EXPLORATIONS IN ECONOMIC HISTORY **33,** 107–137 (1996)
Article No. 0005

Do Price Wars Facilitate Collusion? A Study of the Bromine Cartel before World War I*

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This paper uses documentary records of the bromine cartel from 1885 to 1914 to evaluate the contributions of noncooperative, repeated game models of collusion to our understanding of the determinants of cartel success and the causes of price wars. It finds that many of the variables that determine an industry's ability to collude in these models—the discount rate, the information structure, the ability to design rewards and punishments, the beliefs and expectations of participants—were significant determinants of collusive success in the bromine industry as well as other late 19th century industries. It questions the explanation of price wars offered by these models that price wars are equilibrium punishments, implemented because of problems of imperfect monitoring. In 19th century industries, price wars were more likely to result from bargaining or coordination problems. Price wars resulting from imperfect monitoring tended to be short and shallow. As the bromine industry became more concentrated and gained experience working cooperatively, the cartel collected more information and developed alternative punishments to make the use of price war punishments even less likely.

INTRODUCTION

During most of the 30 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 30 years, prices fell sharply, and industry publications such as the *Oil, Paint, and Drug Reporter* announced that ''a price war was on.'' Stigler (1964) argues that such price wars signal the collapse of collusion. More generally, he argues that the incentive to ''cheat,'' and precipitate price wars, significantly limits firms' ability to collude whenever output levels or transaction prices are private information. The translation of Stigler's insights by modern game theorists has, however, given an entirely different interpretation to

* The author acknowledges helpful comments on earlier versions of this paper from two anonymous referees, David Arsen, Jeff Borland, Insong Gil, Thomas Iosso, Richard Levin, Nancy Lutz, Paul Milgrom, David Pearce, Matthew Shapiro, 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 Lyon, 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.

0014-4983/96 $12.00

the appearance of price wars. For example, in Green and Porter (1984) price wars are ''equilibrium punishments'' which actually help to stabilize collusion. This article compares the history of price wars and cooperation in the bromine industry with those of other industries in the period in order to evaluate the role of price wars in stabilizing collusion. It asks three questions: Did price wars stabilize, or destabilize, collusion? How would one distinguish between price wars that signal the collapse of collusion and equilibrium punishments? How did the role of price wars and other possible punishments change over time?

Most earlier empirical work that has attempted to test game theoretic models of collusion has asked whether time series of observable variables, such as output and prices, are consistent with the predictions of these models. This article takes a different approach. It uses archival records from the bromine cartel, including signed agreements, communications between firms, and internal memoranda of participants, to tease out features of an industry that are usually unobservable to the researcher and, often, to most industry participants. These features—strategies, beliefs, information costs, patience—drive the predictions of most of these models. The article then asks whether these innovative models are focusing our attention on those features that do determine the success of collusion and the occurrence of price wars. This is a test of their intellectual usefulness, rather than whether these fairly abstract models capture the details of any particular industry.

I find that firms during this period did use price wars strategically to support collusion. Price war *threats* underlay most successful collusion, as suggested by writers as diverse as Burns (1936, p. 27) and Friedman (1971). The bromine cartel made very concrete and explicit price war threats in order to encourage cooperation. The internal correspondence of bromine firms makes clear that these threats provided crucial motivation in the decision to cooperate.

The causes of the price wars that occurred varied. As in Green and Porter (1984) and Abreu *et al.* (1986), imperfect information—the inability to monitor compliance with an existing agreement—led to the implementation of price war threats in some circumstances. In these models, firms are unable to monitor each others' output perfectly, so that they cannot distinguish between, say, demand shocks and cheating by other firms. Thus, they rely on a public signal, such as price, to make a probablistic evaluation of whether cheating has occurred. Even though incentives are such that no firm ever cheats, firms must respond to low prices (which could be caused by a negative shock to demand or by cheating) as though they were caused by cheating. If they didn't, firms would have an incentive to cheat, hiding behind demand fluctuations.[1] The price wars in mass production industries after the merger wave of the 1890s seem to have been caused by problems of imperfect monitoring (Lamoreaux, 1985, pp. 134–136).

[1] Firms need not be observing prices; fluctuations in demand need not be the source of uncertainty. And firms need not rely on the ''trigger pricing'' strategy described here. All that is necessary is that firms rely on a noisy public signal, imperfectly correlated with firm behavior. The optimal strategy is to implement punishments when that public signal falls in the range most likely to be caused by cheating behavior.

Two of the six bromine price wars also seem to result from imperfect monitoring problems. Both in bromine and in the industries studied by Lamoreaux, these ''imperfect monitoring price wars'' were short and mild.

In other cases, price wars were ''strategic'' but not the result of difficulty in monitoring compliance. In these cases, there was no ambiguity about whether a firm had cheated; the price war began with a public announcement that a firm intended to violate the collusive agreement. There are two ways to understand the occurrence of these ''bargaining price wars,'' each of which seems to explain the underlying dynamic in some price wars. Consider first the case of an industry in a stable, collusive equilibrium. Suppose one firm experiences a (private) technological shock which lowers its cost. The previously stable collusive agreement is no longer an equilibrium. The firm with a new production technology might signal its new lower cost (i.e., its type) by instigating a price war.[2] If it were individually rational for a low-cost firm to charge such a low price, sustained for a certain length of time, but not for a high-cost firm, the instigation of the price war would credibly signal that the instigating firm truly was low cost. Other firms would then respond to the price war by decreasing their output, accommodating the low-cost firm by giving it a larger share. In this case, the price war is a method of credible communication among continuously colluding firms.

Consider a second explanation for a bargaining price war, which, in the absence of observable (to the researcher) technological shocks, is observationally equivalent to the signaling price war just described. In this case, firms are implementing a stable collusive equilibria, but there exist other, equally stable, collusive equilibria, but with different distributions of rents. We have little *a priori* method for deciding which of these equilibria will be implemented.[3] In this case, a firm might instigate a price war to force the cartel into an equilibrium with a distribution more favorable to them. The instigation of the price war in this case does not signal new information to the other industry participants, but it may change their expectations and beliefs in a way that does move the industry to a new equilibrium with a different distribution of rents.

At least two of the bromine price wars were bargaining price wars. Price wars in 1887 and 1891 began in response to publicly announced violations of collusive

[2] Note that this implies a different information structure than is the case in either the Stigler or the APS models. In both Stigler and APS, output (or price, in a Bertrand game) is assumed to be private information. In the signaling model, it is the observability of the action which gives it signaling value. If in fact the signal is only observed with some error, it may be necessary to continue the price war for longer in order to convince the other firms that the instigating firm has truly increased output (decreased price) to the extent necessary to credibly signal low costs. This may help to explain why these price wars were so severe.

[3] Current research on renegotiation has had a difficult time selecting reasonable criteria to limit the behavior one expects firms or individuals to engage in when they cease to play cooperatively after a long period of cooperation (Pearce, 1992). While I do not suggest that the behavior of participants in the turn of the century bromine industry is the only way that firms behave and form beliefs off an equilibrium path, it is one such case, and a case where we have much more information about the participants' actions and beliefs than in most analogous situations.

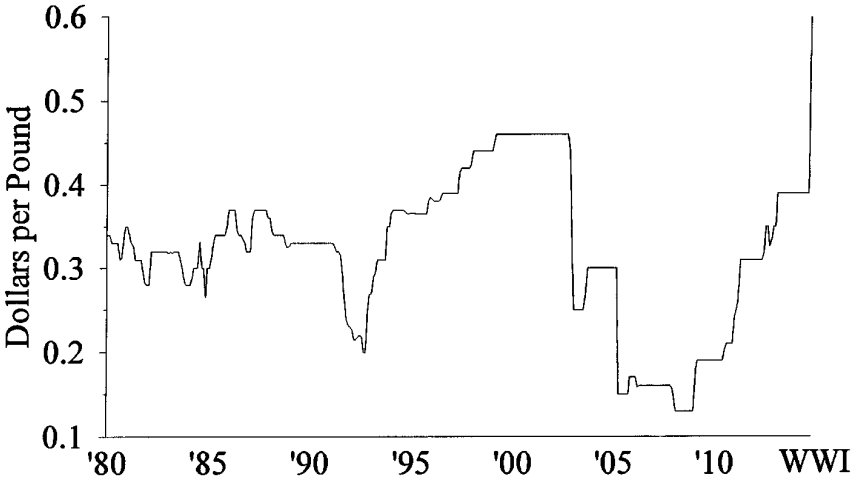

FIG. 1. Potassium bromide prices, 1880–1914. Source: *Oil, Paint and Drug Reporter.*

agreements, with the explicit intention of changing the distribution of rents. These price wars lasted longer, and prices fell further than during the imperfect monitoring price wars (Fig. 1, Fig. 2, and Table 1).

