From End-of-Pipe Technology to Clean Technology:
Effects of Environmental Regulation on Technological Change in the Chlor-Alkali Industry in Japan and Western Europe

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Table of Contents

List of Figures

List of Tables

11

1. Introduction

1.1 *Problem and Research Methods*

Our standard of living has improved significantly through the development of a wide range of industries in the past years. Along with numerous products useful in our life, the intensive industrial development has at the same time produced undesirable emissions, which have begun to impose serious burdens on the natural environment. Metals, for instance, have been used so pervasively that currently there are few industrial operations which do not discharge metal-containing emissions into the air, water, or soil. According to one estimate, world-wide industrial emissions of nickel (Ni), cadmium (Cd), copper (Cu), zinc (Zn), and lead (Pb) into the atmosphere averaged approximately 240, 380, 1,800, 17,000, and 22,000 tonnes per year, respectively, between 1850 and 1900 (Nriagu, 1979). From the beginning of this century to the 1980s, emissions of such toxic metals increased almost exponentially, roughly in parallel to the rate of industrial growth. In the period between 1900 and 1980 the atmospheric emission rates for Cu, Zn, Cd, Pb, and Ni rose by 6-, 8-, 8-, 9-, and 51-fold, respectively (Nriagu, 1994).

As the natural environment does not possess an infinite carrying capacity, the current industrial input rates are increasingly interfering with the limited capabilities of ecosystems to cope with pollution. Responding to the serious concern on the ongoing contamination of air, water, and soil with pollutants such as non-degradable toxic metals, regulations and policies have been introduced by governments around the world for the aim of reducing emissions from industrial activities. We could observe some sign of decline in emissions rates in recent years, reflecting the efforts devoted for pollution abatement, particularly in countries located in the industrialized world.

There is a growing concern, however, about negative impacts of increasingly tightened environmental regulations on industry (Jaffe, Peterson, Portney, and Stavins, 1995). It is argued that stringent environmental regulations will force firms to invest a considerable amount of financial resources for compliance and that as a result their competitiveness will be lost against those in countries where lax regulations are implemented. In other words, environmental restrictions impose significant costs, slow productivity, and thereby hinder the ability of companies to compete in international markets (Palmer, Oates, and Portney, 1995). Theoretical analysis is often employed to show that environmental regulations should reduce

productivity by requiring firms to spend additional resources for pollution abatement and control without increasing production output.

On the opposite side, an increasing number of people claim that stringent environmental regulations will enhance the competitive position of firms. For example, they argue that the ever-increasing stringency of environmental regulations will encourage firms to conduct more research and development (R&D) activities and, consequently, produce more innovation in the long run (Porter and van der Linde, 1995a). That is, the necessity to comply with environmental policy will prompt companies to re-examine their products and production processes carefully and in the end will lead to technological improvements. Spurred by stringent environmental regulations, companies will go beyond mere compliance with regulations and may succeed in creating radically new technologies. That means that regulation-induced R&D activities could lead to an innovation which has not discovered previously. Successful cases, many of which are those in the U.S., are cited to claim that stringent environmental regulations actually encourage innovation in industry (Porter and van der Linde, 1995b). Their views are conflicting, and the debate still continues. A careful analysis is required to fully evaluate technological impacts of environmental regulation. What would be particularly important is to examine the nature and characteristics of technological change and to incorporate it into the analysis.

Recently, the World Commission on Environment and Development has publicly addressed the concept of "sustainable development." The Commission's report, *Our Common Future*, defined the concept as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environmental and Development, 1987). The idea of sustainability has become one of the most important principles in guiding our thinking about our long-term relationship with the environment. We are now urged to take a balanced and integrated approach to the achievement of both environmental protection and economic development in the future. As stressed by the Organisation for Economic Co-operation and Development (1997), full development and extensive utilization of appropriate technologies in industry will be the key to achieving sustainable development. What we need to consider now is to formulate environmental regulations in such a way as to encourage innovations on technologies that have the potential to reduce excessive environmental burdens while securing sound economic development.

Our empirical study is conducted to examine how environmental regulations affect the course and character of technological change through innovative activities of industry. As we can see in empirical studies conducted previously, it is very difficult to measure the stringency of environmental regulations and its effects on subsequent innovations at aggregate levels. To overcome the problems of previous empirical studies due to their aggregate nature and to understand well the nature of the relationship between environmental regulation and innovation, a detailed case study is conducted at a micro-level in this research. It is expected to shed complementary light on the question of how environmental regulations influence firms' activities with regard to the development and adoption of new technologies. It does so by conducting interviews with companies and policy makers as well as analyzing detailed data on patents and technological processes.

While previous empirical studies mainly deal with the effects of environmental regulation either on the invention or the diffusion of new technologies, this research examines the whole process of innovation, which covers the technological situation prior to the introduction of environmental regulations, the development of new technologies by innovators, and their adoption by themselves and other firms. Closely examining environmental regulations relevant to the case, our study aims at assessing their dynamic impacts on companies' R&D and adoption of technologies in the entire process of innovation. A historical approach is thus taken in the empirical study. It covers the technological situation before the introduction of environmental regulations, the contents and schedules of the regulations and their modifications, companies' R&D activities, and adoptions of new technologies, which cannot be analyzed separately when we aim at understanding fully the linkages with one another.

According to the Industrial Pollution Projection System developed by the World Bank (Hettige, Martin, Singh, and Wheeler, 1994), the most pollution-intensive sectors in terms of toxic waste per dollar of output are "chemical process industries" in a broad sense, which include, among others, the chlor-alkali, fertilizers, pesticides, plastics, paper, and metals industries. In contrast to "physical process industries" such as the machinery and automobile industries, in which the assembling process plays a crucial role, the chemical process industries depend critically on chemical reactions to produce main products, and that means that by-products are created almost inevitably in the production processes. Thus, practically speaking, the chemical process industries should be given a prime emphasis in our efforts to reduce pollutants emitted into the environment. And research on these industries is expected

to reveal cases in which the effects of environmental regulations on technological change can be observed more clearly, compared with less pollution-intensive industries. Accordingly, we pay close attention to the chemical process industries in this analysis. As a sector that belongs to the chemical process industries, the chlor-alkali industry is the focus of our case study. This sector is chosen because it is known to emit a large amount of mercury as an effluent while mercury has been the focus of serious public concerns and intensive environmental policies for a long time.

When we analyze process technologies for pollution abatement in chemical process industries, we make extensive use of chemical reaction equations. By doing this, we can clearly classify green innovation into two categories. The first one is end-of-pipe technologies which deal with emissions at the end of the production facilities without any change in the chemical reactions producing the main products. The second category is clean technologies which eliminate undesirable by-products from within the production processes by replacing the current chemical reactions with different routes.

To make an assessment of the impacts of newly introduced environmental regulations on innovation, it is necessary to know the initial conditions of the technological situation. For this purpose, we examine what kinds of technologies had been developed by which companies prior to the introduction of environmental regulations. The trajectory of technological changes is traced by identifying which parts of technologies have been actually modified, in a similar vein to the morphological analysis used by Foray and Grübler (1990). Examination of chemical reactions equations involved in production processes helps us follow the direction and timing of technological change in detail. We also look at data on the types of technologies that had been developed and adopted in order to identify which companies had gained innovative experience and capabilities before environmental regulations started to influence technological outcomes.

As we will see later, in the case of the chlor-alkali industry, basically there are three types of production processes, namely, the mercury process, the diaphragm process, and the ion exchange membrane process. The mercury process had been predominantly developed and adopted in Western Europe and Japan by the time of the early 1970s, just before environmental regulations on mercury emissions were imposed on the chlor-alkali industry. In other words, similar technological conditions existed initially in Western Europe and Japan. Since then, while many of the chlor-alkali manufacturers in Western Europe have continued to use the mercury process, whose mercury emissions have been mainly treated with end-of-

pipe technologies, the ion exchange membrane process has become the dominant production method in the Japanese chlor-alkali industry. Thus, we make a comparison between Japan and Western Europe as a case study appropriate for examining the effects of environmental regulation on technological change, in the sense that we can observe how environmental regulations have contributed to the divergence of initially similar technological situations to different outcomes[1].

Our empirical study examines how environmental regulations on mercury emissions have influenced innovative activities of firms and consequent technological change in the chlor-alkali industry in Japan and Western Europe. We first look at the environmental regulations on mercury emissions from chlor-alkali plants. Considering the difficulties in making quantitative assessment of the stringency of different regulations, we closely look at the details of the regulations related to mercury emissions. We trace the chronology of different regulatory approaches to the same issue in the two regions, while taking into account institutional aspects of the formation and implementation of environmental regulations and other related public policies. Official documents of regulatory bodies are surveyed, and interviews are conducted with public authorities and industry associations in each region to obtain detailed information.

Then we make an in-depth investigation into companies' technological responses to environmental regulations. We examine how and when companies conducted innovative activities for what kinds of technology, end-of-pipe technologies or clean technologies, in particular. Interviews are conducted with innovative companies in the chlor-alkali industry in each region to obtain information on the timing and extent of their R&D activities. It is not easy, however, to secure detailed data on R&D activities specifically linked to particular technologies. Particularly in our case, we are interested in differentiating R&D between end-of-pipe technologies for the mercury process and clean technologies, including the diaphragm process and the ion exchange membrane process for chlor-alkali production. Furthermore, the use of R&D measures is not always satisfactory as a proxy for a wide range of technical activities (Freeman, 1994; Griliches, 1990). Thus we also examine the outputs of technological activities conducted by companies.

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[1] As the diaphragm process has been the dominant production process in the US chlor-alkali industry, its initial technological conditions were different from those of the Western European or Japanese chlor-alkali industry, and thus we do not examine in detail the US case in this research.

As an indicator of innovative outputs, patenting activity is analyzed in our study. Using the data on patents as a measurement of innovation generally poses several difficulties. Firstly, it has been reported that the propensity to apply for patents varies widely across industries (Levin, Klevorick, Nelson, and Winter, 1987). Patenting is relatively unimportant in the automobile industry, for instance, whereas many innovations tend to be patented in the chemical industry. In our study, the focus is placed on innovations in one sector, namely, the chlor-alkali industry, and hence the inter-industry variations of the propensity to patent do not matter. Moreover, since the chlor-alkali industry is a branch of the chemical industry, to which the importance of patents is generally considered to be high, we reasonably expect that patent data would capture many of the relevant innovations made in the industry. Secondly, the propensity to patent might change across time. For example, it is said that recently the ratio of patents to R&D expenditures has fallen in many industrialized countries. Here we are interested in comparing the relative importance in R&D between end-of-pipe technologies for the mercury process and clean technologies, which include the diaphragm process and the ion exchange membrane process, but not necessarily the absolute number of patent applications on each process. As we expect that a change in the tendency to patent across time affects different types of chlor-alkali technologies in the same way, the temporal variations of the propensity to patent will not pose a serious problem. We use data on successful patent applications, instead of that on all patent applications, because the quantity of patent applications would be influenced by the strategies of companies and we are interested in equalizing the quality of patents used as an indicator of technological outputs.

While we assume that patent data captures the extent of R&D activities made in the chlor-alkali industry reasonably well, patents do not necessarily reflect the degree of technological progress exactly. Hence other data on the trends in the performance of various technologies are also collected from other sources. We make an extensive use of reports published in scientific, technical, and trade journals as well as papers presented at seminars and conferences. That contributes to increasing our understanding of technological aspects of each process in detail.

Then the diffusion of new technologies is discussed by examining factors that would affect their adoption by companies. Basically, we consider two prime factors relevant to technological diffusion, namely, the availability of information on new technologies and the profitability of their adoption (Stoneman and David, 1986). The information availability is examined by analyzing reports presented at conferences organized by industry associations

and technical organizations and papers published in trade journals. The profitability of new technologies is evaluated by using data on the construction cost and the operating cost of the new technologies, compared with the old technology. We then examine the age of the plants based on the old technology as it crucially affects the timing of making investments for replacing the existing technology with new technologies. Detailed data on the existing and new processes are obtained from engineering firms which supply production technologies as well as chlor-alkali manufacturers in the two regions.

1.2 Outline of the Thesis

In Chapter 2, we first review theoretical and empirical research previously conducted on effects of environmental regulation on technological change. Our criticism focuses on the way in which technological change for pollution abatement is dealt with in previous studies. In particular, they did not pay sufficient attention to the distinction between end-of-pipe technologies and clean technologies, an aspect which would be crucial in analyzing technological impacts of environmental regulation. Theoretical models mostly assume pollution abatement technologies that reduce emissions incrementally while the marginal pollution abatement cost is increasing. Effectively, that means that the technologies assumed in the models are basically of the end-of-pipe type. On the other hand, the possibility of eliminating emissions from within the production process by using clean technologies has been mostly ignored. Since clean technologies do not produce emissions in the first place, the marginal analysis of the pollution abatement cost curve, which is extensively used in theoretical models, becomes inappropriate when we take into account the existence of clean technologies.

Empirical studies mostly did not pay attention the distinction between different types of technology either when examining impacts of environmental regulation on technological change. As many of the previous empirical work examined patents at aggregate levels as the indicator of innovations, they either focused on equipment of the end-of-pipe type such as scrubbers and filters, or included all the innovations observed. That is because it is very difficult to identify clearly the range of clean technologies which could be relevant for their analyses without detailed information on specific production processes. Without taking clean technologies into account, the group of end-of-pipe technologies will limit too narrowly the range of technological change for pollution abatement. On the other hand, if we include all

types of innovation, the group will contain technologies which have little connection with environmental aspects and be too broad to be appropriately defined as a range of green innovations. We argue that it is important to examine the nature and character of technologies in detail for an accurate analysis of green innovation.

Then we move on to show that there are basically two types of technology, namely, end-of-pipe technologies and clean technologies, to deal with emissions formed by industrial activities. End-of-pipe technologies are aimed at reducing emissions at the end of the production facilities, without changing the reactions which produce the main product. Clean technologies, on the other hand, are defined as those which replace the main reactions with different ones, effectively eliminating undesirable by-products from within the production processes. It is end-of-pipe technologies that have been mostly developed in the past to reduce emissions from industrial processes. Since end-of-pipe technologies treat pollutants at the end of the pipe for emissions without affecting the main production process, it is relatively easy to adopt and operate them, and various types of the end-of-pipe equipment have been widely adopted in industry. While end-of-pipe technologies only increase the production costs because additional costs are required to install them at the end of the manufacturing facilities, clean technologies, which are aimed at avoiding the formation of pollutants from the beginning by altering the whole facilities, could improve the main production process and potentially reduce the manufacturing cost in the long run.

Incorporating this technological distinction between the end-of-pipe technology and the clean technology, our analytical framework is developed for the effects of environmental regulations on technological change. We argue that different environmental regulations could lead to diverging types of technological change. Relatively weak environmental regulations will encourage the adoption of end-of-pipe technologies, which are likely to be much less expensive than clean technologies, at least initially. That in turn will induce more investment in the existing production technology, whose emissions can be expected to be reduced by adopting end-of-pipe technologies. That will make the transition to clean technologies a slow process even when the clean technologies later become more efficient in production, because more plants will have already been built with the old technology by that time, and there will be strong incentives to maintain these existing plants until the end of their lifetimes unless the clean technologies are extremely efficient.

On the other hand, regulations which are stringent enough cannot be complied with just by installing end-of-pipe technologies. That effectively will demand abandoning the existing

24

production technologies, and, as a consequence, R&D activities for innovation on clean technologies will be encouraged. As there are normally multiple options for clean technologies, however, a rigidly fixed regulatory schedule will induce companies to make premature decisions on alternative technologies, which may not be the most appropriate choice from a long-term perspective. Replacement of these technologies with the one which has turned out to be the best in the end will be costly.

With this analytical framework, we conduct our empirical study of the chlor-alkali industry. In Chapter 3, we look at the history of technological evolution in the chlor-alkali industry, which has a history of more than one hundred years. Since the beginning of the 19th century, the production technologies used in the chlor-alkali industry have experienced several major innovations, including chemical and electrolytic processes. Among the electrolytic production processes, we see that the mercury process had become the dominant production process in Western Europe and Japan by the early 1970s, before environmental regulations on mercury emissions started to be imposed in the two regions. We observe that several firms in Western Europe and Japan had developed advanced technologies for the mercury process, and these technologies accounted for the majority of those used by the operators of mercury-based chlor-alkali plants in the two regions. That suggests that there were equally innovative companies in both regions on chlor-alkali production technologies prior to the introduction of environmental regulations, which means that the initial technological conditions in this industry were similar in Western Europe and Japan.

Since environmental regulations were imposed for reducing mercury emissions from chlor-alkali plants in the early 1970s, however, diverging paths of technological change have emerged in Japan and Western Europe. The remaining chapters intend to investigate how different environmental policies have contributed to the different technological outcomes between the two regions. We examine the Japanese case in Chapter 4. In Japan the government imposed a strict regulatory mandate on the chlor-alkali industry to phase out the existing plants based on the mercury process in a very short period of time. That stringent policy gave a spur to innovative companies to develop alternative clean technologies. The regulatory approach, which was initially fixed in a rigid schedule, resulted in inducing many of the chlor-alkali producers to adopt the diaphragm process, as its performance was relatively well established at that time, compared with that of the still-infant ion exchange membrane process. The diaphragm process, however, later turned out to be an inefficient technology, while the ion exchange membrane process was in the process of rapid

improvement. Based on incoming information on the situation of technological developments from the industry, the government interrupted the implementation of the original regulation for a while to assess the extent of progress in developing the ion exchange membrane process. Following an evaluation by experts of the industrial feasibility of the ion exchange membrane process, the regulatory schedule was subsequently modified to allow more time for process conversion. That change in the schedule allowed the remaining mercury process plants to be converted directly to the ion exchange membrane process, which has since progressed to become the best technology among the alternatives, economically as well as environmentally. On the other hand, those mercury-based plants which had adopted the diaphragm process earlier had to be converted again to the ion exchange membrane process. That has made a substantial amount of investment in plants abandoned well before the end of their physical lifetime.

The case of technological change in the chlor-alkali industry in Western Europe is examined in Chapter 5. Less stringent regulations were adopted in Western Europe, where emission standards were imposed on chlor-alkali plants to reduce their mercury emissions. Most of the companies in the industry have chosen end-of-pipe technologies, an option which was much cheaper and more certain than making investment to develop new clean technologies with unclear performance. Various types of end-of-pipe equipment were developed and adopted to reduce mercury emissions to such an extent that regulatory requirements were complied with by most of the mercury process operators. During the following period, many chlor-alkali plants were constructed, relying on the well-established mercury process equipped with end-of-pipe technologies for pollution abatement. Since these plants have not yet reached the end of their physical lifetime, which normally is forty years or longer, chlor-alkali producers in Western Europe have strong incentives to continue to use mercury-based plants, although the ion exchange membrane process has become the most efficient production technology and has been adopted in other countries, including many industrializing countries. In short, relatively weak regulations adopted in Western Europe promoted considerable progress in end-of-pipe technologies to reduce mercury emissions, but resulted in discouraging the development of the ion exchange membrane process, a prime example of the clean technology, even though there were several companies that were innovative on chlor-alkali production technologies. As the mercury process, equipped with end-of-pipe technologies to reduce mercury emissions, has continued to be used in many

chlor-alkali plants, the diffusion of the efficient ion exchange membrane process has been slow and limited.

Finally, Chapter 6 gives the summary and conclusion of our research. Relatively weak regulations, whose introduction is intended to improve the environmental performance of industrial activities, would encourage innovations on end-of-pipe technologies, and that in effect could work to prolong the life of existing production processes which are in fact getting obsolescent. Stringent regulations, while promoting innovative activities on clean technologies, could induce premature decisions to choose inappropriate technologies. Only when the schedule of implementing stringent regulations maintains a certain degree of flexibility, allowing enough time and experiment for technological progress, will the possibility be secured that efficient clean technologies are fully developed and widely adopted in industry. With our finding of the diverging effects of environmental regulations on technological change, we discuss implications for corporate strategies, policy making, and institutional setups in our attempt to make a transition from end-of-pipe technology to clean technology.

2. Analytical Framework for the Effects of Environmental Regulation on Technological Change

2.1 Previous Studies of the Effects of Environmental Regulation on Technological Change

2.1.1 Theoretical Models

Traditionally, the theoretical foundations for correcting environmental problems have been based on the theory of externalities (e.g. Baumol and Oates, 1988)[2]. With no prices to provide the proper incentives for reducing polluting activities, the inevitable result is that excessive burdens will be imposed on the absorptive capacity of the environment. The obvious solution to this problem is to place an appropriate price, the so-called Pigouvian tax, on polluting activities so that the social costs are fully internalized. A set of Pigouvian taxes equal to marginal social damage then can produce an optimal outcome. This approach essentially focuses on the static efficiency of the problem without paying due attention to the dynamic nature of environmental issues, particularly the effects of technological change. It is assumed that necessary technologies already exist and are readily available to anybody who wants to adopt them and that he or she can smoothly adjust the emission level, depending on economic incentives provided by tax or tradable emission permits.

Environmental degradation, however, is usually a long-term process, in which technological change could potentially produce effects of several orders of magnitude larger than the gains and losses calculated in a static framework. Technologies necessary for reducing emissions may not exist, and, even when they exist, their characteristics and performance may not be stable or well established. As Orr (1976) put it, "(w)hat is missing was the view that environmental policy is fundamentally the need to establish a framework that provides *continuous* and *detailed* technological adaptation to the impacts on the environment of growth, change in product mix, and change in process technology" (p. 442). This crucial aspect has begun to be addressed in recent studies which examine the effects of environmental regulation on technological change. The new approaches take into account the decisions made by firms on their investment for the development and adoption of

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[2] There are also other approaches to solving environmental problems. Coase (1960) proposed to assign liability for damages and let parties bargain to mutual benefit to eliminate excessive pollution. This approach, significant

technologies to deal with pollution. These activities essentially take place in a dynamic context, making the traditional arguments exclusively focused on the static efficiency seriously inadequate. We examine in the following section these previous theoretical models on the effects of environmental policy on the development and adoption of new technology for pollution abatement.

Magat (1978) extended the static comparison of effluent taxes and effluent standards to a dynamic world in which firms invest resources in improving their abatement technology as well as their production technology. He employed a simple model of production in which a firm employs one variable input, labor, (at rate L) to produce its output (at rate y) and a pollutant (at discharge rate x). This joint production relation is represented by the production function

$$L = g(Ay, Bx). \hspace{3cm} (2\text{-}1)$$

Technical change occurs through product augmentation, where Ay and Bx represent the effective output rate and the effective effluent rate, respectively, with the augmentation parameters A and B respectively measuring the levels of the output production and effluent abatement components of the technology. It is assumed that employing more of the input L either raises the output rate y, lowers the pollution rate x, or some combination of these two effects. Technological advance occurs through expenditures M by a firm which produces a combination of output technology innovation and effluent abatement technology innovation. The parameter β measures the allocation of effective R&D effort between the two types of technological advance, that is, the bias or direction of technological change. For a given expenditure M on R&D, the tradeoff between output technology innovation $\dot{A}/A$ and abatement technology innovation $\dot{B}/B$ occurs along a smooth innovation-possibilities frontier, and increases in R&D spending M shift out the frontier. A graphic illustration is given in Figure 2-1.

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as a theoretical possibility, requires a strong assumption of low transaction costs to achieve an efficient outcome, however. See Farrell (1987) for more detailed discussions on this approach.
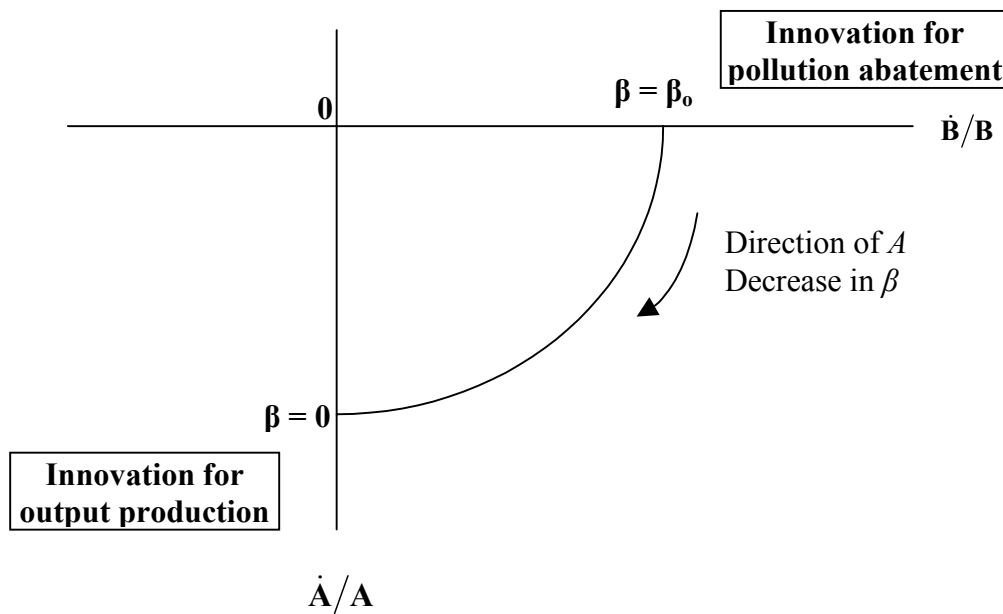
Figure 2-1 Allocation of R&D between Pollution Abatement Technology and Output Production Technology

(Magat, 1978)

With this model, he found that both the constant tax and the constant standard policies will induce a typical firm to increase R&D effort. (Here the typical firm means that labor substitution between output production and pollution abatement is not particularly difficult.) His analysis showed, however, that the two policy control policies lead to a different allocation of R&D effort between improvement in abatement technology and improvement in production technology. On the condition that labor substitution is easy, the constant tax induces a pattern of ever-increasing allocations to effluent abatement technology improvement. The constant standard, on the other hand, leads to a direction of technical advance which diverges toward relatively more output technology improvement or diverges toward relatively more effluent abatement technology improvement, depending on the initial value of the direction.

In this model one of the chief assumptions is the tradeoff in the allocation of R&D between pollution abatement technology and output production technology, analogous to the innovation possibilities frontier model. As we will discuss later, however, in the case of clean technologies, the creation of pollutants is avoided in the first place, and therefore there is no trade-off between pollution abatement and output production. In this case, pollution

abatement technology is not necessary, and all the R&D resources will be allocated to improve the efficiency in output production technology, implying that Magat's model is not appropriate for the analysis of clean technologies.

There are other theoretical studies which focused on the marginal analysis of pollution abatement. Downing and White (1986) constructed a simple model of pollution control innovation by a profit-maximizing polluter who is subject to pollution control policies, including direct regulation as well as economic instruments[3]. A graphic illustration of the model is given in Figure 2-2. The marginal cost curve of abatement and the marginal damage curve of pollution are represented by *MC* and *MD*, respectively. Their analysis assumes that the control authority has perfect information on the costs of reducing emissions as well as on the benefits of improving environmental quality. Furthermore, it is assumed that the authority reacts immediately to the new innovation, which in turn is fully expected by companies.

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[3] Here we consider effluent fees or taxes as representing instruments based on economic incentives. Other economic instruments, notably tradable emission permits, are not examined, as the implementation of emission permits trading is rather difficult because of high transaction costs, particularly when there are many small emitters. Potential sources of transaction costs would be searching and information, bargaining and decision, and monitoring and enforcement (Stavins, 1995). In this context, see also Marin (1991) for a criticism and Milliman and Prince (1992) for their reply.
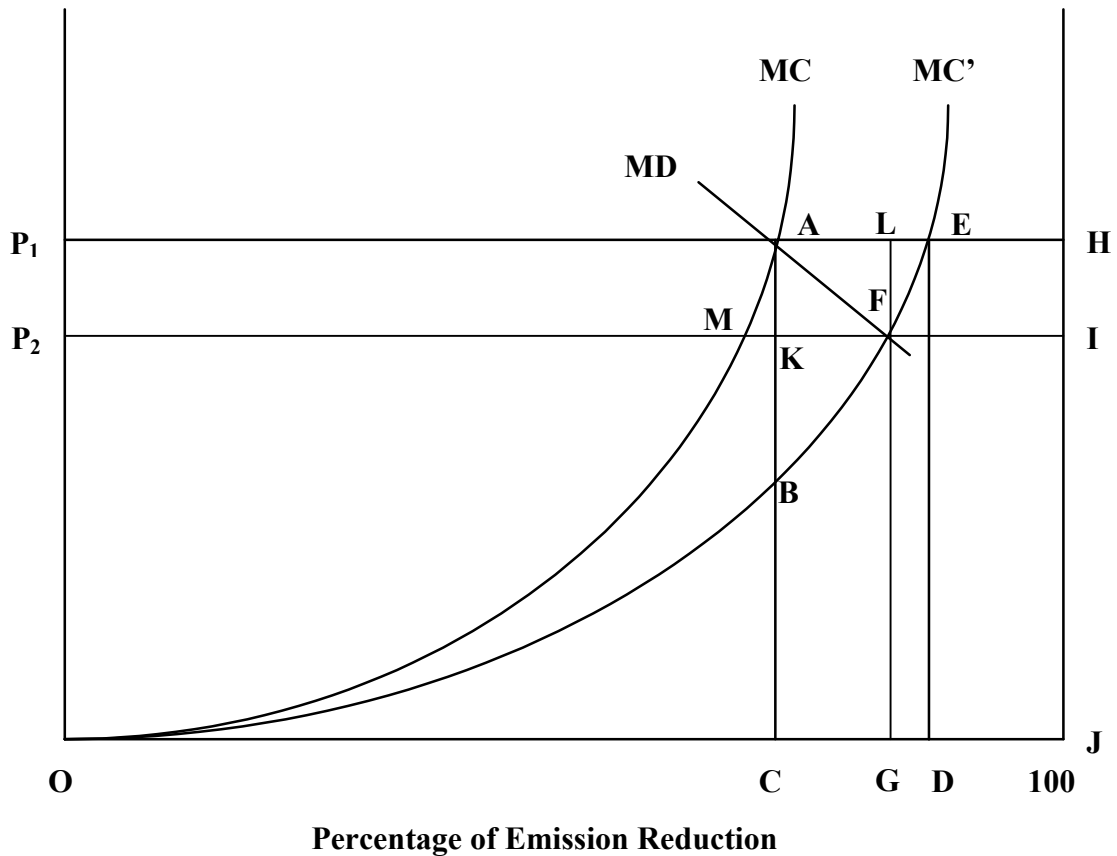
Figure 2-2 Incentives to Innovate without Diffusion, followed by Policy Adjustment
(Downing and White, 1986)

We first consider the case in which the polluter (and the innovation) is a small enough part of the overall pollution problem so that none of the important marginal conditions are changed by the innovation. The benefit to the polluter from the innovation (*MC -> MC'*) under the effluent fee at P_1 is area *OAE*, the same as the social benefits from the innovation, and the polluter will adopt the innovation when the initial cost of investment for abatement *X* is less than *OAE*. On the other hand, under the direct regulation at *C*, the benefit to the polluter from the innovation is area *OAB*, which is smaller than *OAE*:

$$OAB < OAE. \qquad\qquad (2\text{-}2)$$

Thus the methods relying on effluent fees are better than direct controls in encouraging innovation[4].

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[4] Jung, Krutilla, and Boyd (1996) evaluated the incentive effects of policy instruments for innovation at the industry level, taking into account firm heterogeneity. Their results suggest, consistent with the firm-level analysis, that incentive-based instruments provide more incentives than performance standards.

When marginal conditions are changed by the innovation, the results remain the same as long as the policy maker does not make any adjustments. In the case where the pollution control authority makes the socially appropriate adjustments (ratcheting), the effluent fee is reduced from P_1 to P_2 or the emission standard is raised from C to G. The benefit from the innovation under the effluent fee system is area *(OAHJ – OFIJ)*, that is, *OAHIF*, whereas the innovation benefit under direct regulation is area *(OAC – OFG)*, which is equivalent to *(OAB – BFGC)*. Since *OAHIF* is larger than *OAB* and hence is larger than *(OAB – BFGC)*

$$OAHIF > (OAB – BFGC), \qquad\qquad (2\text{-}3)$$

the benefit from the innovation is larger under the effluent system than under direct regulation. Indeed, the innovation benefit under direct regulation could conceivably be negative. This model basically suggests, in line with other studies adopting similar approaches (Wenders, 1975; Zerbe, 1970), that the effluent fee system will provide more incentives to innovate than direct regulation.

While Downing and White (1986) assumed that the innovation is specific to the innovating polluter and cannot be transferred to any other polluter, Milliman and Prince (1989) extended their model by considering the possibility of the adoption of the innovation by other companies. Now there are three steps involved in the entire process of technological change: invention of a new technology; diffusion of the new technology across firms; and optimal agency reaction to adjust pollution controls in response to the innovation. They examined firm incentives for technological change under various policy instruments, including direct controls and economic instruments such as emission subsidies, emission taxes, free marketable permits, and auctioned marketable permits. The model is illustrated in Figure 2-3.

(a) Innovator

mc

mc'

T*   a   f   H

g   d   I

T**

T'   c   J

e^m   e*   e**   e'   0

(b) Non-innovator

mc

L

mc'

T*   a   f   H

g   d

T**   I

T'   c   J

e^m   e*   e**   e'   0

(c) Industry

MC

L

MD

MC''

A   F   H

T*

G   D   I

T**

C   J

T'

E^m   E*   E**   E'   0
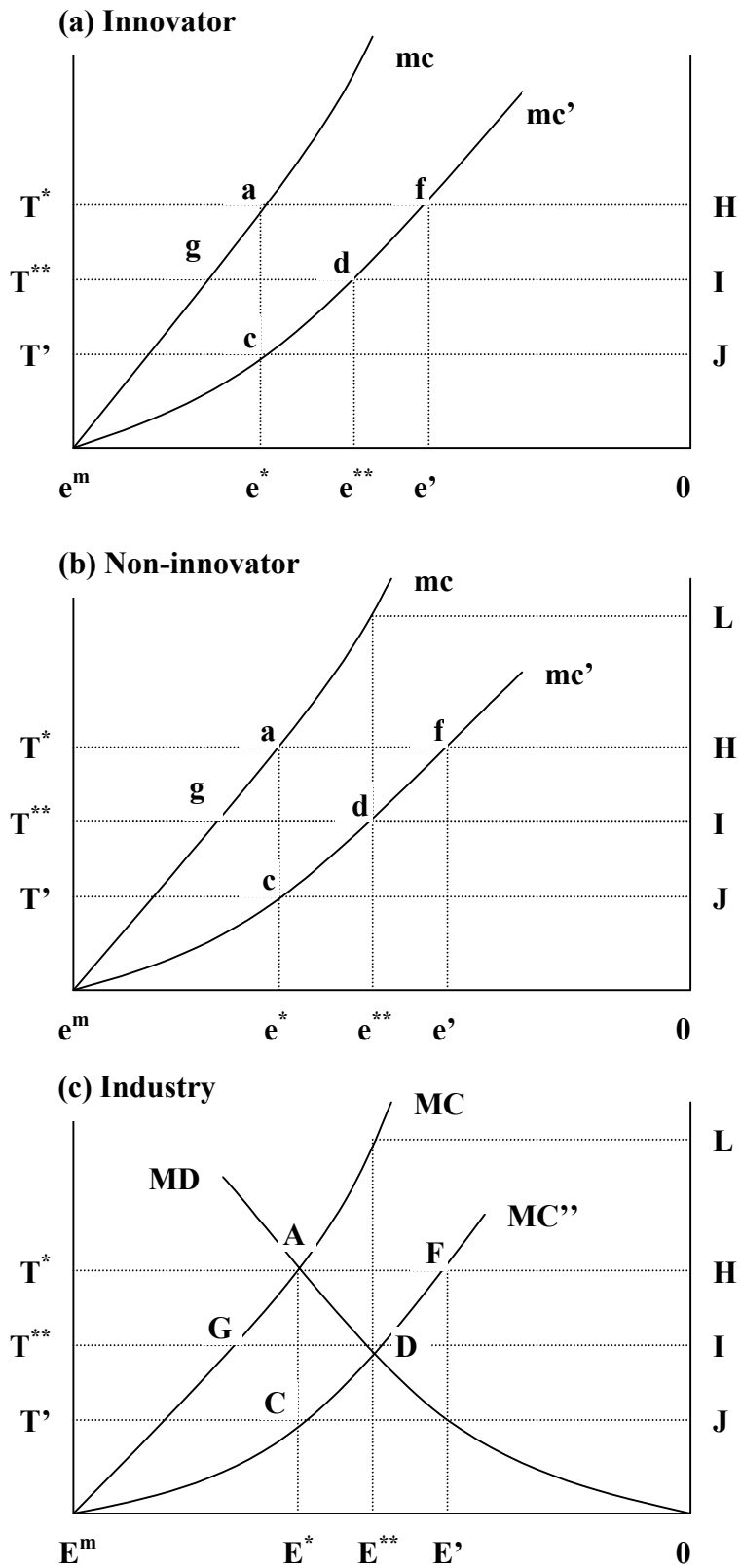
Figure 2-3 Incentives to Innovate with Diffusion and Policy Adjustment

(Milliman and Prince, 1989)

34

A large number N of identical firms in a competitive industry are each discharging a homogeneous emission into the environment. The public regulator intends to reduce these emissions to the optimal rate of E^* per time period at the industry level (Figure 2-3c) either by imposing a direct emission control of e^* per time period on each firm (Figure 2-3a and Figure 2-3b), where $Ne^* = E^*$ (Figure 2-3c), or by establishing a per unit tax equating T^* on firm emissions. A single firm develops an innovation which shifts its marginal cost curve from mc to mc' (Figure 2-3a). Initially, the aggregate curve MC remains unchanged due to the small size of the firm relative to the entire industry. This is different from the case of Downing and White (1986) in Figure 2-2, where the marginal cost curve MC shifts to MC' after innovation. Widespread diffusion, however, shifts mc to mc' for many non-innovating firms (Figure 2-3b), thus eventually shifting MC to MC'' (Figure 2-3c). This necessitates control adjustment to restore efficiency, that is, optimal agency response, either by reducing allowed emission levels to e^{**} per firm under direct controls (E^{**} in industry) or by lowering the tax rate from T^* to T^{**} under emission taxes. It is assumed that the regulator possesses perfect information on current abatement technology, but lags in perceiving a discovery, and that political pressures prevent the regulator from imposing optimal agency response prior to the completion of diffusion.

Firm incentives to promote a particular step, namely, innovation, diffusion, or optimal agency response, are determined by the induced changes in firm abatement costs. Now firm abatement costs are in three forms: the direct cost of abatement (equipment expenses, operating costs); the associated transfer losses (payments made by the firm, such as emission taxes); and the associated transfer gains (payments made to the firm, such as patent royalties). Without any patent on the innovation, diffusion generates no additional innovator gains under direct controls and emission taxes because the innovator lacks a method for capturing rents enjoyed by the copying firms. Hence the innovator gains from the entire process of technological change for non-patented discoveries are the same as in the case of Downing and White (1986); that is, the innovation changes marginal conditions and the control authority adjusts properly, namely, $e^m aHId$ under emission taxes and $e^m ac - e^* cde^{**}$ under direct controls. We can see that emission taxes clearly generate abatement cost reductions for non-patented technologies.

A patent, however, could allow the innovator to capture some of the gains enjoyed by copying firms. Milliman and Prince (1989) incorporated this aspect into their model by assuming that the innovator captures a set percentage z $(0 < z \leq 1)$ of all cost reductions

accruing to non-innovators from patent use, including any beneficial changes in transfer gains or losses. Non-innovator gains from the adoption of the innovation per firm, which are to be divided between the innovating firm and non-innovating firms, are e^macc under direct controls and e^maf under emission taxes. Hence innovator royalties under the two policy instruments are the percentage z times industry-wide non-innovator gains, or $z(N-1)e^macc$ and $z(N-1)e^maf$, respectively. After control adjustments by the regulator, innovator royalties become $z(N-1)e^mkd$ under direct control and $z(N-1)e^mgd$ under emission taxes. Royalties increase under direct controls because, with control adjustment, costs without patent access rise e^mae^* to e^mke^{**} (Figure 2-3b). Under emission taxes, on the other hand, royalties decrease because abatement costs without patent access decline with control adjustment. Initially, area e^maf (Figure 2-3b) is subject to capture by the innovator with tax rate T^*; after the lower tax rate T^{**} is implemented, the smaller area e^mgd becomes subject to capture.

In sum, innovator gains from the entire process of technological change for patented discoveries are gains for non-patented technology plus royalties, that is, $e^macc - e^*cde^{**} + z(N-1)e^mkd$ under direct controls and $e^maHId + z(N-1)e^mgd$ under emission taxes. We can see that the more firms there are in the industry, that is, a larger N, the more royalties the innovator receives and hence the more innovator gains. While the abatement cost reductions under direct controls are smaller than those under emission taxes, that is,

$$e^macc - e^*cde^{**} < e^maHId, \qquad (2\text{-}4)$$

royalties are larger in the former case than in the latter case, that is,

$$z(N-1)e^mkd > z(N-1)e^mgd. \qquad (2\text{-}5)$$

Therefore, we cannot unambiguously tell whether direct controls or emission taxes create more innovation benefits for patented technologies. When the innovator can capture all of the benefits accruing to the adoption of the innovation by non-innovating firms, that is, $z = 1$, the innovator gains from the total process of technological change under direct controls are

$$e^macc - e^*cde^{**} + (N-1)e^mkd$$
$$= Ne^mkd - (e^*cde^{**} + cakd)$$
$$= Ne^mkd - e^*ake^{**}. \qquad (2\text{-}6)$$

That means that the innovator gains from the total process under direct controls consist of the benefits to all N firms of adopting the innovation minus the cost of reducing emissions from e^* to e^{**} by the innovator, which would not have been required if it were not for the regulatory adjustment following the diffusion of the innovation. Similarly, with $z = 1$, the total innovator gains under emission taxes are

36

$$e^m aHId + (N - 1)e^m gd$$

$$= Ne^m gd + e^m aHID - e^m gd$$

$$= Ne^m gd + gaHI. \qquad (2\text{-}7)$$

This means that under emission taxes the total innovator gains consist of the benefits to all N firms of adopting the innovation plus the reduction in the abatement cost by the innovator following the reduction in the tax rate from T^* to T^{**}. To see the difference in the total benefits under the two policy instruments, we have

$$(Ne^m kd - e^* ake^{**}) - (Ne^m gd + gaHI)$$

$$= Ngkd - e^* ake^{**} - gaHI. \qquad (2\text{-}8)$$

We can see that when there are many firms in the industry, that is, N is large, the value could conceivably be positive. In other words, total innovator gains could be larger under direct controls than under emission taxes, a result which is in contrast to the case where the innovation cannot be patented.

They also considered the case in which the innovator is an outside supplier firm. Since the supplier is not discharging emissions, no private gains are forthcoming from innovation itself; only diffusion and optimal agency response are relevant. Here too it is assumed that the supplier firm can patent an innovation and captures a set percentage z ($0 < z \leq 1$) of all private gains accruing to industry firms from patent use. The total patent royalties with diffusion are $zE^m AC$ under direct controls and $zE^m AF$ under emission taxes. With control adjustment, royalties decline under emission taxes to $zE^m GD$, but increase under direct controls to $zE^m KD$. Overall, outside innovator gains from the entire process of technological change are unambiguously positive under all regimes, as they can earn patent royalties without paying any direct costs or taxes. Direct controls, in particular, will encourage innovation by increasing the stringency of the standard, thus increasing the innovation gains.

While Milliman and Prince (1989) assumed that the innovator can appropriate a fixed fraction of the private gains to all the non-innovating firms in the industry from the new technology, Fischer, Parry, and Pizer (1998) considered a case in which the royalty level for the new technology is endogenously determined by the desire of the innovator to attract payment from the marginal, non-innovating firms. Their model consists of a three-stage process of innovation, diffusion, and emission abatement with a fixed number of n identical, competitive firms, one of which is an innovator. First, the innovating firm decides how much to invest in R&D to develop an emissions abatement technology. Then the other $n - 1$ firms decide whether to adopt this technology in return for a royalty fee or to use an imitation

technology which is not completely equivalent to the original innovation. Finally, all firms choose emissions abatement to minimize costs, given an emission tax. In this model it is assumed that the rate of effluent taxes is fixed at the pre-innovation level; that is, there is no policy adjustment following the innovation and its subsequent diffusion to other firms in the industry.

Since firms reduce emissions until the tax rate equals marginal abatement costs, abatement per firm increases as marginal costs shift down, depicted in by a^0, a^σ, and a^1 with the original technology, the imitation, and the patented technology, respectively. The innovator gains the full abatement cost effect for itself, the area *0hj* in the top panel (a). Non-innovators, however, although they realize the same cost savings, are only willing to pay less to adopt the patented technology. This area *0lj* equals the benefit from using the patented technology over the original technology, the area *0hj*, less the benefit from using the imitation over the old technology, the area *0hl*; that is,

$$0hj - 0hl = 0lj. \tag{2-9}$$

Overall, the innovator gets n times the abatement cost effect, *0hj*, less *(n – 1)* times the imitation effect, *0hl*; that is,

$$n0hj - (n - 1)0hl$$
$$= n(0hj - 0hl) + 0hl$$
$$= n0lj + 0hl. \tag{2-10}$$

When the imitation technology performs as well as the new, patented technology, that is, l moves to j, the innovator gains become *0hj*. That means that no firm would pay any royalties, because the equivalent imitation technology is freely available, and the innovator gains are limited to the reduction in its abatement costs only. On the other hand, when it is not possible to adopt any imitation technology, that is, l reaches h, then the innovator gains become *n0hj*. In this case the innovator can gain all the benefits through the reduction in abatement costs in the industry. We obtain similar results in the case of emission standards, although the innovator gains from diffusion are smaller than in the case of effluent taxes. In either case, innovation gains which can be captured by the innovator through licenses are constrained by the availability and performance of imitation technologies.

(a) Innovator
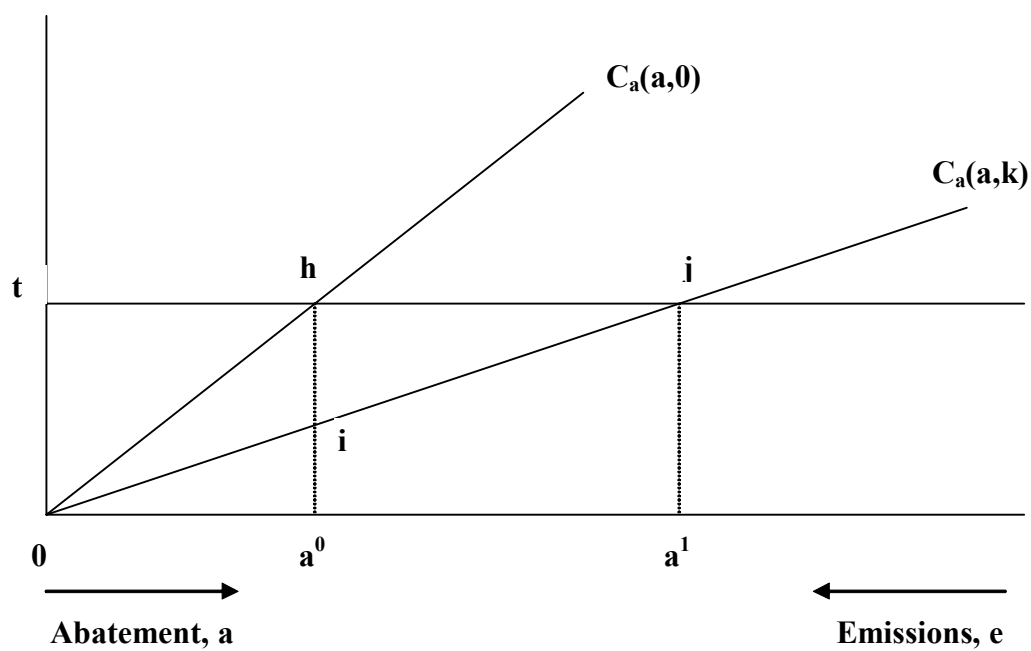
(b) Non-Innovator
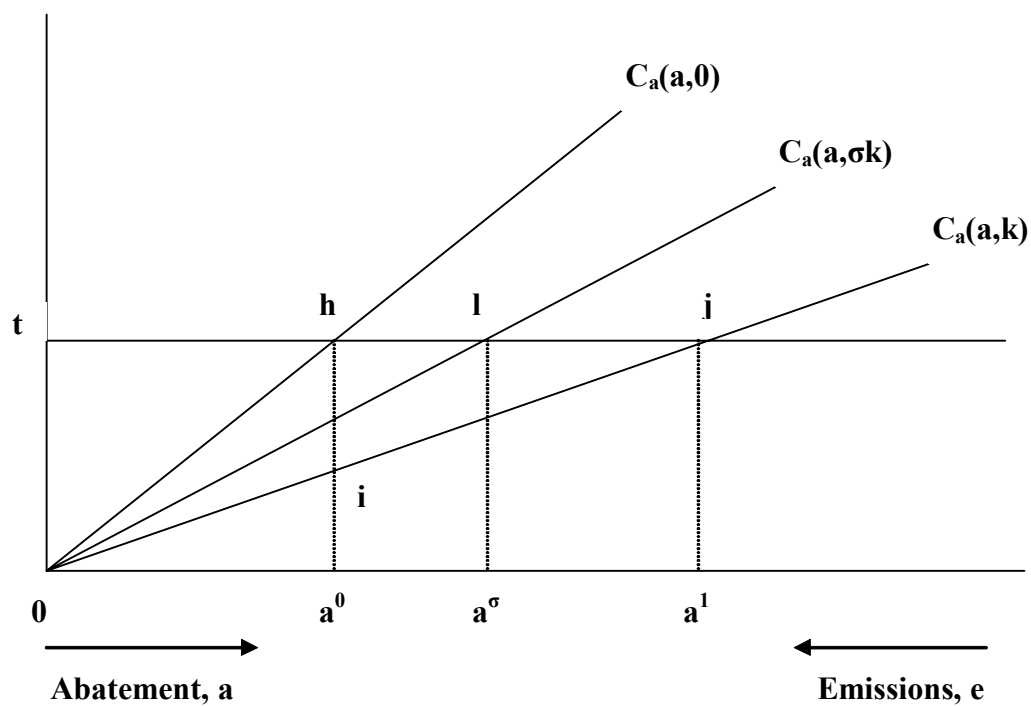
Figure 2-4 Incentives to Innovation with the Possibility of Imitation and No Policy Adjustment

(Fischer, Parry, and Pizer, 1998)

We can draw some implications from these models. First, when each firm develops its specific technology and there is no diffusion of new technologies to other firms, as long as the reduction in pollution emissions is so small that policy is not adjusted to a new, socially appropriate level, innovation benefits under emission taxes are larger than those under command-and-control approaches. In other words, emission taxes will encourage more innovation than command-and-control approaches. When the effects of new technologies are large enough as to prompt policy makers to adjust the control regulation, effluent taxes are again better in inducing innovation than direct control approaches. That is because, while the post-innovation policy adjustment is to raise the effluent standard level under direct control approaches, it is to lower the tax level under emission taxes, which will increase benefits accruing to innovation.

In cases where diffusion of innovation takes place, as long as innovation is patentable, royalties through adoption of innovation by other firms will increase innovation benefits to the innovator. When there is no adjustment of regulation, innovation benefits will be higher under emission taxes than under command-and-control instruments. If the innovation is diffused thoroughly in the industry, followed by an appropriate policy change, innovation benefits under command-and-control could be higher than under emission taxes. The reason is that the policy adjustment required under command-and-control is to raise the emission standard level, and that will increase the benefits of adopting the innovation by other firms, which in turn will increase the royalty payments to the innovator, on the assumption that the royalties are proportional to the benefits through the adoption of the innovation. On the other hand, emission taxes will be lowered after the diffusion of the innovation, and that will reduce the benefits to the adopters of the innovation, hence reducing the royalties to the innovator. When imitation technologies are available, they will work to constrain the level of the royalties to the innovator. As the performance of imitation technologies is better, the adopters of the original innovation are willing to pay less to the innovator.

There are many criticisms to various aspects and assumptions contained in these models [5]. Here our criticism focuses on the assumptions about technological change, particularly the exclusive focus on the end-of-pipe technology for pollution abatement. As we have discussed, Magat (1978) analyzed a case in which there is a tradeoff in R&D between improvement in output production technology and improvement in pollution abatement

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[5] For a comprehensive critique of previous theoretical approaches, see Kemp (1995).

technology. Here the technology considered for pollution abatement is basically that of the end-of-pipe type, and the possibility of developing clean technologies is not taken into account. In our research, the focus is placed on a choice between the end-of-pipe technology and the clean technology. As clean technologies, which do not require any pollution abatement, could achieve improvement in output production as well at the same time, they do not involve any tradeoff between improvement in output production and that in pollution abatement. That is, when a clean technology is chosen, it is not necessary to conduct R&D on end-of-pipe technology. Hence what will be of critical importance to firms is not to consider the optimal combination of R&D efforts between pollution abatement and output production, but rather to choose the end-of-pipe technology or the clean technology for the target of R&D.

Also, the marginal cost curve of pollution abatement, which has been commonly used in theoretical models, basically means the use of end-of-pipe technologies. The previous models we have discussed (Downing and White, 1986; Fischer, Parry, and Pizer, 1998; Milliman and Prince, 1989) assume that the marginal cost of pollution abatement increases as emissions are reduced. And it is also assumed that the scope for innovation is limited to those in which marginal abatement costs are lowered. In other words, marginal abatement costs are continuous and strictly increasing over a relevant region, and technology adoption is modeled simply as a decline in marginal abatement costs. Effectively, these assumptions mean that pollution abatement is implemented with end-of-pipe technologies. There is, however, another type of technologies for dealing with emissions from the production process, namely, clean technologies. In contrast to end-of-pipe technologies, clean technologies will eliminate the creation of pollutants from within the production process by altering the chemical reactions producing the main product. Since there is no pollution emission in the first place, the marginal abatement cost curve becomes irrelevant for the analysis of clean technologies. Later we will discuss the distinction between end-of-pipe and clean technologies in detail and incorporate into our analytical framework the difference in the dynamic character of technological improvement between the two types of green innovation. This point will have crucial implications in considering the effects of environmental regulation on technological change theoretically as well as empirically.

2.1.2 Empirical Studies

There are not so many empirical studies which examined the effects of environmental regulation on innovation[6]. And most of the previous studies were conducted at aggregate levels. As one of the influential studies in this area, Lanjouw and Mody (1996) used patent data to investigate the extent of innovation which occurred in the 1970s and 1980s. They found that the ratio of water pollution patents to total US patents was flat in the early 1970s and rose in the late 1970s to a new plateau, paralleling pollution control expenditures with a two- to three-year lag. And similarly the dramatic fall in water pollution control expenditure during the early 1980s was followed by a dip in patenting. The same pattern was also observed in industrial air pollution. Based on these findings, they suggest that certain plausible connections exist between environmental regulation and innovation.

In similar vein, Bhanagar and Cohen (1999) studied how environmental patent applications by U.S. manufacturing industries responded to environmental regulation during the period of 1983 through 1992. They found that environmental innovation, as measured by the number of successful environmental patent applications, responded to increases in pollution abatement expenditures. They also used government monitoring activities as a proxy for the stringency of environmental regulation and found that increased monitoring and enforcement activities related to existing regulations did not provide incentives to innovate.

Ratnayake (1999) took a broader view of innovation, looking at R&D in addition to patents. He examined whether environmental regulations enhance or hinder R&D expenditures, using the data for eight major U.S. industries for the period from 1982 to 1992. His findings suggest no strong evidence to support the view that environmental regulations, measured by pollution abatement costs, have any significant impact on R&D expenditures on pollution abatement technologies.

Jaffe and Palmer (1997) looked at aggregate innovative activities rather than just environmental technologies. Using panel data on U.S. industries from the middle of the 1970s to the early 1990s, they found that lagged environmental compliance expenditures, which is used as an indicator of the regulatory stringency, have a significant positive effect on total private expenditures on R&D. However, they could not find any evidence that industries' inventive outputs, measured by successful total patent applications, were related to the

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[6] Relatively speaking, more research has been done on the diffusion of environmentally beneficial technologies, particularly those of the end-of-pipe type. For example, Kemp (1998) made a careful study of the diffusion of

compliance costs. They suggest that their finding might imply that incremental R&D activity induced by environmental regulations is not productive or produces results that accomplish only regulatory compliance but that do not come out as patentable innovations.

Overall, these studies produced mixed results on the impact of environmental regulations on innovation. These results require a careful examination, and here we focus our attention to the ways in which the stringency of environmental regulation and the extent of innovation are measured. In these studies, the stringency of environmental regulations is mostly measured by pollution abatement costs and expenditures (PACE)[7]. While this is not unreasonable, as there is no direct way to measure and compare the stringency of environmental regulations between different industries and countries, we can point out several problems in adopting PACE for that purpose. First, the use of them assumes that high PACE is the result of large efforts made by industries to reduce pollution, therefore reflecting strict environmental regulations. That is, the measurement of PACE is a type of input-oriented indicator of environmental regulation, which are based on input efforts devoted to environmental protection (van Beers and van den Bergh, 1997). Regulatory compliance expenditures as a measure of environmental regulatory burden on industry, however, fall short of providing an exogenous measure of regulatory burden, because the level of these costs also depends on the ability of an industry in reacting to regulations. For example, an innovative, competitive industry may respond to environmental regulations in a more efficient, cheaper way than a less innovative industry, and hence the former may spend less for compliance, independent of the stringency of environmental regulations.

Furthermore, there are no precise definition of PACE and no simple way to measure it accurately. For example, an investment in energy-saving equipment, which is itself environmentally friendly technology, may have been carried out as a part of normal, profit-maximizing business behavior. Especially in the case of clean technologies, it is difficult to establish what portion of the total investment expenditures should be allocated to pollution

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biological waste-water treatment technologies in the food and beverage industry in the Netherlands. Here the focus of our discussion is placed on previous studies of the development side of technological change.

[7] Gray and Shadbegian (1993; 1995) also use the PACE data to examine the impact of environmental regulation on manufacturing productivity at the plat level. There are other approaches to the measurement. In Tobey (1990) the degree of the stringency of environmental policy is measured on a scale from one (tolerant) to seven (strict). Gray and Shadbegian (1998) created indices, incorporating the membership rate in major conservation organizations and the percent voting Democratic in Congressional elections to capture differences in political support for regulatory stringency. Qualitative indices of regulatory stringency are also used, such as the Conservation Foundation Index, the Fund for Renewable Energy and the Environment (FREE) Index, and the

abatement and control. Methodologies of their measurement are diverse across countries, which will make international comparisons difficult[8].

Instead of input-oriented indicators like the PACE, output-oriented indicators are also used to measure the stringency of environmental regulations. Output-oriented indicators are generally based on the concrete data of environmental situations, such as pollutant emissions data[9]. The logic supporting this approach is that better environmental quality has been achieved as a result of stricter environmental regulations. Although these output-oriented indicators, unlike the input-oriented indicators, take into account the results of compensating financial support from the government, they also have some limitations. One of the problems is that high quality of the environment is not necessarily due to the imposition of strict environmental regulations. Natural environmental conditions or other social factors might have produced the current situation without any effect of such regulations. Although the aggregate nature of these studies makes it almost inevitable to use the PACE incurred by firms to measure the stringency of environmental regulations, it is an indicator which is indirect at most and could be even misleading. We need other ways to deal with environmental regulations more directly.

The analysis of innovation for environmental protection also needs to be treated with caution. Lanjouw and Mody (1996) used patents on pollution control technology to examine the connections between environmental regulation and innovation. Their patent data cover nine environmental fields, namely, industrial and vehicular air pollution, waste pollution, hazardous and solid waste disposal, incineration and recycling of waste, oil spill clean-up, and alternative energy. Relevant patents were identified by determining the International Patent Classification (IPC) classes corresponding to various types of environmentally responsive innovation. For example, the IPC classes which are considered to include patents on technologies dealing with industrial air pollution are as follows: chemical purification of waste gases (B01D-53/34), chemical purification of waste gases by catalytic conversion (B01D-53/36), purifying/modifying gases containing carbon monoxide (C10K-1/3), adding materials to fuels or fires to reduce smoke (C10L-3), burning uncombusted material… (F23B-

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Green Index, which was complied by simply adding up the number of statutes from environmental laws (Levinson, 1996).

[8] A number of issues related to the concept of PACE and the treatment of its statistical estimation are discussed in Schmalensee (1994).

[9] Xing and Kolstad (1995), for example, adopted sulfur dioxide (SO_2) as a variable to reflect the overall level of environmental regulations when they examined the impact of environmental regulations on foreign direct investment.

5), removing solid residues, i.e., soot blowers (F23J-3), and …devices for treating smoke or fumes (F23J-15). These IPC classes were identified by using three keywords, namely, "treat," "scrub," and "remove." Similarly, Bhanagar and Cohen (1999) used successful environmental patent applications as a proxy for environmental innovation. Those patents counted as environmental patents involve hazardous or toxic waste destruction or containment, recycling or reusing waste, acid rain prevention, solid waste disposal, alternative energy sources, air pollution prevention, and water pollution prevention. As we can see from these lists, most of the technologies identified as environmental technologies are equipment installed at the end of the main process to remove or reduce emissions. That is, these studies basically looked at end-of-pipe technologies when they examined the technological effects of environmental regulations. The possibility of technologies for eliminating pollution from within the production process by changing the main chemical reaction, that is, clean technologies, is mostly missing from their consideration of innovations related to environmental protection.

Jaffe and Palmer (1997), on the other hand, used data on the whole R&D expenditures and patent applications in industries to examine the full extent of innovation. That is, their research covers not only technologies for environmental protection, which would include clean technologies as well as end-of-pipe technologies, but also technologies related to products and production processes in general. While this approach does not fail to capture innovations potentially influenced by environmental regulation in any way, many innovations which are not related to considerations for environmental protection are also included in the data set. Thus this method of technological measurement would not be entirely appropriate for the analysis of the effects of environmental regulation on technological change.

In sum, their results seem to suggest that increased stringency in environmental regulation encourages patent applications for environmental technologies, mainly those of the end-of-pipe type, but does not influence applications for patents on technologies in general. On the other hand, more stringent regulation seems to raise R&D expenditures in general, but not those on technologies designed for pollution abatement and control, which are basically end-of-pipe technologies. As these findings are mixed at aggregate levels, an in-depth analysis is necessary to thoroughly investigate the relationship between environmental regulation and technological change. In particular, attention needs to be paid to the crucial aspect of technological characteristics, that is, the distinction between end-of-pipe technologies and clean technologies. While technologies of the former type are relatively easy to find, those of the latter are particularly difficult to identify at aggregate levels, as they do

not produce pollutant emissions in the first place and require detailed knowledge and observation. In the following sections, we will examine the difference between end-of-pipe technologies and clean technologies and, based on that, discuss our framework for the analysis of effects of environmental regulation on technological change.

2.2 Technologies for Dealing with Emissions from Chemical Industries

Here we analyze technologies for dealing with emissions from the chemical process industries, which are considered to be among the most pollution-intensive sectors, by explicitly considering chemical reaction equations[10]. In the chemical process industries, production processes basically consist of four components, namely, the reaction system, separation system, recycling system, and waste treatment system (Mizsey, 1994)[11]. A production process used in the chemical process industries normally start with input materials I_a and I_b and produce main product M and by-product B

$$I_a + I_b \rightarrow M + B.$$
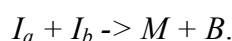
It can be schematically drawn as in Figure 2-5.

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[10] Technological trends in pollution-intensive industries, including, other than those mentioned above, the iron and steel, petroleum refining, and textile industries, are discussed in more detail in Bartzokas and Yarime (1997).
[11] In addition, the reaction system normally involves the heat exchange system for the provision of energy. Energy-consumption wastes, including flue gas and ash from fuel combustion, are emitted from the heat exchange system. For making our discussion simple, we do not consider this type of waste here.
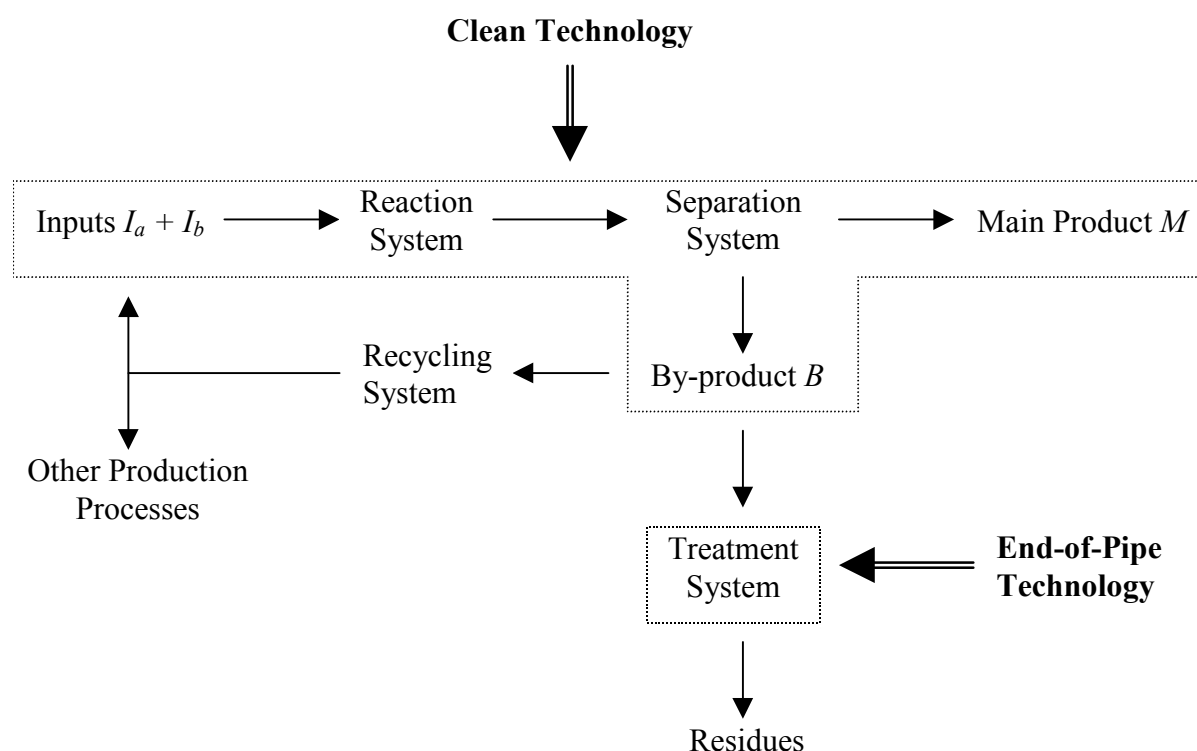
Clean Technology

Figure 2-5 End-of-Pipe Technology and Clean Technology Applied in Chemical Process Industries

The types of technological change designed for environmental protection can be different, depending on the source of pollution, that is, the main product M^* or by-product B^{*12}. When the main product M^* causes disruptions on the environment, the product itself needs to be changed. Among the examples are the chlorofluorocarbons (CFCs), which have been replaced by substitute chemical substances, following the international agreement on the phase-out of their production and use[13]. When the by-product B^* of a manufacturing process is the source of pollution, there are, broadly speaking, two types of technological change to deal with them, that is, the end-of-pipe technology and the clean technology[14]. Since traditionally the source of environmental disruption in the chemical process industries has

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[12] The asterisk denotes that the substance is a pollutant or a hazardous material.

[13] Technological change for the main product is discussed in more detail in Appendix.

[14] Depending on the focus of analysis, other ways of classification would be possible. Green and Irwin (1996), for example, suggest that environmental technologies can be divided into four categories: (1) end-of-pipe treatment; (2) end-of-pipe recovery for use in the same process or for use elsewhere; (3) efficiency improvements in the production process (waste minimization) and substitution of process materials; and (4) radical redesign of the production process.

been the by-product in many cases, we concentrate our discussions on the case of technological change for dealing with the by-product.

2.2.1 End-of-Pipe Technology

End-of-pipe technologies aim at removing or transforming wastes emitted from the production process. Basically, it is just added to the end of the production process and deals with by-product B_1^* without altering the main chemical reactions in the manufacturing process. Therefore, the chemical composition of the main product M_1 will not be affected; that is,

$$I_{a1} + I_{b1} -> M_1 + B_1^*$$
$$\Rightarrow I_{a1} + I_{b1} -> M_1 + B_1^*.$$

In addition to raw materials, auxiliary materials might also be involved in the production process. These materials are not consumed in the chemical reactions, and among notable examples are catalysts. Since auxiliary materials could be hazardous substances, for instance, heavy metals, it is critical to ensure that they are not emitted to the environment. When the chemical reactions involved in the process are not modified, that is,

$$I_{a1} + I_{b1} + A^* -> M_1 + B_1 + A^*$$
$$\Rightarrow I_{a1} + I_{b1} + A^* -> M_1 + B_1 + A^*,$$

end-of-pipe technologies will be employed to deal with the auxiliary material A. Useful materials, including the by-product as well as the auxiliary material, could be recovered and fed back into the original production process[15]. In principle, the application of end-of-pipe technologies does not require any change in the production process *per se*, and its consequent influence will be very limited and predictable.

End-of-pipe technologies have been used extensively in industry for the treatment of air emissions and waste water. A variety of techniques have been used to remove gaseous pollutants from effluent streams. Among the techniques used extensively are absorption,

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[15] In some cases, it could be possible to sell that by-product as an input to other manufacturing processes. The concept of "industrial clustering" has been proposed as a key methodology to achieve Zero Emissions (Pauli, 1995). A potential problem of this approach is that, since the adoption of a new technology in one process will influence other processes through the interconnected web of production processes, once an industrial cluster has been fixed, separate individual introductions of process changes could become very difficult, and coordination among them will be costly. In effect, all the industries involved may get technologically locked-in together (Yarime, 1999).

adsorption, condensation, incineration, and selective diffusion through membrane [16]. For removal of particles from gaseous effluents, there are several classes of control equipment. They are chambers, cyclones, electrostatic precipitators, filters, and scrubbers [17]. Industrial waste waters may contain toxic constituents such as heavy metals, or hazardous dissolved or immiscible solvents. There are also a number of end-of-pipe technologies have been adopted to deal with them [18].

An example of the use of end-of-pipe technologies can be seen in the production of nitric acid (HNO_3). The chief environmental problem of nitric acid plant operation is the discharge of nitrogen oxides (NO_x), which consists of nitric oxide (NO) and nitrogen dioxide (NO_2), from the vent stack (European Fertilizers Manufacturers' Association, 1995). In the oxidation section of nitric acid plants, ammonia is reacted with air on catalysts, forming nitric oxide and water (H_2O) according to the main equation:

$$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O.$$
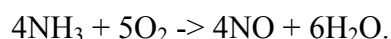
Nitric oxide is oxidized further to nitrogen dioxide as the combustion gases are cooled, according to the equation:

$$2NO + O_2 \longleftrightarrow 2NO_2^*.$$

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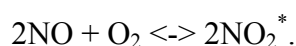
[16] Absorption is commonly used for devices such as columns containing packing or regularly spaced plates, open spray chambers and towers, and combinations of sprayed and packed chambers. Industrial applications of adsorption include odor control and the removal of volatile solvents such as benzene, ethanol, and trichloroethylene from effluent streams. Condensation is carried out in a device which appropriately cools the gas stream to remove condensed liquid. Incineration involves the combustion of unwanted chemicals at high temperature to convert them to harmless products such as carbon dioxide and water and is an important process for the treatment of toxic chemicals, where virtually complete removal is necessary. Selective diffusion processes through membrane have been applied for removing gases such as carbon dioxide, hydrogen sulfide, and hydrogen from natural gas (Flagan and Seinfeld, 1988).

[17] Mechanical collectors such as settling chambers and cyclones are typically suitable for relatively large particles and are often used as precleaners for the more efficient final control devices. Electrostatic precipitators are one of the most widely adopted particulate control devices, routinely used for fly ash removal from power plant flue gases as well as for the collection of particles and acid mists in the chemical and metallurgical process industries. The filtration of particles from gas streams is a major class of particulate air pollution control devices, and fabric filters are frequently used to remove solid particles from industrial gases, whereby the dusty gas flows through fabric bags and the particles accumulate on the cloth, and, in particular, to treat combustion gases from coal-fired boilers. Scrubbers are wet collection devices in which small particles can be removed from the gas flow by collision with water droplets, with the possibility of simultaneously removing soluble gaseous pollutants (Flagan and Seinfeld, 1988). The handling and disposal of large volumes of scrubbing liquids must be undertaken, however.

[18] Liquid waste streams with a high suspended solids content have been cleaned up by solids removal in clarifiers, thickeners, and liquid cyclones and by accelerated settling by inclined settlers. Dissolved air flotation techniques have been used to deal with waste streams with very finely divided solids in suspension. Final de-watering of the sludges obtained can be carried out on a continuous filter or a centrifuge, and the separated solids can be burned or discarded to landfill. Liquid waste streams containing an insoluble liquid, such as those which arise from extraction processes, from steam ejectors operating on solvent distillation systems, or from the loss of heat exchange fluid from a heat exchanger, are phase-separated with a simple settler prior to final

The absorption of the nitrogen oxide to water and its reaction to nitric acid take place according to the equation[19]:

$$3NO_2 + H_2O <-> \underline{2HNO_3} + \underset{\cdots}{NO}^*.$$
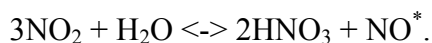
Here the main product is nitric acid (HNO_3), whose production is the purpose of this industrial process, and the by-product are nitric acid (NO) and nitrogen dioxide (NO_2), which together comprise harmful nitrogen oxides (NO_x).

There are two types of end-of-pipe technologies for NO_x control. One type of technology is non-selective catalytic reduction (NSCR), and the other is selective catalytic reduction (SCR). In the NSCR process, NO_x and free oxygen in the waste gas reacts with hydrogen, natural gas, or naphtha over a platinum, rhodium, or palladium catalyst, reducing NO_x to nitrogen and water. In the SCR process, NO_x in the tail gas reacts with ammonia and only to a lesser extent with oxygen over a catalyst, which can be vanadium pentoxide, platinum, iron/chromium oxides, or zeolites. In either case, the tail gas is preheated and mixed with the reactant gas, and the mixture is passed into a reactor containing the catalyst bed. Thus the main reactions producing nitric acid are not changed, and only these end-of-pipe technologies are added to the main process.

These technologies of the end-of-pipe type are basically designed for installation at the end of the production process, without altering the chemical reactions manufacturing the main product. Technical principles and properties of this type of equipment have been well understood in academic disciplines, particularly in chemical engineering, which deals with how to design chemical reactors and equipment based on transport phenomena (Bird, Stewart, and Lightfoot, 1960), thermodynamics (Smith and Van Ness, 1959), and chemical reaction engineering (Levenspiel, 1962). And their feasibilities have been demonstrated through traditional uses for pollution control in many industrial sectors. Thus the scope of R&D activities for end-of-pipe technologies will be relatively limited, and the uncertainty accompanied by this exploration for new equipment will not be so large. Compared with modifying the whole production process, the installation of an end-pipe technology to the existing production facilities will be relatively easy and cost much less, at least from a short-term perspective.

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disposal. The concentration of residual organics can be further reduced with an entrained or dissolved air flotation unit coupled with the initial separator (Hocking, 1998).

[19] To make it easy to make a distinction between the main product and the by-product in chemical reactions, the main product is underlined with a straight line like $\underline{M}$, and the by-product by a dotted line like $\underset{\cdots}{B}$.

Just as end-of-pipe technologies do not affect the main process, being installed at the end of the existing production facilities, however, their operating costs are simply added to the output production costs, which will result in an increase in the total manufacturing costs. While the operating costs of end-of-pipe technologies could decline, the output production costs will not be changed, as R&D activity and learning experience on end-of-pipe technologies will not improve the principal process producing the main product. Furthermore, although there are some types of end-of-pipe technologies which are very effective in reducing emissions, it will be extremely difficult, technically speaking, to completely eliminate pollutant discharges with end-of-pipe technologies, and some of the materials will be inevitably emitted to the environment. When the environmental regulation is so stringent as to require total elimination, the adoption of end-of-pipe technologies is not sufficient, and clean technologies will need to be developed and employed.

2.2.2 Clean Technology

The function of the clean technology is to eliminate the creation of pollutants from within the production process[20]. In chemical process industries, this means that the chemical reactions involved in producing the main product are modified. New routes of chemical reactions in which the formation of pollutants is prevented in the first place had to be found, and technologies which are feasible to implement them at the industrial level need to be developed[21]. By changing the input materials from I_{a1} and I_{b1} to I_{a2} and I_{b2} (including the possibility of using the same I_{b1} instead), the environmentally undesirable by-product B_1^* can be changed to another material B_2; that is,

$$I_{a1} + I_{b1} \rightarrow M_1 + B_1^*$$
$$\Rightarrow I_{a2} + I_{b2} \rightarrow M_1 + B_2.$$

Various types of clean technologies have begun to be developed and utilized in industrial production.

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[20] There are many ways of defining clean technology. Hanmer (1997) takes the term in a broad sense, incorporating technologies for pollutant and waste minimization, as well as energy and natural resource efficiency, applicable to various stages in the production, use, and disposable/reuse of products and to the provision of service. Jackson (1994) adopts a view that it is an operational approach to the development of the system of production and consumption, which incorporates a preventive approach to environmental protection. To address the qualitative difference from the end-of-pipe technology, we define the clean technology rather narrowly in this research. For a detailed discussion on various ways of defining the clean technology, see McMeekin and Green (1995).

For example, methyl methacrylate (MMA, $CH_2=C(CH_3)COOCH_3$), which is an important monomer in the plastic industry, is usually synthesized from propylene ($CH_3CH=CH_2$) and benzene (C_6H_6) via acetone (CH_3COCH_3). This route, which is called the acetone-cyanohydrin (ACH) route, also contains hazardous reagents such as hydrogen cyanide (HCN) and sulfuric acid (H_2SO_4). The chemical reactions involved in this process are given below (Ikeda, Tokutomi, and Nakajima, 1998):

$$C_6H_6 + CH_3CH=CH_2 + -> C_6H_5-CH(CH_3)_2$$

$$C_6H_5-CH(CH_3)_2 + O_2 -> C_6H_5OH + CH_3COCH_3$$

$$CH_3COCH_3 + HCN -> (CH_3)_2C(OH)CN$$

$$(CH_3)_2C(OH)CN + H_2SO_4 -> CH_2=C(CH_3)CONH_2 \cdot H_2SO_4$$

$$CH_2=C(CH_3)CONH_2 \cdot H_2SO_4 + CH_3OH -> CH_2=C(CH_3)COOCH_3 + NH_4HSO_4.$$
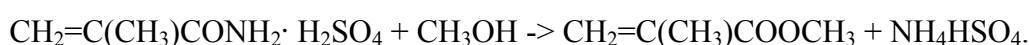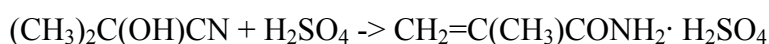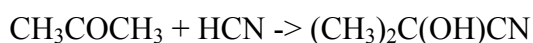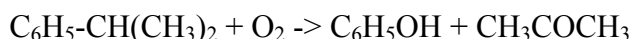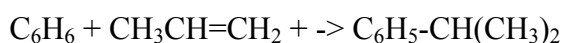
The overall stoichiometry is as follows:

$$CH_3CH=CH_2 + C_6H_6 + O_2 + HCN + H_2SO_4 + CH_3OH$$

$$-> \underline{CH_2=C(CH_3)COOCH_3} + \underline{C_6H_5OH} + \underline{NH_4HSO_4}^*.$$
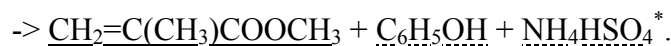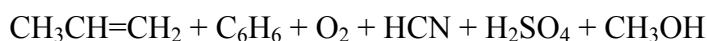
While phenol (C_6H_5OH) can be used for other purposes in different industrial sectors, ammonium hydrosulfate (NH_4HSO_4) is formed as process waste, which has often been simply dumped at sea.

In contrast, a new production path to MMA, the so-called ethylene route, is an example of the clean technology. The route uses as inputs ethylene ($CH_2=CH_2$) and the synthesis gas, which consists of carbon monoxide (CO) and hydrogen (H_2). The chemical reactions involved in the ethylene process are as follows (Suckling, 1994):

$$CH_2=CH_2 + CO + H_2 -> CH_3CH_2CHO$$

$$CO + 2H_2 -> CH_3OH$$

$$CH_3OH + 1/2O_2 -> HCHO + H_2O$$

$$CH_3CH_2CHO + HCHO -> CH_2=C(CH_3)CHO + H_2O$$

$$CH_2=C(CH_3)CHO + 1/2O_2 -> CH_2=C(CH_3)COOH$$

$$CH_2=C(CH_3)COOH + CH_3OH -> CH_2=C(CH_3)COOCH_3 + H_2O.$$
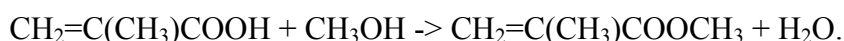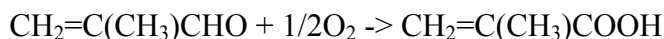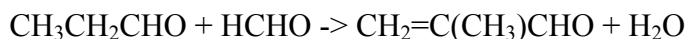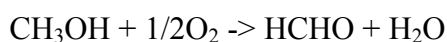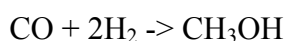
The overall stoichiometry thus becomes:

$$CH_2=CH_2 + 3CO + 5H_2 + O_2 -> \underline{CH_2=CCH_3COOCH_3} + \underline{3H_2O}.$$
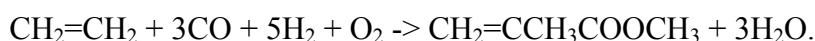
The by-product is only water (H_2O), a harmless substance.

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[21] As a methodology for achieving this, Anastas and Warner (1998) propose "green chemistry," which is defined as the utilization of a set of principles that reduces or eliminates the use or generation of hazardous substances in the design, manufacture and application of chemical products.

Another clean technology, the so-called C_4 oxidation route, starts with isobutane ($CH_2=CCH_3CH_3$) as raw material. Isobutane is oxidized to form methacrylic acid and then to MMA as is shown in the following chemical reactions (Ikeda, Tokutomi, and Nakajima, 1998):

$$CH_2=C(CH_3)_2 + H_2O \rightarrow (CH_3)_3COH$$
$$(CH_3)_3COH + O_2 \rightarrow CH_2=C(CH_3)CHO + 2H_2O$$
$$CH_2=C(CH_3)CHO + 1/2O_2 \rightarrow CH_2=C(CH_3)COOH$$
$$CH_2=C(CH_3)COOH + CH_3OH \rightarrow CH_2=C(CH_3)COOCH_3 + H_2O.$$
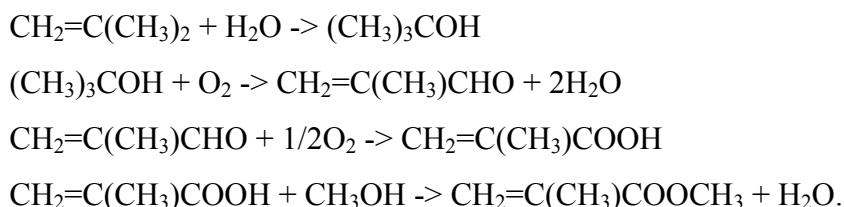
Therefore, the overall stoichiometry can be expressed as follows:

$$CH_2=C(CH_3)_2 + 3/2O_2 + CH_3OH \rightarrow \underline{CH_2=C(CH_3)COOCH_3 + 2H_2O}.$$
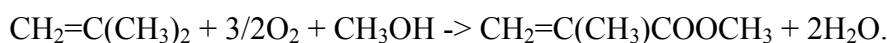
Again, water is the only by-product. The formation of the unwanted by-product ammonium hydrosulfate is avoided by changing the chemical reactions producing the main product MMA.

In many industrial processes, auxiliary materials are also used to produce the main product. An auxiliary material A_1 can enhance the rate of the principal reaction while it is not changed itself during the reaction:

$$I_{a1} + I_{b1} + A_1 \rightarrow M_1 + B_1 + A_1.$$
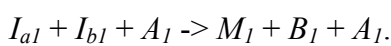
One notable example is the use of catalysts. When a hazardous auxiliary substance A_1^* is used, it is desirable to avoid its discharge to the environment. That could be achieved by replacing it with another material A_2; that is,

$$I_{a1} + I_{b1} + A_1^* \rightarrow M_1 + B_1 + A_1^*$$
$$\Rightarrow I_{a1} + I_{b1} + A_2 \rightarrow M_1 + B_1 + A_2.$$
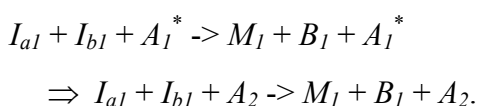
In some cases, it might be necessary to change the input materials from I_{a1} and I_{b1} to different substances I_{a2} and I_{b2}, together with change in the auxiliary material. That would also affect the by-product, changing B_1 to B_2:

$$I_{a1} + I_{b1} + A_1^* \rightarrow M_1 + B_1 + A_1^*$$
$$\Rightarrow I_{a2} + I_{b2} + A_2 \rightarrow M_1 + B_2 + A_2.$$
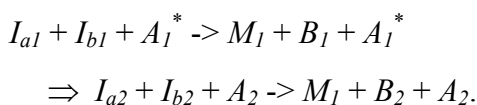
A tragic example of this case concerns emissions of mercury from the production process of acetaldehyde (CH_3CHO), which has been used as a starting material for making many organic compounds. Initially, the industrial process for producing acetaldehyde, the so-called acetylene process, started with acetylene ($CH\equiv CH$), whose production utilized calcium carbide and coke produced from coal. The reactions involved were as follows (Heaton, 1996):

$$CaCO_3 \rightarrow CaO + CO_2$$

$$CaO + 3C \rightarrow CaC_2 + CO$$

$$CaC_2 + 2H_2O \rightarrow CH{\equiv}CH + Ca(OH)_2.$$
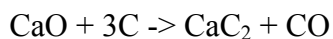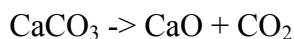
The acetylene was then reacted with water, using mercury (Hg) as a catalyst:

$$CH{\equiv}CH + H_2O + Hg^* \rightarrow \underline{CH_3CHO} + Hg^*.$$
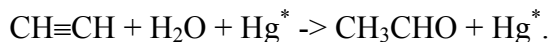
At the same time, a type of organic mercury, namely, dimethyl mercury, was also produced as a by-product in the production process (Nishimura and Okamura, 2001). The waste waters discharged by an acetaldehyde plant at the Minamata Bay in the southern part of Japan contained traces of dimethyl mercury. This harmful substance was then ingested in the fish diet of the inhabitants and eventually caused incidences of brain damage and death among those who had fish in the region. Although the acetylene process had once accounted for two thirds of the total national production of acetaldehyde, it was in the end abandoned completely in Japan following this tragedy (Iijima, 1990a).

The acetylene process has been replaced by the Wacker process. In this process, ethylene ($CH_2{=}CH_2$) is oxidized in aqueous solutions of palladium chloride ($PdCl_2$) and copper chloride ($CuCl_2$) as is shown in the following chemical reactions (Gates, 1992):

$$CH_2{=}CH_2 + H_2O + PdCl_2 \rightarrow \underline{CH_3CHO} + Pd + 2HCl$$

$$Pd + 2CuCl_2 \rightarrow PdCl_2 + 2CuCl$$

$$2CuCl + 1/2O_2 + 2HCl \rightarrow 2CuCl_2 + H_2O.$$
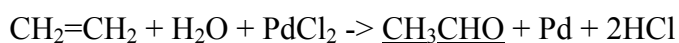
Summing these chemical reaction equations gives the simple stoichiometry of the ethylene oxidation:

$$CH_2{=}CH_2 + 1/2O_2 \rightarrow \underline{CH_3CHO}.$$

Here palladium chloride and copper chloride perform the function of catalysis, and the acetaldehyde production does not rely on the toxic mercury, thus completely eliminating its emissions to the environment. The ethylene process soon become an very efficient technology economically and has completely replaced the acetylene process in the end (Nishino, 1998).

As we have seen, in contrast to end-of-pipe technologies, which are designed for just being installed at the end of to the existing production facilities, clean technologies concern the whole production process. Clean technologies involve fundamental changes in the main chemical reactions for total elimination of pollutant emissions, a result which is very difficult to achieve simply by treating emissions at the end of the production process. The development of clean technologies demands careful and intensive research activities on novel

reactions, input materials, or catalysts. The performance of new clean technologies would be lower initially, with higher costs of producing the main product by using them. The technical performance could make a significant progress subsequently, depending on the extent of R&D efforts and learning experiences, and the output production cost could be reduced in the long run. That is not likely to happen in the case of end-of-pipe technologies, because they do not make any change in the main production process, and their operation costs are simply added to the output production cost.

On the other hand, as we have seen, there are usually multiple choices of clean technologies which can replace the existing, pollution-laden technology. With a large degree of uncertainty about technological and economic consequences of alternative technologies, it is no easy task to choose one which will be the most appropriate from a long-term perspective. Furthermore, as the chemical reactions are changed, so are the reaction conditions, including temperature and pressure. That will require revisions and modifications of the size and shape of plant and equipment and the materials used for their constructions. An important implication of that is that the investment costs required for clean technologies will be much larger than those for end-of-pipe technologies. Once a particular clean technology has been established, it will be very costly to make a switch to another one later.

In sum, by using chemical reaction equations, we have classified pollution abatement technologies used in the chemical process industries into two categories, namely, the end-of-pipe technology and the clean technology. While end-of-pipe technologies have been traditionally adopted and their technical properties have been relatively well established, clean technologies are radically new innovations, affecting the entire production process, and thus involve a large uncertainty in R&D as well as in future progress. And, as clean technologies replace the whole production process, there exists multiplicity in technological options, and the large investment required for installation gives the character of rigidity to clean technologies. With this qualitative distinction between the end-of-pipe technology and the clean technology, we will construct our analytical framework for the effects of environmental regulation on technological change in the following sections. Then our empirical study will examine the case of technological change observed in the chlor-alkali industry in Japan and Western Europe in the subsequent chapters.

2.3 Diverging Effects of Environmental Regulations on Technological Change

2.3.1 Environmental Policy Making under Uncertainty

As we saw in many of the earlier theoretical models, the advantages of policy instruments based on economic incentives have been often claimed by economists. These models are mostly constructed on the condition of the certainty and completeness of information possessed by the agents. The regulator is assumed to have complete information on the marginal damage curve of pollution. In other words, public authorities have sufficient capabilities to identify the mechanism of the behavior and reactions of the pollutants and then to calculate accurately the damage caused by the pollution on the environment. According to this information, the government is assumed to be able to set the proper level of the Pigouvian tax upon the activities of the generator of an externality, which should be equal to the marginal damage produced by that activity.

The amount of information necessary for the implementation of optimal policies, however, will be prohibitively large. There is a significant amount of uncertainty involved in identifying the sources of pollution and in understanding the scientific mechanisms of the behavior of the polluting substances in the environment. And, as research activities continue to generate new findings, scientific information itself will be subject to change[22]. It is unlikely that we can expect, in a reasonable period of time, to have certain, full information concerning the social cost of the damages. Thus it will be extremely difficult, if not impossible, to estimate accurately the costs of the environmental damages imposed by emissions, including increased illness, reduced recreational opportunities, impairment of materials, and ecological impacts[23]. In the presence of such a large extent of uncertainty about sources, mechanisms, and damages of environmental pollution, we cannot expect to be completely sure whether the level of the emission tax is optimal or not[24]. There seems to be

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[22] This point is particularly true in the case of the potential impacts of the greenhouse gasses on climate change. More details on the progress in scientific knowledge can be seen in the reports made by the Working Group I of the Intergovernmental Panel on Climate Change (Houghton, Ding, Griggs, Noguer, van der Linden, Dai, Maskell, and Johnson, 2001; Houghton, Meira Filho, Callander, Harris, Kattenberg, and Maskell, 1996).

[23] The contingent valuation method has been proposed by economists to estimate the damage done by spills of oil, chemicals, or other substances. It involves the use of sample surveys or questionnaires to elicit the willingness of respondents to pay for hypothetical projects or programs. See Portney (1994) for an overview of the technique and the debate surrounding it and Hanemann (1994) and Diamond and Hausman (1994) for cases for and against, respectively.

[24] The choice between price and quantitative instruments in the presence of uncertainty about marginal damage function or marginal control cost has been discussed in terms of static efficiency in the absence of technical change. When the marginal damage function is uncertain, all instruments yield the same expected social surplus because firms respond to the policy choice along the cost curve, independent of the shape of the damage function. In the case of uncertainty about the marginal control cost, on the other hand, the choice of the optimal

56

no general way in which we can obtain the accurate and detailed information required to implement the Pigouvian tax approach.

Instead, Baumol and Oates (1988) propose the environmental charges and standards approach, that is, the use of pollution charges to achieve a predetermined set of standards for environmental quality. They argue that, under appropriate conditions, the use of unit taxes is the least-cost method for the achievement of specified targets. If the initial taxes do not reduce the pollution in the environment sufficiently to satisfy the present acceptability standards, public authorities will raise the tax rates, and some of the polluting firm will have to modify their operations as tax rates are changed. This procedure will be repeated until the level of emissions will be adjusted to meet the specified targets. A crucial problem of this approach, as they acknowledge, is that such an iterative process will not be costless. Policy makers need to keep monitoring the accurate level of pollutants in the environment and to make necessary adjustments in the tax rates frequently. That approach will make the administrative costs rather high[25].

