errors.

[14] Changing the lag structure on real prices did not significantly affect the results.

[15] We tested the robustness of the results to changes in the shape of the underlying hazard function, and found that the signs and magnitudes of the explanatory variables' estimated parameters did not change substantially. The estimated parameters were not statistically different from one (in the case of Weibull) or zero (in the case of Gompertz), and so the assumption of a constant baseline hazard, consistent with the exponential hazard function, seems reasonable.

indirect regulation on the end-uses of chlorine accelerated shutdowns in certain industries. Facilities affected by the pulp and paper cluster rule and the Montreal Protocol were substantially more likely to shutdown than were other facilities. It may appear from the results that facilities that report to TRI were less likely to shutdown than facilities that did not report, but it is important to note that nearly all facilities that were still in operation in 1986 reported to TRI, and so this parameter may be picking up a simple time effect, rather than a true regulatory effect.[16]

7. Conclusions

Diffusion of new technology is the result of a combination of retrofitting at existing facilities and entry and exit of facilities with various technologies in place. In chlorine manufacturing, total capacity using the cleaner membrane technology has been increasing over the past 25 years. This increase is partly a result of retrofitting of membrane cells at existing plants, but mainly a consequence of plant startups and shutdowns.

Our results indicate that economic factors have been the primary determinants of the decision to retrofit the membrane technology. Regulatory factors appear to have had very little influence on the decision to switch to membrane cells from either mercury or diaphragm cells. On the other hand, indirect regulation on the end-uses of chlorine appears to have significantly accelerated facility closures, and thereby to have increased the share of plants using the cleaner, membrane technology for chlorine production.

Environmental regulation, in this study, did affect technological change, but it did so not by encouraging the adoption of cleaner technologies by existing facilities, but by encouraging the shutdown of facilities using the environmentally inferior options.

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[16] We also estimated the model with other shapes of the underlying hazard function. With both the Weibull and Gompertz estimations, the distribution parameter indicated that the baseline hazard was increasing over time.

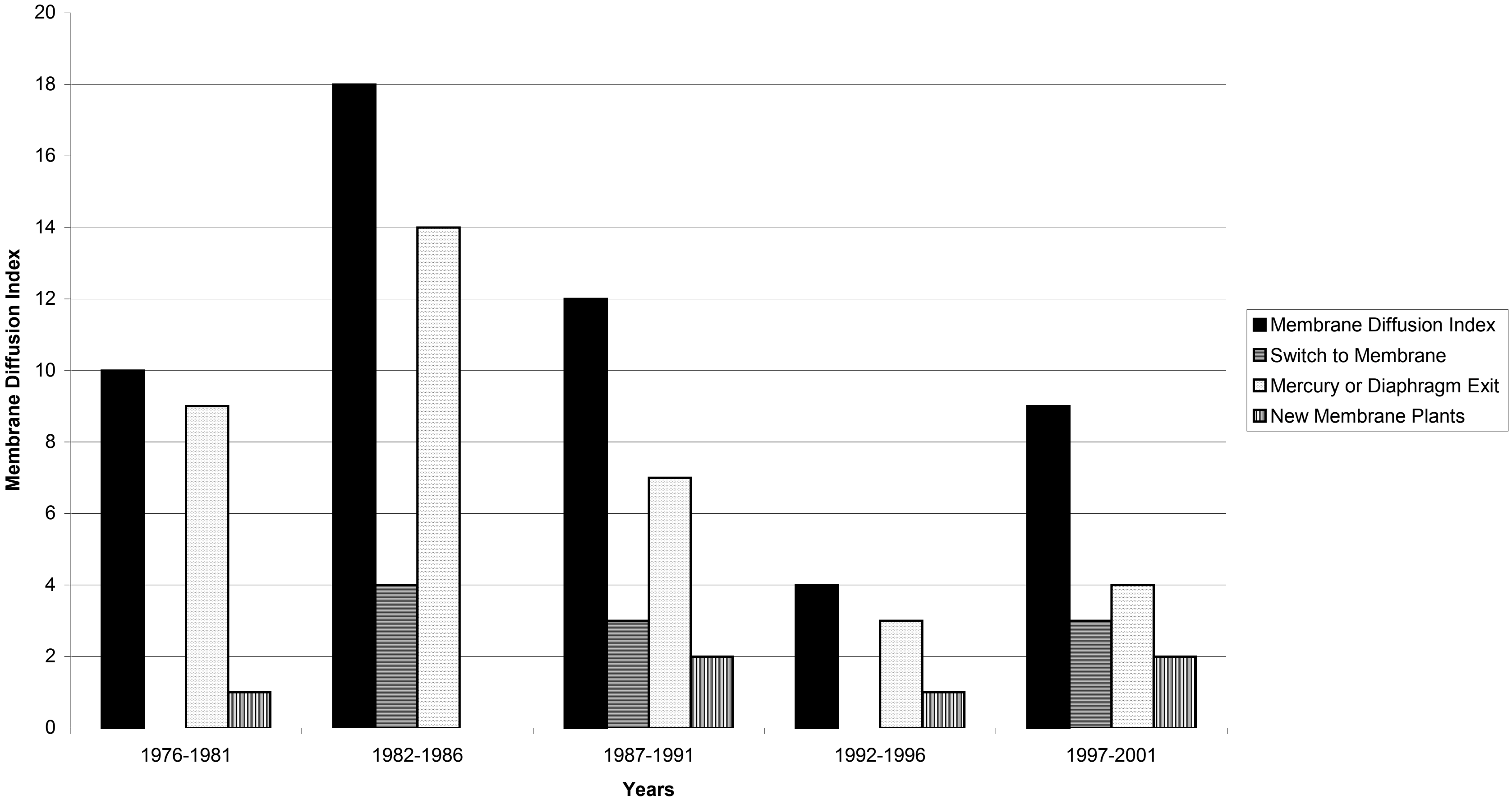

Figure 1: Diffusion of Membrane Cell Technology Over Time, By Source[17]

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[17] The membrane diffusion index is equivalent to the total number of facilities that contributed to diffusion during each five-year period, including plants that retrofitted the membrane technology, non-membrane plants that closed down, and new membrane plants that came on line.