There were other price wars which seem to have been neither equilibrium punishments, supporting stable collusive arrangements, nor bargaining tools. In industries such as the northern trunk railroads of the 1880s and many mass production industries before national consolidations, ''cheating''—undercutting

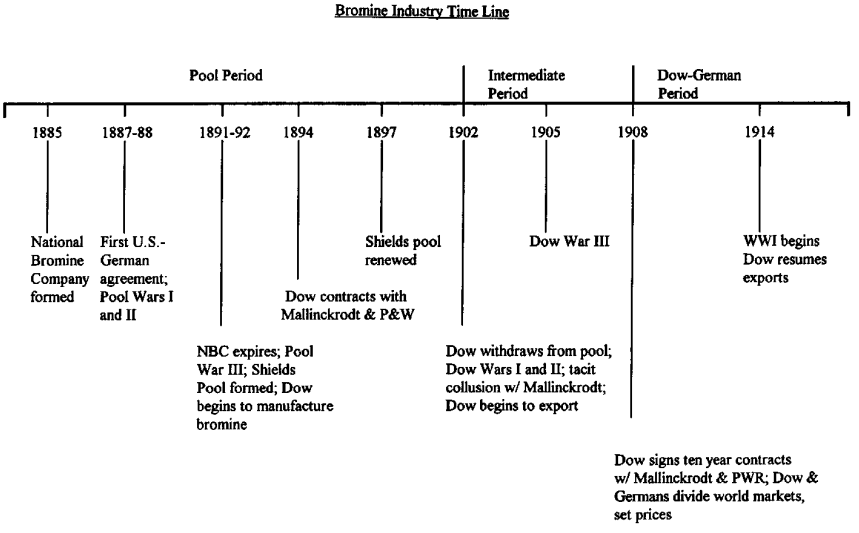

FIG. 2. Major events in the bromine industry, 1885–1914.

TABLE 1
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 U.S. out of Europe	Germans believe U.S. firms export to Europe	NBC expires; dispute over new pool terms	Dow signs with nonpool distributors	Dow tries to raise price; pool distributors refuse	Germans respond to Dow entry into Europe
Central cause[a]	1	2	1	2	1	1

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

[a] 1, bargaining; 2, monitoring.

the cooperative price—actually occurred, but was done secretly (Lamoreaux, 1985, p. 45). The intent of the cheaters was to free ride on the output restrictions made by others. Despite the use of sophisticated incentive schemes, these industries could not make it individually rational for firms to refrain from cheating. In this case, collusion simply could not be sustained. Repeated attempts to collude *dissolved* into price wars because the gains to cheating were large and payoffs in the future—rewards or punishments—too insignificant for firms concerned with survival today. These ''Stiglerian'' price wars represented the collapse of a cooperative agreement which was not an equilibrium and could not be sustained. These price wars were the longest and deepest observed. In many industries they were only resolved through national mergers (Lamoreaux, 1985).

A price war—in some ways similar to these Stiglerian wars—occurred in the bromine industry after the adoption of mass production technology. But unlike the other industries discussed here, this price war was not resolved through government intervention or merger. Because the bromine producers were competing across national boundaries, those options were not available.[4] But both because they were less leveraged, and therefore more patient, than many mass producers, and because they could take advantage of national boundaries and standards to divide markets, they were eventually able to achieve a stable collusive agreement. In this case, however, Dow's ability to produce and sell for several years at low prices did signal to its competitors that it was a low-cost firm, which they had been reluctant to believe prior to the price war. The signaling function of a price war was useful in an industry in which collusion could be sustained, but

[4] Merger across *state* boundaries was generally prohibited until New Jersey's modifications of its state incorporation laws in the late 1880s and early 1890s (Grandy, 1989, p. 681). A merger across international boundaries would have been particularly problematic in this case as several of the German bromine producers were owned by German state governments (Tosdal, 1916).

counterproductive for firms in industries in which firms were not patient enough to sustain collusion.

Finally, the bromine industry went through a learning process in which alternative methods of colluding, and punishing and preventing cheating, were developed, along with institutions to support their implementation. Thus, while the threat of price wars continued to underlie collusive agreements, price wars themselves became less common. A similar education in other industries may help explain the apparent decline in price wars in the years following World War I.[5]

1. MAKING SENSE OF PRICE WARS HISTORICALLY

1.1. *Comparing Models of Price Wars and the Stability of Collusion*

The industrial organization literature has not achieved consensus on the implications of price wars for cartel stability. While there has always been considerable controversy about the stability of collusion, until fairly recently there had been agreement that price wars signified instability. For those who thought collusion was inherently unstable, price wars were endogenous. The rents created by collusion created incentives for price wars, which represented a break down in collusion. For those who believed that industries often managed to maintain collusion, price wars resulted from exogenous shocks, such as fluctuations in demand, to an otherwise stable cartel. In the past decade, even that consensus has broken down. Recent research has focused on the possibility that price wars might help to stabilize, rather than undermine, cartels. In some cases, authors have claimed that the only ''reasonable'' equilibria are those in which firms can successfully collude (e.g., Fudenberg and Maskin, 1990). There has been little discussion of the normative implications of this work for anti-trust policy, or even how one would distinguish price wars that stabilize collusion from those that represent a breakdown in collusion. Because these models were developed to model price wars that earlier authors, such as Stigler (1964) and MacAvoy (1965), thought of as breakdowns in collusion, the models are in many ways observationally equivalent to the breakdown and reestablishment of collusion.[6]

For example, the anti-trust implications of Porter's (1983) analysis of the

[5] The Federal Trade Commission facilitated information collection to limit ''cutthroat competition,'' and the use of these less costly punishment strategies. It advocated uniform cost accounting systems to prevent cut-throat competition (U.S. Federal Trade Commission, 1916; Hurley, 1916; and Levenstein, 1991, p. 46).

[6] Stigler (1964) says, ''Let us assume that the collusion has been effected, and a price structure agreed upon. It is a well-established proposition that if any member of the agreement can secretly violate it, he will gain larger profits than by conforming to it. . . . The literature of collusive agreements, ranging from the pools of the 1880s to the electrical conspiracies of recent times, is replete with instances of the *collapse* of conspiracies because of 'secret' price-cutting'' (p. 46, emphasis added). Thus, according to Stigler, the inability to observe output, sales, or transaction prices, might lead to a price war and the *collapse* of collusion. The exercise of market power by firms in an industry where cheating cannot be detected will, consequently, be limited. The appearance of severe and long-lasting price wars, while consistent with stable collusion in Green and Porter (1984) and Abreu *et al.* (1986), is not in Stigler's view.

railroad price wars of the 1880s are dramatically different from earlier treatments (e.g., MacAvoy, 1965). MacAvoy argued that the railroad price wars, and the subsequent passage of the Interstate Commerce Act, suggested that cartels were not stable without government intervention. Proactive anti-trust policy was not necessary; government regulation which facilitated collusion was the problem. Porter's study of the same cartel is much less sanguine in its implications. The railroad price wars were not inconsistent with stable collusion. Rather, they made it possible for firms to charge prices above competitive levels during the periods when they were not in price wars (75% of the time during the cartel's eight-year existence).[7] Porter argues that the threat of a price war made cheating unprofitable to each railroad. But fluctuations in demand made it difficult for any individual road (which could only observe its own price) to distinguish between cheating by co-conspirators and declines in demand. Thus, when its market share fell below a ''trigger'' level, all the roads would increase output to Cournot levels for a fixed length of time.[8] During this period, the industry would appear to be in a ''price war,'' but no firm would actually have cheated. The price war was not a sign of the ''collapse'' of the cartel, but rather was crucial to providing the roads with an incentive not to engage in the secret price cutting which would cause its collapse.

The small body of empirical analysis using these new models of price wars asks whether the models are consistent with the quantitative evidence of prices, output levels, and the incidence of price wars (Porter 1983; Berry and Briggs 1988; Levenstein, 1994a). But, as Levenstein (1994a) argues, even when the quantitative evidence is consistent with the models, these tests tell us little about whether price wars functioned in the unique way described in the recent literature. This article focuses on just those qualitative aspects of these models. It analyzes the secondary literature on 19th century price wars and the documentary history of the bromine price wars to discern which features of these models, if any, capture the determinants of collusive success. Then it analyzes the history of the price wars in these industries to distinguish between price wars which are usefully thought of as equilibrium price wars, and those which are more properly thought of as breakdowns in collusion.

Noncooperative game theory's most basic contribution to our understanding of collusion has been to recognize that firms can adopt schemes to manipulate their own incentives so as to lessen the incentive to cheat.[9] The implementation of such a scheme can run into three types of problems. First, monitoring problems can increase the cost of manipulating incentives; if firms cannot determine with certainty whether others have cheated, punishments must be enacted even when

[7] Ulen (1979, p. 98).

[8] Abreu *et al.* (1986) shows that the optimal strategy would not necessarily involve trigger pricing, might increase output above Cournot levels, and would have stochastic length.

