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POLICY VS. CONSUMER PRESSURE: INNOVATION AND DIFFUSION OF ALTERNATIVE BLEACHING TECHNOLOGIES IN THE PULP INDUSTRY

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ABSTRACT

In the late 1980s and early 1990s, concern over dioxin in both paper products and wastewater led to the development of techniques that reduced the use of chlorine in the pulp industry. Both regulatory and consumer pressure motivated this change. We use patent data to examine the evolution of two completing bleaching technologies in five major paper-producing countries, both of which reduce the use of chlorine in the pulping process. By the end of the 1990s, nearly all pulp production in these countries used one of these technologies. Unlike other papers using patents to study environmentally-friendly innovation, we focus on a process innovation, rather than on end-of-the-pipe solutions to pollution. Moreover, while previous studies emphasize the importance of regulation for inducing innovation, here we find substantial innovation occurring before regulations were in place. Instead, pressure from consumers to reduce the chlorine content of paper drives the first round of innovation. However, while some companies choose to adopt these technologies in response to consumer pressure, not all firms will differentiate their product in this way. Thus, governments need to regulate if their goal is broad diffusion of the environmental technology.

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This paper uses patent data to examine the evolution of elemental chlorine free (ECF) and totally chlorine free (TCF) technologies used by the pulp and paper industry. In both cases, the technologies reduce (or eliminate) the use of chlorine in the bleaching stage of pulp production. Use of these technologies grew rapidly during the 1990s, beginning in the Nordic countries (Finland, Norway, and Sweden) and then spreading to the United States and Canada. One advantage of studying innovation on these technologies is that they are process technologies. Most previous studies of environmental innovation using patents examine end-of-pipe pollution control technologies, as it is easier to identify patents for specific end-of-pipe technologies than for modifications to the production process.[1] However, for ECF and TCF technologies, there are well-defined patent classes related to these processes. Thus, this study is among the first to study the evolution of a process environmental technology using patent data.

Another advantage of studying ECF and TCF technologies is that it offers a window into the effects of different policy regimes on innovation. While there is a large theoretical literature on the different effects of various policy instruments on innovation, few empirical studies compare innovation under different types of policy incentives.[2] Here, at least three types of policies are relevant. First, in each country, command and control regulation limits the amount of chlorine releases from the pulp bleaching process. In the U.S. and Canada, national (or provincial, in the case of Canada) standards set the basic limits on chlorine usage. There is some variation across plants, as each plant operates under an environmental permit. In the Nordic countries, decisions on allowable emissions are made on a plant-by-plant basis as part of a plant permitting system.

[1] Examples include Popp (2003, 2006), Taylor *et al.* (2003), and Lanjouw and Mody (1996).
[2] The theoretical literature includes Magat (1978), Milliman and Prince (1989), and Fisher *et al*. (2003). These papers predict that market-based environmental policies, such as a tax or permit trading, will induce more innovation than a comparable command and control policy.

In addition to these two regulatory systems, some European mills also chose to adopt TCF production because of consumer preferences in the European market (Reinstaller 2005). Much of the early demand for reductions in chlorine came from consumers, rather than from regulators. Chlorine used in bleaching not only affects wastewater released from mills, but also persists in the final paper product (Galloway, Helminen, and Carter, 1989). Concerns over chlorine in paper products led to increased demand for chlorine-free paper in the late 1980s and early 1990s. A growing literature in environmental policy looks at the possibility of voluntary provision of environmental quality by firms (see, for example, Lyon and Maxwell, 2002). One reason often proposed for such behavior is that firms are responding to consumer demand. This study considers the potential effects of such demand-side influences on environmentally-friendly innovation. In addition, we ask whether product labeling requirements allowing consumers to identify paper made without chlorine magnify demand-side influences by making information about paper quality more readily available to consumers.

Finally, this paper also offers a look at the links between environmental regulation and innovation across countries. In previous work, Popp (2006) finds that innovations for sulfur dioxide and nitrogen oxide control at coal-fired power plants responds primarily to domestic regulation. Looking at patents in these fields, that paper finds increases in patents assigned to own-country inventors when a country passes or strengthens environmental regulations for power plants, but little increase in innovations from other countries. An important question is whether this finding is robust to other technologies, or is unique to the electric power industry. One important difference between the electric power industry and pulp and paper is that there is little trade in electric power. Moreover, regulations affecting air pollution from power production focus on the location of production. In contrast, while regulations addressing chlorine in pulp and paper production do focus on the location of production, the final paper product is a traded commodity. As such, consumer preferences for chlorine-free paper in trading partner countries may influence innovation in producer countries.

I. The Pulp & Paper Industry

The pulp and paper industry consists of two main types of firms. Pulp and paper mills process raw wood fiber or recycled fibers to make pulp and paper. Converting facilities use these primary materials to manufacture specialized products such as paperboard products, writing paper, and sanitary paper (EPA 2002). The focus of this study is on pulp mills. Pulp mills are typically located near where trees are harvested. 65% of the world pulp market is supplied by the NORSCAN countries (the U.S., Canada, Sweden, Finland, and Norway) (Reinstaller 2005).

Table 1 summarizes the top pulp producing nations in 2000, sorted by chemical pulp production and percentage of value added from the pulp and paper industries.[3] The first panel shows the top pulp producers using chemical pulp methods. This panel includes countries from around the world. The second panel shows the top countries based on value added in the pulp, paper, paper products, and printing & publishing industry. Value added data are from the OECD STAN database, and have two weaknesses. First, the data only include OECD countries. Second, the value added data are for the entire paper industry, not just pulp production. Note, for example, that some of the top 10 in value added have no chemical pulp production. Nonetheless, note that four countries (U.S., Canada, Finland and Sweden) appear in both panels. In addition, Japan comes close to being on both lists, as it ranks 12th among OECD nations in percentage of

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[3] Pulp can be produced using chemical or mechanical methods, as described in the following section. Most production, particularly in developed countries, uses chemical methods.

value added from the pulp and paper industry. As it is also an important source of patents for ECF and TCF technologies, we include Japan in our study as well.[4]

Because consumer pressure played an important role in the reduction of chlorine bleaching, it is also important to consider where paper produced in these countries is sold. Table 2 shows the percentage of exports going to each of the countries in the study, along with Germany, other EU countries, and the rest of the world. Germany is included separately because, as shown in the next section, consumer pressure in Germany played an important role in the diffusion of chlorine-free paper. These data show that much trade in paper products is regional. Most exports from Sweden and Finland go to other European countries. Most exports from Canada and the US flow between the two countries. Japan paper exports go primarily to other countries. Given that consumer pressure varied across the world, its effects are likely to vary by region.

A. Pulp & Paper Manufacturing

Manufacturing paper products includes two main steps. First, the pulping process dissolves wood chips into lignin and fibers that will be used for paper production. Depending on the desired quality of the final paper product, this can be a chemical or mechanical process. The most common process in the countries in this study is the kraft process, which is a chemical pulping process.[5] In the kraft process, wood chips are boiled with an alkaline liquor (white liquor) to dissolve the lignin bonds holding cellulose fibers together. The process results in wood fibers (pulp) and a liquid containing the dissolved lignin solids (black liquor) (EPA 2002).

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[4] Despite being a NORSCAN country, Norway appears on neither list, and has few ECF or TCF patents. Thus, we do not include Norway in the analysis.
[5] 83% of all US pulp tonnage in the year 2000 was produced using kraft pulping (EPA 2002).

After these fibers are produced, they must be processed before they are used to produce paper. If the pulp will be used to produce high quality paper products (instead of, for example, boxes or paper bags), the fibers must be bleached. Also, for professional quality paper, the fibers of the pulp must be strong enough to produce paper that will hold up to the demands of printing presses. For this, a delignification treatment that does not damage the fibers is needed. Oxygen delignification was introduced in the 1970s to meet these requirements (Reinstaller 2005). In addition, extended delignification can have environmental benefits, as it reduces the amount of bleaching chemicals needed (EPA 2002).

The bleaching process is a major source of water pollution from the pulp and paper industry. This bleaching occurs in stages, generally alternating between acid and alkaline stages. The acid stages increase the whiteness of the pulp, while the alkaline stages remove any residual lignin and alkali from the pulping stage. Until the development of ECF and TCF technologies, most pulp mills used elemental chlorine (Cl_2) for the first bleaching stage. In the second stage, remaining alkali from cooking the pulp are eliminated using caustic soda. In the third stage, chlorine dioxide (ClO_2) is used to further bleach the pulp. In the fourth and fifth stages, the alkali removal using caustic soda and the ClO_2 bleaching are repeated (Norberg-Bohm 1998, Reinstaller 2005, EPA, 2002).

During the 1970s and 1980s, evidence that chlorine bleaching produces dioxins, which are highly toxic, led to stricter regulation and the development of alternative bleaching technologies.[6] Mills switched to chlorine dioxide (ClO_2) in the first bleaching stage or to processes that eliminated chlorine entirely. These are the basis for the elemental chlorine free

[6] Acceptable levels of dioxin in wastewater are lower than what can be detected. Thus, regulations often focus on the level of absorbable organic halogens (AOX). AOX is a measure of the total halogens (chlorine, bromide, and iodine) in the water. Reductions in these halogens correlate with reductions in the level of dioxins in wastewater (Norberg-Bohm and Rossi, 1998).

(ECF) and total chlorine free (TCF) technologies commonly used today. Bleaching with elemental chlorine has been reduced dramatically since 1990, with only 10 percent of chemical pulp production still using such technologies. Elemental chlorine has been completely eliminated in the Nordic countries. Most of this capacity has been replaced with ECF bleaching, although over 20 percent of plants in the Nordic countries use TCF (Alliance for Environmental Technology, 2006).

