An Empirical Study of an Auction with Asymmetric Information

By KENNETH HENDRICKS AND ROBERT H. PORTER*

This paper examines federal auctions for drainage leases on the Outer Continental Shelf from 1959 to 1969. These are leases which are adjacent to tracts on which a deposit has been discovered. We find that the data suggest that neighbor firms are better informed about the value of a lease than non-neighbor firms, that neighbor firms coordinate their bidding decisions, and that both types of firms bid strategically in accordance with the Bayesian-Nash equilibrium.

Since the seminal work of Robert Wilson (1967, 1977), auction theory has recognized that auctions in which information about the value of the object being sold is symmetrically distributed among participants are qualitatively different from those in which information is asymmetrically distributed. In the context of a common value auction, information is said to be asymmetric if the precisions of the signals observed vary across the participants. A polar case is an auction in which one agent has (exact) private information about the value of the object, and others have access only to (noisy) public information. The theoretical work by M. Weverbergh (1979) and Richard Engelbrecht-Wiggans, Paul Milgrom, and Robert Weber (1983) that followed Wilson's articles has focused on this case, and provided a general characterization of Bayesian Nash equilibria. The purpose of this paper is to adapt this theory to the institutional framework of a particular auction, the federal offshore oil and gas drainage lease sales, in which information is asymmetric, and to confront the predictions of this theory with field data. A virtue of our data set is that it is possible to identify agents with superior information, and indeed to quantify the information available to them and to the other, relatively less informed agents.

A drainage sale consists of the simultaneous auction of tracts which are adjacent to tracts on which deposits have been discovered. By contrast, a wildcat sale consists of tracts in areas that have not been drilled, and on which firms are permitted to acquire only seismic information. Bidding and drilling behavior, and *ex post* returns, differ significantly on these two types of tracts. Table 1 gives selected statistics on the sample of wildcat and drainage tracts off the coasts of Louisiana and Texas that were sold by the federal government during the period 1954 to 1969. The figures are based on bidding, drilling, and production data which the federal government provides on each tract, and on the annual survey of drilling costs conducted by the American Petroleum Institute. All dollar figures are in millions of 1972 dollars. Tract value is the estimated *ex post* present value of revenues minus drilling costs. Net profit is estimated tract value minus the discounted royalty and bonus payments made by the winning firm. The numbers in parentheses are standard deviations of the sample means.

Table 1 reveals several striking facts about the sample. The fractions of drainage tracts drilled, and which contained oil, were substantially higher than those of wildcat tracts. The average value of drainage tracts was

*Hendricks: Department of Economics, University of British Columbia, B.C. V6T 1Y2. Porter: Department of Economics, Northwestern University, Evanston, IL 60208. This research was funded by the National Science Foundation under grant nos. SES-8511068 and SES-8721231. We are indebted to Harry Paarsch and Richard Spady for advice, and to Michael Riordan for helpful discussions. Much of this research was conducted while Hendricks was visiting the Hoover Institution and Porter was at Bell Communications Research. An earlier version of this paper was presented at the 1987 North American Summer meetings of the Econometric Society at Berkeley, and at a number of universities. We are grateful to the participants in these sessions, and to the referees for their comments.

TABLE 1—SELECTED STATISTICS ON WILDCAT AND DRAINAGE TRACTS[a]

	Wildcat	Drainage
Number of Tracts	1056	144
Number of Tracts Drilled	748	124
Number of Productive Tracts	385	86
Average Winning Bid	2.67	5.76
	(0.18)	(1.07)
Average Net Profits	1.22	4.63
	(0.50)	(1.59)
Average Tract Value	5.27	13.51
	(0.64)	(2.84)
Average Number of Bidders	3.46	2.73

[a]*Source:* Kenneth Hendricks, Robert Porter, and Bryan Boudreau (1987). Dollar figures are in millions of $1972. The numbers in parentheses are standard deviations of the sample means.

more than twice the average value of wildcat tracts. Yet, there was less competition, and profit was roughly four times higher on drainage tracts than on wildcat tracts. The profit differential was even greater when measured in dollars per acre, since drainage tracts were typically half the size of wildcat tracts.[1] The government captured 77 percent of the value of wildcat tracts, but only 66 percent of the value of drainage tracts. Thus, even though drainage tracts were lower risk investments and yielded a significantly higher rate of return, firms were less likely to participate in these auctions. What can explain these facts?

The main difference between wildcat and drainage auctions is the distribution of information. Information in a wildcat auction is essentially symmetric, since the precision of seismic survey information is not likely to vary much across firms. This is not true in drainage auctions. Firms which own neighbor tracts obtain information about the drainage tract from their drilling activities on adjacent tracts. Non-neighbor firms derive their information from private seismic surveys, and observable production on adjacent tracts. The latter sources of information are imperfect substitutes for the information that on-site drilling on adjacent tracts can reveal. Consequently, neighbor firms are likely to be better informed than non-neighbor firms, which, if true, would give them an advantage in bidding against the latter. Non-neighbor firms would have to bid cautiously, if at all, since they would have to worry that their bids will win only if the neighbors' estimate is low. (This affliction is often called the "Winner's Curse.")

We find that the data strongly support this hypothesis. Conditional on publicly available information, the participation and bidding decisions of neighbor firms are significantly better predictors of tract profitability than the participation and bidding decisions of non-neighbor firms. Neighbor firms won most of the profitable drainage tracts, and their average share of the value of drainage tracts is about 44 percent. By contrast, non-neighbor firms earned approximately zero profits.

A naive theory of bidding in a drainage auction with one neighbor firm might predict that non-neighbor firms will not bid, on the grounds that they can never make money against a better-informed neighbor firm. However, such reasoning requires firms to hold incorrect beliefs about the bidding behavior of their rivals. If non-neighbor firms choose not to participate, and the neighbor firm correctly anticipates this strategy, its optimal response is to bid the reservation price when it is worthwhile. But, in that case, the non-neighbor can bid slightly more, win the auction, and earn positive profits on average. Thus, for the firms' behavior to be consistent with an equilibrium model of bidding, non-neighbor firms must behave strategically, and participate in such a manner that the neighbor firm is forced to consider the possibility that it will lose the tract if it bids too low.

We find that the data are consistent with the predictions of the Bayesian Nash equilibrium model of bidding in first-price, sealed bid auction with asymmetric information. Non-neighbor firms were relatively cautious in their bidding, but at least one non-neighbor firm bid in 69 percent of the auctions. The number of non-neighbor bids was more

[1]Walter Mead et al. (1984) obtain similar results, in that the internal rates of return they calculate are higher on drainage tracts. They also note that these returns are higher for firms owning neighbor tracts.

than twice that of neighbor bids, but neighbor firms won well over one-half of the drainage tracts on which they bid. Average net profits to non-neighbor firms were significantly negative on the set of tracts where no neighbor firm bid, and positive on the set of tracts where a neighbor firm bid. As mentioned earlier, average net profits of non-neighbor firms were approximately zero. We also find that the restrictions which equilibrium imposes on the joint distribution of neighbor and non-neighbor bids conditional on tract profitability and publicly available information are not rejected by the data.

The strong support for the asymmetric information model with one informed bidder was somewhat surprising, since approximately two-thirds of the sample of drainage tracts had multiple neighbor firms. In these cases, competitive bidding among neighbor firms should have eliminated most, if not all, of the information rents. The fact that these rents were positive, and large, suggests that neighbor firms may not have competed against each other. Several facts support this hypothesis. First, there is no law prohibiting firms from forming a bidding consortium in federal offshore auctions, and the neighbor firms may have previously formed such a consortium in order to manage production from the common pool. Second, there were 74 tracts with multiple neighbor firms, but only 17 tracts had multiple neighbor bids. Third, net profits were not significantly lower on tracts with multiple neighbors than on tracts with one neighbor firm. Fourth, the bids of the neighbor firms are strictly decreasing in the number of neighbor firms. Given plausible assumptions on the distributions and given the range of the data, this result is inconsistent with the theory of competitive bidding (see Albert Smiley, 1979). It is consistent with neighbor firms coordinating their bidding decisions, and submitting one serious bid on tracts which are considered worthwhile.