[9] Ulen (1979) calls the assumption of the older literature that firms could not design rewards and punishments ''selectively-granted rationality . . . the wit to see that it pays to collude and that it pays to cheat, but . . . not . . . the sense to put these two bits of information together in order to realize that their real problem is the prevention of cheating'' (p. 76).

no one has cheated. Second, if there are more than one Nash equilibria, some mechanism for coordinating firms on one must be found; the prior history of the industry may create expectations and beliefs which focus the industry on a particular equilibrium.[10] Third, incomplete information about the characteristics of other firms in the industry may require that firms use costly signals to convince others of their characteristics before a scheme that provides each firm with appropriate incentives can be achieved. For example, if firms in an industry are uncertain about the costs of other firms, a low-cost firm might be able to convince other firms that it was low cost only by cutting its prices to a level that would never be charged by a high-cost firm. The set of schemes which an industry can use to cooperate is further limited by the lack of enforceability (in the period before 1890) and illegality (after 1890) of many of the contractual forms which firms might use.[11] Finally, the game theoretic literature generally assumes that costs, demand, etc. are stationary. In fact, firms also strive to design cooperative schemes which give them flexibility in response to changing conditions.[12]

Game theoretic models of collusion focus our attention on a new set of determinants of the stability of collusion. These features include the firm's discount rate, repeated interaction among firms, firm beliefs and expectations, firms' ability to manipulate incentives with punishments and rewards, and the information available to firms about their customers and their competitors (and the costs of collecting other information).[13] The discount rate, or more colloquially, ''patience,'' is central to these models because firms weigh punishments and rewards in the future against the gains from cheating, and increasing profits, in the present. A firm's patience may depend on the individual time preferences of its owners. This is most likely to be the case in a closely held or family-owned firm, where life-cycle considerations may influence firm decision-making. In a firm with dispersed ownership, its patience is more likely to be influenced by factors such as the firm's debt load. Firms with high fixed payments (as opposed simply to fixed costs) which must be paid under the threat of bankruptcy will care more

[10] Of course, this means that a history can make it more difficult, as well as easier, to collude. It depends on the particular history. Fudenberg (1992) discusses the importance of priors, or other *ad hoc* assumptions, in restricting the number of possible equilibria. See Cooper and Haltiwanger (1993) for an interesting study of this problem as it relates to the U.S. auto industry during the 1930s. They argue that the NRA allowed auto producers to coordinate on a more efficient—for consumers as well as producers—equilibria that, because of the effect of prior history on expectations, they could not move to through individual action.

[11] This suggests that the passage of the Sherman Anti-Trust Act in 1890 represented a sharp break in anti-trust policy in this country. In fact, many anti-trust activities were illegal under state laws before the passage of the Sherman Act. Even after its passage, its enforcement was uneven. Firms in the bromine industry did not show any concern about violations of anti-trust law until well after the turn of the century (Levenstein, 1994b, 1995; McCurdy 1979).

[12] See Levenstein (1994b), and Ulen (1979, p. 103) where he discusses cartel ''judicial systems.''

[13] The information structure can provide too much information to sustain cooperation, as well as too little (Fudenberg and Tirole, 1991, pp. 74–77; Abreu *et al.*, 1991).

about the present relative to the future (that is, be less patient) than less leveraged firms.[14]

Repeated action over time can facilitate collusion among firms by creating a future in which punishments and rewards can be implemented. Repeated interaction across markets may also facilitate collusion, by providing other, perhaps less costly, venues for the implementation of punishments (Benoit and Krishna, 1985; Bernheim and Whinston, 1990). The information structure—what players know about competitors' (and customers') actions and characteristics—determine what kinds of incentive schemes can be implemented.

These key features of these game-theoretic models were also the important determinants of collusive success in the turn-of-the-century industries discussed below. As we will see below, these features frequently seem more important than those central to the older industrial organization literature, such as product and cost homogeneity (Scherer, 1980, Chaps. 5 and 6).[15]

1.2. *Nineteenth Century Price Wars and the Stability of Collusion*

An examination of the secondary literature on price wars and collusion during the 19th century shows that in many instances the ability to sustain collusion did depend crucially on the determinants discussed above: patience, repeated interaction, a history of cooperation, the information structure. While game-theoretic descriptions of optimal punishments may seem to assume extreme levels of rational forethought, the history of cartels is replete with schemes for providing rewards for cooperation and punishments for cheating.

In Lamoreaux's (1985) description of American industry before the merger wave of the 1890s, patience plays a crucial role in determining which industries could sustain collusion. Industries, such as wire nail and newsprint, which had grown rapidly by investing in mass production technologies with high fixed, low marginal costs, and incurred debt to finance that investment, could not sustain collusive agreements (Lamoreaux, 1985, pp. 55–61). Low marginal costs increased the current payoff to cheating. High debt ratios made these firms impatient; increased sales today were more important than high prices in the future, when they might be bankrupt.

These same industries, populated by new firms, had little prior history of cooperation to focus firms' beliefs or expectations on a cooperative equilibrium. In contrast, in industries such as fine writing paper, where firms were more established and had not adopted mass production technologies, collusion was much more stable (Lamoreaux, 1985, pp. 16–27). Firms had established customers and differentiated products; they did not expect a small decline in their own price to increase significantly their market share (Lamoreaux, 1985, p. 85). Thus,

[14] See Blair (1993) for a similar analysis of the importance of leverage in firm decision-making during the merger wave of the 1980s.

[15] Lamoreaux (1985) argues that collusion was actually less stable in industries with identical products and costs, and more stable in industries with differentiated products and more varied production technologies (p. 45).

they had little incentive to cut prices and possibly instigate a price war. They did not have high fixed charges, so they could respond to a decline in demand with a decline in output without facing the threat of bankruptcy.

The mechanisms for rewarding cooperation (in addition to higher prices) depended on the marketing structure of the industry. Nineteenth century salt pools frequently offered a guaranteed sales level or access to merchandise credit. In some cases, the pool delayed part of its payment to the producer until successful cooperation was observed (Stealey, 1993). In the railroad industry, the network of connecting lines provided another mechanism for offering firms a reward contingent upon cooperation. Participants in railroad pools had customers directed to them from connecting lines that were cooperating with the pool.[16]

Finally, we observe cartels use price wars as punishments. Where collusion was stable and monitoring difficult, we do observe imperfect monitoring price wars. For example, according to Lamoreaux (1985), price wars in *post-merger* mass production industries facilitated collusion. Newly created national firms, such as the International Paper Company, became price leaders in their industry. When the large firm's sales dropped below some critical level, usually following a decline in demand, it cut its price sharply, as International Paper did in 1905. Higher prices shortly resumed, and cooperative pricing was maintained in the future. This pattern, she argues, emerged in several post-merger industries, including tin and steel. Thus, price wars became tools to sustain collusion following a shock to demand (much as in Green and Porter, 1984).[17]

One finds many other price wars, however, which seem fundamentally different. They did not arise from the difficulty of distinguishing cheating from demand fluctuations and they did not resolve themselves by returning to the preexisting collusive equilibrium. In these price wars, disgruntled firms intentionally and publicly disrupted collusion in order to force a renegotiation to a different collusive arrangement. This was the case during the steel rail price war of 1896, when Illinois Steel, after cooperating with the pool through the depression years of the early 1890s, decided to slash its prices. Illinois Steel believed that industry demand was more elastic than the pool's officers had assumed. It wanted the pool to change its strategy, lowering prices, because Illinois believed that a price decrease would lead to a sufficient increase in consumption to increase profits as well. When the pool continued to pursue a policy Illinois opposed, it publicly cut prices and forced the pool to adjust its policy (Lamoreaux, 1985, pp. 81–85).[18]

[16] Ulen (1979, p. 101) says, ''The railroad which chose to ignore the cartel agreement in the late nineteenth century found that its transfer privileges with other roads were cut off, thus denying the road access to important markets.''

[17] Lamoreaux (1985, p. 134) says, ''As a result of the consolidation movement, then, price warfare had become a device that dominant firms could control. This was an enormously significant development, for it meant that the threat of price warfare could be used to enforce cartel-like behavior . . . especially during periods of slack demand.''

[18] In this case, cutting prices gave the pool information about the elasticity of demand and proved correct Illinois's claims that adjusting pool policy could increase profits for the industry as a whole.

At least two of the railroad price wars in the 1870s and 1880s were also instigated by firms interested in changing pool policy. Ulen (1979) reports that in 1877 the Macon and Brunswick Railroad line announced that unless the Southern Railway and Steamship Association started setting prices for cotton shipments, it would start cutting prices on the shipment of other goods. That December the Association decided to pool all cotton business (pp. 153–55). In a similar case,

> [t]he Chicago and Grand Trunk, a Canadian road, . . . disrupted the cartel through rate-slashing so as to make known the strength of its dissatisfaction . . . with the size of its allotment in the livestock cartel. . . . Arbitrators agreed and the trouble ended (Ulen 1979, p. 93 and Footnote 38, p. 115).

These price wars did not arise from problems of imperfect monitoring; violations of the agreement were public. Their observability was in fact crucial to the usefulness of the cheating. But as in the imperfect monitoring models, these appear to be cases of fairly stable collusion. Price wars were used by disgruntled firms to force a renegotiation of the agreement. Very generally, we can think of these as ''bargaining'' price wars which, either by signaling private information about the instigator of the war or by changing firms' expectations, facilitated the reestablishment of collusive pricing. The price cutting itself could signal important information to other firms, facilitating the renegotiation to a new collusive equilibria.

