NBER WORKING PAPER SERIES
ON
HISTORICAL FACTORS IN LONG RUN GROWTH

PRICE WARS AND THE STABILITY OF COLLUSION: A STUDY OF THE PRE-WORLD WAR I BROMINE INDUSTRY

Margaret Levenstein

Historical Paper No. 50

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
September 1993

The author acknowledges helpful comments from David Arsen, Jeff Borland, Insong Gil, Thomas Iosso, Kevin Lang, Richard Levin, Nancy Lutz, Paul Milgrom, David Pearce, and David Weiman, and participants in seminars at the University of Chicago, Stanford University, UCLA, and the 1990 Cliometrics Society Summer Conference. She also appreciates the valuable assistance she has received from E. N. Brandt, Barbara Brennan, Margaret Lynn, and Delores Goulet, all of the Post Street Archives, and from the archivists at the Baker and New England Depository Libraries. All errors, of course, remain her own. This paper is part of NBER's research program in the Historical Development of the American Economy. Any opinions expressed are those of the author and not those of the National Bureau of Economic Research.

NBER Historical Paper #50
September 1993

PRICE WARS AND THE STABILITY OF COLLUSION: A STUDY OF THE PRE-WORLD WAR I BROMINE INDUSTRY

ABSTRACT

Bromine producers colluded to raise prices and profits during most of the period between 1885 and 1914. Collusion was punctuated by price wars in which prices fell sharply. The characteristics of these price wars are compared with those in the Green-Porter and Abreu-Pearce-Stachetti models. Some of the bromine price wars resulted from the imperfect monitoring problems in these models. Those price wars were short and mild. More severe price wars were part of a bargaining process, in which firms tried to force a renegotiation to a new collusive equilibrium with a different distribution of rents.

Margaret Levenstein
Department of Economics
University of Michigan
Ann Arbor, MI 48109-1220
and NBER

Introduction

During most of the thirty years preceding World War I bromine producers in the United States and Europe colluded, pooling output, dividing up markets, and raising prices. Six times during those thirty years, prices fell sharply, and industry publications such as the *Oil, Paint and Drug Reporter* announced that "a price war was on." Students of cartels have for years argued about the causes and consequences of price wars. Stigler (1964) argues that price wars arise as a result of cheating or entry. The profit created by the cartel create the seeds of its own demise. More recently, game theorists have argued that, operating in a world of imperfect information, cartels may be required to engage in price wars to provide sufficient incentives to prevent cheating. These "equilibrium price wars" do not reflect the demise of the cartel, but are instead a crucial element in its stability. In this paper I analyze internal documents - contracts, correspondence, minutes of negotiations - never before made available to the public, as well as published industry sources, to evaluate the role of price wars in stabilizing, and destabilizing, the bromine cartel.

I find that while the statistical evidence is consistent with the description of equilibrium price wars in Abreu et al (1986, hereafter referred to as APS), a closer examination of the circumstances leading to price wars and the punishments enacted to support collusive agreements suggests a more complex analysis is necessary.

First, the bromine cartel did use the threat of price wars to provide individual firms with an incentive to participate in the cartel, as suggested by Friedman (1971). Second, some price wars did result from imperfect information - that is the inability to distinguish between random fluctuations and real cheating. In contrast to the severe punishments proposed in APS, however, those price wars were relatively short and mild. In other cases, price wars began in response to real, and frequently publicly announced, violations of the collusive agreement. These price wars were the result of disagreements among participant firms regarding the distribution of rents generated by collusion.

These price wars lasted longer, and prices fell much further. It is more sensible to describe these price wars as breakdowns in collusion, perhaps resulting from coordination problems, than as equilibrium punishments.

This paper is divided into four sections. The first section gives a brief history of the bromine industry and describes the structure of the bromine cartel. The second section evaluates the success of the cartel in raising prices and restricting output. The third section uses two simple statistical tests to distinguish between industries implementing APS and Green-Porter (1984) type collusive strategies. The final section examines in more detail the circumstances leading to each of the bromine price wars, and explores the implications for modelling oligopolistic collusion.

I. The Bromine Industry: background and cartel organization

Collusive institutions controlled the bromine market during most of the period between 1885 and 1914. Both the composition of the industry and the internal structure of the bromine cartel changed during this period. From 1885 to 1902, a bromine pool, working closely with two distributors, controlled the bromine market. The entry of the Dow Chemical Company into an industry previously characterized by a number of small, equal-sized, technologically similar firms introduced new tensions into the pool. The pool was able to mediate those tensions until 1902, when Dow withdrew its cooperation from the pool. A more informal agreement to refrain from price cutting allowed relatively high prices to remain in effect until 1905. Between 1905 and 1908 bromide prices spiralled down, as Dow and the German bromine cartel battled for control of the world market. A truce was established in 1908, with a new division of world markets between German and American producers.

Bromine was first produced commercially in 1845 (Haynes 1954). During the Civil War medics discovered the sedative properties of potassium bromide. It quickly became a popular offering of patent medicine producers as a cure for headaches and nervous disorders. In Europe bromine was used in the production of aniline dyes, but such demand was virtually nil in the United States until after World War I.

Before 1892, a dozen small companies, mostly located near the Ohio River in southeast Ohio and northwest West Virginia, produced the entire U.S. output of bromine.[1] Underground brine was pumped and heated, allowing removal of the bromine.

The Ohio River firms sold liquid bromine to "manufacturing chemists." The manufacturing chemists were larger, urban companies with manufacturing facilities and well-established sales networks. They converted the volatile liquid bromine into potassium bromide powder, and distributed it to pharmacies around the country. The most important manufacturing chemists in the bromine industry, Powers & Weightman (P&W) and Mallinckrodt Chemical Works, supplied hundreds of pharmaceutical products to their customers around the country.

Mallinckrodt and P&W helped organize the bromine pools. Their role included the negotiation of market division agreements with the only other significant producers of bromine, the German potash mines.[2] The German bromine producers all belonged to a sister cartel to the German potash cartel, which had the active support of the German state (Tosdal 1916).

In 1885 the first bromine pool was established. Under the name the National Bromine Company (NBC), it contracted with the Ohio River firms to purchase the entire domestic output of bromine for the next five years. The NBC contract specified the price the Ohio River producers would receive for their bromine, and prohibited them from selling to anyone but the NBC.

---

[1]*Manufactures of the United States at the Tenth Census*, pp. 21-22, Crawford (1935), p. 1109, and "history of the bromine industry", undated, Dow Chemical Company internal records, undated, file #050036. All "file" cites refer to items in the Herbert Dow Papers.

[2]See Levenstein (1993) for further discussion of the role of the manufacturing chemists in facilitating collusion.

Mallinckrodt and P&W in turn agreed to purchase all of the NBC's bromine (Figure 2).[3] Mallinckrodt and P&W made regular, coordinated announcements of the price of potassium bromide. Prices for potassium bromide rose from a low of 26.5 cents per pound at the end of 1884 to 34 cents immediately after the signing of the NBC contracts in March 1885 (Figure 1).

The NBC expired by limitation of its charter in March 1891. A new pooling and territorial division arrangement was not achieved until the following October.[4] W. R. Shields, of Columbus, Ohio, was the principal of the new pool. Shields at one time owned a salt and bromine plant in Ohio, and was closely connected to the management of other Ohio River firms. Shields played a key role in negotiating each of the bromine industry's collusive accords up until 1910. At different times, Shields was employed by both Dow and Mallinckrodt.[5]

Shields contracted with each of the U.S. bromine producers to purchase its entire output for the next five years. He contracted with Mallinckrodt and P&W to sell them all the bromine to be converted into bromide salts (Figure 3). Mallinckrodt and P&W agreed, with the German bromine cartel, to refrain from shipping abroad and to prevent any American bromine from being exported. In return, the Germans agreed to purchase $25,000 of bromine from the American manufacturing chemists each year.[6]

---

[3] *Mineral Resources of the United States* (*MRUS*) 1885, pp. 486-487, *Oil Paint and Drug Reporter* (*OPDR*) Anniversary Supplement March 3, 1897, and *OPDR* July 28, 1885, p. 38.

[4] *OPDR* October 3, 1892, p. 38, October 10, 1892, p. 7, and letter from W. R. Shields to Herbert Dow, December 9, 1892, file #920004, quoted below.

[5] Letter from Herbert Dow to H. E. Hackenberg, secretary of the Dow Chemical Company, June 11, 1909, reports his offer to Shields of "a salary of $100 per month ... for such information as he is able to gather and transmit to us regarding the Ohio River and other bromin or bromid matters" file #090019. Letter from Dow to Hackenberg, February 12, 1910, indicates that Shields may be a paid agent of the Pomeroy Salt Association, file #100011. Letters from Dow to Hackenberg, May 12, 1910, and June 6, 1910 indicate that Shields was working for Mallinckrodt, file #100013.

[6] Letter from J. H. Osborn to Herbert Dow, November 18, 1896, file #960005.

During the period of the "Shields pool" Herbert Dow began to produce bromine and bromides in Midland, Michigan in a new firm, the Midland Chemical Company.[7] Mr. Dow, a young chemist and inventor, had developed a new process for separating bromine from brine. His process was electrolytic rather than thermal. It introduced the continuous, integrated production of elemental bromine and bromide salts, replacing the costly, time consuming, and dangerous procedure of all other producers, in which liquid bromine was put into small glass bottles and shipped to a manufacturing chemist, who then emptied out each bottle and combined it with potassium (Campbell and Hatton 1951 and Whitehead 1968). Though perfection of the process took some time, it eventually produced bromine and bromide salts at lower cost and higher purity than had previously been achieved. Its minimum optimal scale was at least ten times that of the Ohio River producers.

Although Midland, and its successor, the Dow Chemical Company, never joined the bromine pool, their actions allowed the collusive setting of prices to continue. In 1894 Midland signed a one-year contract directly with P&W and Mallinckrodt (bypassing Shields) to sell them its entire output at a fixed price (Figure 3).[8] The contract limited Midland's total output, and prohibited it from selling bromides to any other party. Midland signed two more one-year contracts with Mallinckrodt and P&W before agreeing to a five year contract, with similar terms, in 1897.

In the Spring of 1902 Dow ended its cooperation with the bromine pool. It signed contracts with two competitors of Mallinckrodt and P&W, Rosengarten & Sons and George Merck & Company, to distribute Dow bromides.

Dow began to supply its new distributors when its contract with Mallinckrodt and P&W

[7]Herbert Dow was the first general manager of the Midland Chemical Company, incorporated in 1892. The Dow Chemical Company, also of Midland, Michigan, was founded in 1897. The two companies merged in 1900.