Table 1: Summary Statistics

Dependent Variables					
	Obs.	Number of Facilities	Number Yes		
Retro	1,181	74	10		
Shutodown	1,181	74	37		
Continous Variables					
	Obs.	Mean	St. Dev.	Min	Max
Capacity (short tons per year)	1,159	272	390	5	2,600
Net Sales (millions of $)	856	10,123	15,624	143	128,051
Real Price ($)	1,181	170	68	75	420
GDP Chemicals (billions of $)	1,143	93,546	46,982	35,516	191,135
Releases (pounds per year)	445	1,648,459	7,931,919	6	97,700,000
Complex	1,181	0.68	0.71	0	2
Indicator Variables					
	Obs.	Percent Yes			
TRI	1,181	56.05			
Superfund	1,181	20.58			
Mercury	1,181	42.08			
Pulp and Paper	1,181	1.27			
Montreal	1,181	9.48			

Table 2: Membrane Retrofit Results
Hazard Rates with Standard Errors in Parentheses

	Exponential 1	Exponential 2	Exponential 3	Weibull	Gompertz
Capacity	1.001408 * (0.0007359)	1.001425 ** (0.000715)	1.00144 ** (0.000728)	1.001281 (0.0008219)	1.001465 * (0.0007888)
Net Sales	1.000034 *** (0.000012)	1.000036 *** (0.000013)	1.000038 *** (0.0000146)	1.000033 ** (0.0000136)	1.000036 ** (0.0000151)
Real Price L1	0.9962007 *** (0.0013475)				
Real Price 2YMA		0.9889946 *** (0.0012278)		0.9894295 *** (0.0013935)	0.9888585 *** (0.0015909)
GDP Chem 2YMA			0.9999951 (0.0000133)		
Complex	0.2273803 * (0.2021476)	0.2167036 * (0.1897748)	0.2267147 * (0.191659)	0.2324703 (0.2242048)	0.2124177 * (0.1919757)
Mercury	0.2381428 (0.2688402)	0.245625 (0.27747)	0.2547808 (0.2904984)	0.2146882 (0.2513167)	0.2550602 (0.300874)
TRI	2.364816 (2.235411)	2.521225 (2.338243)	2.9724 (4.287978)	0.9250197 (1.681225)	2.962435 (4.714663)
Distribution Parameter (Weibull and Gompertz)				1.777713 (0.8484747)	-0.0158065 (0.0846714)
Obs.	714	714	694	714	714
Facilities	51	51	51	51	51
Number of Adoptions	8	8	8	8	8

*** implies significance at the 1% level, ** implies significance at the 5% level, * implies significance at the 10% level

Table 3: Exit Results
Hazard Rates with Standard Errors in Parentheses

	Exponential 1	Exponential 2	Exponential 3	Weibull	Gompertz
Capacity	0.9935006 ** (0.0026075)	0.9934958 ** (0.0026257)	0.9934109 ** (0.0028161)	0.9920599 ** (0.003117)	0.9915017 ** (0.0035577)
Public					
Net Sales	1.00001 (0.000011)	1.00001 (0.0000113)	1.000013 (0.0000125)	1.000009 (0.0000108)	1.00001 (0.0000113)
Real Price L1	1.001726 (0.004135)				
Real Price 2YMA		1.002104 (0.0054413)		1.001276 (0.0050366)	1.000793 (0.0049645)
GDP Chem 2YMA			0.9999942 (0.00000909)		
Complex	0.8999574 (0.2692206)	0.8989523 (0.2695786)	0.8759823 (0.2822191)	0.9751524 (0.3111844)	1.010431 (0.331682)
Mercury	0.8135648 (0.3459433)	0.8162428 (0.3456025)	0.8284507 (0.3552766)	0.6803751 (0.3065831)	0.6986621 (0.3294897)
TRI	0.1945822 ** (0.1298227)	0.1927051 *** (0.121083)	0.2335083 (0.216497)	0.0300541 *** (0.0269087)	0.0179782 *** (0.0247064)
Pulp and Paper Cluster	6.175861 * (6.414415)	6.272212 * (6.456244)	8.486411 * (10.38227)	4.041377 (4.316898)	3.779936 (3.952134)
Montreal Protocol	8.646184 ** (8.40288)	8.733212 ** (8.466869)	8.541132 ** (7.752672)	7.597009 * (8.428295)	7.744444 (10.15993)
Distribution Parameter				2.654821 ** (0.6288498)	0.2115686 *** (0.074077)
Obs.	830	830	740	830	830
Facilities	55	55	54	55	55
Number of Exits	21	21	20	21	21

*** implies significance at the 1% level, ** implies significance at the 5% level, * implies significance at the 10% level

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