There were also true Stiglerian price wars. In some industries collusion appears not to have been stable; *secret* price cutting undermined attempts at cooperation. This was the case in industries where there were problems of imperfect monitoring—cheating was not easily detected—and firms were relatively impatient, so that future punishments or rewards had little influence on firm behavior. These features characterized many mass production industries prior to the merger wave of the 1890s, and the price wars which arose were truly Stiglerian. Lamoreaux (1985) describes these price wars, and the futility of the attempts of these firms to sustain collusion.

> It was generally this type of mass production industry, in which no firm had a clear-cut advantage over the rest, that suffered the most severe price competition. . . . In striking contrast to the experience of small firms which differentiated their products, firms in industries such as tin plate and newsprint failed to adjust their production to declines in demand. Indeed, despite sharply falling prices, production often increased dramatically as firms struggled to run their plants at full capacity. Normal collusive arrangements proved utterly incapable of stemming this virulent competition. So . . . did the increasingly sophisticated and formal pools that the manufacturers devised (p. 45).

One might argue that the price wars of the northern trunk railroads in the 1880s were also Stiglerian price wars. Even the commissioner of the Joint Executive Committee, Albert Fink, called the arrangement a ''house of cards'' (Ulen, 1979, p. 90). Despite some short-term success, the pool was continuously confronting either cheating by incumbent firms or demands from new entrants (MacAvoy,

1965; Ulen, 1979, Chap. 2). With better access to international capital markets, railroads relied more heavily on debt than industrial firms of the day.[19] The industry was young, so many firms were new, and customers, particularly those of the trunk railroads, were not particularly loyal. With high fixed, low marginal costs, the incentive to cut prices was usually overwhelming. When it was not, entry quickly followed.[20]

In this brief review of the secondary literature on 19th century price wars, we have seen that noncooperative game theory appears to capture many of the determinants of collusive success in a variety of industries. These cartels were adept at designing rewards and punishments to support collusion; we do observe a few examples of price wars used as equilibrium punishments. Most price wars during this period, however, do not appear to result from monitoring problems, and some were clearly the result of the collapse of collusion, not part of its support. We now ask the same set of questions of the bromine cartel's collusive success and unsettling price wars.

2. THE BROMINE INDUSTRY

2.1. *History of the Industry*

Bromine was first produced commercially in 1845 for use in daguerreotype photography (Haynes, 1954, p. 324). 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 nonexistent 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 West Virginia, produced the entire U.S. output of bromine as a byproduct of sodium chloride salt manufacture.[21] Low-grade coal from local (and frequently jointly owned) coal mines provided a cheap supply of energy. Underground brine was pumped and heated, allowing extraction of sodium chloride salt, then bromine, and then, in some firms, calcium chloride. All these firms participated, at one time or another, in salt pools that attempted, without great success, to restrict output and increase prices (Levenstein, 1995).

The Ohio River firms sold their liquid bromine to firms called ''manufacturing

[19] Livesay (1975) says that many railroads had debt worth several times the value of the stock invested in the firm, and that generally ''most American railroads were capitalized more by bonds than by stock'' (pp. 30–31).

[20] The class of models discussed in this paper assumes that no new entrants appear, say, after observing incumbent firms earn rents. The models can easily accommodate foreseen, potential entry, as did many of the agreements adopted during the 19th century. But public policy largely prevented exit by railroads, so the cartel faced a very different problem after entry than before the entrant's investment was made.

[21] U.S. Census (1880, pp. 21–22), Crawford (1935, p. 1109), and ''history of the bromine industry,'' undated, Dow Chemical Company internal memoranda, Herbert H. Dow *Papers* File 050036. Citations to the Dow *Papers* below will give the file number assigned by the Post Street Archives.

chemists.'' The manufacturing chemists were larger, urban companies with manufacturing facilities and well-established sales networks. They converted the volatile liquid bromine from the Ohio River into potassium bromide powder. They then distributed it to pharmaceutical jobbers around the country, as well as to national-brand patent medicine producers. The most important manufacturing chemists in the bromine industry, Powers & Weightman (hereafter, P&W) and Mallinckrodt Chemical Works, supplied hundreds of pharmaceutical products to their customers around the country.[22]

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.[23] 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).

2.2. *The Bromine Pools*

The first bromine pool was established in 1885 (Fig. 2). Called 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. Mallinckrodt and P&W in turn agreed to purchase all of the NBC's bromine (Fig. 3).[24] Mallinckrodt and P&W made regular, coordinated announcements of the market price of potassium bromide. Prices for potassium bromide (in bulk) rose from a low of 26.5¢ per pound at the end of 1884 to 34¢ immediately after the signing of the NBC contracts in March 1885 (Fig. 1). The average price of potassium bromide during the NBC pool (1885–1891) was almost 10% higher than the average price of the previous five-year period (Levenstein, 1994a).

The NBC expired by limitation of its charter in March 1891 (Fig. 2). A new pooling and territorial division arrangement was not achieved until the following October.[25] 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

[22] The former was a Philadelphia firm founded in 1818 and a well-known and highly respected producer of a wide range of pharmaceutical products which it distributed nationally (Mahoney, 1955, p. 30). Mallinckrodt Chemical Works was a younger firm, founded in 1867, in St. Louis, MO, that had itself invested in bromine plants in the Ohio River region. In its early years it distributed a wide range of pharmaceutical products to the western part of the country; by the turn of the century it had established a factory in New Jersey and marketed its products nationwide (Stout, 1933, passim; Haynes 1954, p. 54).

[23] See Levenstein (1993, 1995) for a more complete discussion of the role of the manufacturing chemists in facilitating collusion in the bromine industry.

[24] U.S. Geological Survey (1885, pp. 486–487) and *Oil Paint and Drug Reporter* (hereafter, *OPDR;* Anniversary Supplement 3 March 1897; 28 July 1885, p. 38.

[25] OPDR (3 October 1892, p. 38; 10 October 1892, p. 7), and letter from W. R. Shields to Herbert Dow, 9 December 1892 (File 920004), quoted below.

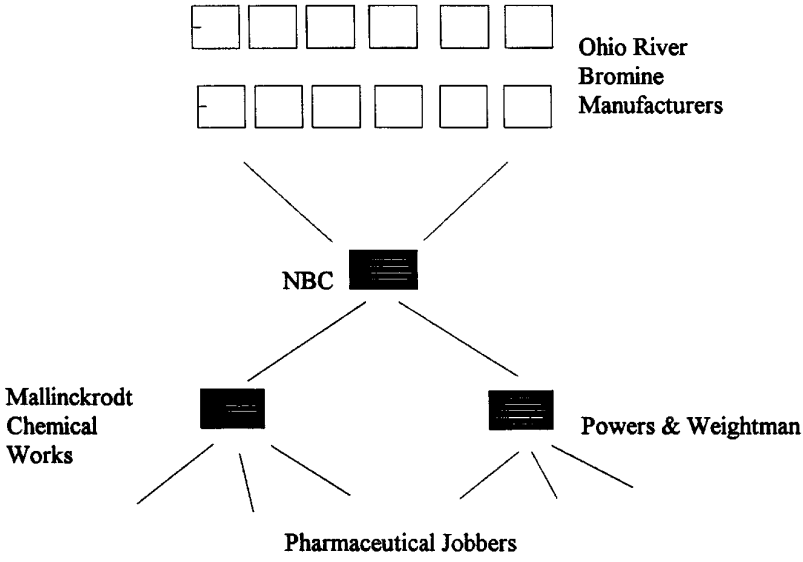

FIG. 3. Contractual relationships in the bromine industry, 1885–1891 (National Bromine Company Pool).

in negotiating each of the bromine industry's collusive accords up until 1910. At different times, Shields was on the payroll of both the Dow Chemical Company and Mallinckrodt Chemical Works.[26]

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 (Fig. 2 and Fig. 4). Mallinckrodt and P&W agreed, with the German bromine cartel, to refrain from shipping abroad and to prevent any American bromine (or bromides) from being exported. In return, the German cartel agreed to purchase $25,000 bromine from the American manufacturing chemists each year.[27]

The pool successfully raised prices during this period. The average price during the Shields pool was 60% higher than during the period between the pools, and almost double the predicted price if all firms were producing at Cournot levels (Fig. 1 and Table 2).[28]

[26] See letter from Herbert Dow to H. E. Hackenberg, secretary of the Dow Chemical Company, 11 June 1909, regarding 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, 12 February 1910, indicates that Shields may be a paid agent of the Pomeroy Salt Association (File 100011). Letters from Dow to Hackenberg, 12 May 1910 and 6 June 1910, indicate that Shields was working for Mallinckrodt (File 100013).

[27] Letter from J. H. Osborn to Herbert Dow, 18 November 1896 (File 960005).