[8]Letter from B. E. Helman, treasurer of the Midland Chemical Company, to H. S. Cooper, general manager, March 23, 1894, instructing him to begin shipments to P&W and Mallinckrodt on the new contract, file #940003.

expired in August. Shields' contracts with the Ohio River producers expired in October and were not renewed.[9] After a brief price war, described in more detail below, Dow and Mallinckrodt agreed to refrain from undercutting one another's prices.

At this juncture Dow had its first direct contact with the German bromine combine. Its director, Herr Jacobsohn, visited Dow in August, at the expiration of P&W and Mallinckrodt's contracts. This conference was followed by a confirming letter,

> With reference to the interview which took place a short time ago between your Mr. Dow and our Mr. Jacobsohn, we have to thank you for the kind reception extended to the latter and beg now to confirm the agreement entered into by your Mr. Dow on behalf of your Company, by Mr. Jacobsohn on behalf of the German Bromine Combine, to the effect that the Dow Chemical Co. engage on their own and their agents' and their customers' behalf not to export or allow to be exported any Bromide of Potassium to the European market, whereas the German Bromine Manufacturers undertake at and for the same time not to export or allow to be exported any Bromide of Potassium to the United States of Amerika [sic] (September 23, 1902, file #020069).

Dow confirmed agreement to this understanding in a letter on October 15, but, in fact, soon began secretly exporting bromides to Europe.[10] The growing tensions between Dow and the Germans did not disrupt the U.S. market until three years later, when the German's abrogated their side of the agreement and entered the U.S. market.

Dow and the Germans came to an extensive and detailed price setting, market division agreement at the end of 1908. Under that agreement, Dow and the Germans jointly set prices in the U.S., Europe, and the "Rest of the World." Dow withdrew from the European market in return for a payment of $32,000 a year. Dow was guaranteed a one-third share of all bromine sales in the "Rest of the World," conditional on its appointing a Hamburg chemical house as its sole representative in

[9]"The bromine trust has come to an end...." *OPDR* October 6, 1902, p. 42.

[10]Dow wrote, "The agreement as outlined in your letter of Sept. 23" is satisfactory to us. We will use our best efforts to see that no Bromid of Potash is exported to Europe without giving you previous notice of such shipments in consideration of your treating us in like manner as regards this side of the Atlantic," October 15, 1902, file #020069.

the neutral territory.[11] The Germans completely withdrew from the North American market.[12] This agreement, with various modifications, remained in force until the beginning of the First World War.

Dow simultaneously signed ten-year contracts with three manufacturing chemists, Powers-Weightman-Rosengarten, Merck, and Mallinckrodt to supply them with all their requirements of bromine (Figure 4).[13] The contract prohibited the manufacturing chemists from purchasing bromine from the Ohio River producers. Dow in turn made the three its "exclusive" pharmaceutical bromine representatives within the United States, except for several patent medicine producers and large industrial customers which it supplied directly (Figure 4). Dow kept the price of potassium bromide in the United States quite low (below 20 cents per pound) for a year and a half after its agreement with the Germans (Figure 1).[14] At this price the Ohio River producers could not profitably sell their bromine to anyone to convert into bromide salts, nor convert it themselves.[15]

In May 1910 Dow contracted with all but one of the Ohio River producers to purchase their

---

[11]Contract, October 29, 1909, letter from Dow to Julius Grossmann of same date, file #090024, and Dow to Grossmann, September 22, 1909, file #090023.

[12]"Final agreement between the Dow Chemical Company, represented by H. H. Dow and H. E. Hackenberg, and the German Bromine Convention, represented by Herman Jacobsohn, Robert Voss, W. Bruckman, and Walter Hoehl, on November 26, 1908" at London, England, file #080017 and "Report of meeting with representatives of Vereinigte Chemische Fabriken zu Leopoldshall A.-G.," November 24-26, 1908, by H. E. Hackenberg and Herbert Dow, file #080017 and *OPDR* December 7, 1908, p. 35.

[13]Contract, dated November 1908, between Dow, Mallinckrodt, and Powers-Weightman-Rosengarten, file #090105.

[14]Letter from Herbert Dow to Deutsche Bromkonvention, December 27, 1909, "... regarding the effect of increasing the price on Bromides ... an advance beyond the equivalent of 21 cents per pound for Potassium Bromide ... would not be advisable for the reason that a firm on the Ohio River, which manufactures a small amount of Bromine, has just begun the manufacture of Potassium Bromide..." file #090026.

[15]As mentioned in note 14 above, such attempts were made. The product was not pure enough, however, to pass the pharmacopeias of Europe and the United States (letter from Dow to Deutsche Bromkonvention, December 27, 1909, #090026, and correspondence between Dow and Shields during 1909 and 1910).

entire output of bromine on a sliding scale price, based on the published market price of potassium bromide (Figure 4).[16] Thus Dow controlled competition at home and prevented the export of bromides into territory reserved for the Germans. Prices of bromine and its salts rose slowly but steadily until the beginning of World War I (Figure 1).

Six price wars disrupted cooperation during the period of this study (Table 7). Each of these price wars was described as such in the leading industry publication, the *Oil, Paint and Drug Reporter*, which regularly and explicitly discussed pool activity. Three of these price wars preceded Dow's entry into the industry; for convenience, I have denoted these Pool Wars I, II, and III. The three price wars following Dow's entry have been named Dow Wars I, II, and III. The history of these price wars will be discussed in more detail in section IV below.

II. Evaluating the success of the cartel

Before analyzing in more detail the function of price wars in the bromine industry, we address a more basic question. Was the bromine cartel a success? Did it restrict output, raise prices, and increase the profits of the participating firms? And if so, by how much? I present two types of evidence of the success of the cartel: first, direct and indirect evidence of excess profits, and second, comparison of prices during periods of cooperative behavior with periods where cooperation had broken down. The evidence supports the contention of this paper, and the belief of the participants in the industry, that cooperation increased prices and profits.

A. Excess profits evidence

Because their account books have not survived, direct profit measures for the Ohio River firms and Mallinckrodt and P&W are not available. Evidence of Midland's profitability is available. Between 1894 and 1900, potassium bromide sold to Mallinckrodt and P&W was Midland's sole

[16]Dow signed contracts with Schlaegel, Buckeye, Excelsior, J. Q. Dickenson, and Hartford City on May 19, 1910, file #100044.

product. Midland issued its first dividend after signing its contract with Mallinckrodt and P&W in 1894. Regular monthly dividend payments of two to five percent followed.[17] Annual interest rates in the region averaged less than 6.5% (Davis 1965). It is, of course, difficult to distinguish between profits accruing to cartel prices and those accruing to Dow's patented inventions.

The substantial and continuing investment of industry participants in maintaining collusion provides indirect evidence of its success. Dow, Shields, Mallinckrodt, and the Germans all made trans-Atlantic trips for no other purpose than to negotiate collusive agreements. Similar trips were regularly made to St. Louis, Philadelphia, Michigan, and the Ohio River Valley. These firms presumably expected at least a normal rate of return on this investment. Shields supported his family for a decade on the rents which he retained for his role in organizing the bromine pool.[18]

Thus while direct evidence of excess profits is not available, the indirect evidence is not inconsistent with the existence of such profits. Furthermore, there is evidence that one firm earned very high rates of return, and that large sums of money were available to facilitate the cartel's continuation.

B. Price Trends

The price of bromine fell continuously after the commencement of commercial production. It fell from six dollars a pound before the Civil War to thirty cents in 1875. It fell 7% between 1875 and 1880, and almost 30% between 1880 and 1884 (Table 1).

With the establishment of the bromine pool in 1885, this trend reversed. Prices increased

---

[17]Levenstein (1991, p. 64), letter from B. E. Helman to H. S. Cooper, July 16, 1895, file #950014, H. H. Dow to A. W. Smith, February 7, 1910, file #100002, and Whitehead (1968) p. 37.

[18]Shields' earnings were not simply a return on bromine distribution services. After Dow contracted with the Ohio River firms in 1910 it offered them money that Shields had previously been offered for his cooperation. If Dow had been providing similar "distribution" services itself, it would have required a return on the cost of providing those services. Instead, having achieved control over the market, excess profits were available to purchase the good will of the Ohio River firms (letter from Dow to W. H. Van Winckel, Dow Sales Manager, June 8, 1910, file #100041).

23% over the course of the year (Figure 1). The average price of potassium bromide during the NBC pool (1885-1891) was almost ten percent higher than the average price of the previous five year period.[19] When the NBC contracts terminated in 1891, prices returned to their pre-pool pattern, falling by almost thirty percent (Figure 1).

With the establishment of the Shields pool in October 1892, prices began a steady upward climb. The average price during the Shields pool was 60% higher than during the period between the pools.[20] At the expiration of the Shields contracts in 1902, the price again fell quite sharply (43.2% in one month).

After 1902, the importance of Dow's output, produced at lower cost, makes comparisons with pre-1885 prices less meaningful. The average price after 1902 was lower, during both cooperative and non-cooperative periods, than during the preceding decades. The difference between prices during cooperation and non-cooperation remains. Between 1902 and 1914, the average price during cooperation was almost 75% higher than during non-cooperative periods.[21] Similarly, the price increased by almost 50%, from 13¢ to 19¢, on December 21, 1908, when the Dow-Deutsche Bromkonvention agreement took effect. The price trend for the previous three years had been flat or negative (Figure 1). The price remained at 19¢ until May 1910, when the extant Ohio River firms

---

[19]After the NBC contracts went into effect, virtually all elemental bromine traded at contract prices. The bromine price quotations in the trade press (e.g. *OPDR*) were for small lots of bromine purchased from the NBC, not the Ohio River producers. For market prices, we rely on quotations of <u>bromide</u> prices. The average price of potassium bromide between February 18, 1880 and February 11, 1885 was 31.07¢. The comparable price during the NBC, February 18, 1885 to March 4, 1991, was 34.08¢. The average price during "non-price war periods" of the NBC was 34.29¢.

[20]The average price of potassium bromide during the Shields pool (October 13, 1892 to October 20, 1902) was 40.88¢, 60% above the average price of 24.75¢ from March 11, 1891 to October 3, 1892. Since the low price in between the two pools could reflect pricing strategies below competitive prices, the relevant comparison may be to the pre-pool prices of 1880-1885. The increase associated with the Shields pool would in that case be 31.6%.