In practice, economic instruments have been used only to a minor degree, compared with conventional, command-and-control instruments. Regarded as more practical and easier to implement than the economic approaches, command-and-control instruments have been adopted far more frequently in the past to combat various types of pollution[26]. For air and water pollution control, all of the OECD countries have policies based on ambient environmental standards, and all use specific source discharge standards to accomplish them

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instrument depends on the relative slopes of the marginal damage and marginal cost functions. When the marginal damage curve is steeper than the marginal cost curve, quantitative instruments will be the better policy approach, and vice versa (Adar and Griffin, 1976; Fishelson, 1976; Weitzman, 1974). Mixtures of policy instruments are discussed by Roberts and Spence (1976). Mendelsohn (1984) shows that when innovation is possible, additional welfare loss is induced with price instruments, because firms overreact to the price instrument, producing too much or too little emission.

[25] Cole and Grossman (1999) argue that where abatement costs are relatively low and monitoring costs are relatively high, command-and-control is likely to be at least as efficient (and effective) as effluent taxes.

[26] Other factors could be considered for the predominance of command-and-control over market-based instruments: the training and experience of legislators may make them more comfortable with a direct standards approach than with market-based approaches; the time needed to learn about market-based instruments may represent significant opportunity costs; standards tend to hide the costs of pollution control while emphasizing the benefits; standards may offer greater opportunities for symbolic politics; and finally, at the level of the legislature, command-and-control standards offer legislators a greater degree of control over the distributional effects of environmental regulation (Keohane, Revesz, and Stavins, 1998). On the other hand, firms would be likely to prefer direct controls over emission taxes because emission standards serve as a barrier to entry for new firms, thus raising profits of existing firms (Dean and Brown, 1995). Taxes also require firms to pay not only abatement costs to reduce pollution to a specified level, but also costs of polluting up to that level (Buchanan and Tullock, 1975). For a unified framework for the political economy of environmental regulation, which views the outputs of environmental policy as emerging from a struggle between key interest groups, see Hahn (1990).

(Kopp, Portney, and DeWitt, 1990). According to a comprehensive survey of the use of economic instruments in OECD member countries, the number of economic instruments, defined narrowly to exclude subsidies, liability and administrative charges, was about 100, which was equivalent to an average of seven per country (Organisation for Economic Co-operation and Development, 1994). Many of these instruments were of little significance, and only a small proportion could be categorized as economic instruments in the stricter sense of measures which use financial incentives to encourage more appropriate environmental behavior. Economic efficiency was seldom a stated goal of the economic instruments[27], and the principal objective of the charging systems appeared to raise revenues. Based on these findings, the study concluded that the way in which environmental policies in OECD countries achieved changes in polluting behavior and consequent improvements in the environment was through measures of the command-and-control type. It is thus very difficult for an empirical study to compare the effects of different economic instruments on technological change in the same environmental issue.

Accordingly, in the subsequent discussions, we will focus on the analysis of the effects of command-and-control approaches on technological change. Given the presence of uncertainty concerning the estimation of damages on the environment due to pollutants, the decisions on emission standards will be inevitably influenced by subjective evaluations of what must be met for an acceptable environment[28]. It could be possible that different standards are adopted for the reduction in emissions of an identical pollutant, depending on historical, political, or social circumstances. For example, in one country, based on a very high estimation of the social costs of the pollution, the polluting industry might be required to completely eliminate emissions of the pollutant from the production process. In another country, on the other hand, the estimation of the damage of the pollutant on the environment might be lower, leading to the imposition of relatively weak standards on the same pollutant.

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[27] A notable exception is the emission trading systems, which have been adopted for pollution control over the past decade. The use of this type of instrument, however, has been largely confined to the United States (Stavins, 2000; United States Environmental Protection Agency, 2001), and other countries have little experience of implementing it.

[28] An increasing number of science and technology studies suggest that, when there is a debate on the estimation of the damage caused by pollution, we cannot not always expect that the debate will be closed purely in an objective way. For case studies on how disputes in various issues concerning science and technology have been resolved or closed, see, for example, Brickman, Jasanoff, and Ilgen (1985), Engelhardt, Tristram, and Caplan (1987), and Nelkin (1992).

2.3.2 Choice between the End-of-Pipe Technology and the Clean Technology

With the distinction between the end-of-pipe technology and the clean technology, we discuss the effects of command-and-control instruments on innovation[29]. We first consider firms' decisions on the adoption of the two types of technologies. For the existing original technology, we assume the following conditions about the abatement costs:

$AC_o(0) = 0$ (cost of no pollution abatement is zero)

$\dfrac{\partial AC_o(a)}{\partial a} > 0$ (marginal cost of pollution abatement is positive)

$\dfrac{\partial^2 AC_o(a)}{\partial a^2} > 0$ (marginal cost is increasing)

$AC_o(1) = \infty$ (cost of total abatement is infinite),

where a represents the degree of pollution abatement and $0 \leq a < 1$. The marginal cost curve is shown by MC_o in Figure 2-6. New equipment of the end-of-pipe type can be installed to the existing production facilities with the (annualized) investment cost IC_e. The new technology satisfies the following conditions[30]:

$AC_e(0) = 0$

$0 < \dfrac{\partial AC_e(a)}{\partial a} < \dfrac{\partial AC_o(a)}{\partial a}$

$\dfrac{\partial^2 AC_e(a)}{\partial a^2} > 0$

$AC_e(1) = \infty.$

That is, pollution abatement can be achieved at lower cost with the new end-of-pipe technology, as is illustrated by the marginal cost curve MC_e in Figure 2-6. Since the end-of-pipe technology does not affect the main reactions of the manufacturing process, as we can see in Figure 2-5, the costs of its installation and operation are simply added on to the original production cost PC_o, which will not be affected by the technological change from MC_o to MC_e.

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[29] The impacts of environmental policy on market structure or competitive conditions are not considered here. See, for example, Ulph (1997) for more discussions on these issues.
[30] The scrubber technology used for flue gas desulfurization, an equipment of the end-of-pipe, is assumed to satisfy these conditions in Bellas (1998).
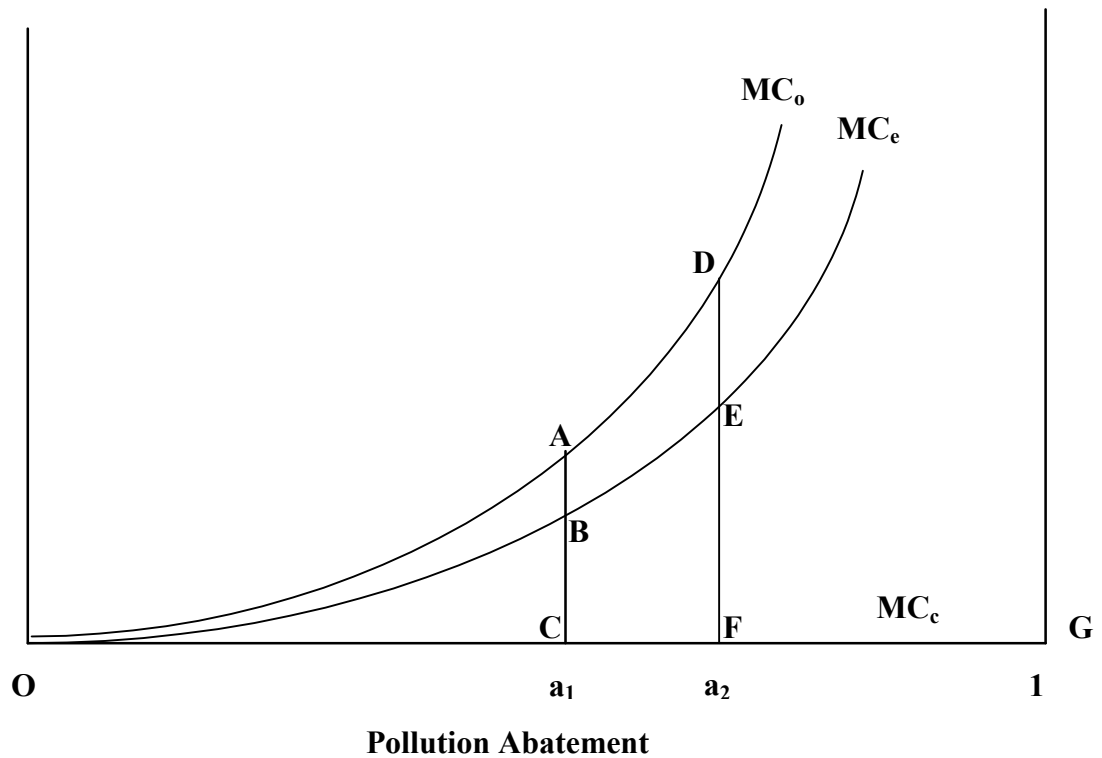
Figure 2-6 Pollution Abatement Costs with End-of-Pipe and Clean Technologies

The clean technology, on the other hand, is a type of technology with which pollution is eliminated from within the production process, meaning that pollutants do not form in the first place. Hence the convex, strictly increasing marginal cost curve assumed for the end-of-pipe technology becomes inappropriate for the analysis of the clean technology. Instead, the marginal cost is zero over the whole region of pollution abatement:

$$AC_c(0) = 0$$

$$\frac{\partial AC_c(a)}{\partial a} = 0.$$

That is, we can simply write

$$AC_c = 0.$$

Hence, the marginal cost curve for the clean technology MC_c does not depend on the level of pollution abatement a, and is represented by the straight line OG. On the other hand, since the clean technology involves radical modifications of the main production process, as Figure 2-5

shows, the output production cost PC_c will be significantly affected, and the (annualized) investment cost of its adoption IC_c will be very large.

With the distinction between the end-of-pipe technology and the clean technology, we first consider which technology firms will choose. Broadly speaking, there are two types of theoretical approaches to the adoption of technologies, depending on what is considered as the key factor in determining technological adoption, namely, information-based and profit-based approaches (Karshenas and Stoneman, 1995). The first type of theoretical approach, analogous to the epidemic or contagious models for the analysis of the spread of diseases, emphasizes that technological diffusion results from the spread of information (Griliches, 1957). In the simplest models, the use of new technology is constrained by the number of people who know the existence of that technology. As time proceeds, the experience of users leads to the spreading of knowledge on the existence of that technology to non-users, who in turn become users, leading to a further spread of information. In the case of process technologies, however, it is very unlikely that manufacturers are unaware of their existence for a long time, at least in industrialized countries, because normally information on technologies are quickly available through trade journals, meetings, conferences and other opportunities. Specialized engineering firms, in particular, are eager to provide detailed information on their technological information to potential customers. While this is basically an empirical question, we assume that manufacturers will adopt a technology when the benefits from adoption is larger than the cost of adoption, that is, the profit-based approach (David, 1975).

Thus we consider that firms will choose a technology which is less costly to adopt, given the different nature and characteristics of the end-of-pipe technology and the clean technology. As we have discussed, the end-of-pipe technology does not fundamentally influence the main production process, and hence its output production cost will not be affected, remaining the same as the original one PC_o. The clean technology, on the other hand, means that the main manufacturing process is significantly changed, and accordingly the output production cost PC_c will diverge from PC_o. Since the clean technology is a newly developed technology, it is likely that its output production cost is larger than that of the old technology, at least initially, because otherwise it would have been already adopted. Hence we assume that

$PC_c > PC_o.$

As for initial investment, the end-of-pipe technology is generally less complicated, designed to be installed at the end of the manufacturing process, whereas the clean technology changes the main process and requires the alteration of the whole production facilities. Hence we can reasonably assume that the investment cost, which would not vary depending on the degree of pollution abatement, is much larger for the clean technology than for the end-of-pipe technology[31]. Thus we have

$$IC_c > IC_e.$$

Regarding the pollution abatement costs with the end-of-pipe technology, when an emission standard a is introduced at $a = a_1$ (Figure 2-6), we can see that the operating cost of the equipment aimed exclusively at reducing emissions is area OBC. When a more stringent emission standard a_2 is imposed, then the cost necessary for operating the end-of-pipe equipment for reducing emissions will be increased to OEF; that is, we have

$$AC_e(a_2) = OEF > OBC = AC_e(a_1) \ (a_2 > a_1).$$

The clean technology, on the other hand, does not produce any emissions, and thus there is no cost specifically for reducing emissions. As the emission standard is raised, while the clean technology will not be affected, the pollution abatement cost with the end-of-pipe technology will be increased. Regarding the scale of the abatement cost, however, Robinson (1985) reports that the operating cost of abatement equipment normally represents less than 2 percent of the production costs in chemical process industries. Thus, as long as the emission standard a is not extremely stringent, we expect that the operation cost of the end-of-pipe equipment $AC_e(a)$ would be much smaller than the level of the output production cost:

$$PC_o >> AC_e(a).$$

With the output production costs PC_o and PC_c, investment costs IC_e and IC_c, and pollution abatement cost $AC_e(a)$, we can see which technological choice can provide a less costly measure for emission reduction. Given that the investment cost and the output production are higher with the clean technology than with the end-of-pipe technology, unless the emission standard is imposed at such a high level that the pollution abatement cost becomes significantly large, we can reasonably expect that it is more costly to deal with emissions with the clean technology than with the end-of-pipe technology; that is,

$$PC_c + IC_c - (PC_o + IC_e + AC_e(a)) > 0.$$

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[31] Yanagioka (1993) reports that the cost of installing end-of-pipe equipment for dealing with emissions from electric power plants, whose sector is considered as one of the most polluting in industry, accounts for 20 per cent of the investment cost for the whole plant.

This implies that, facing a relatively weak regulation imposed on pollutant emissions, companies will choose to adopt the end-of-pipe technology, rather than to newly introduce the clean technology, at least while the development of the clean technology is still in its infancy. Only when the emission standard is too stringent to be complied with by the end-of-pipe technology, effectively demanding that the phase-out of the existing production technology is necessary, companies will adopt the clean technology to eliminate emissions. Otherwise, it is likely that the imposition of a moderate emission standard will create incentives for companies to adopt the end-of-pipe technology, rather than the clean technology[32].

Innovating firms, on the other hand, make a choice for their R&D investment between the two types of technological measures for pollution abatement. In making that decision, innovating firms consider the demands for the technologies they develop, because, as discussed in the models of Milliman and Prince (1989) and Fischer, Parry, and Pizer (1998), innovation gains to the innovating firms will be significantly influenced by how much of their technologies will be adopted by other producers in the industry[33]. When the innovating firms are those outside the industry, notably, specialized engineering firms[34], the adoption of their technologies by other firms is particularly important, because, as they are not involved in production, there are no benefits from the reduction in production cost, and thus technology licensing is the only source of revenues. As long as it is regarded that the clean technology is more costly for pollution abatement than the end-of-pipe technology, polluting manufacturers will choose the latter, not allowing the developers of the clean technology to recoup R&D expenditures on it through its adoption by other firms. Expecting that, the innovating firms will have little incentive to invest a large amount of resources in the clean technology, whose development will take a long period of time with a large uncertainty in ultimate outcomes.

To sum up, pollution-emitting producers, under pressure to comply with emission standards within a regulatory framework, will adopt end-of-pipe technologies as long as the cost of pollution abatement with them is smaller than that with clean technologies. The expectation that few innovation benefits can be gained from the development of clean

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[32] Here there is another choice to companies that that they simply do not comply with the regulation. This possibility, however, is increasingly difficult to take, at least in the industrialized countries, considering that, when it is disclosed to the public, potential negative effects on corporate image and reputation will be prohibitively high.

[33] It is reported by Arora (1997) that in chemical process industries technology licensing is actually used by many innovating companies as an important means of generating revenue from process innovations.

[34] The importance of innovation activities of process plant contractors is discussed in Hutcheson, Pearson, and Ball (1996).

technologies will in turn encourage innovating firms to concentrate their R&D efforts on end-of-pipe technologies, rather than on clean technologies. Thus the development of clean technologies will not be promoted, even when there is a possibility that these radically new technologies will become

On the other hand, if the regulation imposed on pollutant emissions is so stringent that it is extremely costly or technically impossible to achieve that target with the end-of-pipe technology, then pollution-laden manufacturers will be prompted to adopt the clean technology. In this case, innovating firms can be sure that there will be sufficient demands for the clean technology to be adopted by manufactures in the industry and thus will be encouraged to make investments for R&D on their new innovations. As the investment cost of installing the clean technology and the production cost with it will be higher than with the end-of-pipe technology, however, manufacturers have to incur larger expenditures for pollution abatement, at least initially.

2.3.3 Technological Progress through R&D and Learning

In the previous section we have assumed that the performance of the two types of pollution abatement technologies and hence the production costs with them are fixed. It is well known, however, that technologies generally do not remain the same and will progress. In particular, we can conceptually identify two mechanisms, namely, R&D activities and actual experimentation of technologies, that is, technological learning, which will work to improve the performance of technologies. The importance of R&D for technological progress has been well illustrated in the history of industrial innovations, including those in the chemical industry (for example, Freeman, 1982). Technological learning basically takes place in two forms. The first is learning-by-doing (Arrow, 1962). It has been generally considered as a form of leaning that takes place at the manufacturing stage after the product has been designed, that is, after the R&D stage has been completed. Leaning at this stage consists of reducing real labor costs per unit of output[35]. Learning-by-using (Rosenberg, 1982), on the other hand, depends, not on the experience involved in producing the product, but on its utilization by the final user, particularly in the case of capital goods. The performance characteristics of a durable capital good often cannot be understood until after prolonged experience with it, and many significant characteristics are revealed only after prolonged use,

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[35] For a historical review of various types of the learning curve, see Yelle (1979).

notably, the useful life of a durable capital good. Thus extensive uses of capital goods generate valuable information for innovating firms to make important modifications which will be incorporated in subsequent models.

While we can conceptually differentiate the R&D activities and technological learning, in practice there are intricate interactions between R&D and technological learning. In contrast to the traditional "linear model," in which innovation proceeds linearly from scientific research to development, the newly proposed "chain model" places importance on feedback from downstream phases in the linear model to upstream phases as well as interactions between science and innovative process at every phase of the innovation process (Kline and Rosenberg, 1986)[36]. As Watanabe (1995) discusses the "virtual spin cycle" between R&D, adoption, and learning in the case of photovoltaic development in Japan, phases of technological change are closely interlinked, and it is very difficulty to treat them separately as sources of technological dynamics. Hence here we simplify our argument by formulating a model in which technologies will improve as time passes[37].

By incorporating the crucial point that the performance of the two types of pollution abatement technologies will improve, we now modify the previous argument on the effects of environmental regulation on technological change. An improvement in the performance of the end-of-pipe technology will reduce the cost of operating the equipment for pollution abatement $AC_e(a)$. In Figure 2-7, the marginal cost curve improves from MC_e to MC_e' after time t' has passed.

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[36] The linear model has also been criticized by other models which emphasize much more complex, evolutionary interactions between innovation phases (McKelvey, 1996; Ruttan, 2001; Stokes, 1997).

[37] On this point, Grubler (1998) constructed a model in which production costs (i.e. a measure of technological improvement) decrease in response to total expenditures including both R&D investments and production capacity investments (i.e. a measure of technological learning). As R&D investments and capacity investments are qualitatively different, a question remains whether it is appropriate to just combine the two types of investments into one figure.

MC$_o$ **MC$_e$** **MC$_e$'**

D

A

E

t'

B

E'

B'

C F **MC$_c$** G

O a$_1$ a$_2$ 1

Pollution Abatement, a
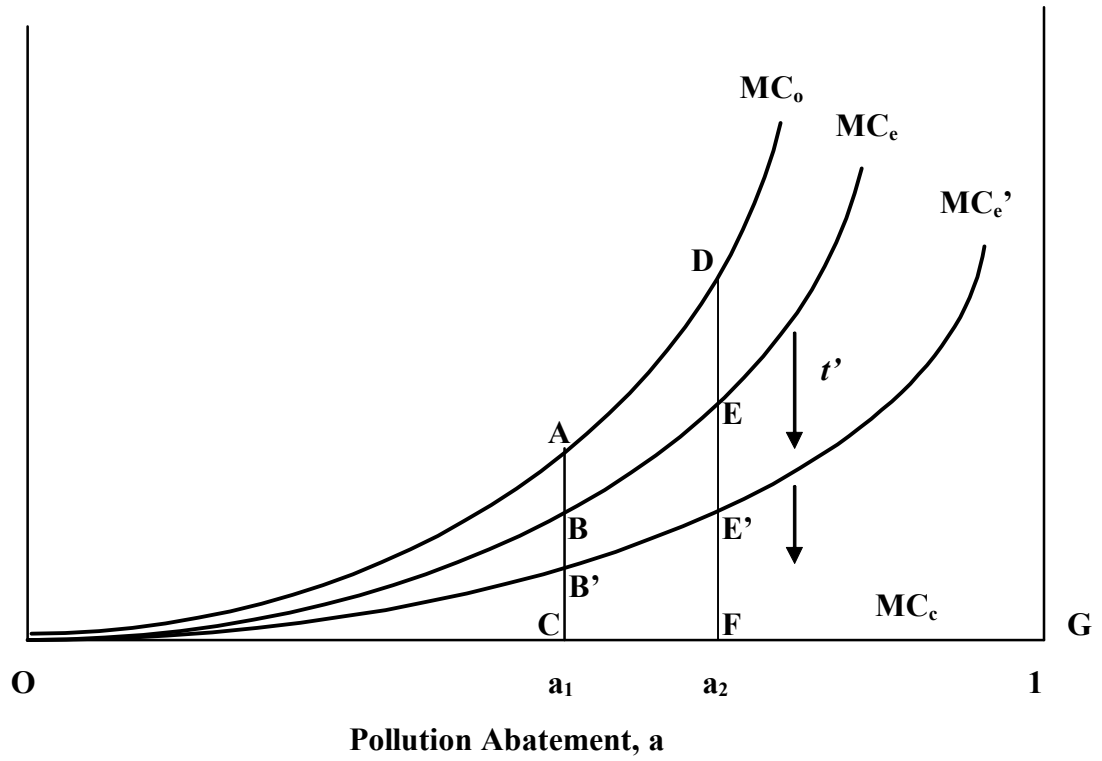
Figure 2-7 Pollution Abatement Costs with Improvements in the End-of-Pipe Technology and the Clean Technology

As the end-of-pipe technology is basically separate from the output production technology, however, R&D on the end-of-pipe technology will have no impact on the main production process. Hence the production cost PC_o will not be affected. And, as we discussed above, the abatement cost $AC_e(a)$ is larger when the level of pollution abatement is higher. A schematic illustration is given in Figure 2-8(a). The following conditions are satisfied:

$$\frac{\partial AC_e(a,t)}{\partial t} < 0$$

$$\frac{\partial^2 AC_e(a,t)}{\partial^2 t} > 0$$

$$AC_e(a_1, t) < AC_e(a_2, t)\ (a_1 < a_2)$$

$$\frac{\partial PC_o(t)}{\partial t} = 0\,(PC_o \text{ is constant}),$$

where t represents the time passed since the time when the technology was developed for the first time. While improvements can be expected in the performance of the end-of-pipe technology, which will reduce the pollution abatement cost $AC_e(a, t)$ with it, basically they will not affect the main production process, and the production cost PC_o will remain the same. The abatement cost is simply added to the production cost of the original process. Hence the total production cost with the original production process equipped with the end-of-pipe technology will be $PC_o + AC_e(a, t)$.

On the other hand, the clean technology will not show any improvement specifically in pollution abatement costs because it makes no pollutant emissions in the first place. That means that the marginal abatement cost curve MC_c remains unchanged in Figure 2-7. Technological progress through R&D and learning, however, will be directed to reduce the output production cost PC_c. As we discussed above, the clean technology involves a wholly new process, and the extent of technological progress is subject to uncertainty. Moreover, there are usually multiple choices of the clean technology, whose ultimate outcomes cannot be predicted accurately in advance. For the sake of simplicity, here we consider only two kinds of the clean technology. The first clean technology c_1 looks promising at the beginning, but will fail to achieve significant progress in the long run. The second clean technology c_2 initially seems to be far inferior to the existing production technology, but will succeed in improving rapidly, reducing the output production cost to less than that with the original technology. Figure 2-8(b) gives a schematic illustration. That is, we have

$$PC_o < PC_{c1}(0) < PC_{c2}(0)$$

$$\frac{\partial PC_{c2}(t)}{\partial t} < \frac{\partial PC_{c1}(t)}{\partial t} < 0$$

$$PC_{c2}(t^*) = PC_o$$

$$\frac{\partial^2 PC_{c1}(t)}{\partial t^2} > 0$$

$$\frac{\partial^2 PC_{c2}(t)}{\partial t^2} > 0 .$$

We have assumed that the decline in the production cost will be subject to diminishing returns. After the time t^* has passed since the technological development, the production cost with the clean technology c_2 will become lower than that with the original technology.

(a) End-of-Pipe Technology

$PC_o + OEF$

$PC_o + OE'F$

$PC_o + OBC$

$PC_o + OB'C$

PC_o

$PC_o + AC_e(a_2, t)$

$PC_o + AC_e(a_1, t)$

Original Technology

0   t'

Time, t

(b) Clean Technology

$PC_{c2}(0)$

$PC_{c1}(0)$

$PC_{c1}(t)$
Clean Technology c_1

Original Technology

PC_o

$PC_{c2}(t)$
Clean Technology c_2

0   t^*

Time, t
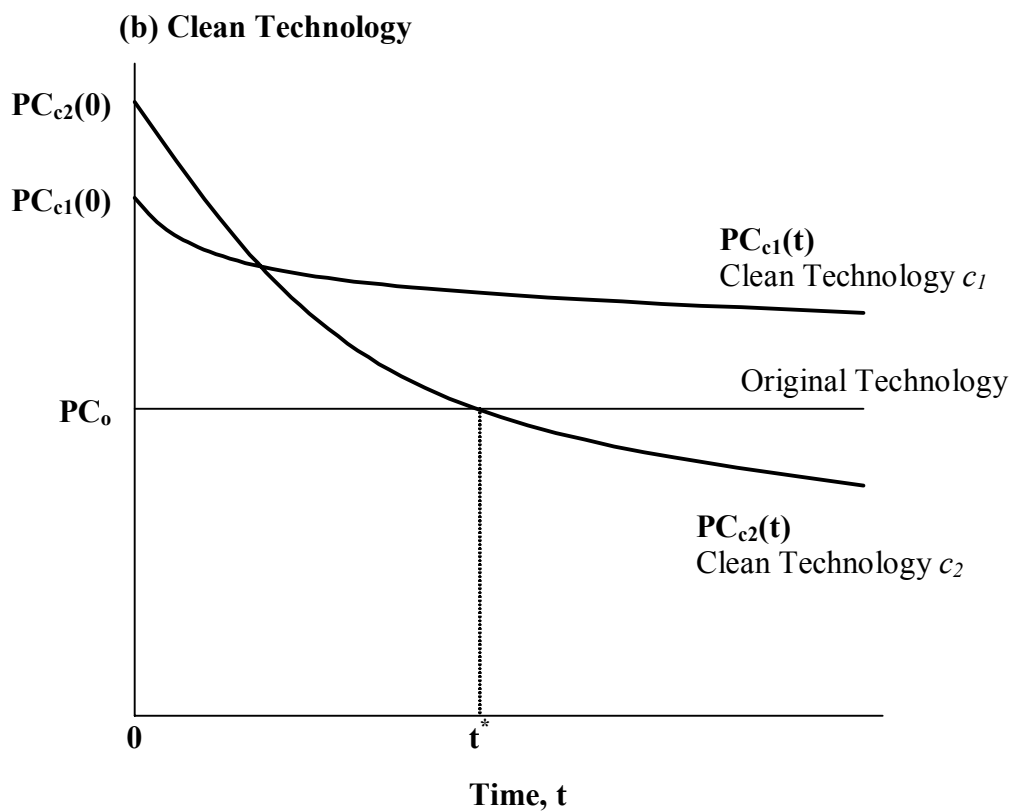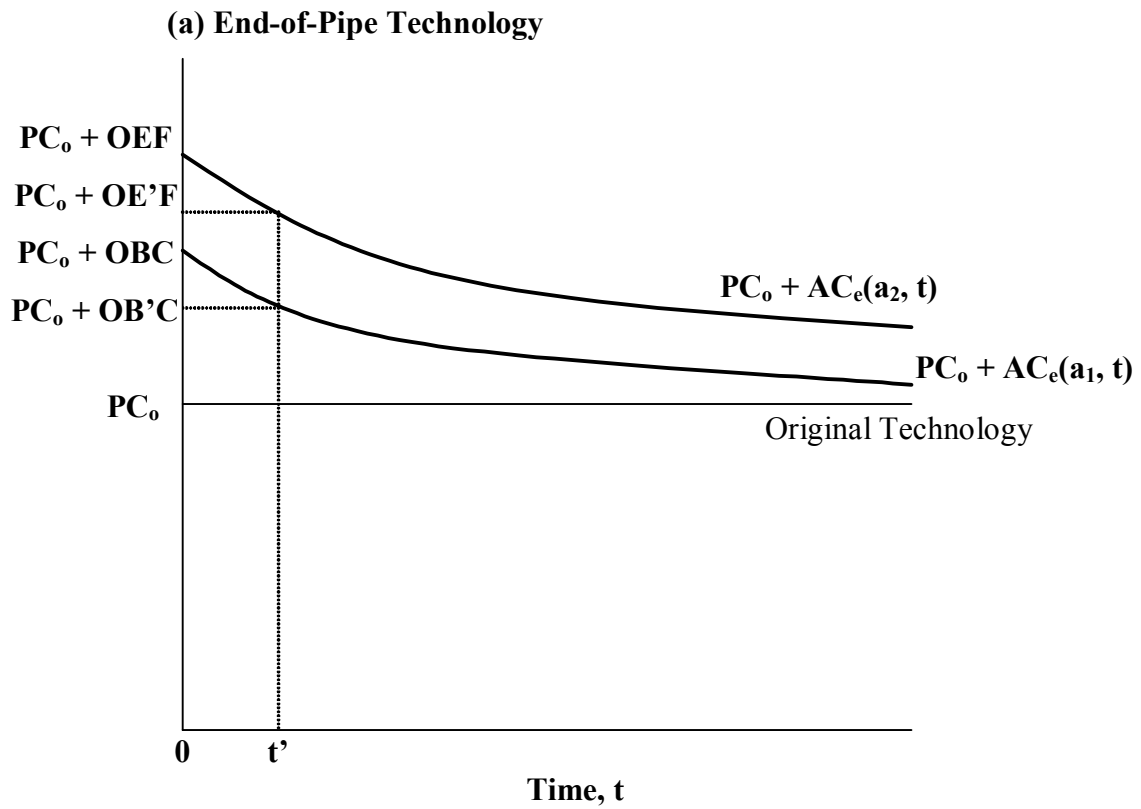
Figure 2-8 Operating Costs with the End-of-Pipe Technology and the Clean Technology

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As we discussed in the static case, when the effluent standard introduced is not extremely stringent, meaning that the pollution abatement cost AC_e is relatively small, it is likely that even the clean technology c_1, which is initially more efficient the clean technology c_2, is costly to adopt, compared with the end-of-pipe technology; that is, we have the same result as in the case of no technological progress:

$$PC_{c1}(0) + IC_{c1} - (PC_o + IC_e + AC_e(a, 0)) > 0.$$

That is, prompted by the regulation to reduce pollution to a certain emission standard, normally by a specified deadline, companies will adopt the end-of-pipe technology, rather than the more expensive clean technology. Users' decisions on the adoption of the end-of-pipe technology will create more demands for it, and that will encourage further research and development and learning on the end-of-pipe technology, reducing the pollution abatement cost further. While there is a possibility for the development of the clean technology c_2, which will become better than the original technology in the long run economically as well as environmentally, it is unlikely that this technological option will be pursued, as the regulation normally requires compliance with emission standards in a relatively short period of time, which will not give sufficient time for technological progress. As long as the end-of-pipe technology works to reduce emissions to a certain extent, pollution-emitting producers have a strong incentive to continue to use the existing production technology.

In contrast, when the environmental regulation is such a stringent one that effectively the phase out of the existing production technology is the only option, manufactures need to switch to a new clean technology. As there are normally multiple options of the clean technology, which one will turn out to be the most efficient could not be known *ex ante* without intensive R&D efforts and technological learning through the use of it. If the regulatory schedule demands an immediate abolishment of the existing production technology, however, companies will have no choice other than to adopt a clean technology whose production cost is the smallest at that time, that is, the clean technology c_1. Adoptions of that technology will promote progress in performance through R&D and learning, but how much the technological progress will be cannot be exactly predicted under the existence of a high degree of uncertainty concerning subsequent technological change. Eliminating diversity in technological options at an earlier stage, the stringent regulation will result in forcing firms to choose a particular type of the clean technology which may not be the best option from a long-term perspective. A schematic illustration of this situation is given in Figure 2-9.
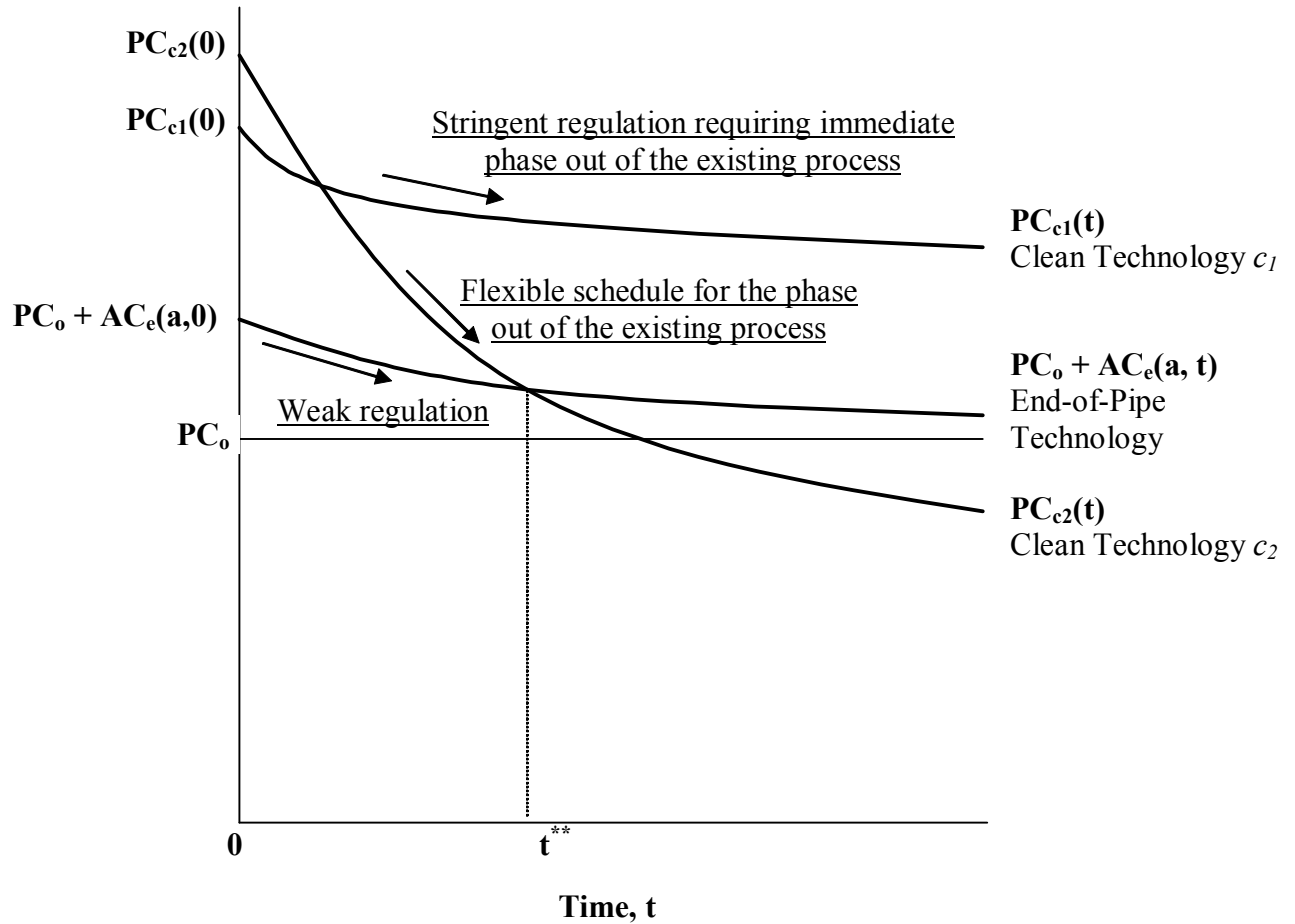
Figure 2-9 Production Costs with the End-of-Pipe Technology and the Clean Technology

As investment expenditures entail sunk costs and cannot be fully recouped later, investment has a characteristic of some degree of irreversibility. Especially in the case of the chemical process industries, plant investment takes a long period of time and costs a significant amount of money, and the degree of irreversibility is significantly large. Once a large investment has been made on a particular type of the clean technology, it will be considerably costly to switch at a later stage to a better technology, which will be known *ex post*. In other words, the initial choice of the clean technology c_1 carries the character of technological lock-in[38].

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[38] The possibility of technological lock-in has been addressed theoretically by Arthur (1989) and empirically by David (1985). Foray and Grübler (1990) examined the case of technological lock-in in the ferrous casting industry, which has had observed the diffusion of different technologies between France and Germany. Their analysis emphasizes the crucial nature of the initial stage of diffusion, where the accumulation of knowledge and learning occurs, bringing about the different technological trajectories. Frankel (1955) and Balmann, Odening, Weikard, and Brandes (1996) showed that technological complementarity and the existence of sunk costs can

With a flexible schedule, however, government regulation can provide an opportunity to experiment other technological alternatives, including the clean technology c_2, which seems to be a promising technology but is still in its infancy at an initial stage. Through R&D investment and learning experience, further technological progress will be promoted subsequently, which otherwise would not happen under a rigidly fixed regulatory schedule. Therefore, there are two possibilities concerning the consequence of the imposition of the stringent regulation for the phase out of the existing technology; that is, we will observe the dominance of the ultimately inefficient technology c_1 or the emergence of the best technology c_2. By allowing more time and flexibility for actual experimentation of various types of the clean technology, the stringent regulation can help to make the right technological choice, that is, the clean technology c_2.

Even in a region where such a strong regulation has not been introduced, there is a possibility that the efficient clean technology c_2, whose development has been encouraged by a stringent regulation, will become available later to pollution emitters. In that case, those producers who has been subject to relatively weak regulations, observing that the clean technology has become more efficient than the original technology, that is,

$$PC_{c2}(t) < PC_o + AC_e(a, t) \ (t > t^{**})$$

in Figure 2-9, will choose the clean technology when they construct new plants, on the assumption that the initial investment cost is equal between the original technology and the clean technology c_2:

$$IC_o = IC_{c2}.$$

For plants which have already been well established with the original pollution-burden technology, equipped with the end-of-pipe technology for pollution reduction, however, the replacement of the old technology with the new clean technology c_2 will not happen immediately after time t^{**}. That is because the saving in the production cost from the conversion of the existing technology to the clean technology will not yet be sufficient at this moment to offset the large amount of the initial investment cost IC_{c2} required for the introduction of the new clean technology; that is,

$$IC_{c2} > PC_o + AC_e(a, t) - PC_{c2}(t) \ (t \approx t^{**})$$

---

lead to a state of lock-in. Cowan and Gunby (1996), Cowan and Hultén (1996), and Foreman-Peck (1996) also discussed other cases of technological lock-in. In the case of technologies for environmental protection, Kemp (1995) emphasizes the importance of creating "market niche" to secure the diversity of technological options. For a critical appraisal of the arguments on technological lock-in, particularly from the perspective which emphasizes the efficiency of the market mechanism, see Liebowitz and Margolis (1990; 1995).

in Figure 2-10. If the clean technology c_2 progress substantially to the extent that, after time t^{***} has passed, the saving in the production cost can cover the investment cost, that is,

$$IC_{c2} < PC_o + AC_e(a, t) - PC_{c2}(t) \ (t > t^{***})$$

in Figure 2-10(a), then the operators of the plants based on the old production technology will switch to the new clean technology.

On the other hand, if the efficiency of the clean technology c_2 does not improve sufficiently, then the cost saving from the technological conversion will never offset the investment cost; that is, for any t,

$$IC_{c2} > PC_o + AC_e(a, t) - PC_{c2}(t),$$

as shown in Figure 2-10(b). In this case, it will not be economical to convert the existing plants based on the original production technology to those based on the new clean technology. After time t^{**}, there will be no new introduction of the old production technology, and the clean technology will be adopted whenever plants are newly constructed. By that time, however, more plants will have been constructed with the old technology, equipped with the end-of-pipe technology, whose development was encouraged by the relatively weak environmental regulations. Once investment has been made on plants with the old production technology, there will be strong incentives to continue to utilize them until they cannot be used physically. As the lifetime of chemical plants is normally over 40 years[39], it will take a long period of time before the clean technology replaces the old technology, even though it has become clear that the latter is inferior to the former, economically as well as environmentally.

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[39] Jaffe, Newell, and Stavins (1999) argue that a primary driver of replacement purchases for durable goods is the goods useful lifetime. In the case of industrial facilities, the typical service life would be in the range of 40 to 80 years.

(a)

$$PC_o + AC_e(a, t) - PC_{c2}(t)$$

IC_{c2}

0   t^{**} t^{***} Time, t

(b)

IC_{c2}

$$PC_o + AC_e(a, t) - PC_{c2}(t)$$

0   t^{**} Time, t
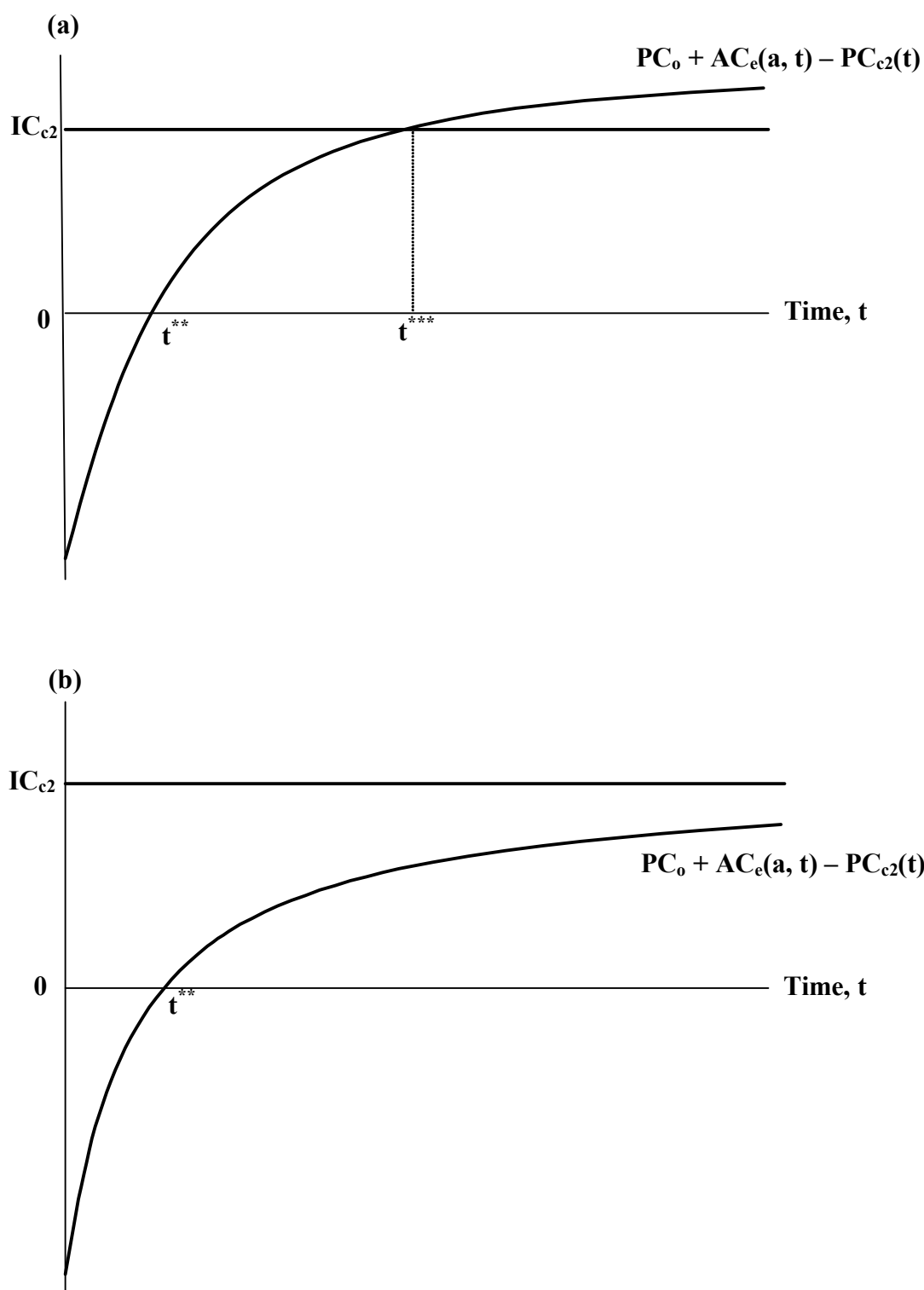
Figure 2-10 Cost Saving with the Process Conversion from the Original Technology Equipped with the End-of-Pipe Technology to the Efficient Clean Technology

Under a weak regulatory framework, the end-of-pipe technology will be favored for reducing emissions, because it is initially much cheaper than the clean technology. With the

end-of-pipe technology installed, the original production technology will continue to be adopted, and more investments will be made on plants with this technology. By the time that a more efficient clean technology becomes available, many plants will have already been constructed with the old production technology. Adoptions of the end-of-pipe technology, by succeeding in reducing pollutant emissions, effectively function to prolong the lifetime of the original, pollution-intensive technology, which may be in a process of technological obsolescence. In other words, the imposition of weak regulation, by pushing the course of technological trajectory towards an extension of the existing technology, will block the development of clean, potentially more efficient, technologies.

Figure 2-11 summarizes our analytical framework for the effects of environmental regulation on technological change.

```
┌─────────────────────────────────────┐
│   Use of the existing production     │
│   technology with pollutant emissions│
└─────────────────────────────────────┘
        ↙                    ↘
   *Uncertainty concerning the*
   *scientific mechanism and*
   *impacts of pollution on the*
   *environment*

┌──────────────────────┐        ┌──────────────────────┐
│ Stringent regulation │        │ Relatively weak      │
│ for the phase out of │        │ regulation on        │
│ the existing         │        │ emissions by the     │
│ production technology│        │ existing production  │
└──────────────────────┘        │ technology           │
          │                     └──────────────────────┘
          ↓                               │
  ┌──────────────┐                        ↓
  │ R&D on clean │              ┌──────────────────────┐
  │ technologies │              │ R&D on end-of-pipe   │
  └──────────────┘              │ technologies         │
      ↙        ↘                └──────────────────────┘
                                          │
                                          ↓
┌────────────────┐ ┌────────────────┐ ┌──────────────────────┐
│ Rigid and      │ │ Flexible and   │ │ Adoption of          │
│ short-term     │ │ long-term      │ │ end-of-pipe          │
│ regulatory     │ │ regulatory     │ │ technologies         │
│ schedule       │ │ schedule       │ └──────────────────────┘
└────────────────┘ └────────────────┘           │
        │                  │                     ↓
        ↓                  ↓          ┌──────────────────────┐
┌────────────────┐ ┌────────────────┐ │ Further investment   │
│ Insufficient   │ │ Technological  │ │ in plants based on   │
│ time and       │ │ progress in    │ │ the existing         │
│ opportunities  │ │ alternative    │ │ production technology│
│ for            │ │ clean          │ └──────────────────────┘
│ technological  │ │ technologies   │           │
│ progress       │ └────────────────┘           ↓
└────────────────┘        │          ┌──────────────────────┐
        │                 ↓          │ Continuing use of the│
        ↓        ┌────────────────┐  │ existing production  │
┌────────────────┐│ Diffusion of   │  │ technology until the │
│ Premature      ││ the best clean │  │ end of plant lifetime│
│ choice of an   ││ technology     │  └──────────────────────┘
│ inferior clean │└────────────────┘
│ technology     │
└────────────────┘
```

Figure 2-11 Diverging Effects of Environmental Regulations on Technological Change

2.4 Conclusion

Previous studies on the effects of environmental regulation on technological change mostly considered only the end-of-pipe technology for pollution abatement. In theoretical models, the increasing marginal abatement cost curve has been normally used to represent the character of technologies which reduce emissions. In empirical investigations, the focus has been mainly

on technologies exclusively used for reducing emissions, including, for example, filters and scrubbers. These technologies are basically equipment of the end-of-pipe type.

In our discussion, we explicitly took into account the possibility of clean technology and emphasized the qualitative difference between the end-of-pipe technology and the clean technology by using chemical reaction equations. Basically, the end-of-pipe technology is just installed at the end of manufacturing plants and will not affect the main production process. While the cost of pollution abatement is relatively small with the use of the end-of-pipe technology, it will rise as emission standards become more stringent. The clean technology, in contrast, eliminates the formation of pollution from within the production plant by altering the whole process. The use of the marginal pollution abatement cost curve, traditionally used in previous studies, is thus inappropriate for the analysis of the clean technology, which produces no emission in the first place. Although the initial investment necessary for the installation of the clean technology will be large, there is a possibility that its performance will improve significantly through R&D and learning, as the clean technology involves radical innovations in the whole production facilities. This difference between the two types of technologies for pollution abatement is crucial in our analytical framework for the diverging impacts of environmental regulations on technological change.

When an environmental issue occurs, normally there is a large degree of uncertainty about where the sources of pollution are located, what the mechanisms of physical, chemical, or biological transformation of the substances are, and how much damage has been or is expected to be made on the human health or other living organisms. Given the existence of this uncertainty, scientific arguments cannot exclusively determine environmental policies, and other factors, including historical, political, and social contexts, will influence the outcome of policy discussions. Reflecting that, it would be quite possible that diverse regulations are imposed on the same environmental issue in different regions.

When a relatively weak regulation is imposed, firms will be induced to choose end-of-pipe technologies, rather than clean technologies. That is because it is cheaper, at least initially, to reduce emissions by using end-of-pipe technologies, which are just installed at the end of the manufacturing facilities, than clean technologies involving radical changes in the whole production process. As there are more demands for end-of-pipe technologies, R&D efforts will be directed toward improving the performance of end-of-pipe equipment, and learning experience will be accumulated on this type of technology. With end-of-pipe technologies installed for successfully reducing emissions, companies will invest in and

continue to use the existing production technology, instead of trying to develop radically new clean technologies, which may be the most efficient from a long-term perspective.

On the other hand, when the imposed regulation is so stringent as to effectively require the abolishment of the existing production technology, firms will be prompted to find new clean technologies. Normally, there are multiple options of clean technologies, and a large degree of uncertainty exists concerning which technology will progress to become the best in the long run. Thus, as long as the regulation is rigidly fixed, demanding the phase out of the existing technology immediately, there is a possibility that a wrong technological choice could be made by companies, without sufficient time or opportunities allowed for R&D and learning. It will be known *ex ante* that the chosen technology may not be appropriate, after it has been used extensively for a certain period of time. Only when the regulatory schedule maintains some flexibility in schedule and timing, various types of clean technology will be tested and experimented, and there is a chance that the most efficient clean technology will be developed and adopted in the end.

Then the best clean technology developed in a region with a stringent regulation could later become available to polluting manufacturers in other regions where the imposed regulations were not so strong. Induced by the relatively weak regulations, however, those manufacturers have adopted end-of-pipe technologies to reduce emissions, and by the time when the best clean technology is available, new plants have been already established, based on the existing pollution-laden production technology. Unless the new clean technology is significantly more efficient than the old production technology equipped with end-of-pipe technologies, the operators of these new plants will have strong incentives to continue to use them until the end of their physical life time, which normally goes beyond forty years. Effectively, the weak regulations work to help the survival of the existing production technology, which may be actually in a process of technological obsolescence.

In short, when the regulation is relatively weak, firms will be induced to adopt end-of-pipe technologies, instead of clean technologies. On the other hand, when a very stringent regulation is imposed, firms will be encouraged to make innovative efforts to develop new clean technologies, but an inappropriate technology might be chosen by companies if the regulation is implemented in a rigid and inflexible way. Stringent environmental regulations coupled with flexibility which allows sufficient time for R&D and learning will work to promote the emergence of the best clean technology. With this analytical framework for the diverging effects of environmental regulations on technological change based on the

distinction between the end-of-pipe technology and the clean technology, we will examine in the next two chapters the technological impacts of environmental regulation on mercury emissions in the chlor-alkali industry in Japan and Western Europe.

Appendix

Product Change

The main product M could be the source of environmental problems. Usually that means the existing main product has to be replaced with a different one, as, particularly in the chemical industry, it would be difficult to recycle completely used products, which are mainly in gas or liquid phase[40]. A new product should be designed so that its detrimental effects on the environment will be eliminated or reduced[41], although the impact of products on the environment may not be always predictable or even understood for decades. In the chemical industry, a product change normally requires a change in the chemical composition of the final product.

When the chemical composition of the main product $M_1{}^*$ is changed to obtain M_2, at least one of the input materials I_{a1} and I_{b1}, needs to be replaced with different substance(s) I_{a2} and I_{b2} (including the possibility of the same I_{b1}). Therefore, the whole chemical reaction will be altered as follows:

$$I_{a1} + I_{b1} \rightarrow M_1{}^* + B_1$$
$$\Rightarrow I_{a2} + I_{b2} \rightarrow M_2 + B_1.$$
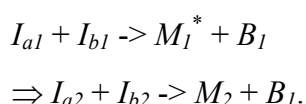
It should be noted that in many cases the composition of the by-product B_1 would also be transformed to B_2 as a result; that is,

$$I_{a1} + I_{b1} \rightarrow M_1{}^* + B_1$$

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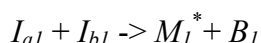
[40] In the "mechanical" industries, including automobile and electric and electronic industries, practices of closed-loop recycling, now called "inverse manufacturing," has been emerging. What would be potentially crucial in achieving inverse manufacturing is dynamic aspects of technology, in particular, the gap between the pace of innovation and the product life-span, that is, the length of time that each product is likely to be used by consumers. When consumers finish using products, say, five years later, while the parts of old products might be reusable physically, probably they could be obsolescent technologically, and it would be very difficult to incorporate them to new commercial products. This gap would be particularly large in the case of high-tech products like computers (Baba, Yarime, and Hatashima, 1997).

[41] As a useful tool for integrated designing, Life Cycle Assessment (LCA) has been proposed recently and begun to be adopted among firms. That approach is aimed at evaluating the environmental impacts of a product throughout its life cycle from the phase of raw material acquisition via production to consumption. For more information on LCA, see, for example, Society of Environmental Toxicology and Chemistry (1991).

$\Rightarrow I_{a1} + I_{b2} \rightarrow M_2 + B_2.$
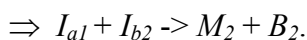
That means the whole chemical reaction would be changed. Therefore, although this case could be considered basically as product innovation, process innovation would also be required at the same time.

The use of tetraethyl lead $(Pb(C_2H_5)_4)^*$ in gasoline provided a high-octane gasoline for many years. However, this substance has now been phased out in many parts of the world, including Europe, Japan, and the US, in favor of methyl t-butyl ether $(CH_3OC(CH_3)_3, MTBE)$. Commercial production of MTBE began in 1979, shortly after the discovery of its octane-improving capability for motor fuels. Although a higher proportion of this additive was required for equivalent octane enhancement, it was less costly and eliminated the hazardous lead particulate discharges associated with the tetraethyl lead previously used for this purpose. Hence the convenient industrial method of producing tetraethyl lead, that is, the reaction of a sodium-lead alloy (Na-Pb) with chloroethane (C_2H_5Cl)

$$Na\text{-}Pb + 4C_2H_5Cl \rightarrow \underline{Pb(C_2H_5)_4}^* + \underline{Na^+} + \underline{4Cl^-}$$
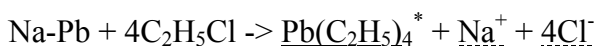
was replaced with the liquid phase reaction of methanol (CH_3OH) with isobutylene $(CH_2=C(CH_3)_2)$, which gives this novel, oxygenated gasoline additive (Hocking, 1998):

$$CH_3OH + CH_2=C(CH_3)_2 \rightarrow \underline{CH_3OC(CH_3)_3}$$

Another recent example involves the replacement of chlorofluorocarbons (CFCs). CFCs were once hailed as wonder products, following the discovery of the first substance, CFC-12, in 1930. Their chemical inertness, non-flammability, and non-toxic nature rapidly led to their large-scale use as safe refrigerants, aerosol propellants and form blowing agents in the production of polyurethane foams. In 1974, however, it was first suggested that because of their great stability they could rise, unchanged, into the stratosphere, where they would be broken down by the short wavelength UV-B radiation to form chlorine radicals. These would then attack and destroy ozone molecules through chain reactions. The consequence of the thinning of the ozone layer would be that it could no longer prevent the harmful short wavelength UV-B radiation reaching the surface of the earth. Following the Montreal Protocol signed in 1987, CFCs, including CFC-11 (CCl_3F), CFC-12 (CCl_2F_2), and CFC-113 $(CClF_2CCl_2F)$, were phased out by 1996. To produce CFC-12, tetrachloromethane (CCl_4) could be reacted with hydrogen fluoride (HF):

$$CCl_4 + 2HF \rightarrow \underline{CCl_2F_2}^* + \underline{2HCl}.$$
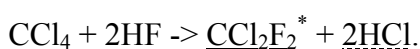
CFC alternatives include hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) such as HFC-134a (CF_3CH_2F) and HFC-32 (CH_2F_2), whose associated ozone depletion potential (ODP) is zero because they don't contain any chlorine and, therefore, will not be able to attack ozone molecules. New products are much more complex than the CFCs they are replacing, and the required change in the route of chemical reactions would also be large. A well-studied multi-step synthesis of HFC-134a involves the hydrogenolysis of CFC-114a (CF_3CCl_2F) derived from tetrachloroethylene ($CCl_2=CCl_2$) through a series of transformation (Manzer and Rao, 1993):

$$CCl_2=CCl_2 + Cl_2 \rightarrow CCl_3CCl_3$$

$$CCl_3CCl_3 + 3HF \rightarrow CF_2ClCCl_2F + 3HCl$$

$$CF_2ClCCl_2F + HF \rightarrow CF_2ClCF_2Cl + HCl$$

$$CF_2ClCF_2Cl \rightarrow CF_3CCl_2F$$

$$CF_3CCl_2F + 2H_2 \rightarrow CF_3CH_2F + 2HCl.$$
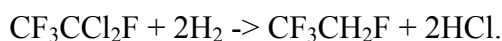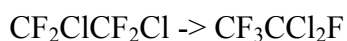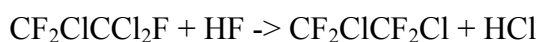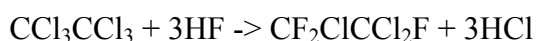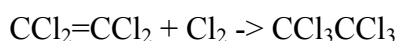
The overall stoichiometry is thus as follows:

$$CCl_2=CCl_2 + Cl_2 + 4HF + 2H_2 \rightarrow \underline{CF_3CH_2F} + \underline{6HCl}.$$
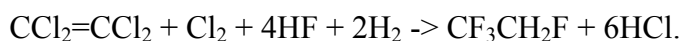
While most CFCs are produced in a single catalytic step, alternatives such as HFC-134a would normally require 2 to 5 complex catalytic steps (Koch, Krause, Manzer, Mehdizadeh, Odom, and Sengupta, 1996).

The long-term viability of HFCs is not secured, however. Although the volumes of HFCs emitted to the atmosphere are very low, compared with carbon dioxide (CO_2), they have a large global warming potential (GWP). As HFCs have been listed as one of greenhouse gases in the Kyoto Protocols, development activities will continue to find more environmentally desirable replacements for CFCs.

3. Technological Background of the Chlor-Alkali Industry

3.1 Production of Chlor-Alkali Products

3.1.1 Chlorine and Caustic Soda

The chlor-alkali industry produces a group of commodity chemicals, including chlorine (Cl_2), sodium hydroxide (caustic soda, NaOH), sodium carbonate (soda ash, Na_2CO_3), potassium hydroxide (caustic potash, KOH), and hydrochloric acid (muriatic acid or anhydrous, HCl). The analysis of this research is focused on chlorine and caustic soda, the most important products in the chlor-alkali industry.

Chlorine

Initially, chlorine was used as a disinfectant for water treatment and the exploitation of natural resources such as pulp and paper. Inorganic chemistry applications followed, and then organic chemicals began to take large quantities. Since chlorine is a highly reactive element, it is used widely in industry as a strong oxidizing agent and as a specific chlorinating agent. Table 3-1 and Table 3-2 give the current distributions of applications of chlorine in Japan and Western Europe.

Table 3-1 Applications of Chlorine in Japan

Application	Amount of Demand (Cl_2 10^3 tonnes/year)
Vinylchloride	1,862 (37.5 %)
Inorganic Chemicals	402 (8.1 %)
Chloromethanes	298 (6.0 %)
TDI[a], MDI[b]	293 (5.9 %)
Propylene Oxide	235 (4.7 %)
Dyes and Intermediates	206 (4.2 %)
Pulp and Paper	177 (3.6 %)
Chlorinated Solvents	171 (3.4 %)
Food	55 (1.1 %)
Others	1,267 (25.5 %)
Total	4,966 (100%)

a: tolylene diisocyanate
b: diphenylmethane diisocyanate
Source: Japan Soda Industry Association (1999a).

Table 3-2 Applications of Chlorine in Western Europe

Application	Amount of Demand (Cl_2 10^3 tonnes/year)
Polyvinyl Chloride	3,200 (35 %)
Chlorinated C_1 and C_2s	1,200 (13 %)
Phosgene	1,000 (11 %)
Propylene Oxide	1,000 (11 %)
Hydrochloric Acid	500 (5 %)
Sodium Hypochlorite	400 (4 %)
Others	1,900 (21 %)
Total	9,200 (100%)

Source: Euro Chlor (1999a).

Although the applications of chlorine are classified in different ways between Japan and Western Europe, they show similar compositions. Polyvinyl chloride (PVC), which is produced by polymerizing vinyl chloride, is the largest single application of chlorine in Japan and Western Europe, accounting for 37.5 % and 35 % of production, respectively. Ethylene is chlorinated to produce ethylene dichloride (EDC), and then hydrogen chloride is removed to produce vinyl chloride monomer (VCM). With an annual production of more than 20 million, PVC is the second largest of all plastics after polyethylene. Since the start of its industrial production in the 1930s, PVC has been used extensively in the building industry and for the production of consumer goods and packages.

Inorganic compounds produced from chlorine include hydrochloric acid (hydrogen chloride, HCl), metal chlorides and non-metal chlorides. Hydrochloric acid is used for food processing. Metal chlorides have many applications, including the use of aluminium and iron chlorides as catalysts in synthesis and as flocculants in water treatment. Zinc chloride is used in galvanization. Non-metal chlorides such as the phosphorus and sulfur chlorides are widely used as intermediates for agrochemicals, notably for pesticides and herbicides. They are also used in the production of plasticizers, stabilizers and coloring materials for plastics. Hypochlorites, including sodium hypochlorite, have been used for a long time as bleaching agents for the paper and pulp industry and as disinfectants for water treatment. Chlorine dioxide has replaced elemental chlorine in new processes for bleaching paper-making pulps.

Chlorine is also widely used for producing chlorinated C_1 and C_2 molecules[42], including chloromethanes and chlorinated solvents. Chloromethane, together with silicon, is used for synthesizing silicones. Silicones are polymeric compounds, and a variety of silicone materials

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[42] C_1 and C_2 molecules denote those which contain one and two carbon atom(s), respectively.

include oils, waxes, and rubbers. Chlorinated solvents have been used widely since the 1920s because they possess properties which are unusual in other organic solvents, such as good solvency, high volatility, and consequently high speed of drying, and non-flammability. Four chlorinated solvents are mainly used, namely, trichloroethylene, perchloroethylene, methylene chloride and 1,1,1-trichloroethane. In recent years, however, because of the concerns about health and environmental impacts, their consumption has been sharply reduced and currently represents only a small percent of the total usage of chlorine[43].

Many chlorinated derivatives are used in organic synthesis, whether or not chlorine is contained in final products. They are frequently used in various chemical reactions which give rise to various chemical products, including food additives, cosmetics, detergents, photographic products, paints and adhesives. Phosgene and propylene oxide, both of which do not contain chlorine, are used for the synthesis of polyurethanes. Phosgene is reacted with amines to produce isocyanates such as tolylene diisocyanate (TDI) and diphenylmethane diisocyanate (MDI), which are intermediates for the synthesis of polyurethanes. Propylene oxide is made by the chlorohydrin process, which requires the use of chlorine. Polyurethanes have many different applications, mainly in the form of foams, including furniture, beds and buildings.

Caustic Soda

Caustic soda has been used for a wide range of industrial applications as well as for the production of consumer products. The current applications of caustic soda in Japan and Europe are shown in Table 3-3 and Table 3-4.

Table 3-3 Applications of Caustic Soda in Japan

Application	Amount of Demand (NaOH 10^3 tonnes/year)
Inorganic Chemicals	498 (13.4 %)
Organic and Petro Chemicals	144 (3.9 %)
Other Chemicals	1,165 (31.5 %)
Pulp and Paper	392 (10.6 %)
Food	132 (3.6 %)
Dyeing Preparation	104 (2.8 %)
Dyes and Intermediates	103 (2.8 %)

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[43] Recently, the environmental effects of chlorinated organic substances have been hotly debated. This is an example of the main product as the source of pollution and is not discussed in detail in this research (see Appendix). For diverse perspectives on this debate, see, for example, Aikawa (1998), Martin and Martens (1996), Thornton (2000), and Kleijn, Tukker, and van der Voet (1997).

Chemical Fiber	91 (2.5 %)
Alumina	76 (2.1 %)
Electrolysis	72 (1.9 %)
Soaps and Detergents	48 (1.3 %)
Oil Refining	34 (0.9 %)
Cellophane	16 (0.4 %)
Others	827 (22.3 %)
Total	3,702 (100%)

Source: Japan Soda Industry Association (1999a).

Table 3-4 Applications of Caustic Soda in Western Europe

Application	Amount of Demand (NaOH 10^3 tonnes/year)
Chemicals	4,900 (53 %)
Paper	1,000 (11 %)
Consumer Products	700 (7 %)
Aluminium Processing	400 (4 %)
Others	2,300 (25 %)
Total	9,300 (100%)

Source: Euro Chlor (1999a).

As in the case of chlorine, the applications of caustic soda in both regions show similar outlets. About half of caustic soda produced is consumed for manufacturing various industrial chemicals. Large amounts of caustic soda are used in the organic and inorganic chemicals industries. Since caustic soda is a highly alkaline material, it is widely used for neutralizing acids and dissolving materials which are difficult to dissolve. A variety of reactions can occur with organic as well as inorganic materials.

Approximately one tenth goes to the pulp and paper industry, in which caustic soda has been widely used for a long time. The Kraft process, which was originally developed in 1879, is currently the preeminent chemical pulping procedure. In this process, wood chips are cooked in pulping liquor consisting of a solution of sodium hydroxide, that is, caustic soda, and sodium sulfide in water, the so-called white water, and much of the lignin originally present in the wood is dissolved. Caustic soda is also used in the bleaching steps for pulp brightening.

In the textile industry, rayon is made from wood pulp by using caustic soda. In the viscose process, the pulp is dissolved in carbon disulfide and caustic soda to give a thick brown liquid, which is then forced through fine nozzles into acid, producing a cellulose filament. Caustic soda has also been important for aluminium processing since around 1900.

Alumina is recovered from bauxite by extraction with caustic soda, which is now frequently referred to as the Bayer process. Caustic soda also plays an important role in manufacturing consumer products. Soaps, for example, are made by boiling animal fats with caustic soda[44].

3.1.2 Production

The world chlor-alkali production capacity was 43.5 million tonnes of chlorine in 1996. Table 3-5 provides a breakdown of the production capacity by geographical region. The world largest producing country is the United States. With its annual production capacity of more than 13 million tonnes of chlorine, it accounts for about 30 % of the world production capacity. Following the United States, Western Europe is globally the second largest chlor-alkali producing region, representing 23 % of the world capacity. Japan's production capacity accounts for approximately one tenth of the world production.

Table 3-5 Chlor-Alkali Production Capacities in the World

Region	Production Capacity (Cl_2 10^3 tonnes/year)
North America	13,500 (31 %)
Western Europe	10,000 (23 %)
Eastern Europe	6,100 (14 %)
Asia (excluding Japan)	6,100 (14 %)
Japan	4,300 (10 %)
Central & South America	1,300 (3 %)
Middle East	1,300 (3 %)
Other	900 (2 %)
Total	43,500 (100%)

Source: SRI (1996).

Within Western Europe, Germany is by far the largest producing country, as is shown in Table 3-6. Germany represents 38 % of the total installed capacity in the region, followed by France, United Kingdom, Italy, Belgium and Spain. The largest two countries account for more than half of the total production capacity in Western Europe.

Table 3-6 Chlor-Alkali Production Capacities in Western Europe

Country	Production Capacity (Cl_2 10^3 tonnes/year)
Germany	4,379 (38.3 %)

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[44] There is the third product of the electrolysis of brine, namely, hydrogen (H_2). It is very pure and has a wide variety of uses. It is used is as a chemical feedstock for organic hydrogenation, catalytic reductions, and ammonia synthesis and to provide hot flames or protective atmospheres in welding technology, metallurgy, or glass manufacture. It is also used in the manufacture of high-purity hydrogen chloride by combustion with chloride and as a fuel for heating and drying.

France	1,686 (14.8 %)
UK	1,216 (10.6 %)
Italy	982 (8.6 %)
Belgium	832 (7.3 %)
Spain	802 (7.0 %)
Netherlands	647 (5.7 %)
Sweden	292 (2.6 %)
Norway	180 (1.6 %)
Finland	115 (1.0 %)
Switzerland	104 (0.9 %)
Portugal	89 (0.8 %)
Austria	60 (0.5 %)
Greece	37 (0.3 %)
Ireland	6 (0.1 %)
Total	11,427 (100%)

Sources: Euro Chlor (1998a), European IPPC Bureau (1999).

The number and scale of chlor-alkali plants in Western Europe and Japan are given in Table 3-7. In 1998 the production capacity of Western Europe was 11.4 million tonnes of chlorine. Across the 15 countries, there were 44 chlor-alkali producers operating 80 plants, with an average production capacity of 142,800 tonnes of chlorine per year. In the same year, the annual production capacity of the Japanese chlor-alkali industry was 4.4 million tonnes of caustic soda, equivalent to 4 million tonnes of chlorine. In total, 29 companies were operating 40 chlor-alkali plants, and the average production capacity was 111,000 tonnes of caustic soda per year, equal to 99,000 tonne of chlorine per year. Thus the average plant capacity in Western Europe is approximately 1.5 times larger than that in Japan.

Table 3-7 Chlor-Alkali Plants in Western Europe and Japan

	Capacity (Cl_2 10^3 t/year)	Producers	Plants	Average Plant Capacity (Cl_2 10^3 t/year)
Western Europe	11,400	44	80	142,800
Japan	4,000	29	40	99,000

Sources: Euro Chlor (1998a), European IPPC Bureau (1999), and Japan Soda Industry Association (1998b).

The production of chlorine and caustic soda is significantly integrated with the downstream businesses, such as the PVC production, and in many cases forms part of an integrated petrochemicals and plastic complex. For example, among 15 petrochemical industrial complexes operating in Japan in 1997, chlor-alkali plants supplied chlorine and

caustic soda in 10 of them (Japan Soda Industry Association, 1998b). Being classified as a toxic and corrosive gas, chlorine is difficult to store and handle, and thus the transportation of chlorine is normally kept to a minimum. More than 85 % of the chlorine produced in Western Europe is used on the same or adjacent sites for other chemical processes and converted to chlorinated organic products and intermediates (Lindley, 1997). While very little chlorine trade occurs in its elemental form, chlorine derivatives, including EDC, VCM, and PVC, are traded widely in the international market. Caustic soda is usually shipped as solution of about 50 % concentration and is bought and sold freely in the world market.

As chlorine and caustic soda, which are co-produced by a fixed ratio through the electrolysis of brine, are consumed separately for different purposes, demands for the two products are not normally balanced. Generally speaking, caustic demand in a developing country exceeds chlorine demand because caustic-consuming basic industries such as mineral processing, paper, glass, and textile manufacture normally precede the development of the chlorine-consuming petrochemical and plastics industries. Hence, industrialized countries, including Western Europe and Japan, tend to have excess amounts of caustic soda, which can be exported to industrializing countries such as those in Asia.

3.2 Three Dominant Technologies for Chlor-Alkali Production: Mercury Process, Diaphragm Process, and Ion Exchange Membrane Process

Traditionally, two types of production technologies were used in the chlor-alkali industry:

- Chemical processes
- Electrolytic processes.

Figure 3-1 gives a schematic illustration of the evolution of various technologies used for chlor-alkali production since the birth of the chlor-alkali industry.

2000
1990
1980

Mercury Process **Diaphragm Process** **Ion Exchange Membrane Process**

1970 **End-of-Pipe Technology** **Clean Technology**

1960 Ammonia Soda Process

1950 *Hydraulic Pressure* *Ion Exchange*

1940 **Mercury Emissions**

1930

1920 Leblanc Process *Chemical Separation* *Physical Separation*

1910

1900

1890

1880

1870

1860

End-of-Pipe Technology

1850

1840

Emissions

1830 • Hydrogen Chloride

1820 • Tank Waste

1810 • Nitrogen Oxides

1800

Chemical Processes   *Electrolytic Processes*

Figure 3-1 Evolution of Production Technologies in the Chlor-Alkali Industry

From the beginning of the industrial production of alkali products at the end of the 18th century through the 19th century, the production processes were based on chemical reactions. There are two types of chemical processes[45]:

- Leblanc process

- Ammonia soda process (Solvay process).

At around the turn of the 19th century, a radically new way of producing alkali was invented based on the principle of electrolysis. In electrolytic processes, an aqueous solution of sodium chloride (NaCl), that is, salt, commonly called brine, is decomposed by electrolysis with direct current, producing chlorine, hydrogen, and sodium hydroxide. For each tonne of chlorine produced, 1.12 tonnes of caustic soda and 0.028 tonnes of hydrogen are produced at the same time[46]. The electrolytic production of chlorine and caustic soda depends on a large current of amount of electricity. Thus the chlor-alkali industry is a major user of electric power, and actually its unit consumption of electricity is the one of the largest, following the aluminium, carbide, and ferroalloy industries. The Japanese chlor-alkali industry, for instance, consumed approximately 10.7 billion kWh of electricity in 1996, accounting for 3 % of the total industry consumption and 18 % of the total chemical industry consumption (Japan Soda Industry Association, 1998a). As energy cost accounts for a significant part of the total manufacturing cost, one of the major targets of innovative activities in the chlor-alkali industry has been to develop technologies to reduce energy consumption.

Three types of electrolytic processes are currently in use for commercial manufacturing of chlorine and caustic soda in the world:

- Mercury process

- Diaphragm process

- Ion Exchange Membrane process

Each process represents a different method of keeping chlorine produced at the anode separate from the caustic soda and hydrogen produced, directly or indirectly, at the cathode[47].

Figure 3-2 shows the shares of the three processes in the chlor-alkali industry in Western Europe, the United States and Japan. (Data are given in Table 3-24 in Appendix at

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[45] Although the Leblanc process and the ammonia soda process are not the focus of our research, the diverging impacts of environmental regulations on technological change are similar to those observed in the case of the electrolytic processes. More detailed discussions are given in Appendix.

[46] As both chlorine and caustic soda are used as the unit of measurement in the industry, both of them appear in this research. The conversion factor is 35.5:40; that is, 1 t Cl_2 = 1.12 t NaOH.

the end of this chapter). As you can see clearly, different production processes are dominant in the three regions. In Western Europe, approximately 60 % of the chlor-alkali plants are based on the mercury process. In the United States, more than 70 % of the chlor-alkali plants are using the diaphragm process. In Japan, while there is no chlor-alkali plants based on the mercury process, the ion exchange membrane process has been adopted by more than 90 % of the chlor-alkali plants. In the other two regions, the diffusion of the ion exchange membrane process is limited to approximately 10 %.
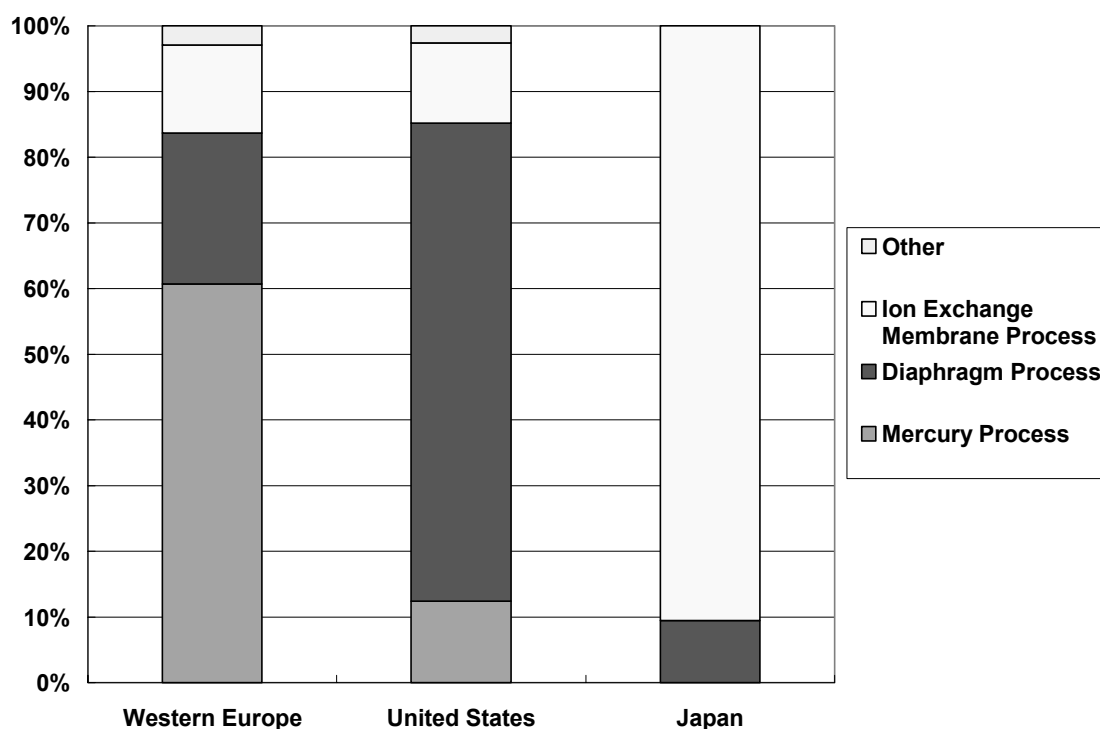
Figure 3-2 Shares of the Mercury, Diaphragm, and Ion Exchange Membrane Processes in Western Europe, the United States, and Japan in 1998

To investigate why the divergent courses of technological change have occurred between Western Europe and Japan, we first trace the historical evolution of the electrolytic processes up to the early 1970s, when environmental regulations began to be introduced on mercury emissions from chlor-alkali plants. Then, in the next two chapters, we examine how environmental regulations have influenced the course of technological change in Western Europe and Japan since then.

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[47] Anode is a positive electrode, to which negative ions (anions) migrate, and cathode is a negative electrode, to which positive ions (cations) migrate.

3.3 Technological Change Prior to the Effects of Environmental Regulations

It had been well known for a long time that electrolysis of brine resulted in the formation of chlorine at the anode, and of caustic soda and hydrogen at the cathode (Haber, 1971). The decomposition of salt water by means of an electric current was demonstrated as early as 1800. During the period 1832-1834, the laws governing the electrolysis of aqueous salt solutions were formulated by Faraday. While a patent was granted in Britain in 1852 for the electrolytic production of chlorine from brine, laboratory success was slowly converted into commercial viability. Since electrolysis is a power-intensive process, the supply of cheap electricity was indispensable for the industrial feasibility of electrolysis. As the accumulator was not useful for industrial purposes, progress was delayed until the development of an efficient dynamo in the late 1860s. The first experiments on an industrial scale were not until the 1880s because of technical as well as commercial difficulties to overcome. One of the most demanding technical difficulties facing the infant electrolytic technology was how to devise a means of continuous separation of chlorine and sodium hydroxide. Eventually, two different processes were developed in the late 1880s and the early 1890s to accomplish this separation by using mercury and diaphragm, that is, the mercury process and the diaphragm process.

3.3.1 Development of the Mercury Process

A simplified flow diagram of the mercury process is given in Figure 3-3. Several steps are common to all of the chlor-alkali production processes, whether mercury, diaphragm, or ion exchange membrane (Curlin, Bommaraju, and Hansson, 1991; Hocking, 1998; Kelham, 1996; Schmittinger, Curlin, Asawa, Kotowski, Beer, Greenberg, Zelfel, and Breitstadt, 1986).
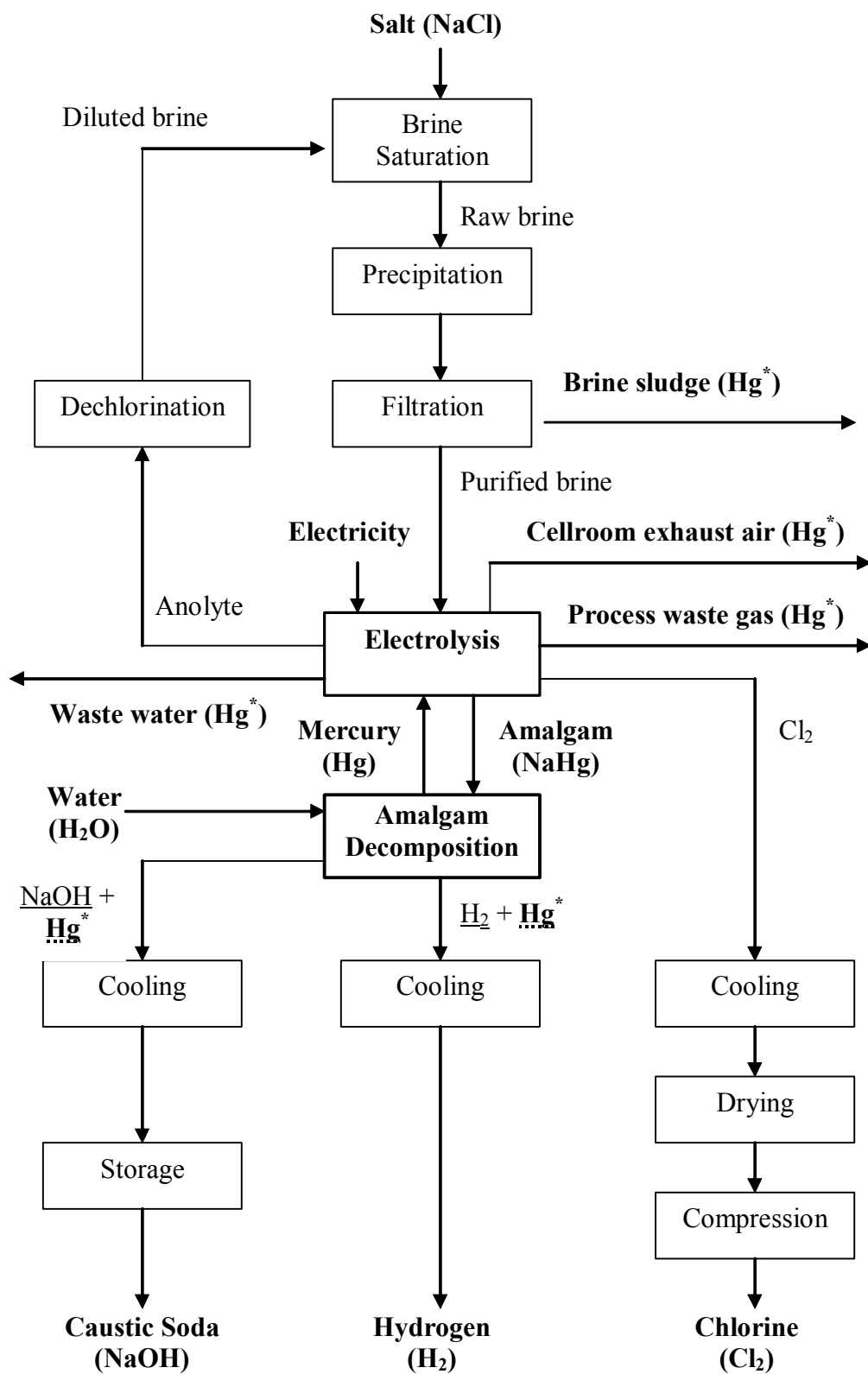
Figure 3-3 Flow Diagram of the Mercury Process

Based on Schmittinger et al. (1986).

The basic raw material for the mercury process is normally solid salt. Saturated brine first goes through the precipitation-filtration step because sodium chloride, whether solution-mined or obtained as either mined or solar-evaporated solid salt, contains various impurities. Since these traces of heavy metals in the brine give rise to dangerous operating conditions in the electrolyzer, brine for the mercury process must meet stringent purity standards. For undertaking electrolysis, electricity must be provided in the form of direct current, and rectifiers are used to transform alternate current to direct current.

The mercury process involved two electrochemical units, namely, an electrolytic cell and an amalgam decomposer (Schmittinger, 2000). Amalgam decomposition is a unique step for the mercury process, which thus requires mercury removal from the products. Figure 3-4 gives a schematic illustration of the two electrochemical units. In the electrolytic cell, the purified brine flows through an elongated, slightly inclined trough. Mercury, which functions as the cathode, flows concurrently with the brine over the base plate. Anodes are suspended in the brine from above. The evolution of chlorine takes place at the anode in all of the three processes. At the anode, chlorine ions (Cl^-) lose electrons (e^-) to form chlorine atoms ($Cl^\bullet$):

$$Cl^- \rightarrow Cl^\bullet + e^-.$$
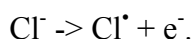
Then chlorine atoms combine to escape as chlorine molecules (Cl_2):

$$2Cl^\bullet \rightarrow \underline{Cl_2}.$$
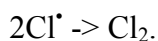
As the chlorine produced by any of the electrolyzer processes is saturated with water vapor at high temperature, it is first cooled, with water removed, and then dried.

Unlike the diaphragm or ion exchange membrane process, in which hydrogen and sodium hydroxide are produced at the cathode, the cathodic reaction in mercury cells is the discharge of sodium ions (Na^+) to form dilute sodium amalgam with a thin film of mercury. As mercury itself acts as a separator for the anode and cathode products, the mercury process contains no mechanical barriers. First, sodium ions gain electrons to form sodium atoms (Na):

$$Na^+ + e^- \rightarrow Na.$$
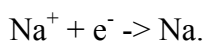
Then, the sodium atom immediately dissolves in the mercury (Hg^*) film electrode to form sodium amalgam (NaHg):

$$Na + Hg^* \rightarrow NaHg.$$
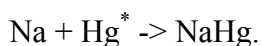
The liquid amalgam then passes into the decomposer, where it reacts with water (H_2O) to form sodium hydroxide (NaOH) solution and hydrogen (H_2):

$$2NaHg + 2H_2O \rightarrow \underline{2NaOH} + \underline{H_2} + 2Hg^*.$$

Chlorine (Cl$_2$)

Anode (+)

Depleted brine

Saturated brine (NaCl)

Mercury (Hg)

Na$^+$

Cl$^-$

Cathode (-)

Amalgam (NaHg)

Electrolytic cell

Mercury (Hg) recycled to electrolyzer

Amalgam (NaHg) sent to decomposer

Hydrogen (H$_2$)

Mercury (Hg)

H$_2$O

Graphite packing

NaHg

Water (H$_2$O)

OH$^-$

Na$^+$

Caustic soda (NaOH) 50 %

Hg

Hg

Mercury (Hg)

Amalgam Decomposer
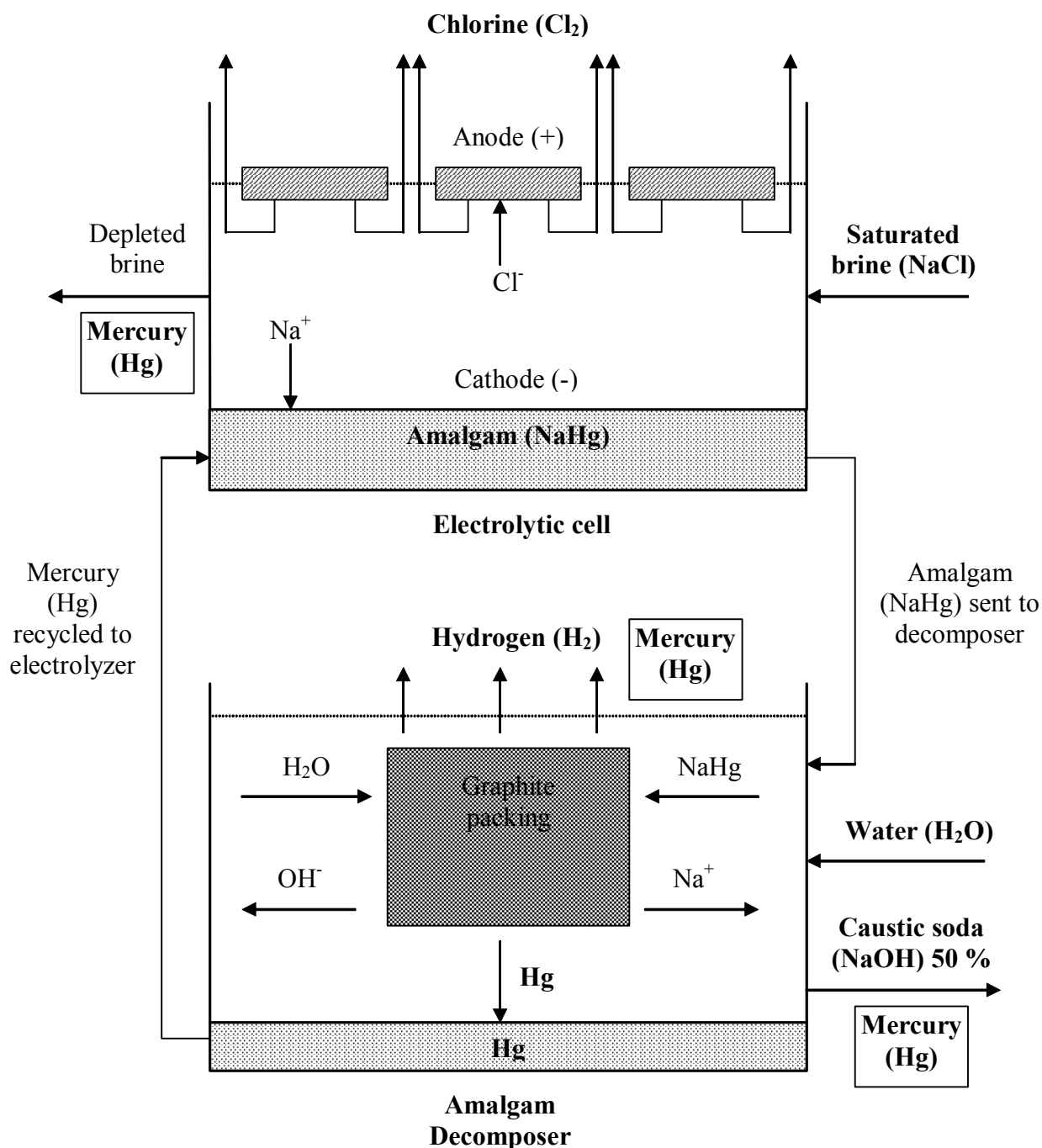
Figure 3-4 Mercury Electrolyzer and Amalgam Decomposer

Based on Schmittinger et al. (1986).

The process has been made continuous by periodically replenishing the brine and removing the caustic soda. The depleted brine leaving the electrolyzers is dechlorinated to recover the dissolved chlorine and to prevent corrosion during further processing. Dechlorinated brine is then resaturated with solid salt and returned to the cell for further use.

94

The hydrogen produced in the mercury process is relatively pure and thus requires only cooling to remove water along with entrained salt and caustic.

While physical barriers, such as diaphragms and ion exchange membranes, are used in the case of the diaphragm process and the ion exchange membrane process, mercury is a crucial substance to separate caustic soda from chlorine in the mercury process. As can be seen in Figure 3-3 and Figure 3-4, the facilities are designed to recover most of the mercury used in the production process within the plant, by allowing mercury to flow from the decomposer back into the electrolysis cell once the sodium hydroxide has been removed. It is inevitable, however, that some amount of mercury is released to the environment through products, air, water, and solid wastes. That necessitates the adoption of technological measures to prevent the emissions of mercury from the mercury-based plants. Basically, there are two ways to meet this purpose. One is to install equipment at the end of the production process, that is, the end-of-pipe technology. The other is to replace the mercury process with another production process which does not use mercury, that is, the clean technology. As we will see later, this difference in the adoption of technological measures for pollution abatement will have significant consequences.

To solve the difficulty of separating chlorine and caustic soda, an electrolytic cell in which the cathode consisted of a layer of mercury was invented by an American chemist, Hamilton Young Castner (Warren, 1980). By 1892 he had patented the electrolytic cell, and subsequently an electrolytic alkali plant was constructed in Britain[48]. Almost in the same period, a similar mercury-cathode system was developed by an Austrian engineer, Carl Kellner. He set up a company to work his process in Austria and sold the other European rights to Solvay in Belgium. Ultimately the two inventors licensed their patents and conducted industrial operations jointly. A new company, the Castner-Kellner Alkali Company, was established in 1895 at Runcorn in Britain, and their process was successfully put into operation two years later. Of 35 electrolytic alkali works in production or near ready to begin outside Britain by the beginning of 1900, seven were using the Castner-Kellner process.

The Castner-Kellner process was subsequently established in Germany, Belgium, and Russia by Solvay (Haber, 1971). The design of the Castner-Kellner cell, which was rocked periodically from side to side so that mercury flowed from one compartment to the other, received modifications by the engineers of Solvay. Experiments started in 1898, resulting in

the development of a sloping cell, the so-called long cell, in which the mercury flowed continuously by gravity along the bottom of an elongated trough. The long cell became the basis of all subsequent mercury cell designs. Solvay later started to offer two models of the mercury process to the market.