[28] The average price during the Shields pool was 40.88¢. The average price during the NBC was 34.08¢. The average price between the two pools was 24.75¢. The predicted Cournot price, with 12 firms using the Ohio River production process, is 20.8¢ (Table 2).

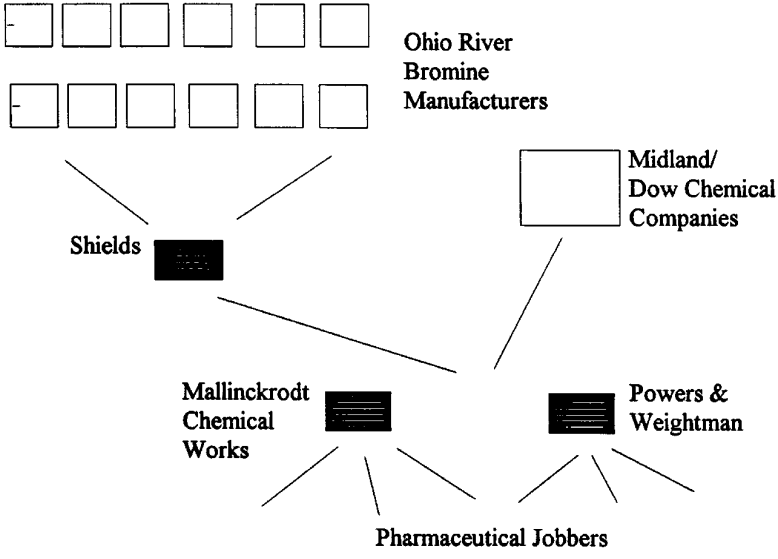

FIG. 4. Contractual relationships in the bromine industry, 1891–1902 (shields pool).

During the ''Shields pool'' Herbert Dow began to produce bromine and bromides in Midland, MI in a new firm, the Midland Chemical Company (Fig. 2).[29] Mr. Dow, a young chemist and inventor, had developed a new process for separating bromine from brine. His process was electrolytic rather than thermal and did not require the removal of sodium chloride salt from the brine. 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; 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 10 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 (Fig. 2 and Fig. 4).[30] The contract limited Midland's total output and prohibited it

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

[30] Letter from B. E. Helman, treasurer of the Midland Chemical Company, to H. S. Cooper, general manager, 23 March 1894, instructing him to begin shipments to Powers & Weightman and Mallinckrodt on the new contract (File 940003).

TABLE 2
Price and Output of Potassium Bromide When Cournot Competitors Used the Ohio River
Bromine Process

Cost function: $TC_i = F_{salt} + 0.85q_iP_{Br} + 0.6q_iP_{KOH} + 4q_i$
Demand function: $P_{KBr} = 60.55 - 0.03388\ Q_{KBr}$

Number of firms	q_i (000's lbs)	Q_{KBr} (000's lbs.)	P_{KBr} (¢)
1 (jointmax)	555.3	555.3	39.0
2	283.2	566.4	38.6
12	85.4	1025.2	20.8
∞		1110.7	17.5

Note. Twelve firms manufactured bromine in 1891. The shape and parameters of the cost function are taken from estimates made by the Dow Chemical Company of the costs of their Ohio River competitors. P_{KOH} is assumed to be 4¢, its average cost during the pool period (from *OPDR*). P_{Br} is assumed to be 12¢, the Dow Chemical Company's estimate of the marginal cost of producing bromine using the Ohio River bromine process. The parameters of the demand function are estimated from annual data on industry output (from U.S. Geological Survey (1886 to 1915) and average annual potassium bromide prices (from *OPDR*). Average annual potash prices and the percentage of the year the industry was colluding are used as instruments.

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 the Dow Chemical Company (Midland's successor) 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 sell Dow bromides to the wholesale drug trade.[31]

Dow began to supply its new distributors when its contract with Mallinckrodt and P&W expired in August. Shields' contracts with the Ohio River producers expired in October and were not renewed.[32] After a brief price war, described in more detail below, Dow and Mallinckrodt agreed informally to refrain from undercutting one another's prices. Prices were lower during the informal cooperation which followed than during the pool (28.61¢ compared to 38.57¢ over both pools), but still substantially above the hypothetical Cournot price (Table 2).

At this time Dow had its first direct contact with the German bromine combine,

[31] Rosengarten & Sons was a Philadelphia-based fine chemical firm whose origins dated to 1822. Merck & Company was a New York company with manufacturing in Rahway, NJ. It was formed in 1891 by George Merck, the son of Wilhelm Merck, head of E. Merck (Chemical Works) of Darmstadt, Germany. Dow also contracted to sell directly to one patent medicine producer, Meyer Brothers Chemical Company of St. Louis, MO (letter from Rosengarten & Sons to Herbert Dow, 13 April 1902, File 020062; Minutes of Midland Conference, 14 April 1902, File 020027; and Minutes of Company Conference at Midland, 14 July 1902, File 020028).

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

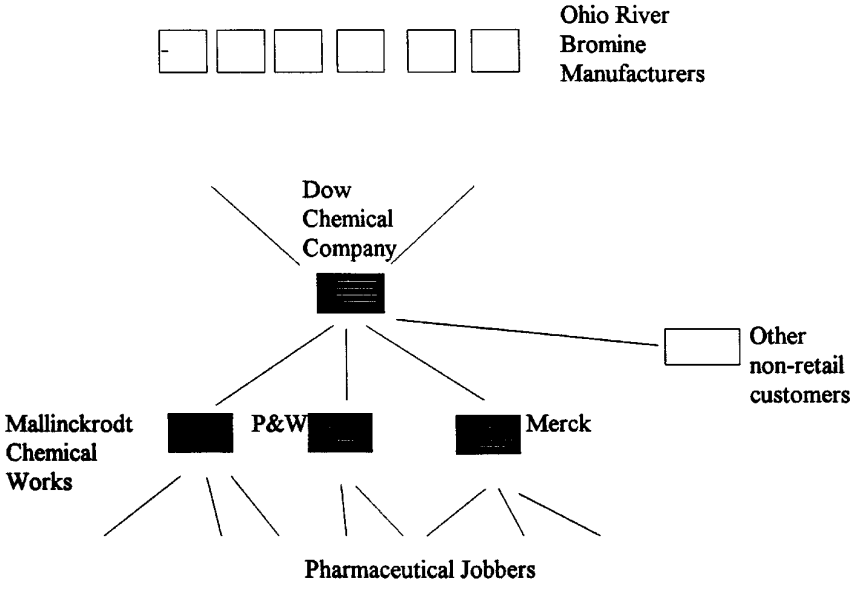

FIG. 5. Contractual relationships in the bromine industry, 1910–1914.

the Vereinigte Chemische Fabriken zu Leopold shall, Stassfurt.[33] Its director, Herr Jacobsohn, visited Midland in August, at the expiration of the contracts with P&W and Mallinckrodt. This conference was followed by a confirming letter:

> [W]e . . . 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] (23 September 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.[34] The growing tensions between Dow and the Germans did not disrupt the U.S. market until three years later, when the Germans abrogated their side of the agreement and entered the U.S. market (note the sharp drop in price in 1905 in Fig. 1).

Dow and the Germans came to an extensive and detailed price setting, market division agreement at the end of 1908 (Fig. 2 and Fig. 5). Under that agreement,

[33] On 1 January 1909 the official name of the German bromine cartel became Deutsche Bromkonvention zu Leopold shall-Stassfurt (letter from the member firms to the Dow Chemical Company, 31 December 1908, File 080017).

[34] Herbert 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 Bromide 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" (15 October 1902, File 020069).

Dow and the Germans jointly set prices in the United States, Europe, and the ''Rest of the World.'' Dow withdrew from the European market in return for a payment of $32,000 a year.[35] 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 its sole representative in the neutral territory.[36] The Germans completely withdrew from the North American market.[37] This agreement, with various modifications, remained in force until the beginning of the First World War.[38]

Dow also (virtually) simultaneously signed 10-year contracts with three manufacturing chemists, Powers–Weightman–Rosengarten, Merck, and Mallinckrodt to supply them with all their requirements of bromine.[39] 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 (Fig. 5).

Prices rose immediately after the signing of these agreements (from 13¢ to 19¢) and continued to increase through World War I (Fig. 1). Prices averaged 29.5¢. They increased gradually from 19¢ to 39¢ after the signing of the Ohio River contracts, described below. Average industry costs had fallen with the increase in Dow output, so the markup over marginal cost was even greater than during the pool period (Levenstein, 1994a).[40]

[35] The payment Dow received from the Deutsche Bromkonvention was based on a sliding scale depending on the selling price of bromides. The maximum payment was $32,000 based on an average selling price of 28¢ per pound. That price was achieved shortly after the Dow Company contracted for the output of the Ohio River firms in 1910.