The paper is organized as follows: in Section I, we study an auction in which one firm has private information about the drainage tract, and others have access only to public information. In Section II, the data and estimation strategy are discussed. In Section III, we examine the evidence for the hypotheses that neighbor firms are better informed than non-neighbor firms, and that they bid according to the bidding model described in Section I. In Section IV, we investigate an alternative model in which neighbor firms bid competitively against each other.

I. The Bidding Model

Our bidding model is a version of the noncooperative first-price, sealed bid model with asymmetric information that was introduced by Wilson (1967), and subsequently studied by Weverbergh (1979) and Engelbrecht-Wiggans, Milgrom, and Weber (EMW) (1983). The focus is on the individual tract, and we ignore any structural or strategic factors which may link a firm's bidding decisions on different tracts. Specifically, we assume that (*i*) there are no information externalities between tracts sold in the same sale; (*ii*) each firm is risk neutral; and (*iii*) the bidding strategy of each firm for a tract depends only on the state of information and competition for that tract. Assumption (*i*) is justified by the observation that drainage tracts in a sale are usually drawn from geographically distinct areas. Assumption (*ii*) is not unreasonable since, for most of the participants, bids in an OCS drainage sale represent only a small part of their annual exploration budgets. Assumption (*iii*) implies competitive bidding between the neighbor and non-neighbor firms. It rules out the use of punishment strategies in which bidding behavior on a tract is made contingent on bidding outcomes on tracts sold in previous sales.

There is one neighbor firm and an arbitrary number of non-neighbor firms. Let X and Z denote, respectively, the private and public signals on V, the unknown value of the representative drainage tract. The neighbor firm observes the realizations of X and Z prior to bidding on the tract, while non-neighbor firms observe only the realization of Z. Realizations of the random variables will be denoted by lowercase letters. In what follows, we treat z as given, and are explicit about the dependence of the distributions on its value. However, for notational convenience, we will suppress the dependence of bidding strategies on z.

The essential feature of our model is that the information revealed by on-site drilling of an adjacent tract by a neighbor firm is a sufficient statistic for the information non-neighbor firms acquire from seismic surveys. The assumption that this information is known to the neighbor firm is made in order to obtain a precise characterization of the equilibrium and its properties. A more realistic, but less tractable, assumption is that the non-neighbor firms have noisy, but private, estimates of tract value.[2] However, as long as the estimates of the non-neighbor firms are not too informative, we can use the result by Milgrom and Weber (1985) on the upper hemicontinuity of the equilibrium correspondence to argue that the behavioral implications of this descriptively more accurate model are approximately the same as those of a model in which the estimates of non-neighbor firms are based on public information.

The strategy of non-neighbor firm i is a distribution function $G_i(\cdot)$ over the nonnegative real numbers. Adopting the approach of EMW, we summarize the information of the neighbor firm by the real-valued, random variable $H = E[V|X, z]$. We shall assume that H has an atomless distribution, $F(\cdot|z)$, with finite mean, $\bar{H}$. The strategy of the neighbor firm can then be defined as a function σ which maps realizations of H, which are associated with the realizations of X, into the nonnegative real numbers. We shall assume that $\sigma(h)$ is a differentiable, strictly increasing function on the range (R, ∞), where R is the reservation price, and denote its inverse function on this interval by $\tau(b)$.

Define $G(b) = G_1(b) \cdots G_n(b)$ to be the distribution function of the maximum of the bids submitted by the uninformed firms on the tract. Given the strategy combination $(\sigma, G_1, \dots, G_n)$, the payoff to the neighbor firm, when its estimate of V is h, is the product of the probability that its bid is highest and its expected value of the tract less its bid.

$$G(\sigma(h))(h - \sigma(h)). \tag{1}$$

If the drainage tract contains any oil, it is usually part of a pool which the neighbor firm has discovered on the adjacent tract. This makes the value of the drainage tract to each firm contingent upon the manner in which production is allocated among the firms. If the firms bargain to an efficient allocation, tract valuations are identical across firms. In many instances, however, competition leads to some dissipation of rents (see Gary Libecap and Steven Wiggins, 1985). In these cases, the neighbor firm is likely to have a higher tract valuation than the non-neighbor firm, since it can take the externality into account and internalize its effects.

We parameterize the possible difference in tract valuations by letting the expected value of the drainage tract to the non-neighbor firm be equal to $E[H|z] - c$, where c is a fixed, nonnegative constant. (This constant could also reflect any cost differences.) The expected payoff to non-neighbor firm i which submits a bid b greater than R is

$$E[H - b - c|\tau(b) > h; z] \cdot F(\tau(b)|z) \cdot \Pi_{j \neq i} G_j(b). \tag{2}$$

The first term in equation (2) is expected profits, conditional on winning the tract (and hence $b > \sigma(h)$). The remaining terms represent the probabilities of outbidding the neighboring firm and the other non-neighbors. Ties at the reservation price are assumed to be settled by randomization.

A Bayesian Nash equilibrium for the bidding game is an $(n+1)$-tuple of strategies $(\sigma^*, G_1^*, \dots, G_n^*)$ such that the expected payoff to each firm conditional on its information is maximized, given the strategies employed by the other firms.

[2]See Wilson (1975) for an analysis of an example of such an auction.

We turn next to a characterization of the equilibrium bid distributions. Define

$$(3)\quad \phi(h) = \exp\left\{ -\int_h^\infty \frac{f(s;z)\int_h^s F(u;z)\,du\,ds}{cF(s;z)^2 + F(s;z)\int_h^s F(u;z)\,du} \right\}.$$

Note that if c is equal to zero, then $\phi(h)$ is equal to $F(h;z)$. Our theorem is a restatement of the theorem proved by EMW, extended to auctions with asymmetric tract valuations. The proof is essentially the same as the one given by EMW, and is given in the Appendix.

THEOREM: *The* $(n+1)$*-tuple* $(\sigma^*, G_1^*,\ldots, G_n^*)$ *is an equilibrium point if and only if*

$$G^*(b) = \begin{cases} 1 & b > \overline{H} - c \\ \phi(\tau(b)) & R < b < \overline{H} - c \\ \phi(R) & 0 \le b < R \end{cases}$$

$$\sigma^*(h) = \begin{cases} E[H \mid H \le h; z] - c & h > \hat{h} \\ R & \hat{h} \ge h \ge R \\ 0 & h < R \end{cases}$$

where $\hat{h}$ *solves* $E[H \mid H < \hat{h}; z] - c = R$.

The theorem states that the supports of the equilibrium distribution functions are identical, and consist of $\{0\}$ and the interval $[R, \overline{H} - c]$. We interpret a zero bid as no bid. The equilibrium strategy of the neighbor firm on $(R, \overline{H} - c]$ is uniquely determined by the condition that, in equilibrium, non-neighbor firms must earn zero profits. That is, suppose a non-neighbor firm submits an equilibrium bid b. Then, since σ^* is strictly increasing at b, there is a unique h' such that $b = \sigma^*(h')$. The expected profit of the tract to the non-neighbor firm conditional on the event that it wins is $E[H \mid H < h'; z] - b - c$. Setting this equation equal to zero implies that $\sigma^*(h') = E[H \mid H < h'; z] - c$.

