THE EFFECTS OF ENVIRONMENTAL REGULATIONS ON POLLUTION EMISSIONS: EVIDENCE FROM PLANT-LEVEL DATA[†]

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

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In order to assess the effects of regulation on the environmental and economic performance of firms, it is important to understand the interaction between regulation and technological change. The costs of compliance with environmental regulations are determined, in part, by the cost and availability of alternative production and abatement technologies, and regulations themselves can affect the nature and rate of technological change (Adam B. Jaffe et al., 2003). As a result, the economic and environmental impacts of regulation are affected by the technology choices made by individual plants.

We study 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 both mercury-cell and diaphragm-cell technologies. The chlorine manufacturing industry has experienced a substantial shift over time toward the membrane technology. This diffusion is the result of three different processes: adoption of cleaner technologies at existing plants (adoption),[1] the use of membrane cells by newly constructed facilities (entry), and the closing of facilities using diaphragm and mercury cells (exit).

In this paper, we examine econometrically two of these aspects of diffusion (adoption and exit behavior) to assess the effects of environmental regulation.[2] Employing plant-level data on technology choice, economic variables, and regulatory variables from 1976 to 2001, we examine these adoption and exit decisions with a hazard model, considering the effects of both direct regulation of chlorine manufacturing and regulation of downstream users of chlorine.

I. 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: the mercury cell, the diaphragm cell, and the membrane cell.

The mercury cell is widely viewed as having the greatest potential for environmental damage, due to the potential release of mercury, a highly persistent and bio-accumulative toxin. The diaphragm-cell technology, which accounts

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[1] In this context, adoption by an existing plant can mean both conversion of all of an existing plant's capacity (retrofitting) or a combination of retrofitting and new capacity expansion at an existing plant. In the latter case, some capacity is maintained using the older technology.

[2] The entry aspect 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 could have entered during a time period but did not. This renders probabilistic empirical analysis of the entry decision infeasible.

for two-thirds of chlorine produced in the United States (Chlorine Institute, 2001) is considered to be more environmentally benign than the mercury-cell technology, although not without its own environmental risks, since the diaphragm cell is composed of layers of asbestos. The newer membrane process is the most environmentally benign.

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 for 22 percent of total chlorine capacity, plants using diaphragm cells accounted for 73 percent, and membrane-cell plant capacity was less than 1 percent of the total. By 2001, mercury-cell capacity had fallen to 10 percent, diaphragm cells accounted for 67 percent, and membrane cells accounted for 20 percent (Chlorine Institute, 2001).[3] Some of the significant increase in membrane-cell capacity has come from adoption of membrane cells at existing facilities, but the bulk of the diffusion has taken place through exit of facilities using mercury and diaphragm cells.

II. 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 1970's. 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 1987.

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 choices of chlorine manufacturing technology because a large share of chlorine is manufactured for on-site use in the production of other products. 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, 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.

III. Empirical Model

We utilize a proportional hazard model to analyze the effects of economic and regulatory variables on adoption and exit decisions by chlorine manufacturing plants from 1976 to 2001. The hazard model is appropriate because our focus is on the *timing* of technology decisions (Nicholas Kiefer, 1988; Suzi Kerr and Richard G. Newell, 2001). Plants face different anticipated returns to adoption of membrane technology. Economic and regulatory conditions can affect expected costs and returns and, hence, affect the timing of adoption.

We employ 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, $\exp(\mathbf{X}'\boldsymbol{\beta})$. In a proportional hazard model, changes in the explanatory variables shift the baseline hazard. The baseline hazard

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[3] The remaining 4 percent of chlorine in 1975 and 3 percent in 2001 was produced at facilities that used a method other than electrolysis.

function can be left unspecified, as in a Cox proportional hazard model, or parameterized. 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. Since these effects are potentially important, we adopt the parameterized-baseline hazard approach.

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 (Peter Kennedy, 1998 pp. 249–62). Without strong a priori notions regarding the shape of the underlying baseline hazard, we begin by assuming a constant baseline hazard function (i.e., an exponential density function) and estimate the hazard model for adoption and exit decisions. We conduct sensitivity analyses to determine the robustness of the results to the specification of the baseline hazard function.

IV. Data

Data on cell technology use at U.S. chlorine manufacturing plants were obtained from the Chlorine Institute (2001) and from the *Directory of Chemical Producers.* One of our two dependent variables, CONVERT, is an indicator of membrane adoption at an existing plant and takes a value of 1 in the last year a facility used the old technology. The other dependent variable, SHUTDOWN, takes a value of 1 if a facility closed during a given year.

We construct variables that reflect both economic and regulatory determinants of adoption or exit timing:

Size.—Empirical research on technology diffusion has frequently found that larger plants are more likely to adopt new technologies or adopt more quickly (Zvi Griliches, 1957; Kerr and Newell, 2001). We employ two measures of size: plant capacity and net sales of the parent company. 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 serve as a proxy for access to capital, risk-aversion, and other firm-specific factors.