[36] The November 1908 agreement made all of the world but Europe and North America, including Panama and the West Indies, neutral territory. The agreement originally envisioned the establishment of uniform shipping rates to each port in the neutral territory. They also considered the appointment of a single representative for both Dow and the Germans for the entire neutral territory. This proved too difficult, and in October 1909, Dow accepted a guaranteed one-third share of the sales in neutral territory and appointed Julius Grossmann, a Hamburg chemical distributor who had sold Dow bromides since 1906, its exclusive representative for pharmaceutical bromides in the neutral territory (contract, 29 October 1909, letter from Herbert Dow to Julius Grossmann of same date, File 090024, and Dow to Julius Grossmann, 22 September 1909, where Dow accepts the one third-two thirds division, File 090023).

[37] ''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, ''Report of meeting with representatives of Vereinigte Chemische Fabriken zu Leopold shall A.-G.,'' 24–26 November 1908, by H. E. Hackenberg and Herbert Dow (File 080017), and *OPDR* (7 December 1908, p. 35).

[38] See Levenstein (1994b) for further discussion of the implementation of the agreement between Dow and the Deutsche Bromkonvention.

[39] Powers & Weightman merged with Rosengarten on December 31, 1905, following the death of Mr. Weightman. Letters from R. E. Paris, Dow's sales manager, to Herbert Dow, 6 October 1908 (File 080032), Edward Mallinckrodt to Herbert Dow, 24 October 1908, Herbert Dow to Edward Mallinckrodt, 27 October 1908 (File 090105), minutes of meeting between Edward Mallinckrodt and Herbert Dow, 1 November 1908 (File 080017), Herbert Dow to A. E. Convers, 2 November 1908 (File 080026), Squires, Sanders & Dempsey to Dow Company, 5 November 1908 (File 080017), and contract, dated November, 1908, between Dow, Mallinckrodt, and Powers–Weightman–Rosengarten (File 090105).

[40] If Dow and the Germans had behaved as Cournot competitors (assuming the Germans' costs were the same as Dow's), the price would have been 20.2¢ per pound.

Dow kept the price of potassium bromide in the United States at 19¢ per pound for a year and a half after its agreement with the Germans (Fig. 1).[41] At this price the Ohio River producers could not profitably sell their bromine to anyone to convert into bromide salts, nor convert it themselves.[42] In May 1910 Dow contracted with all but one of the Ohio River producers to purchase their entire output of bromine on a sliding scale price, based on the published market price of potassium bromide (Fig. 5).[43] 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 the First World War (Fig. 1).

2.3. *The Bromine Price Wars*

Six price wars disrupted cooperation during the period of this study (Fig. 2). 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.

There were four relatively brief price wars—two during the NBC pool (1886–1887 and 1888) and two following the end of the Shields Pool (1902 and 1903). There were two longer price wars between the NBC and Shields pools (1891–1892) and following Dow's entry into the European market (1905–1908). Table 1 summarizes relevant differences in these price wars.

Pool War I (1886–1887) was initiated by Germans exporting bromides to the United States and offering them at just below the NBC price. After 22 weeks of imports, the Germans and Americans agreed to withdraw from each other's

[41] Letter from Herbert Dow to W. R. Shields, 9 January 1909, "... prices have gone to 18 cents per pound for Potassium Bromide Granular. I think you will agree that the present price is still very low, but so far as we are aware, there are no conditions that are likely to change it in the near future. . . ." and on 22 January 1909, "We regret that it proved impossible to find a way to get higher prices" (File 090009). See also letter from Herbert Dow to Deutsche Bromkonvention, 27 December 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).

[42] As mentioned above, such attempts were made. The product was not pure enough, however, to pass the pharmacopeias of Europe and the United States (letter from Herbert Dow to Deutsche Bromkonvention, 27 December 1909, File 090026, and correspondence between Herbert Dow and W. R. Shields during 1909 and 1910). These pharmacopeia were industry, not government standards, and were in large part written by the manufacturing chemists. Dow and Mallinckrodt agreed, after signing their 1908 contract, that Mallinckrodt would arrange to raise the purity standard for potassium bromide to a level that was higher than that attainable by the Ohio River producers, but still below the European pharmacopeia. This allowed the Dow Company to keep the purity of its product below that of the Germans, facilitating distinction between the two products and, therefore, detection of violations of territorial agreements.

[43] Dow signed contracts with Schlaegel, Buckeye, Excelsior, and Hartford City (of Ohio and West Virginia) salt companies on 19 May 1910. A slightly different contract was signed with J. Q. Dickenson, of Malden, West Virginia (File 100044).

markets:

> One outcome of the importation of bromine in 1886 and 1887 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*, 29 June 1891, p. 5).

Pool War II (1888) was the result of the Germans' belief that this agreement had been violated. It is not clear whether the Europeans were simply mistaken or whether there were resales of bromine by U.S. customers who were not a party to the market division agreement. In its coverage of the price war, the *Oil, Paint and Drug Reporter* tried, unsuccessfully, to identify its instigator. All that was clear was that there was a misunderstanding which was quickly resolved. The *OPDR* wrote,

> Up to the present time there have been two distinct syndicates of manufacturers, one controlling the English market and the other the American . . . each syndicate acting under a written or implied agreement with the other, was to enjoy exclusive control of its own market. This agreement the English syndicate seems to have now violated by coming here for trade, but according to the best information at hand it was not the transgressor in the first instance, or at least it believes itself to be the aggrieved party (5 December 1888, p. 6).

Pool War III (1891–1892) began at the expiration of the NBC pool contracts. The price war occurred, despite attempts to negotiate new contracts, because of disagreement over the distribution of rents between the bromine manufacturers and Mallinckrodt and P&W.[44] In order to increase their bargaining power, bromine producers sold bromine to other distributors who had not been party to the NBC pool agreements:

> 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. . . . [O]ur expectation of a very interesting fight are being fulfilled . . . (*OPDR*, 10 August 1891, p. 5).

After over a year and a half of falling prices and several ultimately false reports of agreement, the Shields contracts described above were signed.

Dow War I broke out in 1902 when Dow signed new contracts for the distribution of its bromides with two competitors of Mallinckrodt and P&W, Rosengarten and Merck. Despite Dow's conscious selection of distributors with reputations for refraining from price cutting, Mallinckrodt and P&W announced price cuts as soon as the pool contracts expired. This price war was the briefest in the study, lasting only six weeks. It was resolved following an exchange of letters between Dow and Mallinckrodt in which each agreed not to undercut the published market price.

[44] In March of 1891 [the NBC] expired, because of the inability of the company to renew expiring contracts with the consumers [the manufacturing chemists]" (U.S. Geological Survey, 1891, p. 579). See *OPDR* (29 June 1891, p. 5; 20 July 1891, p. 38; and 3 August 1891, p. 36).

Collusion broke down again in 1903 (Dow War II) when some firms (Dow, followed by 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 14 weeks).

The last, and longest, price war (Dow War III) began in 1905, when the Germans retaliated against Dow's entry into the European market by offering bromides in New York City at half the current market price. 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. Dow 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 when we commenced making a much purer Bromide than we had made before, we found that we could make goods that would pass the Pharmacopoeias of the European countries and therefore 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. This price they maintained for about a year, anticipating that we had taken some annual contracts, but when 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, and also had considerable selling expense (25 October 1906, File 060060).

This price war continued for two more 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. Dow did, however, receive better terms than those described above.

3. THE FUNCTIONS OF PRICE WARS IN THE BROMINE INDUSTRY

Collusion in bromine was successful and, for the most part, stable. During the 30 years before World War I, the industry was cooperating (i.e., not in a price war) 80% of the time; there were no price wars for the 11 years of the Shields pool (1891–1902) or the 6 years of the Dow–Deutsche Bromkonvention agreement (1908–1914). During these cooperative periods, prices were higher, well above cost, and participants earned large profits (Levenstein, 1994a). The features of the bromine industry which made collusion possible are analogous to those of other successful colluders during the 19th century. Participants were patient. The participants interacted repeatedly over time, and, with the vertical connections the pools had with the manufacturing chemists, over products as well. Both the bromine producers and the manufacturing chemists had a prior history of colluding in other markets which, even without the use of cross-market power, facilitated cooperation by creating a favorable set of expectations and beliefs. The information structure created by the use of the pool and the distributors also facilitated collusion, by monitoring both production and consumption sites, but keeping that information at arms' length from the producing firms. Each of these features of collusion in bromine is discussed briefly below.

Finally we turn to the question, ''did the bromine price wars facilitate collusion?'' Were they imperfect monitoring price wars? As in the other industries described above, imperfect monitoring models capture the salient features of some, but not all, of the bromine price wars. Imperfect monitoring price wars had some of the characteristics of the ''optimal punishments'' described in Abreu *et al.* (1986); prices fell once and stayed there for the duration of the price war. But these price wars were short, and prices did not fall to the Cournot level, as assumed by Green and Porter (1984), let alone below it, as proposed by Abreu *et al.* (1986). (Compare Tables 1 and 2.) Over the course of the period studied, the industry created institutions designed to remove informational limits to collusion so as to avoid the necessity of imperfect monitoring price wars.