The equilibrium strategies of non-neighbor firms are indeterminate. However, the equilibrium distribution function of the maximum uninformed bid is unique. It is chosen in order to induce the neighbor firm to bid according to the function given above. The two distributions differ in the probability of the events of no bid, and of a reservation bid R. G^* possesses a mass point equal to $F(\hat{h})$ at $\{0\}$, and is constant at this value on the interval $(0, R]$. The distribution of the neighbor bid also possesses a mass point at $\{0\}$, but it is equal to $F(R)$, which is less than $F(\hat{h})$. The distribution is constant at $F(R)$ on the open interval $(0, R)$, and then jumps discontinuously upward at R. The value of the mass point at R is equal to $F(\hat{h}) - F(R)$. If c is equal to zero, G^* is identical to the distribution of the informed bid on $(R, \overline{H})$.

The randomized strategies of non-neighbor firms are a direct consequence of the assumption that the neighbor firm knows their estimates. If non-neighbor firms bid according to a pure (and hence predictable) strategy which specifies a bid for each realization of the public information variables, the optimal response of the neighbor firm is to bid slightly above the maximum non-neighbor bid if the tract is worth more than this number, and not bid otherwise. But this implies that on average the non-neighbor firm is certain to lose, since it will win only those tracts whose expected value is less than its bids. By randomizing, non-neighbor firms can induce the neighbor firm to bid according to a strategy in which it will lose profitable tracts some of the time. As a result, non-neighbor firms will earn positive expected profits on some tracts, and it is only on average that their expected profits are zero.

Nevertheless, some readers may find the mixed strategy equilibrium objectionable, since non-neighbor firms obviously do not determine their bids by spinning roulette wheels. Mixed strategy equilibria, however, can often be justified as a limit of a sequence of pure strategy equilibria in an appropriately specified perturbed game. In our context, a natural candidate perturbed game is one in which the signals of non-neighbor firms are noisy estimates of V, and are independently and continuously distributed conditional on X, the information of the neighbor firm. The theorems of Milgrom and

Weber (1985) imply that there is an equilibrium in this game where each firm's bid is a function of its private estimate, and which distributionally approximates the mixed strategy equilibria of our model.

A. *Properties of Equilibrium*

The public information variable Z affects the bidding strategy of the neighbor firm in two ways, through its expectations about V and its response to its rivals. Integrating by parts, σ can be expressed as

$$(4) \quad \sigma(h;z) = h - c - \int_{-\infty}^{h} F(s;z)\,ds/F(h;z).$$

The integral term represents the factor by which the neighbor shades its bid downward from its estimate of the value of tract. Equation (4) reveals that even if, given the private signal, the public signal is redundant information (i.e., $E[V|X,Z]=E[V|X]$), the public signal continues to play an important strategic role in determining the neighbor firm's bid. It affects the magnitude of the "shading" factor. Consequently, any public information variable which helps the non-neighbor firms to predict the value of the drainage tract will be an important explanatory variable in the bidding equation of the neighbor firm.

Under what conditions is this relationship monotone? Given any h in the support of F, define the probability distribution function

$$k(H;z) = \begin{cases} f(H;z)/F(h;z) & H<h \\ 1 & H\geq h. \end{cases}$$

It is easily verified that $k(\cdot;z)$ has the monotone likelihood ratio property (MLRP) if and only if f has this property. It then follows from the well-known result that distribution functions which possess the MLRP can be ranked by first-order stochastic dominance that $E[H|H<h,z]$ is an increasing function of z. Using this result and equation (4), one can then show that, conditional on its private signal, the neighbor firm bids higher when non-neighbor firms are more optimistic about the value of the drainage tract. In what follows, we will assume that f has the MLRP.

The *ex ante* probability of the neighbor firm winning a drainage tract, conditional on the event that at least one firm bids, is easily calculated when c is equal to zero. Recall that, in this case, $G^*(\sigma(h)) = F(h)$ for all $\sigma(h) > R$. Integrating $F(h)$ over h using the density f, and taking into account the mass points at $\{0\}$ and $\{R\}$, yields the expression for the *ex ante* probability of the neighbor firm winning,

$$1/2 + (1/2)F(\hat{h};z)\left[F(\hat{h};z) - F(R;z)\right] \Big/ \left[1 - F(\hat{h};z)F(R;z)\right],$$

which is strictly greater than 1/2. This implies that the neighbor firm is likely to win more than one-half of the drainage tracts in our sample.

An increase in c causes the neighbor firm to bid less at every value of h, and, as a result, the cutoff value $\hat{h}$ rises. This increases the likelihood of the event that the neighbor firm bids R, and of the event that no non-neighbor firm bids are submitted. It can also be shown that the likelihood of the event that the neighbor firm wins the drainage tract is increasing in c.

The number of non-neighbor firms has no effect on the equilibrium bid distributions and payoffs, provided this number is not zero. From an empirical viewpoint, this is a particularly desirable feature of the model. The number of non-neighbor firms is not an observable variable to the econometrician. We observe only the number of non-neighbor firms which choose to participate in the auction. In most bidding models, this would lead to a selection bias in the estimates of the coefficients of the bid functions. However, in our context, the problem does not arise.

In summary, we list below the main empirical predictions of the model.

1. The event that no neighbor firm bids occurs less frequently than the event that no non-neighbor firm bids.
2. The neighbor firm wins at least one-half of the tracts.

3. Expected profits to non-neighbor firms are zero. They are negative on the set of tracts where no neighbor firm bids, and positive on the set of tracts where the neighbor firm bids.

4. Expected profits to the neighbor firm incorporates an information premium which makes its earnings above "average."

5. If c is equal to zero, the *ex ante* bid distributions (i.e., prior to the realization of X) are approximately the same.

6. The bidding strategy of the neighbor firm is independent of the number of non-neighbor firms.

7. The bidding strategy of the neighbor firm is an increasing function of the public signal, when a larger signal is "good news."

II. Data and Estimation Methods

Our study focuses on the federal lands off the coasts of Louisiana and Texas which were leased between 1959 and 1969. During this period, the government held 8 drainage sales, in which it auctioned off 144 tracts. This number does not include 25 drainage tracts on which the high bid was rejected, for which we have no data.

In our sample, each lease is sold via a first-price, sealed bid auction. A bid is a dollar figure which the firm promises to pay to the government at the time of the sale if it is awarded the tract. This payment is called the *bonus*. The terms of the lease are that, if no exploratory work is done after five years have elapsed, then ownership of the lease reverts to the government. If oil and/or gas is discovered in sufficient quantities so that the firm begins production, the lease is automatically renewed for as long as it takes the firm to extract the hydrocarbons. A fixed fraction of the revenues from any oil and/or gas extracted, one-sixth throughout our sample, accrues to the government. This sum is paid on an annual basis and is called the *royalty* payment. A nominal rental fee ($3 per acre on wildcat tracts, and $10 per acre on drainage tracts) is paid by the firm each year until either the lease expires or production begins.

The government may enter the auction as a bidder in two ways. In our sample, it announced a reservation price of $25 per acre on most drainage leases. (The reservation prices varied from sale to sale.) In addition, it retains the right to reject the high bid on a tract if it believes the bid is too low. The usual basis on which it makes this judgment is its private estimate of the value of the tract. These estimates may be based in part upon the geological and seismic reports which the firms are required to submit. For sales in our sample, the high bid was rejected on 7 percent of the wildcat tracts, and on 15 percent of the drainage tracts.

Our data set contains the following information for each tract: the date it was sold; its location and acreage; which firms bid and the value of their bids; the number and date of any wells that were drilled; and annual production through 1980 if any oil or gas was extracted. The drilling and production data were used, together with the annual survey of drilling costs conducted by the American Petroleum Institute, to calculate *ex post* discounted revenues and costs for each tract. Real wellhead prices in the United States were virtually constant from 1950 until 1973, and we assume that the expectations of the bidders in our sample would be that this pattern would continue. Accordingly, future production paths were converted into revenues by using the real wellhead prices at the date of sale, and discounted to the auction date at a 5 percent per annum rate. See our previous paper with Boudreau for further detail.

