Risk Aversion, Risk Sharing, and Joint Bidding: A Study of Outer Continental Shelf Petroleum Auctions

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I. INTRODUCTION AND BACKGROUND

The outer continental shelf (OCS) of the United States accounts for a substantial portion of domestic crude oil and natural gas production. From about 2% of total output in 1954, crude oil from the OCS rose to almost 18% of total production in 1971 and declined, in part due to the influence of petroleum price controls, environmental litigation, and slower leasing and permitting policies, to about 12% in 1980, rebounding somewhat to 12.8% in 1982. The OCS share of U.S. natural gas production has risen dramatically and consistently from 1% in 1954 to between 25% and 26% in 1978 where it has remained. With the decontrol of natural gas, OCS production will become even more important in the rest of this century: between 30% and 50% of recoverable petroleum yet to be discovered probably will be found in the OCS (Hunt 1979, p. 538). Thus, an understanding of the motivations of firms developing and producing petroleum on the OCS is crucial for the appropriate choice of regulatory policies.

OCS leases are innately risky investments. Over the period 1954–68, 62% of the tracts leased in the Gulf of Mexico were abandoned without production, 15% were productive but unprofitable, and only 23% were both productive and profitable. The average bonus (price) for all leases was $2,228,000, and the percentage of productive leases was higher for higher-priced leases—the average bonus for productive tracts was $3,540,000. Yet, even the higher-priced leases were still quite risky: of tracts with bonuses of $3,250,000 or greater, only 58.1% were productive (Mead et al. 1980, pp. 1, 27, 28).

For tracts auctioned during 1954–68, Mead, et al. (1980) estimated the average before-tax internal rate of return anticipated through 2010 to be 11.43%; for profitable leases it is 19.40%. This yield, significantly higher than typical rates of return on total assets of petroleum companies during this period which were on the order of 9% to 10% before tax (U.S. FTC, Table 7), is the predictable inducement for risk bearing if decisionmakers are risk averse. Risk aversion is, by definition, an unwillingness "to take a bet which is actuarially fair" [Arrow (1970), p. 90]. Consequently, risk-averse decisionmakers require a higher return on a risky asset than on a nonrisky asset; equivalently, they value risky assets at less than their actuarial value. Further evidence consistent with risk aversion is the prevalence of joint bidding by firms of all sizes.[1]

The Outer Continental Shelf Land Act of August 7, 1953, provides that the federal government may lease OCS tracts under either of two primary arrangements: *(a)* fixing the roy-

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[1]The theory of risk aversion (Arrow [1963, 1970], Pratt [1964]) has recently been applied in models of OCS auctions—Leland (1978) and Ramsey (1980*a*). Reece (1978, 1979) argues that bids of less than expected values result from strategic behavior by profit-maximizing (i.e., risk neutral) firms but does not examine the joint bidding decision.

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alty payment on the value of oil and gas recovered (minimum: $12^1/_2\%$) and letting the bonus payment be determined through competitive bidding; or *(b)* fixing the bonus payment and letting royalty rate be determined through competitive bidding. Except for 38 tracts, the first alternative (with a $16^2/_3\%$ royalty rate) was used in auctioning over 3,100 OCS tracts through 1977.

Joint bidding has been permitted under the presumption that it is a single temporary activity, an arrangement which the federal courts have generally held to be exempt from antitrust legislation. Such joint ventures have been justified on the grounds that these activities are unusually risky or require unusually large amounts of capital. If so, joint ventures assure the undertaking of some projects which might otherwise not take place.[2] The anticompetitive effects may be minimized by the narrow function of the consortium—i.e., limited to the development of a single tract—although the same consortium may be involved in many such projects.[3]

This paper develops a testable model of the bids offered by a risk-averse firm participating in OCS auctions in which the joint-bidding decision is one part of the complex bidding decision. Estimates of this model provide an assessment of the dependence of OCS bids on the firm's net worth, its specialization in production of petroleum, and the extent of its OCS involvement as well as the effects changes in the depletion allowance, petroleum price controls, and the costs of labor and capital in OCS production. These issues are formulated as hypotheses for the bids of risk-averse firms in section II, and tested in section III. The implications of the findings for the management of OCS resources are discussed in the concluding section IV.