The long cell was also introduced to Britain in 1902 by Castner-Kellner, replacing the rocking cell (Collins and Entwisle, 1980). A majority share of the Castner-Kellner, together with the Runcorn plant, was acquired by Brunner-Mond in 1920. Subsequently, they became part of the newly formed Imperial Chemical Industries (ICI) in 1926. Technological development continued at ICI, with emphasis on steel baseplates to alleviate the current loading limitation associated with cathode mushrooms, and the steel baseplate cell became widely adopted throughout the ICI group. The area of the brine cell was increased from 12.5 m^2 in the 1940s to 25 m^2 in the 1960s.

In the United States, Mathieson Alkali acquired the license on the mercury cell from Castner-Kellner in 1894, and the first U.S. plant of this type was subsequently opened at Saltville, Virginia (Haber, 1971). Initially, the cells were fitted with carbon anodes, which had only a very limited lifetime. Castner invented a method of graphitizing his carbon, which, together with some other improvements, made it possible to build a much larger commercial plant in 1897 at Niagara Falls, New York. Cheap and abundant supply of electricity as well as good local supply of salt was essential for successful working of the electrolytic process. Thus, it was after large amounts of direct current electricity could be supplied economically with the invention of dynamos in such a place as Niagara Falls, that the electrolytic process became commercially feasible. Since then, Mathieson had been the only major licensor of the mercury process in the United States.

In the 1930s and the 1940s, rapid progress was made on the mercury process technology in the German I. G. Farbenindustrie plants through exchange of information and sharing of the results of research and development. By the end of the Second World War, Germany had reached a position of technical leadership in the mercury process for chlor-alkali production (MacMullin, 1947)[49]. After the end of the war, IG Farben was broken up

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[48] A number of patents dealing with mercury cells actually issued prior to 1982, the first being that of Nolf, British patent 4349 (1882) (MacMullin, 1962).

[49] Just after the end of the Second World War, many American technical investigators, including a dozen people selected from the chlor-alkali industry, were sent to Germany to study the technical developments and progress there. Many reports were written on German chlor-alkali progress and developments, and a tremendous amount of information was uncovered in the files of the German chemical plants. Much of this was brought back to the United States later. Through the Chlorine Institute, the chlor-alkali industry association in the U.S., about 1,900

into three companies, namely, Badische Anilin & Soda-Fabrik (BASF) in Ludwigshafen, Bayer in Leverkusen, and Hoechst in Frankfurt (Aftalion, 1991). Subsequently many prototypes were developed in the plants of Bayer and Hoechst. In 1952 Hoechst, through its subsidiary Knapsack-Griesheim, acquired a share in Uhde, an engineering company, and the cooperation between the two companies started in 1954 (Krupp Uhde, 2001). Hoechst-Uhde cells later came to be regarded to represent the achievement of the horizontal German mercury cell. BASF, on the other hand, had cooperated with the Krebs engineering group since 1951 for the development and installation of mercury cells (MacMullin, 1962). Various prototypes were installed at the Ludwigshafen works of BASF. Many installations of Krebs-Zurich cells and Krebs-BASF cells were in operation principally in Europe.

Mercury cells of the horizontal type were also developed by De Nora based in Milan, Italy. The De Nora cells had evolved through a series of changes since they were introduced in 1950, although the basic principle remained unchanged; all the cells had a protected electrolyzer trough and a vertical decomposer. They were widely adopted, as there were at least 60 De Nora plants located in 25 countries in the 1960s (MacMullin, 1962). The company also offered a commercial version of the vertical cathode mercury cell, which was known as the fluent amalgam cell. The principal advantage of the fluent amalgam cell was the economy of building space as compared to that of horizontal mercury cells.

In Japan, on the other hand, the production of electrolytic alkali began during the First World War. The development of the mercury process started by Osaka Soda in 1911, and its Daiso cell was industrialized in 1915. By 1918, about 10,000 tons of caustic soda had come to be produced annually in this way (Japan Soda Industry Association, 1952). The Krebs mercury cell was imported to Japan for the first time in 1935. By the Second World War, the Daiso and Krebs cells, which shared similar structures, had come to become the major technologies used in Japan. In 1937 the production of caustic soda reached 369,000 tonnes, the maximum level before the war. After the end of the war, information on advanced mercury process technologies developed by the German chlor-alkali industry became available to those in the Japanese chlor-alkali industry through a research report. The so-called PB report soon began to work as the textbook for chlor-alkali engineers in the post-war

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pages of scientific reports on the German chlor-alkali industry, called the "Chlor Fako Reports," were translated and distributed. All these reports constituted significantly to the subsequent development of the chlor-alkali technology (Murray, 1949).

Japan[50]. In particular, the Kureha cell was subsequently developed in Japan by Kureha Chemical. It later came to be regarded as one of the best mercury cells in the world and was exported to other countries.

By the middle of the 1960s, a number of technologies for the mercury process had been developed and become available in the market. They were mainly provided by Western European and Japanese companies, except for one technology supplier based in the United States. In particular, Solvay, De Nora, Hoechst-Uhde, Krebs, and ICI in Western Europe, and Osaka Soda, Kureha Chemical, Asahi Glass, Toyo Soda, Tokuyama Soda, and Mitsui Engineering and Shipbuilding, which later established Chlorine Engineers Corp. (CEC), in Japan were the companies which made major innovations on the mercury process, as suggested by technical papers and books written by industry experts at that time (Chlorine Institute, 1972; Japan Soda Industry Association, 1975; Kuhn, 1971; MacMullin, 1962; Smith, 1968, 1975; Sommers, 1965; Sommers, 1967). Table 3-8 gives some of the characteristics of each of the technologies supplied by these companies. This implies that both in Western Europe and in Japan there were several companies which were equally innovative on the mercury process for chlor-alkali production.

Table 3-8 Major Technologies of the Mercury Process in the Early 1970s

Technology	Cell current (kA)	Current density (kA/m^2)	Power consumption (DC, kWh/ton Cl_2)
Solvay (WE)			
V-100F	96	5.33	3,125
V-200F	160	5.33	3,125
De Nora (WE)			
14 x 3F	60	5.05	3,240
18 x 4	100	4.878	3,240
24 x 5	200	5.85	3,312
Hoechst-Uhde (WE)			
10 m^2	60	6.0	3,240
20 m^2	120	6.0	3,240
31.5 m^2	189	6.0	3,240
Krebs-BASF (WE)			
	50	4.25	3,175
	150	4.13	3,240
Krebs-Zurich (WE)			
ZT 80-10-8	80	8.0	3,310
ZT 120-15-8	120	8.0	3,310

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[50] According to an engineer who studied and worked on the PB report, even 90 per cent of the technologies subsequently developed in Japan could be said to have originated from this report (Sugino, 1991).

ICI (WE)			
Steel Base	90	7.2	3,380
Olin Mathieson (US)			
E-8	35	5.58	3,164
E-11	125	8.33	3,444
Osaka Soda (JP)			
Daiso	n/a	n/a	n/a
Kureha Chemical (JP)			
HD-3	80	8.13	3,175
HD-4	150	7.57	3,096
Toyo Soda (JP)			
TOSO III-A	140	5.49	3,024
TOSO IV	180	6.62	3,130
Asahi Glass (JP)			
Rotation Type 60kA	60	7.27	3,240
Mitsui-Toa Gosei (JP)			
TOA 270-G	200	9.3	3,190
Tokuyama Soda (JP)			
Tokuso 59	120	4.01	n/a

WE: Western Europe; US: United States; JP: Japan
Sources: Sommers (1965), Sommers (1967), Japan Soda Industry Association (1975), Collins and Entwisle (1980), Japan Soda Industry Association (1982).

3.3.2 Development of the Diaphragm Process

Another electrolytic route to produce chlor-alkali products is the diaphragm process. There are several differences in the flow diagram between the mercury and diaphragm processes (Curlin, Florkiewicz, Luke, Minz, and Schmittinger, 2000; Hocking, 1998; Kelham, 1996; Schmittinger, Curlin, Asawa, Kotowski, Beer, Greenberg, Zelfel, and Breitstadt, 1986). Figure 3-5 gives a basic flow diagram of the diaphragm process. As in the case of the mercury process, electricity is transformed by rectifiers and provided in the form of direct current. On the other hand, for the diaphragm process solution-mined brine could be used in place of solid salt. Salt recovery is also undertaken in the diaphragm process.

```
                                         Water        Salt
                                        (H₂O)        (NaCl)
                                          │            │
                                          ▼            ▼
                        NaCl          ┌─────────────────┐
              ┌──────────────────────▶│     Brine       │
              │                        │   saturation    │
              │                        └─────────────────┘
              │                                 │  Raw brine
              │                                 ▼
              │                        ┌─────────────────┐
              │                        │  Precipitation  │
              │                        └─────────────────┘
              │                                 │
              │                                 ▼
              │                        ┌─────────────────┐
              │                        │   Filtration    │
              │                        └─────────────────┘
              │                                 │  Purified brine
              │          NaCl                   ▼
              │  ┌──────────────────────▶┌─────────────────┐
              │  │                        │     Brine       │
              │  │                        │  resaturation   │
              │  │                        └─────────────────┘
              │  │                                │        Electricity
              │  │                                ▼       ╱
              │  │                        ┌─────────────────┐
              │  │        NaOH +          │   Electrolysis  │──────────────▶ Cl₂
              │  │  ┌─────  NaCl  ────────┤                 │
              │  │  │                     └─────────────────┘         ┌─────────────┐
              │  │  │                            │                    │   Cooling   │
              │  │  ▼  NaCl                       │ H₂ + O₂            └─────────────┘
              │  │┌───────────────┐              ▼                           │
              └──┼┤ Concentration │      ┌─────────────┐            ┌─────────────┐
                 │└───────────────┘      │   Cooling   │            │   Drying    │
         Steam───┘       ▲               └─────────────┘            └─────────────┘
                         │                      │                          │
                         ▼                      ▼                          ▼
                 ┌───────────────┐      ┌─────────────┐            ┌─────────────┐
                 │    Cooling    │      │   Oxygen    │            │ Compression │
                 └───────────────┘      │   Removal   │            └─────────────┘
                         │              └─────────────┘                   │
                         ▼                      │                          ▼
                 ┌───────────────┐              │                  ┌─────────────┐
                 │    Storage    │              │                  │ Liquefaction│
                 └───────────────┘              │                  └─────────────┘
                         │                      │                          │
                         ▼                      ▼                          ▼
                                                                   ┌─────────────┐
                                                                   │ Evaporation │
                                                                   └─────────────┘
                                                                          │
                                                                          ▼
                   Caustic Soda           Hydrogen                    Chlorine
                     (NaOH)                 (H₂)                       (Cl₂)
```
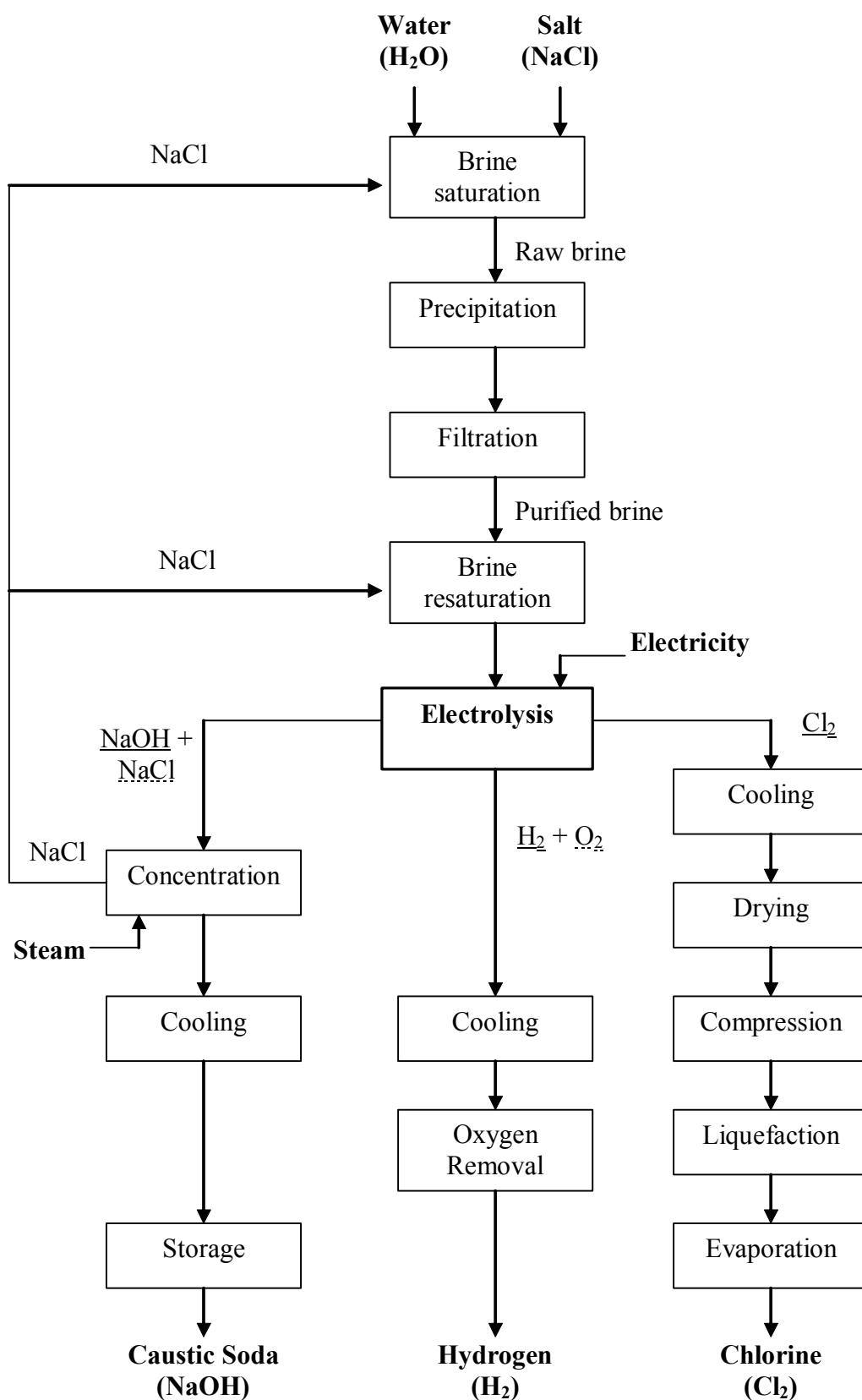
Figure 3-5 Flow Diagram of the Diaphragm Process

Based on Schmittinger et al. (1986).

In the diaphragm electrolyzer, the anode area is separated from the cathode area by a porous diaphragm based on asbestos (Curlin, Bommaraju, and Hansson, 1991). As shown in Figure 3-6, saturated brine is introduced into the anode compartment. The principal reactions at the anode are the same as those in the mercury process. First, chloride ions lose electrons to form chlorine atoms:

$$Cl^- - e^- \rightarrow Cl^\bullet.$$
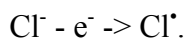
Subsequently, chlorine atoms combine to escape as chlorine molecules:

$$2Cl^\bullet \rightarrow \underline{Cl_2}.$$
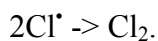
The liquid solution in the anode compartment (anolyte) flows through the diaphragm into the cathode compartment due to the hydraulic pressure originating from the difference in liquid level between the two compartments.

At the cathode, water is decomposed to form hydrogen and hydroxyl ions (OH^-):

$$2H_2O + 2e^- \rightarrow \underline{H_2} + 2OH^-.$$
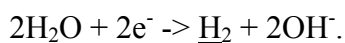
Then hydroxyl ions combine with sodium ions to form sodium hydroxide, that is, caustic soda in the catholyte:

$$OH^- + Na^+ \rightarrow \underline{NaOH}.$$
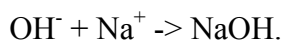
Unlike the mercury process, which can produce highly concentrated caustic soda, the concentration of caustic soda produced in the diaphragm process is lower than that required for commercial purposes. Thus the unit for caustic concentration is necessary in the diaphragm process. This step, however, requires additional energy, and this is basically responsible for the fact that the total energy consumption for chlor-alkali production by the diaphragm process is larger than that by the mercury process.
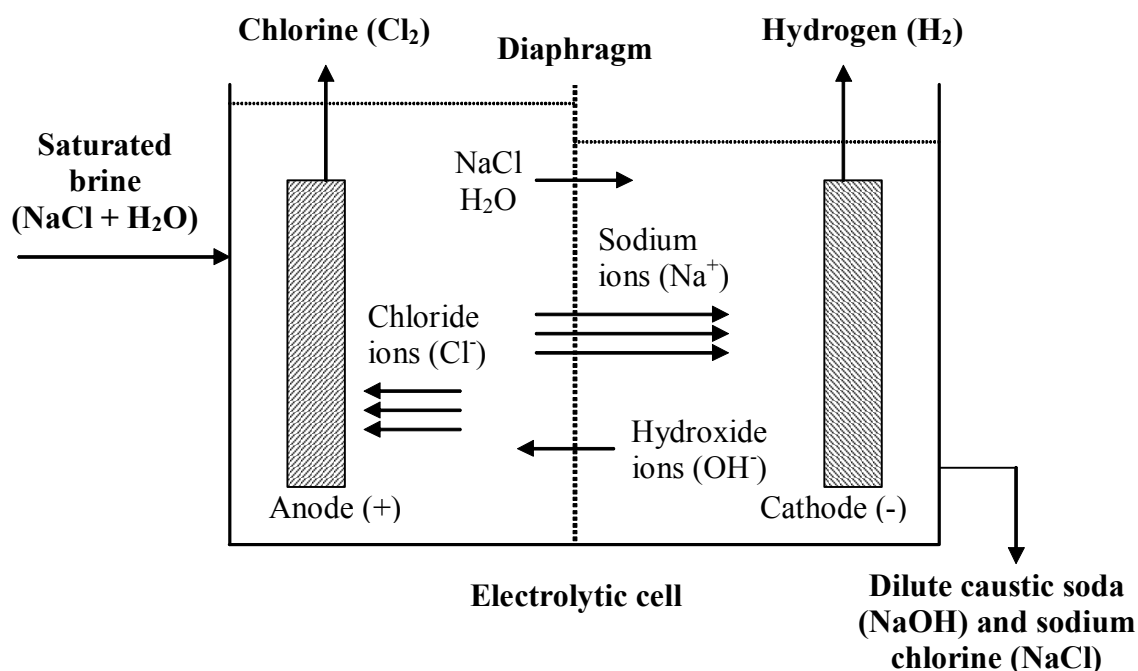
Figure 3-6 Diaphragm Electrolyzer

Based on Curlin, Bommaraju, and Hansson (1991).

As you can see, the diaphragm process does not rely on the use of mercury in producing chlorine and caustic soda, which are separated by the porous diaphragm. Thus there is no emission of mercury from the production process. On the other hand, asbestos used in the diaphragm has long been known as a hazardous substance, and regulations have been introduced, including exposure levels at workplace, in many countries[51]. The chlor-alkali industry, however, has been mostly exempted from these regulations, mainly because of the claim that asbestos is an indispensable material for the diaphragm used in chlor-alkali production. According to the industry, asbestos exhibits a highly favorable combination of essential characteristics, including sufficient mechanical strength, high chemical resistance to both acids and bases, low electrical resistance, uniform and consistent deposits on the cathode, appropriate physical structure to permit flow of depleted brine with minimum back migration

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[51] In the Untied States, for instance, the Occupational Safety and Health Administration of the Department of Labor and the Environmental Protection Agency have introduced various types of regulation on asbestos (see, for example, Occupational Safety and Health Administration, 1993; United States Environmental Protection Agency, 2000).

of hydroxyl ion, and an acceptable service life, and controlled use of asbestos should be allowed (Chlorine Institute, 1995; Trettin, 1997)[52].

As an alternative technique to separate chlorine and caustic soda, porous cement diaphragms were originally invented by Breuer in 1886 (Haber, 1958). The first electrolytic plant based on the diaphragm process started to operate in 1890 by the Griesheim Company near Frankfurt, Germany. In this plant, potassium chloride (KCl), instead of sodium chloride, was treated because caustic potash (potassium hydroxide, KOH) was more valuable at that time. While the cell was operated batch-wise and the current efficiency was poor, at around 70 to 80 per cent, the cell was simple, inexpensive and relatively large in capacity (Kircher, 1962). The Griesheim cell was the first commercially successful diaphragm cell, and the simplicity of the design of the process led other firms to apply for a license. By 1900, four out of eight German electrolytic plants and two out of four French plants had come to use the Griesheim diaphragm cell (Haber, 1971).

The Griesheim cell was followed by about twenty other designs. In Britain, another type of diaphragm cell was developed in the 1890s by Hargreaves and Bird. They formed a company at Cheshire in 1899, and their plant with the Hargreaves-Bird cell was opened two years later (Kircher, 1962). This cell was based on a non-percolating diaphragm and reduced the back migration of hydroxide ions by adding carbon dioxide and steam to the cathode compartment, converting the caustic to sodium carbonate. This was the first commercialization of the vertical diaphragm cell.

In the United States, a type of the diaphragm process was developed by Le Sueur, who had also designed a mercury cell, and a small plant based on it was built in 1893 (Haber, 1958). It was the first commercial production of electrolytic caustic soda in the world. The Le Sueur cell made use of a percolating diaphragm for the first time and had become the basis of all modern diaphragm chlor-alkali cells. Brine was permitted to flow into the anolyte and through the diaphragm by the device of maintaining the electrolyte level higher on the anode than on the cathode side. The slow percolation of electrolyte through the diaphragm countered the migration of hydroxyl ions toward the anode compartment. Consequently, continuous operation became possible, and much higher current efficiency was obtained than with a non-percolating diaphragm such as in the Griesheim cell. The Le Sueur cell was licensed to

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[52] As attempts have been made recently to avoid the use of asbestos in, for example, fireproofing materials, one of the principal applications of asbestos (Block, Dolhert, Petrakis, and Webster, 2000), several companies have started to develop diaphragms which do not consist of asbestos (Florkiewicz, 1998; Stadig, 1993).

several companies in the U.S., notably paper-making firms, which were dependent on a cheap supply of chlorine.

These early diaphragm cells have been mostly replaced by designs invented in the 1900s (Haber, 1971). In the United States, Townsend and Sperry made electrolytic cell inventions and sold their design to the development company founded by a civil engineer, Hooker. The Townsend cell, later known as Hooker cell, was first used in 1906 at the plant of Hooker Electrochemical Company at Niagara Falls. In Germany, the Billiter cell was developed in 1907 and was widely used in the world during the 1920s. Another widely employed diaphragm cell, the Gibbs cell, was developed in the United States in 1908.

The next major development took place in 1913, when a cell with finger cathodes and side-entering anodes was designed by Marsh (Kircher, 1962). This increased the electrode area per unit of cell volume or cell floor space, reducing capital investment per unit of production. Diaphragms were made of asbestos paper wrapped around the cathodes and sealed with cement and putty. The putty joints, however, provided a poor seal, and the Marsh cell was plagued with leaks and its current efficiency never equaled that of cells with more simple construction. In an attempt to overcome the disadvantage of the Marsh cell, Stuart, a technologist of Hooker Electrochemical Company, invented in 1928 a method of depositing asbestos fiber onto the cathode by immersing it in slurry and applying a vacuum. With the flexibility of cell design permitted by the deposited asbestos diaphragm, the Hooker Type S cell was developed and has been further improved through various stages.

Filter press cells, which had been used extensively for hydrogen-oxygen electrodialysis, started to be designed also for chlor-alkali production by several early workers. Although the filter press design was attractive in terms of requiring a minimum of conductor material between cells, a minimum of floor space and low investment cost, the only commercial use of the filter press for chlor-alkali had been limited to the Dow Chemical Company in the U.S. (Murray, 1949). Dow had developed filter press cells through several stages characterized by simple, rugged, inexpensive construction. Detailed data on the performance of this technology, however, had not been disclosed to outside companies for a long time.

In the late 1960s PPG Industries in the U.S. made development efforts and succeeded in commercializing its Glanor electrolyzer in the early 1970s (PPG Industries, 1981). It consisted of ten bipolar elements securely clamped together with tie rods between two end electrode elements, forming a sealed electrolyzer module of eleven cells. They were called bipolar because one side of each element acted as a cathode and the other as an anode, and

they were clamped together with the anode side of one element toward the cathode side of the next element so that the space between formed a cell. The advantage of the bipolar design was that it permitted current to flow internally within an electrolyzer from one cell to another. Accordingly, the current path could be shorter and of lower resistance than in conventional cells, in which the current flowed through external bus bars.

In Japan, the diaphragm process was industrialized for the first time by Hodogaya in 1915 (Yamaguchi, 1999b). Subsequently, the Nakano cell and the Yoshimura cell, named after the inventors, respectively, were developed and began to be installed in 1920. Nippon Soda also developed a bipolar diaphragm cell, and Tsurumi Soda developed and installed a monopolar diaphragm cell in its own plants. At the same time, various types of the diaphragm cell, including the Townsend cell, Allen-Moore cell, Nelson cell, Billiter-Siemens cell, and Billiter-Leykam cell, were all introduced from foreign countries. After the Second World War, however, as the mercury process increased its share steadily, many types of the diaphragm electrolytic cell, such as the Nakano cell and Allen-Moore cell, disappeared from chlor-alkali plants in Japan. Overall, compared with the remarkable technological advance made on the mercury process, the extent of technological progress of the diaphragm process in Japan was rather limited, and the main focus was placed on incremental improvements on the existing technologies, which were mainly introduced from technology suppliers based in foreign countries, particularly the United States.

Although more than thirty types of diaphragm cells had been developed in the past, all new diaphragm cells available in the early 1970s were basically of two types: the Stuart (Hooker) type and the filter press type (Chlorine Institute, 1972; Jackson, Cooke, and Woodhall, 1971; Kircher, 1962; Kuhn, 1971; Smith, 1968; Sommers, 1957a, 1957b, 1965). The Stuart type cells included the Hooker Type S cells and Diamond cells whereas the filter press type cells included the Dow cells and Glanor cells. Table 3-9 gives some characteristics of the technologies for the diaphragm process which were available at the time of the early 1970s. As you can see, technological development of the diaphragm process was basically led by the US companies, namely, Hooker, Diamond Shamrock, Dow, and PPG, which were followed by some Japanese companies.

Table 3-9 Major Technologies of the Diaphragm Process in the Early 1970s

Technology	Cell Current (kA)	Current Density (kA/m^2)	Power Consumption (DC, kWh/short ton Cl$_2$)
Hooker (US)			

S-3D	40	1.435	2,810
S-4	55	1.287	2,830
H-4	150	-	2,671[*]
Diamond Shamrock (US)			
D-3	30	1.294	2,750
DS-85	100-150	1.82-2.74	2,459-2,882[*]
Dow (US)			
Dow	n/a	n/a	n/a
PPG (US)			
Glanor V 1144	792	1.975	2,487-2,513[*]
Nippon Soda (JP)			
B-5	25	0.975	2,540[*]
BM-50	250-300	1.80-1.90	2,540-2,681
Tsurumi Soda (JP)			
TSB-4	24	0.81	2,328[*]
TSBM-7	50	2.0	2.513[*]
Showa Denko (JP)			
SD-7	75	1.73	2,521[*]

* The unit is kWh/t NaOH.
Sources: Sommers (1965), Japan Soda Industry Association (1975).

3.3.3 Diffusion of the Mercury Process in Western Europe and Japan

As we have seen in the previous section, the industrial production of chlor-alkali products started with the mercury and the diaphragm processes almost simultaneously at the end of the 19th century. Technological development of the two production processes was initially pursued both in the Western Europe and in the United States. Subsequently, however, technological progress in the mercury process was mainly made by companies in Western Europe, whereas the diaphragm process was mainly improved by companies in the United States. Although the two production processes had remained basic to the chlor-alkali industry, different types of production technologies had come to be adopted in Western Europe, the United States, and Japan.

In Western Europe, the mercury process has been dominant since the beginning of the electrolytic production of chlor-alkali products. Table 3-10 gives the distribution of the chlor-alkali production processes in Western Europe in the late 1950s. As you can see, more than 80 per cent of the chlor-alkali production capacities were based on the mercury process while the diaphragm process accounted for only 15 of the total capacities. For the mercury process,

almost all of the technologies were supplied by Western European companies, notably, Solvay, De Nora, ICI, Krebs, and Uhde[53].

Table 3-10 Chlor-Alkali Production Processes in Western Europe in 1957

Type of Technology	Installed Units	Production Capacity[a] (Cl_2 t/day)
Mercury process	83 (71%)	6,010 (83.1%)
Solvay (WE)	10	875
De Nora (WE)	14	867
BASF (WE)	6	805
ICI (WE)	5	660
Krebs (WE)	23	634
Uhde (WE)	3	593
I.G. (WE)	7	463
Hoechst (WE)	3	407
Other/Unknown	12	706
Diaphragm process	25 (21%)	1,106 (15.3%)
Gibbs (US)	4	520
Billiter (WE)	4	174
Hooker (US)	3	165
Krebs (WE)	4	33
Other/Unknown	10	214
Sodium	3 (3%)	61 (0.8%)
Other/Unknown	6 (5%)	52 (0.7%)
Total	117 (100%)	7,229 (100%)

* Data as of June 1, 1957. No data was available either on process or on capacity for 23 plants, which are hence excluded from the table.
a: When both the mercury and the diaphragm processes were used, the production capacity was divided equally between them.
Calculation based on Sommers (1957a).

Although official data on the trends in production technologies in the Western European chlor-alkali industry are scarcely published, we can infer that the mercury process continued to be used in the subsequent period[54]. As you can see in Table 3-11, which shows the compositions of technologies used in Western Europe in 1972, the mercury process accounted

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[53] BASF cooperated closely with Krebs for technological development whereas Hoechst and Uhde jointly developed its technologies of the mercury process.

[54] Before the World War I the alkali industry of the whole world was characterized by concerted action, with the exchange of information and adherence to apportioned markets. The center of this unofficial combine was Solvay & Cie. of Belgium, which, with its associates in other countries, exercised a dominant influence on the alkali industry (Ahlqvist, 1936). Because of the peculiar tradition of the alkali industry, no official figures were published in Europe either by the industry or by the government agencies, and hence most of the information was derived from individual investigations.

for almost 80 per cent of the total installations at chlor-alkali plants. The major suppliers of technologies for the mercury process were De Nora, Hoechst-Uhde, Krebs, Solvay, and ICI. Compared with Table 3-10, we can see that the composition of the technology suppliers for the mercury process in Western Europe had basically remained unchanged since the end of the Second World War.

Table 3-11 Chlor-Alkali Production Processes in Western Europe in 1972

Type of Technology	Installed Units
Mercury Process	146 (78%)
De Nora (WE)	29
Hoechst-Uhde (WE)	24
Krebs (WE)	24
Solvay (WE)	14
Krebskosmo (WE)	12
I.G. (WE)	8
ICI (WE)	5
BASF (WE)	5
Other/Unknown	25
Diaphragm Process	34 (18%)
Hooker (US)	6
Pestalozza (WE)	6
Billiter (WE)	4
Other/Unknown	18
Sodium	5 (3%)
Other	1 (1%)
Total	186 (100%)

No data was available for 36 plants, which are hence excluded from the table.
Calculation based on Chlorine Institute (1972).

As regards the production capacity in the same year, there is no detailed data available to outside the industry. Table 3-12 only gives rough estimations about the shares of the mercury and the diaphragm processes used in some Western European countries. Nevertheless, we could see from this table that the mercury process remained the dominant technology in the early 1970s for the chlor-alkali production.

Table 3-12 Shares of the Chlor-Alkali Production Processes in Western European Countries in 1972

Country	Mercury Process	Diaphragm Process
Belgium	90	10
France[a]	70	28
West Germany	89	11

Italy	99	1
Netherlands	75	25
Sweden	100	0
United Kingdom	90	10
Total[b]	86	13

a: Electrolysis of molten salt of metallic sodium accounts for 2 %.
b: All others account for 1 %.
Source: Koyama (1972).

In the United States, in contrast, there was a proliferation of the diaphragm process to chlor-alkali plants. By the Second World War, the diaphragm process had come to dominate the U.S. chlor-alkali industry. Table 3-13 shows the distribution of various types of the mercury process used in the chlorine plants in the United States immediately after the war. In 1946, the diaphragm process accounted for almost 90 per cent of the total production in the U.S. Most of the technologies for the diaphragm process were provided by American companies; Hooker cells were used most extensively, in 43 per cent of the capacity, followed by Dow's bipolar cells representing 17.5 per cent. Mercury cells, on the other hand, accounted for only 4 per cent of the U.S. chlor-alkali production.

Table 3-13 Chlor-Alkali Production Processes in the United States in 1946

Type of Technology	Installed Units	Production Capacity* (Cl_2 short tons/year)
Mercury Process	3 (5%)	68,400 (4.3%)
Castner (US)	1	40,200
ICI (WE)	1	23,800
Sorensen (WE)	1	4,400
Diaphragm Process	54 (90%)	1,411,790 (88.6%)
Hooker-S (US)	24	491,000
Hooker-Columbia (US)	3	193,500
Dow-Bipolar (US)	3	278,000
Vorce (US)	4	151,700
Gibbs (US)	3	93,000
Diamond (US)	2	90,500
Allen-Moore KML (US)	5	64,700
Wheeler (US)	3	23,400
Hargreaves Bird (WE)	3	11,000
Nelson (US)	1	7,300
Larcher (US)	1	4,400
Townsend (US)	1	2,560
MacDonald (US)	1	730
Fused Salt Process (Downs)	2 (3%)	92,000 (5.8%)

Nitrosyl process	1 (2%)	20,000 (1.3%)
Total	60 (100%)	1,592,190 (100%)

* Built or under construction at the time of 1946.
Source: MacMullin (1947).

Shares of the chlor-alkali production processes used in the United States in the following years are given in Table 3-14. The share of the mercury process increased gradually after the end of the war, reaching the peak of just less than 30 per cent in the late 1960s. Nevertheless, the diaphragm process remained the dominant process in the United States throughout the post-war period. The share of the diaphragm process started to rise again at the end of the 1960s, and by the early 1970s, the diaphragm process had come to account for more than 70 per cent of the total capacity in the U.S. chlor-alkali industry.

Table 3-14 Trends in the Shares of the Chlor-Alkali Production Processes in the United States

Year	Mercury Process	Diaphragm Process	Other Processes
1952	12	80	8
1957	14.4	79.0	6.6
1962	18.5	76.2	5.3
1963	20.8	74.1	5.1
1964	23.0	72.2	4.8
1965	24.2	71.2	4.6
1966	26.5	69.7	3.8
1967	26.7	69.8	3.5
1968	28.6	68.1	3.3
1969	27.9	69.2	2.9
1970	27.2	69.6	3.2
1971	27.2	69.8	3.0
1972	24.2	72.4	3.4

Figures are expressed as percentages of the total production capacity.
Sources: Gardiner (1978) for 1952; Sommers (1957b) for 1957; Chlorine Institute (1999b) for 1962 onward as of July 1 of each year.

The composition of chlor-alkali production processes used in the U.S. in the middle of the 1960s is given in Table 3-15[55]. The diaphragm process had remained the main technology for the U.S. chlor-alkali production for the 20 years following the end of the Second World War. Hooker continued to be a dominant supplier of technologies, accounting for more than one third of the total production capacities in the U.S., followed by Dow Chemical. On the

other hand, production units based on the mercury process were also introduced during the same period. They were mostly provided by Mathieson in the United States, and De Nora, Solvay, and Uhde in Western Europe.

Table 3-15 Chlor-Alkali Production Processes in the United States in 1965

Type of Technology	Installed Units	Production Capacity (Cl_2 short tons/day)
Mercury Process	31 (37%)	4,811 (26.6%)
Mathieson (US)	7	1,365
De Nora (WE)	11	1,285
Solvay (WE)	6	1,091
Uhde (WE)	3	480
ICI (WE)	1	230
Krebs-BASF (WE)	1	185
Dow (US)	1	125
BASF (WE)	1	50
Diaphragm Process	45 (54%)	11,984 (66.4%)
Hooker (US)	27	6,548
Dow (US)	4	3,010
Diamond (US)	5	1,333
Columbia Southern (US)	1	600
Gibbs (US)	2	274
Allen-Moore (US)	2	78
Vorce (US)	2	70
Tucker Windecker (US)	1	35
Wheeler (US)	1	26
Townsend (US)	1	10
Fused Salt Process (Downs)	5 (6%)	780 (4.3%)
KNO_3-HNO_3 Reaction	1 (1%)	60 (0.3%)
Unknown	2 (2%)	425 (2.4%)
Total	84 (100%)	18,060 (100%)

Data include projected constructions and expansions.
Source: Sommers (1965).

In Japan, both the mercury process and the diaphragm process were used at the initial stage of industrial development. Table 3-16 gives the shares of the chlor-alkali production processes in Japan shortly after the Second World War. In 1949, the mercury process accounted for 43 per cent of the total production capacity whereas the diaphragm process accounted for 57 per cent. While most of the diaphragm process technologies were introduced

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[55] The data for 1965 in Table 3-15 is slightly different from that in Table 3-14. That is probably because of the difference in the date of counting.

from foreign providers, notably Billiter-Siemens, almost two thirds of the production capacities based on the mercury process were provided by one Japanese company, Osaka Soda (currently Daiso), with the rest of the mercury process provided by two companies based in Western Europe, namely, Krebs and Solvay.

Table 3-16 Chlor-Alkali Production Processes in Japan in 1949

Type of Technology	Installed Units	Production Capacity (NaOH t/month)
Mercury process	18 (44%)	7,153 (43.1%)
Osaka Soda (JP)	11	4,257
Krebs (WE)	6	2,422
Solvay (WE)	1	474
Diaphragm process	23 (56%)	9,434 (56.9%)
Billiter-Siemens (WE)	8	3,573
Allen-Moore (US)	4	1,468
Nakano (JP)	1	1,363
Horizontal (JP)	4	954
Cylinder (JP)	1	661
Hooker (US)	1	645
Nelson (US)	4	524
Total	41 (100%)	16,587 (100%)

Calculation based on Japan Soda Industry Association (1952).

After the end of the Second World War, detailed information on advanced technologies for the mercury process developed in Western Europe became available to Japan. As many Japanese companies started to direct innovative efforts toward the mercury process, various types of technologies were developed in the post-war period. Table 3-17 gives the trends in the shares of the chlor-alkali production processes used in the Japanese industry. As you can see, the mercury process had come to become the dominant technology in Japan by the early 1970s, representing more than 95 per cent of the total production capacity at that time. In the meantime, technological development for the diaphragm process had stagnated since the end of the war, and its share continued to decline steadily.

Table 3-17 Shares of the Chlor-Alkali Production Processes in Japan

Year	Mercury Process	Diaphragm Process
1950	43.6	56.4
1951	41.8	58.2
1952	46.1	53.9
1953	47.9	52.1

1954	51.5	48.5
1955	55.6	44.4
1956	55.2	44.8
1957	62.9	37.1
1958	66.6	33.4
1959	66.8	33.2
1960	71.6	28.4
1961	78.8	21.2
1962	80.3	19.7
1963	80.9	19.1
1964	82.2	17.8
1965	85.6	14.4
1966	86.3	13.7
1967	87.3	12.7
1968	89.9	10.1
1969	91.1	8.9
1970	92.2	7.8
1971	95.2	4.8
1972	95.6	4.4

Figures are expresses as percentages of the total production capacity.
Source: Calculation based on the production capacity data in Japan Soda Industry Association (1982) as of March in each year, except for August in 1959 and May in 1952.

The types of technologies used for chlor-alkali production at the time of 1972 are shown in Table 3-18. We can observe that technologies for the mercury process were mainly provided by De Nora, Uhde, and Krebs based in Western Europe, and Mitsui Engineering and Shipbuilding (MES), Osaka Soda, Asahi Glass, and Kureha Chemical based in Japan. Although there are cases in which the technology suppliers are not known, considering other information sources on the development of technologies in technical and trade journals, we could safely infer that the remaining chlor-alkali producers in Japan have adopted technologies provided by these suppliers mentioned above.

Table 3-18 Chlor-Alkali Production Technologies in Japan in 1972

Type of Technology	Installed Units
Mercury Process	66 (76%)
De Nora (WE)	9
Mitsui Engineering and Shipbuilding (JP)	8
Osaka Soda (JP)	6
Uhde (WE)	4
Kureha Chemical Industry (JP)	4
Asahi Glass (JP)	4

Krebs (WE)	3
Krebskosmo (WE)	3
Toyo Soda (JP)	1
Tokuyama Soda (JP)	1
Asahi Chemical Industry (JP)	1
Olin (US)	1
Other/Unknown	21
Diaphragm Process	16 (18%)
Billiter (WE)	4
Hooker (US)	3
Allen-Moore (US)	1
Nelson (US)	1
Nippon Soda (JP)	1
Tsurumi Soda (JP)	1
Other/Unknown	5
Sodium	4 (5%)
Unknown	1 (1%)
Total	87 (100%)

Calculation based on Japan Soda Industry Association (1952), Chlorine Institute (1972).

There are several factors which are considered to have contributed to the different courses of technological change prior to the 1970s between the mercury process in Western Europe and Japan and the diaphragm process in the United States. We first consider the availability of materials necessary for chlor-alkali production. They include mercury for the mercury process and asbestos for diaphragm used in the diaphragm process, and different types of salt suitable for use in each of the two production processes. Then we also consider demand-side factors, including the different qualities of caustic soda between the mercury process and the diaphragm process, which would influence the technological preference.

Regarding the choice of the mercury process in Western Europe, a large amount of mercury was readily available for use in the chlor-alkali industry in Western Europe, particularly in Spain and Italy. In 1928, a cartel known as Mercurio Europeo was organized by Spanish and Italian producers to control production, distribution, and sale at a time when world stocks of mercury were in excess of demand (Goldwater, 1972). Although detailed data has not been available, it is estimated that more than 80 per cent of world production was controlled by the interests who formed the combine. By agreement, 55 per cent of sales were allocated to Spain and 45 per cent to Italy. While the Mercurio Europeo cartel was dissolved in 1950, the two countries remained the two major mercury-producing countries. As Table

3-19 shows, the production of mercury in Spain and Italy in the middle of the 1960s accounted for more than half of the world production.

Table 3-19 World Production of Mercury in the Middle of the 1960s

Country	Annual Production[a] (flasks[b])
Spain	78,322 (30.7%)
Italy	57,001 (22.4%)
U.S.S.R.	35,000 (13.7%)
China	26,000 (10.2%)
Yugoslavia	17,318 (6.8%)
United States	14,142 (5.5%)
Mexico	12,561 (4.9%)
Other	14,629 (5.7%)
Total	254,973 (100%)

a: Data are of the year 1964.
b: The standard commercial unit of mercury is the flask containing 76 pounds avoirdupois. The flask has not always been exactly 76 pounds, but the Spanish flask was 34.5 kg, the Californian, Russian, and Italian flasks 34.7 kg, and the Mexican flask 34.15 kg (Goldwater, 1972).
Source: United States Department of the Interior (1968).

In the United States, on the other hand, most of the chlor-alkali plants in had been based on the diaphragm process. The main material of diaphragms used for chlor-alkali production was asbestos. As Table 3-20 shows, the principal asbestos-producing countries in the late 1930s were Canada, the Soviet Union[56], Southern Rhodesia, the Union of South Africa, the United States, and Swaziland. In particular, Canada was the dominant producer of asbestos, accounting for 60 per cent of the world production.

Table 3-20 World Production of Asbestos in the Late 1930s

Country	Annual Production[a] (short tons)
Canada	364,472 (60.2%)
Southern Rhodesia	58,313 (9.6%)
Union of South Africa	22,050 (3.6%)
United States	15,459 (2.6%)
Swaziland	7,973 (1.3%)
World Total	605,000 (100%)

a: Data are of the year 1939, except for the world total, with the data of the average of 1937-1939.
Source: United States Tariff Commission (1951).

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[56] Although the statistics on the Soviet Union was not available, it was estimated that its asbestos production accounted for most of the remainder, making the country the second largest producer after Canada (United States Tariff Commission, 1951).

As the production of asbestos in the United States was minor in relation to the world production, the country depended upon imports for most of its asbestos requirements. Table 3-21 gives the figures for imports, exports, and consumption of asbestos in the United States in the late 1930s. Imports totaled 243,000 tons, accounting for 96 per cent of the consumption of asbestos in the United States. And more than 90 per cent of the imports came from the neighboring Canada, the largest producing country in the world. Asbestos was basically free of duty, under the Tariff Act of 1922 and later under the Tariff Act of 1930, and its duty-free status was bound in the trade agreement with Canada, effective January 1936 and January 1939 (United States Tariff Commission, 1951). Also, the Canadian asbestos deposits, which were primarily located in the Eastern Townships of Quebec, the Cochrane district of Ontario, and the Cassiar district of north-western British Columbia, were close to the main United States consuming centers (Avery, Conant, and Wiessenborn, 1959). As several of the United States asbestos manufacturers owned and operated asbestos mines in Canada, there was a close relationship between Canadian producers of asbestos and United States consumers of it. Thus we can see that asbestos was readily available for use as the key material of the diaphragm to chlor-alkali producers located in the United States.

Table 3-21 Imports, Exports, Production, and Consumption of Asbestos in the United States in the Late 1930s

	Quantity (short tons)	
Imports	243,079	
Canada		221,973
Southern Rhodesia		4,893
Union of South Africa		4,761
All other countries		11,452
Exports	2,653	
Production	12,659	
Consumption	253,085	

Data are of the average of 1937-39.
Source: United States Tariff Commission (1951).

The sources of salt, the principal input material for chlor-alkali production, could have also influenced the technological choice between the mercury process and the diaphragm process. Solid salt can be obtained from three sources: rock salt, salt from solution-mined brine, and solar salt. While the diaphragm process can take full advantage of cheap brine where it is available from brine wells, the mercury process requires solid salt to achieve

efficient utilization of salt, although it can also operate with brine as a raw material where that is sufficiently cheap to offset the high unit consumption (MacMullin, 1947). As you can see in Table 3-22, the sources of salt were different between countries in Western Europe and the United States. While the salt produced in West Germany was mostly rock salt, 60 per cent of the salt production in the United States came from brine wells. Hence, the diaphragm process was favorable in the United States whereas the mercury process was favorable in West Germany, and probably in neighboring countries as well.

Table 3-22 Production of Salt in West Germany and the United States in the Early 1950s

Country	Rock	Brine	Evaporated	Total
West Germany	3,523 (91.5%)	328 (8.5%)	0	3,851 (100%)
United States	4,479 (21.5%)	12,608 (60.6%)	3,702 (17.8%)	20,789 (100%)

Data are of 1953. Figures are expressed in 10^3 short tons.
Source: Harris (1960).

These factors can be considered to have influenced the choice of technological options at the initial stage of the technological development in the chlor-alkali industry. Technological development of the mercury process was mainly pursed by companies in Western Europe, notably Solvay, Krebs, De Nora, Uhde, and ICI, whereas companies in the United States mostly concentrated their innovative efforts on the diaphragm process, particularly companies such as Hooker, Diamond, PPG, and Dow. Without extensive technological interactions between the two regions, each process had been improved in its unique way and chlor-alkali producers subsequently adopted the process which was readily provided by technology suppliers in that region. In this way, learning experiences had been accumulated on the production process specific to the region, which in turn had contributed to further technological progress on that process.

In the post-war period, the mercury process was increasingly adopted all over the world. As you can see in Table 3-14, the share of the mercury process increased rapidly in Japan. Even in the United States, where the majority of the chlor-alkali plants had been originally based on the diaphragm process, the mercury process increased its share gradually following the end of the war. One of the reasons for the increased use of the mercury process can be considered to concern a demand-side factor, particularly, the quality of caustic soda. High-quality caustic soda with little impurity is required for the production of rayon, a textile made from cellulose. As Table 3-23 gives the world-wide trends in the production of rayon since 1930, the rayon industry experienced a significant expansion and became one of the major

sectors which consume caustic soda in the post-war period. Since the quality of the caustic soda produced by the mercury process is much purer than that produced by the diaphragm process, the increased demand for caustic soda from the rayon industry induced chlor-alkali producers to choose the mercury process for their production. In Japan, where the chlor-alkali industry had used the mercury process and the diaphragm process equally, mostly relying on technologies introduced from Europe and the United States, several innovative companies, including Osaka Soda, Kureha Chemical, Mitsui Engineering and Shipbuilding, and Asahi Glass, started to focus their efforts to develop technologies for the mercury process. By the middle of the 1960s, however, the rayon production had leveled off in most parts of the world. In the United States, as the production of rayon had declined by 1970, the mercury process also started to decrease its share in the chlor-alkali industry.

Table 3-23 World Production of Rayon

Year	Western Europe	United States	Japan	Socialist countries	Others	Total
1930	130	58	17	-[a]	2	207
1940	665	214	225	-[a]	23	1,127
1950	791	375	121	-[a]	54	1,341
1955	967	495	425	425	47	2,359
1965	1,101	506	446	684	238	2,975
1970	1,021	391	451	901	240	3,004

Figures are expressed in 10^3 tonnes/year.
a: Figures of socialist countries from 1930 to 1950 are included in those of Western Europe.
Source: Sakota (1977).

In this way, by the beginning of the 1970s, most of the chlor-alkali plants in Western Europe and Japan had come to be based on the mercury process. Figure 3-7 shows the shares of the mercury and the diaphragm processes in Western Europe, the United States, and Japan in 1972. (Data are given in Table 3-25 in Appendix at the end of this chapter).
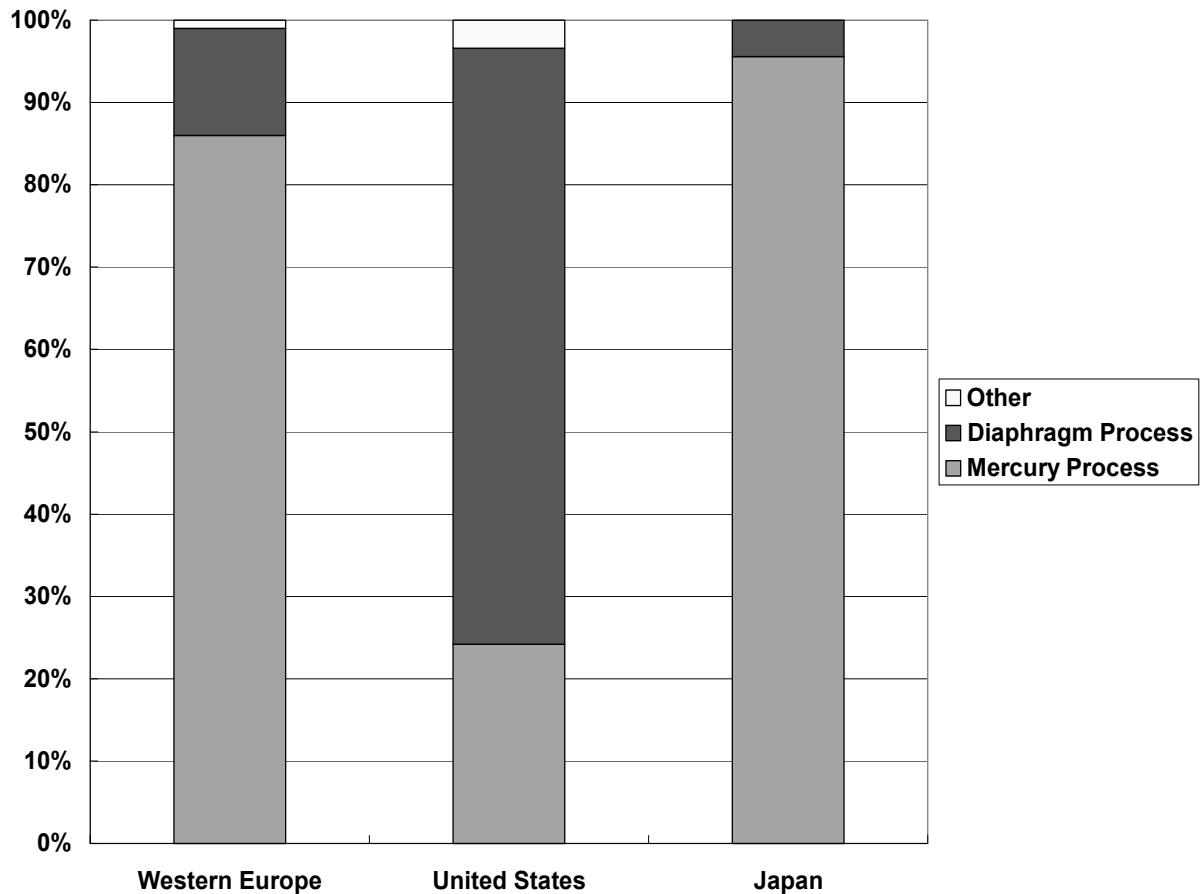
Figure 3-7 Shares of the Mercury and the Diaphragm Processes in Western Europe, the United States, and Japan in 1972

While the diaphragm process had continued to be the major technology in the Untied States, the mercury process had become dominant in Western Europe and Japan. Several companies in each of Western Europe and Japan succeeded in making innovations on the mercury process, and their technologies had been widely adopted by chlor-alkali producers in these regions. Therefore, we can say that the initial conditions in terms of technological development and adoption in Western Europe and Japan were similar at the time of the early 1970s, just before environmental regulations started to be imposed on mercury emissions from chlor-alkali plants in the two regions. That will make it easier to see clearly the effects of the introduction of environmental regulations at a later stage on the course of technological change, without influences of other complicating factors.

119

3.4 Conclusion

The main products of the chlor-alkali industry are chlorine and caustic soda. The two substances have been widely used as intermediate materials in various industries, including the inorganic chemical, organic chemical, pulp and paper, and aluminum industries. Although chemical processes had been traditionally used in the industry, currently the chlor-alkali products are produced by the electrolysis of brine, that is, salt water. As brine is electrolyzed with intensive use of electricity, the chlor-alkali industry consumes a large amount of electric power. There are three types of electrolytic processes used in the world for commercial production of the chlor-alkali products, namely, the mercury process, the diaphragm process, and the ion exchange membrane process. Currently, the mercury process is the dominant technology in Western Europe whereas the diaphragm process is widely used in the U.S. chlor-alkali industry. In Japan, the ion exchange membrane process accounts for almost all of the production technologies used in chlor-alkali plants. In this way, the three processes are used as the major technology in different regions.

The mercury process and the diaphragm process for chlor-alkali production were invented almost in the same period, at the end of the 19th century. Since then, technologies for the mercury process had been mainly developed in Western Europe whereas U.S. companies had been involved in improving technologies for the diaphragm process. Both processes were initially introduced from Western Europe and the United States to the Japanese chlor-alkali industry at the beginning of the 20th century. After the end of the Second World War, in the United States, where the diaphragm process had been initially preferred, technological progress was pursued subsequently by innovating companies on the diaphragm process. Although the share of the mercury process increased slightly in the post-war period, the diaphragm process had remained the dominant technology in the United States. On the other hand, innovative companies in Western Europe and Japan devoted research and development efforts to the mercury process. Through learning and knowledge accumulation based on the increased use in the industry, technologies for the mercury process were improved further, and more chlor-alkali producers adopted the mercury process in these two regions.

By the late 1960s, the mercury process had come to dominate the chlor-alkali industry in Japan as well as in Western Europe. In each region, there were several innovative companies which made successful technological developments for the mercury process. In

Western Europe the major innovating companies included De Nora, Uhde, Krebs, Solvay, and ICI, whereas in Japan Osaka Soda, Kureha Chemical Industry, Asahi Glass, Tokuyama Soda, Asahi Chemical Industry, and Mitsui Engineering and Shipbuilding, which later established Chlorine Engineers Corp., succeeded in developing their own technologies. That suggests that several companies in Western Europe and in Japan were equally innovative on the mercury process technologies, before environmental regulations started to be introduced in the early 1970s to reduce mercury emissions to the environment. In other words, the initial technological conditions in the chlor-alkali industry were similar in Western Europe and Japan prior to any influence of environmental regulations.

Since then, Western Europe and Japan have taken divergent courses of technological change in the same industry. The mercury process has been phased out in Japan, and currently almost all of the chlor-alkali production capacities are based on the ion exchange membrane process, which has been developed since the 1970s. In contrast, the mercury process has continued to be dominant in Western Europe, while the penetration of the membrane process to chlor-alkali plants has been relatively limited. In the following two chapters, we will investigate how environmental regulations on mercury emissions have influenced the patterns of technological change in Japan and Western Europe. We will closely look at the ways in which different technological trajectories have emerged between the two regions; that is, we will examine why and how the option of developing end-of-pipe technologies have been chosen to reduce mercury emissions in Western Europe whereas the ion exchange membrane process, a clean technology which eliminates mercury pollution from within the production process, has been invented and widely diffused in Japan.

Appendix

Table 3-24 Shares of Chlor-Alkali Production Capacities Based on the Mercury, Diaphragm, and Ion Exchange Membrane Process in Western Europe, the United States, and Japan in 1998

	Mercury Process	Diaphragm Process	Ion Exchange Membrane Process	Other
Western Europe	60.7	23.0	13.4	2.9
United States	12.4	72.8	12.2	2.6
Japan	0	9.5	90.5	0

Sources: Western Europe: Euro Chlor (1998a) and European IPPC Bureau (1999); United States: Chlorine Institute (1999b);and Japan: Japan Soda Industry Association (1998b).

Table 3-25 Shares of Chlor-Alkali Production Capacities Based on the Mercury and the Diaphragm Processes in Western Europe, the United States, and Japan in 1972

	Mercury Process	Diaphragm Process	Other
Western Europe	86	13	1
United States	24.2	72.4	3.4
Japan	95.6	4.4	0

Sources: Western Europe: Koyama (1972); United States: Chlorine Institute (1999b); and Japan: Japan Soda Industry Association (1982).

4. Environmental Regulation and Technological Change in the Japanese Chlor-Alkali Industry

4.1 Regulatory Decision on the Phase out of the Mercury Process

In May 1956, four cases of an unknown disease with nervous symptoms were reported in Minamata in the southern part of Japan. Further investigations revealed that more patients were suffering from the same symptoms among inhabitants in the Minamata Bay area. Initially, heavy metals such as selenium, manganese, and thallium were suspected as the agent causing the disease, but later the disease was proved to be methyl mercury poisoning caused by ingestion of seafood caught in the Minamata Bay and the neighboring seas; hence it has become called the Minamata disease. Although cases of poisoning from methyl mercury had been known for one hundred years, it was the first case in which mercury poisoning was caused by inhalation or absorption of fish and shellfish contaminated by methyl mercury (Tsubaki and Irukayama, 1977).

Near the Minamata Bay an acetaldehyde plant had been operated by Chisso, the largest manufacturer of this chemical substance in Japan at that time, while also producing chemical fertilizers, industrial chemicals, and synthetic plastics and fibers. Mercury had been used as a catalyst for producing acetaldehyde and vinyl chloride. As mercury began to be regarded as the suspect of causing the Minamata disease, the wastewater from both the acetaldehyde and vinyl chloride plants was first stored in a pool, and later it was processed in a cyclator. While dissolved inorganic mercury compounds were precipitated, methyl mercury in the wastewater was not removed in the cyclator, however, and the effluent containing methyl mercury continued to be discharged into the Minamata Bay. As subsequent examinations revealed that seafood from the Minamata Bay still contained abnormal levels of mercury, the wastewater flow from the acetaldehyde plant was finally altered to form a complete recirculating system in May 1966. In the meantime, another case of patients suffering from the same symptoms was reported in the Agano River basin, Niigata, in July 1965, which subsequently came to be called the second Minamata disease. In May 1968, 12 years after the first discovery of the Minamata disease, the acetaldehyde plant finally ceased its operation. Four months later, the Ministry of Public Health and Welfare made an official statement that the causative agent of the Minamata disease was the methyl mercury compound emitted from the acetaldehyde plant

of Chisso. In March 1971, the vinyl chloride manufacturing process was converted to the ethylene process, in which no mercury was involved.

Mercury had been widely used as a catalyst for synthesizing acetaldehyde by the hydration of acetylene. During the period from 1932 to 1968, 456,300 tonnes of acetaldehyde were produced in the Minamata plant (Iijima, 1990b). Of 1,181.1 tonnes of mercury inputted in total, 204.9 tonnes were consumed, and the loss of mercury discharged in the wastewater was estimated to be 81.3 tonnes. The synthesis of vinyl chloride was made by a process in which acetylene was reacted with hydrogen chloride in the gaseous state, and mercuric chloride adsorbed onto activated carbon, so-called mercury dregs, was used as a catalyst. The total amount of 510,000 tonnes of vinyl chloride was produced in the period from 1941 to 1971. With 178 tonnes of mercury consumed in total, the estimated loss of mercury was 0.2 tonnes, a figure which was much smaller than that for the acetaldehyde manufacture. While it had become clear that the material which caused the Minamata disease was the methyl mercury emitted from the acetaldehyde plant, at that time there was no scientific explanation which explained in a satisfactory manner, qualitatively as well as quantitatively, why methyl mercury, a form of organic mercury, was formed in the plant, where acetaldehyde was synthesized from acetylene with the use of inorganic mercury as a catalyst[57].

Having seen the misery of the Minamata disease, which caused at least 700 patients who had been recognized by the government by the end of 1972, the general public started to have a grave concern about pollution in the environment. The Basic Law for Environmental Pollution Control was enacted in August 1967, establishing environmental quality standards based on the designation of pollutants' target ranges, the liability of polluters, and the responsibilities of the national as well as local governments. It was then followed by other regulations to control mercury emitted to the environment. The chlor-alkali industry, in particular, was using a large amount of mercury for the mercury process in the 1960s and thus invited public attention, although the emissions from the industry did not include any trace of methyl mercury, the organic mercury which caused the Minamata disease. Without any organic substances involved in the relevant chemical reactions, there was no possibility of the formation of organic mercury within chlor-alkali plants. Nevertheless, in June 1968 the

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[57] A book which has been published recently tries to elucidate the scientific mechanism of the formation of methyl mercury in the process of synthesizing acetaldehyde from acetylene with inorganic mercury (Nishimura and Okamura, 2001). According to the authors, methyl mercury was formed at the Minamata plant because the high concentration of chlorine ions in the reactor, caused by the inappropriate management of the process water,

Ministry of International Trade and Industry (MITI)[58] started to investigate mercury uses in chlor-alkali plants, in the presence of a significant degree of uncertainty in the scientific mechanism of the transformation of mercury in the environment[59]. This was the first involvement of the government in issues related to mercury emissions of the chlor-alkali industry. In February 1969, all the waters linked to chlor-alkali plants based on the mercury process became subject to the Law for the Conservation of Water Quality in Public Areas (Japan Soda Industry Association, 1982). At this moment, the emphasis of these measures was basically place on how to reduce, but not necessarily eliminate, mercury emissions into the environment.

Table 4-1 lists chronologically major regulations and measures on mercury emissions, particularly those related to the chlor-alkali industry.

Table 4-1 Chronology of Environmental Regulations on Mercury Emissions from Chlor-Alkali Plants in Japan

Year	Environmental Regulation
June 1968	First government investigation on mercury uses in chlor-alkali plants
February 1969	All mercury chlor-alkali plants subject to the Law for the Conservation of Water Quality in Public Areas
May - June 1973	Newspaper reports on the third and fourth Minamata disease due to mercury pollution from chlor-alkali production processes (proved later to be false)
June 1973	Establishment of the Council for the Promotion of Countermeasures against Mercury Pollution
November 1973	Government mandate for completion of the closed system of mercury by December 1973 and conversion of 2/3 of the mercury process to the diaphragm process by 9/1975 (phase I) and the rest by 3/1978 (phase II)
April 1976	Completion of the first phase of process conversion to the diaphragm process
May 1977	Postponement of the second phase of process conversion
June 1979	Evaluation report on the ion exchange membrane process
September 1979	Government mandate for completion of the second phase of process conversion to the ion exchange membrane process by December 1984
June 1986	Completion of the second phase of process conversion to the ion exchange membrane process and phase-out of the mercury process

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helped to create methyl chloride mercury, which was easy to evaporate, thus easy to leak to the outside of the system.

[58] MITI has been recently reorganized into the Ministry of Economy, Trade, and Industry (METI).

[59] At that time there were some research results which suggested that aquatic micro-organisms could convert inorganic mercury into the methyl mercuric ion and, under certain conditions, also into the water-immiscible, volatile dimethyl mercury (Bouveng, 1972).

Then, in May 1973, a newspaper published an article which suggested that a case of the third Minamata disease was discovered in the Ariake Sea area in Kyushu (*Asahi Shinbun*, 1973a). Just one month later the same newspaper reported a similar incident which happened near Tokuyama Bay in the western part of Japan (*Asahi Shinbun*, 1973b). As both cases were linked to industrial complexes which involved chlor-alkali plants, the public pressure was growing to demand some measures to stop mercury emissions from these plants, although there was no scientific evidence to support these allegations, which proved to be false later. Many fishermen went on demonstrations against mercury-based chlor-alkali plants in coastal areas throughout Japan, and some of the plants were actually forced to halt their operations. The Environmental Agency, which had been established just two years earlier, organized the Health Examination Committee, and conducted medical examinations of inhabitants of nine marine areas, including the Ariake Sea and Tokuyama Bay areas. No case of the Minamata disease or methyl mercury poisoning was found in any area other than Minamata Bay and its neighboring seas (Irukayama, 1977). Nevertheless, the public pressure for immediate actions was so fierce that the Japanese government was prompted to take measures to cut mercury emissions.

On June 12, 1973, in the wake of the controversies triggered by the newspaper reports, the government established the Council for the Promotion of Countermeasures against Mercury Pollution (Countermeasures Council) in the Environmental Agency. It was chaired by the Minister of State for Environment, assisted by the Administrative Vice-Minister and the State Secretary for Environment, and consisted of members from twelve ministries and agencies in the government (Japanese Ministry of International Trade and Industry, 1979). As all relevant ministries and agencies were represented, with only the Ministry of Justice and the Ministry of Posts and Telecommunications absent, the Countermeasures Council could coordinate policies of different government bodies and thus was decisive in making the government's position on the issue of mercury emissions.

At the first meeting held on June 14, 1973, the Countermeasures Council decided that, after the completion of installing the so-called closed system for effluents containing mercury by the end of September 1974, as many mercury plants as possible should be converted to the diaphragm process by the end of September 1975. The chlor-alkali industry association argued that there were many technical as well as economic difficulties in the conversion of the existing mercury plants to the diaphragm process and that its implementation would take a long period of time (Japan Soda Industry Association, 1973a). The statement of the industry

was also handed over to the Minister of the Environmental Agency when the representatives of the industry visited the Agency to discuss the issue (Japan Soda Industry Association, 1973b). The industry's request was not accepted by the Minister, however, and the third meeting of the Countermeasures Council, which was subsequently held on November 1973, agreed on the following concrete schedule for the process conversion program (Council for the Promotion of Countermeasures against Mercury Pollution, 1973):

Two thirds of the existing mercury plants are to be converted to the diaphragm process by September 1975, and the remaining one third by March 1978.

That means that there were only less than two years left for many of the existing mercury plants to conduct the technological conversion from the mercury process to the non-mercury, diaphragm process.

4.2 Conversion of the Mercury Process to the Diaphragm Process

Following the government's decision to convert the existing mercury plants to the diaphragm process, MITI organized the Committee for the Promotion of Process Conversion in the Soda Industry (Conversion Committee) on September 14, 1973, as a private consulting body to the Director-General of MITI's Basic Industries Bureau. As shown in Table 4-2, the members of the Conversion Committee were selected from banks, academics, journalism, and industry, reflecting the relevant issues to be discussed. Along with a subcommittee, three expert groups were established on finance and tax, technology and regulation, and supply and demand coordination to have more detailed and informed discussions on the schedule and criteria for the process conversion program and financial and tax incentives to support it.

Table 4-2 Members of the Committee for the Promotion of Process Conversions in the Soda Industry

President, Japan Development Bank; Member, Central Council for Countermeasures against Public Nuisance	ISHIHARA Amao (Chairman)
Governor, Chiba Prefecture	TOMONO Takeo
President, Industrial Bank of Japan	MASAMUNE Isao
President, Long-Term Credit Bank of Japan	SUGIURA Shunsuke
Professor, University of Tokyo	MUKAIBO Takashi
Professor, Yokohama National University	MATSUNO Takeo
Member, Central Council for Countermeasures against Public Nuisance; Member, Science and Technology Council	KUROKAWA Matake
Editorial Board Member, Asahi Newspaper; Member, Central Council for Countermeasures against Public Nuisance	KISHIDA Junnosuke

Editorial Board Member, Nihon Keizai Newspaper	KAMADA Isao
Chairman, Japan Paper Manufacturers' Association	KANEKO Saichiro
Chairman, Japan Chemical Fibers Association	YASUI Yoshizo
Chairman, Vinyl Chloride Industry Association	SHIMAMURA Michiyasu
Counselor, Japan Soda Industry Association	NINOMIYA Yoshimoto
Vice Chairman, Japan Soda Industry Association; Chairman, Committee for Countermeasures against Mercury	IMAI Hiroshi
Director-General, Basic Industries Bureau	IIZUKA Shiro

Source: Japan Soda Industry Association (1974a).

The Conversion Committee decided on the criteria for the conversion of mercury plants specified as follows (Japanese Ministry of International Trade and Industry, 1973):

1. Plants whose mercury consumption per unit caustic soda is higher than the average of the soda industry are to be completely converted by September 1975.

2. Plants whose mercury consumption per unit caustic soda is lower than the average of the soda industry are to be converted in the following way.

   a. Facilities which will end their lifetime by September 1975 are to be converted partially by September 1975 and completely by March 1978, depending on the conditions of depreciation and mercury management.

   b. Facilities which will not end their lifetime by September 1975 are, in principle, to be converted completely by March 1978.

In this way, the process conversion program was decided to be implemented in two steps: the first phase for two thirds of mercury plants to be converted by September 1975 and the second phase for the remaining one third to be converted by March 1978.

For the implementation of the process conversion program, tax reductions were introduced to support newly converted or expanded production facilities. Table 4-3 shows the new scheme for tax reductions. The special depreciation rate applicable for the first year was one third at the beginning and then was reduced gradually. While the new tax reduction scheme was initially targeted to the diaphragm process, after the fiscal year 1978 this preferential tax treatment became applicable to the ion exchange membrane process, which had been just developed by several innovative companies in the Japanese chlor-alkali industry.

Table 4-3 Tax Reductions for the Process Conversion in the Chlor-Alkali Industry

Fiscal Year[a]	Targeted process	Special depreciation rate[b]	Special tax rate on fixed assets[c]

1973	D	1/3	1/2
1974	D	1/3	1/2
1975	D	1/3	1/2
1976	D	25/100	3/5
1977	D	25/100	3/5
1978	IM	25/100	3/5
1979	IM	25/100	3/5
1980	IM	20/100	3/5
1981	IM	20/100	3/5
1982	IM	18/100	3/5
1983	IM	18/100	3/5
1984	IM	18/100	3/5
1985	IM	16/100	2/3
1986	IM	16/100	2/3

D: Diaphragm process; IM: Ion exchange membrane process
a: A fiscal year starts in April and ends in March next year. Exceptions in the table are April – December in 1984, January – December in 1985, and January – June in 1986.
b: The special depreciation rate was applied for the first year, in addition to the normal depreciation rate.
c: The special tax rate was applied for three years after purchase.
Source: Japan Soda Industry Association (1985).

When the official decision was made on the phase out of the mercury process, it was by far the dominant technology adopted for the chlor-alkali production in Japan, accounting for 95 % of the total capacity as you can see in Table 3-17. In replacing the mercury process, the only alternative technology available at that time was the diaphragm process, a type of process technology which was used for only 5 % of the total production. As the regulatory schedule for process conversions specified that two thirds of the mercury process plants must be converted to the diaphragm process just in two years, there was not sufficient time for companies in the chlor-alkali industry to newly develop by themselves diaphragm-based technologies which could be feasible at the industrial level. Consequently, technologies necessary for the diaphragm process had to be introduced mostly from foreign companies.

The types of technologies for the diaphragm process adopted during the first phase of the process conversion program are shown in Table 4-4. Under the policy schemes, the first diaphragm plant converted from the mercury process started to operate in March 1974, and other conversions followed in the subsequent period up to 1976. Reflecting the most advanced development of the diaphragm process in the U.S. at that time (see Table 3-9), many of the technologies adopted for the diaphragm process were provided by American

suppliers; Diamond Shamrock based in the U.S. accounted for 32 % of the total capacity, Hooker based in the U.S. for 27 %, and PPG based in the U.S. for 26 %. Only 15 % of the total production capacity relied on technologies provided by Japanese companies. While Nippon Soda, Tsurumi Soda, and Showa Denko had previous technical experiences on the diaphragm process, the technology developed by Kureha Chemical Industry was the first to be introduced for commercial purposes in the chlor-alkali industry.

Table 4-4 Technologies for the Diaphragm Process Adopted during the First Phase of the Process Conversion Program

Technology (Company)	Start-up Year	Plant	Capacity (NaOH t/y)
DS (Diamond Shamrock, US)	1974	Asahi Glass, Kita-Kyushu	16,300
	1974	Sumitomo Chemical, Ohita	15,400
	1974	Mitsui Toatsu, Nagoya	59,100
	1975	Ajinomoto, Kawasaki	35,700
	1975	Tokuyama Soda, Tokuyama	190,400
	1975	Mitsui Toatsu, Ohmuta	80,200
	1975	Nihon Vinyl Chloride, Chiba	86,600
	1975	Osaka Soda, Matsuyama	44,400
	1976	Toagosei Chemical, Tokushima	148,500
	1976	Hodogaya Chemical, Kohriyama	24,500
	1976	Nikkei Kako, Kanbara	36,600
	1976	Toyo Soda, Yokkaichi	70,800
	1977	Nankai Chemical, Tosa	15,700
	Total	13 plants	31,216,793 (31.9%)
Hooker (Hooker, US)	1974	Mitsubishi Gas Chemical, Naniwa	12,200
	1974	Kanegafuchi Chemical, Takasago	99,300
	1974	Central Chemical, Kawasaki	61,000
	1974	Sanyo Kokusaku Pulp, Iwakuni	28,000
	1975	Hokkaido Soda, Tomakomai	119,500
	1975	Shin-etsu Chemical, Naoetsu	40,200
	1975	Osaka Soda, Amagasaki	51,100
	1975	Denki Kagaku Kogyo, Ohme	61,000
	1975	Mitsubishi Monsanto, Yokkaichi	56,400
	1975	Tekkosha, Sakata	36,500
	1975	Mitsubishi Chemical, Kurosaki	40,000
	1975	Ryonichi, Mizushima	97,600
	Total	12 plants	702,800 (27.2%)
Glanor (PPG, US)	1975	Asahi Glass, Kashima	160,000
	1975	Toyo Soda, Nanyo	156,200
	1975	Asahi Glass, Chiba	180,000

	1976	Sumitomo Chemical, Kikumoto	174,200
	Total	4 plants	670,400 (26.0%)
BM (Nippon Soda, Japan)	1974	Nippon Soda, Nihongi	25,800
	1975	Chiba Chlorine Chemical, Chiba	111,400
	Total	2 plants	137,200 (5.3%)
TSBM (Tsurumi Soda, Japan)	1974	Tsurumi Soda, Tsurumi	10,500
	1974	Showa Enso, Gushikawa	3,100
	Total	2 plants	13,600 (0.5%)
SD (Showa Denko, Japan)	1975	Showa Denko, Kawasaki	103,100
	1975	Kanto Denka Kogyo, Mizushima	38,200
	Total	2 plants	141,300 (5.5%)
SK (Kureha Chem., Japan)	1976	Kureha Chemical Industry, Nishiki	93,500
	Total	1 plant	93,500 (3.6%)
Total		36 plants	2,583,000

Sources:
DS and Glanor: Chlorine Engineers Corp. (1999b).
Hooker: European Chemical News (1974) (converted from daily capacities).
BM: Calculation based on Japan Soda Industry Association (1982) (converted from monthly capacities).
TSBM: Tsurumi Soda (2001), Nikkei Sangyo Shinbun (1975b), Showa Chemical (2001).
SD: Takeshita (1990), Nikkei Sangyo Shinbun (1975a), Kanto Denka Kogyo (1998).
SK: Shibata, Kokubu, and Okazaki (1977).

As many mercury-based plants were converted to the diaphragm process, however, the serious concern which had been raised previously, that is, the high production cost of the diaphragm process with the output of low-quality caustic soda, materialized in the industry. Many users who had previously purchased caustic soda produced by the mercury process demanded the same level of high quality for caustic soda. For about 25 % of all the applications, caustic soda produced by the diaphragm process was considered not to be suitable, especially for the manufacture of chemical fibers such as rayon (Japan Soda Industry Association, 1982). Since rayon is a thin fiber whose diameter is in the order of micro, i.e. 10^{-6} meters, it can be easily cut when impurities exist in caustic soda (Sakota, 1977). Hence the manufacturing of chemical fibers requires caustic soda which contains as fewer impurities as possible.

Table 4-5 shows the results of an analysis of the quality of caustic soda produced by the mercury and diaphragm processes. While the caustic soda produced by the mercury process was relatively pure, the diaphragm process produced caustic soda which contained more

impurities, notably sodium chloride. Its concentration was 1 %, a level which was much higher than that acceptable for use in the manufacture of chemical fibers.

Table 4-5 Quality of Caustic Soda Produced with the Mercury Process and the Diaphragm Process

	Mercury process[a]	Diaphragm process[b]	Chemical fiber grade[c]	
			No. 1	No. 2
Sodium chloride (NaCl)	0.003	1.0	> 0.07	> 0.40
Sodium carbonate (Na_2CO_3)	0.037	0.07	> 0.3	> 0.4
Silicon dioxide (SiO_2)	0.0035	0.02	> 0.03	> 0.15
Aluminium oxide (Al_2O_3)	0.00044	0.0005	> 0.02	> 0.04
Calcium oxide (CaO)	0.0004	0.003	> 0.005	> 0.008
Iron(III) oxide (Fe_2O_3)	0.00015	0.0009	> 0.003	> 0.005
Sodium sulfate (Na_2SO_4)	0.0026	0.02	-	-

Figures are expressed in percentage.
a: 1975
b: 1974
c: Japan Industrial Standard (JIS) K 1204-1955, K 1205-1955
Sources: Sakota (1977), Industrial Structure Council (1972).

As the demand for the poor-quality caustic soda was low, manufacturers who had already converted their plants to the diaphragm process had difficulties in selling their products to customers. They argued for a level playing-field; that is, they demanded that diaphragm and mercury plant operators deal with, that is, consume and sell, caustic soda produced by the diaphragm and mercury processes in the same proportion by making barter trades with each other. MITI, intending to promote the conversion program smoothly, responded to this claim by issuing an administrative guidance in June 1975. With its instruction, caustic soda producers had to submit their production plans every three months to MITI. MITI, in turn, based on its demand projection for the quarter, revised the production plans and mediated barter trades among the producers between caustic soda produced by the diaphragm process and that produced by the mercury process (Japanese Ministry of International Trade and Industry, 1975b).

Furthermore, the diaphragm process was also at a disadvantage in terms of the energy consumption, which occupies a major part of the chlor-alkali production process. At that time, the energy consumption of the diaphragm process was approximately 3,400 kWh per tonne of caustic soda, which was larger than that of the mercury process, 3,200 kWh per tonne of caustic soda (Japan Soda Industry Association, 1975). This difficulty worsened by the oil crisis which happened during the 1970s. Table 4-6 shows the trends in the electricity prices for average consumers, large consumers, and chlor-alkali producers in Japan since the beginning of the 1970s. The price of electricity used for chlor-alkali production almost tripled after the first phase of the energy crisis, from 3.10 yen/kWh in 1970 to 9.10 yen/kWh in 1977. By the early 1980s, the electricity price for chlor-alkali producers had reached 14.80, a level which is more than four times larger than the price at the beginning of the 1970s.

Table 4-6 Electricity Prices in Japan

Year	Normal Consumer	Large Consumer	Chlor-Alkali Producer
1970	6.35	3.92	3.10
1971	6.52	3.98	3.40
1972	6.57	3.99	3.30
1973	6.76	4.17	4.16
1974	10.62	7.72	7.14
1975	11.61	8.49	7.69
1976	13.20	9.75	8.42
1977	14.51	10.62	9.10
1978	14.02	9.95	8.42
1979	14.69	10.52	9.12
1980	22.47	17.07	14.31
1981	23.14	17.30	14.80
1982	23.44	17.40	14.45
1983	23.53	17.35	14.35
1984	23.53	17.23	13.34
1985	23.71	17.38	13.36
1986	21.93	15.66	11.73

Source: Japan Soda Industry Association (1988).

Heavily dependent on electricity, chlor-alkali producers were particularly hit by the soaring energy cost. As the cost of caustic soda produced at newly constructed diaphragm plants became significantly larger than that at the existing mercury plants, the barter trading system was modified in October 1976 to include financial compensations reflecting the cost difference. In exchanging caustic soda, mercury process operators had to pay their

counterparts using the diaphragm process for the cost difference, which was initially determined to be 5,000 yen per tonne of caustic soda and was changed one year later to 5,500 yen per tonne (Japan Soda Industry Association, 1980a). Table 4-7 gives the figures which show the extent to which caustic soda was exchanged between the operators of the two types of production processes. Until the barter trading system was finally abandoned in September 1980, approximately 6 % of the total caustic soda production was exchanged in average, and more than 3 billion yen was transferred from operators of the mercury process to those of the diaphragm process.

Table 4-7 Exchange of Caustic Soda between the Mercury Process and Diaphragm Process Operators

Period	Quantity exchanged (tonnes)	Exchange/Production (%)	Financial transfer (thousand yen)
1975			
July – September	32,674	4.4	-
October – December	57,167	7.3	-
1976			
January – March	58,165	7.6	-
April – June	60,718	8.5	-
July – September	49,517	6.8	-
October – December	50,240	7.3	251,200
1977			
January – March	48,275	6.8	241,375
April – June	51,791	7.2	258,955
July – September	49,805	6.8	273,927
October – December	46,993	6.6	258,462
1978			
January – March	44,037	6.1	242,203
April – June	45,240	6.6	248,820
July – September	45,335	6.5	249,343
October – December	43,598	6.6	239,789
1979			
January – March	38,731	5.8	213,020
April – June	39,758	5.6	218,669
July – September	41,623	5.1	228,927
October – December	46,005	5.5	253,027
1980			
January – March	42,402	5.0	233,211
April – June	41,576	5.2	228,668
July – September	41,647	5.5	229,059
Total	975,297	6.3	3,868,655

Source: Japan Soda Industry Association (1982).

The first phase of the conversion program was completed in April 1976. By that time, the proportion of the production capacity of the mercury process had dropped to approximately 40 % whereas the share of the diaphragm process had increased significantly from the level of less than 5 % prior to the conversion program. That was achieved half a year behind the schedule, due to the technical as well as economic problems caused by the oil crisis at that time (Japanese Ministry of International Trade and Industry, 1975a). Heavily impacted by the rising energy cost following the oil crisis, the chlor-alkali industry, particularly its members which was still operating mercury-based plants, claimed that they did not have sufficient financial resources to conduct more process conversions and made a request to the Liberal Democratic Party, the party in power at that time, as well as to MITI that the implementation of the second phase of the process conversion program should be postponed (Japan Soda Industry Association, 1979a).

4.3 Interruption of the Process Conversion Schedule and Evaluation of the Ion Exchange Membrane Process

In these circumstances, the fourth meeting of the Countermeasures Council took place in May 1977. MITI explained to the other members that the caustic soda produced by the diaphragm process had a low quality and thus was very difficult to use. And at the same time, it was also mentioned that a newly developed process, the ion exchange membrane process, was in a process of rapid progress and that it was expected to be able to produce high-quality caustic soda. Taking into account the situation of the technological progress of the emerging ion exchange membrane process, the Countermeasures Council made a decision that the implementation of the second phase of the conversion program should be suspended until an appropriate judgment could be made on the feasibility of the ion exchange membrane process at the industrial scale (Council for the Promotion of Countermeasures against Mercury Pollution, 1977)[60].

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[60] It was also decided at the meeting that the safety of the closed system, which had been already installed in the existing mercury plants, would be examined thoroughly by an expert group. Accordingly, the Expert Committee for Examination of the Closed System (Examination Committee) was established in June 1977 as a subcommittee in the Conversion Committee. It was chaired by an academic researcher, MATSUNO Takeo, Professor of Yokohama National University, for independent investigations. The first result of its investigations was published in October 1977, concluding that the closed system installed at mercury plants was functioning properly and that there was no mercury pollution which would pose threat to the health of the local people

Then, an expert group was established to make a technical evaluation of the ion exchange membrane process, with a specified deadline of October 1977. The newly created subcommittee, the Expert Committee for Technical Evaluation of the Ion Exchange Membrane Process, the so-called Evaluation Committee, set out to do its assigned task in June 1977. As Table 4-8 shows, the four members who constituted the Evaluation Committee were all academic researchers of public research institutes. This selection of the experts was a reflection of the government's intention that the committee's technological evaluation should be conducted in a neutral arena, avoiding any intervention of particular industrial or corporate interests.

Table 4-8 Members of the Expert Committee for Technical Evaluation of the Ion Exchange Membrane Process

Position	Name	Expertise
Professor, Kyoto University	YOSHIZAWA Shiro	Electrochemistry
Professor, Yokohama National University	MATSUNO Takeo	Electrochemistry, Environmental Chemistry
Professor, University of Tokyo	TSURUTA Teiji	Polymer Chemistry
Director, Tokyo Industrial Laboratory	ISHISAKA Seiichi	System Engineering

Source: Expert Committee for Technical Evaluation of the Ion Exchange Membrane (1977).

The Evaluation Committee made a thorough examination of technologies which were being developed at that time by chlor-alkali companies, domestic as well as foreign, through documents, interviews, and, in some cases, visits to plant sites. In evaluating the technologies, the committee paid particular attention to the following aspects: performance, including power and steam consumption, caustic soda concentration, electricity density, and product quality; operation and maintenance management; durability and stability of ion exchange membranes; environmental and safety measures; and construction and operational costs. The findings of the Evaluation Committee were published in October 1977 (Expert Committee for Technical Evaluation of the Ion Exchange Membrane Process, 1977). The Committee's technical evaluation of the ion exchange membrane process at that time was as follows:

> While we could consider overall that, as far as the current situation in Japan is concerned, the ion exchange membrane process technology has reached a level appropriate for industrialization, we should be cautious about its evaluation,

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(Expert Committee for Examination of the Closed System, 1977). The conclusion of the first report was reconfirmed by the Examination Committee in June 1979 (Expert Committee for Examination of the Closed System, 1979).

taking into full account the importance of caustic soda and chlorine as basic chemical materials and its impacts on other industries. In order to conclude that this technology is industrially viable, it is indispensable that the durability of various materials, including, among others, ion exchange membranes and electrolytic cells, and the operational performance of plants are well demonstrated. At this moment, however, we have not yet obtained sufficient data on these aspects, and thus it is necessary to continue our observation to obtain more data on the operation of commercial plants for at least two years. If it is confirmed that the current operational performance is maintained throughout the period, we can regard this technology as industrially established.

As regards the development of the ion exchange membranes, they are only produced in a small scale, just meeting the demand. Hence it is also necessary, by the time when the ion exchange membrane process technology reaches the level of industrial viability, that a system for stable supply of ion exchange membranes is established.

While recognizing that several companies had already possessed technologies for the membrane process ready for industrial applications, the Evaluation Committee asked for more data to reach a conclusion with sufficient confidence. Based on the recommendation, the government made a decision to postpone the process conversion program for about two years. In September 1978, almost one year after the publication of the first report, the members of the Evaluation Committee resumed their activities to see the technological progress made during the past year [61]. Basically, they followed the same procedure, evaluating again different types of the membrane process by reviewing reports and documents, undertaking interviews with firms in Japan as well as in foreign countries, and doing fieldwork. It was found that, as several companies actively conducted R&D activities, a considerable progress had been made on the ion exchange membrane process in one year.

In particular, three companies, namely, Asahi Chemical Industry, Asahi Glass, and Tokuyama Soda, were found to be well ahead of other companies in developing their technologies for the ion exchange membrane process. Asahi Chemical Industry's first

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[61] One of the members, ISHISAKA Seiichi, was replaced by SHIROZUKA Tadashi, Professor of Waseda University (applied chemistry), before the publication of the second report (Expert Committee for Technical Evaluation of the Ion Exchange Membrane Process, 1979).

commercial plant and Asahi Glass's demonstration plant had already had experiences of stable operation for several years. Another commercial plant constructed by Asahi Chemical Industry and the first commercial plant of Asahi Glass had been operated reliably since the beginning of their operations, though for shorter periods. Tokuyama Soda had also started to operate commercial plants, and both of them had been running without any serious problems since the replacement of the original ion exchange membranes with those currently in use. These examples of stable and reliable plant operation convinced the members of the Evaluation Committee that the ion exchange membrane process not only eliminated mercury emissions into the environment, but also had surpassed the mercury process in the efficiency of energy consumption while producing caustic soda with the same quality as the mercury process.

With these findings in hand, the Evaluation Committee published its second report in June 1979, making the following judgment (Expert Committee for Technical Evaluation of the Ion Exchange Membrane Process, 1979):

> Taking into account the operating experiences of various plants overall, our Committee considers that the ion exchange membrane process technology in Japan has reached a level which could be regarded as an established industrial technology.

In the following section, we examine in detail how the ion exchange membrane process has been developed by innovative companies in the Japanese chlor-alkali industry.

4.4 Technological Development of the Ion Exchange Membrane Process

4.4.1 Characteristics of the Ion Exchange Membrane Process

We first closely examine the technological characteristics of the ion exchange membrane process by analyzing the chemical reactions involved, as we have done previously for the mercury process and the diaphragm process. The ion exchange membrane process operates in a similar way to the diaphragm process, with basically the same chemical reactions which does not involve any use of mercury throughout the whole production process (Curlin, Bommaraju, and Hansson, 1991; Schmittinger, 2000). Figure 4-1 gives a simplified flow diagram of the ion exchange membrane process.

In the ion exchange membrane process, a higher degree of brine quality is required than the mercury process because ion exchange membranes are extremely sensitive to brine impurities such as calcium and magnesium ions (Japan Soda Industry Association, 1998b). When impurities precipitate, ion exchange membranes are physically disrupted, which will lead to a substantial reduction in the current efficiency[62]. The circulating brine must be rigorously purified to avoid any buildup of these substances to undesirable levels. While the primary purification step, which consists of precipitation and filtration, produces brine satisfactory for both the mercury process and the diaphragm process, it is not sufficient to meet the extremely high level of brine purity required for the ion exchange membrane process makes. Thus, following the primary purification by the precipitation-filtration step, the brine goes through an additional step for fine purification, as the life expectancy of the expensive ion exchange membrane also depends on the purity of the brine.

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[62] The current efficiency of an electrolytic process is the ratio of the amount of material produced to the theoretically expected quantities. Inefficiencies arise from secondary reactions occurring at the anode and cathode and in the bulk.
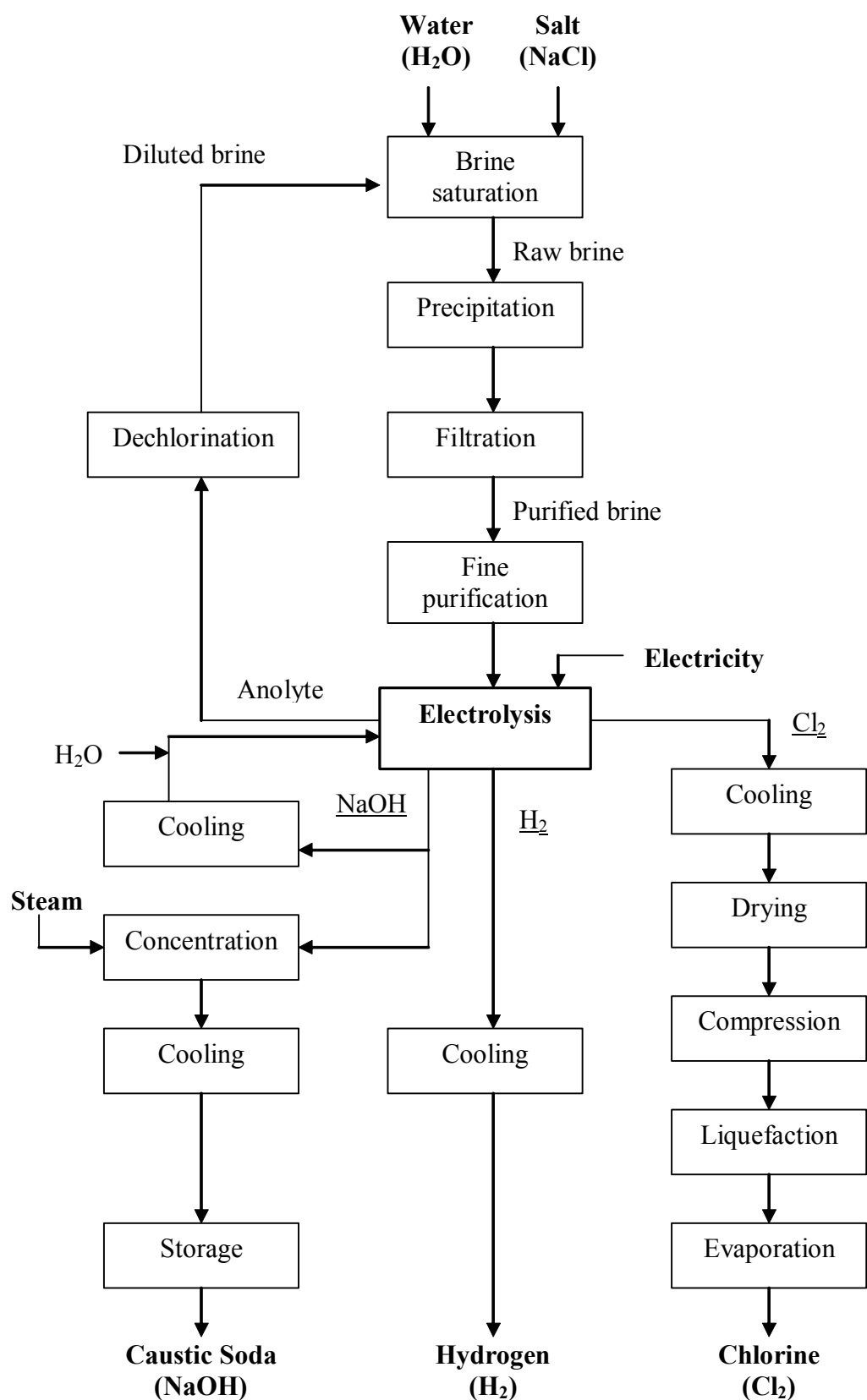
Figure 4-1 Flow Diagram of the Ion Exchange Membrane Process

Based on Curlin, Bommaraju, and Hansson (1991).