From the original sample of 144 drainage tracts, we selected 114 tracts which were adjacent to previously leased federal tracts. (The remaining tracts were adjacent to state tracts, about which we have no information.) For each drainage tract, we then designated neighboring tracts as those which had previously been sold and were adjacent to it, and designated firms as neighbors if they had purchased the rights to one of these tracts. By the same methods we used for the drainage tracts, we computed discounted revenues and costs for each of the neighboring tracts.

The tracts are typically in a square grid pattern, but can vary in size. Wildcat tracts are usually either 5,000 or 5,760 acres,

	0	1	2	3	4	5	6
No. of tracts	0	40	43	21	5	4	1

FIGURE 1. NUMBER OF NEIGHBOR FIRMS

	0	1	2	3	4	5	6
No. of tracts	19	79	15	0	0	1	0

FIGURE 2. NUMBER OF NEIGHBOR BIDS

TABLE 2—DEFINITION OF VARIABLES[a]

	Mean	Standard Deviation
B_I: maximum bid by neighbor	3.78	11.52
B_U: maximum bid by non-neighbor	3.60	9.57
N_I: number of neighbor bids	1.00	0.67
N_U: number of non-neighbor bids	1.69	2.09
N: number of neighbor tracts	3.01	1.98
NF: number of neighbor firms	2.06	1.08
π: *ex post* tract gross profitability	8.75	20.83
V: *ex post* gross profits of adjacent tract	14.51	20.16
A: tract acreage	2.679	1.533

[a] Dollar figures are in millions of $1972. Tract acreage is in thousands of acres.

and drainage tracts are often 2,500 acres or less. Consequently, the number of possible neighbor tracts is never less than eight, and is sometimes larger. The actual number is usually much less, and the number of neighbor firms is even smaller, since one firm frequently owned more than one neighbor tract. The frequency distribution of neighbor firms per drainage tract is given in Figure 1.

There were 74 tracts with more than one neighbor firm. However, in most of these cases, only one of the neighbor firms bid. The frequency distribution for the number of neighbor bids per drainage tract is given in Figure 2.

The fact that only 16 of the 74 tracts received more than one neighbor bid suggests that neighbor firms may have coordinated their participation and bidding decisions. Such behavior was not prohibited by the federal government in offshore oil auctions during the sample period. In fact, neighbor firms may have formed a joint venture prior to the sale in order to manage production from the common pool. This would also have provided neighbor firms with a mechanism for distributing the benefits from cooperation. Neighbor firms which did not bid could have received transfer payments through the allocation of production shares.

In what follows, we shall assume that the neighbor firms coordinated their bid decisions and submitted one serious bid on tracts which were considered worthwhile. The alternative hypothesis of competitive bidding among neighbor firms is examined in Section IV.

Table 2 lists the empirical analogues of the theoretical variables. The largest neighbor bid is denoted by B_I, or the reservation price in the event that no neighbor firm bid. Similarly, the largest non-neighbor bid is denoted by B_U, or the reservation price in the event that no non-neighbor firm bid. The number of non-neighbor bids is given by N_U, the number of neighbor bids by N_I, and the number of neighbor firms by NF. Our proxy for the private information of the neighbor firms is the gross profitability of the tract, which is denoted by π. This is defined as discounted revenues less drilling costs and less royalty payments (one-sixth of revenues in our sample). It is *not* net of the bid. Our proxies for the public information variables are: the number of neighbor tracts (N), the gross profitability of the most recently sold neighbor tract, or the average of these values if more than one neighbor tract was sold at the same time (V), and tract acreage (A).

A. Likelihood Function

The estimates reported in Tables 6, 7, and 8 are obtained from similar likelihood functions. Define indicator variables for the maximum neighbor and non-neighbor bids:

$$Y_{it} = W_{it}'\theta_i + \varepsilon_{it}, \quad i = I, U;\ t = 1, \dots, T$$

where W_{it} is a vector of regressors for tract t, θ_i is a parameter vector, and $\{\varepsilon_{It}, \varepsilon_{Ut}\}$ are i.i.d. drawings from a bivariate normal distribution with zero mean, variances σ_I^2 and σ_U^2, and covariance σ_{IU}. Here T is the number of tracts which received at least one bid. Bids are determined as follows:

$$\log(B_{it}/R_t) = Y_{it} \quad \text{if } Y_{it} \geq 0$$
$$= 0 \quad \text{otherwise,}$$

where R_t is the reservation price on tract t. Thus, bids are assumed to be lognormally distributed, in accord with previous evidence. (See Smiley, 1979, for example.) We have data only for tracts in which at least one bid is positive. Therefore, we are faced with both truncated dependent variables and sample selection issues.

We partitioned the tracts into three mutually exclusive sets: Ω_{++} is the set of tracts with at least one neighbor bid and at least one non-neighbor bid, Ω_{+0} is the set of tracts with at least one neighbor bid and no non-neighbor bids, and Ω_{0+} is the set of tracts with no neighbor bids and at least one non-neighbor bid. The log likelihood function for the entire sample can then be defined as follows:

$$\log L = \sum_{t \in \Omega_{++}} l_{1t} + \sum_{t \in \Omega_{+0}} l_{2t} + \sum_{t \in \Omega_{0+}} l_{3t}$$

where

$$l_{1t} = -\left[\log(2\pi) + (1/2)\log|\Sigma|\right] - (1/2)(\varepsilon_{It}, \varepsilon_{Ut})\Sigma^{-1}(\varepsilon_{It}, \varepsilon_{Ut})' - \log(1 - Z(-W_{Ut}\theta_U/\sigma_U, -W_{It}\theta_I/\sigma_I; \rho_{IU})),$$

$$l_{2t} = \log\left(\Phi\left\{\left[-W_{Ut}\theta_U - \sigma_{IU}\sigma_I^{-2}\varepsilon_{It}\right] / \left[\sigma_U^2 - \sigma_{IU}^2\sigma_I^{-2}\right]^{1/2}\right\}\right) - \log(\sigma_I) + \log(\phi(\varepsilon_{It}/\sigma_I)) - \log(1 - Z(-W_{Ut}\theta_U/\sigma_U, -W_{It}\theta_I/\sigma_I; \rho_{IU})),$$

$$l_{3t} = \log\left(\Phi\left\{\left[-W_{It}\theta_I - \sigma_{IU}\sigma_U^{-2}\varepsilon_{Ut}\right] / \left[\sigma_I^2 - \sigma_{IU}^2\sigma_U^{-2}\right]^{1/2}\right\}\right) - \log(\sigma_U) + \log(\phi(\varepsilon_{Ut}/\sigma_U)) - \log(1 - Z(-W_{Ut}\theta_U/\sigma_U, -W_{It}\theta_I/\sigma_I; \rho_{IU})).$$

Here Σ is the covariance matrix, ρ_{IU} is the correlation coefficient, Φ and ϕ are the standard normal distribution function and density function, respectively, and $Z(\cdot,\cdot)$ is the function for the probability of the event that no bid is observed on a tract, as defined in Norman Johnson and Samuel Kotz (1972, p. 93).