[21]The average price of potassium bromide during non-cooperative periods was 16.8¢. The average price during cooperation was 29.3¢.

agreed to sell their output to Dow. Immediately thereafter prices began an upward trend that continued until World War I. By 1914, nominal prices had returned, despite continued decreases in costs, to the levels charged prior to the breakup of the pool in 1902 (Figure 1).

All of these results hold if we examine real instead of nominal prices.[22] The secular decline in bromine prices remains: the real price fell over 90% between 1860 and 1880. It fell another 18.4% from 1880 till the founding of the NBC in 1885. The pool reversed this trend; the real price increased 15.6% during the 1885. The average real price was consistently higher during cooperative than non-cooperative periods, both before and after Dow's entry.[23]

Each and every change in price trends can be explained by a change in the cooperative behavior of the firms in the industry. Prices were higher during periods of cooperation than non-cooperation. There is no evidence that changes in demand or cost can explain the price trends observed.

C. Price-cost margins

Direct comparison of prices and costs suggests that the pool succeeded in pricing above marginal costs. We do not have cost data from the Ohio River manufacturers themselves. However, Dow estimated the marginal cost of producing a pound of bromine, using the Ohio River process, at 12¢.[24] The price Ohio River producers received from the pool was not the figure reported in the *Oil, Paint and Drug Reporter*, but that specified in the pool contracts. We do not know the NBC

---

[22]Nominal bromine and potassium bromide prices have been deflated using wholesale chemical price indices from the *United States Historical Statistics* (series E49 and E60), pp. 200-201.

[23]The average real price was 21% higher during the NBC pool than during the previous five years. At the expiration of the NBC, the price fell over 40%. The average price during the Shields pool was 64% higher than during the period between the NBC and Shields pools. When the Shields contracts expired in 1902, the price dropped 32% in one month. After 1902, real prices were, on average, 74% higher during cooperation than non-cooperation.

[24]Minutes of Conference at Midland, Michigan, January 27, 1902, file #020026.

contracts prices, but we do know the prices in Shields' contracts. Shields purchased the entire stock on hand on the Ohio River in 1892 at 14¢ per pound. The Ohio River producers received 16¢ per pound during the first year of the contract, and a 2¢ increase each year (up to 22¢).[25] Assuming Dow's estimate was correct, the Ohio River firms received prices above marginal cost.

Figure 5 reports estimates of the cost of manufacturing potassium bromide during the Shields pool and compares them to the price of potassium bromide. The average price during this period was 40.9¢, while the average cost was 24.1¢. The average markup over cost during the Shields pool was almost seventy percent. Fluctuations in the cost of potassium bromide do not explain changes in its price. The correlation between changes in price and cost is not even positive (-0.042).

Dow's average cost of a pound of potassium bromide before 1902 was about 8¢.[26] Dow's contract with Mallinckrodt and P&W between 1897 and 1902 specified a price of 25¢ per pound. After 1902, Dow's average cost increased, as its contracts with Merck and Rosengarten required that it produce a wider variety of bromide salts than had previously been the case.[27] Between 1902 and 1905, Dow's bromide cost averaged 10¼¢. Dow's contract with Rosengarten and Merck specified that Dow receive 80% of the *OPDR* price. Thus the price-cost margin during cooperative periods between 1902 and 1905 averaged 12.7¢, an over 100% markup on costs.[28]

D. Price stability

The stability of prices during cooperation was greater than during non-cooperative periods.

---

[25]Letter from Herbert Dow to H. L. Davies, November 11, 1903, file #030039.

[26]Weekly Factory Reports, file #010070.

[27]Dow correspondence, 1903, files #030030, #030046, and #030044.

[28]The price-cost margin was greater than this. This calculation compares the average cost of producing all bromides with the price received on potassium bromide. The prices received on other bromides were substantially higher.

This does not imply that prices were higher, but does suggest that they were set non-competitively.[29] During cooperation prices changed on average every 41.1 weeks. During non-cooperative periods prices changed every 11.5 weeks. The results are similar if the pool (1885-1902) and post-pool (1902-1914) data are separated. During the pools, prices changed every 35 weeks during cooperation, every 6.8 during non-cooperation. After 1902 the pattern remained; prices endured 64.7 weeks during cooperation, 17.5 weeks during non-cooperation. The point here is not that prices did not change during cooperation; they did. But the monopoly power exerted by cooperating firms allowed them to ignore minor fluctuations in demand or cost. It may have even required infrequent price changes as they had to be coordinated among firms in different regions. During non-cooperative periods, many firms independently announced prices, increasing the probability that a price change would occur in any given week.

Average prices were higher during periods of cooperation. Prices increased during cooperation, and fell at its conclusion. Prices were well above costs, and fluctuations in costs cannot explain fluctuations in prices. Price fluctuations were greater during non-cooperative periods, reflecting the independent price setting behavior of firms. All this scheming was not for naught. Cooperation in the bromine industry did succeed in increasing prices and profits.

E. How much success is success?

Having concluded that the bromine cartel was successful, one might ask, how successful? Bromine prices exceeded competitive levels, but did they approach the joint-profit maximizing price? How large were the welfare losses? Table 2 presents three different paramaterizations of demand,

[29]The issue of price stability under different types of market organization has recently been addressed in Slade (1991).

each of which is consistent with aggregate data.[30] The monopoly prices implied by these demand functions range from 40¢ to 93¢ per pound. The most reasonable of the three (Demand Function I) implies a monopoly price of 47.3¢, a Bertrand price of 16.6¢, and a Cournot price of 21.3¢. The price during collusive periods ranged from a low of 19¢ to a high of 46¢. The average price during the pool period (1885-1902, excluding price wars) was 38.6¢. This suggests that the pool increased prices above the perfectly competitive price, and usually above Cournot levels, but did not permit collusion to the extent that would have been possible under monopoly.

Again using Demand Function I and a 38.6¢ price, the deadweight loss induced by collusion was about $45,000 per year. While for the average consumer this amounted to virtually nothing (less than six one hundredths of a penny per capita in 1900), it is about twenty-five percent of average industry revenues.[31]

III. Comparing models of price wars

If collusion in the bromine industry was successful, why were there price wars? Were price wars more likely to arise from problems of private information (e.g. cost or output levels) or coordination and bargaining (e.g. choosing an "equitable" distribution of rents)? Did these price wars help to resolve structural tensions, as is the case with "equilibrium price wars," or did they simply further disrupt collusion and require the renegotiation of a new collusive structure?

Green and Porter (1984) and APS have described price wars as punishments that make

---

[30]Demand Function II is the least consistent with firm level data. The implied monopoly price is lower than prices charged by the pool. The twelve firm Cournot output level implies a bromine output level that is greater than was the case for any of the Ohio River firms. Demand Function III, on the other hand, errs in the other direction, implying an extremely high monopoly price and a very steep demand curve. This curve more likely reflects demand at the end of the period under study, when (as a result of research by Dow and others) new uses for bromine were found. Most of the following discussion focuses on Demand Function I, which most accurately captures demand during the period under study.

[31]Using demand function I, the deadweight loss associated with 38.6¢ price is $44,567.73. Total industry revenues under this scenario are $197,516.20.

collusion feasible. Friedman (1971) demonstrated that price war threats can provide sufficient disincentive to cheating to permit a patient, oligopolistic industry to collude. However, price wars were never observed in equilibrium. Green-Porter and APS argue that the successful use of punishment threats in an industry where cheating is unobservable will occasionally require their implementation. When firms cannot directly observe deviations from prescribed strategies ("cheating") they rely on observations of a public variable (e.g. prices) whose distribution depends jointly on the actions of each firm and a random disturbance. When the public variable falls into a certain range (e.g. prices fall below some p^*) firms revert to punishment behavior (e.g. higher output levels). Price wars occur despite incentives being set so that firms do not cheat; since firms cannot distinguish between cheating and low realizations caused by random fluctuation, they must punish to keep incentives intact.

Both Green-Porter and APS predict that price wars will follow an unexpectedly low realization of the public variable.[32] Green-Porter predict that price wars will either be permanent or last for a fixed number of periods. APS, on the other hand, predict that price wars will continue until the public variable indicates, with high probability, that all players have participated in the punishment. Thus price war duration is stochastic, and the state of the industry (collusion or price war) follows a first order Markov process.

Berry and Briggs (1988) suggest a procedure for testing whether an industry which is known to have switched from collusive to "price war" phases was implementing an APS-type mechanism. They test whether the state of the industry follows a first order Markov process, against the

---

[32]APS does not restrict us to trigger price strategies. If a realization in a bounded range were a better predictor of cheating, it would be a realization in that range that would precede a price war.

alternative of a Markov process of higher order.[33]

They use this procedure to test data from the Joint Executive Committee (JEC), a nineteenth century railroad cartel, and conclude that it was more likely to have been implementing an APS type agreement than a Green-Porter one (as concluded in Porter 1983). I replicate their test for the bromine industry for the period 1885-1914. I construct two series, both of which measure the state of collusion in the industry.[34] The first series has periods of one week length. This was the frequency of public price announcements. The second series has one month periods, which more closely correspond to the time it took to arrive at a coordinated response, given the geographical distance separating firms.[35]

The bromine industry results resemble those Berry and Briggs obtained for the JEC. Where it was possible to formally test the hypothesis of a first order Markov structure against one of second or

---

[33]This alternative is approximately that suggested by the Green-Porter model. Their model suggests that the industry will stay in the low profit regime (with probability one) for T periods. If we let T be a random variable (with mean equal to the optimal T*), the probability of switching would be a function not simply of the previous period, but an increasing function of the difference between the number of periods since the switch and T*. Thus for a given T*, the state variable will follow a Markov process of order T*.

[34]Each series $\{I_t\}$ is defined such that $I_t = 1$ if firms in the industry are colluding that period, $I_t = 0$ otherwise. The data are based on published reports of collusive activity in the *Oil, Paint and Drug Reporter* and the private papers of the Dow Chemical Company and other firms in the industry. Price data were <u>not</u> used to construct these series.

[35]I do not use an estimated series, as Berry & Briggs do, because the sales data necessary to replicate the switching regressions of Porter (1983) and Lee and Porter (1984) are not available. Their technique would not successfully identify switching in the supply behavior in the bromine industry because demand was unstable across switches in supply behavior. Bromine is non-perishable good. When consumers observed a fall in price and believed it was due to a short-term break-down of collusion, speculative demand arose. The response to a similar fall in price, if believed to be permanent was quite different. Instances of such speculative demand are recorded in both the *OPDR* and Dow internal memoranda. To make estimation even more difficult, there were instances where a break in prices was associated with consumer beliefs that there would not be a rapid settlement but even lower prices. In that case, the price decline caused a completely cessation of demand. Thus, without controlling for the beliefs of consumers about the future actions of suppliers, successful estimation of supply behavior is unlikely.

third order, it was impossible to reject the null that more distant periods were irrelevant (Tables 3 and 4).[36] On the other hand I could reject the hypothesis (with greater than 99.9% probability) that the probability of observing a collusive phase was constant and independent of history when tested against the alternative that one-period histories mattered (Table 5).