The purified brine is then fed into the electrolyzer, which consists of cell, electrodes, that is, anode and cathode, and ion exchange membrane. The anode and cathode are separated by a cation-permeable ion exchange membrane, as is shown in Figure 4-2. Saturated brine (NaCl) is first fed into the anode compartment. Chlorine ions (Cl^-) are attracted to the anode to form chlorine (Cl_2):

$$2Cl^- \rightarrow \underline{Cl_2} + 2e^-,$$
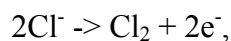
whereas sodium ions (Na^+) migrate through the ion exchange membrane into the cathode compartment. Depleted brine is discharged from the cell and, as in the mercury process, is dechlorinated and recirculated. While hydraulic pressure prevents the reverse flow of hydroxide ions (OH^-) physically through the porous diaphragm in the case of the diaphragm process, the ion exchange membrane allows only sodium ions to pass through in the direction from the anode to the cathode and thus inhibits the reverse flow of hydroxide ions electrochemically.

Water (H_2O) is electrolyzed in the cathode compartment. Hydrogen (H_2) is evolved at the cathode by combining hydrogen ions (H^+):

$$2H^+ + 2e^- \rightarrow \underline{H_2}.$$
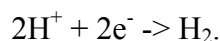
Hydroxide ions, together with the permeating sodium ions, form sodium hydroxide (NaOH), that is, caustic soda:

$$Na^+ + OH^- \rightarrow \underline{NaOH}.$$
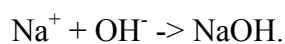
Strong caustic of about 33 % is produced either by controlling the water addition rate directly to the catholyte or by recirculating caustic to which water has been added. To produce 50% caustic soda, the caustic solution coming out of the cell needs to be concentrated by evaporation. Caustic soda solution obtained by the ion exchange membrane process contains few impurities, owing to the selective permeability of the ion exchange membrane, and the chloride content in it is as low as that from the mercury process. Since the catholyte is a strong caustic, however, there is some inevitable back-migration of hydroxide ions into the anolyte, which results in a loss of current efficiency.
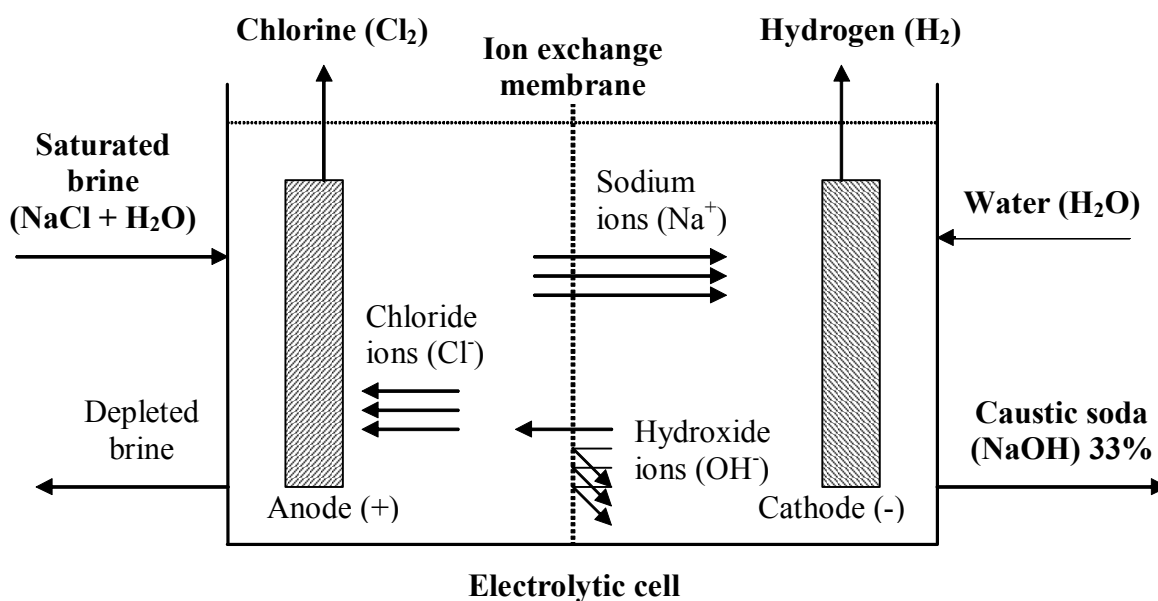
Figure 4-2 Ion Exchange Membrane Electrolyzer

Based on Curlin, Bommaraju, and Hansson (1991).

As you can see in examining the chemical reactions involved in the ion exchange membrane process, the process's most important advantages is that it poses no serious environmental problems. In contrast to the mercury process, there are no chemical reactions involving mercury (Hg) within the production process (see Figure 3-3 and Figure 3-4). Hence the ion exchange membrane process avoids the serious environmental concern regarding the mercury process while achieving the same level of high purity of caustic produced by the mercury process. Without any pollutant included in the manufacturing process from the very outset, the ion exchange membrane process is a prime example of the clean technology as defined in Chapter 2. This is in sharp contrast to the end-of-pipe technology, which is aimed at reducing emissions of pollutant, mercury for example, at the end of the production process facilities.

As you would expect, the component which is critical to the well functioning of the ion exchange membrane process is the ion exchange membrane. While the ion exchange membrane determines the electrolytic cell performance, including the current efficiency and cell voltage, and hence energy consumption, it also needs to have a sufficient strength to withstand exposition to chlorine on one side and strong caustic on the other in the electrolytic cell. Although the idea of the ion exchange membrane process for the production of chlorine

and caustic soda had been known for many years, earlier work failed as a result of non-availability of suitable ion exchange membranes which could resist the very demanding conditions within the chlor-alkali cell. A significant amount of research and development efforts had been devoted to invent the ion exchange membranes suitable for the production of chlorine and caustic soda.

Basically, ion exchange means the exchange of ions of the same charge between a solution, which is normally aqueous, and a solid in contact with it (Dorfner, 1990). The process occurs widely in nature, particularly in the absorption and retention of water-soluble fertilizers by soils. For example, when a potassium salt is dissolved in water and applied to soil, potassium ions (K^+) are absorbed by the soil and sodium ions (Na^+) and calcium ions (Ca^{2+}) are released from it. In this case, the soil is acting as an ion exchanger. Synthetic ion exchange resins consist of various copolymers with a cross-linked three dimensional structure to which ionic groups have been attached. An anionic resin has negative ions built into its structure and hence exchanges positive ions whereas a cationic resin has positive ions built in and exchanges negative ions. The ion exchange membrane is an ion exchange body in membrane form and thus provides special functional characteristics which cannot be obtained with ion exchange resins.

A report on ion exchange resins was published for the first time in 1935 by researchers in the United Kingdom, and the first industrial production of ion exchange resins stared in 1938 at the Wolfen plant of IG Farben in Germany (Shimizu, 1992). In the United States, Resinous Products and Chemical started its industrial production of ion exchange resins in 1940. Some experimental work on ion exchange membranes was done in the 1930s and 1940s, but it was not yet possible to obtain ion exchange membranes to be applicable for industrial purposes. In 1950, Juda and McRae reported the first successful development of ion exchange membranes which had electrical resistance combined with adequate mechanical strength for use on the industrial scale (Juda and McRae, 1950). With this report of the fabrication of membranes from ion exchange bodies of synthetic resin, a period of technological progress of ion exchange membranes started in the United States, Western Europe, and Japan. Research efforts were devoted for the development and utilization of ion exchange membranes composed of hydrocarbon polymers and their use for electrodialysis, a method of separating water containing a salt into pure water and more concentrated solution.

In the United States and Western Europe, research activities were directed toward water desalination. The companies and organizations which sought for the production and

utilization of ion exchange membranes for that purpose included Ionics in the U.S., Permutit in the U.K., and T.N.O., the Dutch Organization for Applied Scientific Research (Kawate, Tsuzura, and Shimizu, 1990). The Kennedy administration of the U.S. lent its support to water conversion projects in its space programs, and research and development activities were pursued vigorously with financial assistance from the Office of Saline Water. Since electrodialysis inherently involves concentration, the problem of scale formation also impeded progress at early stages in water desalination applications. This problem was solved later by a technology developed by Ionics, leading to the widespread use of ion exchange membranes for water desalination. American Machine and Foundry and General Electric also manufactured ion exchange membranes in the early 1960s, when they were cooperating with the National Aeronautic and Space Agency (NASA) for developing fuel cells with ion exchange membranes as barriers (McRae, 1974).

The possibility of using the ion exchange membrane for chlor-alkali production had been considered since a relatively early stage in the history of its development. A number of companies, such as Hooker cooperating with Rohm and Haas, and Ionics with Diamond Alkali, worked for developing the ion exchange membrane process for the chlor-alkali production in the 1950s and 1960s (Currey and Ahern, 1974). Technologies developed in these periods, however, were never put into commercial use, primarily because the available ion exchange membranes, which were mostly based on hydrocarbons, did not have either sufficient chemical stability or economic viability. Since the chemical structure of the plastic materials was not inert to chlorine, hypochlorite, and caustic, the ion exchange membrane was eroded or corroded after a relatively short period of use (see Figure 4-2). Its degradation proceeded to the extent that it had to be replaced with a new one. The second problem was the performance of the ion exchange membrane. While the ion exchange membrane was the key to the cell's performance with regard to voltage and current efficiency, good voltages could be achieved only at the expense of low current efficiencies and visa versa. The marginal cell power performance coupled with the membrane replacement problem was never fully resolved initially, discouraging chlor-alkali producers to make further development efforts on the ion exchange membrane process until the 1970s.

These long-standing problems started to be solved by the advent of the perfluorinated ion exchange membrane, Nafion. Prior to the development of Nafion by Du Pont, the Plastic Development Group of the company had already discovered Teflon, a form of tetrafluoroethylene (TFE) polymer (Edwards, 1979). Looking for uses of this material, the

group started to do research on a new type of monomer with which to co-polymerize TFE and succeeded in establishing a general method for synthesizing perfluorovinylether. The co-polymerization of TFE and perfluorovinylether produced XR resins, a precursor to other useful types of polymer invented later. Then, the Nafion membrane was invented at the company's experimental station in 1962 (Grot, 1986). This membrane possessed the heat and chemical resistance necessary for use in such a harsh environment as in chlor-alkali electrolyzers and, with functional groups of sulfonic acid, also provided low electric resistance, although it exhibited low current efficiency. It was actually demonstrated in 1964 that these perfluorinated polymers in a film form could be used as a separator in chlor-alkali cells (Brooks, 1988). Together with early applications of them for fuel cells, that led to a broader recognition of the potential for these materials within the chlor-alkali industry.

Nevertheless, substantial technological progress had to be made in the following years in order to achieve commercial applications of the membrane. While the perfluorinated films had the desirable electrical and chemical properties, it was necessary to supplement the physical properties with appropriate mechanical strength and handling characteristics to be used in commercial chlor-alkali electrolytic cells. And, as the ion rejection properties of the membranes had resulted in current efficiencies less than 90 %, one of the most difficult problems to be solved was how to prevent the diffusion of hydroxyl ions (OH^-) at a high concentration of caustic soda (see Figure 4-2). On this aspect, several Japanese companies later succeeded in making innovations and removed the obstacles along the way toward the industrial application of the ion exchange membrane for use in chlor-alkali production. In the subsequent sections, we will examine in detail how the Japanese companies conducted their innovative activities for the development of the ion exchange membrane process in the chlor-alkali industry.

4.4.2 Patents on Technologies for Chlor-Alkali Production

To investigate the extent of innovative activities conducted by the Japanese firms, we analyzed data on patent applications on the ion exchange membrane process, along with those on the mercury process and the diaphragm process. Figure 4-3 shows the trends in successful applications for Japanese patents by Japanese firms from the late 1960s to the late 1980s. (Detailed data are given in Table 4-23 in Appendix at the end of this chapter). Patent data on technologies related to the mercury process were obtained from the data assembled by the industry association (Japan Soda Industry Association, 1982). The data covers patents granted

up to the end of the 1970s. Patents on technologies related to the diaphragm process and the ion exchange membrane process were selected by using the data set constructed by the industry association and shared by its member companies (Japan Soda Industry Association, 1976, 1977, 1978a, 1978b, 1979b, 1991a, 1991b, 1992a, 1992b). The data set contains both granted patents and unexamined patent applications which were published in the period until 1988.

We picked up only patent applications which were successfully granted, and those selected patents are classified into three processes, that is, the mercury process, the diaphragm process, and the ion exchange membrane process. They are arranged by the year of application, rather than by the year of publication. As it normally takes 18 months before patent applications are published, that is expected to make it possible for us to examine when innovations were actually made. In the case of patents on the mercury process, information on the date of patent application is not included in the data. As it took at least two years for patents to be granted after their application, we here assumed a two-year lag between patent application and granting.
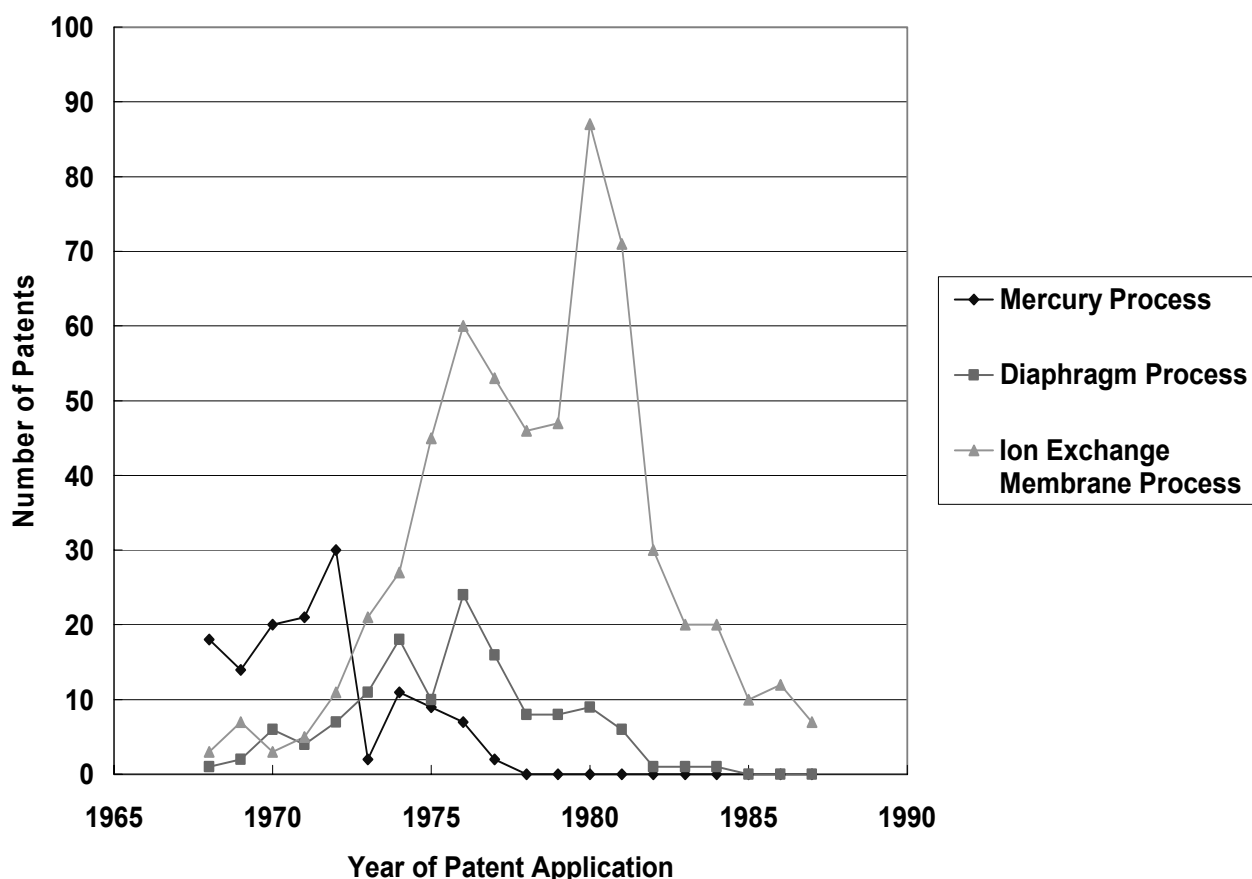
Figure 4-3 Japanese Patents Successfully Applied for by Japan Companies on the Mercury, Diaphragm, and Ion Exchange Membrane Processes

As you can see in Figure 4-3, most of the patents granted in the late 1960s were related to the mercury process. The number of successful patents on the mercury process rose at the beginning of the 1970s, as the general public's concern on mercury pollution increased. It then decreased subsequently, coinciding with the government decision that the mercury-based plants in the Japanese chlor-alkali industry were to be phased out rather immediately. On the other hand, patents successfully applied on technologies related to the diaphragm process were few in the later 1960s and the early 1970s. They increased to some extent in the middle of the 1970s, as patent applications on the mercury process declined. Then, successful patent applications on the diaphragm process started to drop in the late 1970s, and it had almost stopped by the middle of the 1980s.

Regarding the ion exchange membrane process, although several patent applications were already seen in the late 1960s, most of the patents granted were on ion exchange

membranes based on hydrocarbon polymers (e.g. Japanese Patent Publication No. 47-40860, No. 49-28351). As salt had been traditionally produced at salt fields by using the solar power, this type of ion exchange membranes was developed for the purpose of replacing solar evaporation as the method of producing salt from sea water. Hydrocarbon-based ion exchange membranes, however, could not maintain its chemical stability in a strong alkaline environment, and the application of ion exchange membranes for use in chlor-alkali electrolytic cells had been very limited. In the early 1970s, at the time of the government's decision to phase out the mercury process in Japan, applications for patents on ion exchange membranes started to rise rapidly. After a patent application was filed on a new type of ion exchange membranes based on fluorocarbon polymers (Japanese Patent Publication No. 52-13228), on which there had been only one patent application before (Japanese Patent Publication No. 36-20742), other patent applications continued for this type of ion exchange membranes (Japanese Patent Publication No. 57-3699, No. 54-20960). Then successful patent applications on the ion exchange membrane process increased rapidly in the middle of the 1970s and remained large in the 1980s, while there were few patent applications of the mercury process and the diaphragm process in the 1980s.

In Section 3.3, we identified the Japanese firms which were innovative on the mercury process, namely, Mitsui Engineering and Shipbuilding (MES) [63], Osaka Soda, Kureha Chemical Industry, Asahi Glass, Toyo Soda, Tokuyama Soda, and Asahi Chemical Industry, and those companies which were innovative on the diaphragm process, namely, Nippon Soda, Tsurumi Soda, and Showa Denko (see Table 3-8, Table 3-9, and Table 3-18). We examine how these companies, which had strong expertise on the technologies for chlor-alkali production in the past, pursued their innovative activities on the production processes without the use of mercury, when they faced the government's decision to abolish the mercury process in the early 1970s.

We first look at the patenting activities of these companies for clean technologies for chlor-alkali production, that is, the diaphragm process and the ion exchange membrane process. Table 4-9 and Table 4-10 show the trends on Japanese patents successfully applied by these innovative companies, that is, Asahi Chemical Industry, Asahi Glass, Tokuyama

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[63] Mitsui Engineering and Shipbuilding established an engineering company, Chlorine Engineers Corp. (CEC), with Mitsui in 1973 (Chlorine Engineers Corp., 1998). Since then, the new company has provided technologies and related services for the replacement of chlor-alkali plants based on the mercury process.

Soda, and CEC, on technologies related to the diaphragm process and those related to the ion exchange membrane process, respectively.

Table 4-9 Japanese Patents Successfully Applied by Japanese Companies on the Diaphragm Process and the Ion Exchange Membrane Process (I)

Year[a]	Asahi Chemical		Asahi Glass		Tokuyama Soda		CEC[b]	
	D	IM	D	IM	D	IM	D	IM
1968	0	0	0	1	0	0	0	0
1969	0	3	0	1	0	3	0	0
1970	1	2	0	1	1	0	0	0
1971	0	0	0	0	0	2	0	0
1972	4	0	0	0	1	8	0	0
1973	0	2	0	0	3	13	0	0
1974	1	8	0	1	2	4	0	0
1975	1	5	2	13	1	14	1	0
1976	1	6	3	12	8	20	0	9
1977	2	6	2	10	2	23	2	6
1978	0	6	2	6	1	20	2	6
1979	0	10	0	15	0	7	3	9
1980	0	15	3	51	1	2	0	11
1981	1	2	0	30	0	17	1	13
1982	0	1	0	4	0	5	0	9
1983	0	1	0	2	0	1	0	18
1984	0	0	0	7	0	3	1	4
1985	0	1	0	4	0	1	0	1
1986	0	0	0	6	0	5	0	1
1987	0	2	0	5	0	0	0	0
Total	88	560	96	1352	160	1184	0	0

a: Year of patent applications.
b: Data of CEC includes that of Toyo Soda.

Table 4-10 Japanese Patents Successfully Applied by Japanese Companies on the Diaphragm Process and the Ion Exchange Membrane Process (II)

Year[a]	Kureha Chemical		Osaka Soda		Nippon Soda		Tsurumi Soda		Showa Denko	
	D	IM	D	IM	D	IM	D	IM	D	IM
1968	0	0	0	0	0	0	0	0	1	0
1969	0	0	0	0	0	0	0	0	0	0
1970	0	0	0	0	2	0	0	0	1	0
1971	0	0	0	0	1	0	0	0	1	0
1972	1	0	0	0	1	0	0	0	0	0
1973	2	0	2	0	2	0	0	0	0	0
1974	8	7	2	0	0	0	1	0	0	0

1975	3	9	1	2	1	0	0	0	0	0
1976	1	0	0	0	1	0	0	0	0	1
1977	1	1	2	2	1	0	0	0	1	0
1978	0	3	0	0	0	0	0	0	2	0
1979	0	0	1	0	1	0	0	0	1	0
1980	0	0	2	0	0	0	0	0	0	4
1981	0	0	1	0	0	0	0	0	1	2
1982	0	0	1	0	0	0	0	0	0	0
1983	0	0	0	1	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	3
1985	0	0	0	1	0	0	0	0	0	1
1986	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	2	0	12	12

a: Year of patent applications.

These tables suggest that Asahi Chemical Industry, Asahi Glass, and Tokuyama Soda had been doing research on technologies related to ion exchange membranes since the late 1960s, although the level of successful patent applications was low. Detailed analysis of the patent data shows that these ion exchange membranes mostly belonged to the hydrocarbon type, which was basically intended for use in the salt production process. Then, in the early 1970s, the three companies started to be actively engaged in applying much more for patents on the ion exchange membrane process for chlor-alkali production. A little later, Chemical Engineers Corp. (CEC), cooperating with Toyo Soda, followed them in the middle of the 1970s. These intensive R&D activities later led to their success in developing their own technologies for the ion exchange membrane process and subsequently provided these technologies to other chlor-alkali producers.

On the other hand, Kureha Chemical Industry and Osaka Soda, which had also been innovative companies on the mercury process in the past, did not have any successful patent applications on the ion exchange membrane process until the beginning of the 1970s. While they were granted patents for their technologies related to the diaphragm process in the 1970s, their successful patent applications for the ion exchange membrane process technologies remained relatively few in the 1970s and the 1980s, compared with Asahi Chemical Industry, Asahi Glass, and Tokuyama Soda. Similarly, the three companies which had previously developed their own technologies for the diaphragm process, namely, Nippon Soda, Showa Denko, and Tsurumi Soda, successfully applied for patents on the diaphragm process in the

1970s. Their patent applications on the ion exchange membrane process, however, were few, and were not comparable to those made by Asahi Chemical Industry, Asahi Glass, or Tokuyama Soda.

4.4.3 Technological Developments of the Ion Exchange Membrane Process by Innovative Companies in Japan

As we have seen in the preceding section, Asahi Chemical Industry, Asahi Glass, Tokuyama Soda, and CEC were actively engaged in R&D activities on the ion exchange membrane process. In the present section, we examine in detail how these companies conducted R&D activities for chlor-alkali production and subsequently succeeded in developing their own technologies for the ion exchange membrane process.

Asahi Chemical Industry

Among the Japanese firms which were innovative on chlor-alkali production technologies, Asahi Chemical Industry[64] was the first to reach the industrial stage of the ion exchange membrane process. Since 1950, the company had already working on an R&D program on ion exchange membranes based on hydrocarbon to be used for various types of separating operation in chemical processes. In 1961, after ten years of R&D activities on ion exchange membranes, the first plant started to operate at Kawasaki for the manufacture of its ion exchange membranes, Aciplex. At the same time, the company began the commercial production of salt by electrodialysis with these membranes at Onahama. The plant, with a capacity of 50,000 tonnes per year, which was expanded later to 190,000 tonnes per year, represented the first commercial application of ion exchange membranes in the world. This eventually led to increasing the range of applications of ion exchange membranes in other industrial areas, including the desalination of brine by electrodialysis and the electroreduction of uranium. In 1971 Asahi Chemical succeeded in commercializing the synthesis of adiponitrile, an intermediate to nylon 6/6, at the Nobeoka plant (25,000 tonnes/year) through the electrolytic dimerization of acrylonitrile by using ion exchange membranes. The electrolytic cells adopted in this process turned out later to be the prototype of electrolyzers

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[64] This section is based on the information obtained through the author's interview with Mr. Hiroshi Oh-hama, Mr. Masao Hamada, and Mr. Mitsuo Yoshida of Asahi Chemical Industry (Oh-hama, Hamada, and Yoshida, 1998).

for the chlor-alkali production. This development helped the company to recognize the ion exchange membrane as a promising technology in the future.

These previous experiences of working on ion exchange membranes have functioned as the basis for the subsequent technological development of the ion exchange membrane process for chlor-alkali production. In 1967 Asahi Chemical started R&D activities on the ion exchange membrane process of brine electrolysis for chlor-alkali production, with bench-scale facilities constructed at the Nobeoka site. Engineers found that the knowledge and expertise gained through developing other electrochemical processes in the past, including the manufacture of salt, adiponitrile, and other materials, were often useful in dealing with practical problems in this development work. Although initial research efforts were directed toward the development of a three-compartment method using hydrocarbon-based ion exchange membranes, they were later concentrated on the development of a two-compartment method using ion exchange membranes of the perfluorosulfonic acid type.

In May 1973 a pilot plant started to operate at an annual capacity of 4,000 tonnes, utilizing Nafion membranes, the only type of ion exchange membranes based on perfluorosulfonic acid which were available for large-scale applications at that time. The operation of the plant generated some data, which suggested that, as a production process for high-quality caustic soda, chlorine and hydrogen, the ion exchange membrane process would surpass the diaphragm process and become comparable to the mercury process. Intensive discussions within the company were followed by the formation of a large organization, together with a basic strategy for the ion exchange membrane technology. It was almost at the same time that the newspapers reported the case of the third Minamata disease, leading to the government's decision to phase out all the mercury processes used for the chlor-alkali production.

The company's chlor-alkali plant in Nobeoka was originally built in 1933 to supply caustic soda and chlorine for the manufacturing of other products, notably, rayon at the production site. The plant was based on the mercury process, and its production capacity had grown to approximately 100,000 tons of caustic soda per year by the time that the official process conversion program was mandated. Initially, it was planned that the mercury plant would be converted to the diaphragm process with separators made of asbestos. However, since the diaphragm process was found to produce caustic soda which contained various impurities, including, among others, 1 % of salt, it was not an appropriate process for providing caustic soda to be used in the production of rayon, which was one of the company's

main products at that time. The necessity of high-quality caustic soda required a change in the original conversion plan, and in 1974 the company made a decision to adopt the ion exchange membrane process for the plant, although that technology was still in its infancy and was not yet established for industrial applications. With this decision, Asahi Chemical was exempted from the mandate for immediate conversion of the mercury process to the diaphragm process and was allowed some time for technological development of the ion exchange membrane process.

At that time, the perfluorosulfonic acid membrane Nafion, which was developed in the 1960s, was the only type of ion exchange membranes applicable to the chlor-alkali cell because it did not contain any C-H bond. However, ion exchange membranes having sulfonic acid exchange groups did not have high current efficiency in strong concentrations of caustic soda due to the counter migration of OH^- ions from catholyte to anolyte. By the time when the decision was made to convert the mercury plant, the company, with the idea that a higher current efficiency could be achieved if the ion exchange membrane contains perfluorocarboxylic acid functional groups, had initiated R&D on this type of ion exchange membranes.

In 1975, with an annual production capacity of 40,000 tonnes, a new plant with the use of ion exchange membranes came on stream at the Nobeoka site. It was the first commercial-scale plant relying on the ion exchange membrane process in the world. Since the performance of the company's own ion exchange membranes was not yet sufficient for industrial applications, the Nafion membranes were adopted for the plant at the beginning. The electric power consumption of the new process was 3,520 kWh/t NaOH, whereas that of the mercury process was approximately 3,200 kWh/t NaOH. In addition, since the concentration of the caustic soda was low, steam was necessary to increase it to the commercial level of 50 %, raising the total energy consumption to 3,925 kWh/t NaOH. This relatively low performance, coupled with the low current efficiency of 80 %, prompted the company to focus its research efforts to improve the quality of ion exchange membranes.

A result of the intensive R&D was the invention of ion exchange membranes based on perfluorocarboxylic acid. The production of this type of ion exchange membranes was made possible by chemically modifying one side of sulfonic acid membranes to obtain a region of carboxylic acid groups. Contributing to achieving a higher current efficiency of more than 95% without increasing the electrical resistance, this development proved to be one of the technological breakthroughs in establishing the ion exchange membrane process as an

industrially viable technology for chlor-alkali production. The Nafion membranes based on perfluorosulfonic acid which were adopted at the beginning of the plant operation were all replaced by the newly developed membranes in 1976. As a result, the electric power consumption was reduced to 2,700 kWh/t NaOH. The initial production capacity of the Nobeoka plant was doubled to 80,000 tons in August 1977 and was further increased to 120,000 tons in March 1982, when the last of the mercury electrolyzers was shut down at the Nobeoka site.

Table 4-11 gives the chronology of technological developments related to the ion exchange membrane process at Asahi Chemical Industry.

Table 4-11 Chronology of Technological Developments Related to the Ion Exchange Membrane Process at Asahi Chemical Industry

Year	Technological Development
1967	Start of R&D on the ion exchange membrane process of brine electrolysis for chlor-alkali production with bench-scale facilities
1973	Pilot plant for brine electrolysis with Nafion membranes based on fluorosulfonic acid
1974	Decision to convert the mercury process at the Nobeoka site to the ion exchange membrane process Start of R&D on ion exchange membranes based on fluorocarbonic acid
1975	First commercial chlor-alkali plant with Nafion membranes at the Nobeoka site Bench-scale facilities for the production of ion exchange membranes based on fluorocarbonic acid
1976	Replacement of Nafion membranes by Asahi Chemical's membranes First license of Asahi Chemical's ion exchange membrane process to an outside firm
1977	Expansion of the ion exchange membrane process at the Nobeoka site
1982	Expansion of the ion exchange membrane process at the Nobeoka site, eliminating the mercury process

Innovative efforts were conducted intensively for the development of the ion exchange membrane process. Figure 4-4 gives the trends in the R&D expenditures and personnel which Asahi Chemical Industry devoted for innovation on the ion exchange membrane process. The absolute figures of the expenditures as well as personnel in 1975 are normalized to 100.
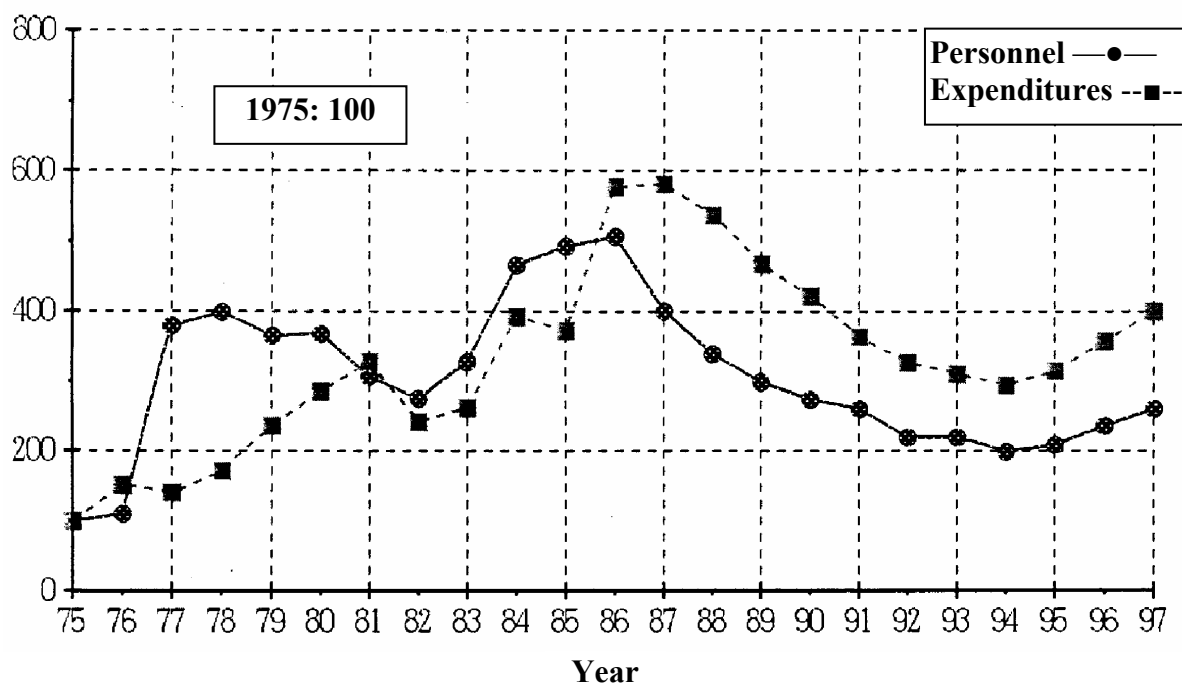
Figure 4-4 R&D Expenditures and Personnel for the Ion Exchange Membrane Process at Asahi Chemical Industry

Source: Asahi Chemical Industry.

In the period from 1973 to 1997, R&D expenditures amounted to 13 billion yen at the ion exchange membrane process division and to three billion yen at the headquarters, with roughly one half spent on personnel and the other half on actual research activities. During this period the annual R&D expenditures fluctuated between 400 million yen and one billion yen. In the first five years three billion yen was spent on R&D by the corporate headquarters. As the headquarters is normally responsible for conducting R&D projects whose outcomes are perceived to be highly uncertain, that suggests that the development of the ion exchange membrane process for chlor-alkali production was regarded by the company as a risky project. Following the initial period in which R&D activities were conducted at the corporate as well as the division levels in parallel, the main responsibility for the project was shifted to the ion exchange membrane process division. The number of the personnel involved in this technological development varied from the minimum of 50 to the maximum of 250. The R&D expenditures and personnel, with small declines at the beginning of the 1980s, continued to increase until the middle of the 1980s, when the government's process conversion program was completed, and then decreased steadily. Recently they have started to rise again, as the company, having finished providing its ion exchange membrane process technology to other

155

chlor-alkali producers based in Japan, is now trying to increase the business of supplying its technology to chlor-alkali producers in other parts of the world.

The effects of the rapid increase in R&D activities in the middle of the 1970s can be seen in some measures of innovation outputs. Table 4-9 shows the trends in successful patent applications by Asahi Chemical Industry on technologies related to the ion exchange membrane process. A small number of patents were applied on ion exchange membranes in the late 1960s, as the company was engaged in producing as well as using ion exchange membranes for salt production. These membranes were based on hydrocarbons, however, and were not suitable for use in chlor-alkali production. In the early 1970s, immediately after the government's decision on the phase out of the mercury process, patent applications on the ion exchange membrane process began to pick up quickly. They had a peak at the beginning of the 1980s and were then followed by a rather rapid decrease. In this period, there were several patents granted on technologies which were crucial for the successful application of the ion exchange membrane process for chlor-alkali production. Among notable examples were the invention of a bumpy surface on the ion exchange membrane and the invention of carbonate membranes with three layers.

Having developed its technology for the ion exchange membrane process and used it at its own chlor-alkali production plant, Asahi Chemical Industry started to supply it to outside companies. Chlor-alkali plants to which Asahi Chemical Industry provided its technology for the ion exchange membrane process are listed in Table 4-27 in the appendix to the present chapter. Encouraged by the government's decision on the phase-out of the mercury process in Japan in 1973, the company's ion exchange membrane process was adopted by other chlor-alkali producers in Japan. The first process which was installed in plants outside the company was for Denki Kagaku Kogyo at Ohme, Tokyo, for a 60,000 tonne/year plant which started operation in 1976. At that time the potential performance of the ion exchange membrane process was not yet fully realized. While the Nafion ion exchange membranes were initially adopted for the plant, they were subsequently replaced with the ion exchange membranes developed by Asahi Chemical Industry in 1978. The completion and startup of a chlor-alkali plant in 1982 at Akzo Zout Chemie (currently Akzo Nobel) in the Netherlands was based on the technology provided by Asahi Chemical and was the first large-scale ion exchange membrane process adopted in Western Europe. The total capacity of the chlor-alkali plants based on the ion exchange membrane technology of Asahi Chemical Industry is currently about 4.8 million tonnes out of about 16.7 million tonnes all over the world. The company is

also supplying its ion exchange membranes to other companies and has so far provided about 6 million tonnes of them in the world.

Asahi Glass

Asahi Glass[65] was established in 1907 as the first company to begin the production of sheet glass in Japan. The chemical division started operations in 1917 with the production of soda ash, which was used for its own manufacturing of sheet glass. Subsequently, the company expanded its business activities to include various alkalis and chlorine derivatives. In 1963 the company moved into the field of fluorine chemistry with the production of chlorofluoromethane refrigerants, solvents, and urethane-forming agents. This was followed by the introduction of a series of new products, including an ethylene-TFE copolymer and a fluorinated rubber.

In the meantime, the company started R&D activities in 1952 on ion exchange membranes for desalination and concentration of sea water as well as on electrodialytic cell technology. In 1960 Asahi Glass began to produce its ion exchange membrane, Selemion, at the industrial level for the first time in Japan, and subsequently the company's plant for salt production utilizing ion exchange membranes started to operate. In 1964 the company started to produce chlorine and caustic soda by brine electrolysis, changed from the traditional chemical processes. Hence the company had technical experiences on fluorine chemistry and sea water dialysis with ion exchange membranes and chlor-alkali production, prior to developing its own technology for the ion exchange membrane process of brine electrolysis.

In May 1973, amid the widespread public concern over mercury pollution triggered by the newspaper articles, the company started to conduct R&D activities aimed at developing a new process using ion exchange membranes for the chlor-alkali production. A project team was established at the central research center, along with the chemical division and its R&D department. The deadline of September 1975, which was initially set by the government for the conversion of the mercury process, however, allowed too short a time for sufficient technological development of the ion exchange membrane process for industrial applications, and consequently Asahi Glass introduced the diaphragm process from Diamond Shamrock to its Kitakyushu plant in 1974 and from PPG to its Kashima plant in 1975 (see Table 4-4).

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[65] This section is based on the information obtained through the author's interview with Mr. Kimihiko Sato of Asahi Glass (Sato, 1998). The company has no organizational or financial relationship with Asahi Chemical Industry. Asahi literally means the rising sun and is used for many corporate names in Japan.

Then, in 1975, the company succeeded in developing the perfluorocarboxylate membrane, Flemion, which made it possible to produce strong caustic solution with high current efficiency. A pilot plant with a production capacity of 155 tonnes of caustic soda per month started to operate at its Kansai plant in Osaka with the newly developed ion exchange membranes. During the following two years, intensive R&D efforts were continued to improve the Flemion membranes. The introduction of a carboxylic acid grouping to the side-chains gave a high current efficiency, but with a relatively poor voltage, and was attacked by the anolyte-side conditions. A technological compromise was that a laminated membrane was produced with a thick layer of a sulfonic acid structure on the anolyte side to give low voltage and physical integrity and a thin layer containing carboxylic structures on the catholyte side to provide a good current efficiency. A demonstration plant with a production capacity of 269 tonnes of caustic soda per month was constructed in 1976. The first commercial chlor-alkali plant based on ion exchange membranes started to operate at the Osaka site in 1978 with an annual production capacity of 795 tonnes of caustic soda.

A further enhancement of the performance of ion exchange membranes was made by adding surface coatings to promote the release of bubbles, which reduced thickness, and by incorporating reinforcing meshes. In 1981 an improved type of the Flemion membrane was developed, with a hydrophilic surface on non-conductive porous materials. This technological invention made it possible for the first time to operate the so-called zero-gap electrolyzer, a type of electrolyzer which has little space between the electrodes and the ion exchange membrane, leading to a reduction in the electric current resistance. While the limit to the minimum distance between the electrodes was previously 7 mm, because of the necessity to remove gases, the zero-gap electrolyzer reduced the inter-electrode distance to virtually zero and brought about a significant voltage reduction, resulting in a decrease in energy consumption. Subsequently, a new electrolyzer system, AZEC, was commercialized in 1982 and began to be provided to other companies.

Table 4-12 summarizes the chronology of technological development related to the ion exchange membrane process at Asahi Glass.

Table 4-12 Chronology of Technological Developments Related to the Ion Exchange Membrane Process at Asahi Glass

Year	Technological Development
1973	Start of R&D on the ion exchange membranes process for chlor-alkali production

1975	Development of a perfluorocarboxylate ion exchange membrane, Flemion Start-up of a pilot plant based on the ion exchange membrane process
1976	Start-up of a demonstration plant based on the ion exchange membrane process
1978	Start-up of a commercial plant based on the ion exchange membrane process at Osaka Start of the commercial production of the Flemion ion exchange membranes Development of a large filter press type cell with finite gap
1980	First supply of Asahi Glass's ion exchange membrane process to an outside firm
1981	Development of the Flemion membranes with hydrophilic inorganic coating
1982	Development of the AZEC electrolyzer with zero gap and activated cathodes

The trends in the R&D personnel involved for the development of the ion exchange membrane process at Asahi Glass are shown in Figure 4-5[66]. The R&D project which was initiated in 1973 conducted in such a large scale that about one third of the company's engineers who have expertise on chemical technology were engaged in this project at that time. The central research center led the initial stage of the project, which was followed by the chemical division's attempts to industrialize the ion exchange membrane process. More than 100 scientists and engineers continued to be engaged until the new technology for the ion exchange membrane process was fully established.

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[66] Since the scale of the vertical axis has not been disclosed for this figure, it is not possible to discuss the trends in detail. Nevertheless, we can see at least that R&D activities increased from 1973 to 1976, initially at the central research center and subsequently at the division.
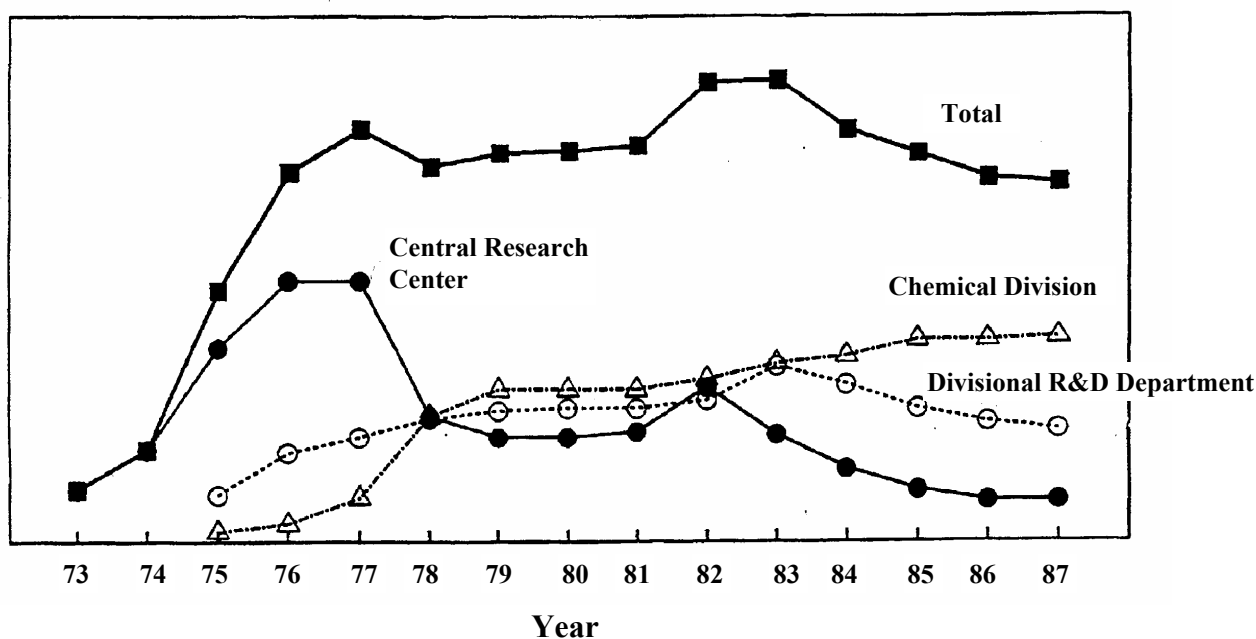
Figure 4-5 R&D Personnel for the Ion Exchange Membrane Process at Asahi Glass
Source: Asahi Glass.

The increased R&D activities at the central research center and later at the divisional department were followed by many patent applications made on technologies related to the ion exchange membrane process, as you can see in Table 4-9. In the late 1960s, most of the patents granted were on ion exchange membranes of the hydrocarbon type, which were basically used for salt production. Then, after a few years in the early 1970s when there was no patent applications related to the ion exchange membrane process, successful patent applications started to increase rapidly in the middle of the 1970s, particularly on ion exchange membranes based on perfluorocarbon, followed by those on electrolytic cells related to the ion exchange membranes for use in chlor-alkali production.

The technologies developed by Asahi Glass were provided to other chlor-alkali producers. The chlor-alkali plants to which the company's ion exchange membrane process was supplied are given in Table 4-28 at the end of this chapter. The first plant outside the company began to operate at Nippon Carbide in Toyama in November 1980. Asahi Glass's technology was also adopted by Kashima Chlorine & Alkali in July 1983 for its large-scale plant with an annual production capacity of 400,000 tonne of caustic soda in Kashima. Since then, Asahi Glass's technology for the ion exchange membrane process had been mainly adopted by other chlor-alkali producers based in Japan up to the middle of the 1980s. Then

160

recently it has been increasingly adopted for chlor-alkali plants overseas, particularly in other Asian countries, and in total the company has supplied approximately 50 plants with its ion exchange membrane process technology. The cumulative annual production capacities of these plants have reached more than 3.7 million tonnes of caustic soda. As with any new technology, the company faced many technical problems in the early stages of the commercial operation of the ion exchange membrane process. Nonetheless, these problems were finally solved, as the company could have a wide variety of learning experience and know-how in cell operations and their conditions. In developing the ion exchange membrane process, it has been crucial to gain practical experiences of operating commercial plants by closely cooperating with the users of the company's technology.

Tokuyama Soda

Tokuyama Soda[67] started its corporate history in 1918, when the first ammonia-soda plant in Japan was constructed by the company. The company had obtained experience and knowledge about the mercury process since the first mercury-based plant was constructed in 1952. Tokuyama Soda was one of the largest producers and suppliers of caustic soda, chlorine and other related products in Japan in the 1970s. As regards ion exchange membranes, the company started R&D activities in 1950, mainly on electrodialysis for brine desalination and salt production. The production of Tokuyama Soda' ion exchange membrane, Neosepta, started in 1963, and the company' trial salt plant based on the ion exchange membrane began to operate in 1965. The company subsequently had become one of the major suppliers in the world of ion exchange membranes and related system technologies for electrodialysis. These previous experience of working on the mercury process and technologies related to ion exchange membranes used for salt production gave Tokuyama Soda useful expertise in later developing the ion exchange membrane process for chlor-alkali production.

Tokuyama Soda began to undertake R&D on the ion exchange membrane process for chlor-alkali production in 1972 by using ion exchange membranes of a hydrocarbon type. As the ion exchange membrane containing perfluorinated sulfonic acid groups, Nafion, was introduced to the market, a bench-scale plant with this type of ion exchange membranes was set up in 1973. Subsequently, a semi-commercial plant was constructed in 1975 with a production capacity of 1,500 tonnes of caustic soda per year. The technologies for the ion

exchange membrane process, however, had not been sufficiently developed by September 1975, the deadline set by the Japanese government for the conversion of the mercury process, and the diaphragm process was introduced from Diamond Shamrock based in the United States to its chlor-alkali plant in 1975 (see Table 4-4).

In the meantime, as the performance of the Nafion membranes originally used was not satisfactory in the electrolysis of sodium chloride solution for chlor-alkali production, the company later developed a type of ion exchange membranes which had a thin layer of carboxylic acid groups on one of the surfaces of the membrane of perfluorinated sulfonic acid groups. Following several years of intensive R&D activities on laboratory cells, pilot cells and intermediate-size practical cells, a commercial plant based on the ion exchange membrane process with a production capacity of 10,000 tonnes per year came into operation in June 1977. This commercial plant was equipped with three electrolyzers, each containing 40 bipolar cells and ion exchange membranes based on a fluorocarbon resin which were developed by the company, Neosepta.

Table 4-13 gives the chronology of technological developments related to the ion exchange membrane process for chlor-alkali production at Tokuyama Soda.

Table 4-13 Chronology of Technological Developments Related to the Ion Exchange Membrane Process at Tokuyama Soda

Year	Technological Development
1972	Start of R&D on the ion exchange membrane process with the hydrocarbon-type ion exchange membranes
1973	Start-up of a bench-scale plant with the Nafion membranes
1974	Construction of a pilot plant with the Nafion membranes
1975	Construction of a semi-commercial plant with the Nafion membranes
1976	Long-run durability test of ion exchange membranes based on fluorocarbon resins in small-sized laboratory cells
1977	Test run of a practical electrolyzer of the TSE-270 type Construction of a commercial plant with the Nafion membranes Test run of Neosepta-F C-1000 membranes at the semi-commercial plant
1978	Start of commercial operation with the Neosepta-F C-1000 membranes Development of the Neosepta-F C-2000 membranes
1979	Start of commercial operation with the Neosepta-F C-2000 membranes Construction of a manufacturing plant for the Neosepta-F membranes
1981	First supply of the ion exchange membrane process to an outside firm

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[67] This section is based on the information obtained through the author's interviews with Dr. Sata and Mr. Matsuura of Tokuyama Soda (Matsuura, 2002; Sata, 2002).

The trends in successful patent applications made by Tokuyama Soda are shown in Table 4-9. At the end of the 1960s there were several patent applications made on ion exchange membranes. They were basically based on hydrocarbons and hence were primarily intended for use in the salt production process. Then, in the early 1970s, as R&D on the ion exchange membrane process for chlor-alkali production was initiated, relevant patent applications increased rapidly. The number of patents successfully applied on technologies related to the ion exchange membrane process remained large until the late 1970s, and then started to decline in the 1980s. By the late 1980s, there had been no new patent grated on the ion exchange membrane process.

Tokuyama Soda's technology for the ion exchange membrane process became available for adoption by other chlor-alkali producers at the beginning of the 1980s as a package of ion exchange membranes, electrolyzers, and associated facilities. Table 4-29 in the appendix to this chapter shows the chlor-alkali plants to which Tokuyama Soda's ion exchange membrane process was installed. As you can see, the company's ion exchange membrane process has been adopted mainly by companies in other Asian countries. The first adoption of Tokuyama Soda's technology occurred in 1981 at a small plant of Kokuto Chemical based in South Korea. It was followed by the adoption of the technology by a Taiwanese chlor-alkali producer in 1982. After an interval of a few years, a chlor-alkali producer in Kuwait adopted in Tokuyama Soda's process technology in 1986, and the last adoption was made by a Chinese chlor-alkali producer in 1987. Since then, however, the company has basically stopped providing its ion exchange membrane process to other chlor-alkali producers[68].

Chlorine Engineers Corp.

Chlorine Engineers Corp. (CEC)[69] is an engineering company which was established in 1973 as a joint venture between Mitsui Corporation and Mitsui Engineering and Shipbuilding (MES). MES had previously been one of the major suppliers of the mercury process to chlor-alkali plants in Japan (see Table 3-18). The creation of CEC was to provide engineering and related services for the conversion of mercury-based chlor-alkali plants, as was mandated by the government decision on their phase out at that time. While Asahi Chemical, Asahi Glass,

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[68] Recently, the company has changed its corporate name to Tokuyama, removing Soda from the original name. That suggests that the company's focus has shifted from the chlor-alkali business to other areas, while continuing the operation of its chlor-alkali production plant.

[69] This section is based on the information obtained through the author's interview with Dr. Kenzo Yamaguchi of Chlorine Engineers Corp. (Yamaguchi, 1999a).

and Tokuyama Soda has been producing chlor-alkali products, CEC has not been engaged in chlor-alkali manufacture, but is a specialized engineering company supplying production technologies to chlor-alkali producers.

The initial target of CEC's technological development was on the diaphragm process. When the government made the decision on the phase out of the mercury process in the early 1970s, the ion exchange membrane process for chlor-alkali production was still in its infancy, and its technological performance was far inferior to that of the diaphragm process, which had been well established at the industrial level. CEC hence expected that most of the chlor-alkali producers would adopt the diaphragm process when converting mercury-based plants. Rather than trying to develop its own technologies for the diaphragm process within the short period of time limited by the regulatory schedule, the company chose to introduce necessary technologies from outside. These technologies were supplied by foreign companies, namely, the DS cell by Diamond Shamrock and the Glanor cell by PPG, both of which were based in the United States. The chlor-alkali producers to which the diaphragm process was installed by CEC are listed in Table 4-30. The first case of the adoption of CEC's diaphragm process technology was implemented by Asahi Glass in Kitakyushu in February 1974. By May 1977, when the government decided to review the initial schedule of the conversion program, 18 chlor-alkali plants in Japan had adopted the diaphragm process supplied by CEC. The production capacities of chlor-alkali plants based on the company's diaphragm process had reached almost 1.5 million tonnes of caustic soda per year, which accounted for more than 50 % of the total domestic capacity in the Japanese chlor-alkali industry at that time.

It was getting clear, however, that the ion exchange membrane process was emerging as a new promising technology for chlor-alkali production, with its technical performance in a process of rapid improvement. Thus the company also started to develop its own technologies for the ion exchange membrane process. As major technological innovations had been already made on ion exchange membranes by the first movers, including Asahi Chemical Industry, Asahi Glass, and Tokuyama Soda, the focus of the company's R&D activities was placed on electrolytic cells, another major component of the ion exchange membrane process (see Figure 4-2). The first program intended for commercial applications was the development of the Chlorine Engineers' Membrane Electrolyzer (CME). In the process of developing CME, CEC maintained cooperation with Toa Gosei, the partner company for the development of technologies for the mercury process in the past (see Table 3-8). A test cell of CME was installed in 1975, during the first phase of the conversion program of mercury-based plants.

164

Two pilot cells were subsequently established in 1977. In 1980 the CEC's first commercial plant, with a production capacity of eight tonnes of caustic soda per day, was constructed in Okinawa, Japan. It was a plant converted from the diaphragm process. In the same year, another electrolytic cell was added to the pilot facilities, which was based on the carboxylic-type Nafion membrane. Table 4-31 in the appendix to this chapter shows the chronology of installations of the CME ion exchange membrane process to chlor-alkali plants.

In the meantime, chlor-alkali producers in Japan were severely hit by the rapid rise in the energy price following the oil crisis in the late 1970s. In particular, those chlor-alkali producers who had converted their plants from the mercury process to the diaphragm process suffered most from the price hike. As the diaphragm process consumed more energy, hence raising its production cost, there was a strong demand for replacing the diaphragm process. An installation of the ion exchange membrane process, a new technology which consumed less energy with a lower production cost, however, required a large amount of initial investment, and it was difficult for the plant operators, who had already hit by the rise in the energy cost, to implement process conversions again. Thus CEC tried to develop a new type of electrolytic cells for the ion exchange membrane process which could be readily retrofitted to the existing plants based on the diaphragm process. In 1980 CEC started to cooperate closely with Mitsui Toatsu Chemical[70] in conducting R&D activities on the Membrane Bag Cell (MBC). While the CME technology was intended for use to replace mercury- or diaphragm-based plants, the MBC technology was designed to be retrofit to the existing plants using the diaphragm process. In the MBC process, ion exchange membranes formed like a bag were mounted on the anode in place of the deposited asbestos diaphragm. The anode assembly and the cathode can used in the existing diaphragm cells could be utilized with only minor adjustments, thus making the cost of process conversion significantly smaller than that necessary for complete replacement.

The development of MBC was completed in 1981, and the first MBC-type electrolyzer, with the Nafion membranes installed, began to operate at Mitsui Toatsu Chemical's Nagoya plant in 1982. Table 4-32 in the appendix to the present chapter gives the supply record of the MBC process to chlor-alkali producers by CEC. Most of the retrofittings of the ion exchange membrane process to the existing plants based on the diaphragm process were carried out in the period from 1982 to 1984, just before the completion of the second phase of the

conversion program mandated by the government. While the electric power consumption of the retrofit ion exchange membrane process was higher than that of a newly installed process, the initial investment required for retrofitting was set by the company to be less expensive. Almost 90 % of the DS diaphragm electrolytic cells which had been installed by CEC during the first phase of the process conversion program turned out to be converted again to the retrofit ion exchange membrane process. In 1988, just after mercury-based plants finished process conversion completely, the retrofit-type technology accounted for 29 % of all of the ion exchange membrane process installed in the Japanese chlor-alkali industry.

As the technical performance of the ion exchange membrane process continued to improve further, however, these retrofit cells were to be eventually replaced with ion exchange membrane cells which were designed for new installations. Then, in 1991, CEC started to develop a new type of membrane electrolyzer, jointly working with Tosoh, formerly known as Toyo Soda[71], one of the largest chlor-alkali producers in Japan. Following the stage of establishing pilot plants, the development of the BiTAC (an abbreviation of Bipole of Tosoh and CEC) process reached at the industrial level in 1993. As Table 4-33 in the appendix to this chapter shows the supply list of the BiTAC process since then, CEC has provided the BiTAC technology to chlor-alkali plants in other countries as well as to Tosoh's plants. The chronology of technological developments related to the ion exchange membrane process at CEC is given in Table 4-14.

Table 4-14 Chronology of Technological Developments Related to the Ion Exchange Membrane Process at CEC

Year	Technological Development
1975	Start of R&D on the ion exchange membrane process with installation of a test electrolytic cell
1977	Construction of a pilot plant based on the ion exchange membrane process CME
1980	Construction of the first commercial plant based on the ion exchange membrane process CME Test of large-size cells with the Nafion membrane
1981	Development of the retrofit ion exchange membrane process MBC
1982	First installation of the retrofit ion exchange membrane process MBC
1984	Application of the ion exchange membrane technology CME for commercial conversion projects
1993	Development of the ion exchange membrane process BiTAC

[70] Mitsui Toatsu Chemical merged with Mitsui Petrochemical in 1997 to create Mitsui Chemical (Mitsubishi Chemical, 2001).

In developing technologies for the ion exchange membrane process, CEC cooperated with several chlor-alkali producers, including Toa Gosei for CME, Mitsui Toatsu Chemical for MBC, and Tosoh for BiTAC. That was particularly important, because CEC, as an engineering company specializing in providing technologies and related services to chlor-alkali manufacturers without engaging itself in manufacturing, needed detailed information on the actual use of its membrane process technologies for further improvement. This is in contrast with the cases of technological development by Asahi Chemical Industry, Asahi Glass, and Tokuyama Soda, all of which have been chlor-alkali producers with their own technologies and thus could utilize their own experiences of using them.

Kureha Chemical Industry

Following the Japanese government's decision made in 1973 to abolish all the chlor-alkali plants employing the mercury process, Kureha Chemical Industry instigated a program to develop an electrolytic cell for the diaphragm process to take the place of the mercury cells used by the company at that time (Shibata, Kokubu, and Okazaki, 1977). In April 1976, the company's electrolytic cells based on the mercury process were abolished. At the same time the company developed a new type of electrolytic cells designed for use in the diaphragm process, the SK diaphragm cells, and the commercial production using them was initiated. One of the primary aims in the development of this type of diaphragm cells was to utilize the existing facilities, including buildings and rectifiers, busbars, and cranes, as much as possible, so as to restrict the investment required for the process conversion.

On the other hand, Kureha Chemical Industry did not develop any technology which could be utilized at the industrial level for the ion exchange membrane process. As we can see in Table 4-10, in the early 1970s, the company's patent applications were targeted on technologies related to the diaphragm process, and then patent applications started to be made on technologies for the ion exchange membrane process in the middle of the 1970s. The number of successful patent applications on the ion exchange membrane process was almost the same as those on the diaphragm process in the end. However, while the research activities on the diaphragm process led to the industrialization of the SK diaphragm cell, the company introduced technologies for the ion exchange membrane process from an outside company, namely, Asahi Chemical Industry, in 1985.

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[71] Toyo Soda was renamed to Tosoh in 1987 (Tosoh, 2001).

Osaka Soda

As we have seen in 3.3.1, Osaka Soda was one of the pioneering companies in Japan in the development of the mercury process. Just after the end of the Second World War, the technology provided by the company accounted for more than half of the production capacities based on the mercury process in Japan (see Table 3-16). By the beginning of the 1970s, the company had come to rank third, following De Nora and MES, in supplying the mercury process to Japanese chlor-alkali plant operators.

Following the government decision on the phase out of the mercury process in the 1970s, however, the company had to use clean technologies without relying mercury for chlor-alkali production. As Table 4-10 suggests, while the number of successful patent applications on the diaphragm process was at the equal level as that of other innovative companies in Japan, there were only much fewer patent applications which were granted on the ion exchange membrane process, suggesting the company's R&D efforts had been mainly directed to the diaphragm process. Eventually, this company did not develop technologies by itself either for the diaphragm process or the ion exchange membrane process. Instead, the diaphragm process was introduced from two U.S. companies, namely, Diamond Shamrock and Hooker, and the ion exchange membrane process was supplied by CEC.

Nippon Soda

Nippon Soda was established in 1920, and its chlor-alkali production was started with the Nakano-type electrolytic cell of the diaphragm process, which was originally developed by the corporate founder, NAKANO Yurei, at the Nihongi site (Nippon Soda, 2001). Although the Nakano cells ceased to operate after the Second World War, the company made further improvements in the electrolytic cell. Subsequently, the company developed the B cells and the BM cells equipped with metal anodes and expanded their production capacities. Table 4-10 suggests that Nippon soda continued to make R&D activities on the diaphragm process throughout the 1970s. The company's enlarged electrolytic cell was later adopted by Chiba Chlorine Chemical in 1975 (Japan Soda Industry Association, 1982). On the other hand, the company did not make any significant innovations on the ion exchange membrane process, as suggested by no successful patent applications seen in Table 4-10.

Showa Denko

Showa Denko started its electrolytic production of caustic soda in 1935 with the diaphragm process using horizontal diaphragm cells (Takeshita, 1990). Later, the mercury process was added to the company's production facilities. With the advent of a dimensionally stable electrode in the 1960s, the company started to develop a type of vertical diaphragm cells, the SD cell. Its commercial operation was initiated in 1969, and the production capacity of the diaphragm plant with it was expanded subsequently. Following the government's decision the phase out of the mercury process in the early 1970s, the operation of the mercury plant was discontinued in 1975. And at the same time the company made an agreement with Hitachi Engineering and Shipbuilding to promote the development of the company's diaphragm process technology and its sales to other chlor-alkali producers (*Nikkei Sangyo Shinbun*, 1976). The result, however, was that Showa Denko's technology was adopted by only one company, Kanto Denka Kogyo, which introduced it to the Mizushima plant in 1975 (Kanto Denka Kogyo, 1998). Table 4-10 suggests that, after having been engaged in developing technologies for the diaphragm process in the late 1960s and the 1970s, the company started to make R&D activities on the ion exchange membrane process in the 1980s. These efforts to innovate on the ion exchange membrane process did not result in a successful development of technologies for industrial uses.

Tsurumi Soda

Tsurumi Soda started to produce chlor-alkali products in 1934 with the diaphragm process (Tsurumi Soda, 2001). The company was the only Japanese company which had never adopted the mercury process for chlor-alkali production since its establishment. Thus the company's technological expertise was accumulated solely on the diaphragm process, and that led to the development of the TSB cell and the TSBM cell, both of which have been designed for use in the diaphragm process. Relying solely on the diaphragm process, Tsurumi Soda did not face technological as well as financial difficulties when other chlor-alkali producers had to cope with the issue of converting the existing plants based on the mercury process in the 1970s. The company's technology for the diaphragm process was also adopted by Showa Enso in 1974 (Showa Chemical, 2001). On the other hand, the company did not make innovations on the ion exchange membrane process, and the technology of Asahi Glass was introduced to its chlor-alkali plant in 1982.

Comparison of the Innovative Companies in Japan

As we have discussed above, various types of technologies for chlor-alkali production were developed by the innovative companies in Japan. Table 4-15 lists these technologies for the mercury process, the diaphragm process, and the ion exchange membrane process.

Table 4-15 Technologies for Chlor-Alkali Production Developed by Innovative Companies in Japan

Company	Mercury Process	Diaphragm Process	Ion Exchange Membrane Process	
			Ion Exchange Membrane	Electrolytic Cell
Asahi Chemical	Asahi Chemical	-	Aciplex	Acilyzer
Asahi Glass	Rotation	-	Flemion	Azec
Tokuyama Soda	Tokuso	-	Neosepta	TSE
CEC (MES)	Mitsui	(DS, Glanor)	-	CME, MBC, BiTAC
Kureha Chemical	HD	SK	-	-
Osaka Soda	Daiso	-	-	-
Nippon Soda	-	BM	-	-
Showa Denko	-	SD	-	-
Tsurumi Soda	-	TSBM	-	-

By the early 1970s, when the government decided to abolish all the mercury-based chlor-alkali plants, several technologies had been developed for the mercury process by innovative companies in Japan. They include the Mitsui-Toa Gosei cell of Mitsui Engineering and Shipbuilding (MES), which later established Chlorine Engineers Corp. (CEC), the HD cell of Kureha Chemical Industry, the Daiso cell of Osaka Soda, the Rotation cell of Asahi Glass, the Tokuso cell of Tokuyama Soda, and the Asahi Chemical cell of the Asahi Chemical Industry.

Among these companies which had previous experiences of developing technologies the mercury process, four companies, Asahi Chemical Industry, Asahi Glass, Tokuyama Soda, and CEC, succeeded in making innovations on the ion exchange membrane process. Technically speaking, the ion exchange membrane process basically consists of the ion exchange membrane and the electrolytic cell, as we can see in Figure 4-2. Asahi Chemical Industry, Asahi Glass, and Tokuyama Soda made innovations on both the ion exchange membrane, developing the Aciplex, Flemion, and Neosepta membranes, respectively, and the electrolytic cell for the ion exchange membrane process, that is, the Acilyzer, Azec, and TSE processes, respectively. CEC initially introduced technologies for the diaphragm process, namely, the DS cell and the Glanor cell, from foreign companies, whereas three types of the

electrolytic cell were developed later by the company for the ion exchange membrane process, that is, the CME, MBC, and BiTAC processes.

There have not been major innovations on the ion exchange membrane process by the other companies with expertise on the mercury process, that is, Kureha Chemical Industry and Osaka Soda. While Kureha Chemical Industry industrialized its own electrolytic cell, the SK cell, for the diaphragm process, the company did not develop technologies for the ion exchange membrane process. Osaka Soda, once a leading innovator on the mercury process, did not make any significant innovations on either the diaphragm process or the ion exchange membrane process. Instead, the company introduced technologies from outside companies for the diaphragm process as well as for the ion exchange membrane process, without making its own innovations on either process.

On the other hand, Nippon Soda, Tsurumi Soda, and Showa Denko had already developed technologies for the diaphragm process, the BM, TSBM, and SD cells, respectively, by the early 1970s. Following the government's decision to phase out the mercury process in Japan, the companies increased their production capacity based on the diaphragm process with their own technologies. Although there were several chlor-alkali producers who adopted the technologies developed by these companies, these cases were relatively rare, as the advanced technologies, that is, the DS and Glanor cells, were introduced from foreign companies, mostly those based in the United States. Regarding the ion exchange membrane process, these companies did not make any significant innovations which could be utilized for industrial applications.

Asahi Chemical Industry, Asahi Glass, and Tokuyama Soda had previously experiences of developing and utilizing ion exchange membranes for salt production. Unlike in Europe or the United States, rainfall has been generally abundant in Japan, and water desalination has not been given priority for the application of ion exchange membranes. On the other hand, natural rock salt has not been available in Japan, and salt had to be produced in solar fields. The traditional process of salt production was labor-intensive and constantly subject to adverse weather, with little prospect of significant improvement (Shimizu, 1993). Hence the three Japanese companies started to conduct R&D activities on ion exchange membranes for the production of salt from sea water. In 1960 Asahi Glass began to produce its ion exchange membrane, Selemion, at the industrial level for the first time in Japan, and at the same time the company's first plant for salt production utilizing ion exchange membranes started to operate. The first trial of salt production with ion exchange membranes was immediately

followed by the other companies. In 1961 Asahi Chemical Industry initiated the manufacture of its ion exchange membrane, Aciplex, and the production of salt based on the membrane. The production of Tokuyama Soda' membrane, Neosepta, began in 1963, and the company' trial salt plant based on the ion exchange membrane started to operate in 1965.

The new method of salt production by using ion exchange membranes was efficient in terms of space and cost, and the quality of the produced salt was sufficiently high as to be used for food (Hanafusa, 1998). Accordingly, the salt production process with the use of ion exchange membranes was diffused rather quickly in the salt industry in Japan. As Table 4-16 gives the start-up years of salt production based on the ion exchange membrane, all of the salt producers in Japan, namely, Shin-Nihon Chemical Industry[72], Ako Sea Water Chemical Industry[73], Kinkai Salt Manufacturing, Naikai Salt Industries, Naruto Salt Manufacturing, Sanuki Salt Industry, and Sakito Salt[74], eventually introduced ion exchange membranes for salt production. The ion exchange membranes used by these salt producers were supplied by three companies, namely, Asahi Chemical, Asahi Glass, and Tokuyama Soda. By 1972, the traditional process had been completely replaced with the process with the ion exchange membrane for the production of salt applied for food in Japan (Japan Salt Industry Association, 2001).

As salt had been traditionally produced at salt fields by using the solar power, technological developments of the ion exchange membrane were conducted for the purpose of replacing solar evaporation as the method of producing salt from sea water. In this process, the three companies, that is, Asahi Chemical Industry, Asahi Glass, and Tokuyama Soda, gained earlier experiences of developing and improving ion exchange membranes. As these ion exchange membranes were based on hydrocarbons, however, they could not maintain their chemical stability in a strong alkaline environment and hence was not readily used for chlor-alkali production. The application of ion exchange membranes for use in chlor-alkali electrolytic cells did not occur until the 1970s.

Table 4-16 Use of Ion Exchange Membranes for Salt Production in Japan

Supplier of Ion Exchange Membrane	Start-up Year	Salt Producer
Asahi Chemical Industry	1962	Shin-Nihon Chemical Industry
	1967	Ako Sea Water Chemical Industry
	1967	Naruto Salt Manufacturing

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[72] Shin-Nihon Chemical Salt has been renamed to Shin-Nihon Salt (Shin-Nihon Salt, 2001).
[73] Ako Sea Water Chemical Industry has been renamed to Ako Sea Water.
[74] Sakito Salt Manufacturing has been renamed to Dia Salt (Dia Salt, 2001).

Asahi Glass	1969	Naikai Salt Industries
	1972	Sakito Salt Manufacturing
Tokuyama Soda	1967	Kinkai Salt Manufacturing
	1971	Sanuki Salt Industry

The chronology of the technological developments made by these companies are compared in Figure 4-6, which indicates the timing of R&D activities, pilot plants, and commercial plants concerning the diaphragm process and the ion exchange membrane process for each company. Although the idea of using ion exchange membranes for electrolytic chlor-alkali production had existed since the 1950s, the lack of suitable ion exchange membranes prevented the industrial realization of the ion exchange membrane process. In the meantime, several companies in Japan, including Asahi Chemical Industry, Asahi Glass, and Tokuyama Soda, had earlier experiences on developing ion exchange membranes primarily used for the manufacture of salt in the 1960s. Then, at the end of the 1960s, the Nafion membrane, which was invented by Du Pont, started to be available to companies in the Japanese chlor-alkali industry. That in effect worked to provide a fertile technological opportunity to these companies for the development of ion exchange membranes to be used in chlor-alkali production.
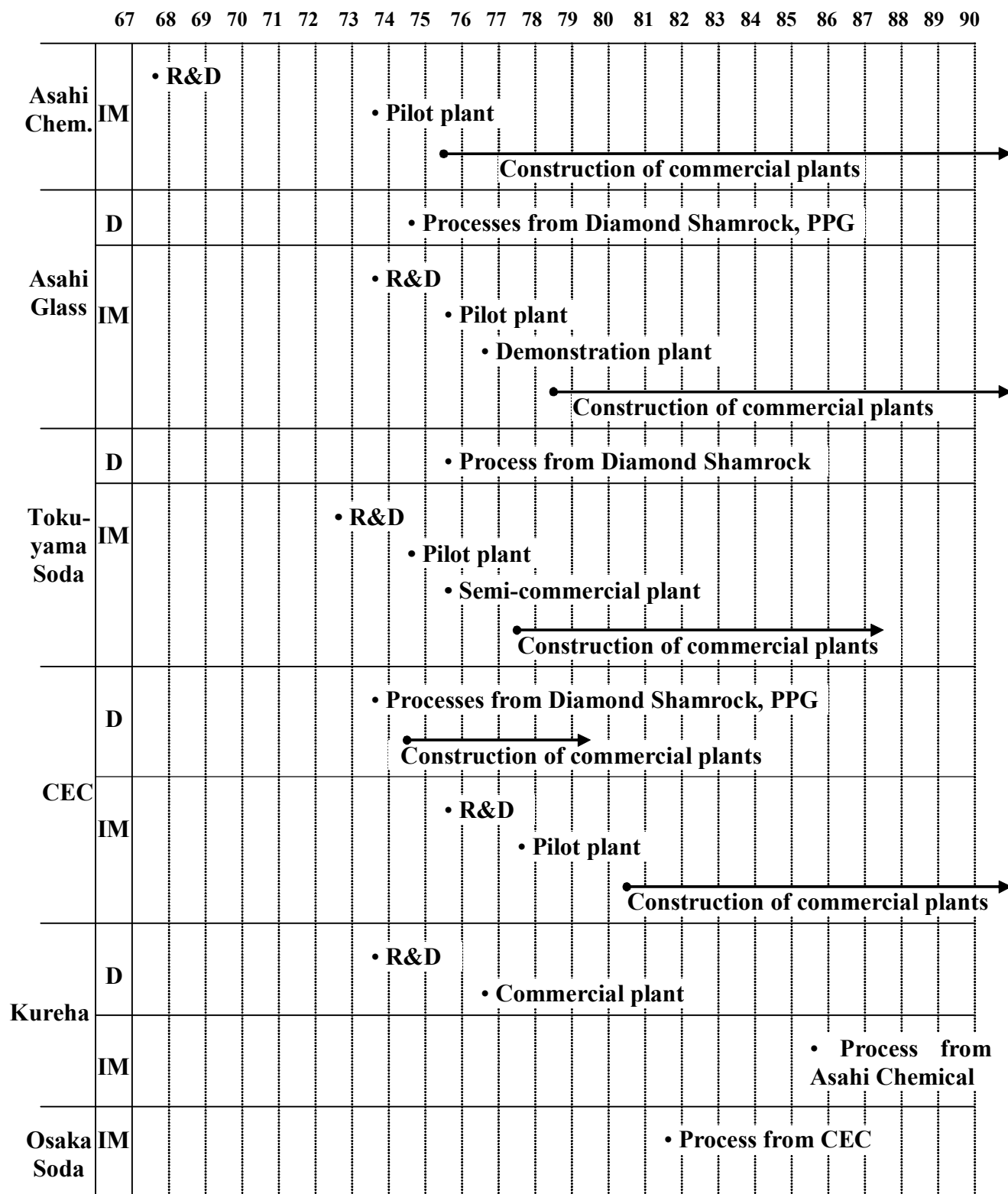
D: Diaphragm Process; IM: Ion Exchange Membrane Process

Figure 4-6 Technological Developments of Chlor-Alkali Production Processes by Japanese Companies

174

Coincided with the emergence of the Nafion membrane, the government's decision made in 1973 to phase out all the mercury-based plants in Japan created demands for clean technologies which would replace the mercury process. In particular, that provided a significant impetus for the innovative companies with previous expertise on ion exchange membranes to start intensive research efforts to develop the ion exchange membrane process for chlor-alkali production. While the government did not give any financial support to these companies when they conducted their R&D activities on the ion exchange membrane process, the decision worked to assure them that there would be a large amount of secured demands for alternative processes and thus encouraged the innovative companies to invigorate R&D efforts for developing the ion exchange membrane process. The guaranteed demand for clean technologies for chlor-alkali production helped the developers of the ion exchange membrane process to overcome the initial obstacle of its poor performance and uncertain technological progress in the future.

On the other hand, other companies which had been previously innovative on the mercury process, namely, Mitsui Engineering and Shipbuilding (MES), Kureha Chemical Industry, and Osaka Soda did not make significant innovations on the ion exchange membrane process. Unlike the three early innovators on the ion exchange membrane, that is, Asahi Chemical Industry, Asahi Glass, and Tokuyama Soda, these companies had not been involved in salt production previously and hence had little experience of developing the ion exchange membrane or utilizing it for other purposes. Thus, the initial focus of technological development was placed on the diaphragm process.

Immediately after the government decision on the phase out of the mercury process in the Japanese chlor-alkali industry, MES established CEC in 1973 to enter the business of converting the mercury process to clean processes which do not rely on any use of mercury in the production facilities. Without sufficient experience or expertise on the ion exchange membrane process, CEC picked up the diaphragm process for their technological target. The company decided to introduce technologies from foreign companies, namely, the DS cell from Diamond Shamrock in the United States and the Glanor cell from PPG also in the United States and provided these diaphragm process technologies to many chlor-alkali producers in Japan. The diaphragm process, however, turned out not to be appropriate for producing high-quality caustic soda, with various types of impurities contained. In the meantime, the company saw a rapid progress in developing ion exchange membranes based

on fluorocarbons by Asahi Chemical Industry, Asahi Glass, and Tokuyama Soda in the 1970s. The company hence started to undertake R&D activities on electrolytic cells designed for use in the ion exchange membrane process in the second half of the 1970s. Following a successful operation of the pilot plant, the first commercial plant based on the ion exchange membrane process started to operate in 1980. Although CEC was the last company in developing technologies for the ion exchange membrane process, the company has since then provided its process to many chlor-alkali producers in Japan. During the technological development, close cooperation with chlor-alkali manufacturers, including Toa Gosei Chemical and Toyo Soda, was of critical importance to CEC. As an engineering company which has not been engaged in chlor-alkali production, the company could receive precious feedback from the practical experiences of these chlor-alkali manufacturers and utilize it for further technological improvement.

Another innovative company without previous experience on ion exchange membranes, Kureha Chemical Industry also chose the diaphragm process for the target of technological development. The company started R&D activities on the diaphragm process in 1973, following the government decision on the phase out of the mercury process. The company subsequently succeeded in developing an electrolytic cell, the SK cell, and converted its own mercury-based plant to the diaphragm process in 1976. The company, on the other hand, did not develop its own technologies for the ion exchange membrane process, although the patent data suggests that some R&D activities were conducted later in the 1970s. Similarly, Osaka Soda, without technical background in the field of ion exchange membranes, made R&D efforts on the diaphragm process, following the government's decision for the abolishment of the mercury process in 1973. As is indicated by the patent data, however, these innovative efforts did not result in successful technological development which could be utilized at the industrial level. In comparison to the diaphragm process, the ion exchange membrane process was not the focus of the company's R&D activities. In the end, its mercury-based chlor-alkali plants were converted to the ion exchange membrane process provided by an outside technology supplier, namely, CEC.

Figure 4-7 shows the trends in the supply of the diaphragm process and the ion exchange membrane process by the Japanese companies. (Detailed data are given in Table 4-26 in Appendix at the end of this chapter.) Following immediately the government decision on the phase out of the mercury process, the supply of the diaphragm process increased rapidly and reached its peak in the middle of the 1970s. While the supply of the diaphragm

176

process then declined quickly and ceased in 1980, the ion exchange membrane process started to be supplied in the middle of the 1970s and showed a large increase in the 1980s. After the supply of the ion exchange membrane process declined in the late 1980s, following the completion of the process conversion program in Japan, it picked up again in the 1990s, mainly because of an increase in its supply to chlor-alkali producers in other countries.
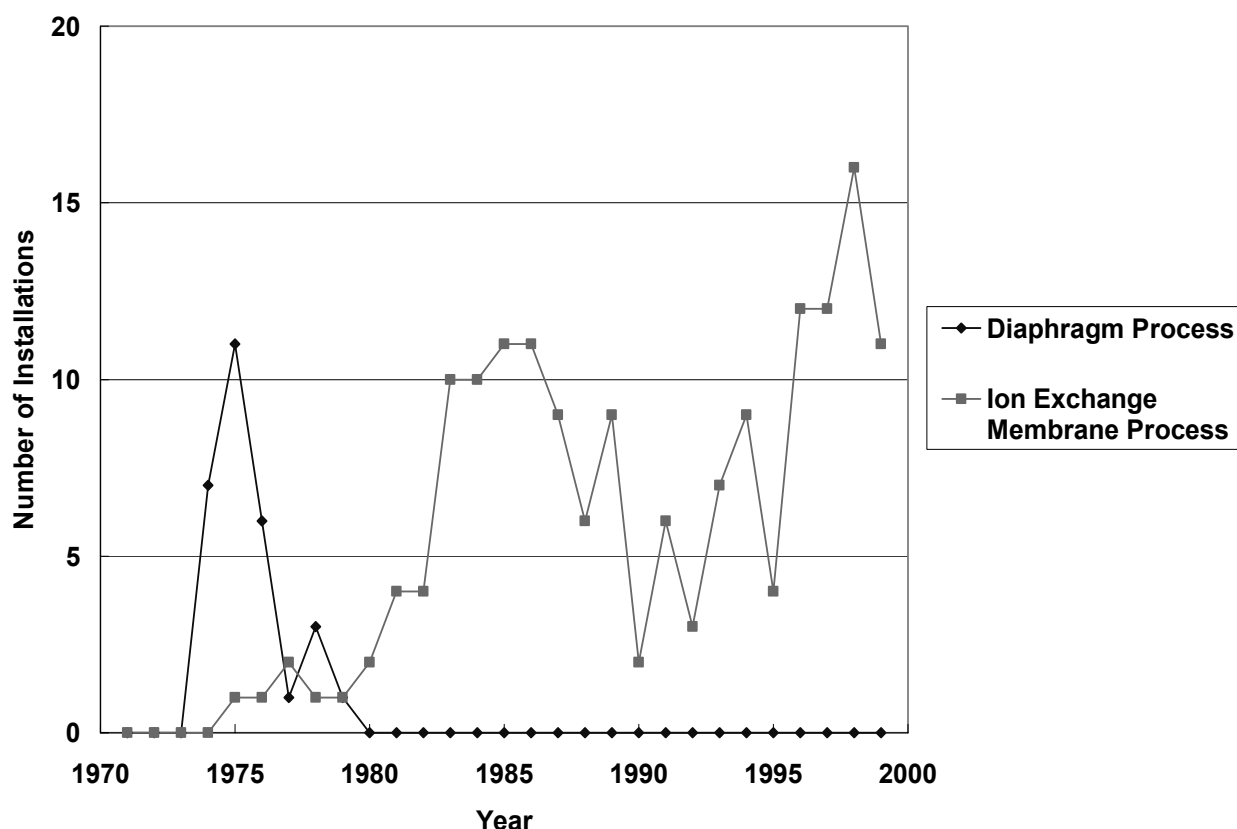
Figure 4-7 Supply of the Diaphragm and the Ion Exchange Membrane Processes by Japanese Firms

Table 4-17 gives detailed data on the supply of the two processes by Asahi Chemical Industry, Asahi Glass, Tokuyama, and CEC. This table has been constructed by using the supply lists of the two production processes provided by these companies. (The supply lists of the companies are shown in Table 4-27, Table 4-28, Table 4-29, Table 4-30, Table 4-31, Table 4-32, and Table 4-33 in Appendix at the end of this chapter.)

Table 4-17 Supply of the Diaphragm and Ion Exchange Membrane Processes by Innovative Companies in Japan

Year	Asahi Chemical		Asahi Glass		Tokuyama		CEC	
	D	IM	D	IM	D	IM	D	IM
1971	0	0	0	0	0	0	0	0
1972	0	0	0	0	0	0	0	0
1973	0	0	0	0	0	0	0	0
1974	0	0	0	0	0	0	4	0
1975	0	1	0	0	0	0	8	0
1976	0	1	0	0	0	0	5	0
1977	0	1	0	0	0	1	1	0
1978	0	0	0	1	0	0	3	0
1979	0	1	0	0	0	0	1	0
1980	0	0	0	1	0	0	0	1
1981	0	1	0	1	0	1	0	1
1982	0	1	0	1	0	1	0	1
1983	0	2	0	2	0	0	0	6
1984	0	0	0	1	0	0	0	9
1985	0	1	0	6	0	0	0	4
1986	0	5	0	4	0	1	0	2
1987	0	4	0	2	0	1	0	3
1988	0	2	0	1	0	0	0	3
1989	0	0	0	6	0	0	0	3
1990	0	0	0	1	0	0	0	1
1991	0	2	0	3	0	0	0	1
1992	0	0	0	1	0	0	0	2
1993	0	2	0	1	0	0	0	4
1994	0	3	0	2	0	0	0	4
1995	0	0	0	1	0	0	0	3
1996	0	4	0	2	0	0	0	6
1997	0	3	0	8	0	0	0	1
1998	0	10	0	3	0	0	0	3
1999	0	3	0	3	0	0	0	5
Total	0	376	0	408	0	40	176	504

D: Diaphragm Process; IM: Ion Exchange Membrane Process

As we can see in the table, in the second half of the 1970s, Asahi Chemical Industry, Asahi Glass, Tokuyama Soda succeeded in industrializing their technologies for the ion exchange membrane process and began to use them basically at their own chlor-alkali production plants. Then, in the 1980s, these companies started to provide their technologies to other chlor-alkali producers in Japan. On the other hand, CEC introduced technologies for the diaphragm process from foreign companies and began to supply them to chlor-alkali

producers in Japan in 1974, immediately after the government policy for the phase out of the mercury process. By 1977, when the initial schedule of the government policy for the phase out of the mercury process reviewed, CEC's diaphragm process was adopted by many chlor-alkali producers in Japan. As the diaphragm process turned out to be an inappropriate technology, however, CEC, cooperating with several chlor-alkali producers, started to develop technologies for the ion exchange membrane process in the late 1970s. The company's ion exchange membrane process was supplied for the first time to a chlor-alkali producer in Japan in 1980. In the middle of the 1980s, as the deadline for the phase out of the mercury process approached, these four companies provided their technologies to many Japanese chlor-alkali producers who had to convert their mercury-based plants.

Having finished supplying domestic chlor-alkali producers with their ion exchange membrane process technologies, these companies started to seek actively their customers in other countries in the late 1980s. Particularly in other countries in Asia, including Taiwan, South Korea, and China, the technologies developed by the Japanese companies were adopted by many chlor-alkali producers. Along with the remarkable economic development in these countries, their chlor-alkali productions have also been growing rapidly, and consequently many of the chlor-alkali producers avoided from adopting the mercury process, which has become technologically obsolescent, and instead could introduce the ion exchange membrane process to their new production facilities.

The intensified R&D activities of the innovative companies in Japan, namely, Asahi Chemical Industry, Asahi Glass, Tokuyama Soda, and CEC, resulted in a rapid improvement in the technological performance of the ion exchange membrane process. One of the major indicators which represent the technological performance of technologies for chlor-alkali production is the energy consumption, as it accounts for a significant part of the total manufacturing cost. Table 4-18 shows the trends in the electric power consumption of the ion exchange membrane process technologies developed by Asahi Chemical Industry, Asahi Glass, Tokuyama Soda, and CEC [75]. Compared with the mercury process, whose energy consumption remained almost unchanged at the level of approximately 3,200 kWh/t NaOH, the ion exchange membrane process has shown a remarkable progress in its power consumption.

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[75] The electric power consumption is normally higher at a higher current density.

Table 4-18 Electric Power Consumption of the Ion Exchange Membrane Process Technologies Developed by Japanese Companies

Year	Asahi Chemical Industry	Asahi Glass	Tokuyama Soda	CEC
1975	3,500	-	-	-
1976	2,700	3,200	3,200	3,200
1977	2,620	2,740	3,000	-
1978	2,570	2,610	-	-
1979	2,500	2,470	2,495	-
1980	2,420	2,340	-	2,600
1981	2,200	2,080	-	2,400
1982	2,200	-	2,160	2,200
1983	2,200	2,080	2,080	-
1984	2,100	-	-	-
1985	2,100	2,100	-	-

Figures are expressed in kWh/t NaOH.
Sources:
Asahi Chemical Industry: 1975: Oh-hama, Hamada, and Yoshida (1998) (at 4 kA/m². 1976: Seko (1976) (at 4 kA/m²). 1977, 1979, 1980, and 1981: Yomiyama (1982). 1978: Seko (1980) (at 3.56 kA/m²). 1982: Seko, Yomiyama, Ogawa, and Ono (1983) (at 4 kA/m²). 1983: Seko, Yomiyama, and Ogawa (1983) (at 4.0 kA/m²). 1984: Seko, Ogawa, Ono, and Suzuki (1984) (at 4 kA/m²). 1985: Seko, Omura, and Yoshida (1986) (at 4 kA/m²).
Asahi Glass: 1976, 1977, 1978, 1980, and 1981: Nagamura, Ukihashi, and Shiragami (1983) (at 3 kA/m²). 1979: Nagamura, Ukihashi, and Shiragami (1980) (at 2 kA/m²). 1983: Ukihashi, Asawa, and Miyake (1983) (at 3 kA/m²). 1985: Ukihashi and Sato (1986) (at 3 kA/m², 35% NaOH).
Tokuyama Soda: 1979: Motani and Sata (1980) (at 2 kA/m²). 1982: Motani (1982). 1983: Sata, Motani, and Ohashi (1983).
CEC: 1976, 1980, 1981, 1982: Yamaguchi and Kumagai (1990).

Among the innovative companies, Asahi Chemical Industry initially took the lead in improving the energy consumption of the ion exchange membrane process. When the company started to operate the first commercial plant in 1975, the power consumption was 3,500 kWh/t NaOH (3,925 kWh/t NaOH, including steam). Then it declined rapidly to about 2,200 kWh/t NaOH in the early 1980s, achieving a reduction by 43 %, and has remained stable since then. The other companies have caught up with Asahi Chemical Industry quickly in a short period of time. When Asahi Glass developed the Flemion membrane in 1976, the power consumption for producing 40 % caustic soda by its ion exchange membrane process was 3,200 kWh/t NaOH, a level which was almost equivalent to that of the mercury process at that time. By 1985, the power consumption with the company's AZEC electrolyzer with ion exchange membranes had been reduced to less than 2,200 kWh/t NaOH. In the case of

Tokuyama Soda, when the first commercial plant based on the ion exchange membrane process was installed in 1977, its power consumption was more than 3,000 kWh/t NaOH. By the early 1980s, it had been reduced to less than 2,100 kWh/t NaOH, the lowest among the three processes. The technological development by CEC for the ion exchange membrane process was delayed, compared with the other innovative companies in Japan. CEC's technology for the ion exchange membrane process, however, showed a rapid progress in reducing the energy consumption from the initial level of 3,200 kWh/t NaOH to the level of 2,200 kWh/t NaOH just in six years.