III. The Evidence

We begin by examining the predictions of the model with respect to the participation rates and returns of neighbor and non-

TABLE 3—SAMPLE STATISTICS ON TRACTS WON BY EACH TYPE OF FIRM[a]

	Wins by Neighbor Firms		Wins by Non-Neighbor Firms		
	A	Total	B	C	Total
No. of Tracts	35	59	19	36	55
No. of Tracts Drilled	23	47	18	33	51
No. of Productive Tracts	16	36	12	19	31
Average Winning Bid	3.28	6.04	2.15	6.30	4.87
	(0.56)	(2.00)	(0.67)	(1.31)	(0.92)
Average Gross Profits	10.05	12.75	−0.54	7.08	4.45
	(3.91)	(3.21)	(0.47)	(2.95)	(1.99)
Average Net Profits	6.76	6.71	−2.69	0.78	−0.42
	(3.02)	(2.69)	(0.86)	(2.64)	(1.76)

[a]Dollar figures are in millions of $1972. The numbers in parentheses are the standard deviations of the sample means. Column A refers to tracts which received no non-neighbor firm bid, column B refers to tracts which received no neighbor bid, and column C to those in which a neighbor firm bid, but a non-neighbor firm won the tract.

neighbor firms. The number of tracts which received no neighbor bid is 19, and the number of tracts which received no non-neighbor bid is 35. Therefore, at least one neighbor firm participated in 83 percent of the auctions, and at least one non-neighbor firm participated in 68 percent of the auctions. This is consistent with the theoretical model.

Table 3 gives sample statistics on the tracts won by each type of firm. Column A refers to tracts which received no non-neighbor firm bid, column B refers to tracts which received no neighbor bid, and column C to those in which a neighbor firm bid, but a non-neighbor firm won the tract.

The evidence is consistent with the model. The neighbor firm won 62 percent of the tracts that it bid on. As we calculated in our previous paper, its share of the tract value was approximately 44 percent, which was considerably higher than the 23 percent average firm share on wildcat tracts. The average net profit of non-neighbor winners was virtually zero. It was positive on tracts which received a neighbor bid, and it was significantly negative on tracts which received no neighbor bid. By contrast, the participation decisions of the non-neighbor firms had no effect on the earnings of neighbor firms. Based on these return figures, it appears as if the neighbor firm was better able to identify which drainage tracts were more likely to contain oil, and was able to exploit this knowledge to obtain above average profits.

We found no evidence of a mass point at the reservation price in the distribution of bids of the neighbor firm. One possible explanation for this result is that firms were afraid that the government would reject reservation price bids. Recall that the government rejected the high bid on 25 drainage tracts.[3]

The existence of a positive reservation price provides an explanation for why non-neighbor firms drilled tracts on which no neighbor firm bid. The lack of participation by the neighbor firm implies that its expectation of net profit is less than R. Since R is positive, and the bid is a sunk cost, it may still have been rational for the non-neighbor firm to drill its lease. Drilling outcomes were not inconsistent with this belief, since the average gross profit of tracts which received no neighbor bid was not significantly different from zero at conventional confidence levels.

An indirect test of our assumption that neighbor firms coordinated their bidding decisions is to compare the bidding behavior of neighbor firms and their net profits on single neighbor tracts to that on multiple neighbor

[3]We study the issue of a random reservation price, and its empirical implications, in a subsequent paper.

TABLE 4—THE EFFECT OF NEIGHBOR FIRM COMPETITION ON NEIGHBOR FIRM PARTICIPATION AND PROFITS[a]

	Single Neighbor Tracts	Multiple Neighbor Tracts No. of Neighbor Bids		
		1	≥ 2	Total
No. of Tracts	40	48	15	74
No. of Tracts with No Neighbor Bid	8	–	–	11
No. of Wins	19	29	11	40
Average Winning Bid of Neighbor Firm	4.795 (1.444)	2.615 (0.697)	17.193 (9.953)	6.624 (2.885)
Average Gross Profits of Neighbor Firm	13.601 (5.608)	4.670 (2.148)	32.597 (11.506)	12.350 (3.965)
Average Net Profits of Neighbor Firm	8.806 (4.762)	2.055 (1.690)	15.404 (10.963)	5.725 (3.297)

[a]Dollar figures are in millions of $1972. The numbers in parentheses are the standard deviations of the sample means.

tracts. If our assumption is correct, they should not be significantly different across the two categories.

The statistics reported in Table 4 are consistent with this prediction. In each category, the neighbor firm won approximately one-half of the tracts. The net profits on the single neighbor tracts won by neighbor firms is somewhat higher than on the multiple neighbor tracts won by neighbor firms, but the difference is not statistically significant. In both categories, net profits were significantly positive, and quite large. High value multiple neighbor tracts tended to attract more than one neighbor bid, but average net profits were substantially *higher* on these tracts than on the multiple neighbor tracts with one neighbor bid. This may be an indication of "shadow" bidding, in which the neighbor firms submit more than one bid in order to convince the government that bidding is competitive.

A. *Information Structure*

An important assumption of our theoretical model, both in terms of its predictive consequences and its influence on our empirical formulation, is that non-neighbor firms have access only to publicly available information. We assume that they have no private signals which are useful in predicting tract profitability, and are not also observed by the neighbor firm.

While we cannot observe the firms' private information signals, it is possible to test this assumption indirectly. In particular, we conducted the following predictive exercise. We first regressed the gross profitability of a given drainage tract on indices of whether a neighbor firm bid (the dummy variable $D_I = 1$ if so), on the number of neighbor bids, on tract acreage, on the number of neighbor tracts, and on a second-order polynomial in the maximum neighbor firm bid and the value of the neighboring tract. We then supplemented this set of regressors with an index of whether any non-neighbor firms bid ($D_U = 1$ in these cases) and, if so, how many do so. We also included the maximum uninformed bid as an additional variable in the second-order polynomial expression. We then performed the same exercise with the roles of the neighbor and non-neighbor reversed. If non-neighbor firms had access to informative private signals, then one would expect their participation and bidding decisions to have some predictive content. If not, then the assumption that no payoff-relevant private information was available to non-neighbor firms may be correct. We have included public information such as acreage, number of neighbor tracts, and adjacent tract value, since the relationship between profitability and bids depend on these values in equilibrium.

In Table 5 we report three regression equations, corresponding to the three sets of

TABLE 5—PREDICTION OF TRACT PROFITABILITY[a]

Variable	Equation (1)	Equation (2)	Equation (3)
Constant	−3.60	0.11	3.16
	(−0.75)	(0.02)	(0.81)
D_I	5.03	−3.12	
	(1.42)	(−0.60)	
D_U		−0.09	4.89
		(−0.03)	(1.03)
N_I	3.98	−2.01	
	(1.01)	(−0.46)	
N_U		1.64	0.93
		(1.68)	(0.87)
N	−0.26	0.003	−1.03
	(−0.48)	(0.007)	(−1.41)
A	−.46	−0.18	0.80
	(−0.62)	(−0.23)	(0.67)
B_I	3.55	3.09	
	(3.90)	(3.35)	
B_I^2	−0.023	0.061	
	(−2.57)	(1.76)	
B_U		−0.229	0.181
		(−0.31)	(0.26)
B_U^2		0.014	0.021
		(0.65)	(1.36)
V	0.013	0.116	0.259
	(0.11)	(1.30)	(1.80)
V^2	$-0.9E-4$	$-0.41E-3$	−0.0013
	(−0.12)	(−0.37)	(−0.72)
$B_I \cdot B_U$		−0.093	
		(−1.99)	
$B_I \cdot V$	−0.0067	−0.026	
	(−0.24)	(−1.04)	
$B_U \cdot V$		−0.034	−0.034
		(−1.41)	(−0.85)
SSE	17673	14766	41483
R^2	.640	.699	.154
d.o.f.	104	98	104

[a]The dependent variable in each equation is π. Heteroskedasticity-consistent t-statistics are displayed in brackets.

regressors discussed in the preceding paragraph. An F-statistic for the test that none of the non-neighbor firm participation and bid variables coefficients are significantly different from zero, which compares the regressions in columns one and two, equals 3.22. Under the null hypothesis, the statistic has (6,98) degrees of freedom, the critical value for which is 3.71 at size 0.05. Most of the explanatory power of the non-neighbor firm variables is derived from the product term involving the neighbor bid.