Where formal hypothesis testing was not possible, because the variance of one of the probability estimates is zero, I can, again following Berry and Briggs, say that it is not at all unlikely, under the null of a first order Markov process, that we would observe the realizations that give us the zero variance. Thus the observation of a zero variance for this small sample is not inconsistent with the null hypothesis. Tables 3 and 4 present probability estimates for each case where we observe a zero variance. In no case is the probability of observing such a realization less than 68%.

In another, more general test, I compare the empirical distribution of the duration of price wars with the hypothesized distribution under a first order Markov process (using the estimated transition probabilities presented in Table 5).[37] I conduct a goodness of fit test using the Kolmogorov-Smirnov test statistic. Using both monthly and weekly data, we accept the hypothesis of a first order Markov process (Table 6).

This would suggest that the bromine industry provides another example of APS type collusive equilibria in nineteenth century markets. However, if we look closely at the history and characteristics of the price wars, serious questions are raised.

The bromine price wars do not display the characteristics of the optimal punishment described

---

[36]The test is essentially a test of the equality of means (probabilities) following the same k-period histories. The test statistic, $(Rp_i)'(RVR')^{-1}(Rp_i)$, follows a chi squared distribution (under the null), when $Rp_i = 0$ is a matrix representing the restrictions under the null that the probabilities following similar k-period histories are equal and $V = \text{diag}\{v_1, v_2, \ldots, v_{2m}\}$ is the $2^m \times 2^m$ variance matrix of p_i. A consistent estimate of v_i is $p_i(1-p_i)/N_i$. The test statistic has degrees of freedom equal to the number of restrictions in R (Berry and Briggs 1988, p. 74).

[37]I am indebted to Kevin Lang for suggesting this test.

in APS. The optimal punishment in APS, following any history, is always the same, specifies the same behavior in every punishment period, and is the worst possible equilibrium punishment. None of these are true of the bromine price wars (Table 7). The initial fall in price varies (ranging from 1¢ to 15¢, or 3% to 50%, Table 7). During the first two price wars (Pool I and Pool II) the price is constant, but prices spiral down in other price wars (Table 7, "weeks to trough"). The lowest prices reached also differ from one another (32.5¢ to 13¢). Even if one ignores the last price war (Dow III) which occurred after a decline in average costs, there is still wide variation in the initial drop, total drop, duration, and lowest price. There was no single, commonly understood, "worst" punishment to which the industry reverted.

In general the price declines during these wars were not large enough to reduce the expected present discounted value of the firm's future profit stream below the Cournot reversion level (as proposed by APS). Only the low prices of Pool III and Dow III wars reached the one shot Cournot level.[38] (Compare Tables 2 and 7.) During no price war do prices fall below marginal costs.[39]

IV. The functions of price wars in the bromine industry

The characteristics of the bromine price wars differ because they had different causes; they were the result of different kinds of strategic behavior. There appears to have been a relationship between the cause of the price war and its duration and depth. In particular, those price wars resulting from the inability to perfectly monitor compliance are characterized by the simplicity, but

---

[38]The low price during the 1905-8 price war is 13¢, less than the 20.5¢-23.6¢ range for the Cournot price reported in Table 2. But the cost function presented reflects the costs of the Ohio River producers. Dow's costs were much lower so the estimates in Table 2 no longer apply in 1905, when Dow produced more than half the U.S. output.

[39]This is true as well for Dow War III, when prices are compared to Dow's costs. The low price reached was 13¢, but Dow's marginal cost was less than 10¢. The German's costs are not known, though they did pay an import duty that almost certainly raised their costs above Dow's. The German cartel provided subsidies from other potash firms to bromine producers when bromine prices fell.

not the severity implied by APS. In contrast, price wars resulting from coordination failures displayed more complicated price patterns and were more severe in both depth and duration. Threats of price wars remained crucial to the stability of collusion.

A. History of the Bromine Price Wars

Pool War I (1886-7) began when the Germans exported bromides to the United States and offered them below the NBC price. After 22 weeks of imports, the Germans and Americans agreed to withdraw from each others' markets.

> One outcome of the importation of bromine in 1886 and '87 was the arrival at an understanding between the American and foreign combines under which each was to restrict its operations to its own field and not attempt to evade [sic] the market of the other, thus accomplishing, no doubt, the purpose of the importers (*OPDR* June 29, 1891 p. 5).

Pool War II (1888) resulted from the Germans' belief

that this agreement had been violated. It is not clear whether the Germans were simply mistaken or whether there were resales of bromine by U.S. customers who were not party to the market division agreement.

Pool War III (1891-2) began at the expiration of the NBC pool contracts. It occurred, despite attempts to negotiate new contracts, because of disagreement over the distribution of rents between the Ohio River producers and Mallinckrodt and P&W.[40] In order to increase their bargaining power, bromine producers sold bromine to other manufacturing chemists who had not been party to the NBC pool agreements.[41] After over a year and a half of falling prices, the Shields contracts described

[40]"In March of 1891 [the NBC] expired, because of the inability of the company to renew expiring contracts with the consumers [the manufacturing chemists]" *MRUS* 1891 p. 579.

[41]"Since the dissolution of the [NBC] pool at least two manufacturers [of potassium bromide] have purchased car lots of American bromine at 19 and 22 cents respectively, and one of them, who has for some time been out of the business, will probably be able to deliver bromide this week. At the price paid for their bromine, these manufacturers could easily undersell the present market and still make money.... [O]ur expectations of a very interesting fight are being fulfilled..." *OPDR* August 10, 1891, p. 5.

above (page 4) were signed.

Dow War I (1902) began when Dow contracted with Rosengarten and Merck, instead of Mallinckrodt and P&W (page 5, above). Despite Dow's selection of distributors known to refrain from price cutting, Mallinckrodt and P&W announced a price cut as soon as the Shields pool contracts expired. This price war was the briefest in the study, lasting only six weeks. It was resolved by an exchange of letters between Dow and Mallinckrodt in which each agreed not to undercut the published market price.[42]

Collusion broke down again in 1903 (Dow War II) when some firms (Dow, Merck, and Rosengarten) raised their price quotation, while other firms (Mallinckrodt and P&W) did not. For 21 weeks there was a large spread in the published price quotations (between 25 and 43¢ for seven weeks, between 30 and 38¢ for fourteen weeks). Few sales took place at either the low or high quotations, because of reluctance on the part of sellers and buyers, respectively.

Dow War III, the last and longest price war began in 1905. The Germans retaliated against Dow's entry into the European market by offering bromides in New York City at half the current market price. Mr. Dow recounted the onset of this price war in a letter to one of the Company's founders, the President Emeritus of Case School of Applied Science, Cady Staley. He wrote,

> ... Formerly the Germans had the monopoly of the business of the whole world outside of the United States, and Powers & Weightman and Mallinckrodt, who controlled the Bromide situation here had an understanding with them, whereby the Germans kept out of the United States in consideration of the American producers keeping out of the rest of the world.
>
> A few years ago [we] went after that trade, as it was quite profitable. The Germans resented it and ... reduced their price throughout Europe to 27 cents, thinking that would absolutely shut off all American importations, as they thought our costs were about 25 cents.... [W]hen they found that our foreign business was increasing they took the very radical step of making a 15 cent price in the United States, on which they paid a 7 cent import duty ... [B]efore the fight began they were getting about 49 cents for their Bromides at home. When this 15 cent price was made over here, instead of meeting it, as we could readily have done at a good profit, we pulled out of the American market altogether and used

[42]Letter from Edward Mallinckrodt to Herbert Dow, November 24, 1902, and response, November 29, 1902, file #020040.

all of our production to supply the foreign demand. This, as we afterward learned, was not what they anticipated we would do...

[O]ur Bromide is always sold at a profit and we have reason to think that our competitors in Germany have lost considerable money during this fight. In the meantime all other producers of Bromine in this country have shut down and we are therefore in a much stronger position than we ever were before, by reason of the Germans having respect for us, which is a very hard thing to obtain, for the reason that they cannot conceive that it is possible for anyone outside of Germany to compete with them in the manufacture of any chemical. In most lines they are undoubtedly invincible and it is hard for them to realize that this does not apply to all lines ... (October 25, 1906, file 060060).

This price war lasted another two years. It was resolved only after prices fell to all-time lows and Dow representatives made three trans-Atlantic trips to negotiate a new agreement with the Germans.

B. Threats of price wars supported collusion

Threats of a price war enforced collusive behavior in the bromine industry. Correspondence among industry participants is replete with dire warnings of imminent price wars if the reader did not cooperate. Internal Dow documents are explicit that such threats induced the Company's cooperation.

For example, shortly after Dow began production of bromides, he received a letter from Shields, which reads in part,

> After the dissolution of The National Bromine Co. in March, 1891, the price of bromine came down from 25 to 15 cents and at that price was a drug in the market ... In October last I purchased the entire out-put of bromine for 5 years ... I have a clause in each contract that should a new producer of bromine appear, I reserve the right to annul the agreement ... I have given your Mr. Hellman [sic] a copy of the contract. I am willing to buy your product at same price and terms ... I am assured by Mr. H. that he will call a meeting of the company and act in the matter. The matter is in your hands. [Mallinckrodt and P&W] will not continue unless all are in and again I could not hold them together with anyone outside. In fact do not wish to (December 9, 1892).

Following these discussions between Helman and Shields, Midland agreed to restrict its output and sell only to Mallinckrodt and P&W.

Similar concerns also explain Dow's continued cooperation with the pool over the next decade. Because its technology had increasing returns to scale, Midland was anxious to increase its output.[43] Between 1894 and 1896, Midland's output quota increased from 150,000 to 200,000 pounds, but its capacity during this period was over 350,000 pounds per year.