In this way, for the past twenty years, the energy consumption of the ion exchange membrane process has shown a remarkable improvement. To see the extent and speed of technological progress, we make a comparison between the mercury process, diaphragm process, and the ion exchange membrane process in terms of progress in the efficiency of energy consumption. Figure 4-8 shows the trends in the energy consumption of the three processes. (Detailed data are given in Table 4-24 in Appendix at the end of this chapter.)
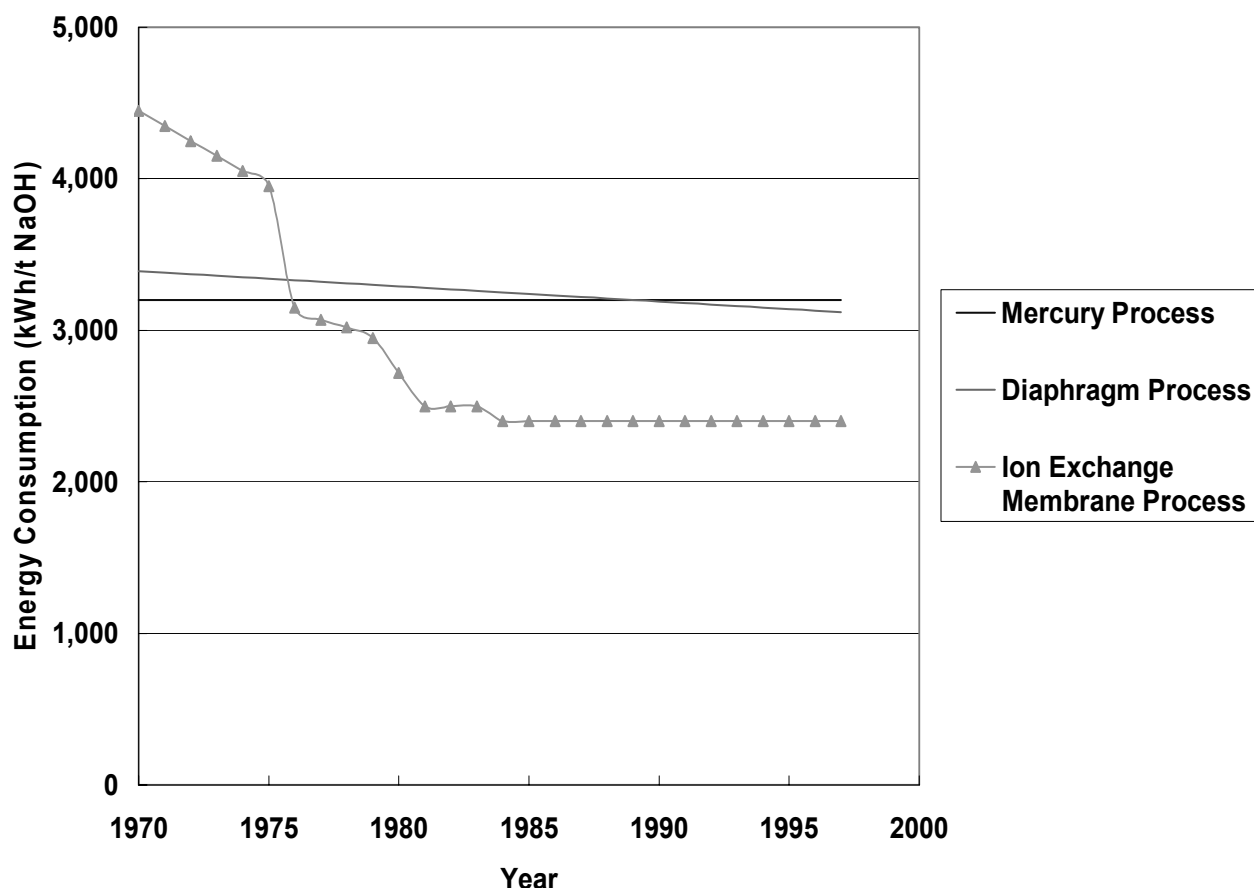
Figure 4-8 Energy Consumption of the Mercury, Diaphragm, and Ion Exchange Membrane Processes

The total energy consumption is the sum of the electric power consumption and, in the cases of the diaphragm process and the ion exchange membrane process, the steam consumption required to increase the concentration of caustic soda. Here the data on the energy consumption of the ion exchange membrane process is represented by that of the technology developed by Asahi Chemical Industry, except for 1970. With regard to the steam consumption required for concentrating caustic soda, it has been assumed to be 470 kWh/t NaOH for the diaphragm process, and 450 kWh/t NaOH until 1979 and 300 kWh/t NaOH thereafter for the ion exchange membrane process[76]. When data is not available, we have made an assumption of linear improvement in the energy efficiency. Figure 4-8 can be seen in

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[76] The development of the ion exchange membrane process can be traced in three phases. While the ion exchange membrane process produced 8 to 15 % caustic soda in the first phase, which ended in 1979, caustic soda of 35 % was produced in the second and the third phases (Chatterjee, 1984).

relation to Figure 2-9, which we have developed in discussing our analytical framework for the effects of environmental regulation on technological change.

Initially, the energy consumption of the ion exchange membrane process exceeded 4,800 kWh/t NaOH (Morris, 1990). In 1970 the development of the ion exchange membrane process was still in its infancy, with a level of energy consumption at 4,500 kWh/t NaOH. At the middle of the 1970s, when the first commercial plant based on the ion exchange membrane process started to produce chlor-alkali products, the total energy consumption was more than 3,900 kWh/t NaOH, which included the consumption of steam for concentrating caustic soda. In the decade from the middle of the 1970s to the middle of the 1980s, when R&D activities were conducted intensively by the Japanese companies, the energy efficiency of the ion exchange membrane process was improved significantly. Its total energy consumption soon surpassed the level of 3,200 kWh/t NaOH of the mercury process, and by the middle of the 1980s, the electric power consumption had reached 2,100 kWh/t NaOH. Since then, the electric power consumption has remained almost unchanged at the same level. Although the theoretical power consumption for chlor-alkali production is calculated as 1,480 kWh/t NaOH, the current level of 2,100 kWh/t NaOH is considered by many industry experts to be fairly close to the practical limit with the current technological design (Seko, Ogawa, Ono, and Suzuki, 1984)[77].

On the other hand, the mercury process, which does not require any steam for the concentration of caustic soda, consumed electric power of 3,200 kWh/t NaOH at the beginning of the 1970s. The smaller figure of energy consumption made the mercury process economically superior to the ion exchange membrane process at that time. The energy consumption of the mercury process has remained almost unchanged until now, at the same level of 3,200 kWh/t NaOH. In the case of the diaphragm process, its energy consumption had been larger than that of the mercury process. In the middle of the 1970s, when the government decision on the phase out of the mercury process, the energy consumption of the diaphragm process was much smaller than that of the ion exchange membrane process. Since then, however, the extent of progress in the technological performance of the diaphragm process has been small, and its total energy consumption, which is currently at the level of 3,120

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[77] Some people expect that it is possible to reduce the electrical energy consumption of the ion exchange membrane process by another 20 to 25 % with the application of a fuel depolarized cathode, which has not yet reached the level of industrialization. Some companies are also working on technologies which can produce directly 50 % caustic soda (Nakao and Miyake, 1995; Shimohira, Saito, Saito, and Miyake, 1993). If successful,

kWh/t NaOH, has been surpassed by that of the ion exchange membrane process. In other words, while there has been basically no change in the energy consumption of the mercury process and very little improvement in the case of the diaphragm process since the 1970s, the ion exchange membrane process has reduced its energy consumption significantly, advancing it from the least to the most economically efficient technology[78].

The quality of caustic soda produced also indicated the extent of technological progress of the ion exchange membrane process. To produce caustic soda of a high concentration, the ion exchange membrane needs to maintain its chemical stability in the strong alkali environment, and that requires technological sophistications in the chemical composition of the ion exchange membrane. In 1975, when the first commercial plant using the ion exchange membrane process started its operation, the concentration of caustic soda was 17 %. Since commercial applications of caustic soda normally require a concentration which is close to 50 %, a further step is necessary to increase the caustic concentration, consuming an extra amount of energy. As the additional energy is normally provided in the form of steam, it raises the production cost of the ion exchange membrane process. Since the middle of the 1970s, the concentration of caustic soda has been increased, and its current level is approximately 35 %, implying that the steam cost for concentrating caustic soda has been reduced. Furthermore, the quality of caustic soda has been improved, as impurities contained in caustic soda have been reduced. The concentration of sodium chloride, a major substance among various impurities, in caustic soda has dropped from the level of hundreds parts per million (ppm) in the 1970s to just a few ppm in the current period.

4.5 Modification of Regulatory Schedule and Adoption of the Ion Exchange Membrane Process

The rapid progress in the technological performance of the ion exchange membrane process was carefully monitored and assessed by the academic experts of the Evaluation Committee.

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that will remove the necessity of using steam to further increase the concentration of caustic soda. This technological progress, however, might increase the consumption of electric power.

[78] While the electric power consumption of the ion exchange membrane process declined significantly, the current density has increased, from 2.5 kA/m^2 to the present level of 5 kA/m^2. This has contributed to keeping the nominal capital cost for the process conversion almost unchanged over the 20 years. On the other hand, ion exchange membranes in the high current density operation usually do not show their good performance which would be obtained at lower current density, and cell operation becomes more difficult because the increasing current requires special cell design to achieve a homogeneous electrolyte distribution in the cell and the reliable

Their final conclusion that the ion exchange membrane process had reached a stage at which it could be applied for industrial applications prompted the Countermeasures Council to review the regulatory schedule which had been rigidly fixed in a short-time framework.

In September 1979 the Countermeasures Council at its fifth meeting made a decision that the remaining mercury process plants were to be converted by the end of 1984 (Council for the Promotion of Countermeasures against Mercury Pollution, 1979). This extension of the deadline for process conversion enabled the operators of mercury-based plants to adopt the more efficient ion exchange membrane process in the second phase of the government program for process conversion, instead of the diaphragm process. Some manufacturers, particularly those whose chlor-alkali production had heavily depended on the mercury process, argued that they would need more time to see whether the newly developed membrane process could be reliably used at the industrial level (Japan Soda Industry Association, 1980b; Katsumura, 1979). Nevertheless, the Countermeasures Council maintained its original schedule for the completion of process conversions at subsequent meetings (Council for the Promotion of Countermeasures against Mercury Pollution, 1980, 1981, 1982).

Subsequently, the ion exchange membrane process technologies developed by the innovating companies came to be adopted by other chlor-alkali producers in Japan. By using Table 4-27, Table 4-28, Table 4-29, Table 4-31, Table 4-32, and Table 4-33, we obtain Table 4-19, which shows the adoption of the ion exchange membrane process at chlor-alkali plants in chronological order.

Table 4-19 Adoption of the Ion Exchange Membrane Process by Chlor-Alkali Producers in Japan

Year	Plant Site	Technology Supplier
1975	Asahi Chemical Industry, Nobeoka	Asahi Chemical Industry
1976	Denki Kagaku Kogyo, Ohme	Asahi Chemical Industry
1977	Tokuyama Soda, Tokuyama	Tokuyama Soda
1978	Asahi Glass, Osaka	Asahi Glass
1980	Nippon Carbide, Uozu	Asahi Glass
	Showa Enso, Gushikawa	CEC
1981	Osaka Soda, Amagasaki	CEC
1982	Tsurumi Soda, Tsurumi	Asahi Glass
	Mitsui Toatsu Chemical, Nagoya	CEC

discharging device. Currently, one of the targets of R&D activities concerning the ion exchange membrane process is to overcome these technical difficulties (e.g. Nakao, Shimohira, and Takechi, 1998).

1983	Nikkei Kako, Kanbara	Asahi Chemical Industry
	Kashima Chlorine & Alkali, Kashima	Asahi Glass
	Nankai Chemical Industry, Tosa	Asahi Glass
	Mitsui Toatsu Chemical, Ohmuta	CEC
	Osaka Soda, Matsuyama	CEC
	Toyo Soda, Yokkaichi	CEC
	Kanto Denka Kogyo, Mizushima	CEC
	Tokuyama Soda, Tokuyama	CEC
1984	Sumitomo Chemical, Ohita	CEC
	Confidential	CEC
	Confidential	CEC
	Chiba Chlorine & Alkali, Chiba	CEC
	Ajinomoto, Kawasaki	CEC
	Kansai Chlor-Alkali, Osaka	Asahi Glass
	Hodogaya Chemical, Kohriyama	CEC
	Toa Gosei Chemical, Tokushima	CEC
	Mitsui Toatsu Chemical, Nagoya	CEC
	Mitsui Toatsu Chemical, Osaka	CEC
1985	Kureha Chemical, Nishiki	Asahi Chemical Industry
	Central Chemical, Kawasaki	Asahi Glass
	Mitsubishi Chemical, Mizushima	Asahi Glass
	Shin-etsu Chemical, Naoetsu	Asahi Glass
	Confidential	Asahi Glass
	Hokkaido Soda, Horobetsu	Asahi Glass
	Toagosei Chemical, Nagoya	CEC
	Osaka Soda, Kokura	CEC
1986	Okayama Chemical, Mizushima	Asahi Chemical Industry
	Kanto Denka Kogyo, Shibukawa	Asahi Chemical Industry
	Hokkaido Soda, Tomakomai	Asahi Glass
	Nankai Chemical Industry, Wakayama	Asahi Glass
	Asahi Glass, Chiba	Asahi Glass
	Nippon Soda, Takaoka	CEC
	Kanto Denka Kogyo, Mizushima	CEC
1987	Sumitomo Chemical, Kikumoto	Asahi Chemical Industry
	Toagosei Chemical, Tokushima	CEC
1988	Hodogaya Chemical, Kohriyama	CEC
	Confidential	CEC
1989	Mitsubishi Chemical, Kurosaki	Asahi Glass
	Asahi Glass, Kashima	Asahi Glass
	Kanegafuchi Chemical, Takasago	CEC
1995	Tosoh	CEC

As we can see, in the second half of the 1970s, the ion exchange membrane process was initially installed at chlor-alkali plants by the innovating companies which had developed technologies by themselves, that is, Asahi Chemical Industry, Tokuyama Soda, and Asahi Glass. Although at that time the technological performance of the ion exchange membrane process was not particularly favorable, compared with the diaphragm process, these companies could gain experiences of actually using their own technologies for industrial production and utilize these practical experiences for future developments of their technologies for the ion exchange membrane process. As further progress had been achieved in the technological performance, other chlor-alkali producers gradually started to introduce the ion exchange membrane process in the early 1980s. In the same period, CEC joined the three early movers in providing technologies for the ion exchange membrane process to chlor-alkali producers.

As chlor-alkali producers were hit by the second oil crisis at that time, severely deteriorating their financial situations, MITI contacted individual companies to see the progress on their conversion plans. It was then becoming clear that some of the companies would not be able to finish converting their mercury-based plants by the end of 1984, the deadline which had been originally set by the Countermeasures Council. The Countermeasures Council convened again in December 1983 to discuss the issue and made a decision to extend the deadline to the middle of 1986, on the condition that the companies would start to convert their mercury-based plants by the end of 1984 (Council for the Promotion of Countermeasures against Mercury Pollution, 1983). As Table 4-19 indicates, most of the introductions of the ion exchange membrane process subsequently took place in a few years just before the extended deadline. The last chlor-alkali plant based on the mercury process was finally converted at the end of June in 1986. It was 13 years after the government's initial decision to phase out the mercury process in the Japanese chlor-alkali industry.

Figure 4-9 shows the overall trends in production capacities based on the mercury process, the diaphragm process, and the ion exchange membrane process from the early 1970s. (Detailed data are given in Table 4-25 in Appendix at the end of this chapter.)
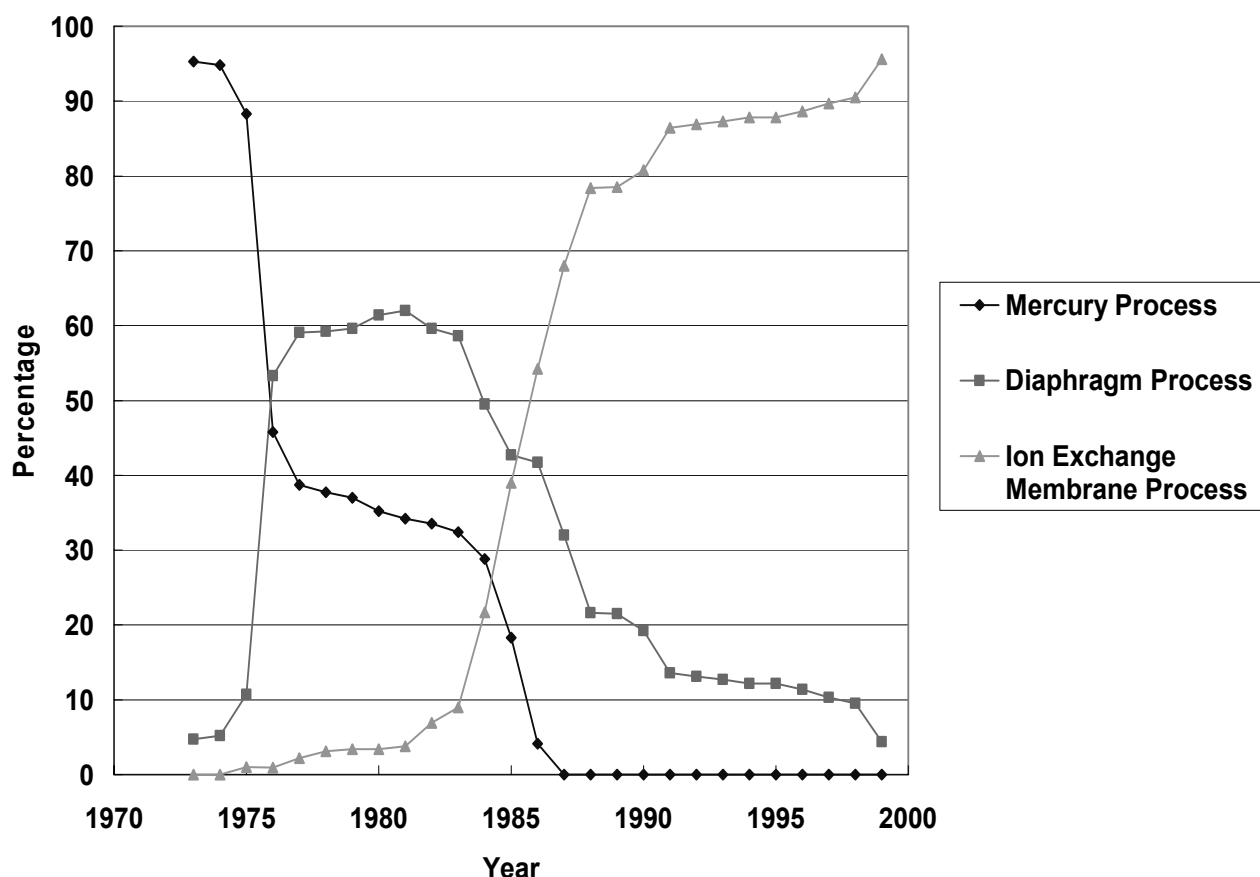
Figure 4-9 Production Capacities of the Mercury, Diaphragm, and Ion Exchange Membrane Processes in the Japanese Chlor-Alkali Industry

In 1973, just before the government's decision to phase out the mercury process, the mercury process accounted for more than 95 % of the total production capacities whereas the diaphragm process was negligible. Following the government mandate for the phase out of the mercury process to be implemented with a rigid schedule, most of the mercury process plants were converted to the diaphragm process, with its energy consumption much lower than that of the ion exchange membrane process, making it the only clean technology which was feasible for industrial applications at that time. Its share was immediately raised to more than 60 % in just seven years while the share of the mercury process declined rapidly.

In the meantime, the ion exchange membrane process began to emerge in the middle of the 1970s and was undergoing significant technological improvement. Due to the rapid rise of energy prices following the oil crisis which occurred in the 1970s, the disadvantage of the diaphragm process in terms of a higher production cost than the ion exchange membrane

process became much worse. Furthermore, while the existing mercury-based plants were being converted to the diaphragm process rapidly in the late 1970s, a serious concern was growing among chlor-alkali producers who had already finished converting their plants to the diaphragm process. The production cost with the diaphragm process became higher than that with the mercury process, and the quality of caustic soda produced with the diaphragm process was not sufficiently high, as Table 4-5 shows that the diaphragm process produced caustic soda which contained much more impurities, notably sodium chloride, making it inappropriate for use in some industrial applications.

Accordingly, the newly developed ion exchange membrane process started to replace the mercury process and later the diaphragm process as well. When the mercury process was completely abolished in 1986, the installed capacity of the ion exchange membrane process accounted for more than half of the total production capacity. Since then, the share of the ion exchange membrane process has increased steadily, reaching more than 95 % in 1999.

4.6 Costly Transition from the Mercury Process to the Diaphragm Process and then to the Ion Exchange Membrane Process

Figure 4-9 shows that the diaphragm process has decreased its share steadily since the early 1980s, with the once dominant diaphragm process currently accounting for less than 5 % of the total production capacities in Japan. This suggests that the mercury-based plants which had been converted to the diaphragm process were shortly converted again to the ion exchange membrane process. We thus examined how long the chlor-alkali plants which had introduced the diaphragm process were operated. Figure 4-10 shows the operating period of the diaphragm process adopted at chlor-alkali plants in Japan. (Detailed data are given in Table 4-34 in Appendix at the end of this chapter.)
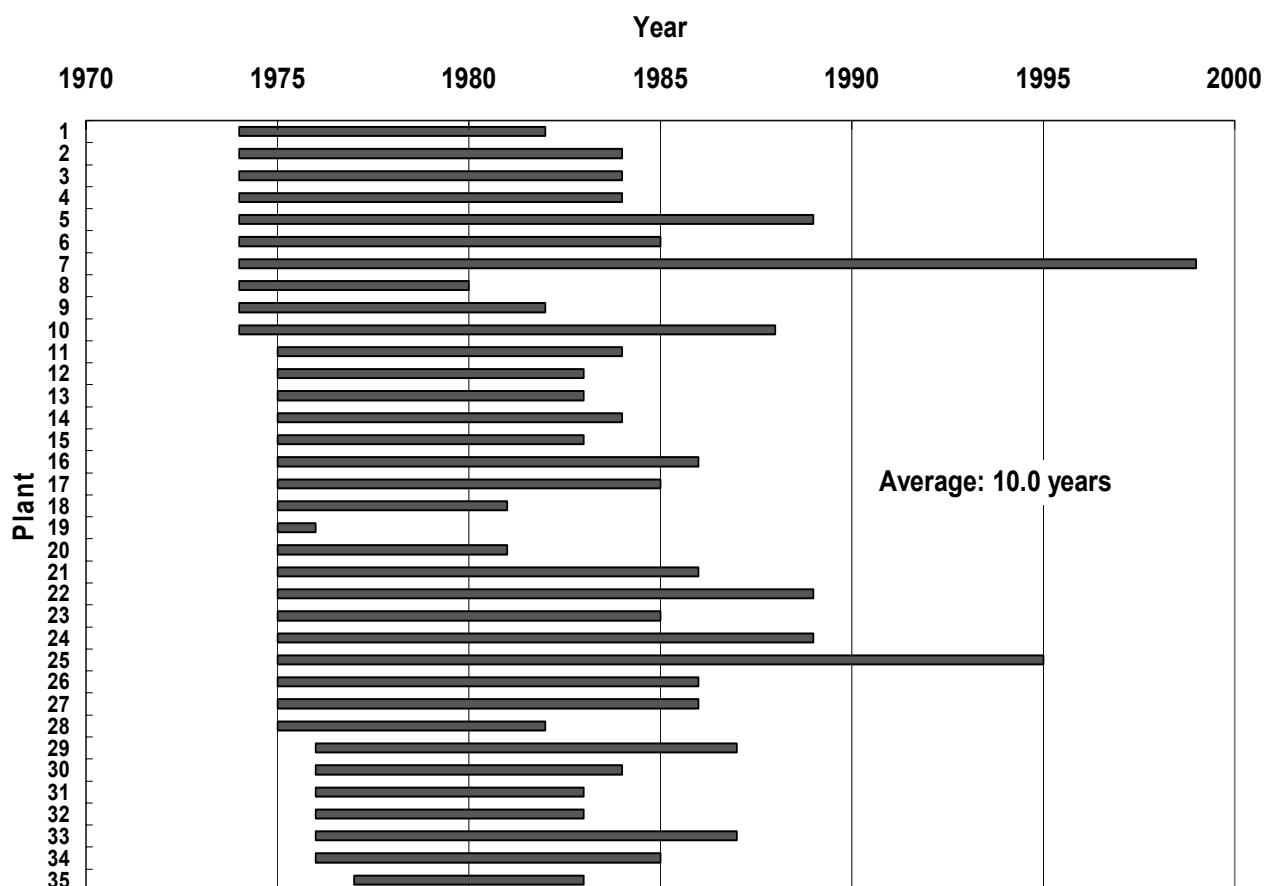
Figure 4-10 Operating Period of the Diaphragm Process at Chlor-Alkali Plants in Japan

As you can see, all of the chlor-alkali plants which had been converted to the diaphragm process following the government decision on the phase out of the mercury process were converted again to the ion exchange membrane process. As a result, the operating period of these diaphragm plants was very short, an average of only 10 years. That is far shorter than the normal period of approximately 40 years for plant operation in the chemical process industry (Society of Chemical Engineers of Japan, 1998). In retrospect, we could argue that the investment needed to convert mercury-based plants to the diaphragm process was scrapped prematurely.

Process conversions at this scale normally require a significant amount of investment in the industry. Table 4-20 gives the composition of the investments used for the conversions of the mercury-based plants in Japan from the beginning of the process conversion program in the early 1970s to its completion in the late 1980s. The investment costs include those for the conversion of the mercury process either to the diaphragm process or to the ion exchange

190

membrane process and those for the conversion of the newly adopted diaphragm process to the ion exchange membrane process. The investment costs are compared with the annual turnovers of the Japanese chlor-alkali industry as a whole.

Table 4-20 Investment Costs for the Process Conversion in the Japanese Chlor-Alkali Industry

Fiscal Year	Mercury Process -> Diaphragm or Ion Exchange Membrane Process	Diaphragm Process -> Ion Exchange Membrane Process	Total Investment	Industry Turnover
1973	231.8	0	231.8	630.9[a]
1974				
1975				
1976				
1977				
1978	1.9	2.7	4.6	594.7
1979				
1980				
1981				
1982	3.7	1.3	5.0	172.1
1983	5.6	10.0	15.6	184.5
1984	11.2	5.0	16.2	190.2
1985	18.6	5.7	24.3	180.4
1986	14.5	6.0	20.5	167.3
1987	0	14.4	14.4	169.0
1988	0	1.6	1.6	185.0
Total	287.3	46.7	334.0	-

Figures are expressed in Japanese billion yen.
a: The annual turnovers for 1973 and 1974 are assumed to be the same as that for 1975.
Sources: Investment: Japanese Ministry of International Trade and Industry (1989). Industry Turnover: Japanese Ministry of International Trade and Industry (1985; 1990).

The process conversions which were undertaken from 1973 to 1988 cost the Japanese chlor-alkali industry 334 billion yen as a whole. Of the total cost of 287.3 billion yen invested in converting the existing mercury-based plants to the diaphragm or ion exchange membrane process, 231.8 billion yen was spent during the first phase of the process conversion program which was implemented from 1973 to 1977. That means that approximately 80 % of the total investment for converting mercury-based plants was made at the initial stage of the process conversion program.

At this stage of the conversion program, as indicated in Table 4-4, 41 plants introduced the diaphragm process, the only clean technology which it had been well-established could be

reliably used for industrial applications. Only 3 plants, as Table 4-19 shows, adopted the ion exchange membrane process, whose technological development was still in its infancy. Assuming that the investment cost for the construction of a plant is equal between the diaphragm process and the ion exchange membrane process, more than 90 % of the investment of 231.8 billion yen spent in the first phase of the conversion program was used to introduce the diaphragm process, rather than the ion exchange membrane process, during the first phase of the conversion program. And almost all of these plants were later switched to the newly developed ion exchange membrane process.

This amount of financial resources constituted a considerable burden on the chlor-alkali industry, which had already been severely hit by the rise in energy prices following the oil crisis in the 1970s. The sum of the industry's annual turnovers in the first phase of the conversion program, that is, from 1973 to 1977, was 630.9 billion yen. The amount of financial resources devoted to convert mercury-based plants to the diaphragm process, which would be converted again to the ion exchange membrane process in a very short period of time, reached more than one third of the industry's turnover in the same period. This clearly indicates that the investment necessary for process conversions had a significant impact on the financial condition of the Japanese chlor-alkali industry as a whole.

As the investment required such a large amount of financial resources in such a short period of time, chlor-alkali producers asked the government for financial support (Japan Soda Industry Association, 1974c). The Conversion Committee made a similar recommendation to provide the industry with financial resources and tax reductions for the process conversion (Committee for the Promotion of Process Conversions in the Soda Industry, 1973)[79]. The Ministry of Finance, however, insisting on the Polluters Pay Principle (PPP), initially claimed that all of the necessary investment should be financed by the industry (Tajima, 1997). Negotiations between MITI and the Ministry of Finance finally resulted in the agreement that Japan Development Bank and Hokkaido-Tohoku Development Finance Public Corporation[80]

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[79] The Conversion Committee also made a recommendation to provide loans for the investments related to scrapping mercury process facilities, most of which had not yet been depreciated completely. This recommendation, although strongly supported by chlor-alkali producers, was rejected by the Ministry of Finance (Tajima, 1997). As some of the mercury process facilities to be abolished were relatively new and technologically sophisticated, plant operators were hoping to sell them in other countries in order to finance the necessary investments. MITI, however, fearing to be criticized for exporting pollution, decided that the scrapped mercury process facilities were in principle prohibited from being exported to foreign countries (Japanese Ministry of International Trade and Industry, 1974).

[80] Japan Development Bank and Hokkaido-Tohoku Development Finance Public Corporation were merged on October 1, 1999, creating the Development Bank of Japan.

were to provide loans for the conversion of the mercury process to the diaphragm process in the chlor-alkali industry (Japan Soda Industry Association, 1974b). The interest rate was set to be the most preferential rate, 7.7 % for the fiscal year 1974, a figure which was less favorable than for loans for technological development but better than those for general countermeasures against public nuisance. Furthermore, 70 % of the investment for the process conversion and 35 % of the investment for the expansion of facilities were decided to be financed by the loans from the public financial institutions.

Table 4-21 shows the sources from which plant operators financed the investment capital necessary for the first phase of the process conversion program. More than half of the total investment of 231.8 billion yen was financed through borrowings from the two public financial institutions. Together with borrowings from private financial institutions, about 90 % of the total investment capital was financed through borrowings, making a heavy burden on the financial conditions of the companies.

Table 4-21 Sources of Investment Capital for the First Phase of the Process Conversion

	Institution	Interest rate (%)	Amount (billion yen)
Borrowing	Public financial institutions	7.9[*]	128.0 (55.2%)
	• Japan Development Bank	8.2	40.8
		7.7	70.1
	• Hokkaido-Tohoku Development	8.2	4.7
	Finance Public Corporation	7.7	12.4
	Private Financial Institutions	n/a	81.6 (35.2%)
Self-financing	-	-	22.2 (9.6%)
Total investment	-	-	231.8

* Average
Source: Japanese Ministry of International Trade and Industry (1979).

In retrospect, these financial resources could have been saved if the mercury-based plants that existed in the early 1970s had been converted directly to the ion exchange membrane process without going through the diaphragm process. To realize that route of technological change, however, a different schedule for the implementation of the government's policy to phase out the mercury process would have been required. If the requirement for the phase out of the mercury process had not been set to complete immediately, but implemented with some flexibility in timing, allowing more time to test and evaluate technological progress of alternative clean processes carefully, it would have been

possible for the operators of the mercury process to switch directly to the ion exchange membrane process, avoiding this considerable waste in investment.

4.7 Conclusion

In this chapter, we examined the effects of environmental regulation on technological change in the Japanese chlor-alkali industry. We paid particular attention to technological developments by those companies which had previous experiences of making innovations on chlor-alkali production technologies. At the beginning of the 1970s, the mercury process had become the dominant technology for chlor-alkali production, accounting for more than 95 % of the production capacities of the Japanese chlor-alkali industry. The technologies used for the mercury process had been developed by several companies in Japan. Notably, Mitsui Engineering and Shipbuilding (MES), Osaka Soda, Kureha Chemical Industry, Asahi Glass, Tokuyama Soda, and Asahi Chemical Industry had been particularly innovative on the mercury process prior to the introduction of environmental regulations on mercury emissions into the environment.

We next examined the environmental regulations introduced in Japan to deal with mercury emissions from chlor-alkali plants using the mercury process. In the 1960s Japan experienced the tragedy of the Minamata disease. Concerns were growing among the general public on the effects of mercury emitted to the environment, whether it was organic mercury, which caused the serious disease, or inorganic mercury. With public pressures increasing, the Japanese government had to take a very strong stance on the emissions of mercury from chlor-alkali plants, despite strong opposition from the chlor-alkali industry in Japan. The regulation set by the government demanded that chlor-alkali producers completely abolish the mercury process in less than five years. To facilitate the conversion of the existing mercury-based plants, the government provided financial support to chlor-alkali producers through preferential tax treatment and low-interest public loans. As the regulatory schedule for converting the mercury process to alternative clean technologies was rigidly fixed, however, most of the chlor-alkali manufacturers had no choice other than to adopt the diaphragm process. It was regarded by many as the only clean technology feasible for industrial chlor-alkali production at that time despite that, as the diaphragm process was less energy efficient, production costs with the diaphragm process were higher than with the mercury process. Although several innovative Japanese firms began to work on the diaphragm process, the

regulatory schedule for process conversions initially lacked flexibility and did not allow sufficient time for new technological development. By 1976, two thirds of the chlor-alkali production capacities in Japan had been converted to the diaphragm process. Overall, the technologies adopted for the diaphragm process in Japan following the government decision on the phase out of the mercury process were mostly those developed by foreign companies.

During this period, however, there were other companies who chose another type of clean technologies to replace the mercury process. Asahi Chemical Industry, Asahi Glass, and Tokuyama Soda focused their R&D efforts on the ion exchange membrane process. These companies had earlier experiences of developing and utilizing ion exchange membranes primarily for the production of salt in the 1960s. While the idea of using the ion exchange membrane for chlor-alkali production had existed since the 1950s, its industrial realization was prevented by the unavailability of ion exchange membranes with chemical stability and mechanical strength that could reliably be used in the chlor-alkali electrolytic cell. Then, in the late 1960s, a new type of the ion exchange membrane developed in the United States became available to Japanese companies. That provided these companies with an opportunity to utilize their technological expertise for the improvement of ion exchange membranes for chlor-alkali production.

Shortly thereafter, the government decision to phase out the mercury process created a secure demand for mercury-free, clean technologies in the Japanese chlor-alkali industry. This provided a strong incentive for innovative companies to develop technologies for the ion exchange membrane process and to supply them to other chlor-alkali producers. In the absence of government financial support for their R&D activities, and as the ion exchange membrane process for chlor-alkali production was still in its infancy in the early 1970s, with its technological feasibility not yet firmly established, only those companies that had previous experience and expertise on the ion exchange membrane, that is, Asahi Chemical Industry, Asahi Glass, and Tokuyama Soda, intensified their R&D activities. These companies succeeded in developing their technologies for the ion exchange membrane process and started to utilize them for their own chlor-alkali plants. Through the practical experiences of using the newly developed technologies, these companies further improved the technical performance of the ion exchange membrane process.

While the ion exchange membrane process was undergoing rapid technological advancement, the disadvantage of the diaphragm process in terms of production costs was worsening, as energy prices soared following the oil crisis in the 1970s. Moreover, it had

become clear among chlor-alkali producers that the quality of caustic soda produced by the diaphragm process was not high enough as to be used for several industrial applications. Under the circumstances, it was decided in 1977 that the implementation of the process conversion program would be interrupted for a while, and at the same time an expert committee was established to evaluate the extent of the technological progress of the newly emerging ion exchange membrane process. The committee members, all of whom were from academic research institutes, interviewed and visited companies for detailed information on the on-going technological developments in the industry. In 1979 they finally agreed on the conclusion that the ion exchange membrane process had reached a stage ready for industrial applications.

With the expert evaluation of the technological progress, the government modified the original conversion program and postponed the deadline for the phase out of the mercury process to the middle of the 1980s. This adjustment of the regulatory schedule allowed more time for innovative companies to undertake R&D activities and to learn through actual experiences of operating chlor-alkali plants based on the ion exchange membrane process, promoting further progress of the promising, but not yet proved, new technology. In the end, the ion exchange membrane process had advanced to become the best technology among the three chlor-alkali processes economically as well as environmentally, and subsequently the remaining mercury-based plants were converted to the ion exchange membrane process. The phase out of the mercury process was completed in 1986, and currently almost all of the chlor-alkali plants in Japan are relying on the ion exchange membrane process. Furthermore, in addition to the environmental benefits and cost savings in the use of the ion exchange membrane process, innovative companies such as Asahi Chemical Industry, Asahi Glass, Tokuyama Soda, and CEC are supplying their technologies to chlor-alkali producers in other countries, particularly in Asia.

On the negative side, the mercury-based plants which had been converted to the diaphragm process, immediately following the government decision on the phase out of the mercury process, had to be converted again to the ion exchange membrane process. The average operating period of the plants based on the diaphragm process was only ten years, a figure which is significantly shorter than the normal operating period of 40 years. This implies that a large amount of the capital investment made for the introduction of the diaphragm process, which was comparable to the industry's annual turnover at that time, was not utilized usefully until the end of the technologies' lifetime and effectively ended up

wasted. In retrospect, this could have been avoided if the initial policy for the phase out of the mercury process had maintained some degree of flexibility in its regulatory schedule, taking into account the state of technological development of alternative processes. As innovations on the ion exchange membrane process were perceived to be on the horizon by several innovative companies at the time of the early 1970s, if the deadline for the phase out of the mercury process had been initially set for a later date, there could have been more time for necessary detailed experiments and evaluations of alternative technologies, and most of the mercury-based plants could have been converted directly to the ion exchange membrane process, without wasting investments on the diaphragm process.

To sum up, government policy for the phase out of the mercury process did encourage innovative companies to undertake R&D activities on clean technologies. Applied on a too rigid schedule, however, the stringent regulation initially did not allow for sufficient time to see further technological progress of the newly emerging ion exchange membrane process while most of the chlor-alkali producers were induced to adopt the diaphragm process, which was to be abandoned soon. Only after the initial rigid regulatory schedule was relaxed, was the ion exchange membrane process widely adopted by the Japanese chlor-alkali industry. One of the policy implications we could draw from this case of technological change in the Japanese chlor-alkali industry is that, while stringent regulation is expected to encourage radical innovations on clean technologies, instead of incremental innovations on end-of-pipe technologies, the regulatory schedule should be sufficiently flexible incorporating accurate information on the state of technological development in industry. That will help to avoid choosing a technology which may not be the best one in the long run. This is particularly important in a case in which the speed of technological change is high and the degree of its uncertainty is large.

Appendix

List of Interviewees in Japan

Asahi Chemical Industries
- Mr. OH-HAMA Hiroshi, Corporate Auditor

- Mr. HAMADA Masao, General Manager, Chemicals Strategic Planning Department, Chemicals Administration
- Mr. YOSHIDA Mitsuo, Senior Staff, Corporate R&D Administration

Asahi Glass
- Mr. SATO Kimihiko, former General Manager, Technology Division

Tokuyama Soda
- Dr. SATA Toshikatsu, former Chief Researcher, Technology Research Center
- Dr. MATSUURA Shunji, Corporate Planning Division

Chlorine Engineers Corp.
- Dr. YAMAGUCHI Kenzo, Technical Advisor

Mitsubishi Chemical Corporation
- Mr. FUJII Toshiharu, General Manager, Global Environmental Department

Sumitomo Chemical
- Mr. FUKUNAGA Tadatsune, Manager, Environment and Safety Department

Japan Soda Industry Association
- Mr. AIKAWA Hiroaki, Director, Global Environment Department
- Mr. SAKAMOTO Akio, Manager, Public Relations Division

Japan Chemical Industry Association
- Mr. KAWAMATA Motoo, Deputy General Manager, Japan Responsible Care Council

Japan Salt Industry Association
- Mr. HANAFUSA Fumiyuki, Manager, Research Division

Ministry of International Trade and Industry

- Mr. FUJII Kenya, Chemicals Division, Basic Industries Bureau
- Mr. TAJIMA Keizo, former Manager, Petrochemical Group, Basic Chemicals Division, Basic Industries Bureau

Table 4-22 List of Chlor-Alkali Plants in Japan

Company	Site	Capacity (NaOH 10^3 tonnes/year)			
		Hg	D	IM	Other
Hokkaido Soda	Tomakomai	-	-	132	-
Tohoku Tosoh Chemical	Sakata	-	-	54	-
Kureha Chemical Industry	Nishiki	-	-	110	-
Showa Denko	Kawasaki	-	59	57	-
Nippon Soda	Takasaki	-	-	65	-
Kanto Denka Kogyo	Shibukawa	-	-	45	-
Kanto Denka Kogyo	Mizushima	-	-	58	-
Central Chemical	Kawasaki	-	-	67	-
Tsurumi Soda	Tsurumi	-	-	90	-
Nippon Light Metal	Kanbara	-	-	50	-
Shin-etsu Chemical	Naoetsu	-	-	46	-
Denki Kagaku Kogyo	Omi	-	-	52	-
Mitsui Chemical	Nagoya	-	-	69	-
Mitsui Chemical	Osaka	-	-	66	-
Mitsui Chemical	Ohmuta	-	-	73	-
Toa Gosei	Nagoya	-	-	73	-
Toa Gosei	Tokushima	-	-	166	-
Nippon Carbide Industries	Uozu	-	-	15	-
Asahi Glass	Kashima	-	173	109	-
Asahi Glass	Chiba	-	-	229	-
Asahi Glass	Kitakyushu	-	-	14	-
Kanegafuchi Chemical Industry	Takasago	-	-	297	-
Daiso	Amagasaki	-	-	90	-
Daiso	Matsuyama	-	-	43	-
Daiso	Kokura	-	-	29	-
Nankai Chemical Industry	Wakayama	-	-	32	-
Sumitomo Chemical	Ehime	-	-	112	-
Sumitomo Chemical	Oita	-	-	13	-
Nippon Paper Industries	Iwakuni	-	27	-	-
Tosoh	Yokkaichi	-	-	76	-
Tosoh	Nanyo	-	163	423	-
Tokuyama	Tokuyama	-	-	342	-
Mitsubishi Chemical	Mizushima	-	-	116	-
Mitsubishi Chemical	Kurosaki	-	-	35	-
Asahi Chemical Industry	Nobeoka	-	-	142	-

Showa Chemical	Gushikawa	-	-	3	-
Kashima Chlorine & Alkali	Kashima	-	-	354	-
Chiba Chlorine & Alkali	Chiba	-	-	94	-
Kansai Chlor-Alkali	Osaka	-	-	38	-
Okayama Chemical	Mizushima	-	-	129	-
Total		0	3,376	32,064	0

Data as of 1998.
Hg: Mercury process
D: Diaphragm process
IM: Ion exchange membrane process
Monthly production capacities have been transformed to annual production capacities: monthly capacity x 12 x 0.86 = annual capacity.
Source: Japan Soda Industry Association (1998b).

Table 4-23 Japanese Patents on the Mercury, Diaphragm, and Ion Exchange Membrane Processes Granted to Japanese Firms

Year of patent applications	Mercury Process	Diaphragm Process	Ion Exchange Membrane Process
1968	18	1	3
1969	14	2	7
1970	20	6	3
1971	21	4	5
1972	30	7	11
1973	2	11	21
1974	11	18	27
1975	9	10	45
1976	7	24	60
1977	2	16	53
1978	-	8	46
1979	-	8	47
1980	-	9	87
1981	-	6	71
1982	-	1	30
1983	-	1	20
1984	-	1	20
1985	-	0	10
1986	-	0	12
1987	-	0	7
Total	1072	1064	4680

Table 4-24 Energy Consumption of the Mercury, Diaphragm, and Ion Exchange Membrane Processes

Year	Mercury Process	Diaphragm Process	Ion Exchange Membrane Process
1970	3,200	-	4,450
1971	-	-	-
1972	-	-	-
1973	-	-	-
1974	3,200	3,350	-
1975	-	-	3,950
1976	-	-	3,150
1977	-	-	3,070
1978	-	-	3,020
1979	-	-	2,950
1980	-	-	2,720
1981	-	-	2,500
1982	-	-	2,500
1983	-	-	2,500
1984	-	-	2,400
1985	-	-	-
1986	-	-	-
1987	-	-	-
1988	-	-	-
1989	-	-	-
1990	-	-	-
1991	-	-	-
1992	-	-	-
1993	-	-	-
1994	-	-	-
1995	-	-	-
1996	-	-	-
1997	3,200	3,120	2,400

Sources:

Mercury Process: 1970: Kuhn (1971). 1974: Japan Soda Industry Association (1975). 1997: Japan Soda Industry Association (1998b).

Diaphragm Process: 1974: Japan Soda Industry Association (1975). 1997: Japan Soda Industry Association (1998b).

Ion Exchange Membrane Process: 1970: Chatterjee (1984). 1975-1984: Asahi Chemical Industry (see Table 4-18). 1997: Oh-hama, Hamada, and Yoshida (1998).

Table 4-25 Production Capacities of the Mercury Process, Diaphragm Process, and Ion Exchange Membrane Process in the Japanese Chlor-Alkali Industry

Year	Mercury Process	Diaphragm Process	Ion Exchange	Total Production

			Membrane Process	Capacity
1973	3,660 (95.3 %)	180 (4.7 %)	0	3,840
1974	3,605 (94.8 %)	196 (5.2 %)	0	3,801
1975	3,479 (88.3 %)	421 (10.7 %)	41 (1.0 %)	3,941
1976	2,064 (45.8 %)	2,403 (53.3 %)	41 (0.9 %)	4,508
1977	1,747 (38.7 %)	2,667 (59.1 %)	102 (2.2 %)	4,516
1978	1,697 (37.7 %)	2,667 (59.2 %)	142 (3.1 %)	4,506
1979	1,652 (37.0 %)	2,655 (59.6 %)	152 (3.4 %)	4,459
1980	1,591 (35.2 %)	2,771 (61.4 %)	152 (3.4 %)	4,514
1981	1,575 (34.2 %)	2,852 (62.0 %)	172 (3.8 %)	4,599
1982	1,278 (33.5 %)	2,273 (59.6 %)	263 (6.9 %)	3,814
1983	1,234 (32.4 %)	2,232 (58.6 %)	343 (9.0 %)	3,809
1984	1,098 (28.8 %)	1,885 (49.5 %)	826 (21.7 %)	3,809
1985	681 (18.3 %)	1,589 (42.7 %)	1,448 (39.0 %)	3,718
1986	144 (4.1 %)	1,445 (41.7 %)	1,880 (54.2 %)	3,469
1987	0	1,174 (32.0 %)	2,489 (68.0 %)	3,663
1988	0	770 (21.6 %)	2,793 (78.4 %)	3,563
1989	0	788 (21.5 %)	2,884 (78.5 %)	3,672
1990	0	751 (19.2 %)	3,156 (80.8 %)	3,907
1991	0	531 (13.6 %)	3,381 (86.4 %)	3,912
1992	0	522 (13.1 %)	3,459 (86.9 %)	3,981
1993	0	511 (12.7 %)	3,524 (87.3 %)	4,035
1994	0	493 (12.2 %)	3,544 (87.8 %)	4,037
1995	0	493 (12.2 %)	3,566 (87.8 %)	4,059
1996	0	473 (11.4 %)	3,689 (88.6 %)	4,162
1997	0	449 (10.3 %)	3,887 (89.7 %)	4,336
1998	0	424 (9.5 %)	4,008 (90.5 %)	4,430
1999	0	190 (4.4 %)	4,155 (95.6 %)	4,345

Figures are expressed in 10^3 tonnes of 100% NaOH per year.

a: production capacity as of the end of March of each year

b: until 1981 annual production capacity = monthly production capacity x 12 months;
since 1982 production capacity = monthly production capacity x 12 months x 0.846

c: 15.4 % = 4.7 % (maintenance and repair) + 10.7 % (day-night fluctuation of power load)

Sources: Japan Soda Industry Association (1995; 1999b).

Table 4-26 Supply of the Diaphragm and Ion Exchange Membrane Processes by Japanese Firms

Year	Diaphragm Process	Ion Exchange Membrane Process
1971	0	0
1972	0	0
1973	0	0
1974	7	0
1975	11	1

1976	6	1
1977	1	2
1978	3	1
1979	1	1
1980	0	2
1981	0	4
1982	0	4
1983	0	10
1984	0	10
1985	0	11
1986	0	11
1987	0	9
1988	0	6
1989	0	9
1990	0	2
1991	0	6
1992	0	3
1993	0	7
1994	0	9
1995	0	4
1996	0	12
1997	0	12
1998	0	16
1999	0	11
Total	0	0

Calculation based on Table 4-27, Table 4-28, Table 4-29, Table 4-30, Table 4-31, Table 4-32, and Table 4-33.

Table 4-27 Supply List of the Ion Exchange Membrane Process by Asahi Chemical Industry

Plant Site	Start-up	Capacity (t NaOH/year)
Asahi Chemical Industry Nobeoka, Japan	1975/77/82/86/91	160,000
Denki Kagaku Kogyo Ohme, Japan	1976	61,000
Saskatoon Chemicals Saskatoon, Canada	1977	30,000
St. Anne Chemicals Nackawic, Canada	1979	10,000
Carter Holt Harvey Pulp and Paper Kinleith, New Zealand	1981	10,000
Tasman Pulp and Paper Kawerau, New Zealand	1982/89	12,000

Akzo Nobel Chemicals Rotterdam, The Netherlands	1983/85	300,000
Nihon Keikinzoku Kanbara, Japan	1983/89	52,000
Kureha Chemical Ind. Nishiki, Japan	1985/90/97	104,000
Okayama Chemical Mizushima, Japan	1986/87/89/96	126,000
Yanguoxia Chemical Plant Lanzhou, China	1986	10,000
Kanto Denka Kogyo Shibukawa, Japan	1986	54,000
P.T. Sasa Inti Probolinggo, Indonesia	1986/88	10,000
Qiqihar General Chemical Factory Qiqihar, China	1986/91	30,000
Sumitomo Chemical Niihama, Japan	1987/89/92/96	113,000
Daku Chemical Factory Tianjin, China	1987/90/96	80,000
Niachlor (Olin) Niagara Falls, USA	1987/98	230,000
Beijing No. 2 Chemical Factory Beijing, China	1987	20,000
Sentrachem Ltd. (NCP Chlorkop) Kempton Park, South Africa	1988/90/96	92,000
Xuzhou Electrochemical Factory Xuzhou, China	1988/95	50,000
Oriental Chemical Industry Kunsan, South Korea	1991/95/96	43,000
Yunnan Chemical Works Kunming, China	1991	20,000
Baling Petrochemical Yueyang, China	1993/95/98	70,000
Jidong Chemicals Plant Tanshan, China	1993	10,000
Samsung Fine Chemicals Ulsan, South Korea	1994/95/99	133,000
Formosa Plastics Kaohsiung, Taiwan	1994	24,000
Modi Alkalies & Chemicals Alwar, India	1994/98	30,000
Qinghai Electrochemical Factory Xining, China	1998	10,000
Hindustan Organic Chemicals Rasayani, India	1996	20,000

DCM Shriram Consolidated Jhagadia, India	1996	52,000
LG Chemical South Korea	1996/98	200,000
Formosa Plastics Corporation Taiwan	1998	440,000
Xian Chemical Plant Xian, China	1997	40,000
CCM Malaysia	1996	22,000
Confidential	1999	92,000
Nanning Chemical Nanning, China	1998	20,000
Tianjin Chemical Tianjin, China	1998	85,000
Dow Chemical Canada	1997	70,000
Dow Chemical Germany	1998/99	330,000
Fuzhou No. 2 Chemical Plant China	1998	40,000
P.T. Sulfindo Adiusaha Indonesia	1997/98	215,000
Zhejiang Gala Chemical China	1998	20,000
Confidential	1998	540,000
P.T. Pabrik Kertas Tjiwi Kimia Indonesia	1998	22,000
Dow Chemical Stade, Germany	1998	130,000
Dow Chemical Free Port, U.S.A.	1999	550,000
Confidential	1999	80,000
Total		38,896,000

* Acilyzer Process
Source: Asahi Chemical Industry (1998).

Table 4-28 Supply List of the Ion Exchange Membrane Process by Asahi Glass

Plant Site	Start-up Date	Capacity (t NaOH/year)
Asahi Glass Kansai Factory Osaka, Japan	August 1978	10,000

Nippon Carbide Toyama, Japan	November 1980	17,000
THASCO Chemical Bangkok, Thailand	July 1981	62,000
Tsurumi Soda Kanagawa, Japan	December 1982	34,000
Kashima Chlorine & Alkali Ibaraki, Japan	July 1983	395,000
Nankai Chemical Industry Kochi, Japan	October 1983	15,000
Kansai Chlor-Alkali Osaka, Japan	April 1984	44,000
Central Chemical Kanagawa, Japan	April 1985	67,000
Mitsubishi Chemical Okayama, Japan	October 1985	127,000
Shin-etsu Chemical Niigata, Japan	November 1985	44,000
Confidential Japan	November 1985	Confidential
Hokkaido Soda Hokkaido, Japan	November 1985	15,000
Yee Fong Chemical & Ind. Taipei, Taiwan	November 1985	46,000
Hokkaido Soda Hokkaido, Japan	May 1986	152,000
Nankai Chemical Industry Wakayama, Japan	May 1986	35,000
Shanghai Tian Yuan Chemical Works Shanghai, China	July 1986	10,000
Asahi Glass Chiba, Japan	September 1986	216,000
Hanwha Chemical Corporation Yeosu, South Korea	April 1987	63,000
Egyptian Petrochemical Company Alexandria, Egypt	September 1987	85,000
Taiwan Chlorine Industry Kaohsiung, Taiwan	April 1988	115,000
ISK Singapore Singapore	January 1989	9,000
Asahimas Subentra Chemical Anyer, Indonesia	June 1989	293,000
Chung Hwa Pulp Corporation Hualien, Taiwan	October 1989	20,000
Mitsubishi Chemical Fukuoka, Japan	October 1989	40,000

Thai Plastic & Chemicals Public Rayong, Thailand	November 1989	26,000
Asahi Glass Kashima, Japan	November 1989	124,000
Shanghai Chlor-Alkali Complex Shanghai, China	April 1990	155,000
Hanwha Chemical Corporation Ulsan, Korea	May 1991	134,000
Jin-Hua Chemical Corporation Liao-Ning, China	October 1991	120,000
Solvay France	December 1991	Confidential
Solvay Belgium	April 1992	Confidential
Zhejiang Gala Chemical Zhejian, China	September 1993	33,000
Jiangmen Electrical Chemical Guangdong, China	June 1994	20,000
Tianjin Chemical Plant Tianjin, China	November 1994	25,000
Baoding Electro-Chlorine Factory Hebei, China	September 1995	20,000
Taiyuan General Chem. Ind. Plant Shanxi, China	January 1996	20,000
Vinythai Rayong, Thailand	March 1996	100,000
Bangladesh Chemical Industries Chittagong, Bangladesh	March 1997	7,000
Travancore Cochin Chemicals Kerala, India	May 1997	33,000
Changzhou Chemical Plant Jiangsu, China	May 1997	60,000
Huhhot Chemical General Factory Inner-Mongol, China	July 1997	20,000
THASCO Chemical Rayong, Thailand	October 1997	115,000
Borregaard Industries Sarpsborg, Norway	November 1997	42,000
Jiujiang Chemical Plant Jiangxi, China	December 1997	20,000
Shanghai Chlor-Alkali Complex Shanghai, China	December 1997	100,000
Taixin Xinpu Chemicals Jiangsu, China	May 1998	40,000
Thai Organic Chemicals Rayong, Thailand	June 1998	33,000

Asahi Glass Kashima, Japan	July 1998	166,000
Resin Factory of Ping Ding Shan Henan, China	January 1999	20,000
Indupa S.A.I.C. Bahia Blanca, Argentina	March 1999	76,000
THASCO Chemical Rayong, Thailand	July 1999	40,000
Total		27,704,000

* AZEC Process
Source: Asahi Glass (1999).

Table 4-29 Supply List of the Ion Exchange Membrane Process by Tokuyama Soda

Plant Site	Start-up Date	Capacity (t NaOH/year)
Tokuyama Soda Tokuyama	1977	10,000
Kokuto Chemical South Korea	1981	3,600
Formosa Plastics Kaohsiung, Taiwan	1982	n/a
Petrochemical Industries Shuaiba, Kuwait	1986	36,000
Dalian Chemical Industry Dalian, China	1987	n/a

* TSE Process
Source: Tokuyama (2002).

Table 4-30 Supply List of the Diaphragm Process by CEC

Plant	Start-up Date	Capacity (NaOH tonne/year)	Technology Type
Asahi Glass Kita-Kyushu, Japan	February 1974	16,300	DS
Ajinomoto Thailand	February 1974	6,000	DS
Sumitomo Chemical Ohita, Japan	September 1974 – March 1976	15,400	DS
Mitsui Toatsu Chemical Nagoya, Japan	December 1974	59,100	DS
Asahi Glass Kashima, Japan	March 1975	160,000	Glanor
Ajinomoto Kawasaki, Japan	April 1975	35,700	DS
Tokuyama Soda Tokuyama, Japan	April 1975	190,400	DS

Mitsui Toatsu Chemical Ohmuta, Japan	May 1975	80,200	DS
Toyo Soda Nanyo, Japan	June 1975	156,200	Glanor
Asahi Glass Chiba, Japan	August 1975	180,000	Glanor
Nihon Enka Vinyl Chiba, Japan	November 1975	86,600	DS
Osaka Soda Matsuyama, Japan	November 1975	44,400	DS
Toa Gosei Chemical Tokushima, Japan	February 1976	148,500	DS
Hodogaya Chemical Kohriyama, Japan	February 1976	24,500	DS
Nikkei Kako Kanbara, Japan	February 1976	36,600	DS
Sumitomo Chemical Kikumoto, Japan	March 1976	174,200	Glanor
Toyo Soda Yokkaichi, Japan	June 1976	70,800	DS
Nankai Chemical Tosa, Japan	April 1977 – August 1978	15,700	DS
Veb Chemi Combinat East Germany	July 1978	120,300	DS
BASF West Germany	November 1978	184,100	DS
AECI South Africa	December 1978	18,000	DS
Pechiney Ugine Kuhlmann France	May 1979	58,600	DS
China National Technical Import Corp., P. R. China	June 1988	200,000	DS
Total	-	16,652,800	-

Source: Chlorine Engineers Corp. (1999b).

Table 4-31 Supply List of the CME Ion Exchange Membrane Process by CEC

Plant	Start-up Date	Capacity (NaOH tonne/year)
Showa Enso Gushikawa, Japan	November 1980 June 1985 November 1989	2,640 240 240
Osaka Soda Amagasaki, Japan	June 1981 August 1982	1,920 960
Mitsui Toatsu Chemical	December 1983 – February	5,880

Ohmuta, Japan	1984	2,940
	April 1988	3,420
	October 1989	1,380
	December 1989	
Mitsui Toatsu Chemical Nagoya, Japan	November 1984 – June 1985	5,880
	April 1988	2,940
	October 1989	1,380
	December 1989	1,380
Mitsui Toatsu Chemical Osaka, Japan	December 1984	22,320
	December 1985	7,440
	February 1986	14,880
	March 1986	11,160
	May 1986	3,720
Chemfab Alkalis India	June 1985	9,000
	September 1988	4,500
Toa Gosei Chemical Japan	October 1985	31,320
	December 1985	31,320
	April 1988	3,960
Osaka Soda Kokura, Japan	December 1985	12,120
	February 1986	13,080
	December 1987	960
Nippon Soda Takaoka, Japan	March 1986	54,000
	September 1987	8,520
Kanto Denka Kogyo Mizushima, Japan	April 1986	11,760
	June 1986	3,960
Plant A Asia	July 1987	8,760
	February 1988	4,380
Toa Gosei Chemical Japan	November 1987	82,800
	March 1988	46,200
	March 1988	1,560
	July 1990	15,960
Bayer Germany	August 1987	792
Hodogaya Chemical Kohriyama, Japan	August 1988	13,680
	July 1990	34,200
Solvay Spain	July 1988	1,764
Plant B Japan	October 1988	5,520
Kanegafuchi Chemical Takasago, Japan	August 1989 – March 1990	139,800
	April 1990	18,840
	May 1991	45,240
Plant C Asia	April 1989	10,320
Plant D U.S.A.	April 1989	10,800
Plant E	February 1991	23,040

	September 1991	3,840
Korea Otsuka Korea	May 1990	21,600
Morro Verde Brazil	November 1992	19,560
FPC U.S.A. U.S.A.	May 1993	684,000
Hukumchand Jute and Ind. India	January 1993	15,660
Ashok Organic Ind. India	July 1993	19,980
Union Ajinomoto Philippine	May 1994	4,320
Vedan Enterprise Vietnam	September 1994	19,800
Vedan Enterprise Vietnam	August 1995	19,800
Ashok Organic Ind. India	March 1996	19,800
Southern Petrochemical Ind. India	July 1996	50,000
Petkim Petrokimya Holding Turkey	December 1996	15,800
Total	-	13,064,288

CME: Chlorine Engineers' Membrane Electrolyzer
Source: Chlorine Engineers Corp. (1999a).

Table 4-32 Supply List of the MBC Ion Exchange Membrane Process by CEC

Plant	Start-up Date	Capacity (NaOH tonne/year)
Mitsui Toatsu Chemical Nagoya, Japan	September 1982 – June 1983	61,680
Tokuyama Soda Tokuyama, Japan	February 1983 – December 1983	191,040
Kanto Denka Kogyo Mizushima, Japan	October 1983 – January 1984	52,920
Mitsui Toatsu Chemical Ohmuta, Japan	December 1983 – March 1984	61,680
Toyo Soda Yokkaichi, Japan	April 1983 – September 1983	58,800
Osaka Soda Matsuyama, Japan	April 1983 – July 1984	36,720
Hodogaya Chemical Kohriyama, Japan	February 1984 – August 1984	35,280

Sumitomo Chemical Ohita, Japan	November 1984	14,760
Toa Gosei Chemical Tokushima, Japan	May 1984 – October 1984	31,560
Name withheld by request Japan	April 1984 – December 1984	6,600
Chiba Chlorine & Alkali Chiba, Japan	October 1984 – March 1985	111,480
Ajinomoto Kawasaki, Japan	December 1984 – July 1985	38,160
Name withheld by request Japan	July 1984	5,880
Name withheld by request Overseas	May 1985	1,560
Total	-	5,664,960

MBC: Membrane Bag Cell
Source: Chlorine Engineers Corp. (1999c).

Table 4-33 Supply List of the BiTAC Ion Exchange Membrane Process by CEC

Plant	Start-up Date	Capacity (NaOH tonne/year)
Tosoh Japan	April 1992	972
Tosoh Japan	September 1993	1,204
Confidential Japan	February 1994	14,820
Confidential Korea	October 1994	27,000
Tosoh Japan	July 1995	20,000
Confidential Korea	December 1995	35,470
Polifin South Africa	April 1996	22,410
Confidential Japan	August 1996	87,900
Tosoh Japan	December 1996	118,900
Wuxi China	May 1997	30,000
P & G Italy	February 1998	8,382
Tosoh Japan	June 1998	40,000

Wuhu China	September 1998	20,000	
Bayer U.S.A.	January 1999	320,000	
Honghe China	March 1999	50,300	
Tosoh Japan	June 1999	96,310	
Tosoh Japan	June 1999	325,000	
Elite Chemicals Pty. Australia	October 1999	2,880	
Total	-	9,772,384	

BiTAC: Bipole of Tosoh and CEC
Source: Chlorine Engineers Corp. (2000).

Table 4-34 Operating Period of the Diaphragm Process at Chlor-Alkali Plants in Japan

Plant	Start-up Year of Diaphragm Process	Conversion to Ion Exchange Membrane Process	Operating Years of Diaphragm Process
Asahi Glass, Kita-Kyushu	1974	1982	8
Sumitomo Chemical, Ohita	1974	1984	10
Mitsui Toatsu, Nagoya	1974	1984	10
Mitsubishi Gas Chemical, Naniwa[a]	1974	1984	10
Kanegafuchi Chemical, Takasago	1974	1989	15
Central Chemical, Kawasaki	1974	1985	11
Sanyo Kokusaku Pulp, Iwakuni[b]	1974	1999	25
Showa Enso, Gushikawa	1974	1980	6
Tsurumi Soda, Tsurumi	1974	1982	8
Nippon Soda, Nihongi	1974	1988[c]	14
Ajinomoto, Kawasaki	1975	1984	9
Tokuyama Soda, Tokuyama	1975	1983	8
Mitsui Toatsu, Ohmuta	1975	1983	8
Nihon Vinyl Chloride, Chiba[d]	1975	1984	9
Osaka Soda, Matsuyama	1975	1983	8
Hokkaido Soda, Tomakomai	1975	1986	11
Shin-etsu Chemical, Naoetsu	1975	1985	10
Osaka Soda, Amagasaki	1975	1981	6
Denki Kagaku Kogyo, Ohme	1975	1976	1
Mitsubishi Monsanto, Yokkaichi	1975	1981[e]	6
Tekkosha, Sakata[f]	1975	1986	11
Mitsubishi Chemical, Kurosaki	1975	1989	14
Ryonichi, Mizushima[g]	1975	1985	10

Asahi Glass, Kashima	1975	1989	14
Toyo Soda, Nanyo	1975	1995	20
Asahi Glass, Chiba	1975	1986	11
Kanto Denka Kogyo, Mizushima	1975	1986	11
Chiba Chlorine Chemical, Chiba	1975	1982[h]	7
Toagosei Chemical, Tokushima	1976	1987	11
Hodogaya Chemical, Kohriyama	1976	1984	8
Nikkei Kako, Kanbara	1976	1983	7
Toyo Soda, Yokkaichi	1976	1983	7
Sumitomo Chemical, Kikumoto	1976	1987	11
Kureha Chemical, Nishiki	1976	1985	9
Nankai Chemical, Tosa	1977	1983	6
Average	-	-	10.0

a: The Naniwa plant of Mitsubishi Gas Chemical was transferred to Kansai Chlor-Alkali in 1984 (Mitsubishi Gas Chemical, 2001).

b: Sanyo Kokusaku Pulp merged with Jujo Paper Industries in 1993, creating Nippon Paper Industries (Nippon Paper Industries, 2001).

c: The Nihongi plant of Nippon Soda was shut down in 1988 (*Nikkei Kinyu Shinbun*, 1987).

d: Nihon Vinyl Chloride was renamed to Chiba Chlorine & Alkali in 1985 (Sumitomo Chemical, 1998).

e: The Yokkaichi plant of Mitsubishi Monsanto (currently Mitsubishi Chemical MKV) was closed in 1981 (Mitsubishi Chemical MKV, 2001).

f: Tekkosha was acquired by Toyo Soda in 1975 (Tosoh, 2001).

g: The Mizushima plant of Ryonichi was transferred to Mitsubishi Chemical in 1986 (Mitsubishi Chemical, 2001).

h: The Chiba plant of Chiba Chlorine Chemical ceased its operation in 1982 (*Nihon Keizai Shinbun*, 1982).

Sources: Table 4-4 and Table 4-19.

5. Environmental Regulation and Technological Change in the Western European Chlor-Alkali Industry

5.1 Imposition of Emission Standards on Mercury

A serious concern was also growing in Western Europe during the 1960s about the impacts of mercury on the environment. However, the cause for the concern was the depletion of bird populations as a consequence of methyl mercury poisoning from seed grain, rather than the impacts on human health like those observed at the Minamata Bay in Japan. High mercury concentrations were also found in other wild fauna, particularly in predator species (Organisation for Economic Co-operation and Development, 1974). As scientific investigations were initiated, information about the use, disposal, fate and effects of mercury and mercury compounds grew gradually. Although some of the research results suggested that inorganic mercury could be transformed into methyl mercury by the action of microorganisms under aerobic conditions (e.g. Jensen and Jernelov, 1969), there was no report which confirmed that finding quantitatively. Nevertheless, that prompted fears that regulations should be imposed on emissions of mercury per se, in addition to methyl mercury, whose intake to human body caused the Minamata disease. Several policy measures were introduced in Sweden in the late 1960s to restrain the discharge of mercury from chlor-alkali plants, requiring these firms to install the "best available technology." These measures, however, did not include the setting of quantitative standards for liquid effluents containing mercury (Organisation for Economic Co-operation and Development, 1974). Similarly, there were no strict regulations introduced in the 1960s on mercury emissions from chlor-alkali plants in other countries in Western Europe.

It was in the 1970s that two institutions in Western Europe, namely, the Paris Commission and the European Community, that began to work almost in parallel to regulate mercury emissions from chlor-alkali plants based in Western Europe. In the following sections, we look at these regulations actually introduced by the two institutions.

5.1.1 Paris Commission

At the end of the 1960s and the beginning of the early 1970s, several regional agreements for the protection of the marine environment surrounding the Western Europe started to be

established[81]. With the increasing concern on its impacts on the environment, mercury became one of the substances which received a special attention in these agreements. In February 1972, the Convention for the Prevention of Marine Pollution by Dumping from Ships and Aircraft, the so-called Oslo Convention, was adopted, and mercury was included in the list of the substances which were prohibited to be dumped into the sea. The prohibition of the dumping of mercury was extended to a global scale when the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Dumping Convention) was agreed in November 1972.

Negotiations on this issue resulted in the signing of the Convention for the Prevention of Marine Pollution from Land-Based Sources (Paris Convention) on 4 June 1974 (Convention for the Prevention of Marine Pollution from Land-Based Sources, 1974). The members of the convention included Denmark, Sweden, France, Norway, The Netherlands, United Kingdom, Portugal, Spain, Iceland, Germany, Belgium, and Ireland. With the European Economic Community also joining the convention by adding its signature in June 1975, the Paris Convention finally entered into force in May 1978[82]. As the sea area covered by the Paris Convention was basically the North-East Atlantic, defined as extending westwards to the east coast of Greenland, eastwards to the continental North Sea coast, south to the Straits of Gibraltar and northwards to the North Pole, the maritime area did not include the Baltic or Mediterranean seas; the Helsinki and Barcelona Conventions applied in these sea areas[83].

The members of the Paris Convention agreed "to eliminate, if necessary by stages, the pollution of the maritime area from land-based sources by substances listed in Part I of Annex A to the present Convention" (Convention for the Prevention of Marine Pollution from Land-Based Sources, 1974). "Pollution from land-based sources" meant the pollution of the maritime area through watercourses, from the coast, including introduction through underwater or other pipelines, from man-made structures placed within the limits of the

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[81] One of the earlier examples is the Agreement for Cooperation in Dealing with Pollution of the North Sea by Oil of 1969 (Bonn Agreement).

[82] The Convention for the Protection of the Marine Environment of the North-East Atlantic, the OSPAR Convention, was adopted in September 1992 and entered into force in March 1998. The new Convention replaces the Oslo and Paris Conventions, but Decisions, Recommendations and all other agreements adopted under those Conventions will continue to be applicable, unaltered in their legal nature, unless they are terminated by new measures adopted under the 1992 OSPAR Convention (Convention for the Protection of the Marine Environment of the North-East Atlantic, 1992).

maritime area, and by emissions into the atmosphere from land or from man-made structures. Mercury, along with other substances such as cadmium and organohalogen compounds, was placed in the "blacklist." They were selected based on the three criteria, namely, persistence, toxicity or other noxious properties, and tendency to bio-accumulation. By the time of the establishment of the convention, it had come to be generally regarded that mercury compounds possessed all three characteristics.

In order to carry out the undertakings set out in the convention, the member countries, individually or jointly, had to implement "programmes and measures" (Convention for the Prevention of Marine Pollution from Land-Based Sources, 1974). They were to include specific regulations or standards governing the quality of the environment, discharges into the maritime area, including discharges into watercourses and emissions into the atmosphere which would affect the maritime area, and the composition and use of substances and products. The convention stipulated that these programmes and measures should take into account the latest technical developments and that the programmes should contain time limits for their completion.

The Paris Commission was created, comprising representatives of each of the members. The commission then set up a standing scientific group, the Technical Working Group, to examine and discuss technical issues in detail. The standing scientific groups were usually assisted in its tasks by preparatory work undertaken by ad hoc or permanent working groups on specific subjects. The working groups reported on their work to the appropriate standing technical group, and each standing group in turn reported on its work to the Commission. The Commission had the power to take decisions and make recommendations, and decisions could be adopted by unanimity. In the case of programmes and measures, when unanimity could not be obtained, they nevertheless might be adopted by a qualified majority, but in such cases they were applicable only to those countries which voted for them (Oslo and Paris Commissions, 1984).

The Commission conducted several studies on substances, particularly those listed in the blacklist, that is, the Part I of Annex. During each of these studies the technical groups tried to determine the origins of the sources of pollution. This was one of the most difficult tasks because these sources were often diffuse; they were not restricted to sources linked with

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[83] The Convention on the Protection of the Marine Environment of the Baltic Sea Area was established in 1974 (Helsinki Convention), and the Convention for the Protection and Development of the Marine Environment and Coastal Region of the Mediterranean Sea in 1976 (Barcelona Convention).

a certain type of production but also included losses associated with the use and consumption of other products. The origins of emissions had to be identified before any decision could be taken regarding programmes and measures, and mercury was no exception.

The sources of mercury emission included chlor-alkali plants, agriculture, dentistry, electrical apparatus, control instruments, and paints. As Table 5-1 shows, the chlor-alkali industry was the only sector in which relatively abundant data was available on the discharges of mercury[84].

Table 5-1 Emissions of Mercury in European Countries in the 1970s

Country	Chlor-Alkali Industry	Agriculture	Dentistry	Electrical Apparatus	Control Instruments	Paints
Austria	3,307[a]	n/a	n/a	n/a	n/a	n/a
Belgium	18,621	n/a	n/a	n/a	n/a	n/a
Denmark	243	1,114	~ 3,000	~ 6,400	~ 2,000	n/a
Finland	1,210	3,540	n/a	n/a	n/a	n/a
France	54,281	n/a	n/a	n/a	n/a	n/a
Germany	101,000[b]	n/a	n/a	n/a	n/a	n/a
Greece	1,500[a]	n/a	n/a	n/a	n/a	n/a
Iceland	n/a	n/a	n/a	n/a	n/a	n/a
Ireland	n/a	n/a	n/a	n/a	n/a	n/a
Italy	155,000[c]	n/a	n/a	n/a	n/a	n/a
Netherlands	~ 4,800	700	4,500	n/a	n/a	~ 150
Norway	2,280	631	n/a	n/a	n/a	n/a
Portugal	n/a	n/a	n/a	n/a	n/a	n/a
Spain	n/a	n/a	n/a	n/a	n/a	n/a
Sweden	2,900	n/a	n/a	n/a	n/a	n/a
Switzerland	2,650	n/a	n/a	n/a	n/a	n/a
UK	282,632	n/a	n/a	n/a	n/a	n/a

Data is of 1975 otherwise noted. Figures are in kilograms.
a: 1974 data
b: 1971 data
c: 1973 data
Source: Organisation for Economic Co-operation and Development (1981).

Emitted mercury entered the sea through several pathways, namely via the atmosphere, rivers, pipelines linked to industry, sewage, and dumped waste. The Paris Commission, despite the scarcity of relevant data, estimated that the chlor-alkali industry accounted for

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[84] Note that the data on mercury in the chlor-alkali industry was assembled in different ways. Some countries equated the figures for the consumption of mercury in the chlor-alkali industry with those for mercury supplied to the industry whereas others equated the figures for the chlor-alkali mercury consumption with those for the industry's mercury emissions. That would make direct comparisons between countries difficult.

40 % of the mercury input to the marine environment in the middle of the 1970s (Oslo and Paris Commissions, 1984). Accordingly, mercury discharges from the chlor-alkali industry became the primary subject for programmes and measures to be adopted.

As the convention itself did not give any quantitative definition of pollution or a level of pollution, the programmes and measures to be taken were open to wide interpretation and possibilities. The majority of the countries favored a policy for elimination of pollution by imposing strict limits on discharges, that is, by the uniform emission standards approach (Paris Commission, 1983a). Among the reasons cited for the advantages of applying emission standards were that emission standards could be based on the "best technical means available"; that they would enable standards to be imposed on an international basis; that emission standards would be easily controlled, enabling industry to take the necessary decisions; and that the emission standard approach would not exclude the use of more stringent standards if demanded by local conditions.

On the other hand, the United Kingdom and Portugal preferred the adoption of environmental quality objectives. Under this system, which was concerned with the use of the receiving waters, rather than the discharges into them, water quality standards were set to which all discharges would have to conform. The advantages of the environmental quality objective approach, its supporters argued, were that it would concentrate upon the protection of the quality of the aquatic environment, the aim and purpose of the convention, after all; that it would take account of all discharges as well as all natural or background levels of particular substances; and that it would also take account of the overall conditions of the water, including its assimilative capacity, and the differences between inland rivers and turbulent coastal waters.

Despite intensive discussions at several meetings of the Technical Working Group[85], it was not possible to a make a conclusive comparison between the two policies on the basis of the monitoring data available. In November 1978, at its first meeting, the Paris Commission therefore decided to follow the dual approach of emission standards and environmental quality objectives for a period of five years (Paris Commission, 1978a). The agreed line of action included that there would be a uniform emission standard for mercury discharges from existing and new plants and that quality objectives for mercury should be formulated for

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[85] For example, in the Fifth Meeting of the Technical Working Group, a number of questions and arguments were put to the United Kingdom, the main proponent of the EQO approach, which in turn made its response, which was shared by Portugal (Paris Commission, 1977).

organisms, as soon as possible for water and, if appropriate, for sediments. The programmes and measures decided upon in implementing the emission standard approach were carried out only by the countries applying them, which represented the majority, whereas programmes and measures for environmental quality objectives were applicable only to the supporters of this type of policy. The measures regarding new plants, however, were applied to all the countries, whether the emission standard or environmental quality objective approach was adopted.

The emission standard approach set maximum values to be applied for mercury discharges in effluent from existing and new chlor-alkali production plants. These maximum values differed, depending on the type of plants, namely, those which operate with brine used only once, generating more mercury emissions, or those with recycled brine. Furthermore, different maximum values were adopted according to whether they were to be applied at the outlet from the whole production site or at the outlet from the treatment plant. While many of the measures adopted were binding decisions, recommendations were used in cases where an agreement on binding decisions was difficult to reach.

The first decision on limit values was made at the second meeting in June 1980 as PARCOM Decision 80/2. Table 5-2 gives the limit values for mercury emissions in water from existing and new brine-recirculation chlor-alkali plants. In particular, the limit value, as a monthly mean, was fixed at 0.5 g of mercury per tonne of chlorine production capacity. These limit values were to apply from July 1, 1983, provided that limit values for waste brine plants have been agreed by that date. As it was acknowledged that discharges from the factory site as a whole could greatly exceed the emissions at the exit of the treatment unit, the Commission asked the Working Group on Mercury Pollution to make proposals for limit values for chlor-alkali factory sites, which would cover all mercury-containing waste water streams.

Table 5-2 PARCOM Decision 80/2 on Limit Values for Mercury Emissions in Water from Existing and New Brine Recirculation Chloralkali Plants (exit of the purification plant)

Limits, expressed as maximum concentration of mercury	Limit, expressed as maximum amount of mercury	Deadline for existing emissions	Remarks
The limits, expressed as maximum concentration of mercury, are calculated by dividing the limits	0.5 g of mercury per metric tonne of chlorine production capacity as a monthly	1 July 1983	The limits given in the preceding columns are applicable to the mercury arising from

(expressed as maximum amounts of mercury) by the amount of water used per metric tonne of chlorine production capacity.	mean, and 2.0 g of mercury per metric tonne of chlorine production capacity as a daily mean.		the production process and thus to be observed at the exit of the purification plant of the installation.

Source: Paris Commission (1980c).

At the third meeting held in 1981, the Commission examined a proposal prepared by the Technical Working Group concerning limit values for mercury emissions in water to be applied to existing waste brine chlor-alkali plants, that is, those without recirculation of brine. As previous reservations were lifted, the limit values for mercury emissions from the existing waste brine chlor-alkali plants were adopted in PARCOM Decision 81/1. Table 5-3 gives the limit values, which were fixed at 8 g of mercury per tonne of chlorine production capacity as a monthly mean to be achieved by July 1, 1983, and at 5 g of mercury per tonne of chlorine production capacity as a monthly mean to be achieved by July 1, 1986.

Table 5-3 PARCOM Decision 81/1 on Limit Values for Existing Waste Brine Chlor-alkali Plants

Limits, expressed as maximum concentrations of mercury	Limit, expressed as maximum amount of mercury	Deadline for existing emissions	Remarks
The limits, expressed as maximum concentration of mercury, are calculated by dividing the limits (expressed as maximum amounts of mercury) by the amount of water used per metric tonne of chlorine production capacity	(i) 8 g mercury per metric tonne of chlorine production capacity as a monthly mean; (ii) 5 g of mercury per metric tonne of chlorine production capacity as a monthly mean.	By 1 July 1983 By 1 July 1986	The limits given in the preceding columns are applicable to the total mercury arising in all mercury-containing wastewater streams and thus to be observed at the exit of the chloralkali factory site.

Source: Paris Commission (1981b).

After intense discussions at the same meeting, the Commission also decided on limit values for existing brine recirculation plants to be applied at the exit of the factory site (PARCOM Decision 81/2). They were 1.5 g of mercury per tonne of chlorine production capacity as a monthly mean and 6 g of mercury per tonne as a daily mean to be applied from July 1, 1983, as given in Table 5-4. These values were legally binding.

Table 5-4 PARCOM Decision 81/2 on Limit Values for Existing Brine Recirculation Chlor-Alkali Plants (exit of the factory site)

Limit values, expressed as maximum concentration of mercury	Limit values, expressed as maximum amount of mercury	Deadline for existing emissions	Remarks
The limit values, expressed as maximum concentration of mercury, as calculated by dividing the values in column 2 (expressed as maximum amounts of mercury) by the amount of water used per metric tonne of chlorine production capacity	1.5 g of mercury per metric tonne of chlorine production capacity as a monthly mean, and 6 g of mercury per metric tonne of chlorine production capacity as a daily mean.	1 July 1983	The limit values given in the preceding columns are applicable to the total mercury arising in all mercury-containing wastewater streams and thus to be observed at the exit of the chloralkali factory site.

Source: Paris Commission (1981a).

Regarding the existing brine-recirculation chlor-alkali plants, the Commission had actually proposed the adoption of more stringent limit values to be applied from July 1, 1986: 0.5 g of mercury per tonne of chlorine production capacity as a monthly mean and 2 g of mercury per tonne as a daily mean at the exit of the factory site. The Technical Working Group had considered these proposals and had recommended that the Commission should adopt the limit values as legally binding. While most of the countries were in favor of a legally binding decision on the limit values, the EEC reserved its position, because the proposed standards were more stringent than those in the relevant EEC Directive, and Spain also claimed that it was not able to accept the adoption of a more stringent limit value (Paris Commission, 1985c). In 1985, the Commission finally agreed to recommend the values referred above to the member countries, with the exception of Spain, which maintained a reservation (PARCOM Recommendation 85/1).

Table 5-5 PARCOM Recommendation 85/1 on Limit Values for Mercury Emissions in Water from Existing Brine Recirculation Chlor-Alkali Plants (exit of factory site)

Limit values, expressed as maximum amount of mercury	Deadline for existing emissions	Remark
0.5 g of mercury of chlorine production capacity as a monthly mean 2 g of mercury per tonne as a daily mean	1 July 1986	The limit values are applicable to the total mercury arising in all mercury-containing wastewater streams and thus to be observed at the exit of the chlor-alkali factory site.

Source: Paris Commission (1985b).

In the meantime, since the environmental quality objective approach was also approved in 1978 along with the uniform emission standards approach, a task had been left to the Commission to set environmental standards for organisms, water and sediments with regard to quality objectives for mercury. In 1980, the Commission adopted its first environmental standards to be applied for organisms (PARCOM Decision 80/1). Based on the Technical Working Group's recommendation, it was decided that a standard of 0.3 mg/kg of mercury in wet fish flesh should be the environmental standard for organisms.

> **PARCOM Decision 80/1 on Environmental Quality Standard for Mercury in Organisms**
>
> The Commission adopted TWG's recommendation that a standard of 0.3 g mg/kg of mercury in wet fish flesh should be the environmental standard for organisms.
>
> *Source: Paris Commission (1980b).*

Regarding the environmental quality objectives for water and sediments, the Technical Working Group had been unable to make progress on an environmental standard for water or on whether an environmental standard for sediments was appropriate. Then the Commission, after intensive discussions, confirmed its approval in principle of a "standstill" principle for water, that is, that the concentrations in water should not increase (Paris Commission, 1980a). Those countries having adopted the environmental quality objective approach were asked to submit data to the Commission every year on the emission standards fixed in order to respect the quality objectives. In the case of the United Kingdom, the emission standards were set in the range of 0 – 20 g of mercury per tonne of chlorine production capacity (Paris Commission, 1985a).

Concerning new plants, the Commission made a recommendation as early as 1978 that new waste-brine plants should not be built in the future (PARCOM Recommendation 78/1).

> **PARCOM Recommendation 78/1**
>
> (b) The Commission recommends that no new waste-brine plans should be built.
>
> *Source: Paris Commission (1978b).*

By the third meeting held in 1981, the Technical Working Group had not been able to decide whether the limit values for new plants should be 0.5 g or 1 g of mercury per tonne of chlorine production capacity (Paris Commission, 1983b). During the meeting, all countries

except France were able to agree that in the construction of new plants account must be taken of the best technical means available to prevent pollution of the maritime area by mercury and were prepared to agree on the limit value of 0.5 g per tonne for new brine-recirculation plants. France argued that a global programme should be adopted, covering both the environmental quality objective and the emission standard approaches as well as prohibiting the construction of new waste-brine plants. With the reservation of France, the Commission was not able to reach a decision on this issue. Nevertheless, the previous recommendation that no new waste-brine plants should be built was maintained.

At the same meeting, the Commission asked the Working Group on Mercury Pollution to make an evaluation of mercury-free chlor-alkali production technologies. The Working Group expressed its opinion that the ion exchange membrane process was very interesting from the economic viewpoint as well as from the environmental aspect. Accordingly, the Technical Working Group agreed to recommend to the Commission that, when the construction of new plants was considered, the use of the ion exchange membrane process should be encouraged whenever circumstances permit. Furthermore, it was also recommended that when major changes were to take place in the existing mercury-based plants, replacement with the ion exchange membrane process should be considered.

With the recommendations of the Mercury Working Group and the Technical Working Group on the feasibility of the ion exchange membrane process, the Commission discussed in its fourth meeting held in June 1982 whether it would be feasible to impose a prohibition on the mercury process in the construction of new chlor-alkali electrolysis plants (Paris Commission, 1984). Although some support was expressed for the eventual phasing out of the mercury process, a number of delegations expressed reservations on a total prohibition at the present time. It was pointed out that the new plants with the ion exchange membrane process being constructed in the Netherlands and Portugal at that time were, although promising, not yet operational and that consequently it would be wise to wait for actual experience with this new technology. In addition, it was expected that experience in countries outside Europe would also become available.

In the end, the Commission made a decision, which was to be effective from July 1, 1982, that authorizations for new plants[86] might be granted only if such authorizations

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[86] "New plants" means existing industrial plants whose capacity for the electrolysis of alkali chlorides was to be substantially increased after July 1, 1982, as well as industrial plants which would become operational after July 1, 1982 (Paris Commission, 1982).

included a reference to the standards corresponding to the "best technical means available" for preventing discharges of mercury (PARCOM Decision 82/1). According to the Commission, the application of the best technical means available would make it possible to limit discharges of mercury from the site of a new industrial plant using the recycled-brine process to less than 0.5 g/tonne of installed chlorine production capacity. These arrangements for the authorization of new plants had to be applied by all members, whether they followed the environmental quality objective or the emission standard approach.

Table 5-6 PARCOM Decision 82/1 on New Chloralkali Plants using Mercury Cells

Condition for authorization of new plants	Achievable level of discharges of mercury	Date for the decision to be effective
Application of the best technical means available	Less than 0.5 g/tonne of installed chlorine production capacity	1 July 1982

Source: Paris Commission (1982).

Furthermore, the Commission agreed that when the construction of new plants was being considered, the use of mercury-free technologies, particularly the ion exchange membrane process, should be encouraged whenever circumstances permitted. It was also decided that the Commission would consider again later whether stricter rules, including the possibility of prohibiting the use of the mercury process, would be appropriate. The Technical Working Group examined the latest information available on the development of alternative technologies and confirmed its earlier opinion that from the technical point of view mercury-free production processes should be encouraged whenever new plants were constructed. At the Commission's meeting held in 1985, however, three countries did not accept the strengthening of the measures on the use of mercury-free technologies, and the Commission's earlier recommendation was retained unchanged (Paris Commission, 1985c).

5.1.2 European Community

The work of the Paris Commission was carried out more or less in parallel with a similar work conducted by the Commission of the European Communities. The differences between the work of the two organizations have been recognized, and it was particularly emphasized that that the Paris Commission considered pollution specifically from the point of view of protecting the marine environment. Nevertheless, a significant degree of duplication has been

observed in the regulations of the two organizations, including those issued on mercury emissions from chlor-alkali plants.

In November 1973, the European Community adopted its First Action Programme on the Environment (Council of the European Communities, 1973). The Action Programme indicated that a detailed examination would be carried out of the different possible methods, such as establishing discharges or emission standards, in order to achieve and respect the quality objectives fixed with regard to water pollution. The programme stated that priority would be given to the regulation of discharges of toxic, persistent and bioaccumulative substances into fresh water.

In order to meet these objectives, the Council of the European Communities started to adopt a series of Directives[87] proposed by the Commission. In May 1976, the Council approved a directive on pollution caused by certain dangerous substances discharged into the aquatic environment of the Community (Council of the European Communities, 1976). Directive 76/464/EEC identified the most dangerous substances, including mercury, in the "List I" or "blacklist" and established the basic principle according to which any discharge of a blacklist substance must be authorized beforehand by the relevant authority in the member countries. This authorization, which could only be granted for a limited period, was required to lay down an emission standard to be respected. As in the case of the Paris Commission, the Council agreed in this directive that, parallel to the emissions standards, quality objectives should also be established for substances on the blacklist. While this parallel approach was formally adopted, the directive indicated clearly that as a general rule the emission standards should be applied. This framework directive established the basic principles of regulations on aquatic pollution in the Community and was followed by a number of implementing directives.

In June 1979, the Commission, in accordance with the agreement reached in the parent Directive 76/464, submitted to the Council two specific proposals for directives concerning emission standards and quality objectives respectively to be applied to mercury discharges by the chlor-alkali industry. In March 1982, after long and difficult negotiations, the Council finally adopted a single directive, Directive 82/176, which contained limit values and quality objectives, together with methods of measurement and monitoring, concerning mercury

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[87] Article 189 of the Treaty of Rome indicates that "[a] directive shall be binding, as to the result to be achieved, upon each Member State to which it is addressed, but shall leave to the national authorities the choice of form and methods" (Craig and de Burca, 1995).

emissions from chlor-alkali plants (Council of the European Communities, 1982). This directive, concerned with only one substance discharged by only one manufacturing process,[88] was the first of the daughter directives resulting from the framework Directive 76/464 on water pollution caused by dangerous substances[89].

The limit values and the time limits by which they were to be complied with are given in Table 5-7. The authorizations issued by the member countries had to contain provisions at least as stringent as these limit values and were to be reviewed at least every four years. Different limit values were laid down for plants using the lost brine and recycled brine processes. The limit values for mercury discharges were expressed in two ways, namely, in terms of concentration and quantity. The directive stated that the limit values expressed in terms of concentration should, in principle, not be exceeded. However, because the concentration of mercury in effluent depends on the volume of water involved, which varies with different processes and plants, the limit values expressed in terms of quantity in relation to installed chlorine capacity had to be observed in all cases. The limit values were expressed as monthly average, and daily average limit values were specified as four times the corresponding monthly average values.

Table 5-7 Limit Values for Mercury Discharges by the Chlor-Alkali Industry in the Council Directive 82/176/EEC

Unit of measurement	Limit values (monthly average)		Remarks
	1 July 1983	1 July 1986	
Concentration for recycled and lost brine plants (micrograms of mercury per litter)	75 µg/l	50 µg/l	Applicable to the total quantity of mercury present in all mercury-containing water discharged from the site of the industrial plant
Quantity for recycled brine plants (grams of mercury per tonne of installed chlorine production capacity)	0.5 g/t	0.5 g/t	Applicable to the mercury present in effluent discharged from the chlorine production unit
	1.5 g /t	1.0 g/t	Applicable to the total quantity of mercury present in all mercury-containing water discharged from the

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[88] A separate directive was adopted in March 1984 (Directive 84/156/EEC), which covered mercury discharges by sectors other than the chlor-alkali industry (Council of the European Communities, 1984a).
[89] As regards other dangerous substances, a directive on limit values and quality objectives for cadmium discharges (Directive 83/513/EEC) was adopted in September 1983 (Council of the European Communities, 1983). Another directive was adopted in October 1984 for discharges of hexachlorocyclohexane (Directive 84/491/EEC) (Council of the European Communities, 1984b).

			site of the industrial plant
Quantity for lost brine plants (grams of mercury per tonne of installed chlorine production capacity)	8.0 g/t	5.0 g/t	Applicable to the total quantity of mercury present in all mercury-containing water discharged from the site of the industrial plant

Source: Council of the European Communities (1982).

Four quality objectives for mercury concentrations were set in the directive, as laid down in Table 5-8. Those countries which adopted the environmental quality objective approach were required to fix emission standards so that the appropriate quality objectives would be complied with in the area affected by discharges of mercury from the chlor-alkali industry. The directive also stipulated that the concentration of mercury in sediments or in shellfish should not increase significantly with time. Furthermore, the quality of the waters had to be sufficient to comply with the requirements of any other directive applicable to such waters as regards the presence of mercury.

Table 5-8 Quality Objectives for Mercury Discharges by the Chlor-Alkali Industry in the Council Directive 82/176/EEC

Organism/water	Quality objective
Fish	0.3 mg/kg wet flesh
Inland surface waters	1 µg/l
Estuary waters	0.5 µg/l
Territorial sea waters and internal coastal waters	0.3 µg/l

Concentrations of mercury in waters are arithmetic means of the results obtained over a year.
Source: Council of the European Communities (1982).