B. Elemental Chlorine Free Bleaching

Elemental chlorine free bleaching replaces the elemental chlorine used in the first stage bleaching with chlorine dioxide. This was aided by improvements in oxygen delignification in the pre-bleaching stage, allowing ClO_2 to achieve results similar to what had been achieved by using elemental chlorine. ECF technologies achieve almost complete delignification, which is important for high quality paper products. Because ClO_2 is used, chlorine substances are still synthesized. However, the different molecular structure of ClO_2 greatly reduces levels of AOX.

C. Total Chlorine Free bleaching

In contrast, total chlorine free bleaching completely eliminates the use of both elemental chlorine and chlorine dioxide. Hydrogen peroxide (H_2O_2) and ozone (O_3) are used as substitute bleaching agents. Denoting peroxide as P, ozone as Z, oxygen delignification as O, and chelation as Q,[7] a typical TCF bleaching sequence is OQPZP. TCF bleaching provides a much better environmental performance than ECF. However, this better environmental performance comes at a cost of lower paper quality. In particular, achieving high brightness using TCF results

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[7] Chelation is the addition of compounds to control the formation of free radicals to retard decomposition of the hydrogen peroxide (Reinstaller 2005).

in lower fiber strength. In addition, early yields from TCF were lower, necessitating more timber use. Bleaching costs can be 40-50% higher than for ECF (Lockie 1998). Nonetheless, despite these disadvantages, TCF technologies were adopted, particularly in the Nordic paper producing countries (Reinstaller 2005).

II. Pollution and the Pulp and Paper Industry

As noted earlier, increased awareness of the links between chlorine and dioxin led to dramatic reductions in chlorine use by the pulp and paper industry. One notable feature of this reduction is that consumer demand played a critical role in both the innovation and adoption of chlorine-free technologies. A series of environmental scares led to increased environmental awareness among consumers. Increasing consumer awareness spurred governments into action, creating regulatory pressure on the industry to rectify environmental problems. At the same time, competition among major industry players to satisfy consumer demand for chlorine-free paper played a vital role. Companies took advantage of the demand for environmentally friendly products through the use of environmental labeling to highlight reduced chlorine content and maintain their share of the global market.

Concerns over the release of halogenated organic compounds in pulp and paper mill effluents grew during the 1980s. Chlorinated organic compounds such as dioxins and furans, which are recalcitrant and bioaccumulative, are by-products of the bleaching process when chlorine gas is used as the bleaching agent. In 1980, the US EPA discovered furans and dioxins in paper mill waste. In 1983 dioxin was found in fish living downstream from pulp and paper mills. These studies were first leaked to the public by Greenpeace in August 1987 (Gray, Lowther, & Todd, 1987). In addition, Greenpeace publicized studies finding trace amounts of dioxin in consumer products such as diapers, milk cartons and coffee filters (Collins, 1992), creating consumer awareness of the environmental impacts caused by the pulp and paper industry.

Some of the most publicized research on the accumulation and adverse effects of chlorinated organic compounds in the environment emerged from Sweden in the mid 1980s (Galloway, Helminen, & Carter, 1989). In 1983, a Swedish report suggested that chlorinated organic compounds in the effluents of pulp and paper mills were to be blamed for the declining health of coastal waters. Government-sponsored scientists did a more comprehensive assessment at the Norrsundet kraft mill at the Gulf of Bothnia in 1984, finding altered fish populations with acute skeletal deformities and other adverse effects in waters receiving mill discharges (Larsson, Andersson, Förlin, & Härdig, 1988; Thulin, Höglund, & Lindesjöö, 1988). Finally, in 1987 the discovery of dioxin in diapers prompted a call for the ban of chlorine in the bleaching of pulp to be used in the manufacture of disposable diapers (Anonymous, 1987). These findings led regulators to reassess discharge limits within the context of possible toxicological and bioaccumulative effects and pressure pulp and paper mills to address the problems associated with chlorine bleaching (Smith & Rajotte, 2001).

Two other key events occurred in the German market, which was a major market for paper producers from Sweden and Finland. In 1989, Tengelmann, a leading toilet tissue manufacturer, announced plans to abandon chlorine and ECF pulp altogether. All its competitors in Germany, Austria and Switzerland took similar steps within 3 months, switching to TCF or deinked secondary fibers. Arguably the most influential action occurred in 1991 when Greenpeace published a spoof of *Der Spiegel*, Germany's most influential weekly. The publication, titled *Das Palgiat*, was published on TCF paper. It provided information on TCF technology and its benefits, including reply cards to the publishers of *Der Spiegel* requesting that future issues be printed on TCF paper. This led to many publishers requesting TCF paper from their suppliers (Smith & Rajotte, 2001).

Finally, in 1992, the Swedish firm Sodrä started its "Z pulp" campaign. This campaign publicized the company's discussions with Greenpeace and embraced the goal of zero discharge. Most influentially, it adopted the political debate rhetoric that brilliant white paper might be poisoning its users. Sodrä is considered to have started the TCF ball rolling (Smith & Rajotte, 2001). The importance of firms exploiting a perceived market niche aided in the diffusion of new bleaching technologies throughout the global industry.

A. Environmental Labeling

Linking chlorine to contamination in everyday consumer products helped drive consumer demand for paper products produced using chlorine-free technologies. However, for such demand to have an impact on production processes, it is important that consumers be informed as to the production processes used. For this, environmental labeling (ecolabeling) emerged as an early policy. Environmental labeling promotes more environmentally friendly consumption for the consumer and acts as an economic instrument for the industry, which can tap into a perceived market niche for green products (Salzman, 1991). Regarding pulp and paper products, most labeling schemes initially emphasized recycled fiber content, rather than chlorine content (Webb, 1994). Table 3 summarizes the major labeling schemes, along with noting the limits on chlorine content for paper products for each ecolabel.

Most labeling schemes began in the late 1980s. One prominent exception is Blue Angel, which was launched in Germany in 1978 with 200 labels across 33 product categories

(Sammarco, 1997). The Blue Angel scheme did not cover chlorine usage in paper until February 1992, when a new category for newsprint was introduced. Among other things, this category, a response to the spoof publication of *Der Spiegel* by Greenpeace, prohibited the use of halogenated bleaches (Webb, 1993).

Many countries adopted similar schemes in the late 1980s, although requirements on chlorine content for paper typically came later. The Canadian government introduced Environmental Choice in 1988. Criterion for paper products were first proposed in 1991, stipulating limits for total absorbable organohalides (AOX), biological oxygen demand (BOD), and total suspended solids (TSS) in wastewater discharge, and requiring that bleached paper products do not produce measurable concentrations of chlorinated dioxins in the wastewater and have no effect on rainbow trout (Webb 1993). However, these proposed limits were postponed (Webb 1994), and it was not until the second iteration of Environmental Choice in 1998 that dioxins were addressed.[8]

The Nordic council launched the Nordic White Swan in 1989, with the first paper standards beginning in November 1991. Among the criteria, halogenated and aromatic hydrocarbon cleaning solvents and fluorescent brightening agents were prohibited in fine papers and overall AOX releases were limited to 0.5 kg/ton. A 1994 revision removed a ban of chlorine bleaching of recycled fibers, replacing it with a general ban on the use of chemicals containing more than 1% of any substance that has been classified as harmful to the environment by the EU (Webb, 1994). This new limit allows the use of ECF, rather than TCF bleaching.

In the United Kingdom, paper merchants Brands Paper introduced Ecocheck in 1991, which included limits for chemical oxygen demand (COD), AOX, BOD, and TSS in wastewater

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[8] We thank Dave Halliburton, Chief of the Forest Products Section of the Natural Resources Division of Environment Canada for this information.

discharge (Webb 1993, 1996). The United States launched Green Seal in 1989. Administered by a private US environmental labeling agency, its first paper standards covered bathroom and facial tissues, and were introduced in 1992. Chlorine bleaching was allowed until 1996, if the wastewater AOX was below 1kg/ton pulp, but banned thereafter (Webb, 1994). Standards for printing and writing paper, issued in 1993, included a complete ban on chlorine-containing bleaches. Japan introduced the EcoMark label in 1989. However, limitations on the use of chlorine were not part of the criteria until 2004, when the use of chlorine bleaching was not allowed for products receiving this label.[9] Finally, the EU launched its Eco-label program in mid-1993 (Sammarco, 1997). Criteria for toilet tissues and kitchen towels were finalized in 1994. By mid 1996 agreement was reached on the criteria for copy papers based on a pass/fail system in four areas: COD and AOX content in wastewater discharge, sulfur-compounds air emissions, energy consumption (Webb, 1996).

III. Regulatory Responses

Increased awareness of the links between chlorine and dioxin also spurred governments into action, creating regulatory pressure on the industry to reduce the use of chlorine in pulp production. In the Nordic countries, regulation is done on a plant-by-plant basis.[10] In Sweden, these permits, which are reviewed every ten years, are issued by the National Licensing Board for Environmental Protection. Regulatory authority regarding pulp mill effluents comes from the Environmental Protection Act of 1969, which emphasized prevention instead of control of

[9] Documentation on the EcoMark label notes that chlorine content were not considered because dioxin pollution had already taken care by all the relevant emitters. We thank Mimi Nameki, First Secretary, Permanent Delegation of Japan to the OECD for Environment & Sustainable Development for this insight.