Other price wars were more like the bargaining price wars described above. Price wars resulting from bargaining problems displayed more complicated price patterns and were more severe in both depth and duration (Table 1). The introduction of a mass production technology led to a potentially destabilizing situation, in which cooperation could have been impossible. The worst price war in the industry's history followed as two mass producers battled. The merger option, turned to by many American firms, was not an option in this case of international competition. The price war eventually ended with the establishment of a new market-sharing, price-setting agreement which relied explicitly on equilibrium punishments. The geographic and legal divisions, which made merger impossible, facilitated the functioning of the new agreement, as did the patience of the participants, relative to Lamoreaux's mass producing competitors.

3.1. *Patience Facilitated Collusion*

The participants in the bromine industry were generally patient, both objectively and subjectively. The Ohio River firms were small (with an average of about $50,000 in assets in 1909), and more importantly, not highly leveraged. Of the six firms still in operation in 1909, four were given a high credit rating and the other two were reported ''fairly prompt'' and ''responsible'' in meeting their current obligations. None are reported to have a bonded debt, and only one is reported to have any debt other than merchandise credit (Credit Reports, 2 August 1909, File 090022). Because they did not rely on debt to finance their operations, they were able to refrain from selling when prices were low.[45] They certainly did not need to risk precipitating a price war in order to increase their cash flow.

Dow's financial situation much more closely resembled that of Lamoreaux's impatient mass producers. Dow had made a substantial investment in bromine production, building a new plant in 1900 with a capacity 20 times that of most of the Ohio River firms. To finance that and other investments, it had issued $300,000 in bonds, equal to 20% of its capital stock. But it is clear from the

[45] For example, after the initial rise in price (to 19¢) following the Dow–Deutsche Bromkonvention agreement at the end of 1908, Shields reported that ''all the plants [in the Ohio River region] have been running and all making bromine except Koehler,'' but they were waiting for higher prices before offering it for sale (W. R. Shields to Herbert H. Dow, 18 April 1909, File 090009).

correspondence among large stockholders and members of the Dow Board of Directors that most understood that investing in Dow's innovations required a long term horizon. The only dissent from this perspective from within the Dow Chemical Company came from elderly stockholders concerned about the size of dividend payments. Herbert Dow wrote to one such investor (and close friend), J. H. Osborn, explaining the company's general attitude:

> I asked our bookkeeper to send you a monthly statement so that you might see exactly what we are doing. From this report you will see that we are making nearer 12% than 6%. The amount of profit above the 6% goes into construction, and I have not heard of anybody that has objected to it . . . (17 April 1901, File 010021).

While this particular correspondence did not address Dow's policy toward the cartel (and describes a company more flush with funds than Dow was between 1905 and 1908), it does express the position held by the Board of Directors throughout this period—invest in the future, rather than extract short-term gains (Levenstein, 1996, Chap. 3).

When the German's ''invaded'' the U.S. market in 1905, offering bromides at half the going price, Dow chose to withdraw from the domestic market, stockpiling its bromides, rather than selling them at a low price.[46] While this kind of behavior—refraining from making sales at a low price in anticipation of higher prices in the future—displays patience, it also requires funds. Herbert Dow wrote to the president of the Dow Chemical Company, A. E. Convers, who was personally a wealthy man:

> In fact, the chances are very much in favor of a higher price, and whether there is a higher price or not, we could make all this bromide into crystals, and unless the market changes materially, we would get very much more for it if we can afford to hold this amount of stock, until the crystallizing plant is big enough to use it up. This extra amount of crystals would go mainly to Europe and would help us materially in our fight with the Germans. It [is] therefore apparent that the proper thing to do is to hold the granular until it can be worked up into crystals, providing you can take care of the finances in the meantime (22 April 1905, File 050010).

Mr. Convers immediately replied in the affirmative, assuring Mr. Dow that he should not worry about funds and endorsing his policy toward the German cartel:

> Personally I am heartily in favor of carrying the Bromide instead of dropping the price to 15¢—It would seem to me better to hit the market where it is highest viz in Germany—If we can only break their home price—so that the whole market is unprofitable to anyone but the Dow Co—the price will eventually come up—if we hold the market in that condition long

[46] Dow also increased its exports of bromides to Europe, where the Germans continued to charge higher prices. But Dow's capacity for making bromide suitable for export (i.e., in crystals, rather than powder) was limited, and so bromide powder accumulated while Dow increased its crystallizing capacity.

> enough—There should be no difficulty in carrying the Bromide even if the company found it difficult to borrow for general purposes. . . . (23 April 1905, File 050010).

Dow was in a position to be patient, even during financially strident times.

3.2. *Repeated Interaction Facilitated Collusion*

Repeated interaction is crucial in most models of collusion, as punishment of cheating will necessarily happen at some later time. Bromine producers certainly competed with one another over many years. The manufacturing chemists interacted with one another not only over time, but also in different geographic markets and in many product lines. But this hardly distinguishes the bromine industry from less successful colluders. Evidence that repeated interaction was crucial to supporting collusion is best offered by a counterexample. When World War I broke out, the Deutsche-Bromkonvention was suddenly powerless to punish Dow, and all future interaction was brought into question. On 3 August 1914, Herbert Dow wrote to two British firms offering to supply them with bromides.[47] Dow raised the price without notifying the Germans (for the first time since 1908) on August 5. When the Germans wrote to complain of these actions, Herbert Dow wrote to members of his Board of Directors that,

> [A]ll the conditions of our agreement with the Germans should be suspended during the war but that as soon as they are able to again deliver Bromides, the provision of the contract could again be made operative . . . (17 September 1914, File 140014).

With little expectation of repeated interaction in the near future, cooperation disappeared in short order.

3.3. *Prior History Facilitated Collusion*

The prior history of the industry, both on the part of the Ohio River producers and the manufacturing chemist distributors, likely made collusion easier. The Ohio River bromine manufacturers had all participated in cooperative schemes to restrict and pool output, and to raise prices, in the salt market (Levenstein, 1995). While collusion in salt was less successful than in bromine, these attempts to collude dated back to the beginning of the century (Stealey, 1993; Eskew, 1948, pp. 88–90). In a situation in which there may have been many equilibria, this prior history may have made cooperation the more likely reality.

The manufacturing chemists who distributed bromine also knew each other well and had a long history of cooperating in a variety of chemical and pharmaceutical markets (Levenstein, 1995; Haynes, 1954; p. 251). They had established customers and market shares, which made cheating less tempting, as customers were less likely to move to a new distributor in response to a small change in price. As in the case of well-established, nonmass-producing firms

[47] Letters from Herbert Dow to George Atkinson & Company and Howard & Son Ltd. (File 140014).

studies by Lamoreaux, this prior history created a set of expectations and beliefs, among both the distributors and the bromine producers, which facilitated the implementation of collusive equilibria.

3.4. *The Pool Information Structure Facilitated Collusion*

The information structure provided by the vertical organization of the pool also facilitated collusion. The manufacturing chemists had longstanding relationships and frequent contact with bromine customers. These customers were primarily pharmaceutical jobbers and patent medicine producers who might well purchase other goods from the manufacturing chemists. Thus, the manufacturing chemists had a great deal of information about customers' demands. This made it easier to detect cheating, as idiosyncratic declines in demand resulting from purchases from nonpool sources could be distinguished from declines in aggregate pharmaceutical demand. But because information about customers' identities and particular preferences was available only to the manufacturing chemists, the pool structure made it more difficult for an individual bromine producer to sell outside the pool. Because the industry was geographically fairly concentrated, the pool's representative (i.e., Hildt, then Shields) could monitor production and shipments, making it more likely that cheating would be detected. Thus, the pool, as an organization, had information about consumers and producers that made the detection of cheating more likely. On the other hand, its vertically disintegrated structure limited the flow of information that might facilitate cheating.

3.5. *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. Correspondence among Dow Company officials makes it clear that it was only such threats that induced the Company's cooperation.

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

> [T]he price of bromine came down from 25 to 15 cents last September, 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, producing 20,000 [pounds] of bromine or its equivalent in bromides, I reserve the right to annul the agreement by giving 4 months notice. . . . I am willing to buy your product at same price and terms provided we can agree as to what that product shall be. . . . 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 (9 December 1892, File 920004).

Following these discussions with Shields, the Midland Company agreed to restrict its output and sell only to Mallinckrodt and P&W. In deciding how to respond to Shields' threat, Dow evaluated the credibility of the threats that were

delivered. For example, Dow demanded verification of the inventories Mallinckrodt and P&W claimed to have.[48] Threats designed to support collusion were useful only when they were credible.

Similar threats also explain Dow's continued cooperation with the pool over the next decade. Because its technology generated increasing returns to scale, Midland was anxious to increase its output.[49] 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.

Negotiations began in 1896 to renew the contracts with Midland and the Ohio River bromine producers, due to expire in 1897. Midland considered ending its cooperation with the pool. It even considered trying to get control of the output of the Ohio River producers, paying them either for their bromine or not to produce.[50] The five-year contract Midland eventually signed limited its output to 200,000 pounds annually.[51] 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, over the preceding five years of the pool, accumulated 800,000 pounds of bromine, which they threatened to put on the market if Midland did not agree to cooperate with the pool.[52] As B. E. Helman, Midland's treasurer, so vividly put it in a letter to Herbert Dow,

> I think you and Cooper [general manager] are completely 'off' on the matter of overproduction . . . You men must reconstruct your policy unless you can prove there is no overstock 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, *now* or *soon* is a good time *but* 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 *hand* a large surplus we would be ruined. There is no question about the outcome (23 November 1896, File 960035).