The directive made it clear that countries could grant authorizations for new plants only if such authorizations contain a reference to the standards corresponding to the best technical means available for preventing discharges of mercury. The directive included a statement of the Council and Commission, while not legally forming part of the directive, that "the application of the best technical means available makes it possible to limit discharges of mercury from the site of a new industrial plant using the recycled-brine process to less than 0.5 g/tonne of installed chlorine production capacity" (Council of the European Communities, 1982). A country, where for technical reasons the intended measures did not conform to the best technical means available, was required to provide the Commission with the justifications for these reasons.

The treatment of new plants was an issue of particular importance in the process of formulating the directive (Haigh, 1987). Originally the Commission proposed limit values for new plants set at the level to be achieved by recycled brine plants in July 1989 whereas the proposal for quality objectives made no such reference. France and Italy, on the one hand, argued that, if a country applying quality objectives did not have to apply the limit values that would otherwise apply in the case of a new plant, there would be distortion of competition. The United Kingdom, on the other hand, thought it was important to uphold the principle underlying the use of quality objectives; that is, the emission standard to be applied to any plant, whether new or not, should be related to the quality to be met in the receiving waters. The resultant compromise was the directive which actually avoided requiring best technical means to be used, but in effect creating an atmosphere in which it would be very difficult not to use them. It was implicitly understood that it would be unrealistic to build a new plant which did not make use of processes based on the best technical means available.

These regulations, including the Decisions, Recommendations, and Directives, imposed since the 1970s were aimed at reducing mercury emissions to water by basically using measures of the end-of-pipe type. It was in the late 1980s that atmospheric emissions of mercury started to become the target of regulations. In 1988 the Paris Commission decided that its work on atmospheric emissions should concentrate on measures aimed at limiting the emissions of heavy metals and established the Atmospheric Inputs Working Group (Paris Commission, 1989). The Commission made discussions in the following year on a draft of a decision on reducing atmospheric emissions of mercury from the existing chlor-alkali plants. The draft specified a standard of 2 g of mercury per tonne of chlorine capacity for emissions to the atmosphere, including mercury in hydrogen released to the atmosphere or burnt. This standard was to be complied with by the end of 1994 unless there was a firm commitment that the plant would be converted to a mercury-free process by the year 2000. The draft also included a recommendation for a complete phasing out of the mercury process by 2010 (Paris Commission, 1990). As it was pointed out, however, that all countries were already obliged to use the best technical means and that the technology necessary to achieve the envisaged reductions was available, the Commission could not agree on the decision.

Meanwhile, environmental ministers from the North Sea coastal countries convened in The Hague, the Netherlands, in March 1990 for the Third International Conference on the

Protection of the North Sea (INSC)[90]. The principal task of the conference was to review the implementation of commitments made at the first and second conferences, held in Bremen in 1984 and London in 1987, respectively[91]. A list of 36 hazardous substances was identified with the target of 50% or more reduction between 1985 and 1995, and, in particular, a 70% reduction target was established for the most dangerous substances to the environment, namely, dioxins, cadmium, lead, and mercury. The adopted Hague Declaration included what went beyond the regulations of the Paris Commission or the European Commission in regard to mercury emissions from chlor-alkali plants. That is, the environmental ministers agreed that existing mercury-based plants should be phased out as soon as practicable on a national basis with the objective that they should be phased out completely by 2010. It was decided that mercury plants should be required to meet by 1996 a limit value of 2 g of mercury per tonne of chlorine capacity for emissions to the atmosphere, including those in hydrogen, unless there was a firm commitment that the plant would be converted to a mercury-free process by the year 2000 (Third International Conference on the Protection of the North Sea, 1990). While this declaration was not legally binding, it represented a political commitment by the environmental ministers[92].

Several months later, following the measures agreed in the Hague Declaration, the Paris Commission adopted a decision, PARCOM Decision 90/3. A limit value of 2 g of mercury per tonne of chlorine capacity was specified for the atmospheric mercury emissions, including mercury in hydrogen. And, most significantly, the decision recommended that existing mercury plants should be completely phased out by 2010. It was formulated as a recommendation because a number of member countries, during negotiations at the Paris Commission, were not able to accept the proposed phase-out in the form of a PARCOM Decision.

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[90] The participating countries were Belgium, Denmark, France, Germany, Netherlands, Norway, Sweden and the United Kingdom, joined for the first time by Switzerland.

[91] The history of INSC started in 1983, when the German government proposed an international conference for the protection of the North Sea environment at ministerial level. The purpose was to make a political declaration which would stimulate and further ongoing work within the existing international conventions, including the Paris Convention, rather than to create another set of international agreements. For details, see Ehlers (1990).

[92] Skjærseth (1998) argues that by excluding the least ambitious countries and focusing political pressure at the ministerial level, it was possible to adopt stringent international commitments that did not merely reflect the interests and preferences of the least ambitious members. Similarly, Haas (1993) argues that collective pollution control efforts for the North Sea have developed through a "leader-laggard dynamic."

PARCOM Decision 90/3 on Reducing Atmospheric Emissions from Existing Chlor-Alkali Plants

Contracting Parties to the Paris Commission for the Prevention of Marine Pollution from Land-Based Sources AGREE:

that existing mercury-based chlor-alkali plants shall be required to meet by 31 December 1996 a standard of 2 g Hg/t Cl_2 capacity for emissions to the atmosphere, unless there is a firm commitment that the plant will be converted to mercury-free technology by the year 2000;

that mercury in hydrogen which is released to the atmosphere, or is burnt, is to be included in this standard;

AND RECOMMEND that existing mercury cell chlor-alkali plants be phased out as soon as practicable. The objective is that they should be phased out completely by 2010.

Source: Paris Commission (1990).

In this way, the two institutions, the Paris Commission and the European Commission, made very similar regulations on mercury emissions almost in parallel. Table 5-9 gives the chronological development of environmental regulations on mercury emissions from the chlor-alkali plants in Western Europe. Unlike the case of Japan, strong regulations such as those requiring the phase out of the mercury process were not adopted in Western Europe in the 1970s. Instead, emission standards were initially set as limit values on mercury released to water by both the Paris Commission and the European Community. These emission standards were subsequently tightened increasingly during the 1980s. Then in 1990, the recommendation was made for the phase out of the mercury process by the year 2010.

Table 5-9 Environmental Regulations on Mercury Emissions from the Chlor-Alkali Plants in Western Europe

Year	Regulation on mercury emissions
1974	Paris Convention • Mercury listed in Annex A
1976	Council Directive 76/464/EEC • Mercury identified as List I substance
1978	PARCOM Recommendation 78/1 • No new waste-brine plants be built

1980	PARCOM Decision 80/1 Environmental quality standard for mercury in organisms • 0.3 mg Hg/kg in wet fish
	PARCOM Decision 80/2 Limit values for mercury emissions in water from existing and new brine recirculation plants (exit of the purification plant) • 0.5 g Hg/t Cl_2 (monthly mean) after 1 July 1983 • 2.0 g Hg/t Cl_2 (daily mean) after 1 July 1983
1981	PARCOM Decision 81/1 Limit values for existing waste brine plants • 8 g Hg/t Cl_2 (monthly mean) after 1 July 1983 • 5 g Hg/t Cl_2 (monthly mean) after 1 July 1986
	PARCOM Decision 81/2 Limit values for existing brine recirculation plants (exit of the factory site) • 1.5 g Hg/t Cl_2 (monthly mean) after 1 July 1983 • 6 g Hg/t Cl_2 (daily mean) after 1 July 1983
1982	Council Directive 82/176/EEC Limit values for recycled brine plants • 0.5 g Hg/t Cl_2 after 1 July 1983 (exit of the purification plant) • 1.5 g Hg/t Cl_2 after 1 July 1983 (exit of the factory site) • 1.0 g Hg/t Cl_2 after 1 July 1986 (exit of the factory site) Limit values for lost brine plants • 8.0 g Hg/t Cl_2 after 1 July 1983 • 5.0 g Hg/t Cl_2 after 1 July 1986 Quality objectives • 0.3 mg Hg/kg wet fish flesh • 1 μg Hg/l in inland surface waters • 0.5 μg Hg/l in estuary waters • 0.3 μg Hg/l in territorial sea waters and internal coastal waters
	PARCOM Decision 82/1 New chlor-alkali plants • Application of the best technical means available (less than 0.5 g Hg/t Cl_2) after 1 July 1982 • Use of mercury-free technology, in particular membrane cells, encouraged
1985	PARCOM Recommendation 85/1 Limit values for mercury emissions in water from existing brine recirculation plants (exit of factory site) • 0.5 g Hg/t Cl_2 (monthly mean) after 1 July 1986 • 2 g Hg/t Cl_2 (daily mean) after 1 July 1986
1990	PARCOM Decision 90/3 Reducing atmospheric emissions from existing plants • 2 g Hg/t Cl_2 for mercury emissions to the atmosphere, including mercury in hydrogen, after 31 December 1996, unless the plant will be converted to mercury-free technology by 2000 • Recommendation for the phase-out of the existing mercury plants by 2010

5.2 Reduction of Mercury Emissions with End-of-Pipe Technologies

5.2.1 Patents on Chlor-Alkali Production Technologies

With the imposition of these regulations, which mainly involved emission standards, chlor-alkali producers operating the mercury process in Western Europe were required to reduce mercury emissions. In the 1970s, their emissions accounted for a major share of the total mercury emissions to the environment. As we have discussed above, there are basically two types of technologies to reduce emissions from the production process, that is, the end-of-pipe technology and the clean technology. Accordingly, two technological options were available to the operators of the mercury process for the abatement of mercury emissions. One option was to adopt end-of-pipe technologies to reduce mercury emissions and then to continue to rely on the mercury process for chlor-alkali production. The other option was to convert the mercury process to a clean technology. As we have seen in the case of technological change in the Japanese chlor-alkali industry, the diaphragm process and the ion exchange membrane process could be alternative production processes.

To see what kinds of technologies were developed in Western Europe, we examined successful patent applications by Western European companies. As there are major differences among countries in procedures and criteria for granting patents (Patel and Pavitt, 1995), international comparisons are most reliable when international patenting or patenting in one country is used. In Western Europe, with the entry into force of the European Patent Convention on 7 October 1977, the first European patent applications were received on 1 June 1978, and subsequently the European patents were granted for the first time in 1980 (European Patent Office, 2000). Therefore, the European patents are not suitable for examining patents applied in the 1970s, a period which is crucial for our examination of the development of chlor-alkali technologies in Western Europe.

We instead used the US patents for our research because the US patent database is a neutral source of information, which covers patents applied since the beginning of the 1970s. Also, companies in Western Europe are reasonably expected to have strong incentives to obtain patent protection in the world's largest market for their technologies, which can be adopted all over the world. Data was obtained from the web-based patent database of the US Patent and Trademark Office[93]. The patents included in this database were those issued in the

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[93] The URL is http://www.uspto.gov/patft/index.html.

period from January 1, 1976, to December 31, 1998. For patents issued in the period from 1971 to 1975, we used the web-based database of the IBM Intellectual Property Network[94].

Relevant patents were identified by using the International Patent Classification (IPC). The IPC, in its sixth edition, divides various types of technology into eight sectors with approximately 67,000 subdivisions, each of which has a symbol consisting of Arabic numerals and letters of the Latin alphabet. The appropriate IPC symbols are indicated on each patent document. In this study, we examined patents included in the following classes:

- C25B-1/16 Electrolytic production of alkali metal hydroxides
- C25B-1/26 Electrolytic production of chlorine or compounds thereof
- C25B-1/34 Simultaneous production of alkali metal hydroxides and chlorine, its oxyacids or salts
- C25B-1/36 • in mercury cathode cells
- C25B-1/38 • • with vertical mercury cathode
- C25B-1/40 • • with horizontal mercury cathode
- C25B-1/42 • • Decomposition of amalgams
- C25B-1/44 • • • with the aid of catalysts
- C25B-1/46 • in diaphragm cells

In the first edition of IPC, which entered into force on September 1, 1968, the above-mentioned classes did not exist. Instead, they were classified in the following way:

- C01B-7/06 Preparation of chlorine by electrolysis
- C01D-1/06 Preparation of hydroxides of sodium and/or potassium by electrolysis
- C01D-1/08 • with the aid of a liquid cathode
- C01D-1/10 • • with a vertical cathode
- C01D-1/12 • • with a horizontal cathode
- C01D-1/14 • • Regulating the distance between the solid anode(s) and the liquid cathode
- C01D-1/16 • • Working up the amalgam
- C01D-1/18 • • • with the aid of catalysts

Accordingly, we used the above patent classes for patents issued from 1971 to 1975.

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[94] The database is currently called the Delphion Intellectual Property Network. The URL is http://www.delphion.com/home.

These patent classes, however, include patents on other areas than the electrolytic production of sodium hydroxide, which is just one type of alkali metal hydroxides, and chlorine. For example, the class of C25B-1/16 includes patents related to the electrolytic production of potassium hydroxide, and the class of C25B-1/24 includes patents on the electrolytic production of hypochlorite. Thus, by examining all the patent documents one by one, we excluded inappropriate patents from our analysis. Then we divided patents on the electrolytic production of sodium hydroxide and chlorine into the three categories of the mercury process, the diaphragm process, the ion exchange membrane process. The judgement was made by examining each patent document closely. For the category of the mercury process, we also picked up patents on technologies for dealing with mercury emissions. By using the following combinations of keywords, namely, mercury, and treat*, reduc*, remov* or recov*, we first collected 1,295 patents which could potentially be relevant. Then we selected those which are related to the chlor-alkali industry by examining each patent.

Figure 5-1 shows the trends in the US patents successfully applied by companies in Western Europe since the end of the 1960s for technologies related to the mercury process and the ion exchange membrane process for chlor-alkali production. (Detailed data are given in Table 5-21 in Appendix at the end of this chapter.)
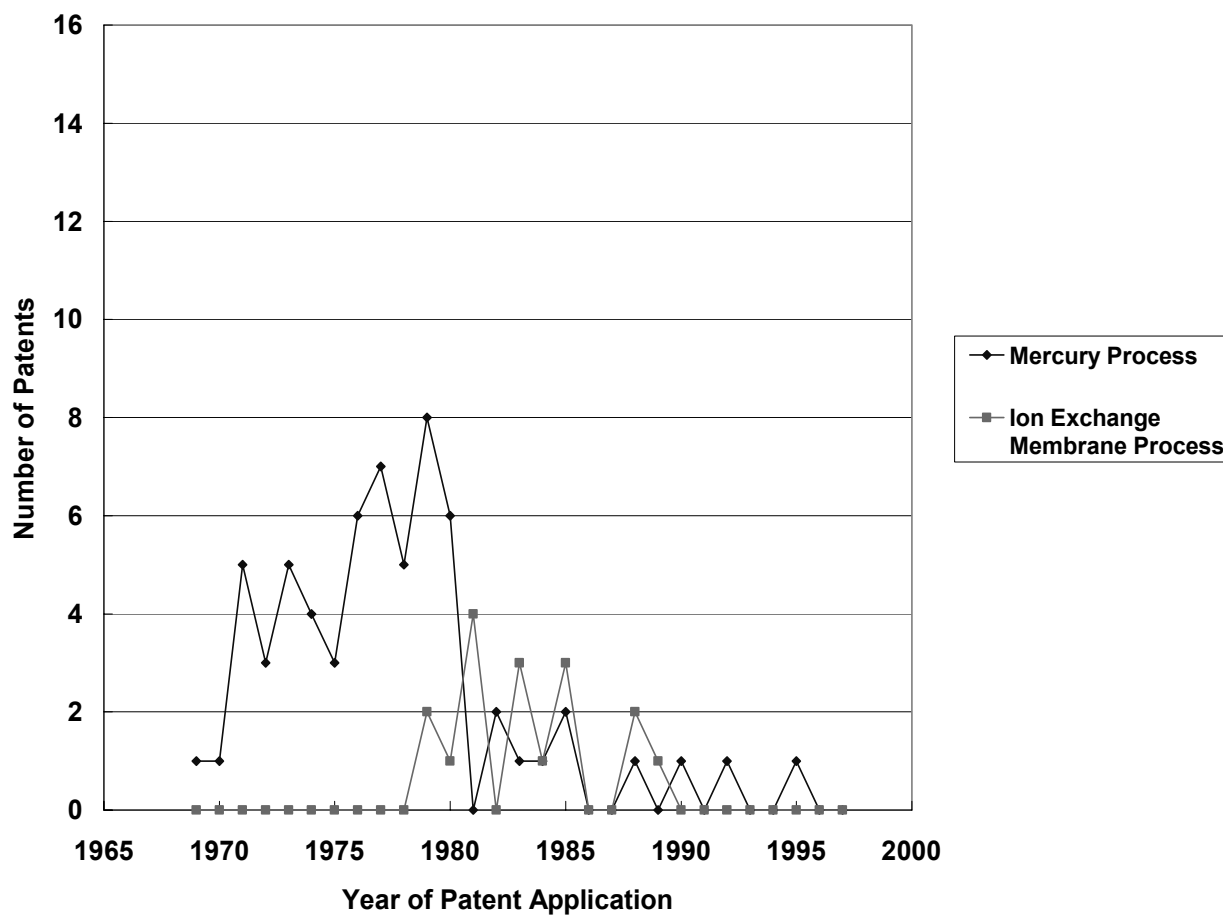
Figure 5-1 US Patents Successfully Applied by Western European Firms on the Mercury and Ion Exchange Membrane Processes

As we can see, most of the patents successfully applied by Western European companies from the end of the 1960s to 1980, that is, 54 out of 60 patents, were targeted for technologies related to the mercury process. On the other hand, only 10 per cent of all the patents granted in the same period, namely, 6 patents, were related to the ion exchange membrane process. The number of patents on the mercury process increased from the level observed at the end of the 1960s and reached a peak in the late 1970s. Thereafter, relatively few patents were granted in the 1980s and 1990s. Although there were several patents on the ion exchange membrane process at the end of the 1970s and in the 1980s, overall more than three times as many patents were granted on the mercury process as on the ion exchange membrane process. That suggests that the focus of R&D activities made by Western European companies were primarily aimed at developing technologies for reducing mercury emissions

through end-of-pipe technologies, especially throughout the 1970s. On the other hand, that implies that these companies did not devote their innovative efforts to developing technologies for the ion exchange membrane process until the end of the 1970s.

In order to make a comparison between Western Europe and Japan valid, it is necessary to maintain the same conditions. Thus we also examined the Japanese case by analyzing the US patent data with the same procedure. Figure 5-2 shows the trends in successful applications for US patents by Japanese companies in the same period on technologies related to the mercury process and the ion exchange membrane process. (Detailed data are given in Table 5-22 in Appendix at the end of this chapter.)
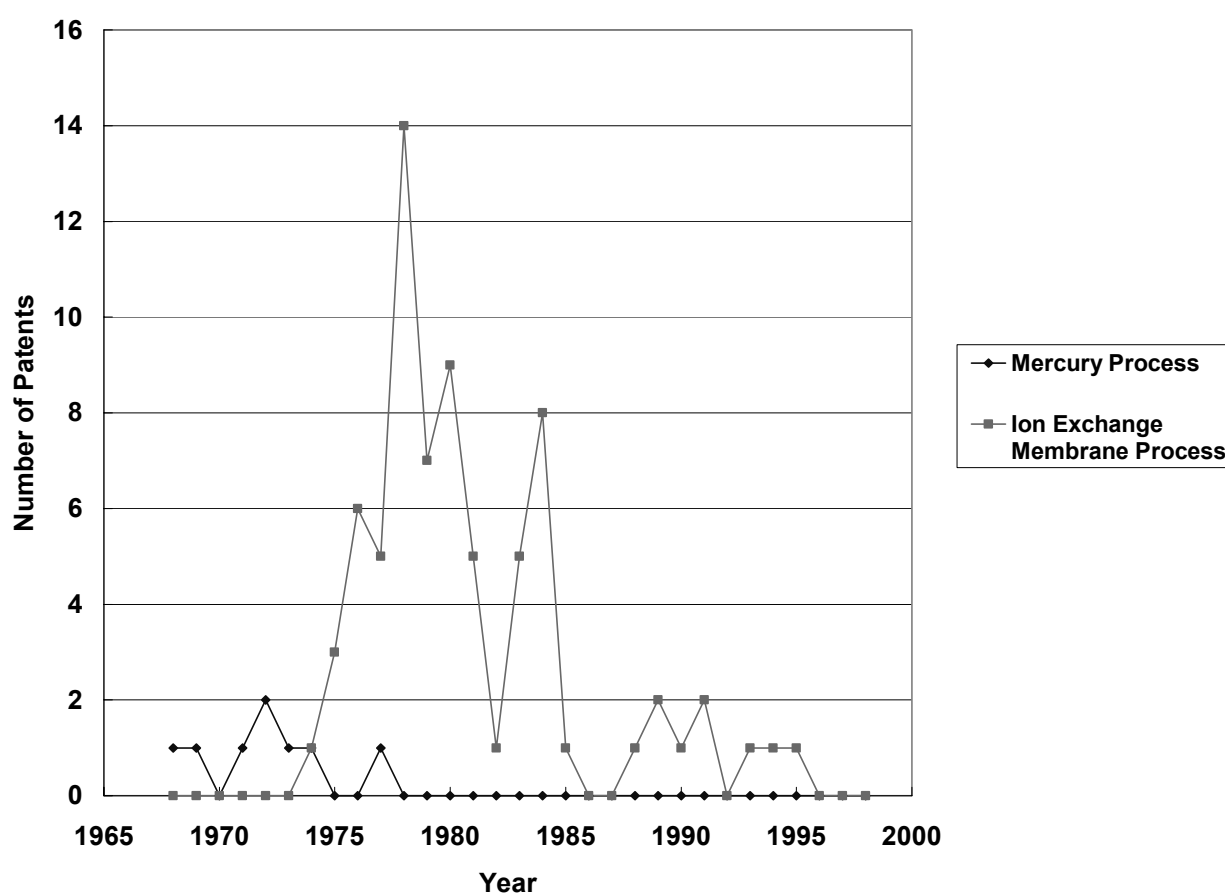
Figure 5-2 US Patents Successfully Applied for by Japanese Companies on Technologies Related to the Mercury Process and the Ion Exchange Membrane Process

Applications for patents on the ion exchange membrane process started to increase rapidly in the middle of the 1970s, following the government policy for the phase out of the mercury process in Japan. Subsequently, successful patent applications on technologies for

237

the ion exchange membrane process reached a peak in 1978. The number of successful patent applications by Japanese firms on the ion exchange membrane process from the end of the 1960s to 1980 was 45, which is far larger than that by companies in Western Europe, that is, 6. Active patent applications on the ion exchange membrane process continued until the middle of the 1980s, and then the number of patents granted declined. On the other hand, the number of patents related to the mercury process remained relatively small, with only several patents applied from the end of the 1960s through the 1970s, compared with patents on the ion exchange membrane process.

Figure 5-1 and Figure 5-2 show a clear contrast in innovative efforts between companies in Western Europe and those in Japan. That is, during the 1970s, the focus of patent applications made by the Western European companies was on the mercury process whereas the Japanese companies' patent applications were targeted at the ion exchange membrane process. As we have seen in Figure 3-3, while mercury can be mostly recovered for reuse during the operation of mercury-based plants, some of it inevitably escapes to the environment, through waste water, air, products, and solid wastes. And we have discussed in Chapter 3 that there are two types of technological options to deal with mercury emissions, namely, the end-of-pipe technology and the clean technology. Figure 5-1 suggests that end-of-pipe technologies for the reduction in mercury emissions from the mercury chlor-alkali process were paid attention to in R&D activities conducted by companies in Western Europe. This is in sharp contrast with the Japanese case. As indicated in Figure 5-2, most of the innovative activities of the Japanese companies were devoted to the development of technologies for the ion exchange membrane process, a prime example of the clean technology. This result supports our analysis based on the Japanese patent data in Chapter 4.

We have also seen in Chapter 3 that in Western Europe there were several companies which had been innovative on technologies related to the mercury process by the end of the 1960s. As Table 3-8 and Table 3-11 show, these companies were ICI, Hoechst-Uhde, De Nora, Bayer, Solvay, and Krebs, cooperating with BASF. We are interested in examining how these innovative companies made R&D efforts on which production process since the 1970s, when regulations on mercury emissions from chlor-alkali plants started to be introduced in Western Europe. We first look at innovations on the mercury process made by these companies. Table 5-10 gives the trends in the US patents which were successfully applied by these innovative companies in Western Europe on technologies related to the mercury process and the ion exchange membrane process.

Table 5-10 US Patents Successfully Applied by Western European Companies on Technologies Related to the Mercury Process and the Ion Exchange Membrane Process

Year[a]	ICI		Hoechst-Uhde		De Nora		Bayer		Krebs[b]		Solvay	
	Hg	IM	Hg	IM	Hg	IM	Hg	IM	Hg	IM	Hg	IM
1970	0	0	0	0	1	0	0	0	0	0	0	0
1971	1	0	0	0	0	0	0	0	2	0	0	0
1972	0	0	0	0	1	0	0	0	0	0	0	0
1973	0	0	1	0	0	0	1	0	0	0	0	0
1974	1	0	0	0	1	0	1	0	0	0	0	0
1975	1	0	0	0	0	0	0	0	0	0	0	0
1976	0	0	1	0	0	0	0	0	0	0	0	0
1977	0	0	1	0	0	0	0	0	0	0	0	0
1978	0	0	0	0	2	0	2	0	0	0	0	0
1979	1	0	2	1	1	1	0	0	0	0	0	0
1980	0	0	0	0	1	1	1	0	0	0	0	0
1981	0	0	0	0	0	4	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	3	0	0	0	0	0	0
1984	0	1	0	0	0	0	0	0	0	0	1	0
1985	0	1	0	1	0	1	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	2	0	0	0	0	0	0
1989	0	0	0	0	0	1	0	0	0	0	0	0
1990	0	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0
1992	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	0	0	0
Total	32	2	4	2	9	9	16	0	2	0	1	0

Hg: Mercury Process; IM: Ion Exchange Membrane Process
a: Year of patent applications.
b: The data of Krebs includes that of BASF.

Although the number of successful patent applications is small, we can see that, while these companies made patent applications basically on technologies related to the mercury process in the 1970s, successful patent applications started to appear on the ion exchange membrane process at the end of the 1970s and the beginning of the 1980s. That suggests that

these companies initially focuses their R&D activities on technologies related to the mercury process in the 1970s, when regulations on mercury emissions began to be introduced in Western Europe. Then they started to shift their innovative efforts to the ion exchange membrane process at the end of the 1970s. To understand exactly what kinds of technologies were developed for the mercury process in the 1970s, particularly whether these innovations were actually technological measures aimed at reducing mercury emissions, more detailed analysis of these technological developments is necessary. In the next section, we examine in detail what kinds of technologies have been actually developed and subsequently supplied by these companies in Western Europe.

5.2.2 Development of End-of-Pipe Technologies for the Reduction of Mercury Emissions

As we can see in Figure 3-3 and Figure 3-4, mercury-based chlor-alkali plants discharge mercury to the environment. It is mainly emitted through waste water, process gases, and products (Schmittinger, Curlin, Asawa, Kotowski, Beer, Greenberg, Zelfel, and Breitstadt, 1986). Liquid effluent streams contain significant amounts of mercury. Mercury-containing wastewater has several sources in the production process. They include condensate and wash liquor from treatment of chlorine, hydrogen, and brine, stuffing-box rinse water from pumps and blowers, and brine leakage. In addition, the cleaning operations of cells, floors, tanks, pipes, and dismantled apparatus normally produce waste waters containing mercury.

Mercury emissions to products include those to chlorine and caustic soda. Hot, moist chlorine leaving the cell contains small amounts of mercury chloride. This is almost completely washed out in the subsequent cooling process and is fed back into the brine with the condensate. As there are only minute traces of mercury in the cooled and dried chlorine gas, normally mercury removal processes are not required for this product. On the other hand, the caustic soda produced with the mercury process inevitably contains mercury, and technical treatment is necessary to reduce the mercury content.

Mercury emissions to the atmosphere are accounted for by mercury in three sources, namely, process exhaust, cellroom ventilation, and hydrogen[95]. Process exhaust refers to all gaseous streams by which mercury is emitted to the atmosphere, apart from in cellroom ventilation air and in hydrogen as a product. Each plant has different streams, but typically

purge air from cell end-boxes, vents from wash water collection tanks and exhaust from any vacuum system used to collect spilled mercury are the main sources of mercury emissions to the air. Mercury spillage occurs during essential operations involving electrolytic cells or decomposers, for example, opening electrolytic cells for anode changing or cleaning, assembling or dismantling equipment, and replacing defective pipes, and spillage leads to small losses in the air owing to the vapor pressure of mercury. Mercury is also emitted through unintended leakage from equipment including cells, pipes and vessels, via faulty seals. The hydrogen gas stream is nearly saturated with mercury when it leaves the decomposer.

To see whether innovations on the mercury process have been aimed at the reduction of mercury emissions through these various routes to the environment, we need to examine what kinds of technological developments have been made by companies in Western Europe concerning the mercury process. We look at the patent data in detail for that purpose. Table 5-11 shows the US patents granted to companies in the Western European chlor-alkali industry on technologies related to the mercury process.

Table 5-11 US Patents Successfully Applied by Companies in the Western European Chlor-Alkali Industry on Technologies Related to the Mercury Process

Company	Patent No.	Year	Patent Title
ICI	US3718457	1971	Process for the recovery of mercury from waste brine from mercury cells
	US3905880	1974	Operation of mercury-cathode cells
	US4060463	1975	Operation of mercury-cathode cells
	US4234405	1979	Electrode for electrochemical processes
Hoechst-Uhde	US3922210	1973	Process of avoiding mercury emission from mercury-using plants
	US4059438	1976	Process for the work-up of a contaminated inactive mercury(II) chloride/active carbon-catalyst
	US4108769	1977	Process for reducing the mercury content of industrial waste waters
	US4212715	1979	Process for reducing losses of mercury in alkali metal chloride electrolysis
	US4244801	1979	Apparatus to measure the distribution of the anode currents in cells for alkali metal chloride
De Nora	US3627652	1970	Method of operating mercury cathode electrolytic cell plant

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[95] Note that hydrogen released to the atmosphere or used or sold as a fuel is included in gaseous effluent, not classified as a product.

	US3833357	1972	A Process for decomposing alkali metal amalgams into mercury, hydrogen and alkali metal hydroxide solutions
	US4161433	1978	Decomposition of alkali metal amalgams
	US4166780	1978	Novel electrolytic process
	US4204937	1979	Novel electrolytic amalgam denuder apparatus
	US4263107	1980	Electrolytic apparatus and process
Solvay	US4565613	1984	Process for removing a layer of thick mercury from the bottom of mercury-cathode electrolysis cells and a process for the electrolysis of an aqueous solution of an alkali metal halide in a mercury-cathode cell
Bayer	US3890211	1973	Process for recovering energy from the decomposition of amalgam in the electrolysis of alkali metal chlorides
	US3895938	1974	Purification of mercury
	US4132759	1978	Method of purifying brine used in electrolysis by the amalgam process
	US4152226	1978	Process and apparatus for monitoring amalgam electrolysis cells
	US4323438	1980	Anode for alkali metal chloride electrolysis
BASF	US3755109	1971	Electrolysis of alkali metal chlorides
	US3755110	1971	Process for the recovery of mercury from the brine filter sludge obtained in the electrolysis of alkali metal chlorides by the amalgam process
	US4077856	1976	Removal of mercury from liquids
Montedison (EniChem)	US3849266	1973	Process for the electrolysis of alkali chloride solution
	US4087359	1976	Process for removing mercury and mercury salts from liquid effluents
	US4303491	1980	Apparatus for cleaning the bottom of electrolytic mercury cathode cells
	US4465560	1983	Method and device for protecting the anodes of electrolytic cells against overloads, short circuits and unbalances
	US5357002	1992	Polymer containing chelating groups, process for preparing it and its use in water purification
Akzo Nobel (Dynamit Nobel)	US3763024	1971	Process and apparatus for controlling the spacing of the electrodes of electrolytic cells
	US3849267	1973	Process for recovering mercury from a gas containing mercury vapor
	US4196173	1978	Process for removing mercury from a gas
BP Chemicals	US3647359	1969	Recovery of mercury
	US3857704	1972	Mercury recovery process
	US3847598	1973	Mercury recovery process
	US4391681	1982	Method of inhibiting formation of and breaking of mercury butter in chlor-alkali cells
Hüls	US3981967	1971	Process for the recovery of bound mercury from mercury-containing catalysts

Wacker Chemie	US4234422	1979	Process for removal of mercury and mercury compounds from aqueous solutions and industrial waste liquors

As we can see in the table, most of the technologies related to the mercury process developed by these innovative companies in Western Europe, including ICI, Hoechst-Uhde, De Nora, Solvay, Bayer, and BASF, are aimed at reducing mercury emissions through various routes to the environment. ICI developed in the early 1970s a process for the recovery of mercury from waste brine from mercury cells (US Patent No. 3718457, 1971). Other innovations concerning the operation of the electrolytic cells of the mercury process are also useful to reduce mercury emissions (US Patent No. 3905880, 1974; No. 4060463, 1975). The system for removing mercury from the waste water at ICI's plant in Wilhelmshaven, Germany, consists of chemical precipitation of mercuric sulfide, followed by filtration (European IPPC Bureau, 1999). Bayer developed a method of purifying mercury (US Patent No. 3895938, 1974) as well as a method of purifying brine used in electrolysis by the mercury process (US Patent No. 4132759, 1978).

Hoechst developed a process for the work-up of a contaminated inactive mercury(II) chloride/active carbon-catalyst (US Patent No. 4059438, 1976). The method of chemical demercurization at normal pressure had already been used by the former IG Farben Industrie and was further developed by Hoechst (*European Chemical News*, 1972). Pre-cooled hydrogen, which was saturated with mercury according to its temperature, was treated with chlorine-bearing brine, wet chlorine or chlorine water. The mercury was then converted to mercuric chloride and removed from the hydrogen. Using this method, the residual mercury content in the hydrogen could be reduced significantly. Other processes were also developed by the company for reducing the mercury content of industrial waste waters (US Patent No. 4108769, 1977) and for reducing losses of mercury in alkali metal chloride electrolysis (US Patent No. 4212715, 1979). Uhde developed a process of avoiding mercury emission from mercury-using plants (US Patent No. 3922210, 1973). Use of the Bayer silver catalyst, developed for this application, instead of the activated carbon filter, could reduce the mercury content significantly.

De Nora also came to develop improved mercury cells designed to reduce mercury emissions both in the ambient air and in the plant effluents (US4166780, US4204937, and US4263107). Among the main features connected to these improvements are the inlet/outlet boxes of the closed type, which significantly reduced the amount of wash water to be added to

avoid carry over of chlorides into caustic soda while practically eliminating the need of sucking and treating mercury-contaminated air from the cell end boxes. Another technology is a cell bottom wiper. This device, which is normally located inside the inlet end box, can be operated from outside, making possible periodical mechanical cleaning of the cell bottom without opening the cell. That is, any impurity accumulated on the cell bottom, which could disturb mercury flow along the cell, can be eliminated by just pushing the wiper from the inlet towards the outlet end.

BASF developed a process for the recovery of mercury from the brine filter sludge obtained in the electrolysis of alkali metal chlorides by the mercury process (US Patent No. 3755110, 1971). The company also developed a technology for the removal of mercury from liquids (US Patent No. 4077856, 1976). At BASF's plant located in Antwerp, hydroxylamine is used to reduce mercury concentration, followed by filtration and activated carbon filters (European IPPC Bureau, 1999). And all gases are treated in an absorption tower. The lower section of the tower is used to neutralize the chlorine in the gas, which is transformed into hypochlorite. While the mercury in the waste gas is partly absorbed by the hypochlorite in the lower section, absorption does not take place in the upper section of the tower, where no hypochlorite is contained, and the technology consists of adding hypochlorite in the upper section. For the treatment of hydrogen, the company uses a chemical reaction with copper oxide after the cooling step in order to absorb mercury.

Solvay developed a process for removing a layer of thick mercury from the bottom of mercury-cathode electrolysis cells and a process for the electrolysis of an aqueous solution of an alkali metal halide in a mercury-cathode cell (US Patent No. 4565613, 1984). At Solvay's plant at Roermond, the process waste water is treated by means of sedimentation of solid mercury and subsequent precipitation of mercury with sodium bisulfide (Information Centre for Environmental Licensing, 1998). The mercury contained in waste gas has been reduced by adsorption on activated carbon impregnated with sulfur. By using filtration with activated carbon, the company achieved a reduction in mercury contained in hydrogen. Similarly, by adsorption on activated carbon, the company's plant at Antwerp removed mercury contained in hydrogen (European IPPC Bureau, 1999). The company's plant at Martorell, Spain, reduced mercury contained in waste gas by adsorption on activated carbon impregnated with sulfur (European IPPC Bureau, 2000).

In addition to the companies which had been previously innovative on the mercury process, other chlor-alkali producers, namely, BP Chemical, Akzo, Montedison (EniChem)[96], Wacker Chemie, and Hüls, also made successful patent applications on technologies for the reduction of mercury emissions. Montedison, Process for removing mercury and mercury salts from liquid effluents (US Patent No. 4087359, 1976). Montedison also developed an apparatus for cleaning the bottom of electrolytic mercury cells (US Patent No. 4303491, 1980), which reduced the frequency of opening the cell, leading to a reduction in mercury emissions to cellroom ventilation air. Wacker Chemie developed a process for removal of mercury and mercury compounds from aqueous solutions and industrial waste liquors (US Patent No. 4234422, 1979). Hüls developed a process for the recovery of bound mercury from mercury-containing catalysts (US Patent No. 3981967, 1971). BP Chemicals developed a process for the recovery of mercury (US Patent No. 3647359, 1969; US Patent No. 3857704, 1972; US Patent No. 3847598, 1973) as well as a method of inhibiting formation of and breaking of mercury butter in chlor-alkali cells (US Patent No. 4391681, 1982), which contributes to a reduction in mercury emissions to cellroom ventilation air.

Akzo succeeded in the early 1970s in lowering the mercury concentration of the waste water by developing a one-stage process with the ion exchange resin[97] (Rekers, 1973). Akzo's plant in Hengelo treats the process water by sedimentation of solid mercury and subsequent removal of mercury in an ion exchange unit (Information Centre for Environmental Licensing, 1998). To remove mercury from hydrogen, the company utilizes a calomel reaction, followed by filtration with activated carbon. At Akzo Nobel in Bohus, the waste water treatment system consists of a mixing unit where hydrazine is added to the waste water, two sedimentation tanks, sand filters, activated carbon filters and ion exchange filters (Information Centre for Environmental Licensing, 1998). Akzo also developed a process for recovering mercury from a gas containing mercury vapor (US3849267, 1973; US4196173, 1978). The company's calomel process has been used at its plant in Hengelo (Rekers, 1973). The mercury concentration in caustic soda at Akzo Nobel's plant at Bohus has been reduced by using filters with activated carbon. The hydrogen gas is scrubbed with chlorinated brine

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[96] The chlor-alkali business of Montedison has been transferred to EniChem, which was founded in 1989 as a joint venture between the chemical operations of the Eni Group and the majority of the chemical operations of the Montedison Group (EniChem, 2001).

[97] Synthetic ion exchange resins normally consist of various copolymers having a cross-linked three-dimensional structure to which ionic groups have been attached. Note that this technology is different from the ion exchange membrane used for the chlor-alkali manufacture.

before adsorption on activated carbon. Mercury emissions via process exhausts at the plant have been reduced by adsorption on activated carbon impregnated with sulfur.

As we have seen, these technologies developed for the abatement of mercury emissions from chlor-alkali plants in Western Europe are basically measures of the end-of-pipe type. Technologies for the reduction of mercury emissions to waste water normally include settling to remove large mercury droplets, followed by oxidation using hypochlorite, chlorine or hydrogen peroxide to take remaining metallic mercury into solution. A process which has been frequently used for purifying depleted brine leaving the plant and any other mercury-containing waste water is the precipitation of mercuric sulfide, followed by filtration. In the precipitation process, the mercuric sulfide is filtered from the waste water in sand or plate filters and then can be dissolved in hypochlorite and recycled to the cellroom brine system.

Several types of end-of-pipe technologies have been developed, notably filters, to remove mercury from caustic soda. They include plate filters with carbon pre-coat, candle filters with carbon pre-coat, and candle filters without pre-coat. Although all types of filters can achieve very low levels of mercury in the product, the predominant technique, which achieves low levels, has been the plate filter with carbon pre-coat. Mercury is absorbed on the carbon pre-coat and is discharged from the filter as a dry cake. On the other hand, the activated carbon filtration generates mercury-contaminated waste, and the discharged filter cake needs to be subjected to distillation to recover the mercury.

To achieve low levels of mercury in process exhaust, there are basically two principal single-stage processes, which are of the end-of-pipe type, namely, chemical process, including scrubbing with hypochlorite or chlorinated brine and use of a calomel reaction, and the use of sulfurized charcoal. By scrubbing with chlorine-containing brine, mercury(II) chloride ($HgCl_2$) is produced, forming a mercury-chlorine complex in the brine. After chlorine is removed, the brine is recirculated. By scrubbing with alkaline hypochlorite solution, the mercury contained in the process exhausts is also oxidized without any necessity of subsequent chlorine removal. The cleaned gas passes through a separator to remove entrained liquid droplets, and the mercury is recirculated via the brine. Another way of removing mercury from the process exhaust is to utilize a calomel reaction. By adding chlorine, mercury contained in the waste gas is converted to calomel (Hg_2Cl_2). The calomel is then collected on rock salt or similar material in a packed column, allowing for direct recycling of mercury to the brine feed to the cellroom. Mercury contained in the process

exhaust is also removed by adsorption on activated carbon impregnated with sulfur or sulfuric acid, although that generates contaminated wastes at the same time.

The common approach to reducing the mercury content in hydrogen has been a two-stage process. The first stage involves cooling, compression and cooling, or chemical process, for example, scrubbing with hypochlorite or use of a calomel reaction. The second stage is adsorption on iodized or sulfurized charcoal, while avoiding water condensation in the charcoal bed.

To keep the cellroom ventilation losses to a minimum, there are basically two ways, that is, purification of the ventilation air and prevention of mercury emissions at the sources. The purification of the ventilation air leaving the cellroom is basically done by using end-of-pipe technologies. Mercury cells are normally set up in very large cellroom buildings, and a huge volume of ventilation air is necessary to remove the heat resulting from electrolysis in the cells. Because of the huge volume of the ventilation air, which is released from many points of the large cellroom, the removal of mercury by using end-of-pipe technologies has not been practical. Hence the only satisfactory way of controlling mercury losses to atmosphere has been to prevent mercury emissions at the sources. That requires a high standard of housekeeping and equipment maintenance in the cellroom[98]. Since some mercury emissions inevitably occur when an electrolytic cell is opened for sampling the amalgam or cleaning the cells, mercury emissions can be reduced by minimizing the frequency and duration of the cell opening. The frequency of cell cleaning is directly related to the quantity of thick mercury, the so-called mercury butter, whose formation results from the existence of impurities in the brine. Thus technologies have been developed to monitor accurately the accumulation of the thick mercury in the cell and to reduce levels of impurities in the brine, such as heavy metals as well as calcium and magnesium. Also cell-bottom wipers have been invented to limit mercury emissions by making possible periodical mechanical cleaning of the cell bottom without opening the electrolytic cells.

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[98] The ease with which mercury cellrooms can be managed for the minimum emission of mercury would be influenced by several factors, including the climate and the age and nature of the plant design (Euro Chlor, 1993). The climate is considered important, as the mercury loss rate varies depending on the ambient temperature. With other conditions held constant, mercury losses are generally higher in summer than in winter and also during the day than at night. For the same reason, cellrooms in Southern Europe would be expected to have higher losses than those in Northern Europe due solely to the different climate conditions. The plant design may also influence the extent to which mercury emissions can be reduced. In general, older plants were not designed for efficient containment of mercury. Older designs of cells operated at lower current density require larger buildings with larger floor areas, resulting in a greater potential for mercury emissions.

As we have discussed above, various kinds of equipment of the end-of-pipe type have been adopted to curb mercury emissions from chlor-alkali plants to water, products, and air. Figure 5-3 gives a schematic illustration of these technologies used to reduce mercury emissions at a mercury-based chlor-alkali plant. Comparing with Figure 3-3, we can see that these technologies are primarily aimed at scrubbing, filtration, and adsorption and are installed at the end of the production process without making any changes in the chemical reactions involved; that is, they are end-of-pipe technologies.

Salt

Diluted Brine

Brine
Saturation

Raw Brine

Precipitation

Dechlorination

Filtration

**Brine sludge
(Hg*)**

Filtration

Purified Brine

Cellroom ventilation (Hg*)

**Good
Housekeeping**

Anolyte

Process exhaust (Hg*)

Electrolysis

**Scrubbing
Adsorption**

**Precipitation
Filtration**

**Wastewater
(Hg*)**

Mercury

Amalgam

Water

Amalgam
Decomposition

**Caustic
solution (Hg*)**

Hydrogen (Hg*)

Chlorine

Cooling

Cooling

Cooling

Filtration

**Refrigeration
Adsorption**

Drying

Storage

Compression

Caustic Soda

Hydrogen

Chlorine

Figure 5-3 End-of-Pipe Technologies Developed to Reduce Mercury Emissions

5.2.3 Continued Use of the Mercury Process with End-of-Pipe Technologies

The previous section shows that various types technologies, most of which are of the end-of-pipe type, have been developed by companies in Western Europe to reduce mercury emissions from chlor-alkali plants to water, products, and air. To see the effects of adoptions of these technologies at mercury-based chlor-alkali plants, we need to examine actual mercury emissions. Figure 5-4 shows the trends in mercury losses per unit production capacity of chlorine to water, products, and air from chlor-alkali plants in Western Europe since 1977[99]. (Detailed data are given in Table 5-23 in Appendix at the end of this chapter.)
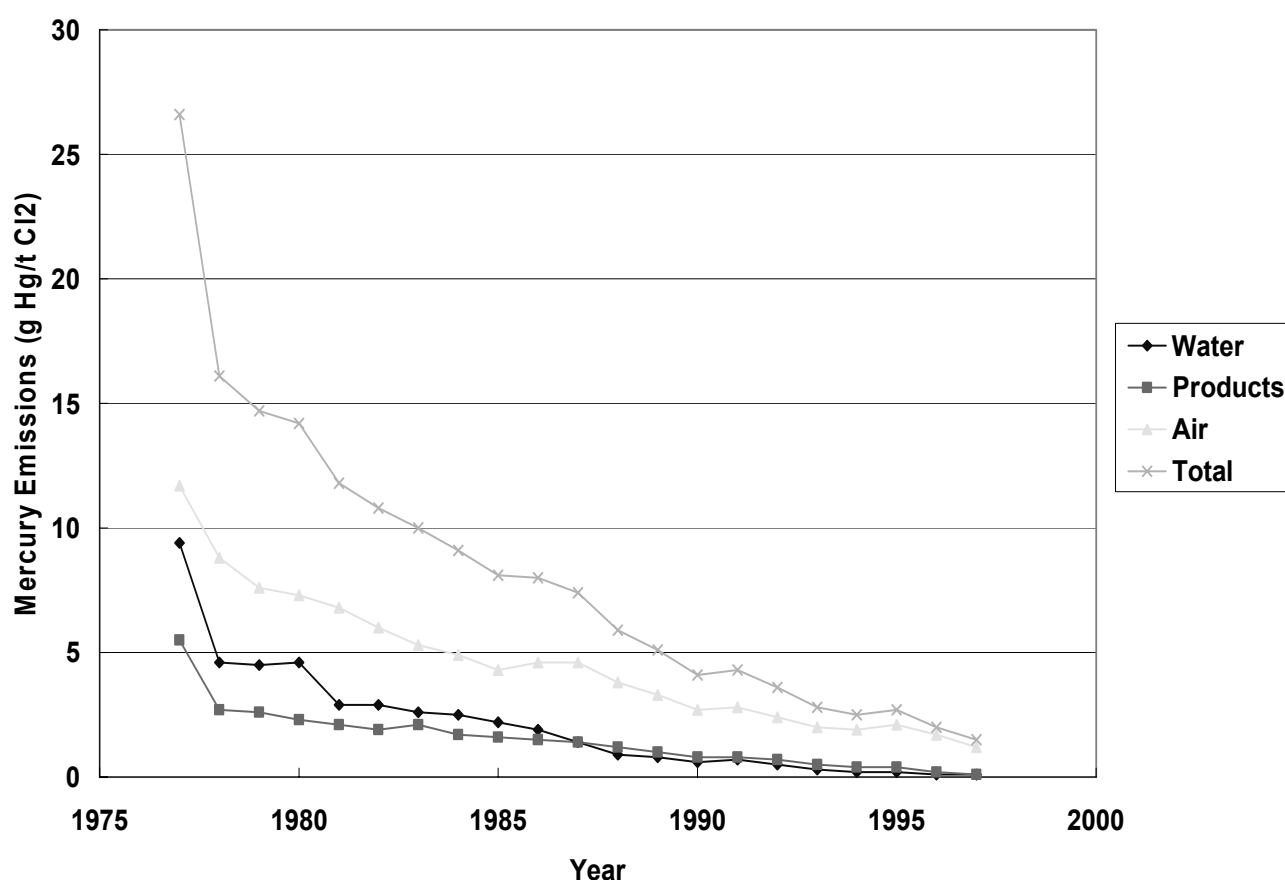
Figure 5-4 Mercury Emissions to Water, Products, and Air from Chlor-Alkali Plants in Western Europe

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[99] The chlor-alkali industry association in Europe, Euro Chlor, represented all 38 Western European chlorine producers in 14 countries at the time of 1997 (Euro Chlor, 1997). Note that the data collected by Euro Chlor includes those of Austria, Finland, Italy, and Greece, which have not been the members of the Paris Commission (subsequently the OSPAR Commission). For more information on the data collected by the Paris Commission, see Appendix.

According to the table, these end-of-pipe technological measures have made significant impacts on the amount of mercury emissions from chlor-alkali plants in Western Europe. Mercury losses per unit production capacity to water from chlor-alkali plants located in Western Europe have decreased steadily since 1977, from 9.4 g Hg/t Cl_2 to 0.11 g Hg/t Cl_2, achieving a 99 % reduction. A similar trend has been observed in the case of mercury losses through products. Over the last 20 years, a decrease of 98 % was achieved, from 5.5 g Hg/t Cl_2 in 1977 to 0.14 g Hg/t Cl_2 in 1997. Mercury emissions to air, that is, those contained in process exhaust, ventilation air and hydrogen used as fuel, have also shown a large decrease since the late 1970s. Atmospheric emissions were reduced from 11.7 g Hg/t Cl_2 in 1977 to 1.2 g Hg/t Cl_2 in 1997. The reduction rate of atmospheric emissions from 1982 to 1997 was 69 %, however, which was much smaller compared with that of emissions to products or water.

Concerning mercury discharges to water from existing waste brine chlor-alkali plants, the Paris Commission adopted in 1981 the limit values of 8 g Hg/t Cl_2 capacity to be complied with at the exit of a factory as a monthly mean from July 1983, and 5 g Hg/t Cl_2 capacity from July 1986. For brine recirculation plants, the European Communities made the decision in 1982 on the limit value of 1.5 g Hg/t Cl_2 to be effective after July 1983, and the Paris Commission also adopted in 1985 the recommendation requiring the limit value of 0.5 g Hg/t Cl_2 capacity from July 1986. Figure 5-4 suggests that, while we would expect variations in the amount of mercury emissions among the individual plants, these emission targets have been met by mercury-based chlor-alkali plants in Western Europe. (For individual chlor-alkali plants located in Western Europe, chronological data since the 1970s is not publicly available. Only for the year 1999, detailed data on mercury emissions to water, products, and air has been published recently. The results are given Table 5-24 in the appendix at the end of this chapter.)

Also, there was the limit value for emissions to the atmosphere, as stipulated in paragraph 1 of PARCOM Decision 90/3, that is, 2 g Hg/t Cl_2 capacity to be complied with by December 1996 (OSPAR Commission, 1999a). Figure 5-4 shows that, while air emissions currently account for the largest share of the total mercury emissions from chlor-alkali plants in Western Europe, all the existing mercury-based chlor-alkali plants have complied with the limit value for air emissions. These technological measures of the end-of-pipe type have functioned successfully to reduce mercury emissions to such an extent that all the environmental regulations introduced in Western Europe have been complied with.

This remarkable success in reducing mercury emissions by using various types of end-of-pipe technologies has made it possible for plant operators to continue to rely on the mercury process for chlor-alkali production. Figure 5-5 shows the trends in the shares of chlor-alkali production capacities based on the mercury process and the non-mercury processes, that is, the diaphragm and ion exchange membrane processes, in Western Europe. (Detailed data are given in Table 5-25 in Appendix at the end of this chapter.)
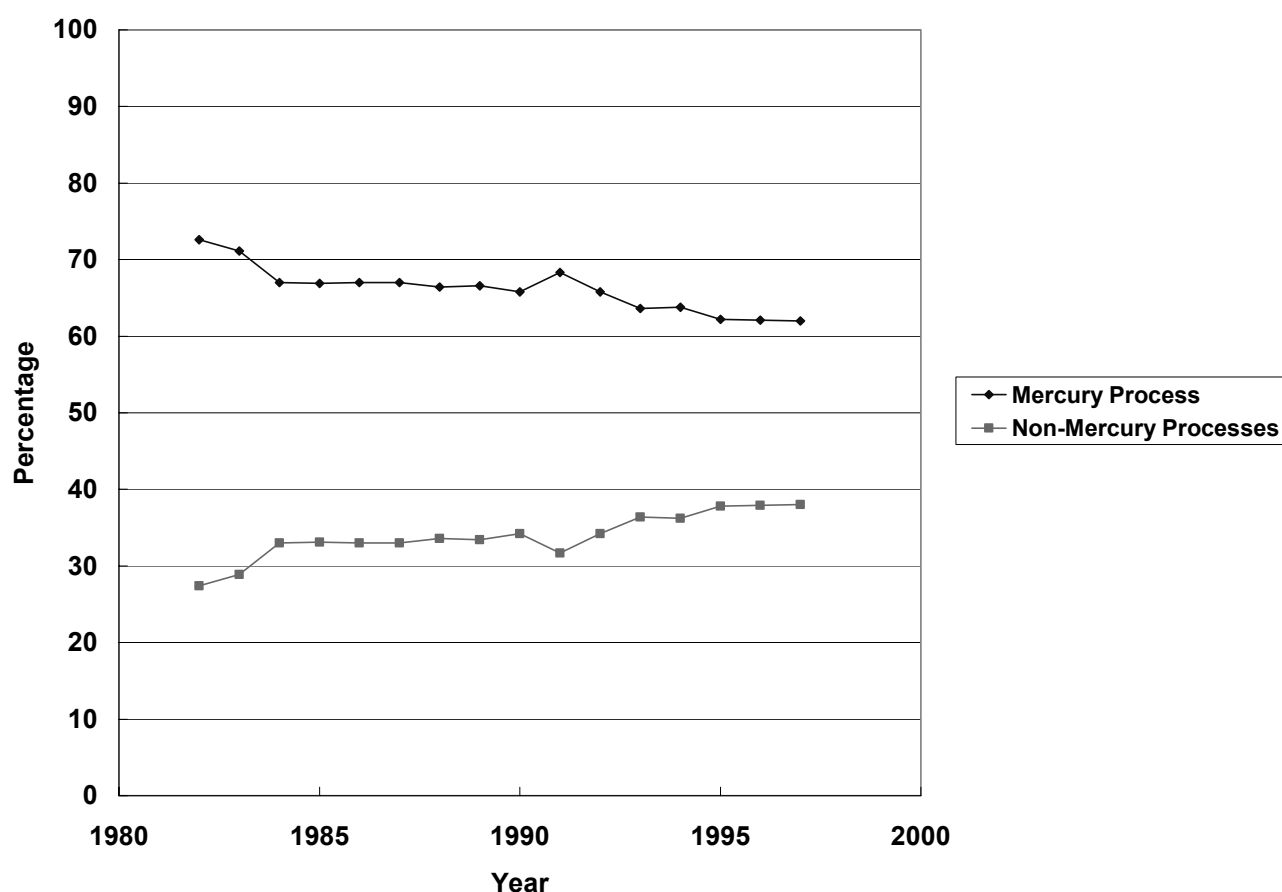
Figure 5-5 Production Capacities Based on the Mercury, Diaphragm, and Ion Exchange Membrane Processes in the Western European Chlor-Alkali Industry

Although the production capacities based on the mercury process have declined slightly since the early 1980s, the mercury process is still the dominant technology, currently accounting for more than 60 % of the total production capacities in Western Europe. In other words, most of the European chlor-alkali producers have continued to use the mercury process by adopting various types of end-of-pipe technologies installed to reduce mercury emissions. This form of technological change is in sharp contrast to the Japanese case, where

mercury emissions have been eliminated by phasing out the mercury process. Rather than installing end-of-pipe technologies for the abatement of mercury emissions, all the existing mercury-based chlor-alkali plants have been replaced with clean technologies, notably the ion exchange membrane process, which currently accounts almost all of the chlor-alkali production capacities in Japan.

5.3 Delayed Development of Technologies for the Ion Exchange Membrane Process

As we can see in while there were many successful patent applications on the mercury process by Western European companies during the 1970s, patents on the ion exchange membrane process started to appear at the end of the 1970s. In Chapter 3, we discussed that several companies in Western Europe, namely, ICI, Hoechst-Uhde, De Nora, Bayer, Solvay, and Krebs, cooperating with BASF, had been innovative on the mercury process in the past. Table 5-10 suggests that, in the 1970s, when environmental regulations on mercury emissions were being introduced, these companies continued to focus on the mercury process, applying successfully for US patents on this process. On the other hand, patent applications made by these companies on the ion exchange membrane process have been relatively few. Only ICI, Hoechst-Uhde, and De Nora were granted patents on technologies related to the ion exchange membrane process. Their successful patent applications started at the end of the 1970s, later and fewer than those made by the innovative companies in Japan. Other companies, including Bayer, Solvay, and Krebs, did not have any US patents on the ion exchange membrane process. In the following sections, we examine in detail when and how innovative activities were conducted by these companies for technological development of the ion exchange membrane process.

Imperial Chemical Industries

The chlor-alkali production of Imperial Chemical Industries (ICI)[100] started at the end of the 19th century, with the Castner-Kellner mercury cells introduced in 1897 at Runcorn in the northwest of England. This site is still the location of ICI's largest chlor-alkali plant with a production capacity of more than 700,000 tonnes of chlorine per year. This figure is

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[100] This section is based on information obtained through the author's interview with Mr. Steve Ingleby, Mr. R. W. Curry and Mr. Cliff Broom of ICI (Ingleby, Curry, and Broom, 1999).

significantly larger than that in the 19th century; only 500 tons of caustic soda was produced in 1897, increasing to 3,500 tons in 1900. Mond Division, which was responsible for the alkali production, was located at Runcorn because the country's main salt resources lied in that region. The electrolytic process was made possible by the increasing availability of electric generation capacity and essentially marked the beginning of the modern chlor-alkali industry. It replaced a variety of inefficient and expensive chlorine manufacturing processes based on oxidation of the by-product, hydrogen chloride, which prevailed before, and provided a new source of high quality caustic soda, another chemical in increasing demand at that time[101]. New cellrooms based on the mercury process were constructed at Runcorn in the 1930s.

Since the beginning of the electrolytic production of chlor-alkali products, ICI's R&D activities had been focused on the mercury process. Their main objective was to improve the reliability of the mercury process and to make it possible to operate the process continuously, as well as to develop technological measures for the reduction of mercury emissions (see Table 5-11). A major mercury cellroom, equipped with computer controlled anode adjustment and shorting resistant anode coatings, was commissioned in 1974, and mercury cells with steel baseplaces were introduced in 1976. The 1970s at the same time brought the realization of a need for reducing mercury emissions from its chlor-alkali plants, as mercury became one of the main targets of environmental regulations introduced in Western Europe. In addition to the development of end-of-pipe equipment, the optimization of process operation was effective in reducing mercury emissions, particularly those from cellrooms to the air.

On the other hand, the application of the ion exchange membrane for use in the chlor-alkali production had been recognized as a promising technology in the future for a long time. Some work on technologies related to the ion exchange membrane process was done by ICI as early as in the 1960s. The first ICI's patent on a zero-gap electrolytic cell, which could be utilized for the ion exchange membrane process, was indeed granted in 1962. As reliable ion exchange membranes with a sufficient lifetime for industrial uses were not available at that time, however, further R&D efforts were not made on the ion exchange membrane process. Then, in the 1970s, there was the rapid technological progress on the ion exchange membrane process in Japan in response to the government regulation to phase out the mercury process in the chlor-alkali industry. Better ion exchange membranes suitable for use in chlor-alkali

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[101] The chemical processes used in the chlor-alkali industry prior to the invention of the electrolytic processes

plants were developed by the Japanese companies and become available to Western Europe. That has provided ICI with strong incentives to invigorate its innovative efforts to develop technologies for the ion exchange membrane process. Subsequently, ICI made an agreement with Asahi Glass to introduce the ion exchange membrane, and an intensive R&D program was initiated in the late 1970s. A pilot plant utilizing the ion exchange membrane process with a production capacity of 6,000 tonnes of chlorine per year started to operate at its Lostock site in 1978.

Table 5-12 gives the chronology of technological development of the ion exchange membrane process at ICI.

Table 5-12 Technological Development of the Ion Exchange Membrane Process at ICI

Year	Technological Development
1962	First patent on electrolyzer for the ion exchange membrane process
1978	Start of a pilot plant based on the ion exchange membrane process
1983	First commercial sale of the ion exchange membrane process technology to outside firms
1989	Introduction of the ion exchange membrane process to its own plant

As with the company's earlier technologies for the mercury process, the development of technologies for the ion exchange membrane process was originally intended to be used at plants within the company's group. Having experienced operating the pilot plant for a few years, however, the company recognized that opportunities would exist to sell its ion exchange membrane process technologies to chlor-alkali producers beyond the corporate group. Accordingly, the company decided to market the technology to outside companies, and the company's FM21 process technology was launched for commercialization in July 1981. Table 5-28 in the appendix to this chapter gives the list of the chlor-alkali plants to which ICI has supplied its ion exchange membrane process technologies.

As you can see, the first major contract was made with Nobel for its plant in Sweden in December 1983 to convert the mercury process. Since then, ICI's technology for the ion exchange membrane process has been adopted by chlor-alkali producers around the world, but not by those in Western Europe. ICI itself introduced the ion exchange membrane process to its Runcorn site in 1989 for the production of caustic potash (KOH) of 26,000 tonnes per year, replacing the mercury process. This represented the company's first installment of the ion exchange membrane process to its own production plants. At the Runcorn site, however,

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and the effects of environmental regulations on technological change are discussed in more detain in Appendix.

most of the chlor-alkali production is still based on the mercury process. The company also maintains a plant based on the mercury process at Wilhelmshaven, Germany, with the production capacity of 130,000 tonnes of chlorine per year. Hence a significant part of the company's chlor-alkali products is still produced by using the mercury process.

Uhde

Uhde[102] is an engineering company, specializing in providing technologies for such product groupings as electrolysis, fertilizers, coke oven plants and machinery, polymers, organic chemicals, industrial plants, oil and gas technology, and off-sites. The electrolysis business accounts for more than one third of the total turnover of the company. Uhde had been associated with Hoechst, one of the major chlor-alkali manufacturers in Germany, with its Griesheim plant going on stream in 1892 as one of the first chlor-alkali electrolyzers in the world[103].

In the past, the focus of the company's technological development had been placed on the mercury process. The Uhde mercury cells were developed through decades of experience and research conducted cooperatively with Hoechst. Facilities necessary for R&D activities were located in the sites of this company. By the 1960s, Hoechst-Uhde had developed four sizes of mercury cells rated according to cathode area, with each size available in two styles, i.e. with decomposer either alongside or underneath the electrolyzer (Table 3-8). More than 100 chlor-alkali plants had been supplied with Uhde's mercury process technologies in the world.

The main emphasis of the R&D activities during the 1970s was placed on the mercury process, particularly on measures to reduce mercury emissions as well as to increase current density. Technological developments by the company have been focused on the removal of mercury from caustic soda, hydrogen, and waste water (see Table 5-11). In the middle of the 1970s, while the mercury process was still the major target of technological development, Uhde started to conduct R&D on the ion exchange membrane process. The availability of ion exchange membranes suitable for commercial-scale application developed by the Japanese companies encouraged the company's technological development of the ion exchange membrane process. A very small cell consisting of 10 single elements was set up in 1975,

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[102] This section is based on the author's interview with Dr. Benno Lüke and Mr. Roland Beckmann of Uhde (Luke and Beckmann, 1999).

primarily intended for the testing of materials. The test runs revealed that the only suitable materials were stainless steel, nickel and titanium sheet for cells with long-term stability, and perfluorinated plastics for gaskets and hoses. Based on this experience, the first pilot plant with an annual capacity of 500 tonnes of caustic soda was commissioned in 1977.

The ion exchange membrane process developed in the late 1970s and the early 1980s was characterized by improved performance of ion exchange membranes. They were at the root of the breakthrough of the ion exchange membrane process technology, opening a broader spectrum of commercial applications. They made it possible to obtain caustic soda solution of a high concentration at reduced power consumption. The Flemion membranes developed by Asahi Glass became available to Uhde through a technical agreement concluded in 1980. These ion exchange membranes were capable of producing caustic soda solution at as high as 35 %. Then electrolytic cells based on the ion exchange membrane process with a large current were assembled and installed at the second pilot plant of Bayer in Leverkusen in 1981.

Table 5-13 gives the chronological development of the membrane process by Uhde.

Table 5-13 Technological Development of the Ion Exchange Membrane Process at Uhde

Year	Technological Development
1975	Start of R&D on the ion exchange membrane process with a small-scale plant
1977	Start-up of the first pilot plant based on the ion exchange membrane process
1981	Start-up of the second pilot plant based on the ion exchange membrane process
1984	First supply of the ion exchange membrane process to outside firms
1987	Construction of the first full-scale pilot plant based on the ion exchange membrane process at Hoechst

As the company shifted the emphasis of its R&D activities from the mercury process to the ion exchange membrane process, the R&D expenditures on the ion exchange membrane process increased significantly, from less than 1 million DM in 1980 to 4 million DM in 1995. This significant increase in R&D expenditure was followed by a similar increase in the supply of the ion exchange membrane processes by the company to chlor-alkali producers around the world. Table 5-29 in the appendix to this chapter shows the chlor-alkali plants which adopted the ion exchange membrane process technologies developed by Uhde.

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[103] In 1996 Uhde was demerged from Hoechst and purchased by the Krupp Group, which formed Krupp-Uhde GmbH.

The first industrial chlor-alkali facility using Uhde's ion exchange membrane process technology was commissioned in 1984 at Tofte in Norway. A full-scale pilot plant was built at Hoechst in Frankfurt in 1987. Compared with the chlorine production capacity of several hundred thousand tonnes per annum at Hoechst, the capacity of the ion exchange membrane process of 10,000 tonnes per annum was relatively small. This pilot plant, however, was intended primarily for testing a modular unit for the use in electrolysis plants with large chlorine capacities, that is, for the construction of new grass-roots plants as well as for the conversion of existing mercury-based plants.

As we can see in the table, installations of Uhde's ion exchange membrane process mostly occurred in the 1990s. In the period from 1994 to 1999, production capacities of 2,943,000 t NaOH/year were commissioned, accounting for more than 80 % of the total capacities of 3,600,000 t/year NaOH constructed by Uhde since 1984. During the same period, the ion exchange membrane process was introduced to 30 chlor-alkali plants, corresponding to 60 % of the total number of chlor-alkali plants at which the ion exchange membrane process has been installed by the company.

De Nora

De Nora[104] was founded as an engineering company, specializing in electrochemistry. The company's activities have been focused for a long time on the manufacture of chlorine, caustic soda (potash) and hydrogen by brine electrolysis with the mercury process. In particular, the company has maintained a share of more than half of the world market of coatings and support materials, with the dimensionally stable electrodes for chlor-alkali cells. Other areas of its activities are also related to chlor-alkali products, including on-site generation of active chlorine solution from seawater or brine for control of fouling in water circuits and disinfection, granular high concentration calcium hypochlorite, cathodic protection and fuel cells.

The company has conducted R&D activities on technologies related to electrochemistry and its applications, particularly on cell designs and electrodes, anode as well as cathode, for use in electrolysis. De Nora's mercury process technologies have evolved through a series of changes since they were first introduced in the 1950s. Subsequently, the company developed electrolytic cells for the mercury process of a horizontal type in various sizes (Table 3-8). By

the early 1970s, more than 130 chlor-alkali plants with a total capacity of over five million tonnes per year had been based on the mercury process provided by De Nora. That corresponded to about one quarter of the world production capacities at that time, and the company was one of the leading providers of the mercury process technologies to chlor-alkali producers not only in Western Europe but also in the United States and Japan (see Table 3-11, Table 3-15, and Table 3-18). Although the construction of new, green-field plants based on the mercury process supplied by De Nora ended in 1985, expansions and relocations of mercury-based plants continued until 1994. Currently, modification of the existing mercury plants and provision of technical assistance for necessary adjustments at mercury-based plants are still undertaken by the company.

Table 5-14 gives the chronology of the technological development of the ion exchange membrane process by De Nora.

Table 5-14 Technological Development of the Ion Exchange Membrane Process at De Nora

Year	Technological Development
Late 1970s	Start of R&D on the ion exchange membrane process
1979	Introduction of ion exchange membranes from Asahi Glass
1983	First supply of the ion exchange membrane process to outside chlor-alkali producers

The company started to conduct its R&D activities on the ion exchange membrane process in the late 1970s, following the development of ion exchange membranes suitable for use in chlor-alkali electrolytic cells by several Japanese companies. A research agreement was made between De Nora and Asahi Glass in 1979, and the ion exchange membranes developed by the Japanese company was introduced for De Nora's electrolytic cells. R&D efforts on the ion exchange membrane process were reinforced in the early 1980s, when a university professor with expertise on electrochemistry was invited to conduct innovative research on the ion exchange membrane process at the company. R&D activities have been intensified since then, increasing expenditures as well as personnel significantly. A result can be observed in the increased patents successfully applied on technologies related to the ion exchange membrane process in the 1980s (see Table 5-10).

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[104] This section is based on the author's interview with Dr. Giuseppe Faita and Mr. Marco Tenconi of De Nora (Faita and Tenconi, 1999).

The trends in the supply of the ion exchange membrane process by De Nora are shown in Table 5-30 in appendix to this chapter. De Nora's first chlor-alkali plant based on the ion exchange membrane process was constructed in 1983. Since then, approximately 40 chlor-alkali plants have adopted the ion exchange membrane process provided by De Nora, with the annual production capacities reaching nearly 1.3 million tonnes of chlorine in the world[105]. Many of these chlor-alkali plants are located in developing countries, notably Asian countries such as India and China, and the number of chlor-alkali plants which adopted De Nora's ion exchange membrane process is still limited in Western Europe.

Solvay

Solvay[106] has been the largest chlor-alkali producer in Western Europe for a long time. In the past its innovative activities had been placed on the mercury process, and Solvay's mercury process had been adopted by many chlor-alkali producers in Western Europe (see Table 3-11). During the 1980s, when environmental regulations on mercury emissions were introduced, Solvay continued to rely on the mercury process for its chlor-alkali production. On the other hand, as Table 5-10 suggests, the company did not make any significant innovations on the ion exchange membrane process in the same period. Then, in the early 1990s, Solvay started to convert its mercury-based plants to the ion exchange membrane process by introducing technologies developed by Asahi Glass, although a significant part of the company's chlor-alkali production is still based on the mercury process.

Krebs

Krebs had been one of the major engineering companies which had developed advanced technologies for the mercury process, cooperating with BASF, one of the major chlor-alkali producers in Germany. The company's technology had been adopted by many chlor-alkali producers not only in Western Europe but also in Japan, as we can see in Table 3-11 and Table 3-18. Regarding the ion exchange membrane process, however, any remarkable innovations have not been made by the company, as is suggested in Table 5-10. Rather than developing its own technologies for the ion exchange membrane process, the company introduced Asahi Glass's technologies at the end of the 1980s (Krebs Swiss, 1997). Currently,

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[105] Recently, Krupp Uhde and De Nora have made public a plan to merge their chlor-alkali R&D, technology licensing, and plant construction activities into a 50-50 joint venture, named UhdeNora, in Milan (Alperowicz, D'Amico, and Westervelt, 2001; *Chemical Week*, 2001).

Krebs is a European representative of Asahi Glass and has been working to provide the ion exchange membrane process technologies to chlor-alkali producers mainly located in Western Europe (Krebs Swiss, 2001).

Technological Developments by Companies in Western Europe

As we have discussed in the proceeding section, several Western European companies which had been previously innovative on the mercury process succeeded in developing their own technologies for the ion exchange membrane process. Table 5-15 lists the technologies developed by the innovative companies in Western Europe.

Table 5-15 Technologies Developed by Companies in Western Europe

Company	Mercury Process	Ion Exchange Membrane Process	
		Ion Exchange Membrane	Electrolytic Cell
ICI	Steel Base	-	FM, BiChlor
Uhde	$10 \ m^2$ $20 \ m^2$ $31.5 \ m^2$	-	Single Element
De Nora	14 x 3F 18 x 4 24 x 5	-	DD
Solvay	V-100F V-200F	-	-
Krebs	ZT 80-10-8 ZT 120-15-8	-	-

Among the innovative companies based in Western Europe, three companies, namely, ICI, Uhde, and De Nora, have developed technologies for the ion exchange membrane process. Solvay and Krebs, on the other hand, did not make any significant innovations on the ion exchange membrane process. As we have seen in Figure 4-2, the electrolyzer of the ion exchange membrane process basically consists of the ion exchange membrane and the electrolytic cell. While the three Japanese companies, that is, Asahi Chemical Industry, Asahi Glass, and Tokuyama Soda, made innovations on both the ion exchange membrane and the electrolytic cell, the Western European innovators, that is, Uhde, De Nora, and ICI developed their technologies only for the electrolytic cell but not for the ion exchange membrane. These European companies have introduced ion exchange membranes for their electrolytic cells from the three Japanese companies.

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[106] Interviews with Solvay and Krebs were not possible to receive detailed information on their R&D activities.

The chronology of technological developments of chlor-alkali production processes by companies in Western Europe is shown in Figure 5-6.
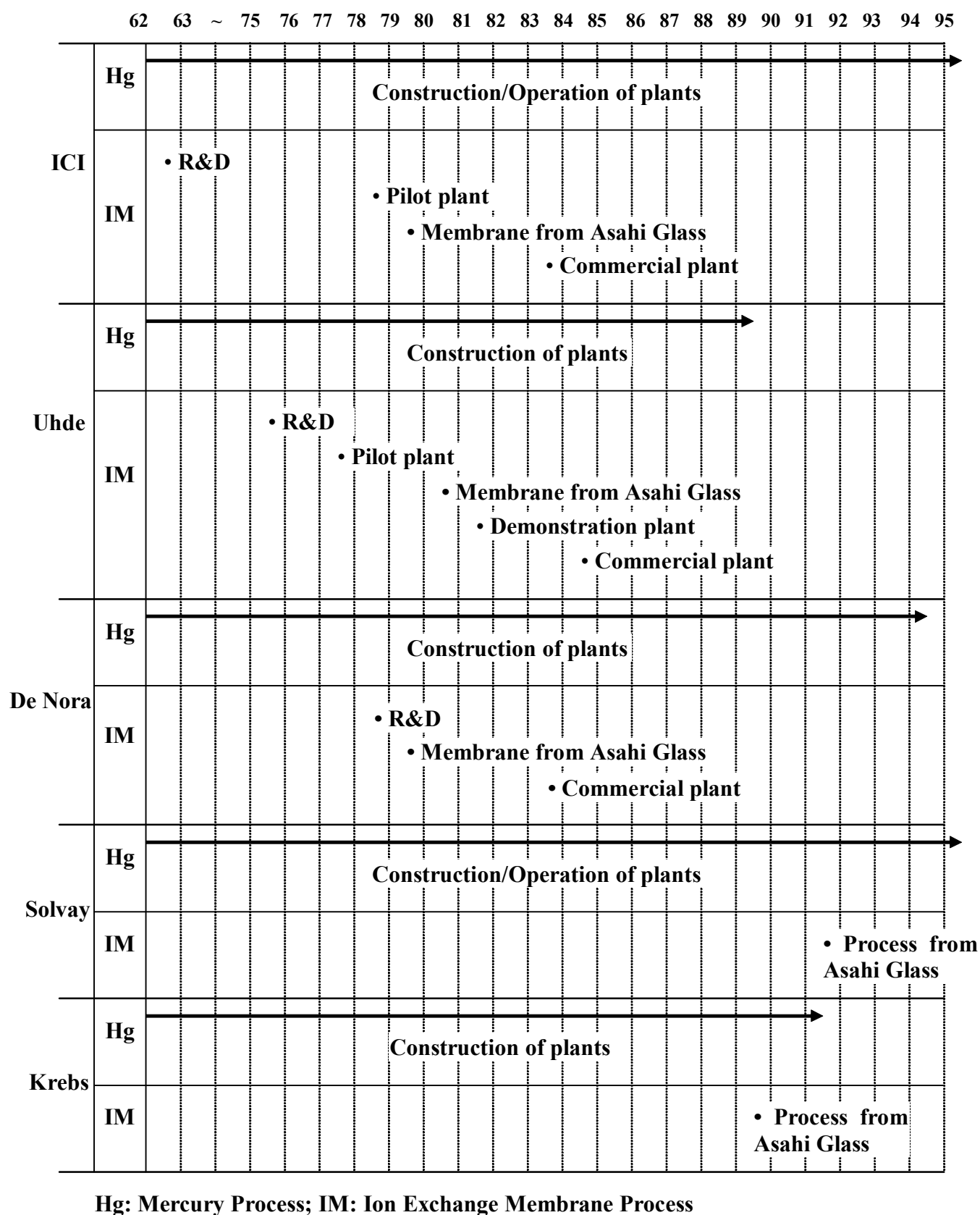
Figure 5-6 Technological Developments by Companies in Western Europe

As we have seen in Figure 4-6, in the case of the Japanese chlor-alkali industry, R&D activities on the ion exchange membrane process were first initiated by Asahi Chemical Industry in the late 1960s and by other innovative companies, including Asahi Glass, Tokuyama Soda, in the early 1970s, and the commercial operation of chlor-alkali plants based on the ion exchange membrane started in the middle of the 1970s at these companies' own production sites. In Western Europe, ICI started to undertake R&D activities on the ion exchange membrane process as early as the beginning of the 1960s. With difficulties, however, in obtaining ion exchange membranes which had sufficient chemical and mechanical strength suitable for use in chlor-alkali electrolytic cells, the company had stopped its innovative efforts on the ion exchange membrane process subsequently. Other companies, including Uhde and De Nora, did not make any significant R&D efforts on the ion exchange membrane process until the late 1970s. In the meantime, the operation of the mercury process continued to be dominant for the production of chlor-alkali products in Western Europe. And R&D efforts were directed towards developments of end-of-pipe technologies for the reduction of mercury emissions, rather than alternative clean technologies for the replacement of the existing mercury process.

By the late 1970s, the Japanese companies had made major innovations on ion exchange membranes and had proved that the ion exchange membrane process was a well-established technology which could be reliable utilized for commercial production. The rapid progress in the technological performance of the ion exchange membrane process in Japan provided strong incentives and technological basis to European companies. Several innovative companies, namely, ICI, Uhde, and De Nora, then intensified R&D efforts to develop their own technologies for the ion exchange membrane process in the late 1970s. By that time, however, novel types of the ion exchange membrane had been already invented by the Japanese companies, and there had been little room left to the later comers. That has induced the European companies to focus their development efforts on the other important components of the ion exchange membrane process, that is, the electrolytic cell. Ion exchange membranes for use in their electrolytic cells were introduced from the Japanese companies. Their technologies started to be applied for commercial plants in the middle of the 1980s.

In short, compared with the Japanese case, technological developments of the ion exchange membrane process were delayed in Western Europe. These Western European firms, including ICI, Uhde, and De Nora, had made significant innovations on the mercury process

by the beginning of the 1970s. With the introduction of emission standards on mercury emissions, the strong technological expertise on chlor-alkali production was not devoted to develop technologies for the ion exchange membrane process. That was in sharp contrast to the Japanese case, in which the mandate for the phase out of the mercury process prompted the equally innovative companies to develop and industrialize chlor-alkali production technologies based on the ion exchange membrane process.

The chlor-alkali production technologies developed by Western European companies have been subsequently adopted by other chlor-alkali producers. Figure 5-7 shows the trends in the number of installations of the mercury process as well as the ion exchange membrane process by companies in Western Europe. (Detailed data are given in Table 5-26 in Appendix at the end of this chapter.)
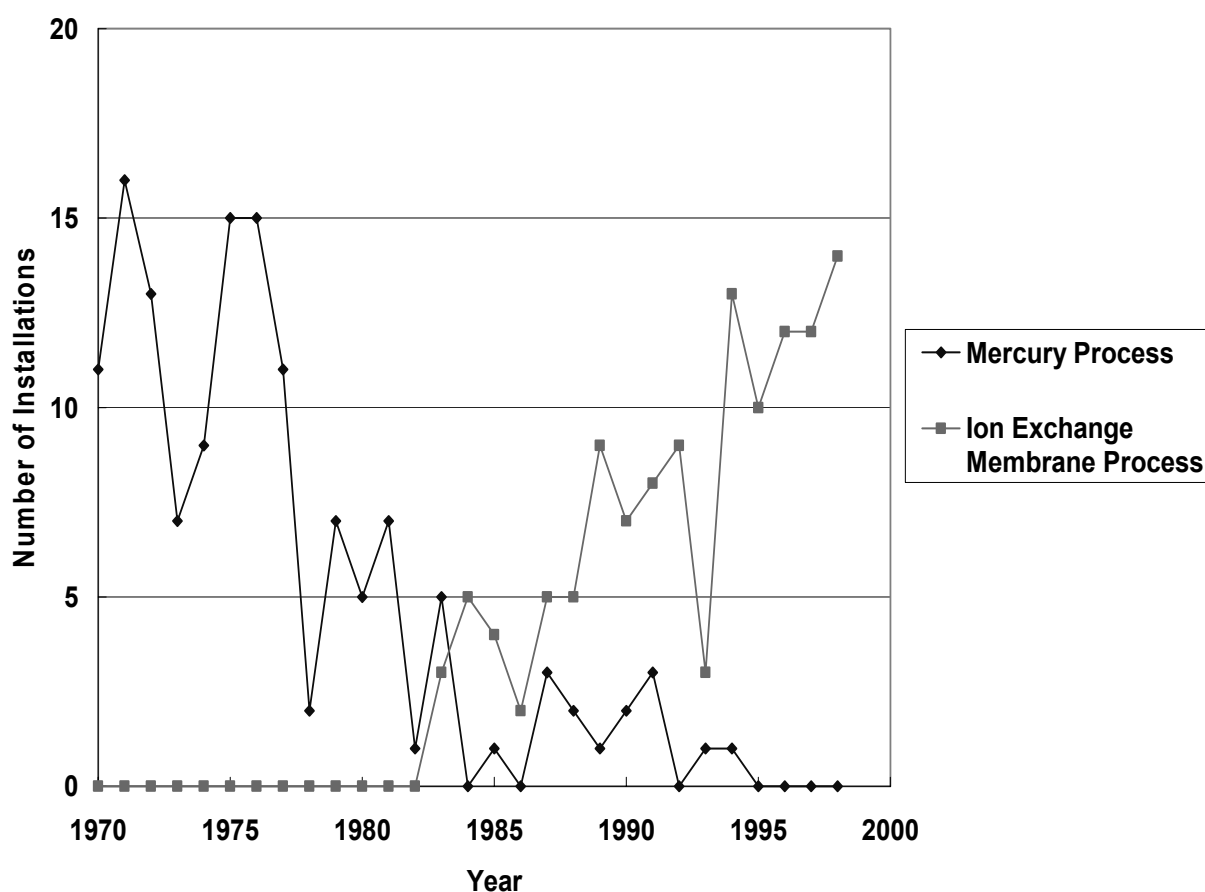
Figure 5-7 Supply of the Mercury and the Ion Exchange Membrane Processes by Western European Firms

Figure 5-7 shows a contrast with the supply of the ion exchange membrane process by the Japanese companies (Figure 4-7). During the 1970s there was a large amount of supplies of the mercury process by Western European firms whereas the ion exchange membrane was not yet developed to such an extent that it could be provided to chlor-alkali producers. Then the supply of the ion exchange membrane started in the 1980s and maintained an upward trend in the 1990s. Although the supply of the mercury process declined in the 1980s, it continued until the middle of the 1990s.

Detailed data on the supply of the mercury and the ion exchange membrane processes by ICI, Uhde, De Nora, Solvay, and Krebs are given in Table 5-16.

Table 5-16 Supply of the Mercury and the Ion Exchange Membrane Processes by Innovative Companies in Western Europe

Year	ICI		Uhde		De Nora		Solvay		Krebs	
	Hg	IM	Hg	IM	Hg	IM	Hg	IM	Hg	IM
1970	0	0	7	0	1	0	1	0	2	0
1971	1	0	5	0	5	0	0	0	5	0
1972	0	0	6	0	6	0	1	0	0	0
1973	0	0	3	0	1	0	0	0	3	0
1974	0	0	2	0	2	0	2	0	3	0
1975	1	0	6	0	6	0	0	0	2	0
1976	0	0	5	0	4	0	0	0	6	0
1977	1	0	3	0	6	0	0	0	1	0
1978	0	0	2	0	0	0	0	0	0	0
1979	0	0	4	0	1	0	1	0	1	0
1980	0	0	0	0	4	0	0	0	1	0
1981	0	0	2	0	2	0	0	0	3	0
1982	0	0	0	0	1	0	0	0	0	0
1983	0	1	4	0	1	2	0	0	0	0
1984	0	3	0	2	0	0	0	0	0	0
1985	0	4	0	0	1	0	0	0	0	0
1986	0	0	0	1	0	1	0	0	0	0
1987	0	2	1	2	0	1	0	0	2	0
1988	0	1	0	3	2	1	0	0	0	0
1989	0	4	1	4	0	1	0	0	0	0
1990	0	3	0	3	2	1	0	0	0	0
1991	0	4	0	1	1	3	0	0	2	0
1992	0	3	0	4	0	2	0	0	0	0
1993	0	1	0	0	1	2	0	0	0	0
1994	0	2	0	5	1	6	0	0	0	0
1995	0	1	0	3	0	6	0	0	0	0
1996	0	1	0	6	0	5	0	0	0	0

1997	0	2	0	8	0	2	0	0	0	0
1998	0	5	0	6	0	3	0	0	0	0
Total	24	296	408	384	384	288	40	0	248	0

Hg: Mercury Process; IM: Ion Exchange Membrane Process.
Figures refer to the number of installations.
Pilot plants are excluded.
Sources:
Mercury Process: Chlorine Institute (1998a; 1998b).
Ion Exchange Membrane Process: Imperial Chemical Industries (1999), Krupp-Uhde (1998),
De Nora (1999).

While regulations on mercury emissions started to be imposed on the chlor-alkali industry in Western Europe in the 1970s, the suppliers continued to provide their mercury process technologies to chlor-alkali producers. Uhde, De Nora, and Krebs were particularly active in providing their mercury process technologies to chlor-alkali producers during the 1970s. On the other hand, there was no commercial construction of the ion exchange membrane process by these companies in the same decade. Industrial applications of the ion exchange membrane process were started by ICI and De Nora in 1983 and by Uhde in 1984, and since then installations by these companies at other chlor-alkali plants have followed steadily. The mercury process, however, continued to be provided by the Western European suppliers, although in a limited scale, during the 1980s. De Nora, in particular, continued to supply its ion exchange membrane process technology until the last one was completed in the middle of the 1990s. While new installations of the mercury process have been terminated, the operation of the mercury process has been still maintained by many chlor-alkali producers in Western Europe, including ICI, which has already developed and started to provide its own technology for the ion exchange membrane process to other chlor-alkali producers.

The extent of the supply of the ion exchange membrane process by the Western European firms can be seen by comparing with that by the Japanese firms. Figure 5-8 shows the trend in the cumulative production capacities based on the ion exchange membrane process which have been supplied by the Western European firms, including ICI, Uhde, and De Nora, and the Japanese firms, including Asahi Chemical Industry, Asahi Glass, Tokuyama Soda, and CEC. (Detailed data are given in Table 5-27).
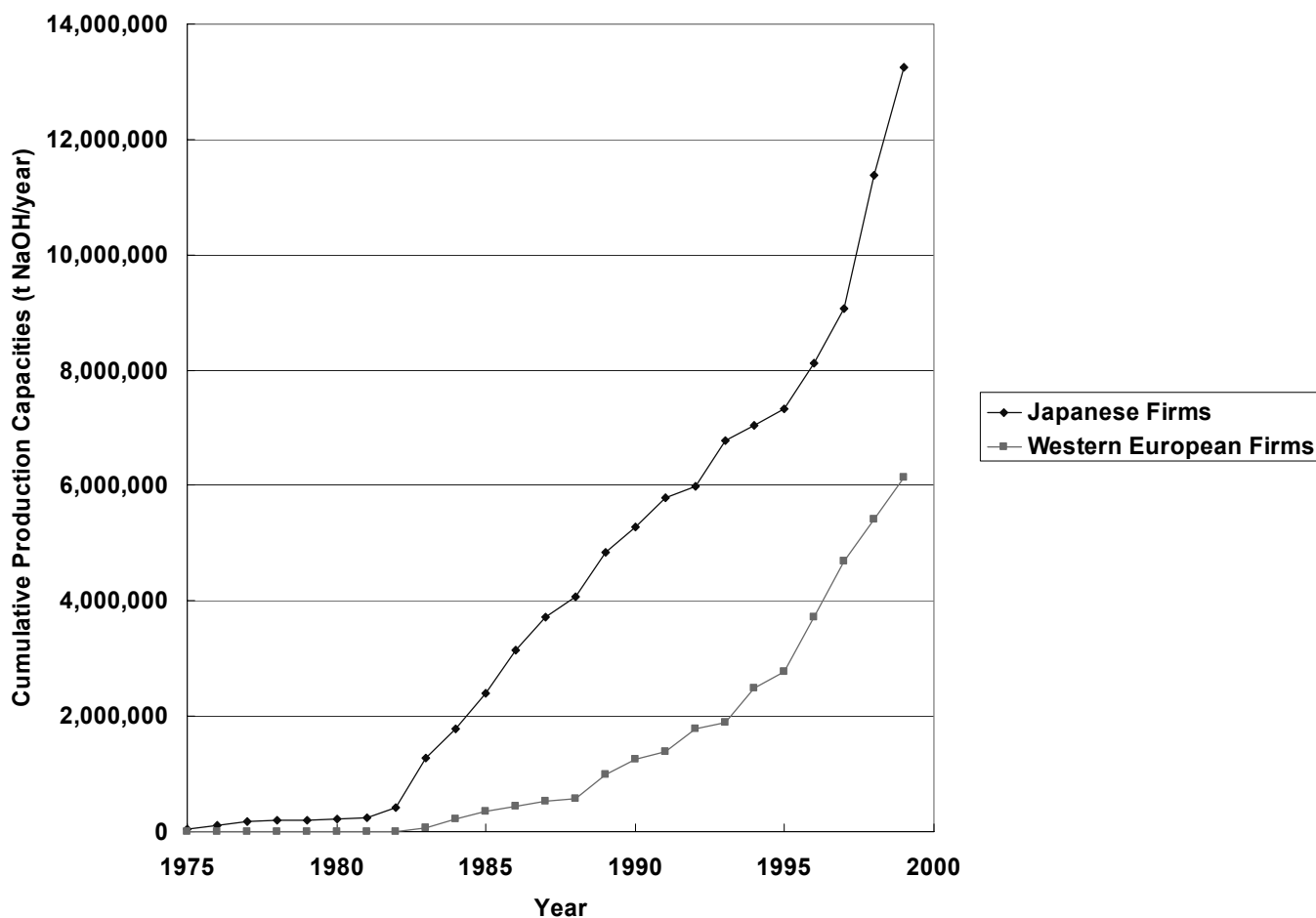
Figure 5-8 Supply of the Ion Exchange Membrane Process by Japanese and Western European Firms

From the middle of the 1970s to the early 1980s, while there was no supply of the ion exchange membrane process by the Western European firms, it was installed by the Japanese firms mainly at chlor-alkali plants operated by the innovative companies themselves. The experienced obtained in this period provided the Japanese companies with expertise valuable to improve their technologies, and that gave them advantages in supplying the ion exchange membrane process to chlor-alkali plants in other parts of the world. Although the Western European suppliers began to provide their technologies in the middle of the 1980s, their delayed start has resulted in the large gap with the Japanese early movers.

5.4 Slow Diffusion of the Ion Exchange Membrane Process

As Figure 5-5 shows, the mercury process has continued to be the dominant technology in Western Europe, whereas the share of the ion exchange membrane process, which is now the most efficient technology without any emission of pollutants, is limited to less than 15 %. Although a sign of increase has been observed recently in the adoption of the ion exchange membrane process, its diffusion is still limited, particularly compared with the case of the Japanese chlor-alkali industry, in which almost all of the production capacities are currently based on the ion exchange membrane process.

In this section, we examine why the diffusion of the ion exchange membrane process has been slow among chlor-alkali producers in Western Europe. As we discussed in Chapter 2, there are basically two factors which would inhibit the diffusion of a new technology. They concern the availability of information on the new technology and the profitability of its adoption. We consider them in turn for the analysis of the adoption of the ion exchange membrane process in Western Europe.