[10] In addition, European Union integrated pollution and prevention control (IPPC) regulations covers European pulp mills. The European Union reached agreement on IPCC in 1996, and is based on similar legislation passed earlier in the United Kingdom (Webb 1999). Directives for pulp and paper production took effect in 2001. For bleached kraft pulp, the new AOX standard is <0.25 kg/adt. Existing standards in both Finland and Sweden already satisfy this requirement.

pollution. For pulp and paper, this was done through in-process changes such as adopting the oxygen delignification process to recycle the waste stream. Such changes gave the industry experience with mill retrofitting and sourcing the best available technology and made chlorine-free technologies available when consumer demand for chlorine-free pulp reached its peak in the early 1990s (Smith & Rajotte, 2001).

The final requirements of each permit are developed after negotiation with each plant. The focus is on application of the best available technology (BAT), which the Swedish Environmental Protection Agency (NV) defines as the “best technology used on a commercial scale at a similar plant anywhere in the world” (OECD, 1999b, p. 176). By 1990, ECF was considered BAT. The Licensing Board also considers technical, environmental, and economic factors. Typically, economic considerations focus on effects on the industry as a whole, rather than a specific plant. Under special circumstances, a plant may be given more time to implement needed upgrades (OECD 1999b).

Because of the use of plant-by-plant licensing, Sweden has not imposed national discharge standards. However, legislative action sets national goals for environmental performance. In 1987, the NV established goals for organochlorine substances. In 1992, Parliament established more stringent national goals, stating that the pulp and paper industry should work to attain no noticeable effect of effluents by the end of the century (OECD 1999a). Recommended limits for AOX releases from kraft pulp mills were just 0.1-0.2 kg/t. (OECD 1999a).

In contrast to Sweden, Finland moved more slowly towards chlorine reduction. Like Sweden, Finland has no regulation specifically limiting AOX emissions, as it issues permits to plants on a case-by-case basis. In 1988, Sweden proposed new discharge limits for chlorinated organics for Nordic states at a meeting of Nordic Ministries. Finland viewed this as an attempt by Sweden to raise its market share, as Swedish mills had already adopted the required technology (Smith & Rajotte, 2001). Instead, Finland set less stringent targets for the kraft pulp industry in 1989, limiting AOX releases to 1.4 kg/ADt by 1994.[11] Finland finally accepted more stringent performance targets developed by a Nordic Working Group in 1993. These targets limited AOX releases to 0.2-0.4 kg/t for bleached kraft mills, with the more stringent guidelines applying to new mills (OECD, 1999b). Finland's willingness to accept these limits came in part because independent research had demonstrated that the limits could be met using their existing waste treatment technology. More importantly, because of increased demand for chlorine-free paper in Europe, Finland had also become anxious about economic risks, as much of Finland's pulp was exported (Auer, 1996; Smith & Rajotte, 2001). At the time, the pulp and paper industry was Finland's most important next exporter earner.

Unlike the Nordic countries, both the United States and Canada have binding national regulations limiting AOX emissions. Individual permits are still needed for each plant, but the national performance standards must be met or exceeded. In the United States, the EPA established an ambient water quality standard for dioxin of 0.013 ppq in 1984. However, pulp mills were not covered as they were not a known source of dioxin at that time. A follow-up study completed in 1989 confirmed that pulp mills were an important source of dioxin. The EPA responded by initially requiring pulp mills to meet the 0.013 ppq ambient standard in their wastewater, although this requirement was later eased to 1.2 ppq (Norberg-Bohm and Rossi 1998).

The EPA first proposed regulations for AOX releases in October 1993. These standards could not have been met using existing ECF technology, suggesting that TCF would be

[11] ADt represents an air dry ton of pulp product.

considered the BAT in the US. Pressure from industry led to the EPA weakening the standard in their final rule, which was issued as part of the Cluster Rules of 1997 (Reinstaller 2005).[12] The final rules established ECF as the BAT, with less stringent AOX limits than the Nordic countries, as shown in Table 4 (Webb, 1998). Mills had until 2001 to comply. To encourage TCF usage, mills that voluntarily chose to install TCF technology are given an additional three years to comply (OECD 1999b). However, as will be evident in the data presented in section V, few plants have chosen this option.

In Canada, federal and provincial governments share responsibility for water pollution control. The federal role in water pollution control is outlined in the Fisheries Act of 1970. Pulp and Paper Effluent Regulations were first introduced in 1971. In May 1992, the federal government introduced new regulations for the pulp and paper industry, which included new standards for dioxins, but did not include specific limits for AOX (OECD 1999b). However, several provinces have established limits for AOX emissions. First to do so was British Columbia, which in 1990 set a limit of 1.5 AOX kg/ADt, to be met by 1995. The 1990 legislation called for eliminating AOX emissions by 2002 (OECD 1999b), but this was later repealed after review by a panel of scientific experts. New standards now limit the monthly average AOX releases to 0.6 kg/ADt.[13] Quebec established AOX limits in 1992, as did Ontario in 1993. In both cases, the standards were phased in gradually, with monthly AOX averages needing to fall to 0.8 kg/ADt by 2000. In addition, new mills in Quebec face a more stringent standard of 0.25 kg/ADt (OECD 1999b). Finally, Alberta's initial response to dioxin was to consider limits as part of individual plant permits, as in Sweden (Galloway, Helminen and

[12] They are called the Cluster Rules because the standards address multiple pollutants, including both air and water, simultaneously.

[13] We thank Dave Halliburton, Chief of the Forest Products Section of the Natural Resources Division of Environment Canada for this information.

Carter, 1989). AOX standards have since been implemented at levels comparable to the other provinces.[14]

Finally, in Japan, regulation took a back seat to voluntary compliance measures by Japanese pulp mills. In 1991, the Japanese pulp and paper industry proposed that AOX levels be limited to 1.5 kg/metric ton by the end of 1993, and recommended the use of oxygen delignification equipment and chlorine dioxide substitution to meet this goal (Management Institute for Environment and Business, 1994). The first law pertaining to dioxin took effect in 2000, limiting dioxins in wastewater to 1 pg/l.[15] This is a general regulation applying to all industries. No specific limits apply to the pulp and paper industry.[16]

Table 4 summarizes the key regulations in each country. Note that the Nordic countries both moved faster and introduced permitting guidelines that were more stringent than regulations elsewhere. Finland first regulated in 1988, and Sweden in 1991. While Canadian provinces also passed regulations in the early 1990s, these did not take effect immediately. Moreover, their standards (0.6-0.8 kg/ADt) are less stringent than those of Sweden and Finland (0.1-0.4 kg/t). While the United States attempted to establish TCF as best available technology in 1993, industry opposition led the EPA to weaken its proposed limits when the final Cluster Rule was published in 1997. The monthly average AOX releases from existing sources must be below 0.62 kg/t for existing sources – a standard comparable to British Columbia. Japan's regulations are weakest, relying on voluntary compliance until 2000.

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[14] We thank Dave Halliburton, Chief of the Forest Products Section of the Natural Resources Division of Environment Canada for this information.

[15] There is no specific standard for AOX in Japan.

[16] We thank Mimi Nameki, First Secretary, Permanent Delegation of Japan to the OECD for Environment & Sustainable Development for this information.

IV. Data

We use patent data to study innovations of ECF and TCF technology. For our purposes, patents have several advantages as a measure of innovation. Most importantly, patent data are available in highly disaggregated forms. Using patent classes, we are able to identify patents specifically pertaining to ECF and TCF technology. Moreover, we can use data on the inventor to identify the source of each patent. Patents are granted by national patent offices in individual countries. Patent protection is only valid in the country that grants the patent. An inventor must file for protection in each nation in which protection is desired. Thus, the choice of an inventor to file a patent in multiple countries suggests that the inventor views these countries as potential markets for the innovation.

Economists have found patents, sorted by their application date, provide a good indicator of R&D activity (see, e.g., Griliches 1990). Nonetheless, when working with patent data, it is important to be aware of its limitations. The existing literature on the benefits and drawbacks of using patent data is quite large.[17] One potential concern is that, although the decision to file a patent obviously follows from the decision to perform R&D, not all successful research results are patented. In return for receiving the monopoly rights inferred by a patent, the inventor is required to publicly disclose the invention. Rather than make this disclosure, inventors may prefer to keep an invention secret. Surveys of inventors indicate that the rate at which new innovations are patented vary across industry (Levin *et al*. 1987). Fortunately, when studying the development of a single technology, this is less of a concern than when using patent data to measure innovation trends across several dissimilar industries.[18] Finally, it is also important to

[17] Griliches (1990) provides a useful survey.
[18] An additional concern that remains is that the propensity to patent may vary over time. For example, the number of patents filed in recent years in the United States has risen dramatically. Some observers argue that at least part of this increase can be attributed to recent court decisions that have increased the value of patent protection. However,

note that, because of the random nature of the innovative process, the quality of individual patents varies widely. Some inventions are extremely valuable, whereas others are of almost no commercial value. The aggregate counts provided in this paper include all such inventions.

We collected data on patents granted in each of our five countries using the Delphion patent database. One advantage of looking at ECF and TCF technologies is that there are specific patent classes pertaining to these technologies. These are listed in Appendix A. Within these classes, the first, D21C 9/14, pertains to ECF production, as it covers the use of chlorine dioxide. Note that chlorine dioxide was used in the later stages of bleaching even before the switch to ECF technologies, so that there will be patents in this class before regulations were in place. However, we would expect an increase in innovation here once the shift from elemental chlorine to ECF begins. The second class, D21C 9/147, includes bleaching processes using oxygen. These can be either ECF or TCF. The last two classes, D21C 9/153 and D21C 9/16 cover bleaching using ozone or per compounds (e.g. hydrogen peroxide). While these also can be used in both ECF and TCF bleaching, they are particularly important for TCF, as these chemicals substitute for chlorine dioxide in the TCF process.