Complexity.—Chlorine is often produced and used on-site as an input in the production of other products. Such "complexity" of operation might affect both exit and adoption 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. This is particularly true for chlorine manufacturing because transportation of chlorine is dangerous and is itself highly regulated. The variable COMPLEX is an integer variable that indicates the number of other production processes, as captured in three-digit SIC codes, that occur at the manufacturing site. We also use a series of dummy variables representing the industry or industries co-located with a given chlorine plant. The variables CO-PAPER, CO-PLASTICS, and CO-ORGANICS take a value of 1 if the plant also produces pulp and paper products, plastics, and organic chemicals respectively.

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.[4]

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. The pulp and paper and Montreal Protocol indicators take a value of 1 if the respective rule was in effect during that year *and* the chlorine plant was co-located with a

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[4] We tried alternative lag structures to account for different expectations mechanisms. The results were robust to changes in the lag structure over 1–5 years.

pulp and paper mill or plant producing ozone-depleting chemicals. 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.

V. Results

For the adoption model, we have complete data on 51 facilities, eight of which adopted the membrane technology during the sample period. We estimate the hazard model under a variety of specifications.[5] Due to the nonlinear nature of the hazard function, the coefficients do not have a direct interpretation. In order to provide information on the relative importance of the explanatory variables on the hazard rate, we calculate the hazard rate when all continuous variables are evaluated at their mean and indicator variables are set to zero. The mean hazard rate for the adoption model is 1.28 percent. The impact on the mean hazard rate of increasing a continuous variable by 10 percent or changing an indicator variable to 1, ceteris paribus, is reported in Table 1.

The analysis shows that larger plants and plants owned by firms with larger sales volumes were slightly more likely to switch to the membrane technology. Facilities co-located with paper mills and plastics plants 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. A potential explanation for this result is that the opportunity cost of the downtime necessary to change technologies is greater when real prices are higher. When GDP in the chemical industry was used as an indicator of business activity, the sign and magnitude of the effect were similar, but the results were not statistically significant.

The effects of the regulatory variables on the likelihood of adopting membrane technology are not statistically significant in any of the specifications. 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 statistically significant effect on adoption decisions, whether TRI is measured as a simple indicator variable, by rank of total releases, or by magnitude of reported releases.

Table 1—Effects of Covariates on the Mean Hazard Rate

	Change from mean hazard (percentage points)	
Covariate	Adoption	Exit
Economic Variables:		
Capacity	**0.08**	**−0.34**
Net sales	**0.10**	0.02
Real price of chlorine	**−0.26**	0.08
COMPLEX		−0.02
CO-PAPER	**−1.28**	
CO-PLASTICS	**−1.27**	
CO-ORGANICS	0.00	
Regulations on Chlorine Production:		
Mercury	0.00	−0.40
Superfund	0.71	−0.28
TRI (Disclosure)	1.10	**−1.69**
Regulations on End-Use of Chlorine:		
Pulp and paper cluster		**11.18**
Montreal		**15.36**

Note: Bold type indicates that the corresponding coefficients are statistically different from zero at the 10-percent level of significance.

We also estimate a hazard model for the exit decision. We have complete data for 55 facilities, 21 of which ceased operations between 1976 and 2001. We test a variety of specifications, controlling for economic and regulatory determinants. The mean hazard rate for the exit model is 2.1 percent. The incremental effect of the covariates relative to the mean hazard can be found in Table 1.

Despite the fact that the results of the exit analysis are not as robust to changes in specification as are the results of the adoption analysis, some interesting and quite striking patterns emerge. Although the economic covariates

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[5] Due to space constraints, only a single specification is reported here. See Snyder et al. (2002) for full regression results. Because the likelihood ratio is estimated using repeated observations on the same plant, the assumption of independent identically distributed error terms is suspect. We instead estimate and report clustered standard errors that are adjusted for correlation among observations from the same plant, but we assume independence across plants.

seem to have had little effect on the timing of exit decisions (with the exception of facility-level capacity, which retarded shutdown slightly), regulations do explain some of the variation in exit decisions. In particular, indirect regulation of 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 shut down than were other facilities.

It may appear from the results that facilities that report to TRI were less likely to shut down 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.

VI. Conclusions

Diffusion of new technology is the result of a combination of adoption 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 adoption of membrane cells at existing plants, but mainly a consequence of plant shutdowns.

Our results indicate that regulatory factors have not had a statistically significant effect on the decision to adopt membrane-cell technology at existing plants. On the other hand, indirect regulation of the end-uses of chlorine appears to have accelerated facility closures significantly, 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. It did so not by encouraging the adoption of membrane cells by existing facilities, but by reducing the demand for chlorine and hence encouraging the shutdown of facilities using environmentally inferior options.

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