When negotiations began in 1896 to renew the contracts with Midland and the Ohio River producers, Midland considered ending its cooperation with the pool. It even considered paying the Ohio River producers, either for their bromine or not to produce. The five year contract Midland eventually signed with Mallinckrodt and P&W limited its output to 200,000 pounds annually.[44] The ultimate acceptance of a contract with which it was clearly unsatisfied was largely the result of its belief that P&W and Mallinckrodt had accumulated 800,000 pounds of bromine, which they threatened to put on the market if Midland did not agree to cooperate with the pool.[45] As Helman so vividly put it in a letter to Dow,

> I think you and Cooper [general manager] are completely 'off' on the matter of over-production... You men must reconstruct your policy unless you can prove there is no over-stock in warehouses. If there are in storage today 500,000 [pounds] (and I am low) how would that affect us if we were to roll up our sleeves and get into the ring? The answer is in sight. ... I believe and repeat that if we want a fight, <u>now</u> or <u>soon</u> is a good time <u>but</u> we would come out of it with feathers gone, minus a leg, wings broken, and breath spasmodic. Prices would be low. If the market is low as I long supposed then we could do it but if there is on <u>hand</u> a large surplus we would be ruined. There is no question about the outcome (November 23, 1896, file #960035).

Agents of the bromine pool made specific and concrete threats of price wars to recalcitrant industry participants. These threats provided an essential component in firms' decisions to cooperate with the pool.

C. All price wars are not the same

---

[43]An obvious question is why P&W and Mallinckrodt did not purchase their entire requirements at a lower price from Midland. First, the Ohio River firms would not immediately exit. Second, P&W and Mallinckrodt did not want to accept the risk of having a sole supplier of their bromine requirements.

[44]Letter from H. S. Cooper to J. H. Osborn, May 29, 1897, file #970084.

[45]Letter from J. H. Osborn to H. S. Cooper, November 18, 1896, file #960005.

Pool War II (1888) and Dow War I (1902) are meaningfully described as caused by imperfect information. In the former case, the Germans observed bromide imports. They interpreted this as a sign that Mallinckrodt and P&W had exported bromides in violation of their agreement. In the latter case, Mallinckrodt and P&W interpreted Dow's contracts with Rosengarten and Merck as a sign that it would undercut the pool price. In both cases, the ensuing price war was short and ended after a written exchange reaffirmed everyone's commitment not to engage in price competition. Pool War II did not change how firms were expected to behave during collusion. In contrast, Dow War I led to the establishment of a new mechanism (focal point pricing, using the announced price in *OPDR*) to prevent further misunderstanding. This difference may explain why prices fell further in 1902 than in 1888 (Table 7). But, in neither case did prices fall to Cournot levels (compare Tables 7 and 2). Information problems did not induce the severe price cutting (which firms tried to avoid through communication) observed when disagreement was the real problem.

These "imperfect information price wars" were mild because more severe punishments would not have been renegotiation-proof. While the pool used price war threats, members discounted threats to lower prices below marginal cost.[46] Dow executives evaluated the credibility of the threats that were delivered. For example, they demanded verification of the inventories Mallinckrodt and P&W claimed to have.[47] Threats designed to support collusion were useful only when they were credible. When imperfect information let to the implementation of such threats, the ensuing price wars were relatively mild.

That limit on the severity of "imperfect information price wars" did not apply to coordination or bargaining price wars. The two most severe price wars (Pool III and Dow III) were undoubtedly

[46]Herbert Dow to B. E. Helman, December 9, 1892, file #920021-A.

[47]Letter from J. H. Osborn to H. S. Cooper, "M & P & W now have on hand about 800,000# bromine... [Shields] showed me his books which gave the production year by year..." November 18, 1896, file #960005.

prolonged by information problems (such as the Germans' ignorance of Dow's cost, described on page 20). But they were not the result of imperfect information. Firms publicly announced their willingness to sell below the pre-existing collusive price. All industry participants understood that these announcements were part of a strategy to renegotiate the distribution of rents. Thus, it was not the threat of a price war but the price war itself that influenced the distribution of rents in a new collusive equilibrium. These price wars were part of the renegotiation of a new collusive, not a punishment phase that would help to re-establish an existing collusive arrangement. In these cases reams of correspondence were not sufficient, by themselves, to resolve these price wars. The spiralling of prices during these price wars, as one firm after another cut prices, is an example of the other types of behavior used to influence the new equilibrium.

Dow War III was particularly severe because rules relating actions during price wars to the new collusive equilibrium were not common knowledge. As Dow wrote to A. E. Convers (president of the Dow Chemical Company) two and a half years into this price war,

> ... while we were abroad [meeting with representatives of the German bromine cartel] we obtained some ideas of commercial warfare that were new to us. They evidently have a species of Queensbury rules, and one of them is that the firm that shows their ability to get the market in a fight is entitled to the same proportion of it when they are working under a truce... (March 6, 1908, file #080022).

With such rules it is not surprising that prices spiralled down. These price wars did not help to stabilize collusion, as did price war threats or "imperfect information price wars." Instead they shaped the terms of any future collusion.

V. Bromine producers learn how to avoid price wars

Dow War III ended in 1908 when a detailed, written contract was signed by Dow and the Germans. It remained in force until the outbreak of World War I. This contract included price war punishments; they were never implemented. Instead, when cheating was suspected, the most likely perpetrator was identified. Cash side payments were then made. These punishments resemble those of Fudenberg et al (1988) and Abreu et al (1990). A more profitable collusive equilibrium can be achieved with punishments which shift profit from one firm to another, rather than lowering profits to all firms in a price war. To implement such punishments firms must have some (probabilistic) information regarding the identity of the cheater.[48] When the information was not available, Dow and the Germans invested resources in obtaining it. For example, chemical analysis of bromides was used to identify its manufacturer. The side payments were determined by a low estimate of the profit from cheating. In one instance, when it was determined with certainty that Dow had cheated its payment to the German cartel was greater than the expected gain from cheating.[49] Even in the latter case, however, Dow's realized gain from cheating was still positive. Thus the punishments were not as severe as might be imagined. Weaker punishments, that would be implemented, were more effective than severe punishments that would lead to the abrogation of the agreement.

There were two reasons the industry first resorted to price war punishments which were later eschewed. First, there was a learning process. The industry was young when the first collusive agreements were made. Industry participants were familiar with other pools which employed market price reduction punishments (Jenks 1916). Second, there was a reduction in the number, and stabilization of the identity of firms who were party to the agreement. This made identification of a cheater easier. It also gave firms the incentive to invest in information gathering mechanisms necessary to enforce firm-specific punishments, as the return to such investments was divided among

[48]The information must be such that the "information revealed by the outcomes satisfy the 'pairwise full rank' condition: for every pair of players [firms] i and j, the probability distributions over outcomes corresponding to different choices of actions by i and j are linearly independent" Fudenberg et al (1988) p. 2.

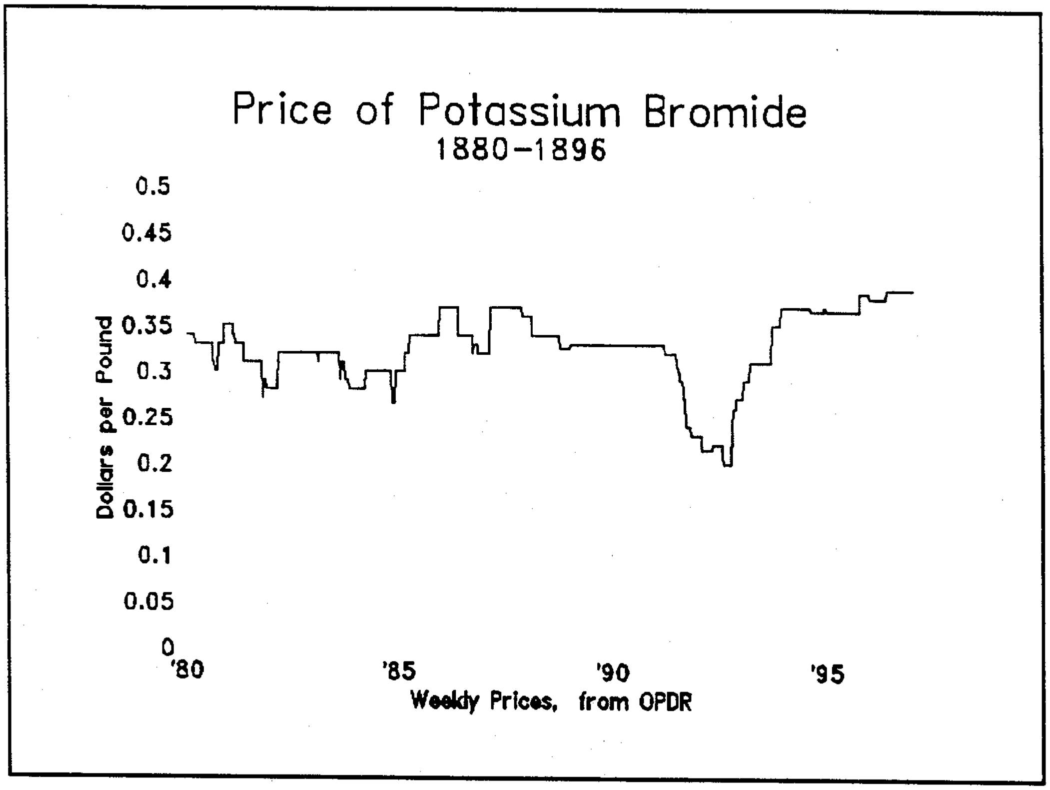
[49]Dow's cheating reflected bounded rationality, not an imperfection of incentives. Shortly after signing a supplementary agreement with the Germans setting prices for mining salts, Dow renewed a contract at a price below that specified. Herbert Dow told his own Board of Directors that it was a mistake, and that he had forgotten what the new price (exchange of letters between Dow and Hackenberg, between Dow and Deutsche Bromkonvention, and between Hackenberg and Deutsche Bromkonvention, May to October 1913, file #130011).

fewer firms.

Conclusion

Threats of price wars helped to sustain collusion in the bromine industry. Punishments as severe as those suggested in APS are not observed because they were not renegotiation-proof. The observed price wars reflect more complex strategies than those described in APS. Some price wars resulted from problems of private information, but in other cases bargaining and coordination problems were much more significant. In the latter cases, the price wars were more severe. They lasted longer, and prices fell further, spiralling down over time.

The collusive agreements in the bromine industry prior to World War I provide a rich set of examples from which we can inform our study of the feasibility and stability of a variety of forms of collusion. This brief venture into those agreements highlights both the light that is shed by recent theoretical work on the underlying causes of the success and failure of collusive regimes, and the importance of paying attention to institutional and historical detail if we are to observe the differences in information structure and firm strategy to which those models are so sensitive.