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[48] 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 . . ." (18 November 1896, File 960005).

[49] An obvious question is why, then, did Powers & Weightman and Mallinckrodt not arrange to purchase their entire requirements at a lower price from Midland. The answer has two parts. The first is that the Ohio River firms were not going to disappear over night, even if they had a less efficient technology, and if their output were not purchased by the large manufacturing chemists who were party to the agreement with the Germans, it might well have been purchased by someone else and exported, disrupting that agreement. The second part of the answer, is that Powers & Weightman and Mallinckrodt Chemical Works did not want to accept the risk of having a sole supplier of their bromine requirements (letter from Herbert Dow to G. E. Collings, 31 December 1907, File 070028).

[50] It expected to have the assistance of the United Salt Company, the Ohio salt pool, in controlling these firms (statement by J. H. Osborn, 4 March 1896, and letter from Osborn to H. S. Cooper, 17 March 1890, File 960001).

[51] Letter from H. S. Cooper to J. H. Osborn, 29 May 1897 (File 970084).

[52] Letter from J. H. Osborn to H. S. Cooper, 18 November 1896 (File 960005) and from Cooper to Osborn, 29 May 1897 (File 970084).

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 or participate in the pool.

3.6. *Imperfect Monitoring Caused Short Price Wars, but Coordination Problems Caused All Hell to Break Loose*

But if these threats obtained the desired cooperative behavior, why were there price wars? Pool War II (1888) and Dow War I (1902) are meaningfully described as having resulted from firms' inability to monitor perfectly the actions of other firms. In the former case, the Germans observed imports of potassium bromides and interpreted this as the result of an abrogation of the agreement to confine sales to one's own continent. In the latter, Mallinckrodt and P&W interpreted Dow's contracting with its competitors as a sign that it would undercut the pool price. In both cases, it appears that neither party intended to undercut the price or violate an existing understanding. The ensuing price wars were very short and ended after a written exchange reaffirmed everyone's commitment not to engage in price competition (Table 1). There was no change following Pool War II in the way firms 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 the *Oil, Paint and Drug Reporter*) to prevent further misunderstanding. This difference may explain why prices fell further, and spiraled, in 1902 (Table 1). Monitoring problems did not induce the severe price cutting (which firms tried to avoid by communicating with one another) observed when disagreement was the real problem. Thus, in both of these relatively simple price wars, prices did not fall even to Cournot levels (compare Tables 1 and 2).

In contrast, the two severe price wars of 1891–1892 and 1905–1908 were undoubtedly made lengthier by monitoring problems. But they were not the *result* of imperfect monitoring problems. As in Pool War I (1887), firms publicly announced their willingness to sell below the preexisting collusive price. All industry participants understood that these announcements were part of a strategy to renegotiate the agreement. Firms took actions during these price wars in order to influence a new, yet to be designed, collusive arrangement. Thus, it was not the threat of a price war but the price war itself that influenced a new collusive equilibrium. These price wars were part of the renegotiation of a new collusive arrangement, not a punishment phase that would help to reestablish an existing one. In these cases, reams of correspondence were not sufficient, by themselves, to resolve these price wars.

Dow War III was particularly severe because rules relating actions during price wars to the new collusive equilibrium were not common knowledge. As Herbert Dow wrote to A. E. Convers 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 . . . (6 March 1908, File 080022).

With rules such as these it is not surprising that prices spiraled down. Bargaining price wars such as these did not help to stabilize collusion, as in the case of price war threats or imperfect monitoring price wars. But they did shape the terms of any future collusion.

3.7. *Bromine Producers Learn How to Avoid Price Wars*

Three years after the Germans cut the price of U.S. bromides by 50% in an attempt to force the Dow Chemical Company to withdraw from foreign markets, a detailed, written contract was signed by Dow and the Deutsche Bromkonvention. This contract called for the use of market price reduction punishments—price wars; these were never implemented. But during the five years in which this agreement regulated competition in the international bromine market, we do observe the use of punishments designed to make cheating unprofitable. When cheating was suspected, significant effort was made to identify the perpetrator. Side payments—transfers into bank accounts—were then made. These ''firm-specific'' punishments resemble those of Fudenberg *et al.* (1994) and Abreu *et al.* (1990), where punishments allow efficient collusion by shifting profit from one firm to another. These punishments rely on (probablistic) information about the identity of the cheater. When such information was not immediately available, both Dow and the Germans invested resources in obtaining it. These activities ranged from chemical analysis of bromides that appeared on continents where they did not belong to identify the likely producer, to hiring Shields to report on activity on the Ohio River.

There are several reasons why firms in the industry first resorted to the use of price war punishments that were later eschewed. First, there was a learning process. Industry participants were familiar with other pools which employed price war punishments; they initially turned to the punishment mechanisms with which they were familiar. 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, as the gains to collusion were not divided among as many firms.

There was another, increasingly important, reason to develop alternatives to price war punishments. Bromine and bromides are nonperishable goods; short-term price fluctuations led to speculation. They also disrupted long-term contracts with customers. It took over a year for Dow to negotiate and receive payment on goods shipped but not paid for at the time of the decline in price due to the German ''invasion'' of 1905. The conflict and lack of trust arising from that episode led to several months of extended negotiations between Dow and Powers–Weightman–Rosengarten before they again signed a long-term contract at the end of 1908.[53] Finally, price fluctuations created uncertainty among

[53] The cause of contention between Dow and Powers–Weightman–Rosengarten was a clause, insisted upon by the Dow Company, which created a disincentive for P–W–R to cut prices to low levels. Herbert Dow wrote to Mallinckrodt, 9 November 1908, ''We, however, do not like the five

customers and could have led to a long-term decline in demand. In particular, price uncertainty was detrimental to Dow's strategy of increasing industry demand by developing new uses for bromine in areas such as gold mining and water purification. Thus, the shift from the use of market punishments to those firm-specific was partly the result of a learning process by firms in the industry, and partly the result of the actions taken by an individual firm.

4. CONCLUSION

Recent contributions from game theory have greatly increased the sophistication of economists' analyses of cooperative behavior among firms. They have provided a much needed richness to the class of cooperative behavior considered. But because they depend crucially on unobservable variables, meaningful empirical testing of these models is difficult. This article takes an alternate tack. It asks, is the intuition of these models consonant with the history of price wars and cartels for which we have evidence of firms' beliefs and intentions? It takes a careful look at one cartel, the bromine cartel, where we have detailed documentation of participants' beliefs, motivations, and the strategies considered, as well as those pursued.

I find that the historical record resonates with many of the findings of these models. Successful cooperation depends upon repeated interactions among sufficiently patient firms. The information firms have can help to support collusion; firms do not take the information structure as exogenous, however. They design cooperative agreements, and specific information-gathering techniques, in order to create an information system which will support collusion. Future modeling of collusion would benefit from an attempt to endogenize the information structure observed. The cost of information collection is determined by both the technology and the structure of the industry. How much information is actually collected will depend on whether firms, individually or collectively, have the incentive to incur those costs. We may also need to take seriously what appears to be costless communication among firms. Firms in the bromine industry clearly believed that there was a cost to lying, measured in the loss of reputation for credibility. There was also a benefit to written, even though unenforceable, contracts. Both oral and written communication helped establish expectations of future cooperation and occasionally helped cognitively limited and honestly forgetful humans coordinate their activities on a single equilibrium. Finally, the multiplicity of equilibria which often confounds theorists, leading to a relentless drive for new, ''reasonable'' equilibrium solution concepts, may be more reasonably solved by looking to the varied history of different industries. The prior history of an industry may

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percent clause [added by P–W–R], for the reason that we have already had experience with Powers–Weightman–Rosengarten in a case in which their contract made them more or less indifferent to the cutting of prices, and think that in the future the only contract we would care to make with them would be one in which they had a vital interest in sustaining the price. Considering the advertising they would receive, they might think it more profitable to them to sell Bromides at 10 cents with a five per cent commission, than at 25 cents and a larger commission . . .'' (File 090105).

well be what determines the most reasonable outcome for that industry at that time.

One of the more novel contributions of such models has been the assertion that price wars may be equilibrium punishments, which firms use to sustain collusion when they do not have sufficient information to distinguish between cheating and stochastic shocks. While I find that threats of price wars helped to sustain collusion in the bromine industry, these imperfect monitoring price wars do not appear to be common in the historical record. Some price wars resulted from problems of imperfect monitoring, but these are the mildest price wars. Over time firms devised alternative and less costly ways of solving the incentive problems caused by imperfect information. Serious price wars were more likely to be caused by bargaining and coordination problems. And sometimes they reflected attempts by determined, but unsuccessful, firms to collude where the underlying conditions simply did not permit it.

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