We shall henceforward frequently refer to non-neighbor firms as uninformed and neighbor firms as informed. The evidence summarized in Table 5 does not contradict this nomenclature.

Note that the significant coefficients in Table 5 also support the view that the informed firms do indeed possess payoff-relevant information. True tract profitability is positively correlated with their bids, over the entire observed range of bids. The final column indicates that the incremental predictive power of the informed firm bid and participation decisions is very significant, even after conditioning on public information and non-neighbor bid and participation information.

B. *Bid Distributions*

One implication of the theoretical model is that, conditioning solely on publicly available information, the distribution of the informed bid and that of the maximum uninformed bid should be approximately the same if tract valuations are symmetric (i.e., c is equal to zero). Accordingly, we computed the maximum likelihood estimates of the parameters of the joint distribution of these two variables. We explicitly accounted for the truncation of the bid variables at the reservation price, for the sample selection rule that the only observed tracts are those in which at least one bid was positive, and for the possibility of correlation between the error terms of the two bid equations. The explanatory variables are the publicly available information in our sample: tract acreage, the number of neighbor tracts, the value of the adjacent tract, and that value squared.

The maximum likelihood estimates, which are contained in Table 6, have two notable features. First, the coefficients and estimated standard errors of the regression equations are similar. The value of the χ^2 statistic of the null hypothesis that the two regression equations are identical is 10.58, which is below 11.07, the critical value of a χ^2 statistic with 5 degrees of freedom at size 0.05. This result accords weakly with the theoretical prediction of our model when tract valuations are symmetric. Second, there is essentially no correlation between the disturbances of the two equations. The esti-

TABLE 6—JOINT DISTRIBUTION OF BIDS CONDITIONAL ON PUBLIC INFORMATION[a]

Independent Variable	Unrestricted: Dependent Variable $\log(B_I/R)$	Unrestricted: Dependent Variable $\log(B_U/R)$	Restricted: Dependent Variable $\log(\mathrm{BID}/R)$
Constant	1.98068	2.05437	−1.99365
	(3.44)	(2.70)	(3.96)
V	0.07391	0.00523	0.04966
	(3.42)	(0.19)	(2.52)
V^2	−0.00073	−0.00009	−0.00050
	(−2.92)	(−0.30)	(−2.17)
A	−0.11092	0.13285	−0.02499
	(−0.82)	(0.74)	(−0.21)
N	−0.08226	−0.28903	−0.14763
	(−0.74)	(−1.97)	(−1.51)
$\begin{bmatrix} \sigma_I & \\ \rho_{IU} & \sigma_U \end{bmatrix}$	$\begin{bmatrix} 2.0151 & \\ (11.7) & \\ 0.1034 & 2.6596 \\ (0.94) & (12.7) \end{bmatrix}$		$\begin{bmatrix} 2.0528 & \\ (11.5) & \\ 0.0638 & 2.6785 \\ (0.57) & (12.8) \end{bmatrix}$
	Log $L = -428.895$		Log $L = -434.184$

[a]Asymptotic t-statistics are in parentheses. They are computed from the analytic second derivatives. They are not appreciably different from the Eicker-White t-statistics.

mated correlation coefficient, ρ_{IU}, is 0.10 and not significantly different from zero. This suggests that there are no omitted variables which might significantly affect both bidding equations. In particular, although tract profitability is correlated with the informed firm's private signals, and so also with the informed firm bid, it appears that this additional information is only weakly correlated with the unexplained component of the maximum uninformed bid.

The theoretical model also predicts that, conditioning on public information and tract profitability, the distributions of the informed bid and the maximum uninformed bid should differ. More precisely, tract profitability should be highly correlated with the neighbor bid, and orthogonal to the maximum non-neighbor bid. To examine this implication of asymmetric information, we computed the maximum likelihood estimates of the joint distribution of bids conditional on tract gross profits and that variable squared, and the public information variables listed above.

The estimation results, which are reported in Table 7, are consistent with the above predictions. The χ^2 statistic of the null hypothesis that the two distributions are the same is 19.84, which is rejected at size 0.01. The coefficients for the tract profitability variables are highly significant in the equation for the neighbor firm bid, and insignificant in the equation for the maximum non-neighbor firm bid. Non-neighbor firms do not appear to have access to information, other than the number and value of neighbor tracts and tract acreage, which is correlated with tract profitability.

The estimates presented in Table 8 can be given a more structural interpretation: they are the maximum likelihood estimates of the coefficients of the informed firm's bid equation and the maximum uninformed firm bid equation, accounting for the truncation of these two variables and the sample selection rule. The maximum uninformed bid is taken to be a function of publicly available information: acreage, number of neighbor tracts, adjacent tract value, and that value squared. The informed bid is a function of these variables, together with our proxies for its private information: actual tract profitability and that figure squared. We also include the number of uninformed firms in both equations. According to the theory, this number

TABLE 7—JOINT DISTRIBUTION OF BIDS CONDITIONAL ON PUBLIC INFORMATION AND TRACT PROFITABILITY[a]

Independent Variable	Unrestricted: Dependent Variable $\log(B_I/R)$	Unrestricted: Dependent Variable $\log(B_U/R)$	Restricted: Dependent Variable $\log(\text{BID}/R)$
Constant	1.86237	2.07435	1.88962
	(4.15)	(2.42)	(4.63)
π	0.09102	0.02765	0.07532
	(4.30)	(0.79)	(3.93)
π^2	−0.00053	−0.00026	−0.00046
	(−2.12)	(−0.62)	(−2.09)
V	0.04428	−0.00323	0.03361
	(2.55)	(−0.12)	(2.05)
V^2	−0.00045	−0.00001	−0.00036
	(−2.25)	(−0.03)	(−1.80)
A	−0.20962	0.10221	−0.13419
	(−1.95)	(0.58)	(−1.34)
N	−0.00888	−0.25858	−0.06645
	(−0.10)	(−1.81)	(−0.83)

$$\begin{bmatrix} \sigma_I & \\ \rho_{IU} & \sigma_U \end{bmatrix} \quad \text{Unrestricted: } \begin{bmatrix} 1.5996 & \\ (11.5) & \\ 0.0492 & 2.6162 \\ (0.46) & (13.1) \end{bmatrix} \quad \text{Restricted: } \begin{bmatrix} 1.6379 & \\ (11.3) & \\ -0.0216 & 2.8014 \\ (-0.20) & (11.8) \end{bmatrix}$$

Unrestricted: $\text{Log } L = -409.0028$; Restricted: $\text{Log } L = -418.9243$

[a]Asymptotic t-statistics are in parentheses. They are computed from the analytic second derivatives.

should have no explanatory power in the informed bid equation, unless it serves as a proxy for omitted public information variables which might affect uninformed firm bidding. Since the maximum uninformed bid is an order statistic whose distribution depends on N_U, it should be significant in this equation. However, it is properly viewed as endogenous and its coefficient has no structural interpretation.

The estimates in Table 8 indicate that the informed bid is an increasing function of tract profitability and the value of the adjacent tract over the range of values encountered in our sample, and it is essentially independent of the number of neighbor tracts and the number of uninformed bids. The lack of correlation between the maximum informed bid and the number of uninformed bids provides further evidence that our list of public information variables is adequate. If it were not, then unproxied public information (omitted elements of Z) would influence both N_U and B_I.

By contrast, the maximum uninformed bid is not significantly correlated with tract profitability or the value of the adjacent tract, and it is a decreasing function of the number of neighbor tracts. As expected, there is a strong positive correlation between the maximum uninformed bid and the number of uninformed bids.