Within each country, we generate patent counts by the home country of the inventor.[19] In our analysis, we focus primarily on patents by domestic inventors, as this shows how inventors are reacting to incentives in that country. Patents are sorted by the priority year. This is the year in which the initial application pertaining to this patent was filed. If a patent is granted, protection begins from the priority date. Inventors who desire patent protection in other nations must file applications in those nations, either directly or by using a Patent Cooperation Treaty (PCT) that designates the countries in which protection is desired, within one year of the priority

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this does not appear to be a problem for these data. As shown in the following section, patent counts for these technologies in the US have been declining since the early 1990s, even as overall patenting activity has increased.

[19] In the case of multiple inventors from different countries, we use the home country of the inventor listed first.

date. If the inventor does file abroad within one year, the inventor will have priority over any patent applications received in those countries since the priority date that describe similar inventions. Thus, the priority year is typically the year in which an application was filed in the inventor's home country. As noted earlier, this corresponds to when the inventive activity took place, as patent applications are usually filed early in the inventive process. Finally, we also make use of data on patent families – that is, the set of patent applications in multiple countries pertaining to the same invention (and thus sharing the same priority date).[20]

V. Analysis

A. Patent Trends

We begin by looking at domestic patent applications in each country. This allows us to compare incentives for invention in each of the countries in our study. Figure 1 shows patents granted in each country to domestic inventors, sorted by the first priority year. What is most notable from this figure is that perceived public pressure, in response to initial reports of dioxin in waterways, appears to drive innovation on ECF & TCF technologies. With the exception of Canada, every country experiences an increase in ECF & TCF patents that begins after release of the Greenpeace report in 1987. While there was some regulation at this time, recall that initial regulations were not strict – Sweden, the first country to pass stringent AOX guidelines, did so in 1992. While the US did announce plans for strict regulations that would declare TCF to be best

[20] In the case of Sweden and Finland, inventors might also choose to file patents through the European Patent Office (EPO), rather than through the national patent offices. EPO patent applicants may designate as many of the 18 EPO member-states for protection as desired. The application is examined by the EPO. If granted, the patent is transferred to the individual national patent offices designated for protection. Because EPO applications are more expensive, European inventors typically first file a patent application in their home country, and then apply to the EPO if they desire protection in multiple European countries. Thus, most Swedish and Finn inventors will first file an application in their home country. However, inventors from other European countries are likely to use an EPO patent if they desire protection in Sweden and Finland. Thus, we also include in our data European Patents that designate Sweden and/or Finland for protection

available technology in 1993, the lack of innovative response from US inventors after this announcement suggests that this initial proposal was not perceived as credible.[21]

The findings that patenting increases *before* regulations were put in place, rather than in response to regulation, and that these increases occur even in countries that did not pass early regulation, suggests that increased public scrutiny played an important role in influencing this first wave of innovation.[22] The American Paper Institute noted as early as November 1988 that several mills where dioxin was detected downstream had begun process modifications, even though no regulations were in place at the time (Chemical Week, 1988). Similarly, the discharge limits adopted by the Nordic states ironically became redundant because green market demand had surpassed those limits for more stringent measures (Smith & Rajotte, 2001, p. 146).

In addition, industry experts expressed concern over future regulation in response to increased scrutiny. An April 1988 article in *Chemical Week* cites a prediction from I. Bruce Sanborn, associate director of research and development, process development and control of Consolidated Paper, that the bleaching process would soon be regulated, and that this would have a "heavy impact on purchasing over the next 5-10 years" (Agoos and Portnoy, 1988, p. 45). Another unnamed paper producer noted at the time that "there is likely to be a substantial change in the way pulp is bleached" (Agoos and Portnoy, 1988, p. 45).

A second implication of these data is that stringent regulation will spur additional innovation. Here, it is worth comparing innovation in the Nordic countries to innovation in the

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[21] In contrast, in the late 1980s, patenting activity for sulfur dioxide control technologies increased in response to early attempts at modifying the U.S. Clean Air Act, suggesting that innovators expected that these attempts would eventually lead to regulatory changes (Taylor *et al*., 2003).

[22] At the same time, the implementation of the Toxic Release Inventory (TRI) in the United States in 1990 led firms to reduce releases of chemicals such as chlorine. However, the finding that innovation is global, rather than just in the US, suggests that the importance of consumer pressure was greater than the pressure from TRI. Of particular importance, TRI data only reports releases from the production process. It says nothing about the levels of chlorine that remain in paper. However, consumer pressure, particularly in Europe, focused on the chlorine content of paper, rather than chlorine releases.

US and Canada. Recall that while Sweden uses plant by plant licensing, its strong definition for best available technology led to ECF being considered BAT as early as 1990. In addition, Sweden also issued guidelines for AOX releases in 1992 that were not only more stringent than any issued at the time, but remain the most stringent guidelines for AOX among the countries in this study.[23] Similarly, in 1993 Finland agreed to the stringent AOX limits recommended by the Nordic Working Group. In both cases, these regulations can be seen as technology forcing, and innovation responds in kind. Both Swedish and Finnish ECF & TCF patents peak within two years of passing these stringent limits.

By comparison, US and Canadian regulations were less stringent than the Nordic guidelines, and typically made use of existing technologies. As such, we see little evidence of innovation in response to these regulations. Canadian patents experience no notable increases. US patenting activity increases dramatically in response to the initial news about dioxin, but not in response to new regulations. Neither the proposed (and ultimately defeated) standards of 1993 nor the final Cluster Rule of l998 led to additional patenting in the US.

We can see further evidence of the importance of both stringent and flexible regulation by looking at the types of innovation taking place. Table 5 provides counts of patents using chlorine dioxide (ClO_2) and chlorine substitutes for selected years. Note that patents using ClO_2 could only be used for ECF processes, whereas those using chlorine substitutes could be used in either ECF or TCF processes. Thus, while we cannot definitely state when research has shifted to TCF processes, we can identify cases where ECF is the main research goal. These counts

[23] One interesting possibility is that case-by-case permitting may hasten the development of new technologies. Ulf Bjällås of Sweden’s National Licensing Board for Environmental Protection notes that Sweden’s approach to permitting encourages innovation by allowing individual plants to propose different solutions to pollution problems. Moreover, the National Licensing Board can postpone decisions in order to investigate new technologies (Bjällås 1999). While we do not have sufficient patent data do not allow us to test whether innovation in Sweden included a greater variety of options for these technologies, this is a question worth further study.

suggest that regulatory stringency, or lack thereof, did shape the nature of innovation. During the first wave of patenting in the late 80s and early 90s, most US patents focused on chlorine substitutes. Sweden had fewer patents at this time, and many used chlorine dioxide. However, after Sweden establishes strict AOX standards in 1992, nearly all Swedish patents use chlorine substitutes. This is also true after Finland adopts stringent standards in 1993. In contrast, not only does US patenting activity fall after the revised Cluster Rule in 1997, but the nature of innovation shifts. Once the revised Cluster Rule establishes ECF as acceptable, most US patents make use of chlorine dioxide, as there is little regulatory incentive for plants to consider alternatives such as TCF bleaching.

Examination of patent family data provides further evidence of the leading innovative role of Sweden and Finland. Patent protection is only valid in the issuing country. To receive protection in multiple countries, an applicant must obtain a patent in each country for which protection is desired. Additional fees apply for each application. However, inventors are given a one-year window after their first filing to decide to patent elsewhere. Because of these features of patent law, only the most valuable inventions are filed in several countries. Moreover, filing a patent application in a given country is a signal that the inventor expects the invention to be profitable *in that country*. Because of this, researchers such as Lanjouw and Schankerman (2004) have used data on patent families as proxies for the quality of individual patents.

Figure 2 shows the average family size of domestic patents in each country by year. Note that Sweden, Finland, and the US consistently produce the largest family sizes, whereas most of Japanese patents are filed only in Japan.[24] Moreover, family sizes are largest after the initial outcry over dioxin in the late 1980s. This provides further evidence of global concern, rather

[24] Japan's small family size is explained by Japan being a technology-follower in this field. Most pulping equipment used in Japan comes from foreign sources (Management Institute for Environment and Business, 1994).

than domestic regulation, driving innovation. Also notable is that the family size of Swedish and Finnish patents remains high throughout the 1990s. In contrast, the average family size of US patents falls dramatically after 1996. A likely explanation for this is the technology following nature of US regulations. Because the Nordic regulations were more stringent than the regulations passed in the US, larger inventive steps would be needed to comply with Nordic regulations. US regulations, in contrast, could be met with existing technology. As such, not only did the level of innovation fall once it was clear that TCF technology would not be required in the US, but also the quality of innovation. Since the mid-90s, most major patents for ECF & TCF technologies come from the Nordic countries.

To better illustrate the flows of knowledge across countries, Figure 3 shows both domestic and foreign patents in Finland, Sweden, and the United States. One thing of note here is that both domestic and foreign regulations appear to influence innovation. For example, patents from US inventors peak in 1990 in the US. However, they peak in 1992 in Sweden and 1993 in Finland – after passage of tighter regulations in those countries. Similarly, we observe an increase in Swedish patents, both in Sweden and the US, after the 1997 Cluster Rule in the US.[25] This contrasts with the results of Popp (2006), which finds that domestic regulations are the primary driver of innovation for air pollution control devices for coal-fired power plants. One difference here is that the pulp and paper industry is a global market, whereas most suppliers of pollution abatement equipment in Popp (2006) were domestic companies.