5.4.1 Availability of Information on the Ion Exchange Membrane Process

First, we examine whether the availability of information has been the limiting factor for the diffusion of the ion exchange membrane process in Western Europe. An academic paper on a successful commercial operation of chlor-alkali plant based on the ion exchange membrane process was published for the first time on the journal, *Industrial and Engineering Chemistry, Product and Research Development*, in 1976 by a researcher of Asahi Chemical Industry (Seko, 1976). In the middle of the 1970s, however, the European chlor-alkali industry was short of "credible" information on the performance and the reliability of the ion exchange membrane process (Mellish, 1977). With fairly short experience of the new technology, chlor-alkali producers needed good solid data on any change in technology before spending money on new plants relying on it. Since 1979, the Electrochemical Technology Group of the Society of Chemical Industry, a UK-based industry association of chemical companies, has organized a symposium on chlor-alkali technologies in London every three years. The organizing committees of these symposiums consisted of representatives of chlor-alkali producers in Western Europe. The proceedings, edited by technological experts of chlor-alkali manufacturers in UK, were published one year after each symposium. Table 5-17 gives the trends in the number of presentations as well as participants of the symposiums.

Table 5-17 Presentations on Chlor-Alkali Production Processes at the London International Chlorine Symposiums

Year	Mercury process	Diaphragm process	Ion Exchange Membrane process	Total[a]
1979	4	5	9	23
1982	0	4	9	24
1985	0	0	12	30
1988	0	1	15	29
1991	1	1	11	26
1994	0	5	9	28
1997	1	4	8	26
2000	1	2	7	25

* Presentations which were not included in the proceedings are excluded. Only for 2000 all the presentations are included.

a: The total also includes presentations concerning general aspects such as economic, safety, and environmental issues.

Sources: 1976: Society of Chemical Industry (1977). 1979: Coulter (1980). 1982: Jackson (1983). 1985: Wall (1986). 1988: Prout and Moorhouse (1990). 1991: Wellington (1992). 1994: Curry (1995). 1997: Sealey (1998). 2000: Society of Chemical Industry (2000).

Entering in the 1980s, paper presentations increasingly dealt with this new field of technology and more detailed technical information started to be disclosed. By the late 1980s, more than half of the presentations had come to focus on the ion exchange membrane process. In contrast, very few presentations have been made on the mercury process since 1980s. At each meeting, technical experts from process developers made presentations on their latest technologies to the audience from chlor-alkali producing companies. The compositions of participants in the meetings held in 1991 and 1994 are given in Table 5-18. As we can see in the table, more than 200 people in each meeting, and the representatives of major chlor-alkali companies in Western Europe, including ICI, Uhde, De Nora, Solvay, and Krebs, as well as those in Japan, such as Asahi Chemical Industry, Asahi Glass, and CEC, were all present at the meetings.

Table 5-18 Participants in the London International Chlorine Symposiums

Country	Company	Number of Participants	
		1991	1994
United Kingdom	ICI	17	19
	Hays	8	10
	Roche	3	5
	Octel	3	4
	British Salt	3	2

	Badger Cat.	3	1
	Others	14	18
		51	59
Germany	Uhde	3	5
	Bayer	4	4
	Lurgi	3	0
	BASF	3	2
	Dow (Stade)	6	3
	Others	8	6
		27	20
Sweden	Eka Nobel	7	5
	Permescand	5	3
	Others	5	4
		17	12
Italy	De Nora	7	6
	Others	7	3
		14	9
France	Rhone Poulenc	6	7
	Elf Atochem	4	4
	Others	2	3
		12	14
Netherlands	Akzo-Nobel	5	7
	Others	4	0
		9	7
Belgium	Solvay	3	3
	Others	6	3
		9	6
Finland		6	2
Norway		5	5
Switzerland		4	3
Ireland		2	2
Portugal		2	1
Spain		1	2
Austria		0	1
Denmark		0	1
Western Europe		164	154
Japan	CEC	7	5
	Asahi Chemical	6	3
	Asahi Glass	4	2
	Mitsui Toatsu	4	1
	Permelec Electrode	2	1
	Du Pont	2	0
		25	12
Other regions		58	65

		247	231
Total		247	231

Source: Shiroki (1994).

In the meantime, following the publication of the seminal paper on the first commercial application of the ion exchange membrane process in 1976, papers and articles showing technical aspects of the ion exchange membrane process started to appear. They were mainly published in trade journals, such as the *Journal of Applied Electrochemistry* (e.g. Bergner, 1982), *Chemistry and Industry* (e.g. Jackson and Kelham, 1984), *Chemical Engineering* (e.g. Means and Beck, 1984), *Chemical and Engineering News* (e.g. Stinson, 1982), *Chemical Week* (e.g. Brooks, 1986), *Chemische Industrie* (e.g. Luke, 1989), and *Chemiker-Zeitung* (e.g. Bergner, 1977). At the same tine, there were an increasing number of reports on cases dealing with conversions of the mercury process to the ion exchange membrane process undergoing in the Japanese chlor-alkali industry. These various sources of information indicated that the newly developed technology of the ion exchange membrane process had reached a stage ready for industrial applications. Therefore, we could arguably conclude that it is highly unlikely that chlor-alkali producers in Western Europe were not aware of the feasibility or performance of the ion exchange membrane process. That would bring us to the second reason why the diffusion of a new technology could be delayed; that is, the profitability of the adoption of the ion exchange membrane process.

5.4.2 Profitability of the Adoption of the Ion Exchange Membrane Process

We discussed in Chapter 2 that a new clean technology is adopted when it is profitable to do so. That means, in the case of technological change for pollution abatement, the existing technology is replaced with a new clean technology when the total cost of operating the existing technology with the end-of-pipe technology is larger than that operating the clean technology:

$$TC_e(a, t) > TC_c(t),$$

that is,

$$PC_o - PC_c(t) > IC_c - IC_e - AC_e(a, t).$$

With this model, we examine the diffusion of the ion exchange membrane process in Western Europe.

Investment Cost of Introducing the Ion Exchange Membrane Process

We first consider the investment cost of introducing the ion exchange membrane process. Capital costs required in the chemical process industries are often assumed to be subject to economies of scale, with a scaling-up factor. One of the most frequently used empirical rules is the so-called "sixth-tenth factor rule" (Bruni, 1964). This empirical rule has been justified by noting that the cost of a piece of equipment or of an entire plant, at least in many industries having a continuous production process, depends mainly on the surface area of the plant equipment whereas production capacity depends on the volume. Assuming that plant equipment of different capacity have walls of equal thickness and that the cost of the equipment is proportional to their weight, the cost varies in proportion to their volume, i.e. their capacity, taken to the power of 2/3[107].

In contrast to this general rule of 2/3 scaling-up factor applied for a single large-scale production unit, a chlor-alkali electrolytic plant has multiple cell elements into a single unit, called electrolyzer. Each electrolyzer consists of a large number of cell elements, following either of two basic designs, monopolar or bipolar. The elements are connected in series with resultant low current and high voltage in a bipolar arrangement whereas in the monopolar type cell all anodes and cathodes are connected in parallel, forming an electrolyzer with high current and low voltage[108]. And then multiple electrolyzers are employed in a single direct current circuit; usually bipolar electrolyzers are connected in parallel with low current and high voltage whereas monopolar electrolyzers are often connected in series, resulting in a high current circuit and low voltage. For example, one of the bipolar type electrolyzers produces 15,000 tonnes of caustic soda per year, meaning that a plant with an annual capacity of 120,000 tonnes of caustic soda would need eight electrolyzers (Schneiders and Luke, 1992). One recent case of the process conversion required 848 cell elements, and another case needed 1,536 cell elements (Kramer and Luke, 1990). In essence, electrolysis for chlor-alkali

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[107] This rule can be demonstrated in elementary geometry by considering spherical or cylindrical tanks whose height is constantly related to their diameter. The surface area A and the volume V of a spherical tank are

$\qquad A = 4\pi R^2$ $\qquad\qquad\qquad$ (5f-1)

$\qquad V = 4/3\pi R^3,$ $\qquad\qquad\quad$ (5f-2)

where R is the diameter of the tank. The capital cost of the plant equipment C is

$\qquad C = c_o A = 4\pi c_o R^2,$ $\qquad\quad$ (5f-3)

where c_o is the unit cost of the equipment material. From equation (5f-2) we can derive

$\qquad R = (3/4\pi)^{1/3} V^{1/3}.$ $\qquad\quad$ (5f-4)

Hence we obtain

$\qquad C = 3^{2/3}(4\pi)^{1/3} c_o V^{2/3} = kV^{2/3},$ $\qquad$ (5f-5)

where $k = 3^{2/3}(4\pi)^{1/3} c_o$, which is constant.

[108] Data on various types of the electrolytic cell are given in Table 5-31 in Appendix at the end of this chapter.

manufacture is a two-dimensional process, which consists of a large number of relatively small electrolytic cells connected with each other. We hence assume that the scaling-up factor can be approximated to unity.

In converting chlor-alkali plants from the mercury process to the ion exchange membrane process, while the rectifier, chlorine and hydrogen systems, and caustic storage could continue to be used, several new facilities will be required to utilize the ion exchange membrane process (Austin and Esayian, 1984). The use of high-performance ion exchange membranes requires a new secondary brine purification step to remove calcium and magnesium to a level of less than 50 ppb, but the cost of the brine system for the ion exchange membrane process is relatively small, 4-7 % of the total capital investment (Schmittinger, Curlin, Asawa, Kotowski, Beer, Greenberg, Zelfel, and Breitstadt, 1986). In addition, many electrolyzer designs for the ion exchange membrane process include a caustic circulation loop to provide temperature control as well as mixing to achieve a uniform concentration profile in the cathode chamber. Deionized water is added to the catholyte loop to control the caustic concentration. When 50 % caustic is required, evaporators will be needed to further concentrate the 32-35 % caustic produced by the ion exchange membrane electrolyzers, and additional steam generating facilities may also be required depending on the site situation. The installation of these facilities cost 3-4 % of the total investment(Schmittinger, Curlin, Asawa, Kotowski, Beer, Greenberg, Zelfel, and Breitstadt, 1986).

Taking these aspects into account, we assume here that the total investment cost of process conversion can be basically represented by the cost for the electrolytic cells and ion exchange membranes. Since the scaling-up factor can be approximated to be 1, the unit capital investment will be almost constant for plants of varying capacities, and thus the total capital investment will rise proportionately as the plant size increases. This treatment can be justified by the fact that the capital investment cost is normally discussed in this way by experts in the chlor-alkali industry, although not so much information has been disclosed on the actual investment costs of converting the mercury process to the ion exchange membrane process[109].

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[109] Converting mercury cells to ion exchange membrane cells incrementally over a period of time within a mercury cellroom is not generally considered to be practical or cost effective by those working in the industry (Lindley, 1997). First, because for ion exchange membrane cells trace quantities of mercury can have a significant impact on the performance of the ion exchange membrane, a separate recirculated brine system would be required. Second, since the cell layouts are totally different for ion exchange membrane and mercury cells, with the power densities and heat loads different, a separate power supply system (rectifiers) would be needed. Furthermore, as the mercury cell room layout is designed to enable mercury to be contained, operating

At the end of the 1970s, when several plants based on the ion exchange membrane process started to operate in Japan, the three technology providers, namely, Asahi Chemical Industry, Asahi Glass, and Tokuyama Soda, reported that the investment cost of installing the ion exchange membrane process would be approximately 7 billion yen for a plant of an annual capacity of 100,000 tonnes of caustic soda (Expert Committee for Technical Evaluation of the Ion Exchange Membrane Process, 1979). That corresponds to 320 US$/t NaOH, which is equivalent to 360 US$/t Cl_2[110]. While this conversion cost was probably estimated to be lower, as this figure did not include a significant amount of investment costs required for dismantling the existing mercury process.

In the United Kingdom, Associated Octel Company converted its chlor-alkali plant at Ellesmere Port, Cheshire, with a capacity of 40,000 t Cl_2 per year in 1992 from the mercury process to the ion exchange membrane process (Lott, 1995). In this case, new electrolytic cells could be installed in the existing cellroom, but the decontamination of mercury at the site required a significant treatment. A completely new caustic recirculating system and a holding tank had to be installed as a guard against iron and mercury contamination. Other equipment included a secondary brine treatment plant reducing calcium and magnesium ions in the brine down to ppb levels. As samples of the pure brine from the mercury cells system indicated high levels of silicate, a salt dissolving pit and a brine handling tank were taken out of service and relined with plastic. The reused brine system was subsequently demercurized. The disposal of the mercury cell steelwork proved more time-consuming and costly. In total the company made an investment of £ 11,583,000 in this conversion project, including cellroom, new equipment, modifications to the existing plant, labor and administration, and the disposal of the contaminated steel. This figure corresponds to an investment of 510 US$/t Cl_2 capacity.

A case of the conversion of the mercury process to the ion exchange membrane process at the Borregaard plant in Norway in 1997 has shown that the total cost was around 200 million NOK, equivalent to US$ 28 million (Borregaard, 1998). A new electrolysis section was constructed, and a brine circuit for filtration, secondary purification with ion exchange and dechlorination, a unit for concentrating caustic soda, and units for chlorine gas drying and

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ion exchange membrane cells within the same cellroom would require some mercury containment activities and some of the working practices. Therefore, conversion from mercury cells to ion exchange membrane cells is normally carried out for a complete cellroom at a single instance.

absorption were newly installed. Among the reused equipment were the rectifiers, the units for hydrogen treatment and chlorine hydroxide production, and the sections for chlorine liquefaction and compression. Mercury filtration units for caustic, hydrogen and process exhaust were removed, and pumps, instruments and pipelines were replaced. A significant portion of the total conversion cost was spent for cleaning the old plant and depositing, about half of which was invested on constructing a mercury disposal facility. With the annual production capacity of 40,000 tonnes of chlorine, the unit cost of the conversion was 710 US\$/t Cl_2.

Technology suppliers, on the other hand, suggest smaller figures for the investment cost of installing the ion exchange membrane process. Asahi Chemical, one of the major technology suppliers, estimates the current investment cost of converting an existing mercury plant to the ion exchange membrane process is in the range of 300-350 million Japanese yen for an annual capacity of 10,000 tonnes of caustic soda (Hamada, 2000). That roughly corresponds to 280-320 US\$/t NaOH, which is equivalent to 310-360 US\$/t Cl_2 capacity. In this estimation it is assumed that only the mercury cells are replaced by the ion exchange membrane cells, while reusing other equipment for salt solution, primary treatment of brine, chlorine and hydrogen treatment. For construction of a new plant in a green field, the cost will be 1.2-1.5 billion Japanese yen for a similar capacity. That means the unit cost of 990-1,200 US\$/t NaOH, equivalent to 1,100-1,400 US\$/t Cl_2. Uhde takes 600 DM/t NaOH, equivalent to 290 US\$/t NaOH, as a current investment figure for the conversion of a mercury-based plant to the ion exchange membrane process (Zimmermann, 2000). This figure, which corresponds to 320 US\$/t Cl_2, is only for cellroom conversion, and various equipment are assumed to be used from the existing plant. Uhde also cites a very rough estimate of the total investment cost of 600-700 US\$/t NaOH for a plant of 250,000-500,000 t NaOH per year (Henson, 1997). This figure includes the total plant and equipment, piping, utilities and constructions, excluding only the land cost.

As we can see, the investment cost quoted varies depending on the technical requirements for any particular conversion as well as on what should be included in the calculation of the necessary costs. Technology suppliers quote figures at the lower end for the conversion costs, at around 350 US\$/t Cl_2. They have not changed so much since the first

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[110] The industry prefers terminology for capacity and power consumption expressed in tonnes of caustic soda (NaOH 100%) because chlorine gas flows are expensive to measure. The conversion factor used is 1.128 tonnes of NaOH 100% for every tonne of chlorine produced.

introduction of the ion exchange membrane process in the late 1970s. Considering inflation, the real cost has indeed declined significantly, due partly to a decline in the price of ion exchange membranes and partly to an increase in the current density, which reduced the number of electrolytic cells (Bordoni, 2000; Luke and Beckmann, 1999). These figures, however, represent the minimum costs necessary for the conversion of the existing mercury-based plants to the ion exchange membrane process. They do not include expenditures for cleanup and safe dismantling and disposal of equipment in contact with mercury, which is increasingly important as mercury-containing wastes above a threshold concentration, for example, 3 % in the European Union as mandated by Directives 91/689/EEC and 94/904/EC, are classified as "hazardous" (Euro Chlor, 1999b).

It would hence be reasonable to take cost figures based on the actual cases of process conversion including the costs of the cleaning and disposal of mercury. In that sense, the investment cost of 700 US$/t Cl_2 for the process conversion at Borregaard would be appropriate as the representative figure for the total investment cost of converting the existing mercury plants to the ion exchange membrane process, as it includes the costs necessary for cleanup and disposal of equipment contaminated with mercury This figure roughly corresponds to estimations made by those people working in the chlor-alkali industry in Western Europe. For example, Straasheijm (2000) cites 1,500 NLG/t Cl_2, equivalent to 630 US$/t Cl_2 whereas Lindley (1997) estimates that a typical conversion cost would be in the range between 560 and 610 ECU/t Cl_2 for an average mercury plant capacity in Western Europe. Euro Chlor (1996) estimates the capital cost of conversion of an average size mercury plant (100,000 t Cl_2/year) to its equivalent ion exchange membrane plant to be approximately 700 ECU/t Cl_2 capacity. Therefore, considering that the nominal minimum investment cost has been virtually unchanged since the late 1970s, we assume here that the nominal total investment cost per unit capacity has been constant at the level of 700 US$/t NaOH.

For this kind of production plants in the chemical process industries, the depreciation period is normally taken to be 10 years, although the physical lifetime of these plants can be much longer. A major reason suggested by industry experts is that, given the unstable nature of developments in the chlor-alkali industry, predicting the economic viability of this type of plant much beyond 10-15 years is considered difficult, and prudent accounting practices tend to be adopted (Lindley, 1997). Accordingly, we here assume a straight depreciation of 10 years. That means that, as the estimated cost for the conversion of the mercury process to the

ion exchange membrane process is about 700 US$/t NaOH, the annualized investment cost of introducing the ion exchange membrane process IC_c is 70 US$/t NaOH.

Cost of Reducing Mercury Emissions with End-of-Pipe Technologies

It is very difficult to assess exactly the costs associated with pollution abatement with end-of-pipe technologies. We could see at least, however, that the scale of the cost of reducing mercury emissions with end-of-pipe technologies has been much smaller than that of converting the mercury process to the ion exchange membrane process. In the 1970s, the investment cost of installing the calomel process for removing mercury from gases was estimated to be 1.58 DM, equivalent to 0.79 US$, per tonne of chlorine capacity (Richter, 2000). A similar estimation of the cost of scrubbing with chlorine-containing brine or with alkaline hypochlorite solution was in the range of 1.74-1.77 DM, corresponding to 0.87-0.88 US$, per tonne of chlorine capacity. The operating cost of these processes, on the other hand, was reported to be in the range of 3-7 % of the investment (Rekers, 1973). The total cost of reducing mercury in liquids with pre-coated carbon filters was also reported to be approximately 1 US$ per tonne of caustic soda. These figures indicate that the cost of reducing mercury emissions with end-of-pipe technologies in the 1970s was a little more than 0.1 % of the cost of plant conversion from the mercury process to the ion exchange membrane process, which has been around 700 US$ per tonne of production capacity.

Currently, the cost of installing a sulfurized active carbon system, including the heat exchanger necessary to increase the temperature after the cooling step, the equipped tower, and the filters, to remove mercury from liquids is reported to be in the range of 0.45-0.5 million Euro for a plant with chlorine capacity of 166,000 tonne (European IPPC Bureau, 1999). That corresponds to 2.7-3.0 US$ per tonne of chlorine capacity. The cost of installing the activated carbon filtration in pre-coated candle or plate filters is around 0.25 million Euro for a production capacity of 100,000 tonne of chlorine per year, which is equivalent to 2.5 US$ per tonne of chlorine capacity. These figures still correspond to less than 1 % of the investment cost of converting the mercury process to the ion exchange membrane process. We could therefore conclude that, compared with the investment cost of converting the mercury process to the ion exchange membrane process IC_c, the cost of installing and operating end-of-pipe technologies $IC_e + AC_e$ has been much smaller; that is,

$$IC_c >> IC_e + AC_e.$$

Saving in Production Cost from the Conversion of the Mercury Process to the Ion Exchange Membrane Process

Next, we consider the saving in the production cost by the conversion of the mercury process to the ion exchange membrane process. The fixed costs for operators and other personnel, taxes, insurance, repairs, and maintenance have been approximately the same for the mercury process and the ion exchange membrane process (Euro Chlor, 1996; Schmittinger, Curlin, Asawa, Kotowski, Beer, Greenberg, Zelfel, and Breitstadt, 1986). Of the variable costs, the expense for salt, chemicals (e.g. precipitants), and anode reactivation are almost equal for both processes. The difference among the three processes shows up in the consumption of energy, in the form of electricity and steam, which normally accounts for about two thirds of the total operating cost. Therefore, we can focus on only one factor, that is, energy consumption, in considering cost saving by switching from the mercury process to the ion exchange membrane process.

As we have seen in Figure 4-8, the energy consumption of the ion exchange membrane process has shown a remarkable improvement since the early 1970s. Concomitant with the technological progress, the cost saving from the conversion of the mercury process to the ion exchange membrane process has increased. Figure 5-9 shows the trends in the cost saving from the conversion of the mercury process to the ion exchange membrane process in Western Europe, as compared with the annualized investment cost necessary for it. (Detailed data are given in Table 5-32 in Appendix at the end of this chapter.) It is constructed by using the data on the extent of technological progress and the electricity price. As mentioned above, we assumed that the energy consumption of the mercury process has been constant at the level of 3,200 kWh/t NaOH. The data on the average electricity price in Western Europe is obtained from International Energy Agency's Energy Information (International Energy Agency, 1992, 1993, 1999). Since the late 1970s, the electricity price in Western Europe has increased steadily; between 1978 and 1995 it rose by about 100 %, measured in US dollars.

279
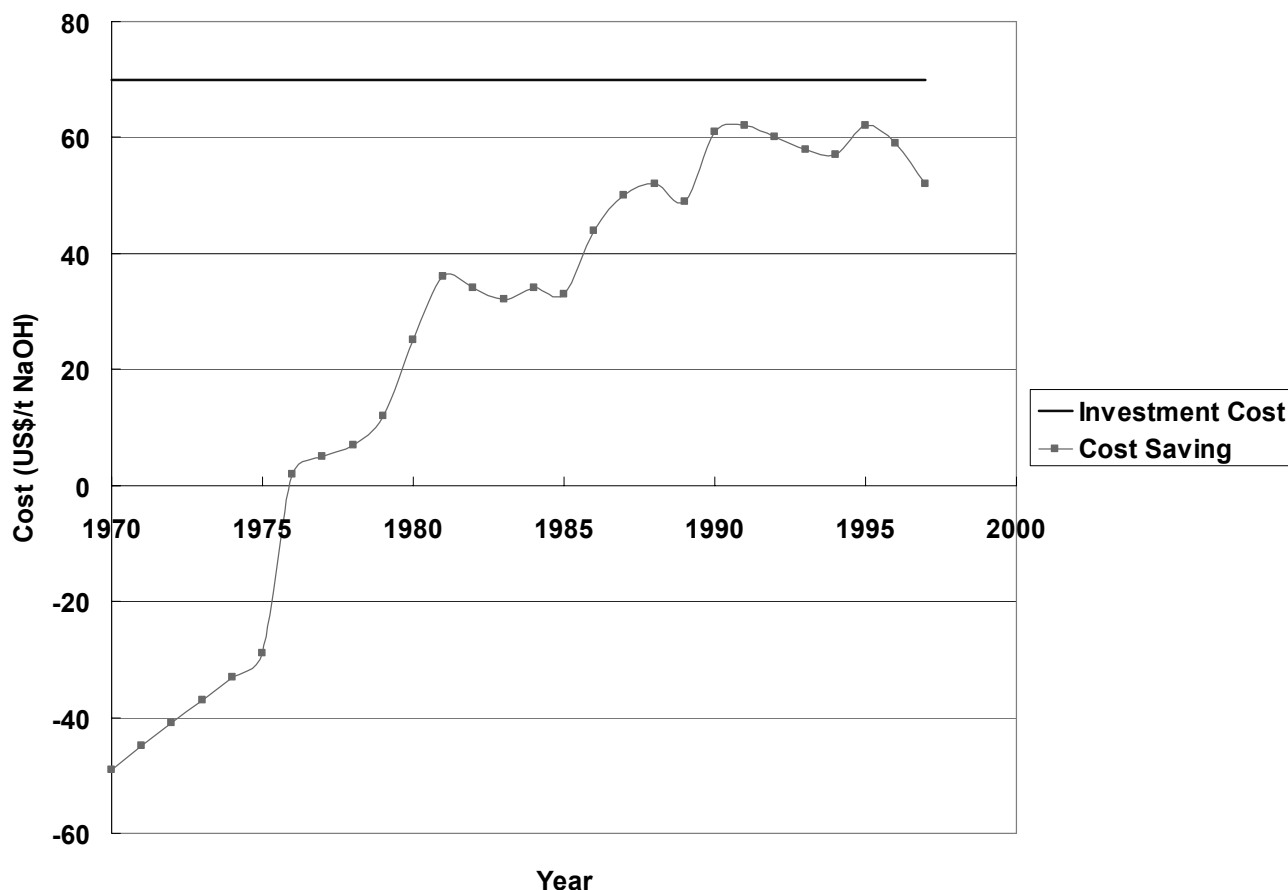
Figure 5-9 Cost Saving from the Conversion from the Mercury Process to the Ion Exchange Membrane Process and Annualized Investment Cost

Until the middle of the 1970s the ion exchange membrane process was less energy-efficient than the mercury process, and thus the production of cost with the former was higher than that of the latter. Accordingly, there was no incentive, at least for commercial purposes, to adopt the ion exchange membrane process for chlor-alkali production in Western Europe. As the energy efficiency of the ion exchange membrane process was improved steadily, the operating cost of the ion exchange membrane process had become substantially lower than that of the mercury process by the early 1980s. Thus, for newly constructed chlor-alkali plants, the ion exchange membrane process has become the preferable technology since then. For the existing plants based on the mercury process, however, considering that these plants can still be used physically for chlor-alkali production, the expected cost saving needed to be large enough to justify the investment cost necessary to convert the mercury process to the ion exchange membrane process.

280

We can see Figure 5-9 in relation to Figure 2-10(b), which has been discussed in the analytical framework. During the 1980s, the cost saving by process conversion $PC_o – PC_c(t)$ was in the range of 30-50 US\$/t NaOH and thus remained short of completely offsetting the investment cost for the ion exchange membrane process IC_c of 70 US\$/t NaOH; that is,

$$PC_o – PC_c(t) < IC_c.$$

Although the investment expenditure for process conversion could be lower for some plants, it has been still uneconomical for most of the mercury plant operators to convert their mercury-based plants to the ion exchange membrane process. Thus there exist large incentives to continue to use the mercury process at their existing plants as long as they can be utilized for chlor-alkali production, while inhibiting the diffusion of the ion exchange membrane process in Western Europe. That consideration leads us to examine the age of chlor-alkali plants based on the mercury process.

5.4.3 Long Lifetime of Chlor-Alkali Plants Based on the Mercury Process

The construction of a chlor-alkali plant, whether it is based on the mercury process or the ion exchange membrane process, is capital-intensive and requires dedicated buildings. The lifetime of a plant depends in part on the functional life of the building in which it is housed. While electrolytic cells and some other inventory are routinely maintained, refurbished, or renewed, plants can operate in the same layout and fulfill the commercial needs for a long period of time (Euro Chlor, 1998b). As we have discussed in the previous section, currently the cost saving from the conversion of the mercury process to the ion exchange membrane process is not sufficient to offset the necessary investment. Therefore, the introduction of the ion exchange membrane process, although currently the most efficient technology for chlor-alkali production, will be delayed until the existing mercury-based plants come to the end of their physical lifetimes.

In this section, we compare the operating period of chlor-alkali plants based on the mercury process and those based on the ion exchange membrane process in Western Europe. We would like to see how long the chlor-alkali plants which had been originally based on the mercury process were operated before conversion to the ion exchange membrane process. To do that, we investigate the timing of the construction of the new membrane-based plants as well as the original mercury-based plants. Then, by looking at the operating years of the existing mercury-based plants, we can examine whether these plants are close to the end of their lifetimes, that is, whether these plants are expected to be converted to the ion exchange

membrane process soon. The data on the construction and conversion of these plants were basically obtained from the companies operating them.

Figure 5-10 shows the operating period of the mercury process before it was converted to the ion exchange membrane process at 15 chlor-alkali plants in Western Europe. (Detailed data on the start-up year of the mercury and the ion exchange membrane processes of each plant are given in Table 5-33 in Appendix at the end of this chapter.)
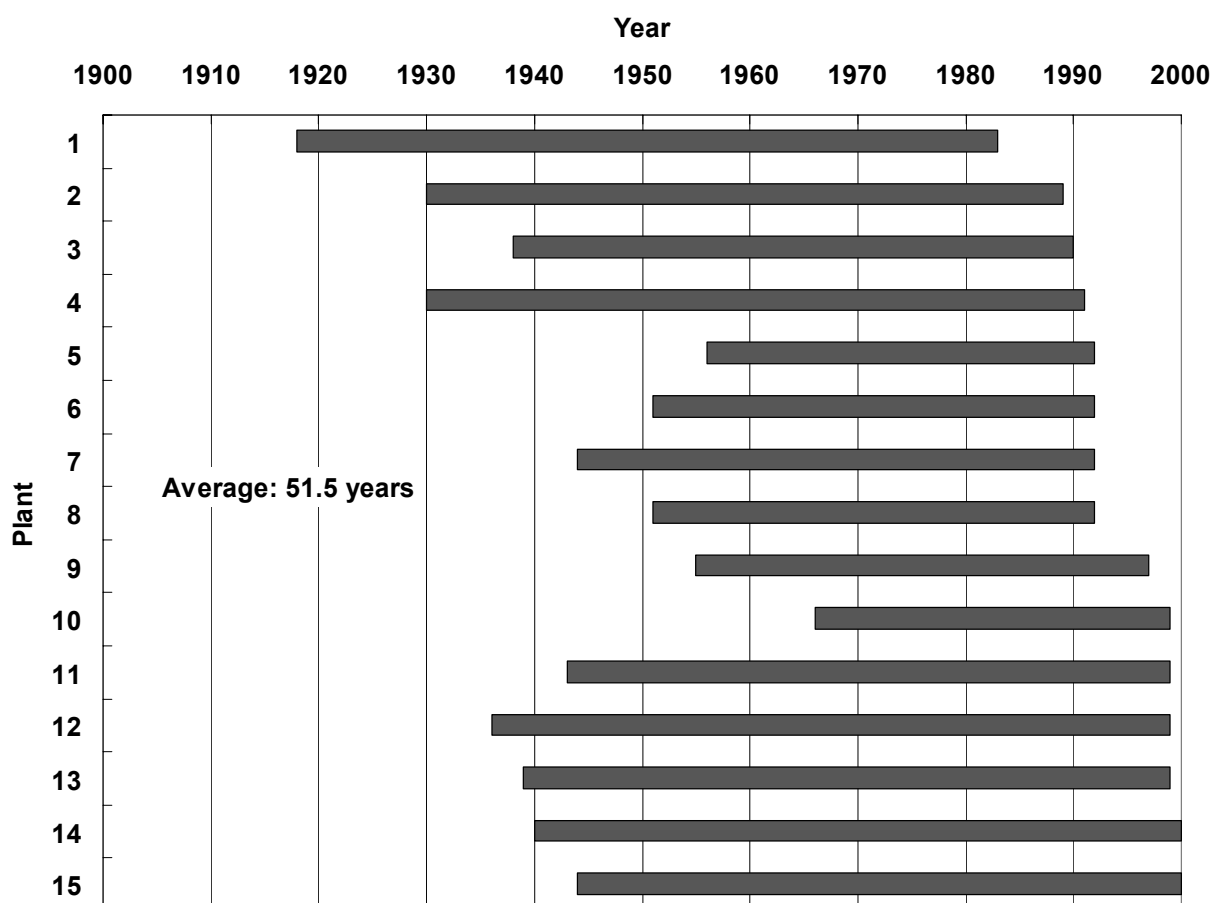
Figure 5-10 Operating Period of the Mercury Process before Its Conversion to the Ion Exchange Membrane Process in the Western European Chlor-Alkali Industry

Most of the installations of the ion exchange membrane process in the 1980s were undertaken for newly constructed chlor-alkali plants, rather than for the conversion of the existing mercury process. As we have seen above, by the early 1980s the energy consumption of the ion exchange membrane process had become much smaller than that of the mercury process. Accordingly, given that the construction cost was almost the same for the two production processes, it was reasonable for chlor-alkali producers to choose the ion exchange

membrane process when they constructed new plants. In the case of Akzo Nobel's plant in Botlek, the company decided to establish a new plant with the ion exchange membrane process just next to a mercury-based plant. While the production capacity based on the ion exchange membrane process was increased significantly in order to meet growing demands for chlorine, the existing mercury plant was abolished subsequently (Straasheijm, 1999). Although the storage and loading facilities which had been already established could be utilized for the ion exchange membrane process, most of the infrastructures, including those for cooling water supply, electrical provision, direct chlorination (for vinyl chloride monomer production) had to be newly constructed (Straasheijm, 2000).

While the ion exchange membrane process was introduced to new plants during the 1980s, the conversion of the existing mercury-based plants was not economically attractive. In all of the cases except for two, the original mercury process was operated for at least 40 years, and in some plants the operating period reached 60 years. On average, the mercury-based plants which had been converted subsequently were utilized for more than 50 years. This figure corresponds to the general view held by experts in the industry that the lifetime of chlor-alkali plants based on the mercury process is normally in the range of 40-60 years (Euro Chlor, 1998b). Once mercury-based plants had been constructed, the operators had strong incentives to continue to utilize them as long as possible, and the conversion of these plants did not take place until they reached their physical lifetimes, the average of which was approximately 50 years.

Next we would like to know how long the existing chlor-alkali plants based on the mercury process have been operating. Figure 5-11 shows the operating period of 51 chlor-alkali plants currently operating with the mercury process in Western Europe. (Detailed data on each plant are given in Table 5-34 in Appendix at the end of this chapter.)
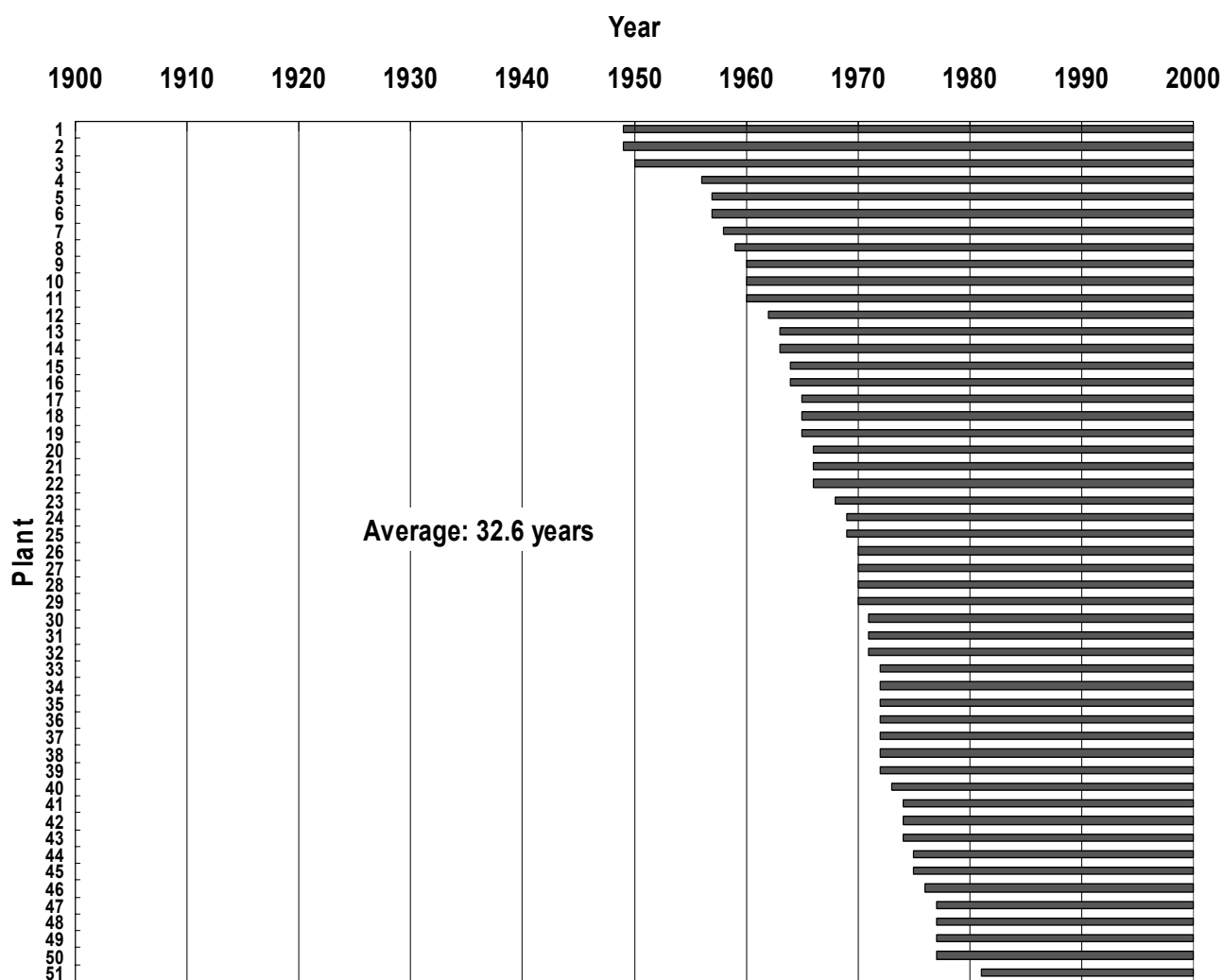
Figure 5-11 Operating Period of the Existing Chlor-Alkali Plants based on the Mercury Process in Western Europe

The figure indicates that many chlor-alkali plants were constructed in the 1960s and the 1970s by adopting the mercury process whereas at the beginning of the 1980s the mercury process ceased to be adopted for newly constructed chlor-alkali plants in Western Europe. The average of the operating years of the existing mercury-based plants is a little longer than 30 years, which is 20 years shorter than the average lifetime of 50 years for the mercury-based plants which have been already converted to the ion exchange membrane process. While new construction of chlor-alkali plants based on the mercury process have been already terminated, most of the existing mercury-based plants have not yet reached the end of their physical lifetimes.

In particular, we should note that there are many mercury plants which were built in the 1970s. In the same period, as we have discussed earlier, environmental regulations on mercury emissions started to be introduced in Western Europe. As these regulations were not so stringent as to require immediate phase out of the mercury process, chlor-alkali producers chose to rely on this process for the construction of new production facilities during the 1970s, rather than to try to innovate on new clean technologies such as the ion exchange membrane process, which was still at its infant stage at that time. To comply with standards on mercury emissions from chlor-alkali plants, innovative companies directed R&D efforts for end-of-pipe technologies designed to be installed at the final stage of the mercury process. Reasonably good end-of-pipe technologies have been developed and adopted to reduce mercury emissions to the extent that the emission standards have been met by all of the mercury-based chlor-alkali plants in Western Europe.

On the other hand, innovations on end-of-pipe technologies to reduce mercury emissions helped chlor-alkali producers continue to build their new plants with the mercury process during the 1970s. That has resulted in the current existence of many mercury-based plants which have not yet reached the end of their lifetimes. The operators of these relatively new plants have incentives to continue to use them as long as they can be utilized, avoiding plant conversions from the mercury process to the ion exchange membrane process. The success of end-of-pipe technologies in reducing mercury emissions has in effect prolonged the lifetime of the mercury process, which is actually in the process of technological obsolescence, while inhibiting the diffusion of advanced clean technologies such as the ion exchange membrane process.

With this background, the European chlor-alkali industry is strongly opposed to the implementation of the mandated phase-out of all the mercury plants in Western Europe by 2010 (Hain, 1999). In an attempt to convince the OSPAR Commission to reverse this decision, the European industry association, Euro Chlor, organized a workshop in September 1999, inviting the members of the OSPAR Commission (OSPAR Commission, 1999b). At this workshop, where technical issues were mainly discussed without making any official decision, Euro Chlor demanded that the recommendation for the phase-out of the mercury process by 2010 be dropped from the Decision 90/3. In place of it, the industry made a proposal for voluntary actions, with the commitment of all of the chlor-alkali producers currently using the mercury process. The voluntary actions specified that the European chlor-alkali industry will not increase production capacity based on the mercury process and that at the same time it

will reduce mercury emissions further beyond the PARCOM Decision 90/3 standard of 2 g Hg/t Cl_2 capacity for emissions to the atmosphere (Euro Chlor, 1999c).

More concretely, the operators of mercury-based plants have pledged to achieve an annual weighted average level of mercury emissions to air, water and in products not exceeding 1.0 g Hg/t Cl_2 capacity by the end of 2007 and to work towards a level not exceeding 0.7 g Hg/t Cl_2 capacity by 2010, "on condition that the plants concerned are allowed to operate beyond the year 2010." In addition, arguing that, depending on various factors such as design, age and geography, some plants may not be able to achieve the specified targets while others will be able to achieve even lower emission levels, the companies have made a further commitment that individual plants will not exceed a level of mercury emissions to air, water and in products of 1.5 g Hg/t Cl_2 capacity by the end of 2007. It has also been agreed that shutdown mercury-based plants will not be sold or transferred to any third party for reuse[111]. Debates are still continued between the industry and the public authorities, and it remains to be seen whether the requirement for the phase out of the remaining mercury plants will be abandoned in Western Europe.

If we look at the situation in the world, the share of the ion exchange membrane process in chlor-alkali production has been increasing steadily. Figure 5-12 shows the trends in the installation of the mercury process, the diaphragm process, and the ion exchange membrane process at chlor-alkali plants in the world. (Detailed data are given in Table 5-35 in Appendix at the end of this chapter.)

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[111] Early in the 1990s a chlor-alkali producer in Pakistan, Ravi Alkalis Ltd., considered importing a Danish mercury-based chlor-alkali plant for rebuilding. The three-plant complex, owned by DS Industries ApS in Copenhagen had been the focus of controversy in Denmark for over 20 years because in the 1960s and 1970s it had a history of violating water emissions limits. Its environmental performance dramatically improved in the 1980s and met all environmental regulations by 1990, when the company decided to shut down the plant. Under the Danish law, the unit would not be considered hazardous if it were reopened or rebuilt and used, as intended (Siddiqi, 1994). In the end, however, the Pakistani producer installed the ion exchange membrane process, instead of the used mercury process (Krupp-Uhde, 1998).
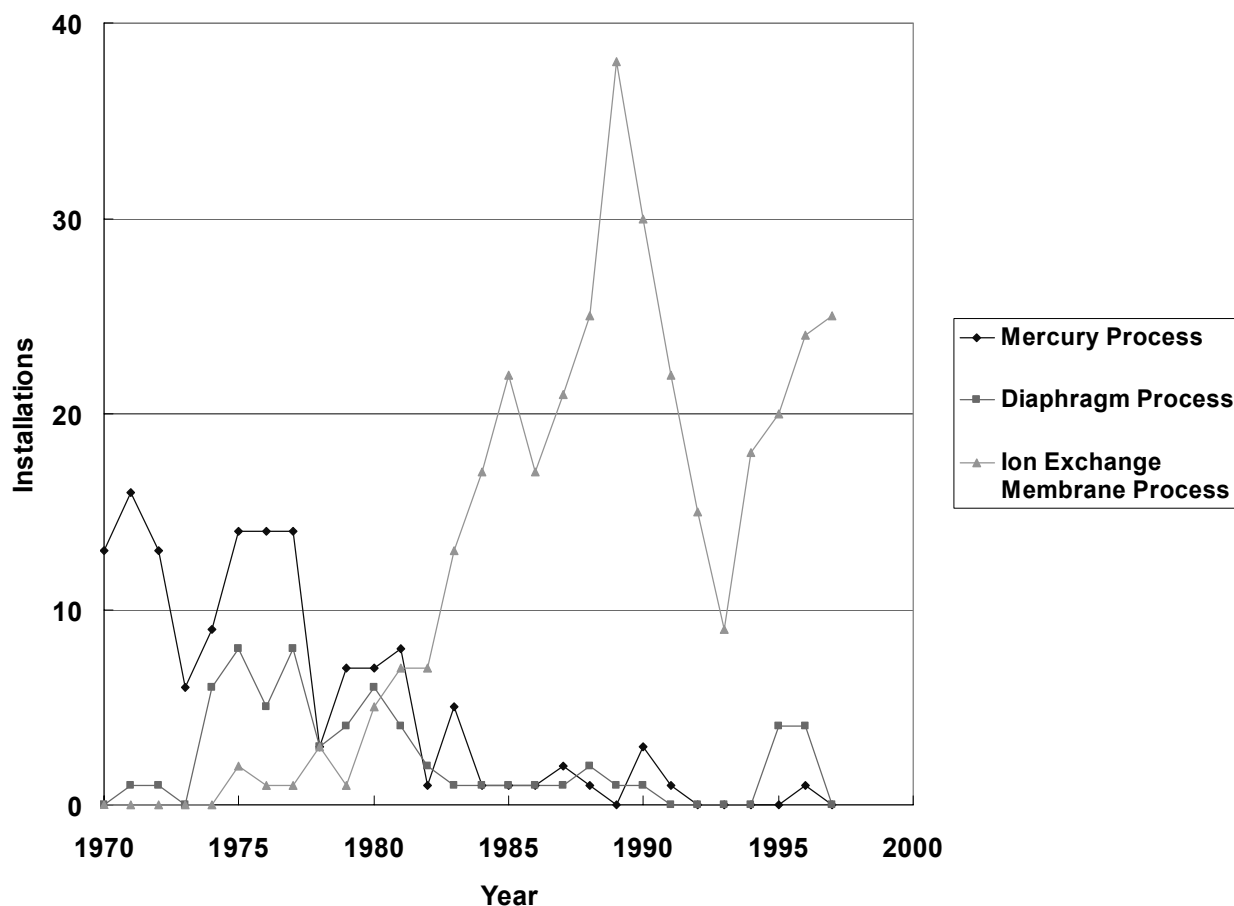
Figure 5-12 Installation of the Mercury, Diaphragm, and Ion Exchange Membrane Processes in the World

During the 1970s, the mercury process was the production technology which was adopted almost exclusively at chlor-alkali plants around the world. The only exception was Japan, where the newly established ion exchange membrane process started to be adopted by several innovative companies in the middle of the 1970s. As the performance of the ion exchange membrane process had been improved by the early 1980s, most of the chlor-alkali production processes installed in the 1980s were based on the ion exchange membrane process. On the other hand, the introduction of the mercury process has been virtually stopped, due to its less energy efficiency compared with that of the ion exchange membrane process, as well as due to the environmental and health concerns with mercury emissions.

These recent trends in the choice of chlor-alkali production technology are reflected in the relative composition of the world production capacities. Although there is no official data

which covers detailed figures for the production capacities in different regions of the world, Figure 5-13 shows an estimation of the trends in the shares of production capacities based on the mercury process, the diaphragm process, and the ion exchange membrane process in the world chlor-alkali industry since 1980. (Data are given in Table 5-36 in Appendix at the end of this chapter.)
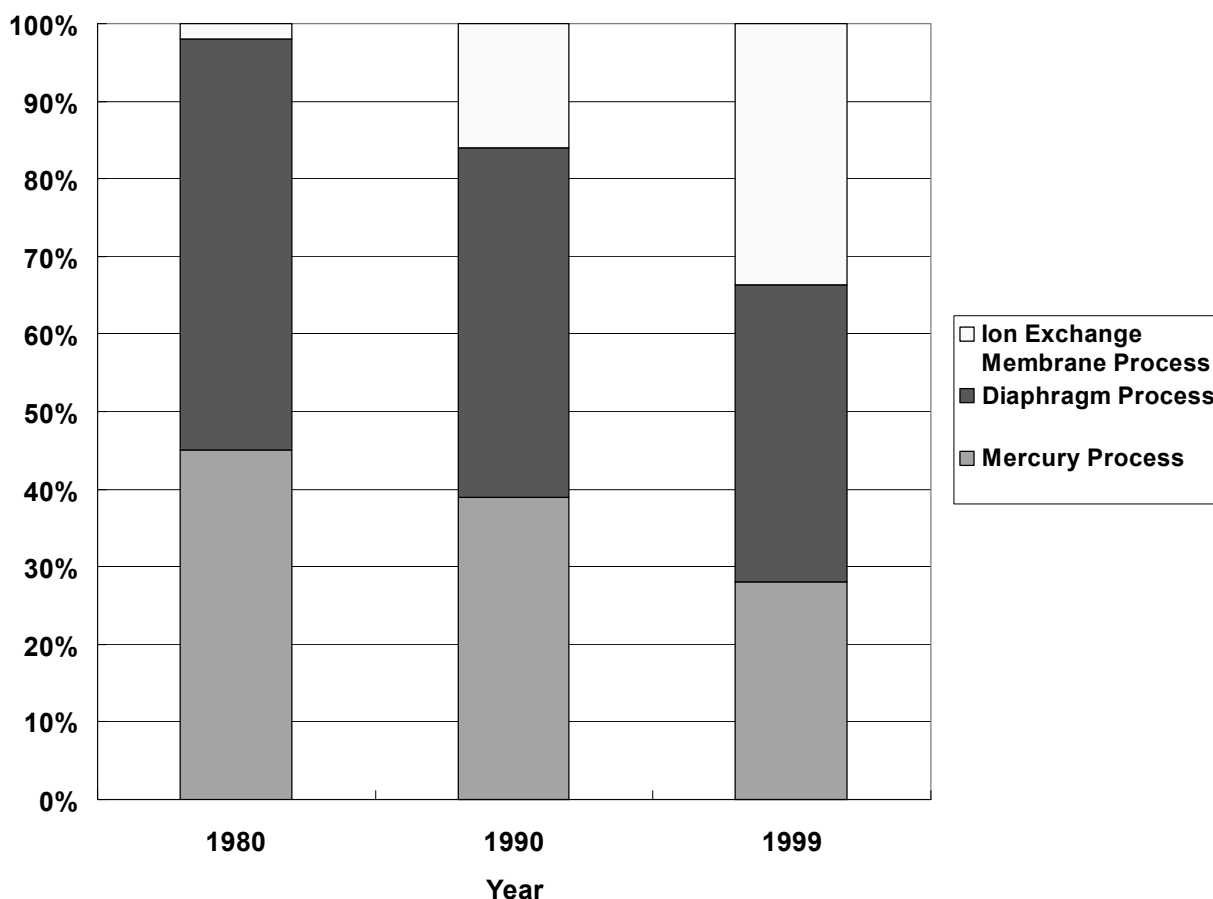
Figure 5-13 Shares of the Mercury, Diaphragm, and Ion Exchange Membrane Processes in the World

We can see that the share of the ion exchange membrane process in the world has been rising rapidly while the mercury process has been decreasing its share. In 1980, about a half of the world chlor-alkali production capacities were based on the mercury process and another half based on the diaphragm process, with the ion exchange membrane process almost negligible. Since then, however, the technological choice of the world chlor-alkali industry as a whole has been shifting steadily from the mercury and diaphragm processes towards the ion exchange membrane process. Over the period between the late 1970s and the end of the 1990s,

the ion membrane process increased its share in the world from almost zero to 30 per cent. That means that the newly established ion exchange membrane process has surpassed the share of the century-old mercury process in just 20 years.

In developing countries, in particular, while the use of the pollution-laden mercury process has been increasingly avoided, the ion exchange membrane process has been in a process of rapid diffusion. In Taiwan, there are no chlor-alkali plants currently operating with the mercury process (Nakanishi, 1993). China and India have been increasingly constructing new chlor-alkali plants based on the ion exchange membrane process, and most of the chlor-alkali production capacities have been already based on the ion exchange membrane process in countries such as Indonesia, Thailand, South Africa, Egypt, and Saudi Arabia (Chlorine Institute, 1999a). This case of technological change in the chlor-alkali industry demonstrates an example of technological leapfrogging by choosing the clean technology over the end-of-pipe technology. At the same time, this case indicates that the "pollution haven," on which intensive research has been made by researchers since the 1970s (see, for example, Leonard, 1988; Low and Yeats, 1992), may not necessarily be an unavoidable fate for developing countries[112].

5.5 Conclusion

In this chapter, we examined the effects of environmental regulation on technological change in the Western European chlor-alkali industry. Since the end of the 19th century, the mercury process had been the focus of technological development in Western Europe. By the early 1970s, advanced technologies had been developed for the mercury process by several innovative companies, notably, ICI, Hoechst-Uhde, De Nora, Solvay, and Krebs. Their technologies had been adopted not only by chlor-alkali producers in Western Europe but also by those in other parts of the world.

Then we look at the environmental polices introduced in Western Europe to regulate mercury emissions from chlor-alkali industry. Unlike Japan, there was no publicly reported case in which human bodies were seriously affected by the intake of mercury in Western Europe. Nevertheless, as public concerns on the potential impacts of mercury increased,

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[112] A recent empirical study shows that major urban areas in China, Brazil, and Mexico, instead of being the pollution haven, have all experienced significant improvement in air quality, contradicting the prediction of the pollution haven hypothesis (Wheeler, 2000).

regulations started to be imposed on mercury released to the environment, particularly to the aquatic ecosystems, in the 1970s. While the introduction of environmental policies on mercury occurred almost in the same period as that in Japan, Western Europe took a different approach to the regulation of mercury emissions from chlor-alkali industry. Rather than imposing a requirement for the phase out of the mercury process, the public authorities set emission standards and environmental quality objectives for mercury released from chlor-alkali plants. The levels of these standards were subsequently tightened during the 1980s.

We next examined the effects of these regulations on R&D activities undertaken by companies in the chlor-alkali industry in Western Europe. With the imposition of regulations limiting the amount of mercury released to the environment, chlor-alkali producers operating plants with the mercury process were required to reduce their emissions. And at the same time companies which had been innovative on chlor-alkali production technologies were encouraged to make R&D efforts on technological measures for the abatement of mercury emissions. The patent data we analyzed indicate that those innovative companies, including ICI, Hoechst-Uhde, De Nora, Solvay, and Krebs, directed their R&D activities to end-of-pipe technologies for the abatement of mercury emissions. Those technologies developed were mainly designed to work for filtration, adsorption, and scrubbing of mercury released from various points of the production facilities to air and waste water. The effects of these end-of-pipe technologies were significant in reducing mercury emissions from chlor-alkali plants; more than 90 % of mercury released to air, waste water, and products in Western Europe has been eliminated since the late 1970s. With the success in reducing mercury emission by adopting these end-of-pipe technologies, many chlor-alkali producers have continued to use the mercury process, whose current share is more than 60 % of all the chlor-alkali production capacities in Western Europe.

On the other hand, the relatively weak regulatory approach to mercury emissions did not encourage innovative efforts to develop clean technologies which do not involve any use of mercury, such as the ion exchange membrane process. Among the innovative companies in the Western European chlor-alkali industry, ICI had been already involved in R&D activities on the ion exchange membrane process since the early 1960s. The company, however, had stopped their efforts to develop technologies for the ion exchange membrane process subsequently, because of the unavailability of ion exchange membranes which had sufficient physical as well as chemical strength to be reliably utilized in the electrolytic cells. In the 1970s, R&D activities of the companies which had technological expertise on the mercury

process, including De Nora, Hoechst-Uhde, Solvay, and Krebs, as well as ICI, were basically focused on the mercury process, rather than the ion exchange membrane process. And these companies continued to provide their technologies to other chlor-alkali producers in the 1980s.

In the meantime, encouraged by the strong regulation for the phase out of the mercury process, the innovative companies in Japan invented new types of ion exchange membranes, and the technological performance of the ion exchange membrane process was improved rapidly. By the early 1980s, this newly developed process had advanced to such an extent that it became effectively the only practical option when constructing new commercial plants. Observing the invention of ion exchange membranes with improved physical and chemical strength, which led to the remarkable progress in the ion exchange membrane process, several innovative companies in Western Europe, particularly, ICI, Uhde, and De Nora, initiated R&D activities on the ion exchange membrane process in the late 1970s. As advanced types of ion exchange membranes had been already developed by the Japanese companies, the focus of R&D activities of these European firms was placed on electrolytic cells to be used in the ion exchange membrane process. Utilizing the ion exchange membranes introduced from Japan, ICI, Uhde, and De Nora started to provide their ion exchange membrane process technologies to other chlor-alkali producers in the middle of the 1980s.

We then considered why the diffusion of the ion exchange membrane process has been slow and limited. Basically, we examined two factors which can be mainly considered to affect the diffusion of a new technology, that is, the availability of information on the new technology and the profitability of the adoption of the new technology. To see whether a sufficient amount of information on the ion exchange membrane process has been available to chlor-alkali producers in Western Europe, we look at the trends in presentations made at industry conferences and papers published on technical and trade journals. We found that, although only a limited amount of information was available in the 1970s regarding the newly developed ion exchange membrane process, there has been a plenty of opportunities since the 1980s to obtain detailed and reliable data on this technology with advanced performance. Therefore, we can reasonably conclude that the factor which has inhibited the adoption of the ion exchange membrane process in Western Europe was not the lack of information on the newly developed technology.

We next considered whether the adoption of the ion exchange membrane process has been economically beneficial to chlor-alkali producers in Western Europe. Estimations of the investment necessary for the installation of the ion exchange membrane process were

obtained from chlor-alkali producers who have introduced the new process and technology suppliers. The investment and operating costs of end-of-pipe technologies adopted for the reduction of mercury emissions were also estimated by using data on actual cases. We found that the investment cost of adopting the ion exchange membrane process is much larger than the cost necessary to install and operate end-of-pipe technologies to reduce mercury emissions. Then we then examined the cost saving from the conversion of the mercury process to the ion exchange membrane process. Although the energy consumption of the ion exchange membrane process for chlor-alkali production was larger than that of the mercury process in the early 1970s, as the performance of the ion exchange membrane process has been improved rather quickly, by the middle of the 1980s the ion exchange membrane process had come to consume much less energy than the mercury process. Accordingly, the operating cost of the latter is currently larger than the former. We found, however, that the scale of the cost saved by switching from the mercury process to the ion exchange membrane process has not yet been sufficient to justify the necessary investment for the replacement of the mercury process with the ion exchange membrane process. While it has been already economically beneficial to adopt the ion exchange membrane process for new green-field plants, there is a strong incentive to continue to use the existing mercury-based plants as long as they are can be utilized to produce chlor-alkali products. That has discouraged the adoption of the ion exchange membrane process by many operators of the mercury process in Western Europe. What is of critical importance for the diffusion of the ion exchange membrane process is the age of chlor-alkali plants based on the mercury process.

Hence we examined the operating years of the mercury-based plants which have already been converted to the ion exchange membrane process as well as that of the existing plants relying on the mercury process. Those mercury-based plants which have already been switched to the ion exchange membrane process had been operated for a little longer than 50 years on average before the process conversion. That suggests that at least for this period of time mercury-based plants can be utilized for chlor-alkali production. On the other hand, the average of the operating years of the existing mercury-based plants is a little more than 30 years, a period which is about 20 years shorter than that in the case of the mercury-based plants which have already been converted to the ion exchange membrane process. That means that many of the existing plants relying on the mercury process have not yet reached the end of their physical lifetime. Thus, the operators of these plants have strong incentives to continue to use them for chlor-alkali production until they can no longer be utilized.

In particular, the data on the start-up year of these existing mercury-based plants shows that there are many plants constructed with the mercury process in the 1970s. As we have discussed above, during the same decade the R&D activities of the innovative companies in Western Europe were focused on technological measures for the reduction of mercury emissions. The patent data shows that there were actually many innovations on end-of-pipe technologies for pollution abatement. While various types of end-of-pipe technologies were successfully implemented in reducing mercury released to outside the production facilities, many plants based on the mercury process continued to be built during the 1970s. These relatively new plants can be utilized for commercial production for a long time before they reach the end of their lifetime.

Currently, despite a recent recommendation made by the regulators that the existing mercury-based plants be completely discarded by the year 2010, the mercury process is still the dominant production technology in Western Europe, accounting for more than 60 % of the total production capacities. The chlor-alkali industry has been consistently opposed to the mandate for the phase out of the mercury process and strongly demanding the policy makers to withdraw the deadline of 2010. The pace of converting the existing mercury plants has been slow, and the diffusion of the ion exchange membrane process has been limited to a little more than 10 % of the total production capacities in Western Europe. On the other hand, the ion exchange membrane process has been adopted by many chlor-alkali producers outside Western Europe, particularly in developing countries, leapfrogging the stage of employing the mercury process. Accordingly, the share of the ion exchange membrane process in the world production capacities has been increasing steadily.

In sum, the public authorities in Western Europe specified emission standards and environmental quality standards with regard to mercury emissions from chlor-alkali plants. This regulative approach, which was less stringent that that of the Japanese government, induced innovative companies in Western Europe to undertake R&D activities on end-of-pipe technologies for the abatement of mercury released from chlor-alkali plants. Operators of mercury-based plants adopted these technologies, which worked successfully to reduce mercury emissions steadily. Thus, most of the chlor-alkali producers in Western Europe continued to use the mercury process supported with end-of-pipe technologies, a less expensive option than converting to clean technologies which would require comprehensive reorganization of the manufacturing process. During the 1970s, many more chlor-alkali plants were built with the mercury process.

On the other hand, these relatively less stringent regulations implemented in Western Europe did not clean did not create strong and secured demands for new clean technologies and initially discouraged innovative companies to make R&D efforts on clean technologies such as the ion exchange membrane process. Although the ion exchange membrane process was ultimately to become better, economically as well as environmentally, than the mercury process in the end, its future progress in the technological performance could not be predicted with sufficient certainty, given the infant stage of technological development in the 1970s. It was only after the ion exchange membrane process had been proved to be feasible for industrial applications with the invention of advanced ion exchange membranes in Japan that these R&D efforts on the ion exchange membrane process were intensified by these innovative companies in Western Europe. By that time, however, many chlor-alkali plants had been constructed by using the mercury process, and that has resulted in the slow conversion of these relatively new plants to the ion exchange membrane process.

The environmental regulations which were aimed at the abatement of mercury emissions encouraged the development and adoption of end-of-pipe technologies, which indeed worked relatively well in reducing mercury emissions less expensively. This success, however, effectively helped to prolong the lifetime of the mercury process, which was actually in the process of technological obsolescence. This case of technological change in the Western European chlor-alkali industry implies that, under the existence of uncertainty, diversity, and rigidity of technological change, environmental regulations which are not very stringent could succeed in reducing pollutant emissions by inducing the development and adoption of end-of-pipe technologies. But at the same time innovations on clean technologies which would be the most appropriate technology in terms of economic efficiency as well as environmental protection could be discouraged, by prolonging the life of the existing, pollution-laden technology.

Appendix

List of Interviewees in Western Europe

Imperial Chemical Industries (ICI)
- Mr. Steve Ingleby, Chlor-chemicals Senior Technologist

- Mr. R. W. Curry, Chlor-Alkali Technical Section Manager
- Mr. Cliff Broom, Manufacturing Manager, JKL Cellrooms

Uhde

- Dr.-Ing. Benno Lüke, Manager Process Department, Electrolysis Division
- Dipl.-Chem. Roland Beckmann, Head of Development Department, Electrolysis Division

De Nora

- Mr. Giuseppe Faita, Director, Research & Technologies
- Mr. Marco Tenconi, Sales Manager (Plants)

Bayer

- Dr. Hermann Schubert, Corporate Staff, Quality, Environment and Safety Policy

Akzo Nobel

- Ir. F. G. Straasheijm, Technology & Manufacturing Manager, Chlor-Alkali

EniChem

- Mr. Antonio Pasquinucci, Research and Technology Manager, Polyurethanes and Chlor-Alkali Division
- Mr. Manlio Inverardi, Environmental Balance and Certification, Safety Health Environment Division

Euro Chlor

- Dr. Barrie S. Gilliatt, Executive Director

OSPAR Commission

- Dr. Stefan Hain, Deputy Secretary

Table 5-19 List of Chlor-Alkali Plants in Western Europe

Country	Company	Site (Basin)	Capacity (Cl_2 10^3 t/year)			
			Hg	D	IM	Other
Austria	Donau Chemie	Brückl (D)	60	-	-	-
	Total	60	60	0	0	0
Belgium	BASF	Antwerp (A)	100	-	-	-
	Bayer	Antwerp (A)	-	-	-	50
	Solvay	Antwerp (A)	230	-	-	-
	Solvay	Jemeppe (A)	82	-	120	-
	Tessenderlo Chemie	Tessenderlo (A)	250	-	-	-
	Total	832	662	0	120	50
Finland	Akzo Nobel	Oulu (C)	40	-	-	-
	Finnish Chemicals	Joutseno (C)	-	-	75	-
	Total	115	40	0	75	0
France	Albemarle	Thann (A)	72	-	-	-
	ChlorAlp	Pont de Claix (B)	-	240	-	-
	Elf Atochem	Fos (B)	-	160	110	-
	Elf Atochem	Jarrie (B)	170	-	-	-
	Elf Atochem	Lavera (B)	166	160	-	-
	Elf Atochem	Saint Auban (B)	184	-	-	-
	Métaux Spéciaux	Pomblières (B)	-	-	-	20
	Prod. Chimiques d'Harbonnières	Harbonnières (A)	23	-	-	-
	Solvay	Tavaux (B)	241	-	122	-
	Tessenderlo Chemie	Loos (A)	18	-	-	-
	Total	1,686	874	560	232	20
Germany	BASF	Ludwigshafen (A)	150	210	-	-
	Bayer	Brunsbuttel (A)	-	-	-	120
	Bayer	Dormagen (A)	300	-	-	80
	Bayer	Leverkusen (A)	300	-	-	30
	Bayer	Uerdingen (A)	130	-	90	-
	BSL	Schkopau (A)	200	-	-	-
	Celanese	Knapsack (A)	150	-	-	-
	Clariant	Gersthofen (D)	60	-	-	-
	Dow	Stade (A)	-	1,040	200	-
	ECI	Bitterfeld (A)	65	147	-	-
	ECI	Ibbenbüren (A)	120	-	-	-
	Hüls	Lülsdorf (A)	98	-	-	-
	ICI	Wilhelmshaven (A)	130	-	-	-
	LII Europe	Frankfurt (A)	150	-	-	-
	Solvay	Rheinberg (A)	-	200	-	-
	Vestolit	Marl (A)	180	-	-	-

	Vinnolit	Gendorf (D)	72	-	-	-
	Wacker	Burghausen (D)	157	-	-	-
	Total		4,379	2,262	1,597	290	230
Greece	Hellenic Petroleum	Thessaloniki (B)	37	-	-	-
	Total		37	37	0	0	0
Ireland	MicroBio	Fermoy (A)	-	-	6	-
	Total		6	0	0	6	0
Italy	Altair Chimica	Volterra (B)	27	-	-	-
	Ausimont/ Montedison	Bussi (B)	70	-	-	-
	Caffarro	Toreviscosa (B)	69	-	-	-
	EniChem	Assemini/Cagliari (B)	-	-	170	-
	EniChem	Porto Marghera (B)	200	-	-	-
	EniChem	Porto Torres (B)	90	-	-	-
	EniChem	Priolo (B)	190	-	-	-
	Eredi Zarelli	Picinisco (B)	6	-	-	-
	Solvay	Rosignano (B)	120	-	-	-
	Tessenderlo Chemie	Pieve Vergonte (B)	40	-	-	-
	Total		982	812	0	170	0
Netherlands	Akzo Nobel	Botlek (A)	-	-	250	-
	Akzo Nobel	Delfzijl (A)	-	125	-	-
	Akzo Nobel	Hengelo (A)	70	-	-	-
	GEP	Bergen-op-Zoom (A)	-	-	62	-
	Solvay	Linne Herten (A)	140	-	-	-
	Total		647	210	125	312	0
Norway	Borregaard	Sarpsborg (A)	-	-	40	-
	Elkem	Bremanger (A)	-	-	10	-
	Norsk Hydro	Rafnes (A)	-	130	-	-
	Total		180	0	130	50	0
Portugal	Solvay	Povoa (A)	-	-	28	-
	Uniteca	Estarreja (A)	48	-	13	-
	Total		89	48	0	41	0
Spain	Aragonesas (EIASA)	Huelva (A)	101	-	-	-
	Aragonesas (EIASA)	Sabinanigo (B)	25	-	-	-
	Aragonesas (EIASA)	Villaseca (B)	135	-	40	-
	Electroq. de Hernani	Hernani (A)	15	-	-	-
	Elnosa	Lourizan (A)	34	-	-	-
	Erkimia	Flix (B)	150	-	-	-
	Quimica del Cinca	Monzon (B)	30	-	-	-

Country	Company	Location				
	Solvay	Martorell (B)	209	-	-	-
	Solvay	Torrelavega (A)	63	-	-	-
	Total	802	762	0	40	0
Sweden	Akzo Nobel	Bohus (A)	95	-	-	-
	Akzo Nobel	Skoghall (A)	-	-	85	-
	Norsk Hydro	Stenungsund (A)	112	-	-	-
	Total	292	207	0	85	0
Switzerland	Novartis	Monthey (B)	22	-	-	-
	Saürefabrik Schweizerhall	Pratteln (A)	27	-	-	-
	Solvay	Zurzach (A)	55	-	-	-
	Total	104	104	0	0	0
UK	Associated Octel	Ellesmere Port (A)	-	-	40	35
	Hays	Sandbach (A)	89	-	-	-
	ICI	Lostock (A)	-	50	20	-
	ICI	Runcorn (A)	738	-	25	-
	ICI	Wilton (A)	-	170	-	-
	Rhodia	Staveley (A)	29	-	-	-
	Roche	Dalry (A)	-	-	20	-
	Total	1,216	856	220	105	35
Total	11,427		22,957	8,986	3,722	670

Data as of 1998.

Basin

A: North-East Atlantic and North Sea (OSPAR Commission)

B: Mediterranean Sea (Barcelona Convention)

C: Baltic Sea (Helsinki Commission)

D: Black Sea (Black Sea Convention)

Process

Hg: Mercury process

D: Diaphragm process

IM: Ion Exchange Membrane process

Sources: Euro Chlor (1998a), European IPPC Bureau (1999).

Table 5-20 Chlor-Alkali Plants in Western Europe within and outside the Catchment Area of the Paris Convention

Country	Within catchment area		Outside catchment area	
	Mercury	Non-mercury	Mercury	Non-mercury
Austria[*]	-	-	1	-
Belgium	4	-	-	-
Denmark	-	-	-	-
Finland[*]	-	-	1	1
France	3	-	4	3
Germany	12	5	3	1

Greece[*]	-	-	1	-
Iceland	-	-	-	-
Ireland	-	1	-	-
Italy[*]	-	-	9	1
Luxembourg	-	-	-	-
Netherlands	2	3	-	-
Norway	1	2	-	-
Portugal	2	-	-	-
Spain	4	-	5	-
Sweden	2	1	-	-
Switzerland	2	1	1	-
United Kingdom	3	5	-	-
Total	280	144	200	48

Data as of 1997.
* Non-member countries of the Paris Commission
Sources: OSPAR Commission (1999c), Euro Chlor (1998a).

Under the Paris Convention, the member countries have been obliged to report annual data concerning mercury losses from chlor-alkali plants operating within the "catchment area" of the Paris Convention. (Data for Switzerland has been included since 1993.) That means those plants whose emissions were not considered to contribute to the pollution of the North-East Atlantic were excluded from the data submitted to the Paris Commission. (With regard to mercury losses to the air, however, data have been collected from all chlor-alkali plants operating in the member countries on a plant-by-plant basis). Table 5-20 gives the distribution of chlor-alkali plants within and outside the catchment area. While 63 % of the chlor-alkali plants in Western Europe were located within the catchment area, 58 % of the mercury plants were located within the catchment area.

Table 5-21 US Patents Successfully Applied by Western European Companies on Technologies Related to the Mercury Process and the Ion Exchange Membrane Process

Year of Patent Application	Mercury Process	Ion Exchange Membrane Process
1969	1	0
1970	1	0
1971	5	0
1972	3	0
1973	5	0
1974	4	0
1975	3	0
1976	6	0
1977	7	0
1978	5	0
1979	8	2
1980	6	1

1981	0	4
1982	2	0
1983	1	3
1984	1	1
1985	2	3
1986	0	0
1987	0	0
1988	1	2
1989	0	1
1990	1	0
1991	0	0
1992	1	0
1993	0	0
1994	0	0
1995	1	0
1996	0	0
1997	0	0
Total	512	136

* US patents issued in the period from 1971 to 1999.

Table 5-22 US Patents Successfully Applied for by Japanese Companies on Technologies Related to the Mercury Process and the Ion Exchange Membrane Process

Year of Patent Application	Mercury Process	Ion Exchange Membrane Process
1968	1	0
1969	1	0
1970	0	0
1971	1	0
1972	2	0
1973	1	0
1974	1	1
1975	0	3
1976	0	6
1977	1	5
1978	0	14
1979	0	7
1980	0	9
1981	0	5
1982	0	1
1983	0	5
1984	0	8
1985	0	1
1986	0	0

1987	0	0
1988	0	1
1989	0	2
1990	0	1
1991	0	2
1992	0	0
1993	0	1
1994	0	1
1995	0	1
1996	0	0
1997	0	0
1998	0	0
Total	64	0

* US patents issued in 1971-1999.

Table 5-23 Mercury Emissions to Water, Products, and Air from Chlor-Alkali Plants in Western Europe

Year	Water	Products	Air	Total
1977	9.4	5.5	11.7	26.6
1978	4.6	2.7	8.8	16.1
1979	4.5	2.6	7.6	14.7
1980	4.6	2.3	7.3	14.2
1981	2.9	2.1	6.8	11.8
1982	2.9	1.9	6.0	10.8
1983	2.6	2.1	5.3	10.0
1984	2.5	1.7	4.9	9.1
1985	2.2	1.6	4.3	8.1
1986	1.9	1.5	4.6	8.0
1987	1.4	1.4	4.6	7.4
1988	0.9	1.2	3.8	5.9
1989	0.8	1.0	3.3	5.1
1990	0.6	0.8	2.7	4.1
1991	0.7	0.8	2.8	4.3
1992	0.5	0.7	2.4	3.6
1993	0.3	0.5	2.0	2.8
1994	0.2	0.4	1.9	2.5
1995	0.2	0.4	2.1	2.7
1996	0.1	0.2	1.7	2.0
1997	0.1	0.1	1.2	1.5

Figures are expressed in gram of mercury emitted per metric tonne of chlorine production capacity.
Source: Euro Chlor (1998c).

Table 5-24 Mercury Emissions from Individual Chlor-Alkali Plants in Western Europe in 1999

Plant	Products	Waste Water	Air	Total
Solvay Lillo, Belgium	0.050	0.020	0.680	0.750
Tessenderlo Tessenderlo, Belgium	0.083	0.010	0.617	0.710
BASF Antwerpen, Belgium	0.049	0.063	1.013	1.125
Solvay Jemeppe, Belgium	0.050	0.280	1.780	2.110
Eka Chemicals Oulu, Finland	0.127	0.125	1.322	1.574
PC de Loos Loos, France	0.100	0.100	1.380	1.580
Albemarle PPC Thann, France	0.102	0.090	1.600	1.792
Solvay Tavaux, France	0.090	0.011	1.330	1.431
Elf Atochem Jarrie, France	0.033	0.030	1.068	1.131
SPC Harbonnières Harbonnières, France	0.320	0.001	1.123	1.444
Elf Atochem Lavera, France	0.043	0.130	0.971	1.144
Elf Atochem St Auban, France	0.031	0.110	1.381	1.522
ECI Bitterfeld, Germany	0.095	0.002	1.610	1.707
Bayer Uerdingen, Germany	0.080	0.008	1.040	1.128
ECI Ibbenburen, Germany	0.080	0.004	0.322	0.406
Bayer Leverkusen, Germany	0.032	0.016	1.175	1.223
BASF Ludwigshafen, Germany	0.030	0.010	1.700	1.740
ICI Wilhelmshaven, Germany	0.025	0.005	0.510	0.540
Vestolit Marl, Germany	0.060	0.010	1.670	1.740
Hüls Lülsdorf, Germany	0.170	0.010	1.790	1.970
LII Frankfurt, Germany	0.063	0.012	0.995	1.070
Bayer	0.036	0.000	1.540	1.576

Dormagen, Germany				
Clariant Gersthofen, Germany	0.060	0.020	1.660	1.740
Wacker Chemie Burghausen, Germany	0.080	0.003	0.760	0.843
Celanese Knapsack, Germany	0.056	0.025	0.829	0.910
Vinnolit Gendorf, Germany	0.040	0.020	1.330	1.390
Akzo Nobel Hengelo, Netherlands	0.054	0.027	0.927	1.008
Solvay Linne-herten, Netherlands	0.100	0.030	1.270	1.400
Uniteca Estarreja, Portugal	0.500	0.300	1.900	2.700
Quimica del Cinca Monzon, Spain	0.300	0.480	1.260	2.040
Hernani Hernani, Spain	0.200	0.490	1.330	2.020
Elnosa Lourizan, Spain	0.440	0.020	1.510	1.970
Ercros Flix, Spain	0.330	0.130	1.450	1.910
Solvay Torrelavega, Spain	0.762	0.055	1.442	2.259
Solvay Martorell, Spain	0.070	0.050	0.750	0.870
Aragonesas Sabinanigo, Spain	0.400	0.300	1.400	2.100
Aragonesas Vilaseca, Spain	0.110	0.070	1.680	1.860
Aragonesas Huelva/Palos, Spain	0.150	0.080	1.500	1.730
Akzo Nobel Bohus, Sweden	0.012	0.006	0.250	0.268
Hydro Polymers Stenungsund, Sweden	0.011	0.004	0.139	0.154
Solvay Zurzach, Switzerland	0.040	0.080	1.370	1.490
Novartis Monthey, Switzerland	0.022	0.007	0.848	0.877
Säurefabrik Pratteln, Switzerland	0.140	0.050	0.370	0.560
Rhodia Staveley, UK	0.050	0.005	0.470	0.525
Hays	0.080	0.020	1.310	1.410

Sandbach, UK				
ICI Runcorn, UK	0.040	0.210	1.750	2.000

* Figures are expressed in gram of mercury per tonne of chlorine production capacity.
** Denmark, Luxembourg, and Iceland have no chlor-alkali plants. Ireland and Norway have only mercury-free chlor-alkali plants. Austria, Greece, and Italy are not Contracting Parties to the OSPAR Convention and thus are not required to provide data on mercury emissions to the OSPAR Commission.
Source: OSPAR Commission (2001).

Table 5-25 Chlor-Alkali Production Capacities based on the Mercury Process and the Non-Mercury Processes in Western Europe

Year	Mercury Process	Non-Mercury Processes	Total
1982	5,137 (72.6 %)	1,935 (27.4 %)	7,072
1983[c]	5,060 (71.1 %)	2,060 (28.9 %)	7,120
1984	5,079 (67.0 %)	2,505 (33.0 %)	7,584
1985	5,076 (66.9 %)	2,510 (33.1 %)	7,586
1986	5,094 (67.0 %)	2,510 (33.0 %)	7,603
1987	5,097 (67.0 %)	2,510 (33.0 %)	7,607
1988	5,012 (66.4 %)	2,538 (33.6 %)	7,550
1989	4,883 (66.6 %)	2,448 (33.4 %)	7,331
1990	4,810 (65.8 %)	2,498 (34.2 %)	7,308
1991	5,036 (68.3 %)	2,337 (31.7 %)	7,372
1992	4,788 (65.8 %)	2,473 (34.2 %)	7,281
1993	4,468 (63.6 %)	2,558 (36.4 %)	7,026
1994	4,438 (63.8 %)	2,519 (36.2 %)	6,957
1995	4,480 (62.2 %)	2,733 (37.8 %)	7,214
1996	4,481 (62.1 %)	2,734 (37.9 %)	7,215
1997	4,486 (62.0 %)	2,747 (38.0 %)	7,233

Figures are in thousand tonnes of chlorine per year.
a: Data for France and Spain are not included.
b: Data for Belgium, France, Spain and UK are not included.
c: For the Netherlands, the average of two figures for January and December 1983 is used.
Sources:
1982-1995: Oslo and Paris Commissions (1997).
1996-97: OSPAR Commission (1999c).

Table 5-26 Installations of the Mercury and the Ion Exchange Membrane Processes by Western European Firms

Year	Mercury Process	Ion Exchange Membrane Process
1970	11	0
1971	16	0
1972	13	0

1973	7	0
1974	9	0
1975	15	0
1976	15	0
1977	11	0
1978	2	0
1979	7	0
1980	5	0
1981	7	0
1982	1	0
1983	5	3
1984	0	5
1985	1	4
1986	0	2
1987	3	5
1988	2	5
1989	1	9
1990	2	7
1991	3	8
1992	0	9
1993	1	3
1994	1	13
1995	0	10
1996	0	12
1997	0	12
1998	0	14
Total	0	0

Calculation based on Chlorine Institute (1998a; 1998b), Imperial Chemical Industries (1999), Krupp-Uhde (1998), and De Nora (1999).

Table 5-27 Supply of the Ion Exchange Membrane Process by Japanese and Western European Firms

Year	Japanese Firms	Western European Firms
1975	40,000	0
1976	101,000	0
1977	181,000	0
1978	191,000	0
1979	201,000	0
1980	220,640	0
1981	250,455	0
1982	411,095	0
1983	1,279,645	61,016
1984	1,790,948	214,016

1985	2,403,497	342,366
1986	3,146,171	431,890
1987	3,730,937	517,954
1988	4,074,327	579,254
1989	4,833,022	995,606
1990	5,283,361	1,263,712
1991	5,796,600	1,379,600
1992	5,989,735	1,788,704
1993	6,774,759	1,889,772
1994	7,035,383	2,489,118
1995	7,334,650	2,776,286
1996	8,111,690	3,714,946
1997	9,066,993	4,681,326
1998	11,379,070	5,418,756
1999	13,241,560	6,133,156

Figures are cumulative production capacities (t NaOH/year).
Calculation based on Table 4-27, Table 4-28, Table 4-29, Table 4-31, Table 4-32, Table 4-33, Table 5-28, Table 5-29, and Table 5-30.

Table 5-28 Supply List of the Ion Exchange Membrane Process by ICI

Plant Site	Start-up	Capacity (t NaOH/y)
Akzo Nobel Sweden	1983/85/89	81,000
Nippon Soda Japan	1984	920 (KOH)
Elkem Bremanger Norway	1984	12,000
CCM Malaysia	1984/92	34,000
Finnish Chemicals Finland	1984	89,000
Tessenderlo Belgium	1985	300 (KOH)
Fort James USA	1985	4,750
Procter & Gamble Green Bay, USA	1985	5,100
Mondi South Africa	1985	22,500
Elf Atochem Tacoma USA	1985	91,000
ICI Lostock UK	1986	18,000
Wesfarmers CSBP	1987	6,000

Australia		
Sabah Forest Industries Malaysia	1987	10,300
Australian Paper Australia	1988	7,700
Fort James USA	1989	5,100
Prodesal Colombia	1989/93	22,000
China General Plastics Taiwan	1989	35,000
ICI Runcorn UK	1989	37,500 (KOH)
Orica Australia	1990/98	10,200
Elf Atochem Portland USA	1990	40,000
PPG Canada	1990	84,000
Confidential USA	1991	2,000
Ansa McAl Ltd. Trinidad	1991	2,500
Yibin Tian Yuan China	1991	12,000
ACC Saudi Arabia	1991/98	16,500
Dong Jin South Korea	1992	8,000
Ak-Kim Turkey	1992/93/95/99	41,000
Associated Octel UK	1992	48,000
TFI Thailand	1993/94	14,300
Jiang Han China	1994/96	37,000
Phoenix Pulp & Paper Thailand	1994	11,000
RIAU Indonesia	1995	43,500
Shandong Pesticide China	1996	30,000
Pioneer Canada	1997	60,000
Confidential	1997	14,000

Indonesia		
Ya'an Pulp & Paper China	1998	4,000
Confidential Iran	1998	950
Shandong Ganglu China	1998	30,000
Confidential North America	1998	20,000
Shriram India	1998	91,000
Total	-	8,823,810

Test plants and pilot plants are excluded from the table.
Source: Imperial Chemical Industries (1999).

Table 5-29 Supply List of the Ion Exchange Membrane Process by Uhde

Plant Site	Start-up	Capacity (t NaOH/y)
Roche Products Dalry, UK	1984/89/91	24,000
		1,800
		+ 7 %
Tofte Industries Norway	1984/87	18,000
		+ 10 %
Potasse et Produits Chimiques France	1984	700 (KOH)
P. N. Kertas Letjes Indonesia	1986	2,500
General Electric Plastics The Netherlands	1987/90/94	Confidential
		+ 30 %
		5,950
Bela Chemical Industries Pakistan	1988	16,000
Hoechst Germany	1988	12,500
AECI Limited/POLIFIN South Africa	1988	23,000
Gujarat Alkalies and Chemicals I India	1989	70,000
Gujarat Alkalies and Chemicals II India	1994	17,500 (KOH)
Formosa Plastics Taiwan	1989/94	185,000
		24,000
Bayer Leverkusen, Germany	1989	1,600

Paik Kwang Corp. Seoul, South Korea	1989	12,600
Ministry of Industry and Minerals Faluja, Iraq	1990	11,800
Cellulose Attisholz Switzerland	1990	9,500
Paik Kwang Corp. I Kunsan, South Korea	1990/93/95	17,800 17,800 17,800
Aracruz Celulose Brazil	1991	36,400
Riocell Brazil	1992	19,600
Standard Alkali India	1992 1995	68,200 5,700
EIASA/Aragonesas Spain	1992/97	35,000 10,600
Compania Manufacturera de Papeles y Cartones, Chile	1992	15,000
CQR Salgema Brazil	1994	275,000
Grasim Industries I India	1994/95	91,000 11,800
Chemfab Alkalies India	1994/97	10,000 10,000
Quimica del Norte/CLOROX Argentina	1994	15,000
Hanwha Chemical Corp. Yeochun, South Korea	1995	60,000
National Chlorine Industries Jordan	1995	7,200
Punjab Alkalies Chemicals India	1995	36,000
Chimcomplex S.A. Borzesti Romania	1996	122,000
Saudi Petrochemical Company Saudi Arabia	1996	250,000
United Phosphorus I India	1996	20,000
Misr Chemical Industries Egypt	1996	59,500
United Phosphorus II India	1996	35,000
S. C. Chimcomplex S.A. Borzesti Romania	1996	122,000

Indian Petrochemicals India	1997	148,000
La Société National de Cellulose et de Papíer Alfa, Tunisia	1997	7,500
Indian Rayon India	1997	35,000
Gujarat Alkalies and Chemicals India	1997	105,000
Kothari Sugars and Chemicals Ltd. India	1997	20,000
Olin Corporation USA	1997	255,700
Bayer Uerdingen, Germany	1997	125,000
Polifin South Africa	1997	36,700
Ravi Chemicals Pakistan	1998	10,000
Oltchim Romania	1998	122,000
Hanwha Chemical South Korea	1998	140,000
Punjab Alkalies Chemicals II India	1998	70,000
Micro Bio Ireland	1998	8,680
Total	-	23,819,340

Test plants and pilot plants are excluded from the table.
Source: Krupp Uhde (1998).

Table 5-30 Supply List of the Ion Exchange Membrane Process by De Nora

Plant Site	Start-up	Capacity (t Cl_2/y)
P.T. Kertas Letjes Probolinggo, Indonesia	1983	6,600
Basic Chemical Industries Dammam, Saudi Arabia	1983	7,700
EniChem Polimeri Cagliari, Italy	1986/90	77,700
		73,130
Sree Rayalaseema Andhra Pradesh India	1987/89/96	22,200
		8,800
		16,000
EIASA Sabinanigo, Spain	1988	2,500 (KOH)

Sitara Chemical Industries Faisalabad, Pakistan	1989	13,300
Ballarpur Ind. Ballarpur, India	1991	13,300
Ballarpur Ind. Yamunanagar, India	1991	13,300
Malay-Sino Chemicals Ipoh, Malaysia	1991/96	13,300 15,000
Century Rayon Kalyan, India	1992	14,200
Atochem Fos-sur-Mer, France	1992	120,000
Sitara Chemical Industries Faisalabad, Pakistan	1993	42,200
Basic Chemical Industries Dammam, Saudi Arabia	1993	10,650
National Rayon Mohone, India	1994	24,800
Novel & Shenyang Chemical Plant Shenyang, China	1994	50,000
Sree Rayalaseema Andhra Pradesh, India	1994	17,000
Chloran Chemical Production Semnan, Iran	1994	3,500
Tecnimont Moshi, Tanzania	1994	3,500
Elf Atochem Colombia Santafé, Colombia	1994	2,000
Chlor-Pars Tabriz, Iran	1995	6,700
Nirouchlor Isfahan, Iran	1995	6,700
Hangzhou Electrochem. Factory Hangzhou, China	1995/97	12,000 8,000
TKI Hrastnik Hrastnik, Slovenia	1995	13,500
Tata Chemicals Mithapur, India	1995	35,000
Siping Chemical Complex Siping, China	1995	20,000
South Vietnam Basic Chemical Bien Hoa, Vietnam	1996	2,000
Qingdao Chemical Works Qingdao, China	1996	60,000
Beijing No. 2 Chemical Works Beijing, China	1996/97	40,000 80,000

Confidential	-	10,000
Mardia Chemicals Gujarat, India	1996	105,000
The Andhra Sugars Kovvur, India	1996	30,000
Taiko Occidental Chem. Kemaman, Malaysia	1997	20,000
S.N.E.P. Mohammedia, Morocco	1997	16,000
Chemical Industries Singapore	1998	20,000
Qilu Petrochemical Corporation Qilu, China	1998	50,000
P.T. Pindo Deli Pulp & Paper Mill Indonesia	1998	45,000
Total	-	935,950

Source: De Nora (1999).

Table 5-31 Number of Cell Elements of Electrolyzers

Company	Asahi Chemical	Asahi Glass	CEC	De Nora	Krupp Uhde
Cell type[*]	ML 32	AZEC-B1	BiTAC 800	DN 350	BM 2.7
Max. No. of cell elements	150	80	80	90	160

* bipolar electrolyzers
Source: Luke (2000).

Table 5-32 Cost Saving from the Conversion of the Mercury Process to the Ion Exchange Membrane Process in Western Europe

Year	Energy Savings (kWh/t NaOH)	Electricity Price (US$/kWh)	Cost Saving (US$/t NaOH)
1970	-1,250	0.039	-49
1971	-1,150	0.039	-45
1972	-1,050	0.039	-41
1973	-950	0.039	-37
1974	-850	0.039	-33
1975	-750	0.039	-29
1976	50	0.039	2
1977	130	0.039	5
1978	180	0.039	7
1979	250	0.046	12
1980	480	0.053	25
1981	700	0.051	36

1982	700	0.049	34
1983	700	0.046	32
1984	800	0.043	34
1985	800	0.041	33
1986	800	0.055	44
1987	800	0.063	50
1988	800	0.065	52
1989	800	0.061	49
1990	800	0.076	61
1991	800	0.078	62
1992	800	0.075	60
1993	800	0.072	58
1994	800	0.071	57
1995	800	0.077	62
1996	800	0.074	59
1997	800	0.065	52

The improvement in the energy consumption from 1970 to 1975 is assumed to be linear.

Source:

Electricity price: International Energy Agency (1992; 1993; 1999). For 1970 to 1977, the price of 1978; for 1979, the average of the prices of 1978 and 1980; for 1981 the average of the prices of 1980 and 1982; for 1983, the average of the prices of 1982 and 1984; for 1992, the average of the prices of 1991 and 1993.

Table 5-33 Start-up Year of the Mercury Process and the Ion Exchange Membrane Process in Western Europe

Plant #[a]	Plant Site	Start-up Year of Mercury Process	Start-up Year of Ion Exchange Membrane Process	Operating Years of Mercury Process
-	Akzo Nobel Botlek, Netherlands	-	1983[b]	-
1	Akzo Nobel Skoghall, Sweden	1918	1983	65
-	Elkem Bremanger Svelgen, Norway	-	1984[b]	-
-	Tofte Industries Tofte, Norway	-	1984[b]	-
-	Finnish Chemicals Joutseno, Finland	-	1984[b]	-
-	Micro-Bio Fermoy, Ireland	-	1984[b]	-
-	General Electric Plastics Bergen op Zoom, NL	-	1987[b]	-
2	ICI (KOH) Runcorn, UK	1930	1989	59

3	Solvay Povoa, Portugal	1938	1990	52
4	Solvay Tavaux, France	1930	1991	61
5	Associated Octel Ellesmere Port, UK	1956	1992	36
6	Solvay Jemeppe, Belgium	1951	1992	41
7	Uniteca Estarreja, Portugal	1944	1992	48
8	EIASA/Aragonesas Villaseca, Spain	1951	1992	41
9	Bayer Uerdingen, Germany	1955	1997	42
10	Bayer Dormagen, Germany	1966	1999	33
11	Donau Chemie Brückl, Austria	1943	1999	56
12	ECI Bitterfeld, Germany	1936	1999	63
13	Vestolit Marl, Germany	1939	1999	60
14	Clariant Gersthofen, Germany	1940	2000	60
15	Wacker Burghausen, Germany	1944	2000	56
-	Average	-	-	1991.4

a: Plant # in Figure 5-10.

b: Newly constructed plant based on the ion exchange membrane process.