The sign and magnitudes of the coefficients for the number of neighbor tracts variable in the bid equations are consistent with the maintained hypothesis that neighbor firms do not compete against each other. Under this assumption, the number of neighbor tracts is a proxy for the amount of information which neighbor firms possess. Therefore, non-neighbor firms should bid less aggressively on tracts with a larger number of neighbor tracts, and, in response, the neighbor firm should shade its bid downward.

The signs of the coefficients for the other two public information variables that possess some incremental explanatory power,

TABLE 8—BID EQUATIONS[a]

Independent Variable	Equation (1) Dependent Variable $\log(B_I/R)$	Equation (1) Dependent Variable $\log(B_U/R)$	Equation (2) Dependent Variable $\log(B_I/R)$	Equation (2) Dependent Variable $\log(B_U/R)$	Equation (3) Dependent Variable $\log(B_I/R)$	Equation (3) Dependent Variable $\log(B_U/R)$
Constant	1.86973	2.13073	1.64933	2.15018	1.67785	0.064395
	(−4.19)	(2.90)	(3.52)	(2.96)	(3.66)	(1.14)
π	0.08967		0.08505		0.08501	
	(4.26)		(4.09)		(4.08)	
π^2	−0.00051		−0.00047		−0.00047	
	(−2.04)		(−1.88)		(−1.88)	
V	0.04452	0.00257	0.04814	0.00120	0.04757	0.02083
	(2.58)	(0.10)	(2.82)	(0.04)	(2.79)	(1.08)
V^2	−0.00045	−0.00006	−0.00047	−0.00005	−0.00046	−0.00011
	(−2.25)	(−0.21)	(−2.47)	(−0.18)	(−2.42)	(−0.58)
A	−0.20738	0.12154	−0.25435	0.12908	−0.25713	−0.22645
	(−1.95)	(0.68)	(−2.32)	(0.74)	(−2.38)	(−1.71)
N	−0.01001	−0.27341	0.03228	−0.27116	0.03506	0.03029
	(−0.12)	(−1.92)	(0.36)	(−1.93)	(0.41)	(0.28)
N_U			0.13505		0.11312	0.83705
			(1.26)		(1.42)	(8.48)
$\begin{bmatrix} \sigma_I & \\ \rho_{UI} & \sigma_U \end{bmatrix}$	1.5956		1.5664		1.5663	
	(11.5)		(11.3)		(11.5)	
	0.0453	2.6238	−0.0782	2.6101	−0.0576	1.8769
	(0.43)	(13.0)	(−0.62)	(13.0)	(−0.56)	(13.0)
	Log $L = -409.3745$		Log $L = -408.6295$		Log $L = -378.5628$	

[a]Asymptotic t-statistics are displayed in brackets. They are computed from the analytic second derivatives.

namely, the value of the adjacent tract and that value squared, are the same in the informed and maximum uninformed bid equations. They are significant only in the bid equation of the informed firm. This is consistent with the prediction of the theoretical model that the bids of the non-neighbor firms are much "noisier" than the bids of the neighbor firms. Finally, note that the estimated standard error of the residuals in the informed bid equation is much lower than that of the maximum uninformed bid, although the informed bid itself has a higher standard deviation. (See Table 2.) We can explain a much higher percentage of the variation in the informed firm bids.

IV. A Competitive Bidding Model

In this section, we consider an alternative to the coordination model of neighbor firm bidding. We shall estimate a bidding model under the assumption that neighbor firms act independently and competitively. Our objective is to determine whether estimation under this behavioral hypothesis leads to implications which are not consistent with the theory of competitive bidding.

In the competitive bidding model, each neighbor firm observes a private signal on the value of the drainage tract, which, conditional on the value of the tract, is independently distributed across firms. The precisions of the signals are assumed to be identical, that is, information is symmetrically distributed among the neighbor firms. We shall continue to assume that neighbor firms view the bids of non-neighbor firms as uninformative random variables, and care only about the distribution of the maximum uninformed bid.[4]

[4]This assumption is somewhat *ad hoc*. In his analysis of an auction with asymmetric information in which uninformed firms have noisy, but private estimates of the informed firm's valuation, Wilson (1975) shows that firms which have access only to public information should never bid. If they do, they will lose money.

The equilibrium outcome depends on the nature of the neighbors' information. If the neighbors each know the exact value of the tract, then competition should lead to complete rent dissipation on multiple neighbor tracts. Table 4 indicates that the profit data are inconsistent with this sort of competition. Therefore, a competitive model can be consistent with the data only if we assume that neighbors' private information is imperfect.

The theoretical prediction concerning the sign of the equilibrium response of neighbors' bids to an increase in the number of neighbor firms is ambiguous: more competition causes the probability of winning to fall, which has a positive effect on bids. But, it also causes the expected value of the tract conditional on winning to fall, since there are now more observations on the value of the drainage tract. Therefore, the "winner's curse" is more acute, which has a negative effect on bids. Participation probabilities should decrease, however, since the reservation signal above which a neighbor firm participates is strictly increasing in the number of neighbor firms.

The ambiguity can be resolved for specific distribution functions of the private information. Smiley (1979) has shown that, for several distributions of the exponential class (including the lognormal), the equilibrium bid function is initially increasing in the number of bidders and then decreasing. The value at which the derivative changes sign depends upon the precision of the signal. For the degree of uncertainty present in our sample, the critical value is generally not less than four. Since there were only ten tracts that had four or more neighbor firms, this implies that, given plausible assumptions on the distribution functions, the neighbor firm's bid should be increasing in the range of the data.

The likelihood function for this model is defined as follows. Let I_t denote the index set for the neighbor firms on tract t. Define indicator variables for the informed firms,

$$Y_{it} = W_{it}'\theta_I + \varepsilon_{it}, \qquad i \in I_t,\ t = 1, \ldots, T,$$

where W_{it} is a vector of regressors for tract t, θ_I is a parameter vector for informed firms, and the ε_{it}'s are jointly normal and independent (across tracts *and* firms) unobservable random variables. The indicator variable for the maximum uninformed bidder is defined as

$$Y_{Ut} = W_{Ut}'\theta_U + \varepsilon_{Ut}, \qquad t = 1, \ldots, T,$$

where W_{Ut} is a vector of regressors for tract t, θ_{Ut} is a parameter vector for the maximum uninformed bid, and the ε_{it}'s are joint normal and independent (across tracts *and* firms) unobservable random variables. Bids are determined as follows: for each $i \in I_t$, and $i = U$,

$$\begin{aligned} \log(B_{it}/R_t) &= Y_{it} \qquad \text{if } Y_{it} \geq 0 \\ &= 0 \qquad \text{otherwise.} \end{aligned}$$

A tract enters the sample only if at least one bid is positive. Therefore, the likelihood function must account for both truncated random variables and sample selection issues. The latter is particularly important in the competitive model, since the likelihood of a tract entering our sample is higher when there are more neighbor firms, *ceteris paribus*.