[25] Since the peaks are different for each destination country, at least some of the variation comes from inventors choosing to file more of their patent applications in other countries. However, our data doesn't allow us to say to what extent inventors are responding to regulation in other countries by increasing innovative activity (e.g. creating more inventions) or simply by choosing to file more of their patent applications in other countries.

B. Adoption of ECF & TCF Technologies

Figure 1 suggests that innovation on ECF and TCF technologies came early, in some cases preceding regulations. However, looking at innovation does not present a complete picture, as it does not consider whether newly developed technologies are put to use. Figures 4 and 5 show the percentage of pulp production using ECF technology and ECF or TCF technology respectively.[26] It is here where the influence of regulation becomes clearer. By 1994, all pulp production in the Nordic countries uses either ECF or TCF technology. In contrast, North American usage grows more slowly. It is not until the Cluster Rule deadline of 2001 that nearly 100% adoption is achieved. One important difference in North America is that public pressure for chlorine-free paper did not persist as it did in Europe. Moreover, the US industry serves a primarily domestic market, exporting just 10 percent of its paper products (Norberg-Bohm and Rossi, 1998). While public pressure was sufficient to jumpstart innovation on ECF and TCF technologies, as well as to encourage some reductions of chlorine use, the adoption data make clear that complete diffusion will not occur unless binding regulations are put in place.

C. Policy vs. Public Pressure

The combination of early innovation and delayed adoption in North America provides some interesting lessons for the induced innovation literature. First, the early influence of public pressure, particularly after Greenpeace leaked EPA reports on dioxin, is striking. Typically,

[26] The chart combines Canada and the US as part of North America, as separate data are available for these countries only through 2001. Using separate data reveals similar trends. Canada has slightly higher adoption rates than the US, due to earlier regulation at the provincial level. The only deviation between the two countries is that increased North American diffusion in 2001 is entirely due to the US, which saw usage of ECF technology increase from 76% to 96% as the deadline for compliance with the Cluster Rule regulations passed (Alliance for Environmental Technology, 2002). Note that less than one percent of plants in the US and Canada use TCF, since it is possible to comply with regulation using ECF technology.

induced innovation studies focus on the effect of regulation on innovation. Here, innovation comes first. Regulation followed, encouraged both by public pressure for action and the availability of alternative technologies for pulp production. The role of leading countries is also important. Sweden and Finland moved quickly to reduce chlorine usage. As discussed earlier, these decisions were made partly because the technologies that had been developed in response to news on dioxin were deemed acceptable to regulators. However, the patent data suggest that additional research was needed to perfect these technologies, as both Sweden and Finland experience an increase in ECF & TCF patenting after announcing stringent national guidelines in the early 1990s. In contrast, the US and Canada delayed regulation, and appear to develop these regulations based on the availability of existing technologies. Early attempts to establish TCF as the best available technology in the US failed. When the US finally adopts the Cluster Rule in 1998, ECF had been clearly established as a viable technology. As such, while the rule served to increase *adoption* of ECF technology, no further innovation was needed.

Note that this result differs from Popp (2006), which finds that even late adopters of coal-fired power plant regulations needed to innovate to adapt technologies to local conditions. One difference here is that domestic innovation did occur in the US *prior* to the Cluster Rule, whereas in the case of power plants, little domestic innovation occurred before regulations were enacted. In the case of power plants, even if there had been public pressure to reduce emissions, consumers' only option before regulation would be to reduce electricity usage. Alternative, clean suppliers of electricity were not available, as regulations for nitrogen dioxide and sulfur dioxide took effect before the movement towards deregulated electricity markets in the late 1990s. In contrast, some pulp manufacturers did face incentives to reduce chlorine usage before regulations were in place, as it enabled these manufacturers to differentiate their product and target environmentally-conscious consumers.

Finally, we turn to labeling. The importance of early publicity suggests a possible role for labeling to encourage both innovation and diffusion of ECF & TCF technologies. However, the first labeling requirement restricting chlorine was the Nordic Swan in 1991. Most schemes did not address chlorine usage until later in the 1990s. While they may have played a role in the diffusion of ECF and TCF technology, labeling schemes appear to incorporate existing technologies in their criteria, rather than serve as technology-forcing standards.[27] Given that these labels are voluntary measures, this is not surprising, as labeling programs do not offer consumer choices unless some products qualify for the label.

VI. Conclusions

This paper uses patent data to study the development of ECF and TCF bleaching technologies in the pulp and paper industry across five OECD countries. While most studies using patent data focus on end-of-the-pipe solutions to environmental problems, this study offers a first look at patenting for a process technology. As in other studies of environmental innovation, regulation plays a role in both the development and diffusion of these technologies. However, it is not the only driver of innovation, and perhaps not even the most important.

[27] Even the influence of labeling schemes to encourage adoption is hard to discern from the data. Clearly, adoption of ECF and TCF technology increases in Scandinavia in the early 1990s, but this is not solely due to labeling, as regulations in Sweden and Finland were also tightened at this time. However, the Nordic Swan standards are more stringent than the AOX requirements in these countries, and may help reduce emissions beyond what is required (personal communication, Grethe Torrissen, Advisor, Sustainable Production and Consumption/IPP, the Norwegian Ministry of the Environment). In contrast, the US Green Seal label allowed chlorine, as long as releases were below 1 kg/ton, until 1996. This may be one explanation for adoption of ECF technology prior to the Cluster Rule. However, although Green Seal banned chlorine bleaching after 1996, there was no shift to TCF technology in the US, with less than 1 percent of production using this technology (Alliance for Environmental Technology, 2002).

One striking result from the patent data is the role of public pressure. While ECF and TCF technologies are process technologies, they do affect the quality of the final product. In the late 1980s, studies linking chlorine bleaching technologies to dioxin led to pressure from environmentalists for reduced chlorine bleaching in paper production. Detection of trace amounts of dioxin in products such as diapers and coffee filters led to increased awareness of the issue, particularly in Europe. In response, the development of alternative bleaching technologies increased rapidly in each of the countries in this study. Moreover, this increase occurred before new environmental regulations could be put in place limiting chlorine use, suggesting that public pressure, rather than regulation, was the primary driver of this first wave of innovation. Finally, although product labeling is important for consumers to indentify chlorine-free products, the formalized labeling schemes developed in the 1990s emphasized available technologies, rather than spurring additional innovation. Because the success of such voluntary programs depends on firms' willingness to participate, these programs do not appear well-suited for spurring additional innovation.

Despite the importance of consumer pressure, public policy does play an important role. In response to increased awareness of the problems of chlorine bleaching, both Sweden and Finland enacted strict regulations in the early 1990s. In both countries, these regulations were followed by both increased innovation and increased adoption of ECF and TCF technologies. Moreover, these tighter regulations shaped the nature of innovation, as firms focused on technologies relevant for TCF production. In contrast, the U.S., Canada, and Japan all enacted weaker regulations that could be satisfied using ECF technology. Moreover, in the U.S. and Japan, these regulations did not come until later in the decade. As such, patenting in the U.S. did not remain at high levels (although it did in Japan, presumably in response to foreign regulations). Moreover, the majority of U.S. patents at the end of the decade focused on ECF, rather than TCF, technology.

Public policy also plays a role in diffusion. While the patent data show the U.S. was an early innovator of ECF and TCF technologies, adoption of these technologies was slower in the U.S. than in Sweden or Finland. While some U.S. plants adopted ECF technology in response to consumer pressure, it was not until regulations requiring its use took effect in 2001 that near universal adoption of ECF or TCF technologies occurred. In contrast, Sweden and Finland achieved 100 percent diffusion of ECF and TCF technologies by 1994, due to earlier regulation requiring these technologies.

Finally, it is worth noting that while this paper illustrates the effect of different policy regimes on innovation, it says nothing about efficiency. TCF technology was more costly and produced lower quality paper than ECF. While the more stringent regulations in Sweden and Finland did hasten the development and diffusion of TCF technology, it is beyond the scope of this paper to assess whether the additional benefits from completely removing chlorine from the bleaching process, compared to the partial reduction achieved by ECF, are worth the additional costs of developing and using TCF technology.

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Table 1 – Top Pulp Producers

Top countries: pulp production

	Chemical pulp production (1000 metric tons)	% Value added from Pulp & Paper
United States	48,198	2.25%
Canada	13,553	2.99%
Japan	9,792	1.73%
Sweden	7,979	3.52%
Finland	7,100	6.06%
Brazil	6,689	N/A
Russian Federation	4,195	N/A
Indonesia	3,626	N/A
Chile	2,220	N/A
France	1,817	1.50%

Top countries: % total value added from pulp, paper, paper products, printing and publishing

	Chemical pulp production (1000 metric tons)	Percentage
Finland	7,100	6.06%
Ireland	0	3.82%
Sweden	7,979	3.52%
Canada	13,553	2.99%
New Zealand	754	2.43%
United Kingdom	0	2.35%
United States	48,198	2.25%
Austria	1,190	2.02%
Netherlands	0	2.01%
Portugal	1,774	1.84%

Source: Pulp production from FAOSTAT (2006). Value added percentages are authors calculations based on data from the OECD STAN database.