Sources:

Year of the set-up of the mercury process:

Akzo Nobel, Botlek: Straasheijm (1999). Akzo Nobel, Skoghall: Cederlund (1999). Elkem Bremanger, Svelgen: Bøsterud (2000). Tofte Industries, Tofte: Thun (1999). Finnish Chemicals, Joutseno: Cowell and Jackson (1986). Micro-Bio, Fermoy: O'Brien (2001). General Electric Plastics, Bergen op Zoom: Vos (1999). ICI, Runcorn: Ingleby, Curry, and Broom (1999). Solvay, Povoa: Chlorine Institute (1972). Solvay, Tavaux: Chlorine Institute (1972). Solvay, Jemeppe: Chlorine Institute (1997). Uniteca, Estarreja: Chlorine Institute (1972). EIASA/Aragonesas, Villaseca: Grupo Aragonesas (1999). Associated Octel, Ellesmere Port: Lott (1995). Borregaard Industries, Sarpsborg: De Flon (1998). Bayer, Uerdingen: Schubert (1999). Bayer, Dormagen: Schubert (1999). Donau Chemie, Brückl: Donau Chemie (2000). ECI, Bitterfeld: Herold (2000). Vestolit, Marl: Chlorine Institute (1972). Clariant, Gersthofen: Teufel (2000). Wacker, Burghausen: Chlorine Institute (1972).

Year of the conversion to the ion exchange membrane process:

Asahi Chemical Industry (1998), Asahi Glass (1999), Chlorine Engineer Corp. (2000), Krupp-Uhde (1998), Imperial Chemical Industries (1999), De Nora (1999), and Eltech Systems (2001).

Table 5-34 Operating Years of the Existing Chlor-Alkali Plants based on the Mercury Process in Western Europe

Plant #[a]	Plant Site	Year of Start-up of Mercury Process[b]	Operating Years[c]
1	Electroq. de Hernani Hernani, Spain	1949	51
2	Solvay Zurzach, Switzerland	1949	51
3	Hüls Lülsdorf, Germany	1950	50
4	Hays Sandbach, UK	1956	44
5	Akzo Nobel Oulu, Finland	1957	43
6	Solvay Rosignano, Italy	1957	43
7	BASF Ludwigshafen, Germany	1958	42
8	Solvay Tavaux, France	1959	41
9	Bayer Leverkusen, Germany	1960	40
10	Altair Chimica Volterra, Italy	1960	40
11	EniChem Priolo, Italy	1960	40
12	Celanese Knapsack, Germany	1962	38
13	ECI Ibbenbüren, Germany	1963	37
14	Hellenic Petroleum Thessaloniki, Greece	1963	37
15	Solvay Jemeppe, Belgium	1964	36
16	Eredi Zarelli Picinisco, Italy	1964	36
17	Elf Atochem Saint Auban, France	1965	35
18	Caffarro Toreviscosa, Italy	1965	35
19	Solvay Torrelavega, Spain	1965	35
20	BASF Antwerp, Belgium	1966	34
21	ICI Runcorn, UK	1966	34

22	Rhodia Staveley, UK	1966	34
23	Elf Atochem Lavera, France	1968	32
24	Quimica del Cinca Monzon, Spain	1969	31
25	Norsk Hydro Stenungsund, Sweden	1969	31
26	Solvay Antwerp, Belgium	1970	30
27	LII Europe Frankfurt, Germany	1970	30
28	Akzo Nobel Hengelo, Netherlands	1970	30
29	Akzo Nobel Bohus, Sweden	1970	30
30	Albemarle Thann, France	1971	29
31	Elf Atochem Jarrie, France	1971	29
32	EniChem Porto Marghera, Italy	1971	29
33	ICI Wilhelmshaven, Germany	1972	28
34	Vinnolit Gendorf, Germany	1972	28
35	Tessenderlo Chemie Pieve Vergonte, Italy	1972	28
36	EIASA/Aragonesas Villaseca, Spain	1972	28
37	Solvay Martorell, Spain	1972	28
38	Novartis Monthey, Switzerland	1972	28
39	Saürefabrik Schweizerhall Pratteln, Switzerland	1972	28
40	EIASA/Aragonesas Huelva, Spain	1973	27
41	Dow Schkopau, Germany	1974	26
42	Tessenderlo Chemie Loos, France	1974	26
43	EniChem Porto Torres, Italy	1974	26
44	Prod. Chimiques d'Harbonnières Harbonnières, France	1975	25

45	Erkimia Flix, Spain	1975	25
46	Ausimont/Montedison Bussi, Italy	1976	24
47	Bayer Uerdingen, Germany	1977	23
48	Tessenderlo Chemie Tessenderlo, Belgium	1977	23
49	EIASA/Aragonesas Sabinanigo, Spain	1977	23
50	Elnosa Lourizan, Spain	1977	23
51	Uniteca Estarreja, Portugal	1981	19
-	Average	-	1967.4

a: Plant # in Figure 5-11.

b: In cases where mercury processes were introduced in multiple times, the year when the first introduction took place is used.

c: Operating years as of 2000.

Sources: Euro Chlor (1998a), Chlorine Institute (1997; 1998a; 1999a).

Table 5-35 Installation of the Mercury, Diaphragm, and Ion Exchange Membrane Processes in the World

Year	Mercury Process	Diaphragm Process	Ion Exchange Membrane Process
1970	13	0	0
1971	16	1	0
1972	13	1	0
1973	6	0	0
1974	9	6	0
1975	14	8	2
1976	14	5	1
1977	14	8	1
1978	3	3	3
1979	7	4	1
1980	7	6	5
1981	8	4	7
1982	1	2	7
1983	5	1	13
1984	1	1	17
1985	1	1	22
1986	1	1	17
1987	2	1	21
1988	1	2	25

1989	0	1	38
1990	3	1	30
1991	1	0	22
1992	0	0	15
1993	0	0	9
1994	0	0	18
1995	0	4	20
1996	1	4	24
1997	0	0	25
Total	1128	520	2744

Source: Calculation based on Chlorine Institute (1998a; 1998b).

Table 5-36 Shares of the Mercury, Diaphragm, and Ion Exchange Membrane Processes in the World

	1980	1990	1999
Mercury Process	45	39	25
Diaphragm Process	53	45	34
Ion Exchange Membrane Process	2	16	30

Figures are expressed in percentage.
Sources: 1980 and 1990: Müller (1993). 1999: TECNON (1999).

6. Summary and Conclusion

In this research, we examined the effects of environmental regulation on technological change. A particular emphasis was placed on the distinction between the end-of-pipe technology and the clean technology, with its implications for diverging impacts of environmental regulations on innovation. We first reviewed theoretical and empirical research which has been conducted on this issue in the past. Previous theoretical models basically suggest that economic instruments, including emission tax and tradable emission permits, are generally superior to command-and-control regulation in encouraging technological change for pollution abatement. Comparing relative scales of incentives under different policy instruments, they claim that economic measures generally give a greater spur to innovate in pollution control than direct controls.

These arguments, however, are based on several very restricted assumptions concerning the nature and characteristics of technological change. Among them is that these theoretical studies pay almost exclusive attention to end-of-pipe technologies as their measures for emission reduction. They basically ignore the possibility of a different type of technological change, namely, clean technologies, which will eliminate the formation of pollutants from within the production processes. Some of these studies assume that there is a tradeoff in R&D between improvement in output production technology and improvement in pollution abatement technology. In this approach, the technologies considered for pollution abatement are basically those of the end-of-pipe type, and the possibility of developing clean technologies is not taken into account. Since clean technologies do not require any measures for pollution abatement, it is not necessary to conduct R&D on end-of-pipe technologies. Thus it could become possible to achieve improvement in both output production and pollution abatement at the same time, and as a result the tradeoff between the two types of improvement would disappear. What would be of critical importance then is to make an appropriate choice between the end-of-pipe technology and the clean technology as the target of R&D, rather than to find the optimal combination of R&D efforts between those for pollution abatement and for output production.

In other theoretical models, marginal cost curves have been typically used for pollution abatement, with an assumption that the marginal cost of pollution abatement increases as emissions are reduced. And the scope for innovation is limited to technologies with which marginal abatement costs are lowered. In other words, marginal abatement costs are

continuous and strictly increasing over a relevant region of emission reduction, and technological change is modeled simply as a decline in marginal abatement costs. Effectively, these assumptions mean that pollution abatement is implemented only through adoption of end-of-pipe technologies. The other type of technologies for dealing with emissions from the production process, that is, clean technologies, has been mostly ignored. Since clean technologies eliminate the creation of pollutants from within the production process by altering the chemical reactions producing the main products, there is no pollution emission in the first place, and thus marginal cost curves for pollution abatement become inappropriate for the analysis of clean technologies.

Empirical studies conducted previously produced mixed results concerning the effects of environmental regulation on technological change. One of the crucial issues affecting the results of these studies is what kinds of technology are included in the category of innovation. As the range of clean technologies can hardly be identified clearly in general terms without regard to details of specific production processes, earlier empirical studies either exclusively focused on technologies of the end-of-pipe type or included all innovations observed in each case. While consideration of only end-of-pipe technologies limits the scope of technological change for pollution abatement too narrowly and excludes clean technologies, the group of all innovations contains technologies that have little relevance to environmental aspects and is too broad to be appropriately used for the analysis of the impacts of environmental regulation on technological change. Previous empirical as well as theoretical studies have looked at only end-of-pipe technologies as technological measures for pollution abatement, and the existence of clean technologies has not been taken into account properly. It is thus of critical importance to incorporate into analysis the possibility of pollution elimination with clean technologies, in contrast to pollution reduction with end-of-pipe technologies.

A detailed analysis of the end-of-pipe technology and the clean technology based on chemical reaction equations clarifies the qualitative differences between the two types of technological change. Basically, the end-of-pipe technology is designed to be installed at the end of manufacturing plants and will not affect the manufacturing process producing the main products. Its pollution abatement cost is relatively small when the level of emission reduction is low and normally starts to rise as the emission standard becomes more stringent. While innovations on the end-of-pipe technology will reduce the cost of complying with any fixed level of the emission standard, the total cost of manufacturing with the use of the end-of-pipe technology will not become smaller than the original output production cost. The cost of

output production will remain unchanged as the end-of-pipe technology does not affect the main production process, whereas the cost of pollution abatement, which will not become zero by whatever innovation, is added to the output production cost.

The clean technology, in contrast, eliminates the formation of pollution from within the production process by altering the whole chemical reactions. Thus the use of the marginal pollution abatement cost curve becomes inappropriate for the analysis of the clean technology, which does not produce any pollutant emission in the first place. As the clean technology is a radical innovation involving the whole production facilities, the capital investment for its installation is normally large and its cost of output production will be larger, at least initially, than that using the end-of-pipe technology. It is possible that the output production cost with the clean technology will later become smaller than that with the original production cost as the performance of the clean technology improves significantly through R&D and learning. On the other hand, there are usually more than one options of the clean technology replacing the original production technology, and the uncertainty concerning future progress in the performance of the multiple alternatives will be large.

Based on the distinctive characters of the end-of-pipe technology and the clean technology, our analytical framework is established for the effects of environmental regulation on technological change (Figure 2-11). When an environmental issue occurs, normally there is a large degree of uncertainty concerning where the sources of pollutant emissions are located, what mechanisms of physical, chemical, and biological transformation of the pollutants are involved, and how much damage has been or is expected to be made on the human body and other living organisms. Given the existence of these various types of uncertainty, it would be rare that scientific arguments can exclusively determine environmental regulations, and other factors, including historical, political, and social backgrounds, will inevitably influence the outcome of policy discussions. Reflecting the diversity of the surrounding conditions, different regulations could be imposed in relation to the same environmental issue.

When the regulations are so stringent as to effectively require the abolishment of the existing production technology, firms will be prompted to find new clean technologies. There are normally multiple alternatives, and a large degree of uncertainty exists concerning which technology will progress to become the most efficient in the long run. Thus, to the extent that the stringent regulations are implemented with a rigidly fixed schedule, it is possible that insufficient time and opportunities allowed for R&D and learning will lead to a technological

choice that is not the most efficient. Yet this will only become apparent *ex ante*, after it has been adopted widely and used for a certain period of time. Only when the regulations maintain some flexibility in schedule and timing, will there be time to test and experiment with various types of the clean technology, and the chance will be high that the most efficient clean technology will be picked up for development and adoption.

When the environmental regulation is relatively weak, in contrast, firms will be induced to choose end-of-pipe technologies because it is less expensive, at least initially, to reduce emissions by using them than by adopting clean technologies that involve radical changes in the whole production process. R&D efforts will be directed toward improving the performance of end-of-pipe technologies, and as long as these technologies work successfully to comply with the target of emission reduction, companies will continue to rely on the original, pollution-laden production technology. By the time when the most efficient clean technology becomes available from a region where more stringent regulations were implemented, more plants have already been established utilizing the present production technology. Unless the saving in the operating cost from the conversion to the clean technology is sufficiently larger than the capital investment necessary to install it, the operators of the relatively new plants will have strong incentives to continue to use the existing production technology, equipped with end-of-pipe technologies for pollution abatement, until the end of the physical life time of their plants, inhibiting the diffusion of the most efficient clean technology.

Figure 6-1 shows in this analytical framework the effects of environmental regulation on technological change in the chlor-alkali industry in Japan and Western Europe. Mercury emissions from chlor-alkali production plants have been subject to intensive environmental regulations in the two regions since the 1970s. Under the influence of different regulatory approaches to mercury emissions, diverging courses of technological change have been observed between the two regions.

Dominant use of the mercury process in Western Europe and Japan (Chapter 3)

Japan
(Chapter 4)

Uncertainty concerning the mechanism and impact of mercury emissions on the environment

Western Europe
(Chapter 5)

Requirement for phase-out of the mercury process

Standards for mercury emissions from the mercury process

R&D on clean technologies (diaphragm process and ion exchange membrane process)

R&D on end-of-pipe technologies for abatement of mercury emissions

Rigid and short-term schedule for the phase out of the mercury process

Interruption and postponement of the phase-out mandate

Adoption of end-of-pipe technologies

Insufficient time and opportunities for R&D and learning

Technological progress in the ion exchange membrane process

Further investment in plants based on the mercury process

Premature choice of the diaphragm process

Diffusion of the ion exchange membrane process

Continuing use of the mercury process until the end of plant lifetime
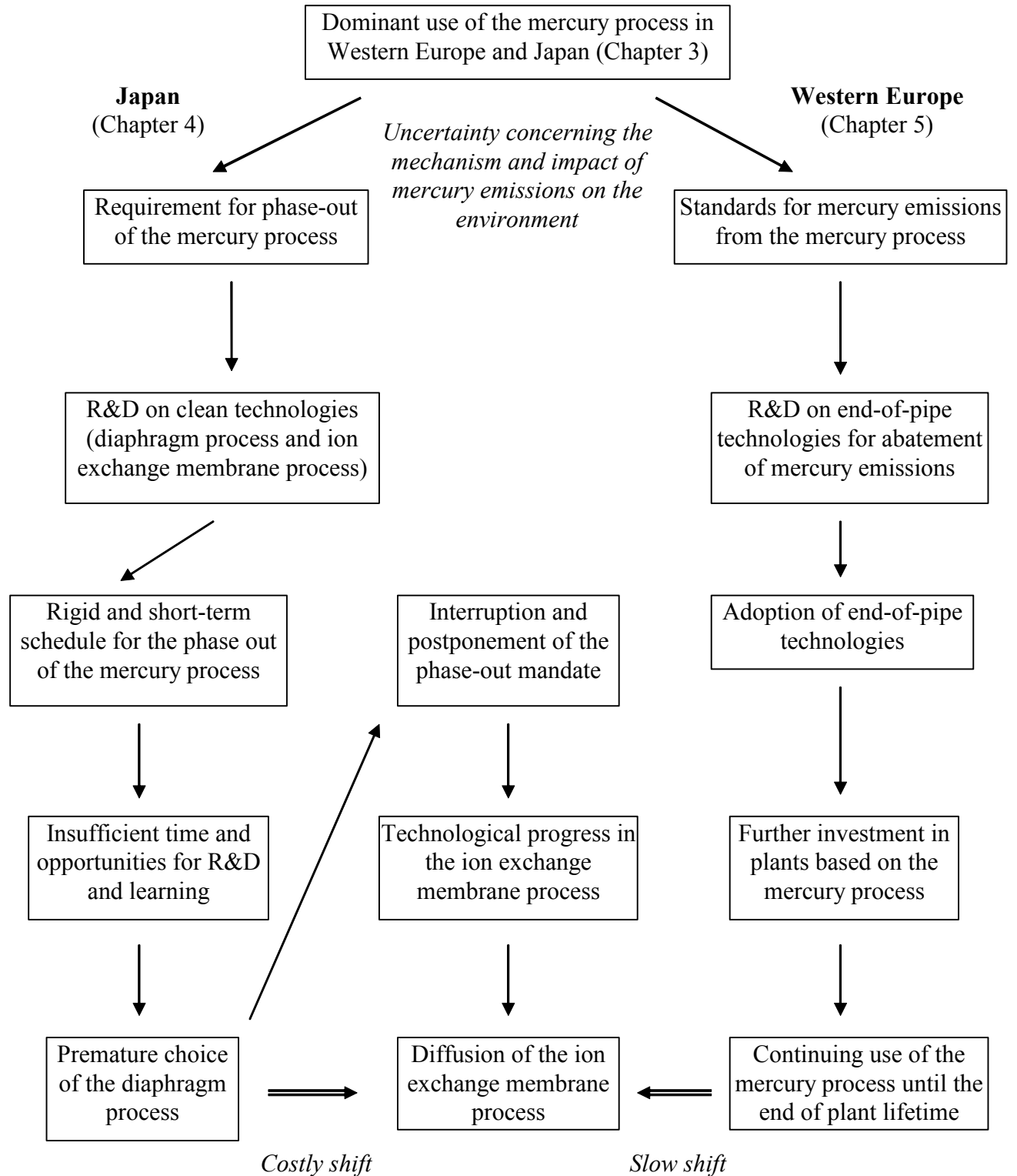
Costly shift

Slow shift

Figure 6-1 Diverging Impacts of Environmental Regulations on Technological Change in the Chlor-Alkali Industry in Japan and Western Europe

323

There are basically three types of technologies used for commercial production of chlor-alkali products: the mercury process, the diaphragm process, and the ion exchange membrane process. The mercury process and the diaphragm process were invented at the end of the 19th century. In Europe and later in Japan, technologies for the mercury process were improved further through learning and knowledge accumulation based on increased use in the industry, and more chlor-alkali producers adopted the mercury process. By the end of the 1960s, the mercury process had come to dominate the chlor-alkali industry in both Western Europe and Japan. In each region, there were several innovative companies which made successful technological developments for the mercury process. In Western Europe these included De Nora, Uhde, Krebs, Solvay, and ICI whereas in Japan these were Osaka Soda, Kureha Chemical Industry, Asahi Glass, Tokuyama Soda, Asahi Chemical Industry, and Mitsui Engineering and Shipbuilding. In the early 1970s, just before regulations started to be introduced to reduce mercury emissions into the environment, these companies in the two regions were equally innovative on the mercury process technologies. That means that the initial technological conditions in the chlor-alkali industry were similar between Western Europe and Japan prior to any regulatory influence.

Japan had a tragic experience of the Minamata disease in the 1950s and 1960s. The disease caused damages on the nerve system of those people who ate fish poisoned with dimethyl mercury, a chemical substance which belongs to the category of organic mercury. It had been contained in the waste water emitted to the sea by a chemical plant producing acetaldehyde nearby. As most of the chlor-alkali plants at that time were based on the mercury process, concerns rose among the general public on the environmental effects of their emissions. What was discharged from mercury-based chlor-alkali plants, however, was actually inorganic mercury, a substance whose chemical characteristics are distinctively different from those of organic mercury, and there was no confirmed incident or scientific evidence showing that the inorganic mercury emitted from chlor-alkali plants caused any symptoms of the Minamata disease. Nevertheless, the public pressure was very intense, and several chlor-alkali plants were forced to suspend their operation because of mass demonstrations.

The increasing public pressure pushed the Japanese government to take a tough stance on mercury emissions from chlor-alkali plants. That resulted in such as stringent regulation set by the government as to demand chlor-alkali producers to completely abolish the mercury process in just a few years, despite the chlor-industry's strong oppositions. While financial

support was given for the adoption of clean technologies through preferential tax treatment and low-interest public loans, the government did not provide any subsidies for R&D on clean technologies. On the other hand, the stringent policy to abandon the mercury process created a large, secured demand for mercury-free technologies, in stead of end-of-pipe technologies aimed at reducing mercury emissions from the mercury process, and thus provided strong incentives for innovative companies to work on new clean technologies and to supply them to other chlor-alkali producers.

As the original process conversion program was implemented in a tight, inflexible schedule, many of the leading companies in developing chlor-alkali production technologies initially chose the diaphragm process as the alternative clean technology, because its technological performance and reliability was considered to be superior to that of the ion exchange membrane process at that time. Mitsui Shipbuilding and Engineering established a specialized company, CEC, to introduce the diaphragm process developed by foreign companies and provided it to chlor-alkali manufacturers. Kureha Chemical Industry also chose the diaphragm process to replace the mercury process and subsequently developed its own technology. Those companies which had been innovative on the diaphragm process, that is, Nippon Soda, Tsurumi Soda, and Showa Denko, expanded their production capacities with the diaphragm process and provided their technologies to outside companies. Only those companies with less expertise on chlor-alkali production technologies, namely, Asahi Chemical Industry, Asahi Glass, and Tokuyama Soda, directed their R&D efforts toward the ion exchange membrane process, a production process which was not yet sufficiently developed as to be utilized for industrial applications when the decision was made for the phase out of the mercury process. Relying on their earlier experiences of developing ion exchange membranes used in different fields, these companies utilized the opportunity offered by the stringent regulation to innovate on the still infant ion exchange membrane process for chlor-alkali production.

As the regulatory schedule for the conversion of the mercury process was initially set with a rigid, short-term deadline, most of the chlor-alkali manufacturers had no choice other than to adopt the diaphragm process, which had been long established at the level of industrial applications. With the amount of time and learning limited, however, the technologies developed by the Japanese companies could not be improved sufficiently as to be used for commercial purposes. By the time that the first phase of the government conversion program was ended, two thirds of the chlor-alkali production capacities in Japan had been converted to

the diaphragm process, but most of the technologies adopted were those introduced from foreign companies. While the mercury process in Japan was mostly converted to the diaphragm process, the disadvantage of the diaphragm process in terms of the production cost was getting worse, as the energy price soared following the oil crisis. Moreover, it was becoming clear that the quality of caustic soda produced by the newly introduced diaphragm process was not high enough as to be used for some industrial applications.

In the meantime, the ion exchange membrane process was undergoing a rapid technological advancement. Under these circumstances, the government interrupted the implementation of the process conversion program for a while and established an expert committee consisting of academic researchers to evaluate the extent of technological progress in the emerging ion exchange membrane process. By conducting interviews and visiting companies for detailed information on on-going technological developments, the committee concluded that the ion exchange membrane process had reached a stage ready for industrial applications. Following the technological assessment of the expert committee, the government modified the original schedule for process conversion and postponed the deadline for complete abolishment of the mercury process. This adjustment of the regulatory schedule allowed more time for innovative companies to undertake R&D activities on the ion exchange membrane process and to gain learning experiences through actual operations of chlor-alkali plants, promoting further progress in the promising, but not yet fully established technology. The ion exchange membrane process had advanced to become the best technology in the end among the three chlor-alkali processes economically as well as environmentally, and subsequently the remaining mercury-based plants were all converted to this process. Currently the majority of chlor-alkali plants located in Japan are relying on the ion exchange membrane process, and its technologies are increasingly adopted by chlor-alkali producers in other countries.

On the other hand, those mercury-based plants which had been converted to the diaphragm process immediately following the government decision on the phase out of the mercury process were later converted again to the ion exchange membrane process. The operating period of these plants based on the diaphragm process turned out to be significantly shorter than that of plants operated in normal conditions. This implies that the substantial amount of capital investment made to introduce the diaphragm process was not utilized to the full extent until the end of the plant lifetime and thus effectively ended up wasted. Although the evaluation of technological development on the ion exchange membrane process by

independent experts finally made it possible to change the regulatory schedule, the transition was costly, going through the conversion of the mercury process initially to the diaphragm process and then to the ion exchange membrane process. In retrospect, the large-scale shift from the mercury process to the diaphragm process could have been avoided if the initial government policy for the phase out of the mercury process had maintained a certain degree of flexibility in the regulatory schedule, taking into account possibilities of future progress in alternative clean technologies. As radical breakthroughs on the ion exchange membrane process were perceived to be on the horizon by several innovative companies at the time of the government decision, if the deadline for the phase out of the mercury process had been set on a later period from the beginning, there could have been more time for detailed experiments and evaluations of multiple choices of clean technologies, and most of the existing mercury-based plants could have been converted directly to the ion exchange membrane process, without devoting large investments in the diaphragm process.

In Western Europe, unlike the Japanese case, there was no reported incident in which human bodies were seriously affected by the intake of mercury, and a less stringent approach was taken to the regulation of mercury released into the environment. Rather than imposing a mandate for complete abolishment of the mercury process, the public authorities specified standards for mercury emissions from chlor-alkali plants, and their levels were gradually tightened in the subsequent periods. As required by the emission standards, companies were encouraged to develop technological measures for pollution abatement. Most of the innovative companies in Western Europe, including ICI, Hoechst-Uhde, De Nora, Solvay, and Krebs, directed their R&D activities to end-of-pipe technologies for the reduction of mercury emissions, rather than to clean technologies which would eliminate the use of any mercury within the production process. Various types of end-of-pipe technologies were successfully developed, and they worked adequately to such an extent that they could meet the imposed emission standards. With a remarkable reduction in mercury emission by using end-of-pipe technologies, chlor-alkali producers in Western Europe mostly have continued to use the mercury process. Although several companies had previously been engaged in R&D on the ion exchange membrane process, the relatively weak regulatory regulations on mercury emissions did not encourage further innovative efforts to develop the clean technology which does not involve any use of mercury.

In the same period, the ion exchange membrane process was under rapid technological progress in Japan, promoted by the strong regulation for the phase out of the mercury process,

and was on a way to become the most efficient technology among the three production technologies. Observing this, the innovative companies in Western Europe started to intensify their R&D activities on the ion exchange membrane process. As advanced types of ion exchange membranes had been already developed by the Japanese companies, however, the focus of R&D activities was placed on electrolytic cells for use in the new process. Relying on ion exchange membranes introduced from outside, the Western European companies began to industrialize the ion exchange membrane process much later.

Although the ion exchange membrane process has become the best clean technology economically as well as environmentally, its diffusion in Western Europe has been slow and limited. There are basically two factors that theoretically could affect the diffusion of a new technology, that is, the availability of information on the new technology and the profitability of replacing the existing technology with the new one. In terms of the amount of information on the ion exchange membrane process, there have been ample opportunities for chlor-alkali producers to obtain detailed and reliable data on its technological performance through presentations made at industry conferences and papers published on technical and trade journals. Thus lack of information could not be a major factor inhibiting a wide diffusion of the ion exchange membrane process in Western Europe. With regard to the profitability of replacing the mercury process with the ion exchange membrane process, the investment cost of adopting the ion exchange membrane process has been much larger than the cost necessary for the installation of end-of-pipe technologies to reduce mercury emissions, whereas the operating cost of the ion exchange membrane process has become lower than that of the mercury process. The scale of the cost saving by switching from the mercury process to the ion exchange membrane process, however, has not yet been sufficient to justify the initial investment necessary for the process conversion, although it is already economical to adopt the ion exchange membrane process for new chlor-alkali plants.

What has been the critical factor influencing the diffusion of the ion exchange membrane process in Western Europe is then the age of the existing chlor-alkali plants based on the mercury process. Compared with chlor-alkali plants which had been constructed previously, the operating period is still considerably short for most of the present mercury-process plants, and that suggests that these plants have not yet reached the end of their physical lifetime. While complying successfully with the emission standards through end-of-pipe technologies, the operators of mercury-process plants have strong incentives to continue to use them as long as they work physically. Particularly during the 1970s, after regulations

were introduced to limit mercury emissions into the environment, chlor-alkali plants continued to be constructed using the mercury process. By the time that the ion exchange membrane process with efficient and reliable performance became available to chlor-alkali producers, many mercury-based plants had been already established. It will still take a long period of time before these relatively new plants reach the end of their lifetime. Although the regulators have recently recommended that the existing mercury-based plants be completely discarded by 2010, the mercury process is still the dominant production technology in Western Europe. The environmental regulations aimed at limiting mercury released to the environment did encourage the development and adoption of end-of-pipe technologies, which indeed worked relatively well in reducing mercury emissions. This success, however, effectively helped to prolong the lifetime of the mercury process, which actually has been in a process of technological obsolescence.

Indeed, the use of the mercury process has been increasingly avoided in the chlor-alkali industry in other parts of the world, including many developing countries. In the past there have been intense debates on the so-called pollution haven hypothesis, which basically claims that developing countries will lower the level of their environmental regulations to attract foreign direct investment by companies in pollution-intensive industries located in developed countries to avoid stringent environmental regulations. The case of the chlor-alkali industry shows that developing countries have been increasingly constructing new plants by adopting the clean ion exchange membrane process, rather than the mercury process equipped with end-of-pipe technologies aimed at reducing mercury emissions, as the ion exchange membrane process has become more efficient without any use of mercury than the pollution-laden mercury process. The case of technological change in the chlor-alkali industry suggests that, given the existence of the two types of technological change to deal with pollutant emissions, pollution haven may not necessarily be an unavoidable fate for developing countries, which instead could leapfrog to the most efficient clean technology.

The case of technological change in the chlor-alkali industry has important implications for analyzing the impacts of environmental regulation on industrial competitiveness. There have been intensive debates between two opposite positions on this issue. On the one hand, concerns have been raised about the negative effects of increasingly stringent regulations on industries. That is, stringent environmental regulations will force firms to invest a considerable amount of financial resources for compliance, and consequently their competitiveness will be lost against those in countries with lax environmental regulations.

Environmental regulations impose significant costs, slow productivity, and thereby hinder the ability of companies to compete in international markets by requiring firms to spend additional resources for pollution abatement and control without increasing the output of main products. On the other hand, the so-called Porter hypothesis claims that stringent environmental regulations will actually enhance the competitive position of firms by encouraging them to undertake more R&D activities and consequently to produce better innovations in the long run. In other words, the necessity to comply with increasingly stringent environmental regulations will prompt companies to re-examine their products and production processes carefully and will ultimately lead to technological improvements. Spurred by strong regulations, companies will go beyond mere compliance and could succeed in creating radically new technologies which have not been realized previously.

Our analysis shows that what is critical in addressing this issue is to ask what kinds of technological change would be promoted by environmental regulations. Since end-of-pipe technologies are designed to be installed at the end of production processes, the costs necessary for their adoption and operation are added to the original production costs, which will only increase the total costs of manufacturing. Thus, we could say that those who argue that environmental regulations decrease industrial competitiveness basically have end-of-pipe technologies in mind. Clean technologies in contrast have the potential to achieve a better performance than present technologies. Then an important question is how to encourage companies to make innovations on a clean technology which will only be known to be the best in the long run. When an environmental regulation is introduced, unless it is so stringent as to require the existing production technologies be abolished, manufacturing companies have two technological choices, that is, end-of-pipe technologies and clean technologies. With the regulation fixed on a short-term schedule, companies will have incentives to comply with the requirement of emission reduction with end-of-pipe technologies, an option which is relatively easy and less costly to develop and adopt than clean technologies. As a result, the present pollution-laden technologies, with emissions reduced through end-of-pipe technologies, will continue to be used, whereas innovative activities will not be actively pursued on clean technologies under the existence of uncertainty concerning the potential for a better performance from a long term perspective.

This situation could be discussed in terms of what Clayton Christensen calls "innovator's dilemma" (Christensen, 1997). The concept basically says that a sound business practice of focusing investments on technologies which meets the current demand of

customers profitably, which are defined as sustaining technologies, can ultimately weaken a good company. Breakthrough innovations, or disruptive technologies, are initially rejected by customers because of the lack of sufficient technological performance. That will lead firms with strong focus on the current market demand to allow innovations which would be strategically important in the future to languish. In a similar manner, we could argue that the strategy of focusing investments on the most efficient measures for pollution abatement, that is, end-of-pipe technologies, to meet the current demand of environmental regulations would function to miss the opportunity of making radical innovations on technologies of critical importance in the long run, that is, clean technologies. That is the case of the Western European companies which had been previously innovative on the mercury process. These companies initially focused on end-of-pipe technologies to reduce mercury emissions, and their technological success in meeting the regulatory requirement effectively led to sustaining the mercury process. The opportunity of inventing new ion exchange membranes was missed, however, inhibiting subsequent technological developments on the ion exchange membrane process, a truly disruptive technology for chlor-alkali production.

We could draw some policy implications from the experience in the chlor-alkali industry. Environmental regulations should seek to encourage innovations on clean technologies, which have the possibility of achieving economic and environmental objectives at the same time, rather than innovations on end-of-pipe technologies, which will only lead to incurring additional costs. At the same time, they need to avoid inducing wrong technological choices prematurely in the presence of uncertainty, diversity, and rigidity inherent in the process of technological change. Therefore, stringent regulations will be effective to create strong and secured demands for clean technologies, shifting away from end-of-pipe technologies which would only sustain the trajectory of the traditional, pollution-laden production processes, but they should be implemented in a long-term framework to allow sufficient time for experience and experiment on alternative clean technologies. To do that, it would be necessary that regulations accommodate a certain degree of flexibility in schedule to reflect accurate and up-to-date information on the state of technological developments undergoing in industry. What would be important is that institutional mechanisms are set up for appropriate information collection and assessment concerning clean technologies, which involve a much larger level of uncertainty than end-of-pipe technologies, particularly in cases where the speed of technological change is high and the uncertainty concerning future progress is large.

We could argue that the Japanese government made a mistake in initially prompting the companies to choose the diaphragm process effectively by implementing excessively stringent regulations, especially given that there was no confirmed incident of Minamata-like disease caused by inorganic mercury emissions from chlor-alkali plants. This occurred because of the unusually strong public pressure, which allowed little time for careful consideration on the potential of alternative clean technologies. At a later stage, only by acquiring and evaluating accurate and up-to-date information on the rapid technological progress through an independent expert committee consisting of researchers in academia, the government could modify the regulatory schedule to accommodate further improvement on the ion exchange membrane process and its subsequent adoption by chlor-alkali producers. Since it is normally difficult for policy makers to closely keep up with the rapidly changing state of technological development in industry, direct support to R&D activities focusing on a specific clean technology would not be appropriate, as a wrong technology could be picked up, given the existence of large uncertainty concerning the extent of technological progress in the future. Rather, it would be more desirable to create and maintain demands for clean technologies through regulatory incentives. When innovative companies are convinced that there will be large and stable demands for clean technologies, they will be encouraged to make innovative efforts on these technologies, as the Japanese companies did, even without receiving any direct support to their R&D activities. What is important is to maintain the diversity of options for clean technologies, avoiding a particular technological target at an initial stage.

One caveat needs to be mentioned here regarding the technological impact of stringent regulations. Stringent regulations do not necessarily promote totally new technologies which have never been imagined. In the case of the ion exchange membrane process, ion exchange membranes had been used for other purposes previously, and the idea of applying them for chlor-alkali production had existed for a long time. The strong regulation for the phase out of the mercury process, giving an assurance of a large market for clean technologies by eliminating the possibility of end-of-pipe solutions, provided confidence sufficient to overcome the barrier of uncertainty concerning potential progress in the ion exchange membrane process which could be seen on the horizon. Thus what would be crucial is that detailed information and knowledge on the state of technological development currently occurring in industries is utilized appropriately in the process of policy making.

In acquiring accurate and delicate information on and making proper assessment of evolving technologies, the way in which communication and information exchange are practiced among policy makers and experts in industry and academia will be particularly important. In this context, the recent emergence of voluntary agreements between industry and government in industrialized countries is an interesting phenomenon deserving careful examinations[113]. Our analysis suggests that voluntary approaches could have potential to make it possible to utilize knowledge and information effectively and to adjust investment schedules efficiently. At the same time, on the other hand, they need to maintain objectively and transparency in setting the targets and monitoring the results through independent actors, avoiding the problem of regulatory capture. As each country has its own peculiarity in the relationship between government, industry, and academia, institutional mechanisms in which information on the situation of technological development is acquired and assessed would be different[114]. Accordingly, the appropriate mode of information acquisition and assessment to encourage innovations on clean technologies could be diverse, depending on the distinct institutional structure[115]. In other words, the structural coherence of the institutional arrangements could prove increasingly central to the emergence of the most appropriate clean technologies. Further research on international comparative analysis of institutional arrangements will be invaluable to deepen our understanding of the effects of environmental regulation on technological change[116]. We hope that this will help us ultimately to make a step toward sustainable development through a transition from end-of-pipe technology to clean technology.

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[113] See, for example, Carraro and Leveque (1999) for theoretical and empirical analyses on voluntary approaches in environmental policy.

[114] For an interesting approach to the analysis of the role of information in institutional evolution and diversity, see Aoki (2000; 2001).

[115] Various types of voluntary agreements have been already observed in the chemical industry in the United States, Europe, and Japan, which could be considered to reflect institutional differences between these regions (Baba and Yarime, 2000).

[116] Vogel (1986) argues that there are "national styles" of regulation by examining environmental regulations in Great Britain and the United States. A recent study by Wallace (1995) is an attempt to analyze the relationship between environmental policy and industrial innovation in Europe, Japan, and the United States in a comparative framework.

Appendix. Effects of Environmental Regulation on Technological Change of the Chemical Processes for Chlor-Alkali Production

In the evolution of production technologies in the chlor-alkali industry, there was another opportunity in which divergent courses of technological trajectory were observed. That happened between the Leblanc process and the ammonia process, both of which belonged to the chemical process of chlor-alkali production. In this Appendix, we examine in a preliminary way how environmental regulations influenced the divergent courses of technological changes between the two processes by paying a particular attention to the chlor-alkali industry in Britain in the 19th century.

A.1 Leblanc Process

The Leblanc process, invented by Nicolas Leblanc in France in 1787, was the first process for the soda production which worked satisfactorily on an industrial scale[117]. In Britain its first operation started in 1822. The Leblanc process had two distinct stages. The first step involved the decomposition of common salt (sodium chloride, NaCl) with sulfuric acid (H_2SO_4) to produce salt cake (sodium sulfate, Na_2SO_4):

$$2NaCl + H_2SO_4 \rightarrow \underline{Na_2SO_4} + \underline{2HCl}^*.$$
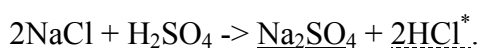
The sodium sulfate was used directly for the glass manufacturer, in its purified form, sold as the purgative Glauber's salts. The vigorous reaction involved also produced large quantities of hydrochloric acid gas (HCl), which had been simply emitted to the atmosphere as waste.

In the second step, the salt cake is fluxed with limestone (calcium carbonate, $CaCO_3$) and charcoal or coal (carbon, C) to produce black ash, a mixture of sodium carbonate (Na_2CO_3) and calcium sulfide (CaS), together with a number of other impurities:

$$Na_2SO_4 + CaCO_3 + 2C \rightarrow \underline{Na_2CO_3} + \underline{CaS} + 2CO_2.$$
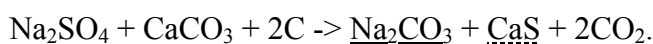
The black ash is dissolved by water and then concentrated by evaporation to produce commercially pure soda ash.

Prior to 1850, caustic soda (sodium hydroxide, NaOH) was not available commercially. Processes such as soap making and paper making which required caustic soda had to obtain

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[117] For detailed treatments of the history of the Leblanc process and the ammonia-soda process, see Derry and Williams (1960) and Clow and Clow (1992).

this by causticizing a solution of purchased soda ash with slacked lime (calcium hydroxide, $Ca(OH)_2$) in the causticization or lime soda process:

$$Na_2CO_3 + Ca(OH)_2 \rightarrow \underline{2NaOH} + \underline{CaCO_3}.$$
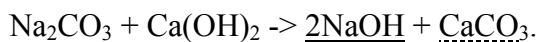
The flow diaphragm of the whole integration of the Leblanc and other related processes is given in Figure A-1. As the Leblanc process developed and got more integrated, it became the source of many other bulk inorganic materials and laid the foundations of the chemical industry for more than a century afterwards. As Hardie and Pratt (1966) put, "during the first half of the nineteenth century, and even later, the alkali industry was the chemical industry."
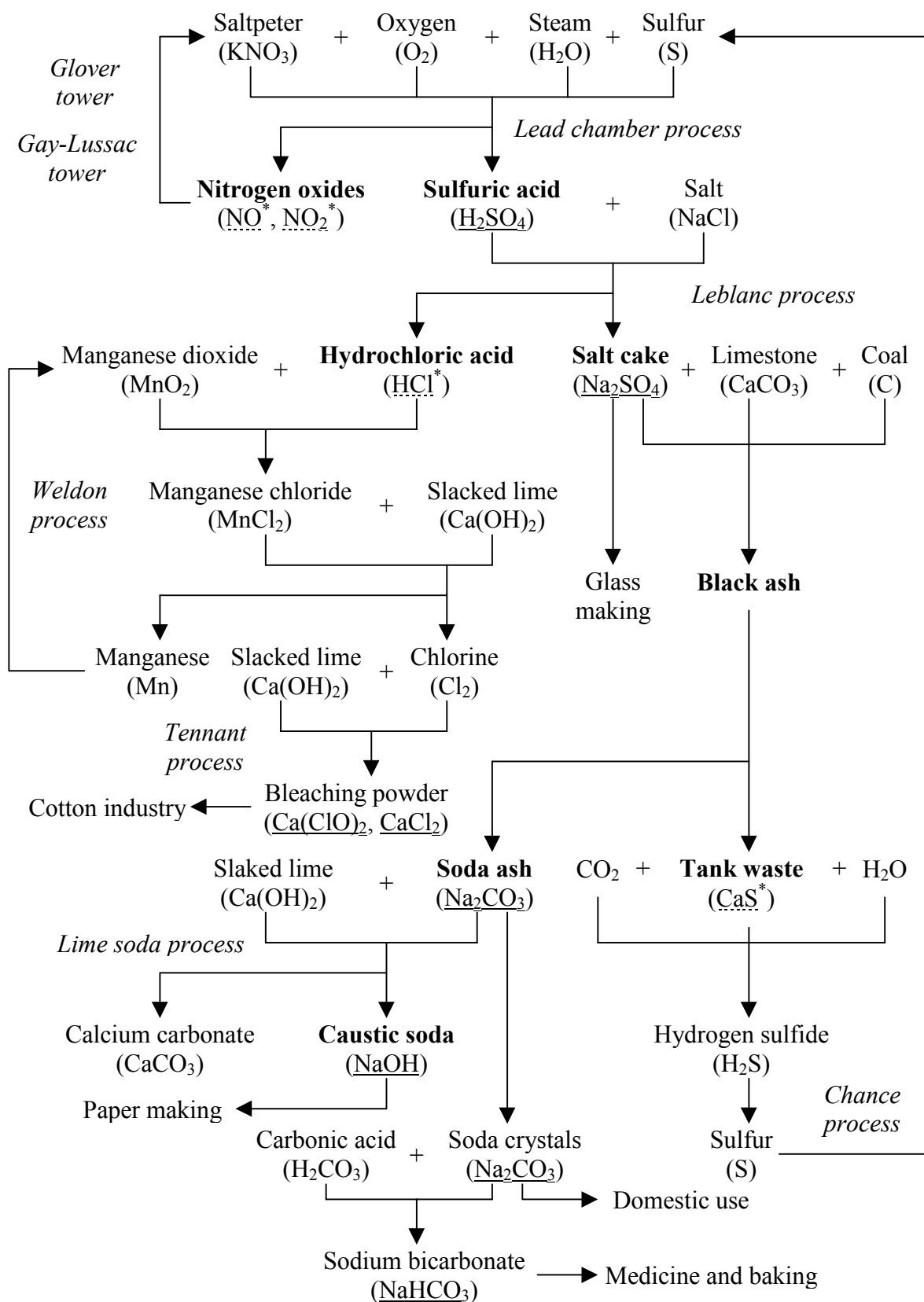
Saltpeter (KNO$_3$) + Oxygen (O$_2$) + Steam (H$_2$O) + Sulfur (S)

Glover tower

Gay-Lussac tower

Lead chamber process

Nitrogen oxides (NO*, NO$_2^*$)

Sulfuric acid (H$_2$SO$_4$) + Salt (NaCl)

Leblanc process

Manganese dioxide (MnO$_2$) + **Hydrochloric acid** (HCl*)

Salt cake (Na$_2$SO$_4$) + Limestone (CaCO$_3$) + Coal (C)

Weldon process

Manganese chloride (MnCl$_2$) + Slacked lime (Ca(OH)$_2$)

Glass making

Black ash

Manganese (Mn) Slacked lime (Ca(OH)$_2$) + Chlorine (Cl$_2$)

Tennant process

Cotton industry ← Bleaching powder (Ca(ClO)$_2$, CaCl$_2$)

Slaked lime (Ca(OH)$_2$) + **Soda ash** (Na$_2$CO$_3$)   CO$_2$ + **Tank waste** (CaS*) + H$_2$O

Lime soda process

Calcium carbonate (CaCO$_3$) **Caustic soda** (NaOH)

Hydrogen sulfide (H$_2$S)

Chance process

Paper making ←

Carbonic acid (H$_2$CO$_3$) + Soda crystals (Na$_2$CO$_3$)

Sulfur (S)

Domestic use

Sodium bicarbonate (NaHCO$_3$) → Medicine and baking

Figure A-1 Flow Diagram of the Leblanc Process

Based on Clow and Clow (1992).

336

A.1.1 Hydrogen Chloride Emissions

While caustic soda was produced in this way until the advent of electrolytic methods at the end of the century, the Leblanc process was very inefficient and produced large amounts of various wastes, which were initially dumped to air and water in the surrounding environment. The overwhelming waste products littered landscapes that had once been productive agriculturally and fouled the air with noxious gases. Among the most serious problems of the Leblanc process was the hydrogen chloride (HCl) gas. For each ton of sodium carbonate produced, about ¾ of a ton of hydrogen chloride was discharged. Initially, the hydrogen gas was passed directly up factory flues and into the atmosphere. In the presence of moisture, it was converted into rapidly into droplets of hydrochloric acid. These "noxious vapours" damaged agricultural property as well as posed a health hazard, and, because of their impact, the airborne emissions from alkali manufacture were called "the monster nuisance of all." In Britain, the effects of the growing alkali industry were so offensive, to the smell as well as to the sight, that the protection of the neighboring communities became a matter of urgent attention. Some of the major technological measures are given in Table A-1.

Table A-1 Regulation and Technological Development for the Treatment of Hydrogen Chloride Emissions from the Leblanc Process

Year	Regulatory and Technological Development
1787	Invention of the Leblanc process in France
1822	Start of the operation of the Leblanc process in Britain
1836	Invention of the Gossage tower to absorb hydrogen chloride
1863	Enactment of the Alkali Act, which required 95% reduction of the hydrogen chloride emission
1866	Development of the Weldon process for recovering manganese
1868	Development of the Deacon process for producing chlorine directly from hydrochloric acid with catalyst
1874	Amendment of the Alkali Act to impose an absolute emission standard of 0.2 g HCl/ft and to cover other gases

In 1836 the so-called Gossage tower was invented to prevent the escape of hydrogen chloride. When the hydrogen chloride gas was passed down through the tower, it was absorbed by a descending stream of water and converted into hydrochloric acid. By using coke or other porous material, the Gossage tower was significantly improved to such an extent that emissions of the hydrogen chloride gas could be significantly reduced if it was used properly. While hydrochloric acid began to be used for making bleaching powder and

for other purposes, it was made in such quantities that the supply of hydrochloric acid far outstripped demand. Moreover, since it was difficult and costly to transport the hydrochloric acid, its market was highly localized. Production costs were increased to condense the gaseous wastes, but the resultant liquid wastes still had to be disposed of in some way. Thus the economic incentive for alkali manufacturers to condense the hydrogen chloride gas effectively was very limited (Dingle, 1982). Although some manufactures had begun to condense the hydrogen chloride gas since the 1830s, others were still not doing so even in the late 1850s.

As the damage to vegetation was considerable while the abatement of fumes from alkali works came to be considered as practicable, the government introduced a bill in 1863, and the Act for the more effectual Condensation of Muriatic Acid Gas in Alkali Works came into force on 1 January next year for a trial period of five years. The act provided that alkali works were to condense 95 per cent of their hydrochloric acid gas by whatever method they preferred. A substantial decrease in pollution from hydrochloric acid was achieved rather quickly; by the end of 1964 the average escape of hydrogen chloride was reduced to 1.28 per cent, which was well within the legally permissible value of 5 per cent (Reed, 1998). This meant a reduction in the weekly escape of gas from roughly 4,000 tons in 1863 to 43 tons by the end of 1864.

Then the Alkali Act was made perpetual in 1868, and its scope was enlarged later. The Alkali Act of 1874 set a volumetric standard of 0.2 g of hydrochloric acid per cubic foot, and extended the definition of noxious gases to cover fumes from sulfuric, sulfurous, and nitric acids, hydrogen sulfide, and chlorine. All alkali manufacturers were required to use the "best practicable means" to prevent their discharges into the atmosphere or render them harmless when discharged (Reed, 1998). At that time 99 per cent recovery rates were common. By 1887 hydrochloric acid gas liberated into the atmosphere amounted to no more than 0.1 per cent of the total gas produced (Warren, 1980). Subsequently, the Alkali, etc. Works Regulation Act of 1881 set fixed standards for sulfur and nitrogen acid gases and included prohibition on deposit and drainage of all alkali sulfur waste[118].

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[118] In 1892 another Alkali Act extended the provisions of previous acts not only to all branches of the chemical industry, but also to a great number of other industries. Finally, a bill repealing previous alkali acts and replacing them by a single, consolidated act was introduced in 1894 and passed two years later (Haber, 1958).

**Table A-2 Emissions of Hydrogen Chloride from the Leblanc Plants in Britain**

Year	1863	1864	1874	1887
Regulation	5 %	-	0.2 g HCl/ft^3	-
Actual emissions	-	1.28 %	1 %	> 0.1 %

These introductions of regulations on emissions of hydrogen chloride made available a large amount of hydrochloric acid recovered from the Leblanc process. That encouraged technological developments for turning it into chlorine, which could be used directly for preparing bleach. The method used to manufacture chlorine was to oxidize hydrochloric acid by the use of manganese dioxide (MnO_2):

$$MnO_2 + 4HCl \rightarrow MnCl_2 + Cl_2 + 2H_2O.$$

This process, however, was wasteful and costly, because all the manganese as well as much of the chlorine as manganese chloride ($MnCl_2$) was lost. While the profitability of bleaching manufacture depended on the recovery of manganese and the maximization of the yield of chlorine, the residual liquid, which contained both hydrochloric acid and chlorine, caused great nuisance in watercourses and drains.

While manganese chloride could be neutralized with lime in the middle of the 1850s, a more efficient process was invented in 1866. The essential feature of the Weldon process was the use of excess lime, precipitating a mixture which contains manganese dioxide:

$$MnCl_2 + Ca(OH)_2 \rightarrow Mn(OH)_2 + CaCl_2$$

$$Mn(OH)_2 + \tfrac{1}{2}O_2 \rightarrow MnO_2 \text{ (recycled)} + H_2O.$$
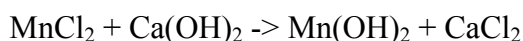
By constantly recirculating the slurry of manganese, the so-called Weldon mud, losses were kept within 4 to 10 per cent. For manufacturing one ton (1,016 kg) of bleaching powder, Weldon's process reduced the use of manganese from 16 cwt. (813 kg) to about 30 lb. (14 kg) by the late 1880s (Warren, 1980). While most of the manganese dioxide was recovered in this way, only one third of the available chlorine was liberated. Although it became possible to make a ton of bleaching powder from 45 to 50 cwt. of salt, instead of 60 cwt. as hitherto, much of the chlorine was still lost as the solid waste calcium chloride ($CaCl_2$).

A direct process for recovering manganese was developed in 1868. The Deacon process produced chlorine and water directly by passing hydrochloric acid gas and air over hot brickwork impregnated with a catalyst of copper chloride ($CuCl_2$).

$$4HCl + O_2 \text{ (air)} \xrightarrow{450\text{-}460°C,\ CuCl_2} 2Cl_2 + 2H_2O$$
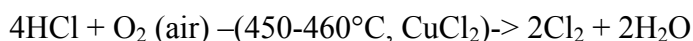
The Deacon process used salt more efficiently, as a ton of bleach could be made from 32 to 40 cwt. of salt. This process, however, had the disadvantage of requiring much more costly and complicated equipment than the Weldon process; a plant with a capacity of 100 tons of bleaching powder a week cost £13,000 whereas a comparable Weldon plant required £12,000 (Warren, 1980). As a result, despite its deficiencies, the Weldon process was adopted for most of the world's chlorine production up to the early year of the twentieth century.

Other countries took different approaches to legislation against atmospheric pollution by chemical and allied works, without specifying any mission standards (Haber, 1958). In France, an Imperial decree issued in 1810 empowered the prefect to control the building of certain works and to prescribe their layout. Industries were classified according to the impact they made on their surroundings, and the most noxious ones were banished to areas where they could do least harm. Chemical plants hence could not be built alongside dwellings, and the police had orders to enforce the decree. In the 1850s they were assisted by "Conseils d'Hygiène," which could investigate abuses and submit recommendations as to their removal to the Ministry of the Interior. In Belgium a royal decree laid down that official permission had to be granted before the building of a works emitting smoke and fumes could be started. As far as is known, however, no action was taken to implement it. Prussia had no regulations of any kind, but from 1861 onwards the public were entitled to state their objections to any new project threatening the amenities. In Basle, 1853, certain types of works, including those preparing chemicals, could not be established without the prior consent of the municipality. The city's sanitary inspector took energetic action against those found guilty of polluting streams and emitting gases and, if the need arouse, called in outside experts to investigate and offer advice.

A.1.2 Tank Waste

Another major waste produced in the Leblanc process was tank waste or alkali waste, of which the main constituent was calcium sulfide (CaS). Every ton of Leblanc soda ash was accompanied with about 1.4 tons of tank waste, an insoluble residue which remained after the soda ash had been extracted from the black ash. This smelly waste was dumped around the works, causing a great loss of space and polluted air and water. The Alkali Inspector estimated in the early 1880s that there were nearly 4.5 million tons of alkali waste in Lancashire alone and that it was increasing at the rate of 1,000 tons a day (Haber, 1958). In Widnes tips began to appear after 1865, and by 1888 it was estimated that 680 acres of land

had been covered with waste to a depth of from 8 to 25 feet, amounting to 9 million tons (Warren, 1980). The loss of sulfur, which consisted of 20 to 25 per cent of the tank waste, was considerable; indeed, it was well known that all the sulfur, in the form of sulfuric acid, employed in the production of Leblanc soda was lost. As sulfur was a substance that was expensively imported to make sulfuric acid, there was a great incentive to recover sulfur from the solid waste.

Attempts were made as early as in the 1830s to liberate hydrogen sulfide from calcium sulfide and to convert this gas to sulfurous acid (Table A-3). Other similar investigations in the 1860s achieved a measure of success. They converted calcium sulfide to hyposulfite and then precipitated sulfur by treatment with excess hydrochloric acid. It was claimed that 50 to 60 per cent of the available sulfur could be recovered, but in practice it was not possible to obtain more than 40 per cent. The process was expensive and troublesome and therefore was only in limited use (Haber, 1958).

Table A-3 Technological Developments for the Treatment of Tank Waste form the Leblanc Process

Year	Technological Development
1837	Gossage's attempts to recover sulfur from calcium sulfide
1862	Mond's and Schaffner's attempts to recover sulfur from calcium sulfide
1882	Invention of the Claus kiln
1888	Development of the Chance process for recovering sulfur from the waste of calcium sulfide

The decisive breakthrough came only in the 1880s. About forty years earlier it had been already realized that an excess of carbonic acid was necessary to liberate hydrogen sulfide from tank waste, but suitable equipment to accomplish this purpose was not successfully devised. Owing to the availability of improved machinery and appliances, an efficient apparatus was invented by Chance in 1888. In the Chance process, tank waste was made into slurry and passed through an arrangement of cylinders, "carbonators", where it came into contact with flue gas containing carbon dioxide. Hydrogen sulfide (H_2S) of the desired concentration was evolved in the last cylinder:

$$2CaS + H_2O + CO_2 -> Ca(SH)_2 + CaCO_3$$
$$Ca(SH)_2 + H_2O + CO_2 -> CaCO_3 + 2H_2S.$$
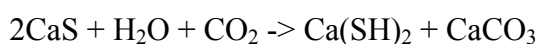
The hydrogen sulfide was then transferred to a kiln, which was invented by Claus in 1882, in which the catalytic action of ferric oxide liberated sulfur (S):

$$2H_2S + O_2 \rightarrow 2S \text{ (recycled)} + 2H_2O.$$
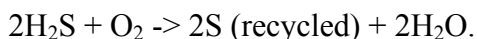
About 65 to 80 per cent of the sulfur in tank waste could be recovered by this process, with its purity very high. In 1893 the Chance-Claus process was worked in Britain on a scale sufficient to yield 35,000 tons of sulfur annually, which found a market for the manufacture of sulfuric acid.

A.1.3 Nitrogen Oxides Emissions

The production of sulfuric acid (H_2SO_4), which was an essential input for the Leblanc process, also created wastes. Since a considerable amount of sulfuric acid, which was difficult to transport, was required, most alkali manufacturers produced it by themselves. The sulfuric acid was originally prepared by heating sulfates such as alum and copperas and condensing the products of distillation. In 1737 sulfuric acid began to be produced by the Bell Chamber method, in which a mixture of sulfur and nitre (saltpeter, KNO_3) was burned in the necks of large glass vessels containing a little water. In 1746, based on essentially the same process, operations on an even larger scale started by replacing the glass vessels with lead boxes, the so-called lead chambers (Table A-4).

Table A-4 Technological Developments of the Treatment of Nitrogen Oxides Emissions from the Leblanc Process

Year	Technological Development
1746	Development of the Lead Chamber process
1827	Invention of the Gay-Lussac tower for recovering nitrogen oxides
1860	Invention of the Glover tower for recovering nitrogen oxides

The Lead Chamber method, however, was not a continuous process and wastefully emitted volumes of foul gases, as demonstrated in the following reactions:

$$SO_2 + NO_2 + H_2O \rightarrow \underline{H_2SO_4} + \underline{NO}^*$$
$$NO + 1/2O_2 \rightarrow \underline{NO_2}^*.$$
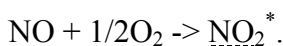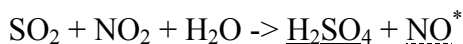
Successful operation of this process required that the waste gases of nitrogen oxides, i.e. nitric oxide (NO) and nitrogen dioxide (NO_2), which were originally carried away to the atmosphere, should be recovered. The process was greatly improved after the addition of the Gay-Lussac and the Glover towers, which made it possible to recycle these waste gases and thus to reduce the amount of saltpeter used in the catalyzing the reaction.

In 1827 Gay-Lussac developed the absorption tower that then made it possible to capture nitrogen oxides from the sulfuric acid chambers to produce nitrosyl sulfuric acid ($ONOSO_3H$), so-called "nitrous vitriol":

$$NO + NO_2 + 2H_2SO_4 \rightarrow 2ONOSO_3H + H_2O.$$
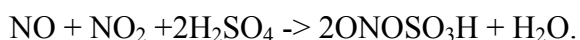
This improved not only the environmental but also the economic aspects of the process, as more than 50 per cent of the saltpeter used could be saved. However, it was not easy to return the active nitrogen oxides to the working chambers without diluting the solution of nitrosyl sulfuric acid in sulfuric acid with water. Because of the high cost of reconcentrating the diluted acid to commercial strength after the release of nitrogen oxides, most producers did not put the Gay-Lussac's invention into practice (Hocking, 1998). With nitrate of soda at £ 12 a ton in the early 1860s, it did not pay to collect and absorb the waste oxides of nitrogen (Warren, 1980).

The development of the Glover tower in 1860 allowed, in the same unit, both the release of nitrogen oxides by water dilution and the reconcentration of the acid via the hot gases generated from sulfur combustion:

$$ONOSO_3H + H_2O \rightarrow \underline{H_2SO_4} + \underline{HNO_2} \text{ (recycled).}$$

This additional innovation made the combination of the two towers more attractive to sulfuric acid producers: the Glover tower at the front-end unit, as a generator-concentrator, and the Gay-Lussac tower at the tail gas recovery unit. A rise in saltpeter prices between 1868 and 1870 led to the widespread adoption of the Glover-Gay-Lussac system in Britain (Haber, 1958).

A.1.4 Improvement of the Leblanc Process through End-of-Pipe Technologies

The years between 1860 and 1880 have been called the golden years of the Leblanc soda industry. The problems of waste and pollution were overcome gradually by technological improvements, which were basically end-of-pipe equipment. That also brought about great savings in raw materials at the same time. The Leblanc process had reached a modicum of efficiency as a self-contained series of interlocking processes by the 1880s. By the end of the 19th century, the cost of raw materials required to make a ton of soda ash had fallen to less than £2, as shown by the trends in the consumption of materials for the Leblanc process in Table A-5.

Table A-5 Consumption and Cost of Raw Materials for the Unit Production of Soda Ash in the Leblanc Process

	1861		1876		1886		1894	
	quant.	£ s. d.	quant.	£ s. d.	quant.	£ s. d.	quant.	£ s. d.
Pyrites	24 cwt.	1 15 0	17 cwt.	15 4	13.5 cwt.	9 3	-	-
Saltpeter	112 lb.	12 0	32 lb.	3 4	23 lb.	2 0	-	-
Salt	25 cwt.	10 0	25 cwt.	1 0 0	25 cwt.	10 0	-	-
Saltcake	-	-	-	-	-	-	33 cwt.	16 8
Limestone	30 cwt.	10 0	32 cwt.	4 4	26 cwt.	6 6	n/a	6 6
Coal (slack)	70 cwt.	1 1 0	60 cwt.	16 6	55 cwt.	12 6	n/a	13 9
Total	-	4 8 0	-	2 19 6	-	2 0 3	-	1 16 11

1861 and 1886: the costs are for a works in Lancashire.
1876: the costs are for a medium-sized business in Tyneside.
*Source: Haber (1958).*

A.2 Ammonia Soda Process

On the other hand, it was shown theoretically as early as 1811 that ammonium salts could be used to generate soda in the so-called ammonia soda process (Table A-6). Although the apparent simplicity of the process was quite attractive, for many years the complexity of the equipment and the problem of the loss of ammonia defeated attempts to develop it on an industrial scale.

Table A-6 Technological Developments of the Ammonia Soda Process

Year	Technological Development
1811	Theoretical investigation on the ammonia soda process by Fresnel
1861	Invention of the Solvay tower for the recovery of ammonia
1864	Operation of the first ammonia soda plant by Solvay
1872	Operation of the first ammonia soda plant in Britain
1880	Operation of the first ammonia soda plant in Germany
1884	Operation of the first ammonia soda plant in the United States

The flow diagram of the ammonia soda process is given in Figure A2-2. First, calcium carbonate ($CaCO_3$) is heated to give calcium oxide (CaO) and carbon dioxide (CO_2):

$$CaCO_3 \rightarrow CaO + CO_2.$$
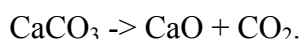
The carbon dioxide is then bubbled into a solution of sodium chloride ($NaCl$) in ammonia (NH_3), and sodium bicarbonate (sodium bicarbonate, $NaHCO_3$) is precipitated:

$$NaCl + NH_3 + CO_2 + H_2O \rightarrow NaHCO_3 + NH_4Cl.$$

The sodium bicarbonate is converted into soda ash (sodium carbonate, Na_2CO_3) by the application of heat:

$$2NaHCO_3 \rightarrow \underline{Na_2CO_3} + CO_2 + H_2O.$$

The ammonium chloride (NH_4Cl) is heated with calcium oxide, which is obtained from the first stage of the process, to regenerate the ammonia:

$$2NH_4Cl + CaO \text{ -(heat)-> } \underline{CaCl_2} + 2NH_3 \text{ (reuse)} + H_2O.$$

Coke ovens

Concentrated brine + Ammonia
(NaCl, H₂O)   (NH₃)

Coke + Limestone
(CaCO₃)

Ammoniacal salt
(NaCl, NH₃, H₂O)

Carbon dioxide
(CO₂)

Solvay tower

Ammonium chloride + Quicklime
(NH₄Cl)   (CaO)

Sodium bicarbonate
(NaHCO₃)

Heat

Ammonia
(NH₃)

Calcium chloride
(CaCl₂)

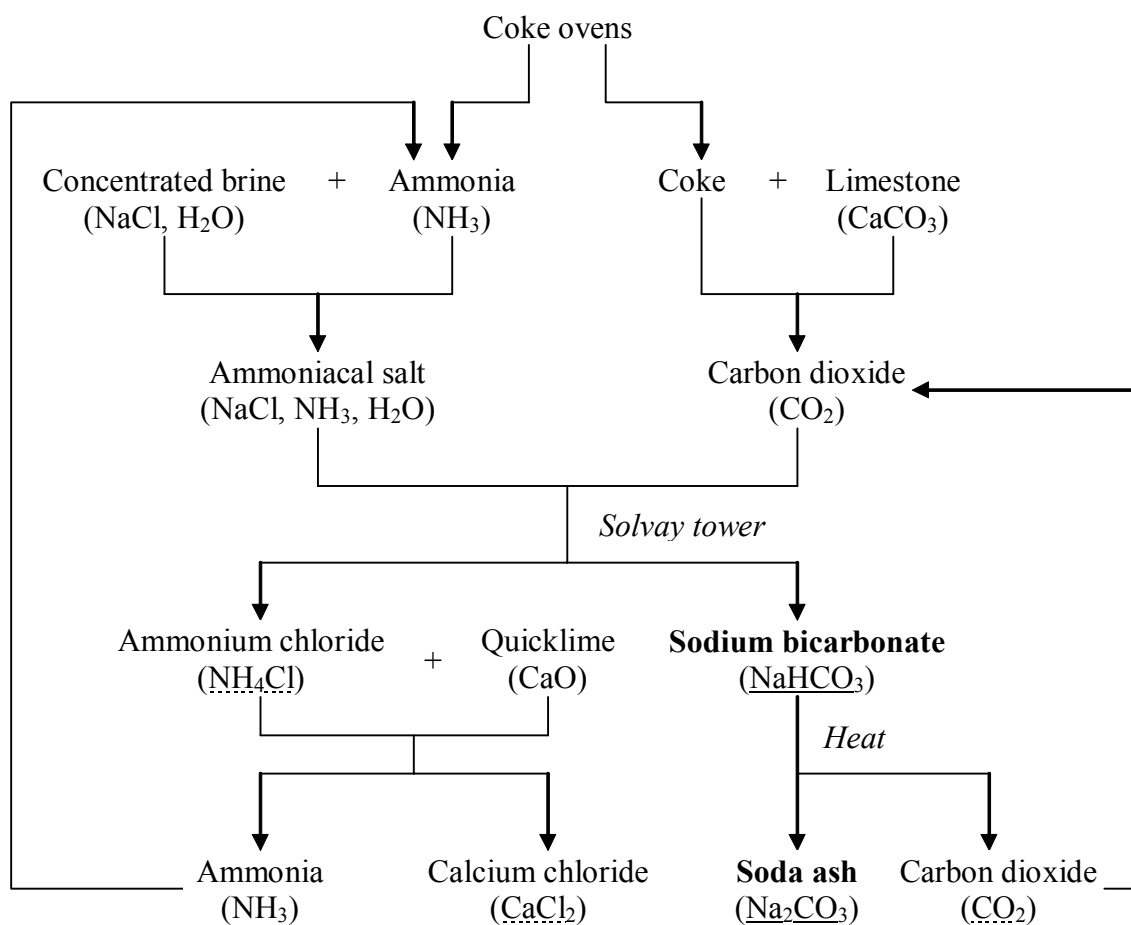**Soda ash**
(Na₂CO₃)

Carbon dioxide
(CO₂)

Figure A-2 Flow Diagram of the Ammonia-Soda Process
Based on Warren (1980).

A similar process was patented in Britain in 1838 and was practiced subsequently. A number of other chemical manufacturers in Britain, France, and Germany attempted to manufacture soda by this ammonia soda method, on which at least eight patents were granted between 1838 and the early 1860s (Warren, 1980). All the efforts, however, proved to be commercial failures, because of practical difficulties, namely, imperfect conversion of the salt

and, more importantly, the loss of ammonia, a light and volatile gas, which was relatively costly to manufacture.

In 1861 the Belgian chemist, Ernst Solvay designed a tower to recover ammonia successfully. In the so-called Solvay tower, a solution of ammoniacal salt was met by an up current of carbon dioxide. By periodic withdrawal of part of the solution from the Solvay tower and its replacement by a fresh solution of ammoniacal salt, the process was made continuous. Ammonia was initially provided from gasworks, but the supply was later increased by installation of by-product coke ovens. Solvay's work on this involved the scrubbing of by-product gases and led to the development of the Semet-Solvay oven design. His other developments included improvements in the kilns for liberating carbon dioxide from limestone and for calcining the sodium bicarbonate. Solvay formed a company in Belgium to work the process, and the first works was built in 1863. It was four years before the Solvay process was finally working satisfactorily.

The ammonia soda process was licensed and introduced into Britain in 1873, and the soda production started one year later. The initial failure of the ammonia soda process was due to the lack of an efficient method of recovering ammonia from the mother liquor and the inability to minimize ammonia losses during operation. Since ammonia was a comparatively expensive commodity, the heavy losses of ammonia in the cycle made it impossible for the process to compete with the Leblanc process. A column distiller designed by Mond and built in 1883 made the recovery of ammonia possible by reacting ammonium chloride with quicklime, leaving calcium chloride as waste material (Hou, 1942). As a result, the loss of ammonia in the ammonia soda process was almost halved between 1862 and 1887 (Warren, 1980).

The ammonia soda process, however, had a weakness that the chlorine used in the salt remained locked up in the calcium chloride ($CaCl_2$). It had to be dumped as solid waste, although on a very much smaller scale than that of the tank waste of the Leblanc process. In 1886 Mond developed a method to make it possible to recover the chlorine by passing calcium chloride over a nickel oxide catalyst. In practice, his method was still ineffective and was superseded by Carl Höpfner's process, in which the chlorine was recovered as zinc chloride and then decomposed electrolytically, making it possible to produce bleaching powder. In 1895 the Löwig process was adopted for making caustic soda by furnacing soda

346

ash with ferric oxide[119] and separating the resulting sodium ferrite, by leaching with water, into caustic soda and ferric oxide[120], which was reused in the process (Warren, 1980).

The ammonia soda process was to a high degree self-contained, and the raw materials of brine and ammonia were readily available. Less fuel was used than in the Leblanc process, and no sulfur or nitre was involved. The ammonia soda process hence had enormous advantages over the Leblanc process. A comparison of costs between the Leblanc and the ammonia soda processes in 1872 is given in Table A-7.

Table A-7 Production Costs of the Leblanc and Ammonia Soda Processes in 1872

Materials and overheads	Leblanc process[a]		Ammonia soda process[b]	
	Quantity per ton	Cost per ton £ s. d.	Quantity per ton	Cost per ton £ s. d.
Pyrites	17.5 cwt.[c]	1 10 8	-	-
Saltpeter	56 lb.	7 0	-	-
Salt	29 cwt.	12 4	40 cwt. (brine)	1 6
Limestone	35 cwt.	11 4	44 cwt.	14 4
Coal (slack)	88 cwt.	1 15 2	39 cwt.	17 3
Coke	-	-	5.5 cwt.	5 0
Ammonia sulfate	-	-	202 lb.	1 16 0
Total material costs	-	4 16 6	-	3 14 1
Wages	-	1 12 0	-	15 0
Salaries, rents, rates	-	1 5 0	-	14 8
Insurance	-	14 0	-	11 0
Packages	-	18 0	-	1 2 0
Freight to Liverpool	-	2 0	-	3 6
Royalty	-	-	-	8 0
Grand total	-	9 7 0	-	7 8 3

(55% Na_2O equivalent)
a: a plant at Widnes
b: a projected plant at Winsford
c: 1 hundredweight (cwt.) = 112 pounds (lbs.) = 50.8 kg
Source: Cohen (1956).

He drew on his experience with Hutchinson at Widnes for the Leblanc figures and on Solvay and Mond for the ammonia soda estimates. The table shows that there was a difference of nearly £2 per ton in favor of the ammonia soda process. As regards the capital investment, it was estimated that an ammonia soda plant with a weekly output of 60 tons cost

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[119] $Na_2CO_3 + Fe_2O_3 \rightarrow 2NaFeO_3 + CO_2$
[120] $2NaFeO_2 + H_2O \rightarrow 2NaOH + Fe_2O_3$

£13,500 and a Leblanc installation of the same capacity, £10,000 (Haber, 1958). Assuming plants were operated for 50 weeks a year, their annual output was

60 tons/week x 50 weeks/year = 3,000 tons/year.

Hence the annual saving in operating cost was

£2/ton x 3,000 tons/year = £6,000/year.

On the other hand, the difference in capital investment between the ammonia soda and the Leblanc processes was

£13,500 – £10,000 = £3,500.

Thus, it did not take one year to recover the initial excess investment in the ammonia process.

As another cost estimation made in 1894 shows in Table A-8, the difference in operating costs between the two processes remained significantly wide and, as far as the Leblanc process was concerned, irreducible. Accordingly, the Leblanc process started to experience severe competition from the ammonia soda process.

Table A-8 Production Costs of the Leblanc and Ammonia Soda Processes in 1894

	Leblanc process[a]	Ammonia soda process[b]
	£ s. d.	£ s. d.
Raw materials	1 16 11	1 1 6
Saltcake	16 8	-
Brine and pumping charges	-	9
Limestone	6 6	4 6
Slack	13 9	9 0
Coke	-	1 3
Loss of ammonia	-	6 0
Wages	14 0	14 3
Management, laboratory, and office expenses	2 0	3 6
Repairs, wages, and materials	4 6	5 6
General charges	4 6	14 0
Total	£3 1 11	£2 18 9

a: 55% Na_2O equivalent
b: 58% Na_2O equivalent
Source: Warren (1980).

Significantly, however, many alkali producers in Britain continued to use the Leblanc process. The British Leblanc soda production increased throughout the 1870s, with the highest point achieved in 1880 (Table A-9). Thereafter, the Leblanc process maintained its position as the dominant technology for the British chlor-alkali industry, although its

production shrank by 10 per cent from 1884 to 1994, from 380,000 tons to 340,000 tons in 1894.

Table A-9 Soda Productions by the Leblanc and the Ammonia Soda Processes in Britain

Year	Leblanc process			Ammonia soda process[d]
	Soda ash[a]	Caustic soda	Total[c]	
1874	-	-	-	800
1875	-	-	-	2,400
1878	196,900	100,800[b]	330,460	11,100
1880	266,100	106,400	407,080	18,800
1882	233,200	116,900	388,093	-
1884	204,100	141,600	391,720	-
1885	-	-	-	77,500
1886	165,900	153,900	369,818	-
1890	-	-	-	179,700
1894	-	-	340,000	181,000
1898	-	-	-	181,000
1903	-	-	-	240,000

Figures are expressed in British tons.
a: as 48 % Na_2O
b: Including production by non-members of the Alkali Association. (Later statistics of the Leblanc soda industry have not been published.)
c: Total production of the Leblanc process was calculated as equivalent to soda ash[121].
d: Production figures of the ammonia soda process are those of Brunner, Mond & Co.
Sources: 1894: Warren (1980). All other years: Haber (1958).

Operators of the Leblanc process made heavy capital investments in plants and had strong incentives to continuing to use it. Over 90 per cent of the British Leblanc manufacturers combined forces to form the United Alkali Company (UAC) in 1890 and began to modernize their obsolescent plants. The new company established a Central Research Laboratory in 1891, which was unusual in any chemical company at that time except for the German dyestuffs industry[122], to conduct a research program to improve the efficiency of the Leblanc process. Hence for a limited period of time UAC could remain viable and increasingly efficient by reducing its output of soda ash and maximizing its output of sulfuric acid, bleach and caustic soda, and the Leblanc process was still the dominant technology at the end of the 19th century.

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[121] As the reaction involved is $Na_2CO_3 + Ca(OH)_2 -> 2NaOH + CaCO_3$, 1 molecule of soda ash is consumed to produce 2 molecules of caustic soda. Since the molecular weight of soda ash, Na_2CO_3, is 106 and that of caustic soda, NaOH, is 40, 1 ton of caustic soda is equivalent to $106/(40 \times 2) = 1.325$ tons of soda ash.

In contrast, the manufacture of soda in France was transformed by the introduction of the ammonia soda process, as shown in Table A-10. While 30 to 40 Leblanc plants produced about 50,000 to 60,000 tonnes of alkali at around the time of 1870, only three plants operated in 1899, whose combined output had declined significantly to 20,000 tonnes. On the other hand, soda production by the ammonia-soda process increased rapidly. Its share in soda production in France surpassed that of the Leblanc process in the middle of the 1880s and had reached more than 80 % by 1993. Solvay, in particular, quickly obtained a dominant position in operating the ammonia soda process; by the end of the century, the company had accounted for over four fifths of the French ammonia soda production.

Table A-10 Soda Productions by the Leblanc and the Ammonia Soda Processes in France

Year	Leblanc process	Ammonia soda process	Total
1874	56,000 (77 %)	17,000 (23 %)	73,000
1880	55,000 (56 %)	44,000 (44 %)	99,000
1883	50,000 (53 %)	44,000 (47 %)	94,000
1888	32,000 (25 %)	97,000 (75 %)	129,000
1893	27,000 (18 %)	120,000 (82 %)	147,000
1896	22,000 (12 %)	168,000 (88 %)	190,000
1899	20,000 (9 %)	195,000 (91 %)	215,000[a]
1902	15,000 (7 %)	215,000 (93 %)	230,000
1905	6,000 (2 %)	270,000 (98 %)	276,000[b]

Figures are expressed in metric tonnes.
a: 2,000 tonnes of electrolytic alkali were made in addition.
b: 4,000 tonnes of electrolytic alkali were made in addition.
Sources: Ogburn and Jaffé (1929), Haber (1958).

Table A-11 shows the world trends in soda production by the Leblanc and the ammonia soda processes from the middle of the 19th century to 1940. From the early 19th century, the alkali industry was a growth industry in the world. In 1863 soda ash production reached an estimated 300,000 tons, all of which were produced by the Leblanc process. The world production had passed 1 million tons by 1890, by which time the ammonia soda process had stolen the edge over the Leblanc process in output. In 1900, of the world total production of 1,500,000 tons, only 200,000 tons were produced by the Leblanc process. In 1920 the last Leblanc plant in Britain was closed whereas by that time the production by the ammonia soda process had already surpassed three million tons.

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[122] Meyer-Thurow (1982) discusses the decisive role that scientific research played in the development of the

Table A-11 World Soda Production by the Leblanc and the Ammonia Soda Processes

Year	Leblanc Process	Ammonia Soda Process	Total
1850	150,000 (100 %)	0	150,000
1863	300,000 (100 %)	0	300,000
1865	374,000 (100 %)	300 (-)	375,000
1870	447,000 (99 %)	2,600 (1 %)	450,000
1875	495,000 (94 %)	30,000 (6 %)	525,000
1880	545,000 (80 %)	136,000 (20 %)	681,000
1885	435,000 (54 %)	365,000 (46 %)	800,000
1890	390,000 (38 %)	633,000 (62 %)	1,023,000
1895	265,000 (21 %)	985,000 (79 %)	1,250,000
1990	200,000 (13 %)	1,300,000 (87 %)	1,500,000
1902	150,000 (9 %)	1,610,000 (91 %)	1,760,000
1905	150,000 (8 %)	1,750,000 (92 %)	1,900,000
1911	130,000 (6 %)	1,900,000 (94 %)	2,030,000
1913	50,000 (2 %)	2,800,000 (98 %)	2,850,000
1916	negligible	3,000,000 (100 %)	3,000,000
1923	0	3,500,000 (100 %)	3,500,000
1927	0	4,100,000 (100 %)	4,100,000
1932	0	5,000,000 (100 %)	5,000,000
1940	0	7,000,000 (100 %)	7,000,000

Figures are expressed in US tons.
Source: Hou (1942).

A.3 Concluding Remark

In this Appendix, we made a preliminary analysis of different courses of technological change between the British and the French chlor-alkali industries in the late 19th century. In Britain, the Leblanc process had become the dominant technology for alkali production by the middle of the 19th century. Following the introduction of the Alkali Act in 1863, various types of technological measures were developed to reduce pollutant emissions and wastes, such as hydrogen chloride, tank waste, and nitrogen oxides. Without changing the chemical reactions involving the main products, these technological measures were basically those of the end-of-pipe type. The performance of these technologies was improved gradually, and eventually the Leblanc process was made more efficient, as fewer inputs were consumed and more wastes were recycled. Thus the Leblanc process continued to be the dominant production technology in Britain, even after the successful industrial operation of a new production process, that is,

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dyestuffs industry in Germany.

the ammonia soda process. Following its successful invention in the 1860s, the new ammonia soda process became more efficient than the Leblanc process as early as the 1870s and came to dominate the chlor-alkali industry. In other countries such as France, the Leblanc process was replaced with the ammonia soda process rather quickly while the Leblanc process remained as a major production technology in the British alkali industry for a long time.

Although this case of technological change needs more detailed and careful analysis, it suggests the possibility that environmental regulations on pollutant emissions in Britain induced alkali producers to develop end-of-pipe technologies for pollution reduction, which in effect delayed the diffusion of the newly developed, more efficient ammonia soda process. The chemical processes, however, were only to be superseded by the electrolytic routes, including the mercury process and the diaphragm process, which at that time were rapidly becoming established, concomitant with the development of the large-scale methods for the production and distribution of electricity.

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Samenvatting

Dit proefschrift gaat over de invloed van milieureguleringen op technologische verandering in de chloor- en alkali-industrie in Japan en West-Europa.

In hoofdstuk 2 wordt een overzicht gegeven van eerder uitgevoerd theoretisch en empirisch onderzoek naar de effecten van milieureguleringen op technologische verandering. De kritiek in dit proefschrift spitst zich toe op de manier waarop deze studies technologische verandering behandelen waar het gaat om het terugdringen van milieuvervuiling. Bij de analyse van de technologische invloed van milieuregulereingen werd in eerdere publicaties onder andere onvoldoende aandacht besteed aan een cruciaal onderscheid tussen end-of-pipe technologieën en schone technologieën. De meeste theoretische modellen gaan uit van technologieën die zijn gericht op incrementele emissievermindering bij stijgende kosten van marginale vervuilingsbestrijding. Effectief betekent dit dat de technologieën die in de modellen worden gebruikt, eigenlijk end-of-pipe technologieën zijn. Anderzijds is in vrijwel geen enkele studie aandacht besteed aan de mogelijkheid om emissies tegen te gaan vanuit het productieproces door het gebruik van schone technologieën. Bij het gebruik van schone technologieën komen geen emissies vrij. De marginale analyse van de kostencurve van vervuilingsbestrijding, die veelvuldig wordt toegepast in theoretische modellen, is daarom ongeschikt als we uitgaan van het bestaan van schone technologieën.

Ook hebben de meeste empirische studies geen aandacht besteed aan het onderscheid tussen de verschillende soorten technologieën bij het bestuderen van de effecten van milieureguleringen op technologische verandering. Een groot aantal van deze studies kijken naar patenten als indicator van innovaties op een hoog aggregatieniveau en zijn dan ook vooral gericht op end-of-pipe technologieën, zoals emissiebehandelingstechnieken en filters, of op alle soorten innovaties die de onderzoekers waren tegengekomen. Zonder gedetailleerde informatie over specifieke productieprocessen is het namelijk erg moeilijk om een duidelijk beeld te krijgen van de verscheidenheid aan schone technologieën. Door schone technologieën buiten beschouwing te laten, wordt de verscheidenheid aan technologische veranderingen t.b.v. vervuilingsbestrijding te sterk beperkt tot de groep van end-of-pipe technologieën. Aan de andere kant zal, als we alle soorten innovaties in aanmerking nemen, de groep ook technologieën omvatten die weinig te maken hebben met ecologische aspecten en te breed zijn om te kunnen worden aangeduid als 'groene' innovaties. Naar onze mening is

een gedetailleerde studie van de aard en het karakter van technologieën belangrijk voor een gedegen analyse van groene innovatie.

Daarna tonen we aan dat er in principe twee soorten technologie zijn voor de vermindering van emissies als gevolg van bedrijfsactiviteiten: end-of-pipe technologieën en schone technologieën. End-of-pipe technologieën zijn gericht op emissiereductie aan het eind van de productiefaciliteiten, en hebben geen invloed op de reacties waarbij het hoofdprodukt wordt geproduceerd. Bij schone technologieën worden de belangrijkste procesreacties vervangen door andere reacties, en worden ongewenste bijprodukten die vrijkomen tijdens het productieproces, op effectieve wijze teniet gedaan. In het verleden zijn veelal end-of-pipe technologieën ontwikkeld om emissies van industriële processen te reduceren. Deze technologieën behandelen milieuverontreinigende stoffen aan het eind van de emissiepijp zonder het productieproces te beïnvloeden, en zijn relatief eenvoudig te installeren en te gebruiken; er zijn dan ook vele soorten end-of-pipe technologieën in de industrie. End-of-pipe technologieën maken de productie duurder vanwege de extra kosten die nodig zijn om ze te installeren aan het eind van de productiefaciliteiten. Dit in tegenstelling tot schone technologieën, die de vorming van milieuverontreinigende stoffen vanaf het begin voorkomen door alle faciliteiten te veranderen en zo het productieproces kunnen verbeteren en op termijn de productiekosten kunnen verlagen.

In het analytisch raamwerk dat wij hebben ontwikkeld om de effecten van milieureguleringen op technologische veranderen te bestuderen, wordt dit onderscheid tussen end-of-pipe en schone technologie wel gemaakt. Op basis van onze bevindingen stellen wij dat verschillende milieureguleringen kunnen leiden tot uiteenlopende soorten technologische verandering. Bij relatief soepele milieureguleringen zullen bedrijven sneller overgaan op end-of-pipe technologieën, die – aanvankelijk althans – waarschijnlijk minder duur zullen uitvallen dan schone technologieën. Dit zal weer leiden tot meer investeringen in de bestaande productietechnologie, waarbij de emissies naar verwachting worden gereduceerd door de installatie van end-of-pipe technologieën. Bedrijven zullen hierdoor niet snel overgaan op schone technologieën, zelfs wanneer later blijkt dat schone technologieën efficiënter zijn in de productie; bedrijven zullen geneigd zijn deze bestaande fabrieken te laten voortbestaan tot het eind van hun levensduur tenzij de schone technologieën extreem efficiënt blijken te zijn.

Anderzijds kunnen bedrijven niet voldoen aan strenge reguleringen door uitsluitend end-of-pipe technologieën te installeren. Ze zullen dus bestaande productietechnologieën

moeten vervangen en investeren in R&D t.b.v. innovaties gericht op schone technologieën. Hoewel er doorgaans diverse schone technologieën voorhanden zijn, zullen bedrijven bij strenge regels waaraan ze op korte termijn moeten voldoen, echter worden 'gedwongen' vroegtijdig beslissingen te nemen over alternatieve technologieën, die op de langere termijn misschien niet de meest geschikte blijken te zijn. Het vervangen van deze technologieën door een betere technologie later betekent extra kosten.

We gebruiken dit analytische raamwerk in onze empirische studie van de chlooralkali-industrie. In hoofdstuk 3 gaan we meer dan honderd jaar terug in de geschiedenis van de technologische evolutie in de chloor- en alkali-industrie. Sinds het begin van de negentiende eeuw hebben zich bij de productietechnologieën die werden gebruikt in de chloor- en alkali-industrie een aantal grote innovaties voorgedaan in de vorm van chemische en electrolytische processen. Wat betreft de laatste zien we dat aan het begin van de jaren zeventig de kwiktechnologie het meest werd gebruikt in West-Europa en Japan, voordat hier voor het eerst sprake was van milieureguleringen voor kwikemissies. Diverse bedrijven in West-Europa en Japan hadden hoogwaardige technologieën ontwikkeld voor deze kwiktechnologie, die in de meeste chloor-alkali-fabrieken werd gebruikt. In beide gebieden waren dus bedrijven actief die vóór de introductie van milieureguleringen even innovatief waren wat betreft chloor-alkali productietechnologieën. Dit wijst erop dat de technologische omstandigheden in deze industrie in West-Europa en Japan, aanvankelijk vergelijkbaar waren.

Sinds de milieureguleringen voor het verminderen van kwikemissies afkomstig van chloor-alkali-fabrieken in het begin van de jaren zeventig lopen de technologische veranderingspaden in Japan en West-Europa echter uiteen. In de overige hoofdstukken van dit proefschrift zien we hoe een verschillend milieubeleid heeft bijgedragen tot de verschillende technologische situaties in de twee gebieden. In hoofstuk 4 kijken we naar Japan, waar de regering de chloor- en alkali-industrie via strikte regelgeving dwong over te schakelen op andere processen, waardoor innovatieve bedrijven werden aangespoord alternatieve schone technologieën te ontwikkelen. Deze strenge regelgeving, aanvankelijk vastgelegd in een strak tijdsschema, leidde ertoe dat een groot aantal producenten van chloor-alkali overging op het diafragmaproces, dat in die tijd relatief goed bleek te functioneren vergeleken met het ionwisselingsmembraanproces, dat toen nog in de kinderschoenen stond. Later bleek het diafragmaproces echter een zeer inefficiënte technologie, minder efficiënt dan het membraanproces dat in rap tempo werd verbeterd. Op basis van nieuwe informatie over deze technologische ontwikkelingen vanuit de industrie onderbraken de Japanse autoriteiten

tijdelijk de implementatie van de oorspronkelijke regulering in afwachting van verdere ontwikkelingen in het membraanproces. Na een evaluatie door experts van de haalbaarheid van het membraanproces in de industrie werd bedrijven meer tijd gegeven hun processen aan te passen. Door deze wijziging in de regelgeving kregen de overgebleven kwikprocesfabrieken de gelegenheid direct over te schakelen op het membraanproces, die zich sindsdien zowel economisch als ecologisch heeft ontwikkeld tot de beste technologie. De kwikprocesfabrieken die eerder waren overgegaan op het diafragmaproces, moesten echter weer overschakelen op het membraanproces. Dit leidde tot aanzienlijke investeringen in fabrieken waarbij bestaande processen ruim voor het einde van hun eigenlijke levensduur buiten werking werden gesteld.

In hoofdstuk 5 komen de technologische veranderingen in de chloor- en alkali-industrie in West-Europa aan de orde. Hier werden minder strenge reguleringen in de vorm van emissiestandaarden opgelegd aan chloor-alkali fabrieken die hun kwikemissies moesten verminderen. De meeste bedrijven in deze industrie kozen voor end-of-pipe technologieën, die veel goedkoper waren en meer zekerheid boden dan nieuwe, kostbare schone technologieën waarvan het effect niet duidelijk was. Het grotendeel van de kwikprocesbedrijven ging over op de ontwikkeling en installatie van end-of-pipe technologieën teneinde te voldoen aan de regels voor de reductie van kwikemissies. Er werden veel chloor-alkalifabrieken gebouwd die functioneerden op basis van kwikprocessen en waren uitgerust met end-of-pipe technologieën om vervuiling tegen te gaan. Deze fabrieken hebben het eind van hun fysieke levensduur, die normaal gesproken zo'n 40 jaar of langer is, nog niet bereikt. Daarom zijn de chloor-alkali producenten in WestEuropa ook nu nog sterk geneigd deze kwikfabrieken te blijven gebruiken, hoewel het membraanproces de meest efficiënte productietechnologie is gebleken en in andere landen wordt toegepast, ook in veel industrialiserende landen. Kortom, de betrekkelijk soepele milieureguleringen in West-Europa hebben geleid tot aanzienlijke vooruitgang in end-of-pipe technologieën om kwikemissies te reduceren, maar hebben ook de ontwikkeling van het membraanproces ontmoedigd, een voorbeeld bij uitstek van een schone technologie, ook al waren er een aantal innovatieve bedrijven die zich richtten op chloor-alkali productietechnologieën. Omdat veel chloor-alkali fabrieken, uitgerust met end-of-pipe technologieën om kwikemissies te reduceren, het kwikproces zijn blijven gebruiken, is de diffusie van het efficiënte membraanproces langzaam en beperkt geweest.

Tenslotte worden in hoofdstuk 6 een samenvatting en de conclusies van ons onderzoek gepresenteerd. Relatief soepele milieureguleringen gericht op betere vervuilingsbestrijding van industriële activiteiten, bevorderen innovaties van end-of-pipe technologieën. In feite zou dit de levensduur van bestaande, acherhaalde productieprocessen kunnen verlengen. Strenge regelgeving bevordert weliswaar innovatieve activiteiten ten behoeve van schone technologieën maar kunnen tevens leiden tot een vroegtijdig keuze voor ongeschikte technologieën. Alleen wanneer in geval van strenge regelgeving de implementatietijd flexibel wordt gehanteerd en ruimte wordt geboden voor technologische experimenten, kunnen bedrijven op efficiënte wijze schone technologieën ontwikkelen en breed toepassen. Op basis van onze bevinding m.b.t. de uiteenlopende effecten van milieureguleringen op technologische verandering gaat dit proefschrift ook in op implicaties voor bedrijfsstrategieën, besluitvorming, en beleidsarrangementen die bedrijven helpen over te schakelen van end-of-pipe op schone technologieën.

Curriculum Vitae

Masaru Yarime was born in Akita, Japan on 3 October 1969. He received his Bachelor of Science in Chemical Engineering from the University of Tokyo, Tokyo, Japan in 1993 and Master of Science in Chemical Engineering from the California Institute of Technology, Pasadena, California, the United States in 1995. He is currently a Research Associate of the Research Center for Advanced Economic Engineering of the University of Tokyo. His research interests include Economics of Technological Change, Environmental Economics, Science and Technology Policy, and University-Industry Collaboration.