Define dummy variables $d_{it} = 1$ if neighbor firm i bids on tract t, and $d_{it} = 0$ otherwise. Similarly, $d_{Ut} = 1$ if at least one non-neighbor firm bids on tract t, and $d_{Ut} = 0$ otherwise. Then the log likelihood function for the sample is given by

$$\begin{aligned} \log L = \sum_t \Bigg\{ & \sum_{i \in I_t} \left[d_{it} \log(\phi(\varepsilon_{it}/\sigma_I)/\sigma_I) \right. \\ & \left. + (1 - d_{it}) \log(\Phi(-W_{it}\theta_I/\sigma_I)) \right] \\ & + d_{Ut} \log(\phi(\varepsilon_{Ut}/\sigma_U)/\sigma_U) \\ & + (1 - d_{Ut}) \log(\Phi(-W_{Ut}\theta_U/\sigma_U))] \\ & - \log\Bigg(1 - \prod_{i \in I_t} \Phi(-W_{it}\theta_I/\sigma_I) \\ & \cdot \Phi(-W_{Ut}\theta_U/\sigma_U)\Bigg)\Bigg\}. \end{aligned}$$

TABLE 9—JOINT DISTRIBUTION OF NEIGHBOR BIDS AND MAXIMUM NON-NEIGHBOR BID[a]

Independent Variable	Equation (1) Dependent Variable $\log(B_I/R)$	Equation (1) Dependent Variable $\log(B_U/R)$	Equation (2) Dependent Variable $\log(B_I/R)$	Equation (2) Dependent Variable $\log(B_U/R)$
Constant	1.7493	2.1856	1.7380	2.1165
	(2.516)	(2.292)	(2.49)	(2.22)
π	0.0971		0.0994	0.0363
	(3.40)		(3.47)	(0.97)
π^2	−0.00038		−0.00040	−0.00030
	(−1.19)		(−1.24)	(−0.68)
V	0.0400	−0.0015	0.0388	−0.0102
	(1.59)	(−0.04)	(1.54)	(−0.33)
V^2	−0.00049	−0.00004	−0.00046	0.00005
	(−1.46)	(−0.11)	(−1.40)	(0.15)
A	−0.2723	0.0626	−0.2759	0.3704
	(−1.94)	(0.33)	(−1.96)	(0.19)
NF	−0.7576	−0.4346	−0.7552	−0.4152
	(−3.96)	(−1.52)	(−3.93)	(−1.44)
$\begin{bmatrix} \sigma_I & \\ \rho_{UI} & \sigma_U \end{bmatrix}$	$\begin{bmatrix} 2.6747 & \\ (12.9) & \\ 0 & 2.7608 \\ & (10.6) \end{bmatrix}$		$\begin{bmatrix} 2.6793 & \\ (12.9) & \\ 0 & 2.7519 \\ & (10.6) \end{bmatrix}$	
	Log $L = -554.468$		Log $L = -553.781$	

[a] t-statistics are displayed in brackets. They are computed from analytic second derivatives.

The maximum likelihood estimates for the bid functions of the firms are reported in Table 9. The first two columns give the estimates of the joint distribution of bids when the conditioning variables for the maximum non-neighbor bid consist of the public information variables, and the neighbor bids are assumed to be a function of these variables, and our proxies for the neighbor firm's private information, tract profitability, and that variable squared. The final two columns give the estimates of the joint distribution when the tract profitability variables are included in the set of regressors for the maximum non-neighbor bid.

There are two ways in which the results reported in Table 9 are *not* consistent with the theoretical predictions of the competitive model. First, the bid function of the neighbor firm is strictly decreasing, not increasing, in the number of neighbor firms. This result is consistent with phantom bids, which are necessarily lower than the collusive bid, being often submitted on multiple neighbor tracts. In contrast, the *maximum* neighbor bid is independent of the number of neighbor firms. Second, the absolute value of the coefficients for the number of neighbor firms in the bid equations of the maximum uninformed bid are smaller than the corresponding coefficients in the bid equations for the neighbor firms. The opposite should be true, since an increase in the number of neighbor firms causes a larger decrease in the expected value of the tract conditional on the event of winning for the non-neighbor firm than the neighbor firm (i.e., the "winner's curse" is more acute for the less informed firms).

The results reported in this section may be consistent with a competitive bidding model in which one neighbor has access to superior information, and the others' information is essentially equivalent to that of the non-neighbors.

V. Conclusion

The data indicate that firms owning neighbor tracts have an informational advantage over non-neighbors in offshore drainage lease auctions. They exploit this advantage by shading their bids substantially below their expectation of the value of the tract. This translates into significantly higher returns, expressed as a percentage of discounted social value, than on wildcat tracts, where the distribution of information is relatively symmetric. The non-neighbors also account for their disadvantage, by bidding conservatively. As a consequence, they do *not* suffer from the winner's curse, but rather break even on average.

The pattern of neighbor bids appears to be inconsistent with a model in which they behaved competitively. Rather, the evidence indicates that they may have coordinated their bids to maximize joint returns. Such behavior may have been encouraged by the legality of joint bids, and by the presence of unitization agreements which could facilitate transfer payments.

The empirical results are also not consistent with a model in which the neighbor and non-neighbor firms are known to differ only in their extraction costs (i.e., roughly speaking, the distributions of neighbor and non-neighbor valuations differ in the first rather than the second moments). In that event, non-neighbors would have to bid cautiously, and as a result, would win fewer tracts. But their bids, conditional on participating, should be correlated with tract values. The evidence refutes this view, for only neighbor participation rates and bids, and *not* non-neighbor bids or their number, exhibit such a correlation.

A final alternative might be that firms adopt simple rule-of-thumb strategies. However, despite the complexity of calculating the Nash equilibrium strategy, the strategies themselves are relatively simple. Consequently, it is not implausible that well-financed bidders with experience in these auctions would employ optimal strategies.

APPENDIX

Proof of Theorem:

One can verify easily that the strategies specified above form an equilibrium. The proof of necessity is essentially the same as the one given by Engelbrecht-Wiggans, Milgrom, and Weber (EMW). Using their arguments, one can show that, in equilibrium, σ is nondecreasing, and that the expected payoff to the uninformed firm is zero. Furthermore, the bid distributions are atomless, except possibly at R and 0. Therefore, given any b contained in the support of G, $E[H-c-b|H<\tau(b); z]=0$. Substituting $b=\sigma(h)$, this implies

$$\text{(A1)}\quad \sigma(h)=E[H|H<h;z]-c = h-c-\int_{-\infty}^{h} F(s;z)\,ds/F(h;z).$$

It then follows immediately from (A1) that the support of G (and the range of σ) is at most $\{0\}$ and $[R,\overline{H}-c]$.

Define

$$\hat{h}=\sup\{h|\sigma(h)=R\}$$

to be the largest valuation at which the informed firm bids R. Let λ denote the Lagrange multiplier associated with the constraint $b\geq R$. Optimality of $\sigma(h)$ implies that, given any h,

$$\text{(A2)}\quad -G(b)+(h-b)G'(b)+\lambda=0, \qquad \lambda\geq 0,\quad b\geq R.$$

Transforming variables and integrating the differential equation on $(\hat{h},\infty)$ for $h>\hat{h}$ yields

$$\text{(A3)}\quad \lim_{s\to\infty}\log G(\sigma(s))-\log G(\sigma(h)) = \int_{h}^{\infty}\frac{f(s;z)\int_h^s F(u;z)\,du}{cF(s;z)^2+F(s;z)\int_h^s F(u;z)\,du}\,ds$$

Applying the boundary condition $\lim_{s\to\infty}G(\sigma(s))=1$ implies

$$\text{(A4)}\quad G(\sigma(h)) = \exp\left\{-\int_{h}^{\infty}\frac{f(s;z)\int_h^s F(u;z)\,du}{cF(s;z)^2+F(s;z)\int_h^s F(u;z)\,du}\,ds\right\},$$

which is strictly positive. Since any bid less than R is rejected by the seller, we have that $G(0)=G(R)$. Thus, the event in which no non-neighbor firm bids occurs with positive probability.

Given any $h\in[R,\hat{h})$, λ is strictly positive, and the informed firm's optimal bid is R. At any $h<R$, it does not submit any bid. Therefore, the equilibrium bid distribution of the neighbor firm contains atoms at 0 and R, and the value of these atoms are $F(R)$ and $F(\hat{h})-F(R)$, respectively.

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[Footnotes]

[1] **Competitive Bidding Under Asymmetrical Information: Behavior and Performance in Gulf of Mexico Drainage Lease Sales, 1959-1969**
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