Table 2 – Percentage of Exports to Each Country: Paper and Paperboard

		Exports to:							
Exporter	**Year**	**Canada**	**Finland**	**Japan**	**Sweden**	**USA**	**Germany**	**Other EU**	**Other**
Canada	1988		0.0%	2.0%	0.0%	82.3%	1.2%	4.7%	9.8%
Finland	1988	0.9%		2.9%	2.9%	6.3%	12.4%	50.1%	24.5%
Japan	1988	1.5%	0.8%		1.1%	18.2%	4.5%	8.6%	65.3%
Sweden	1988	0.3%	1.7%	0.8%		4.6%	17.1%	58.7%	16.9%
USA	1988	19.3%	0.1%	12.4%	0.4%		2.8%	12.3%	52.9%
Canada	1993		0.0%	2.7%	0.0%	81.9%	0.8%	5.3%	9.3%
Finland	1993	0.5%		2.2%	2.6%	7.7%	14.5%	51.9%	20.6%
Japan	1993	0.7%	0.1%		0.2%	14.8%	1.7%	5.6%	76.8%
Sweden	1993	0.1%	2.2%	0.4%		2.0%	19.3%	57.6%	18.4%
USA	1993	27.5%	0.0%	9.2%	0.3%		2.4%	9.6%	51.0%
Canada	1998		0.0%	1.6%	0.0%	87.1%	0.5%	3.1%	7.6%
Finland	1998	0.8%		1.7%	3.0%	7.3%	16.1%	49.1%	21.9%
Japan	1998	0.8%	0.1%		0.1%	21.4%	1.7%	5.9%	70.0%
Sweden	1998	0.1%	2.5%	0.3%		2.0%	19.5%	60.3%	15.3%
USA	1998	30.5%	0.1%	6.5%	0.1%		2.1%	10.5%	50.2%

Source: Authors calculations using data from Comtrade (http://comtrade.un.org). Includes exports in SITC2 categories 641 (Paper and paperboard) and 642 (paper and paperboard, precut and articles of paper or paperboard).

Table 3 – Summary of Ecolabel Programs

Blue Angel (Germany), begins 1978

- 1992: new category for newsprint: no halogenated bleaches

Environmental Choice (Canada), begins 1988

- 1991: limits for AOX proposed, but eventually postponed
- 1998: AOX limits added

Nordic White Swan, begins 1989

- 1991: Chlorine bleaching prohibited
- 1994: Revised to allow ECF

Ecocheck (UK), begins 1991

- 1991: Included limits for COD, AOX, BOD and TSS in wastewater

Green Seal (US), begins 1989

- 1992: Bathroom and facial tissue standards limit AOX to 1kg/ton pulp
- 1993: Standards for printing and writing paper prohibit chlorine bleaching
- 1996: Chlorine bleaching prohibited for bathroom and facial tissues

Eco-label (EU), begins 1993

- 1996: Criteria for copy papers includes pass/fail system in four areas, including AOX

Ecomark (Japan), begins 1989

- 2004: Chlorine gas not to be used in bleaching process

Table 4 – Summary of Key Regulations

Sweden

1991: Environmental legislation establishes strict guidelines for AOX (**0.1-0.2 kg/t**). Enforcement is through plant-by-plant permitting.

Finland

1987: Issues first guidelines for AOX (**1.4 kg/ADT**), to be met by 2004. Enforcement is through plant-by-plant permitting.

1993: Accepts Nordic Working Group performance standards for AOX (**0.2 – 0.4 kg/t**). Enforcement is through plant-by-plant permitting.

Canada

1990: British Columbia sets AOX limits of **1.5 kg/ADt**, to be met by 1995. Since lowered to **0.6 kg/ADt**.

1992: Quebec passes AOX limits that are phased in gradually. AOX limit of **0.8 kg/ADt** by 2000. New mills limited to **0.25 kg/ADt**.

1993: Ontario passes AOX limits that are phased in gradually. AOX limit of **0.8 kg/ADt** by 2000.

United States

1993: Proposed Cluster Rule suggests TCF as best available technology. Never took effect.

1997: Revised Cluster Rule limits monthly average AOX releases to **0.62 kg/t** pulp for existing sources, and **0.27 kg/t** pulp for new sources. Daily discharges cannot exceed 0.95 kg/ton pulp and 0.48 kg/ton pulp, respectively. Mills have until 2001 to comply.

Japan

1991: Pulp and paper industry proposes voluntary AOX limit of **1.5 kg/metric ton** by end of 1993.

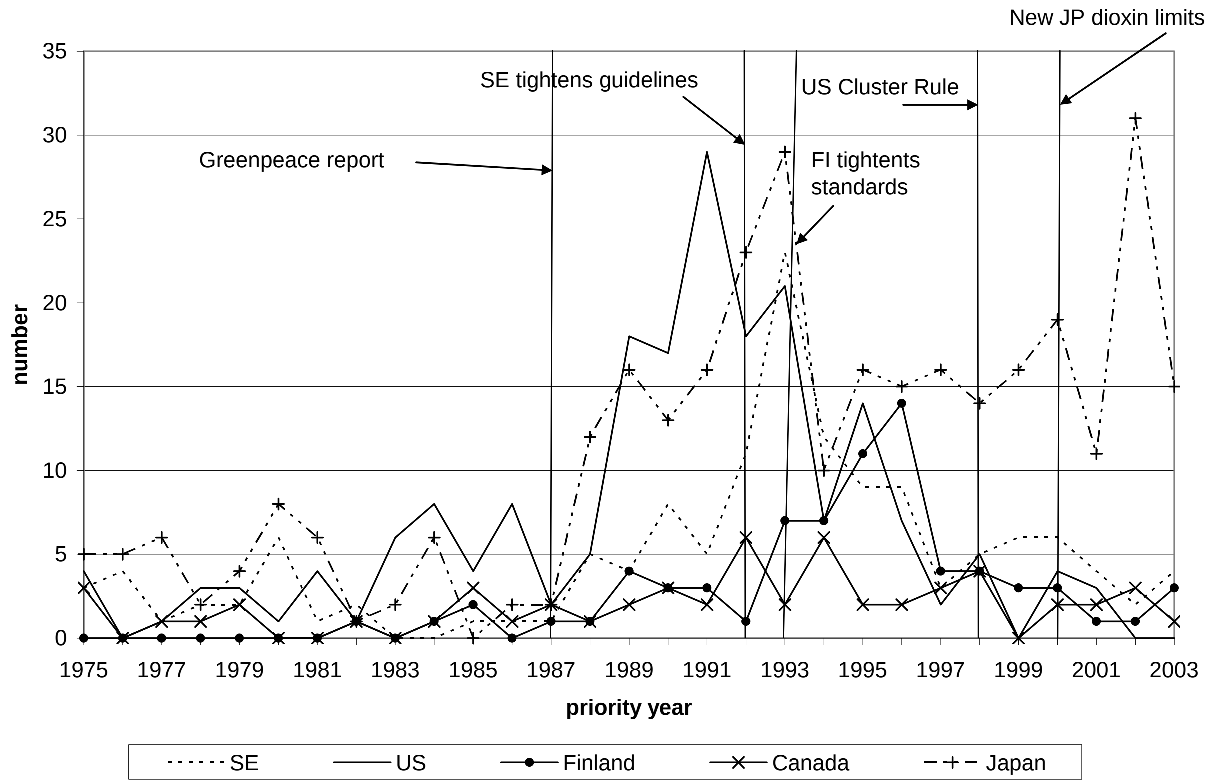
2000: First law limiting dioxins in wastewater (1 pg/l). No specific limit for AOX or for the pulp and paper industry.

Table 5 – Number of Domestic Chlorine and Non-Chlorine Patents, Selected Years

		Priority Year											
		1975	**1980**	**1985**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1998**	**2000**	**2002**
Canada	ClO_2	2	0	1	0	0	1	0	1	0	1	0	1
	Other	1	0	2	1	2	2	2	5	2	3	2	2
Finland	ClO_2	0	0	0	1	2	2	0	0	0	1	3	0
	Other	0	0	2	0	2	1	3	1	7	3	0	1
Japan	ClO_2	3	1	0	4	1	6	2	1	4	3	5	10
	Other	2	7	0	8	15	7	14	22	25	11	14	21
Sweden	ClO_2	1	2	0	1	3	6	0	0	1	0	2	2
	Other	2	4	1	4	1	2	5	11	22	5	4	0
US	ClO_2	1	1	1	1	7	2	2	5	0	5	2	0
	Other	3	0	3	4	11	15	27	13	21	0	2	0