Price of Potassium Bromide
1880-1896
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Dollars per Pound
'80
'85
'90
'95
Weekly Prices, from OPDR

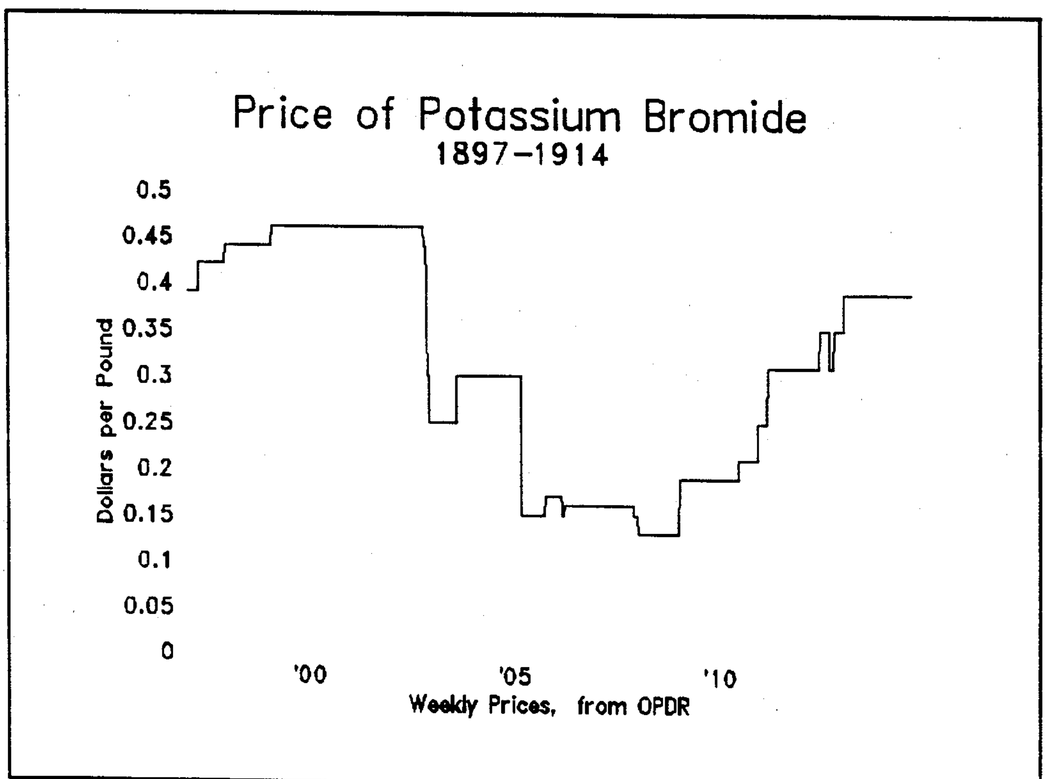

Price of Potassium Bromide
1897-1914
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Dollars per Pound
'00
'05
'10
Weekly Prices, from OPDR

Figure 1

Contractual Relationships During
National Bromine Company Pool (1885-1891)

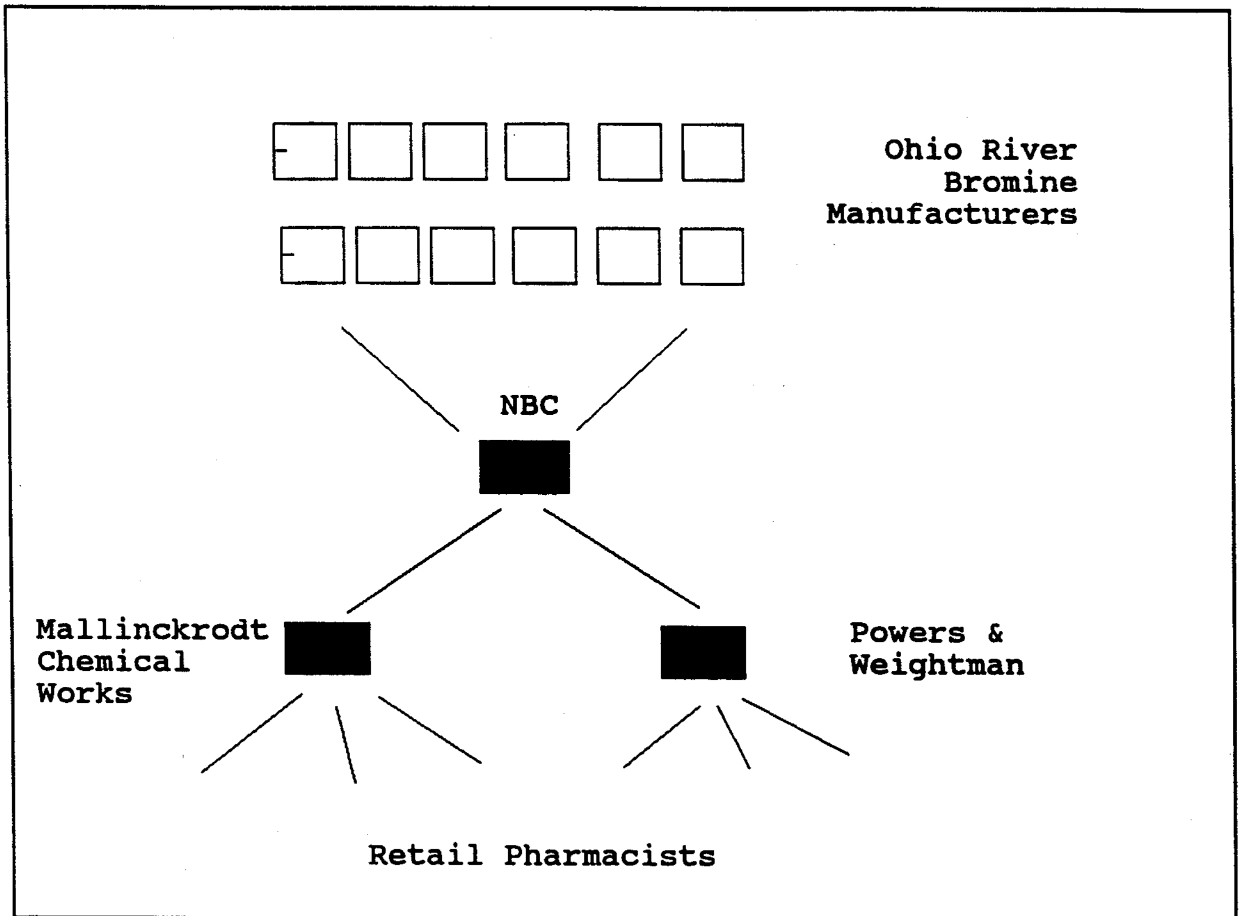


Figure 2

Contractual Relationships During Shields Pool (1892-1902)