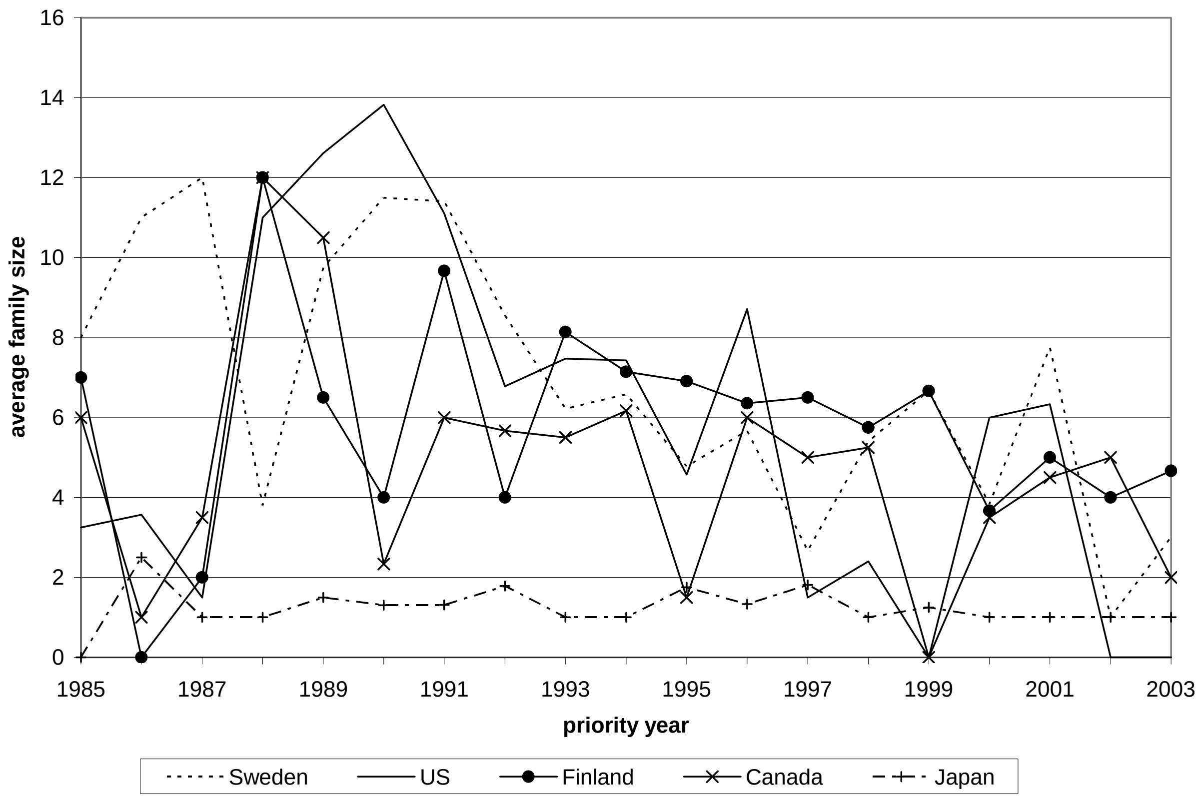
The table shows the number of domestic patent applications for selected years for technologies using chlorine dioxide (ClO_2) and using substitutes for chlorine (other). ClO_2 patents correspond to IPC class D21C 9/14, and other corresponds to the other three IPC classes. Note that ClO_2 patents could only be used in ECF processes, whereas the other patents could be used in both ECF and TCF processes.

Figure 1 – Domestic ECF & TCF Patents by Country



The figure shows patent applications of domestic inventors for each country in our sample. In all cases except the US, both successful and unsuccessful applications are included. Only patents subsequently granted are included in US applications.

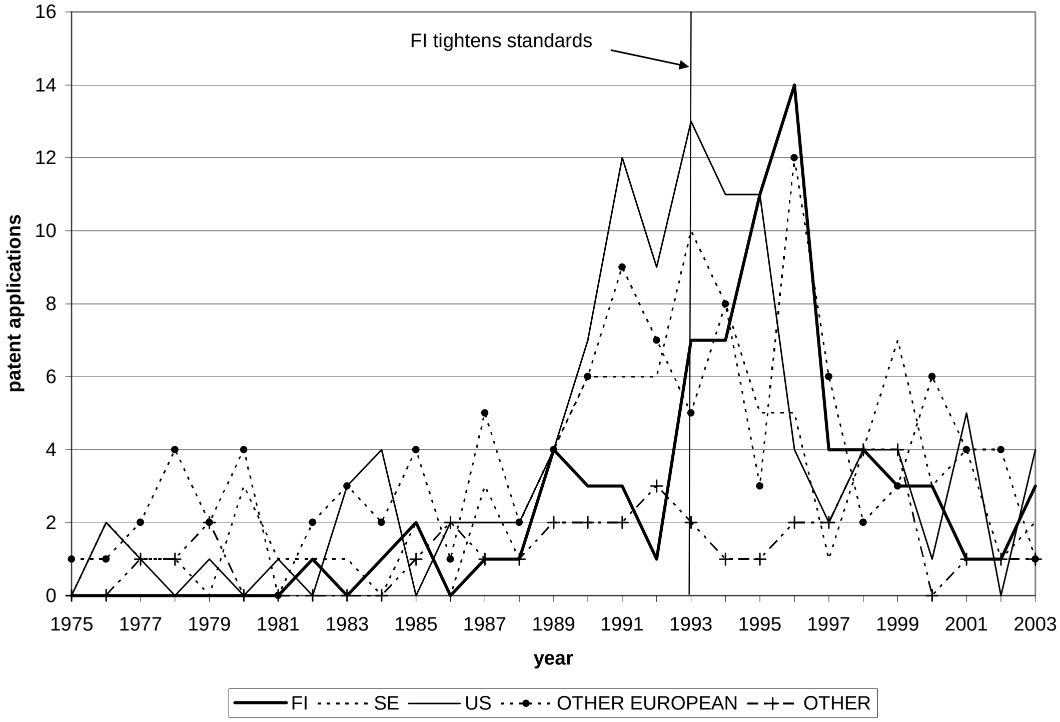
Figure 2 – Average Patent Family Size by Country and Year



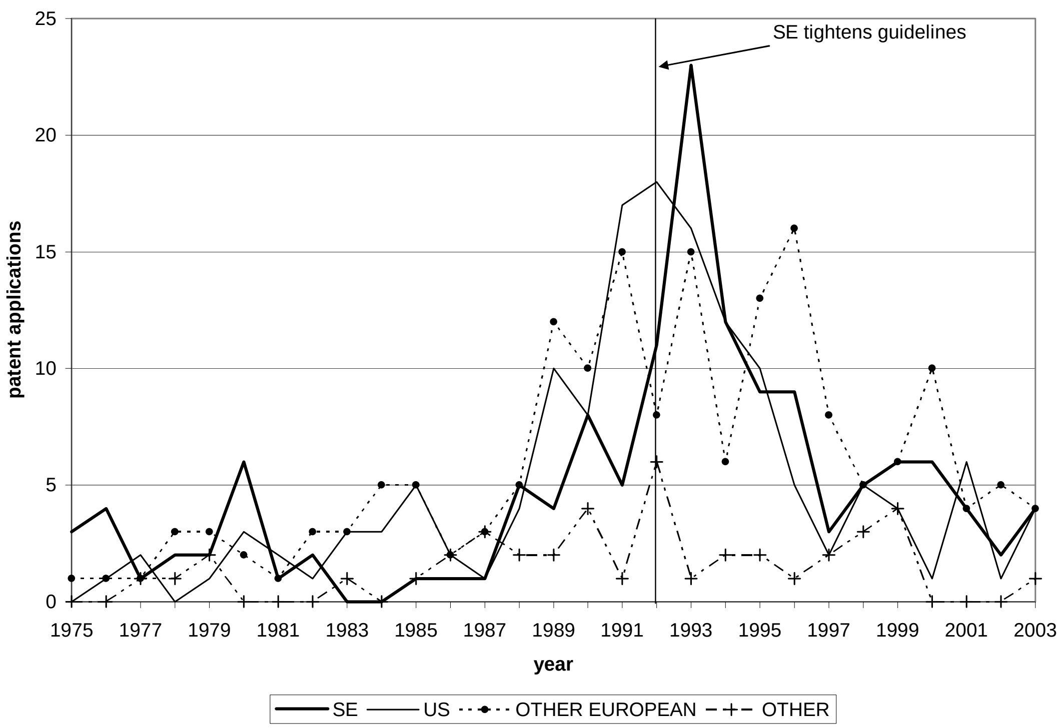
The figure shows the average patent family size of patent applications of domestic inventors for each country in our sample. In all cases except the US, both successful and unsuccessful applications are included. Only patents subsequently granted are included in US applications.