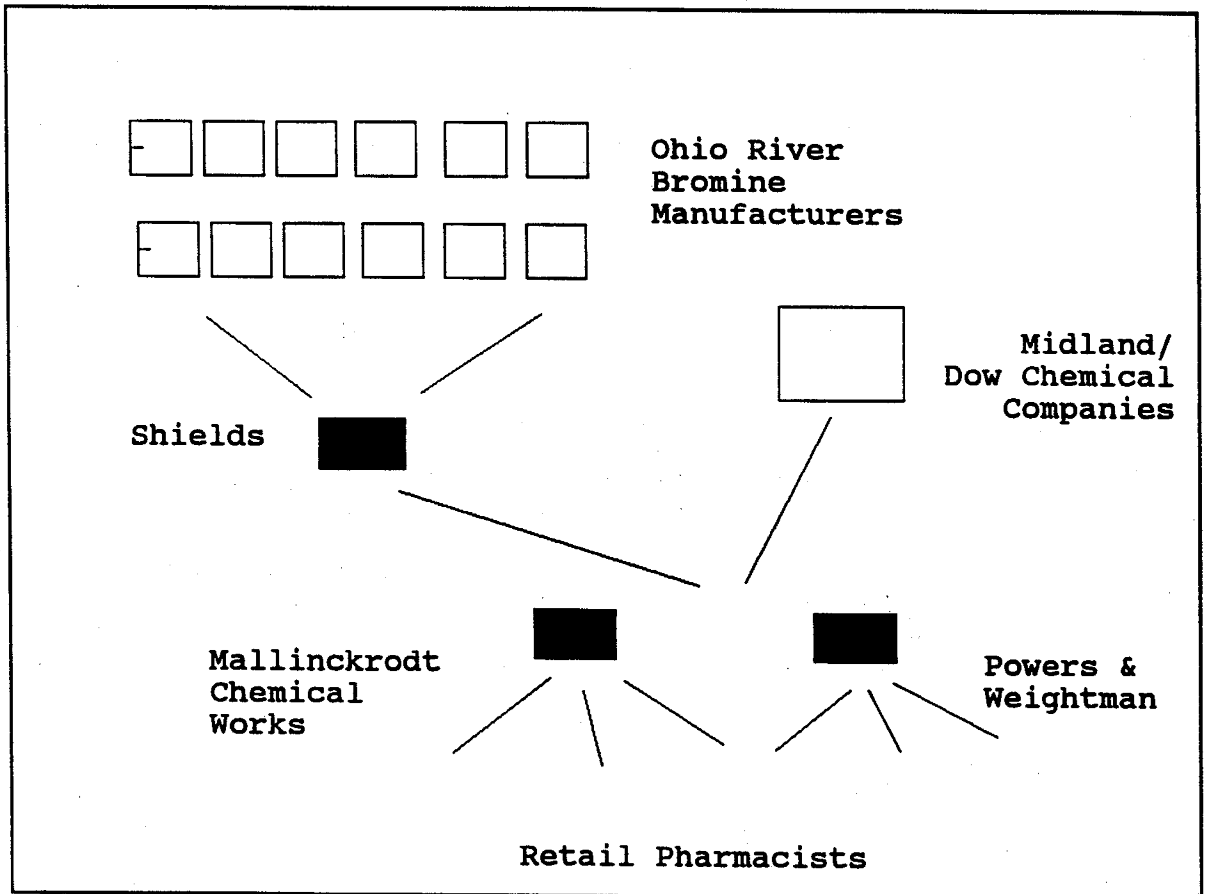


Figure 3

Contractual Relationships After 1910

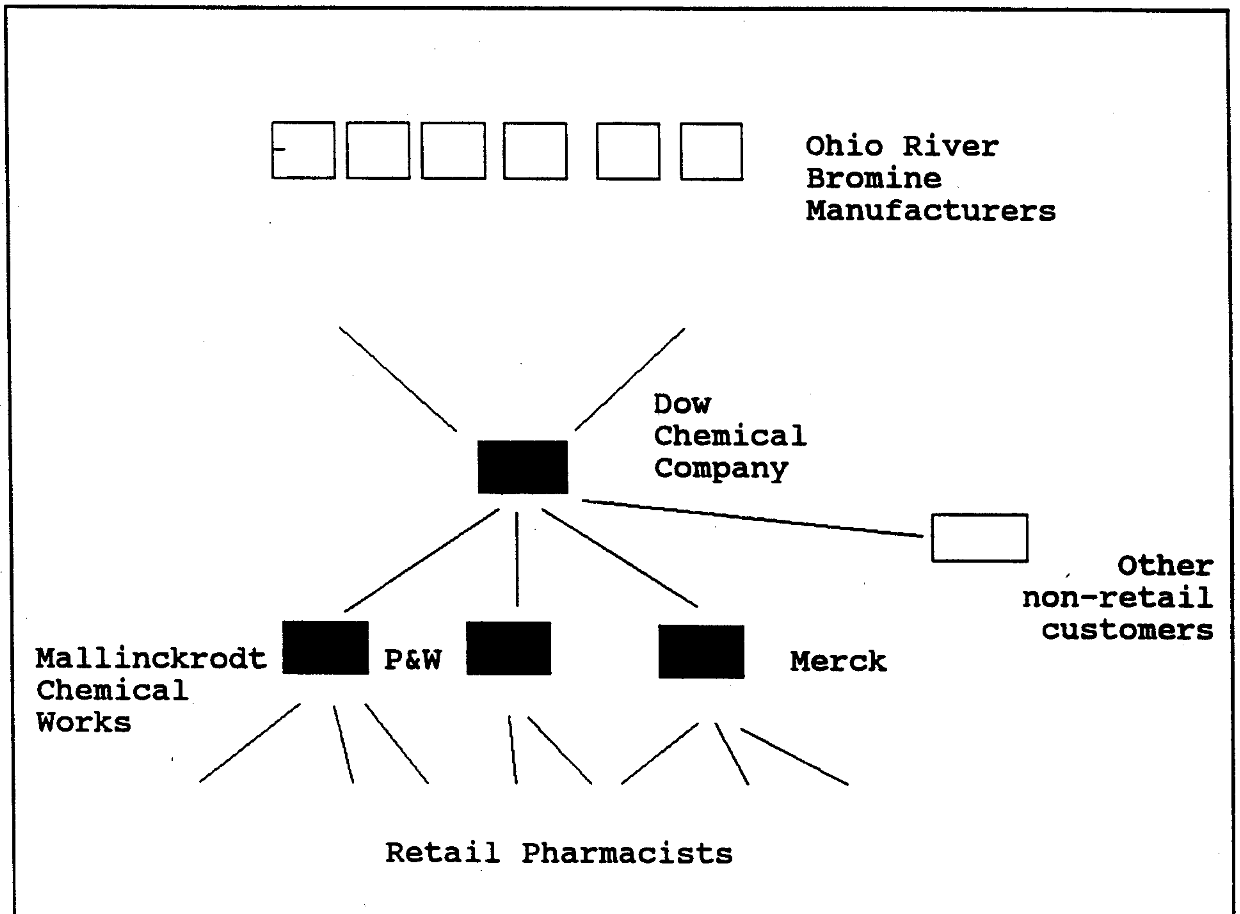


Figure 4

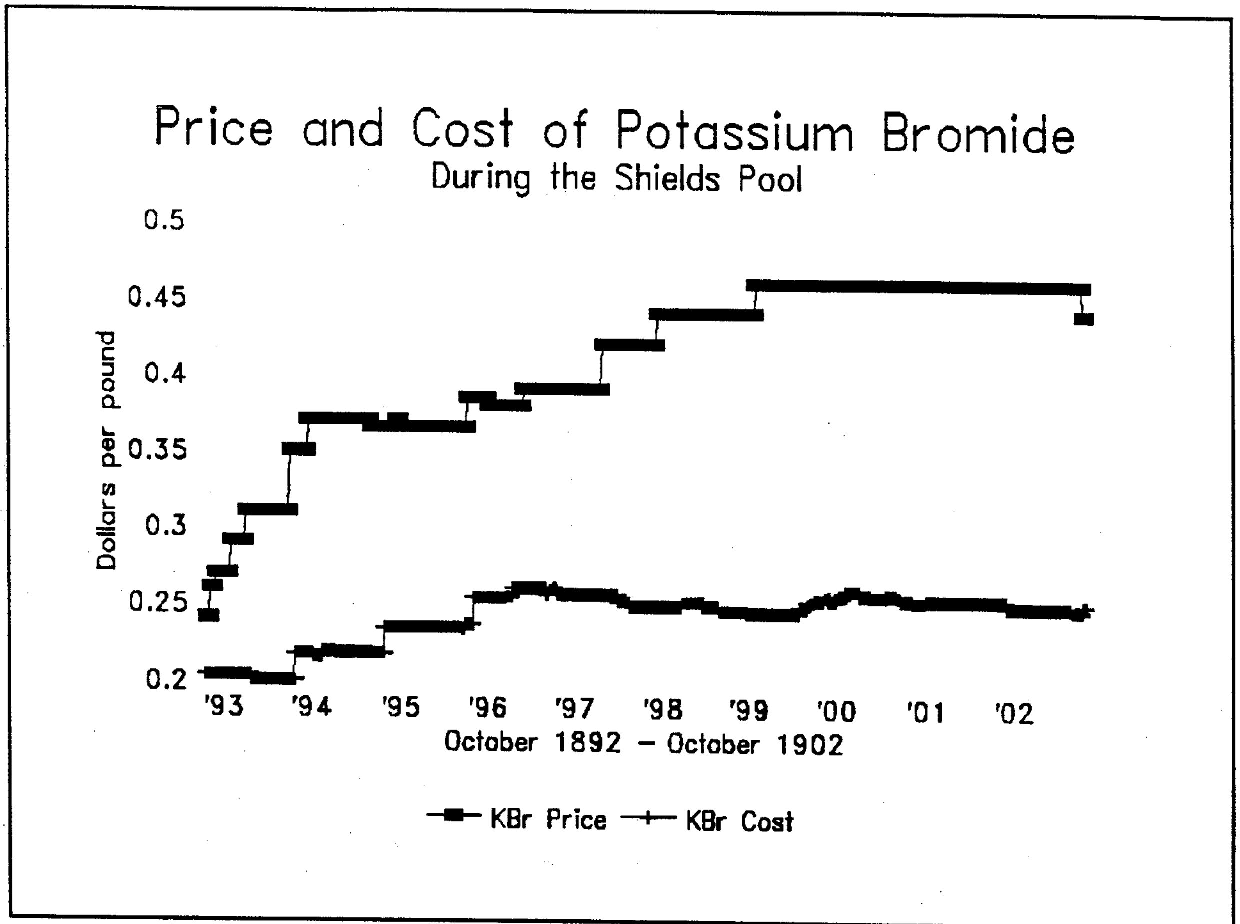


Figure 5

Potassium Bromide
Cost Function: $TC(Q) = Q^*(.85P_{Br} + .6P_{KOH} + C_{mc})$

where P_{Br} is the price specified in the Shields Pool contracts, P_{KOH} is the market price of potash reported in the *OPDR*, and C_{mc} is the processing and distribution cost of the manufacturing chemists (assumed to be 4¢ per pound in the above calculations). The other parameters are based on an estimate of potash and bromine consumption calculated from Midland's Factory Reports, and Dow's estimates of the cost of transforming Ohio River bromine into potassium bromide.

Table 1
The Bromine Industry (1845-1914)

Year	Number firms	Output (pounds)	Bromine Price
1845	1		$6-8[a]
1868			$4.50[a]
1870			0.70[a]
1880	12[b]	404,690[b]	0.28[c] 0.60[d]
1881			0.60 0.26[c]
1882			.55 0.255[c]
1883	11[e]	450,000- 500,000[e] 301,100[c]	.55 0.24[c]
1884		281,100[c]	.55
1885		310,000[c]	NA 0.25-0.33[c]
1886		428,334[c]	.37 0.33-0.35[c]
1887		199,087[c]	0.37 0.31[c]
1888		307,386[c]	0.36 0.31[c]
1889		418,891[c]	0.37 0.27[c]

[a]Haynes (1954) p. 324, and *OPDR* 1880, p. 655.

[b]U.S. Census 1880, pp. 21-22.

[c]*Mineral Resources of the United States*, 1883-1915.

[d]Prices are the January 1 price in the *OPDR* unless otherwise specified.

[e]*OPDR* September 26, 1883, p. 37.

Year	Number firms	Output (pounds)	Bromine Price
1890		387,847[c]	0.37 0.27[c]
1891		343,000[c]	0.37 0.25-0.175[c]
1892		379,480[c]	0.20 0.17[c]
1893		348,339[c]	0.28 0.25[c]
1894		379,444[c]	0.43 0.26[c]
1895		394,854[c]	0.38 0.26[c]
1896		559,285[c]	0.40 0.26[c]
1897		487,149[c]	0.43 0.28[c]
1898		486,978[c]	0.45 0.28[c]
1899		433,003[c]	0.45 0.29[c]
1900		521,444[c]	0.45 0.27[c]
1901		552,043[c]	0.45 0.28[c]
1902	13[c]	513,890[c]	0.48 0.25[c]
1903			0.40
1904		897,100[c]	0.30[c] 0.50
1905		1,192,758[c]	0.15[c] 0.50
1906		1,283,250[c] 938,128[c]	0.50 0.128[c]

Year	Number firms	Output (pounds)	Bromine Price
1907		1,379,496[c]	0.14[c] 0.50
1908	9[f]	1,055,636[c]	0.10[c] 0.50
1909		569,725[c]	.50
1910	7	245,437[c]	.50
1911		651,541[c]	.25
1912		647,200[c]	.25
1913		572,400[c]	.30
1914		576,991[c]	.30

[f]Letter from W. R. Shields to Herbert Dow, January 8, 1908, file #080048. Of these, only Dow was producing.

Table 2
Cournot Solutions: Potassium Bromide Producers

Potassium Bromide
Cost Function: $TC_i = F_{salt} + .85 q_i p_{Br} + .6 q_i p_{KOH} + 4 q_i$

Three demand functions corresponding to different parameterizations of demand:

Demand Functions

I. P = 78 - .077 Q
II. P = 67 - .038 Q
III. P = 173 - .203 Q

Using Demand Function I:

Number of firms	q_i (000#s)	Q (000#s)	P (cents)
1 (joint max)	398.7	398.7#	47.3
2	265.8	531.6	37.1
12	61.3	736.1	21.3
∞		797.4	16.6

Using Demand Function II:

Number of firms	q_i	Q	P
1 (joint max)	663.2	663.2	41.8
2	442.1	884.2	33.4
12	102.0	1224.3	20.5
∞		1326.3	16.6

Using Demand Function #III:

Number of firms	q_i	Q	P
1 (joint max)	385.2	385.2	94.8
2	256.8	513.6	68.7
12	59.3	711.2	23.6
∞		770.4	16.6

Note: There were approximately twelve firms engaged in the manufacture of bromine in 1891 (Table 1). The above calculations assume p_{Br}=12¢, the marginal cost of producing a pound of bromine using the Ohio River process (as estimated by the Dow Chemical Company), and that p_{KOH}=4¢, the average cost during the pool period (from *OPDR*). The other cost parameters are taken from estimates by the Dow Chemical Company of potash and bromine consumption using the Ohio River process. The demand functions cover the range of possible demand functions consistent with aggregate industry data between 1880 and 1914. Demand function I is derived from average price and aggregate output in 1895 and 1909, II from 1896 and 1908, and III from 1897 and 1909.

Table 3

First order Markov Process against two-period alternative

Weekly Series

History (t-1,t-2)	$P(I_t=1 \mid H_i)$	Var(Prob)	N
(0,0)	0.018	0.0177	338
(0,1)	0.000	0.0000	6
(1,0)	1.000	0.0000	6
(1,1)	0.994	0.0060	1188

If $P(I_t=1 \mid I_{t-1}=0) = .018$, then P(6 zeroes in a row) = .897.

If $P(I_t=1 \mid I_{t-1}=1) = .994$, then P(6 ones in a row) = .965.

Monthly Series

History (t-1, t-2)	$P(I_t=1 \mid H_i)$	Var(Prob)	N
(0,0)	0.068	0.063	73
(0,1)	0.167	0.139	6
(1,0)	1.000	0.000	6
(1,1)	0.974	0.025	268

Degrees of freedom: 1
$X^2 = 0.40787059$
Significance = .477

If the $P(I_t=1 \mid I_{t-1}=1) = .974$, then P(6 ones in a row) = .854.

Table 4

First order Markov Process against three period alternative

Weekly Series

History (t-1...t-3)	$P(I_t=1 \mid H_t)$	Var(Prob)	N
(0,0,0)	0.018	0.0177	332
(0,0,1)	0.000	0.0000	6
(0,1,1)	0.000	0.0000	6
(1,1,1)	0.994	0.0060	1181
(1,1,0)	1.000	0.0000	6
(1,0,0)	1.000	0.0000	6

If $P(I_t=1 \mid I_{t-1}=0) = .018$, then P(12 zeroes in a row) = .804.

If the $P(I_t=1 \mid I_{t-1}=1) = .994$, then P(12 ones in a row) = .930.

Monthly Series

History (t-1...t-3)	$P(I_t=1 \mid H_t)$	Var(Prob)	N
(0,0,0)	0.074	0.069	68
(0,0,1)	0.000	0.000	5
(0,1,1)	0.167	0.139	6
(1,1,1)	0.973	0.026	261
(1,1,0)	1.000	0.000	6
(1,0,0)	1.000	0.000	5
(1,0,1)	1.000	0.000	1

Degrees of freedom: 1
$X^2 = 0.357672$
Significance = .450

If $P(I_t=1 \mid I_{t-1}=0) = .074$, then P(5 zeroes in a row) = .681.

If the $P(I_t=1 \mid I_{t-1}=1) = .973$, then P(12 ones in a row) = .720.

Table 5

Zero order Markov Process against a one-period alternative

Weekly Series

History (t-1)	$P(I_t = 1 \mid H_t)$	Var(Prob)	N
(1)	0.995	0.0050	1195
(0)	0.017	0.0167	394

Degrees of Freedom: 1
$X^2 = 18139.065$
Significance level > .999

Monthly Series

History (t-1)	$P(I_t = 1 \mid H_t)$	Var(Prob)	N
(1)	0.978	0.022	275
(0)	0.076	0.070	79

Degrees of freedom: 1
$X^2 = 844.04233$
Significance level > .999

<u>**Table 6**</u>

Goodness of Fit Test of First Order Markov Hypothesis

Weekly data:

Cdf under first order Markov model:

$F(t) = 1 - (1 - .017)^t$

Sample size n=6

Critical value $\alpha=0.20$ gives a critical region $C = \{d_6: d_6 > 0.41$.

The Kolmogorov-Smirnov statistic for this sample is $d_6 = 0.352$.

Monthly data:

Cdf under first order Markov model:

$F(t) = 1 - (1 - .076)^t$

Sample size n=6

Critical value $\alpha=0.20$ gives a critical region $C = \{d_6: d_6 > 0.41$.

The Kolmogorov-Smirnov statistic for this sample is $d_6 = 0.340$.

In each case, the distance between the empirical distribution and the hypothesized distribution is less than the critical value.

Table 7

Characteristics of Price Wars Compared

Price War	1886 - 1887	1888	1891 -1892	1902	1903	1905 - 1908
Price War Name	Pool I	Pool II	Pool III	Dow I	Dow II	Dow III
Initial Drop (¢)	2¢	1.5¢	1¢	4¢	0¢	15¢
Initial Drop (%)	6.0%	4.4%	3.0%	9.1%	0%	50%
Total Drop (¢)	2¢	1.5¢	13¢	19¢	0¢	17¢
Total Drop (%)	6.0%	4.4%	39.4%	43.2%	0%	56.7%
Duration (weeks)	22	12	82	6	21	201
Weeks to trough	1	1	73	6	0	149
Low price	32¢	32.5¢	20¢	25¢	25¢	13¢
Initial Cause	Germans cut price to force US out of Europe	Germans believe US firms export to Europe	NBC expires Dispute over new pool terms	Dow signs with non-pool distributors	Dow tries to raise price; Pool distributors refuse	Germans respond to Dow entry into Europe
Central Cause: 1=Coordination 2=Information	1	2	1	1 & 2	?	1 & 2

Note: All price data are from the *Oil, Paint and Drug Reporter*. Periods of price wars (non-collusive periods) are determined independently of prices, from reports in the *OPDR* and in internal industry documents.

Bibliography

Abreu, Dilip, David Pearce, and Ennio Stacchetti (1986), "Optimal Cartel Equilibria with Imperfect Monitoring," *Journal of Economic Theory* 39(June): 251-269.

Abreu, Dilip, David Pearce, and Ennio Stacchetti (1990), "Toward a Theory of Discounted Repeated Games with Imperfect Monitoring," *Econometrica* 58 (September): 1041-63.

Berry, Steven and Hugh Briggs (1988), "A Non-parametric Test of a First-Order Markov Process for Regimes in a Non-Cooperatively Collusive Industry," *Economics Letters* 27: 73-77.

Campbell, Murray and Harrison Hatton (1951), *Herbert H. Dow: Pioneer in Creative Chemistry*. New York: Appleton-Century-Crofts.

Crawford, E. T., Jr. (1935), "Salt: Pioneer chemical industry of the Kanawha Valley: Development of well drilling," *Industrial and Engineering Chemistry* 27(October): 1109-1113.

Davis, Lance E. (1965), "The investment market, 1870-1914: The evolution of a national market," *Journal of Economic History* xxv(September): 355-399.

Friedman, James W. (1971), "A non-cooperative equilibrium for supergames," *Review of Economic Studies* 38(January): 1-12.

Fudenberg, Drew, David K. Levine and Eric Maskin (1990), "The Folk Theorem with Imperfect Public Information," Cambridge: manuscript.

Green, Edward J. and Robert H. Porter (1984), "Non-cooperative Collusion Under Imperfect Price Information," *Econometrica* 52(January): 87-100.

Grimsley, G. P.(1901), *Iron Ores, Salt and Sandstone*. West Virginia Geological Survey, v.4.

Hale, Dr. John Peter (1876), "Salt Manufacturing in the Kanawha River Valley" in Maury and Fontaine (1876), pp. 274-305.

Haynes, Williams (1954), *American Chemical Industry: Background and Beginnings* v I. New York City: D. Van Nostrand.

Jenks, J. W. (1916), "The Michigan Salt Association" in Ripley (1916).

Lee, L-F and Robert Porter (1984), "Switching Regression Models with Imperfect Sample Separation Information - with an Application to Cartel Stability," *Econometrica* 52: 391-418.

Levenstein, Margaret C. (1991). *Information Systems and Internal Organization: A Study of the Dow Chemical Company, 1890-1914*. Ph.D. Dissertation: Yale University.

Levenstein, Margaret C. (1993), "Vertical Restraints in the Bromine Cartel: The Role of Distributors in Facilitating Collusion," DAE Working Paper 49, National Bureau of Economic Research, Cambridge, Mass.

Pearce, David G. (1987), "Renegotiation-Proof Equilibria: Collective Rationality and Intertemporal Cooperation," Cowles Foundation Discussion Paper No. 855.

Porter, Robert H. (1983), "A study of cartel stability: the Joint Executive Committee, 1880-1886," *The Bell Journal of Economics* 14(Autumn): 301-314.

Ripley, W. Z., editor (1916). *Trusts, Pools and Corporations*. New York City: Ginn & Co.

Slade, Margaret E. (1991), "Market structure, marketing method, and price instability," *The Quarterly Journal of Economics* 106(November):1309-1340.

Stigler, George R. (1964), "A Theory of Oligopoly," *Journal of Political Economy* 72(February): 44-61.

Stout, George Dumas (1933), *Edward Mallinckrodt: A Memoir*. St. Louis, Missouri: Privately printed.

Tosdal, H. R. (1916), "The German potash syndicate: A typical kartell" in Ripley (1916).

United States Census (1880), "Chemical Products and Salt" in *Report on the Manufactures of the United States at the Tenth Census*. Washington, D.C.

United States Federal Trade Commission (1916), "Memorandum on unfair competition at common law," Washington, D.C.: internal publication.

United States Geological Survey (1883-1915). "Bromine" in *Mineral Resources of the United States*.

Whitehead, Don (1968), *The Dow Story*. New York: McGraw-Hill Book Company.

<u>Bibliographical Note</u>

The Herbert Dow Papers are housed in the Post Street Archives, Midland, Michigan.

The *Oil, Paint and Drug Reporter* was first published in 1871. It has been superseded by the *Chemical Marketing Reporter*.