Figure 3 – ECF & TCF Patent Trends, Selected Countries

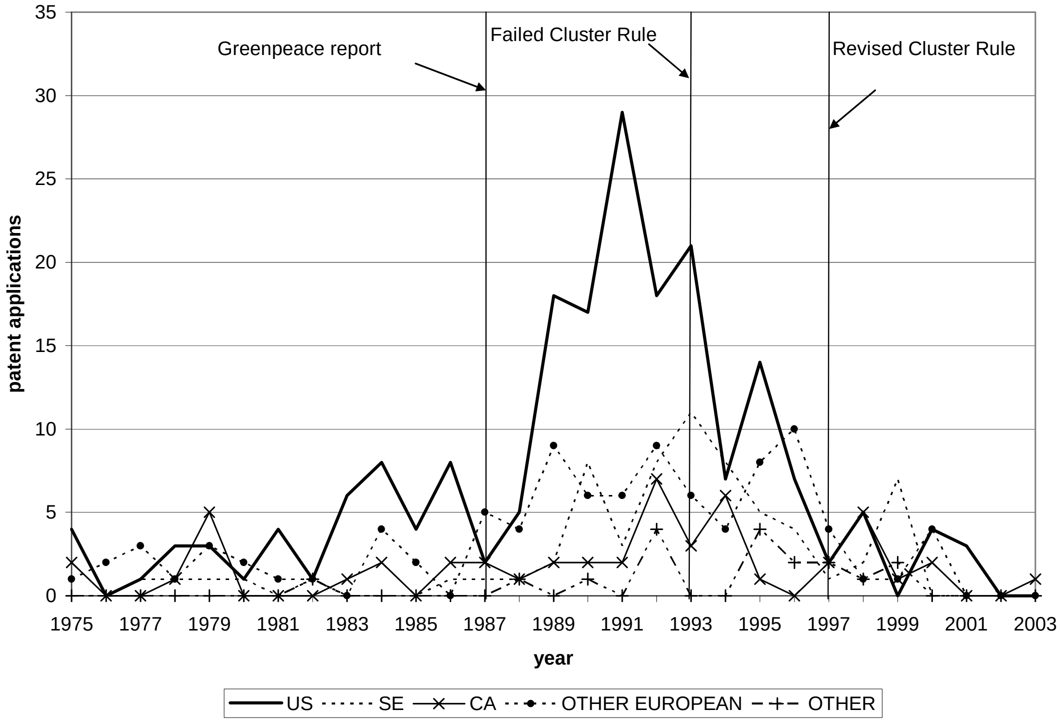
A. Finland



B. Sweden

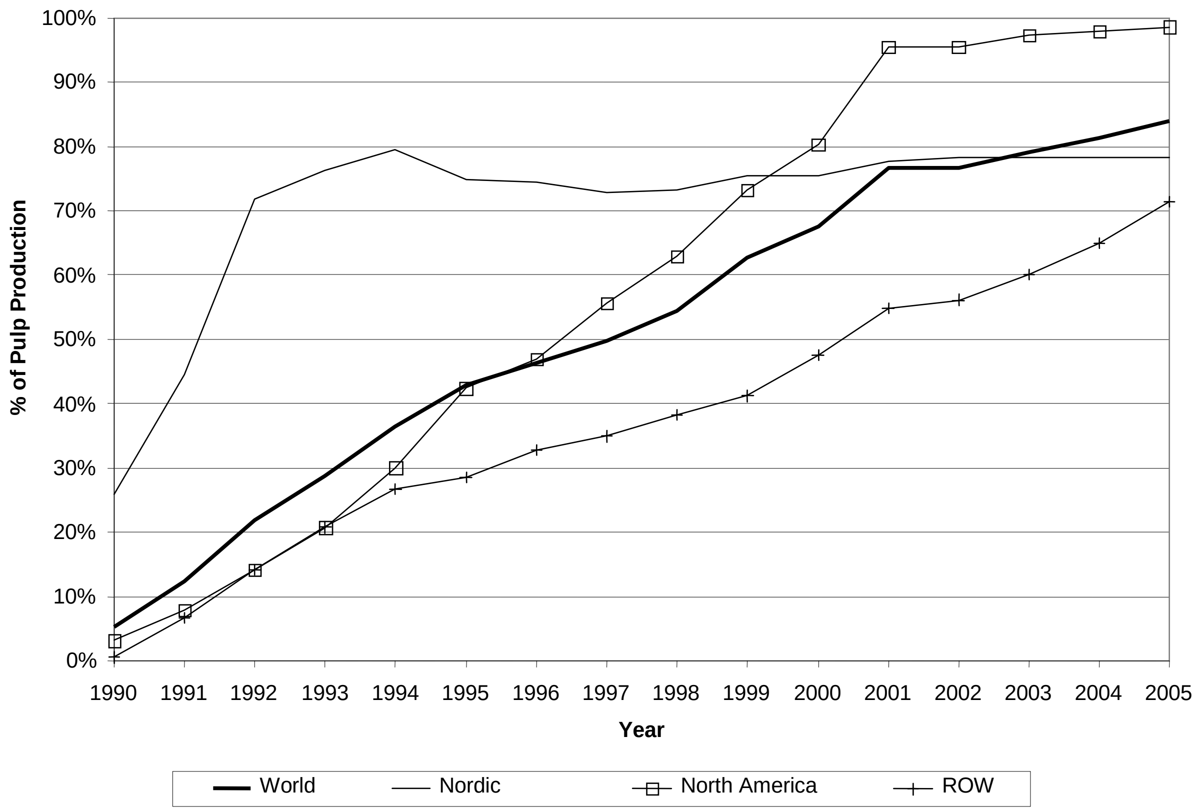


C. United States



The figures show all ECF & TCF patents in Finland, Sweden, and the United States, grouped by inventor country.

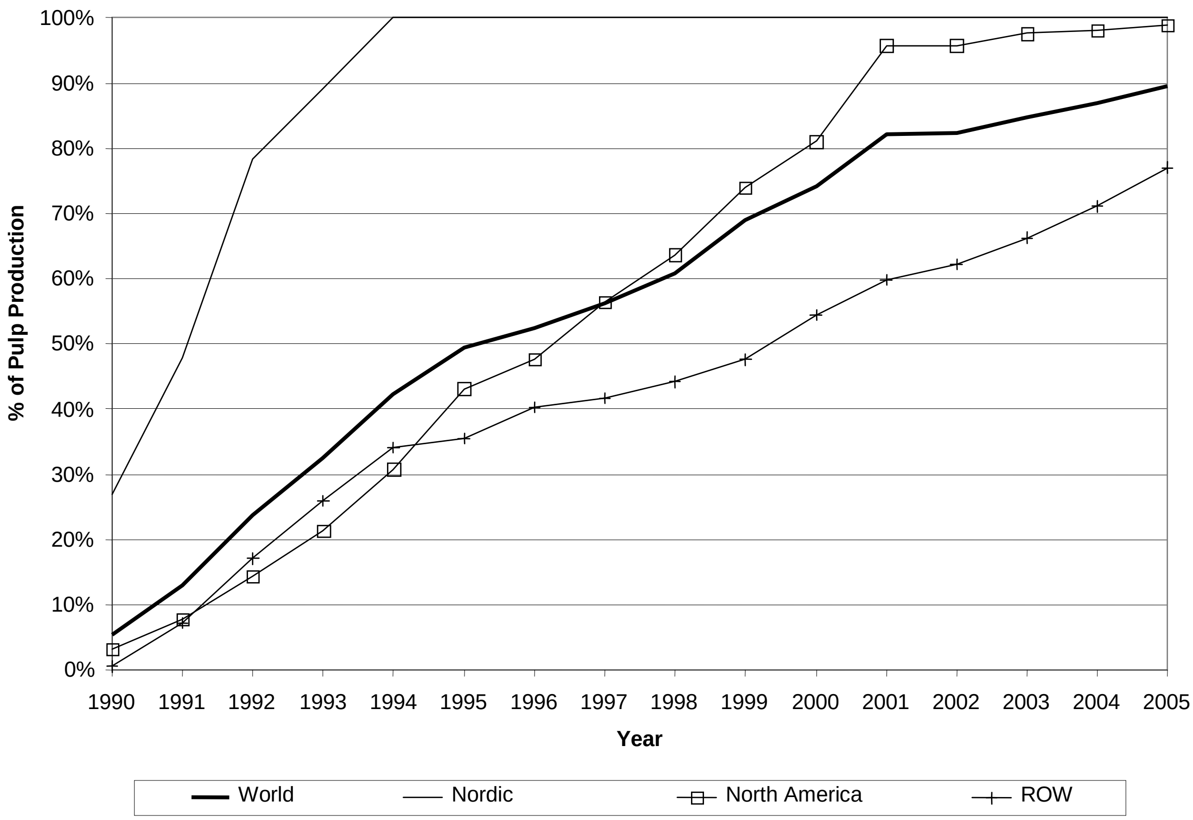
Figure 4 – Diffusion of ECF Bleaching Technologies



The figure shows the percentage of chemical pulp production using ECF technology in the Nordic countries, North America, and the rest of the world (ROW). Note that diffusion of ECF has been rapid in the Nordic countries due to both strong consumer demand and early regulation. In contrast, diffusion in North America has been more gradual until 2001, the deadline for compliance with the US Cluster Rules.

Source: Authors calculation using data from Alliance for Environmental Technology (2006)

Figure 5 – Diffusion of ECF & TCF Bleaching Technologies



The figure shows the percentage of chemical pulp production using either ECF or TCF technology in the Nordic countries, North America, and the rest of the world (ROW). Note that the use of elemental chlorine has been completely eliminated in the Nordic countries, and nearly eliminated in North America since the US Cluster Rules took effect.

Source: Authors calculation using data from Alliance for Environmental Technology (2006)

Appendix A: Relevant Patent Classes for Pulp Bleaching Technologies

D21C 9/14: Paper/Paper-Making; Production of Cellulose/Production of Cellulose by Removing Non-cellulose Substances from Cellulose-containing Materials; Regeneration of Pulping Liquors; Apparatus Therefor/After-treatment of cellulose pulp, e.g. of wood pulp, or cotton liners/Bleaching/with halogens or halogen-containing compounds/with ClO_2 or chlorites

D21C 9/147: Paper/Paper-Making; Production of Cellulose/Production of Cellulose by Removing Non-cellulose Substances from Cellulose-containing Materials; Regeneration of Pulping Liquors; Apparatus Therefor/After-treatment of cellulose pulp, e.g. of wood pulp, or cotton liners/Bleaching/with oxygen or its allotropic modifications (9/16 takes precedence)

D21C 9/153: Paper/Paper-Making; Production of Cellulose/Production of Cellulose by Removing Non-cellulose Substances from Cellulose-containing Materials; Regeneration of Pulping Liquors; Apparatus Therefor/After-treatment of cellulose pulp, e.g. of wood pulp, or cotton liners/Bleaching/with oxygen or its allotropic modifications (9/16 takes precedence)/with ozone

D21C 9/16: Paper/Paper-Making; Production of Cellulose/Production of Cellulose by Removing Non-cellulose Substances from Cellulose-containing Materials; Regeneration of Pulping Liquors; Apparatus Therefor/After-treatment of cellulose pulp, e.g. of wood pulp, or cotton liners/Bleaching/with per compounds