II. RISK AVERSION AND THE FIRM'S BIDDING BEHAVIOR IN OCS AUCTIONS

In evaluating an OCS tract, both the bidding firms and the government utilize the same technology and methods of geological, geochemical, and geophysical analysis.[4] It is natural to think of a bidder or the government as estimating a probability density function of the tract's value. Given the fundamental similarity of evaluative technologies and a competitive market for petroleum geologists, it is reasonable to assume that these estimated density functions and their expected values

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[2]Recognition of such risk-sharing inducements to risk taking is explicit in federal policies and legal decisions, as for example, when the Secretary of the Interior testified:

> Here we examine the risk-sharing consequences of joint bidding whose outcomes are uncertain, and the consequent encouragement offered to smaller, more risk-averse firms to enter bidding competition. We conclude that joint bidding is likely, on balance, to encourage competition if risks are large, and to discourage competition if risks are low." (U.S. Congress Subcommittee on Monopolies, House Judiciary Committee [1976, p. 498]).

Similarly, in 1980, the U.S. Tax Court reversed an IRS decision disallowing the expensing of OCS development costs since it "would thwart the U.S. policy of granting deductions (of intangible drilling costs) to encourage taking risks." ("Tax Report," *Wall Street Journal*, 15 October 1980, 1).

[3]Most studies of OCS bidding have supported the view that joint bidding increases competition and is a legitimate method of risk sharing (Mead [1967], Markham [1970], Erickson and Spann [1974], Dougherty and Lohrenz [1977], Mead, et al. [1980]). However, a controversial study by Gaskins and Vann (1976) led to enactment of a ban on joint bids by "majors" (i.e., the eight largest oil producers: Exxon, Gulf, Mobil, Shell, Texaco, Standard of Indiana, Standard of California, and British Petroleum) based on the hypothesis that shared information from joint bidding conferences was used collusively to lower bids on other tracts; this hypothesis has been tested and refuted in Sullivan and Kobrin (1980) and in Millsaps and Ott (1981).

[4]Bidders often jointly commission seismic surveys ("group shoots") of tracts for which they may subsequently compete. In these cases, the information utilized by the competing bidders is identical. For descriptions of this exploratory process see McKie (1960), Kaufman (1963), or MacRae and Evered (1983). Detailed descriptions of the geological and geochemical techniques of OCS prospecting and evaluation, both before and after leasing, can be found in Hunt (1979); Chapter 12 discusses the evaluation of data and includes discussions of the Pacific, Prudhoe Bay, and Baltimore Canyon OCS areas, as well as the Gulf of Mexico. We assume that firms are identical except for measurable characteristics. While it is probably true that firms differ in their skills and techniques, geologists and techniques at any suction, over longer periods, since geologists and knowledge are competitively allocated, there is unlikely to be an ex ante difference. Consequently, assuming that all firms are equally adept at assessing OCS tracts dooms us to errors in regressions, but not systematic ones.

do not differ systematically among firms or the government. Thus, it follows that, relative to the government's presale evaluations, systematic differences in firms' average bids are not due to information differences.[5]

The hypothesis that a firm is risk averse can be directly inferred from the risk aversion of a firm's decisionmakers. Three arguments have been used to rationalize a risk-averse objective function for the firm: the avoidance-of-bankruptcy argument, the management-incentives argument, and the incompletely-diversified-major-shareholder argument. Their common element is that the firm's net worth is not a matter of indifference for its decisionmakers as it might be presumed to be for a completely diversified investor. In the latter case the diversified investor is insulated from major impacts of any single firm's failure by the statistical property of the near independence of his wealth from a single firm's performance; conversely, for a director or chief executive officer of a corporation, no such independence of wealth, career, or fortune can reasonably be assumed.[6]

The avoidance-of-bankruptcy argument (Roy [1952]; Day, et al. [1971] and other references cited therein, Ramsey [1980b]) assumes that the firm's directors instruct management to make choices in such a way as to maintain at some specified low value the probability of bankruptcy; treating this as a constraint, profits are maximized subject to it. Liabilities may be a contractually fixed total, but the value of assets is a stochastic variable dependent on the outcomes of risky ventures, hence on risk-bearing choices. Therefore, management will not choose investments with the maximal expected value since these choices may have nonnegligible probabilities of large losses and violate this safety-first constraint.

Similar to the avoidance-of-bankruptcy argument, but following from the risk averseness of firm's managers, is the management-incentives argument for the firm's risk aversion.[7] If the executives in a firm are risk averse and if a major portion of their compensation is in the form of stock options or other contingent claims on the firm's net worth, then it follows that their decisions will be made in such a way as to reflect their risk aversion since their own net worth changes in proportion to that of the firm.[8] This also implies that the firm's decisions will reflect the risk aversion of its managers.

Finally, there is the incompletely-diversified-major-shareholder argument. Trivially, if the firm is closely held, then its owner will make decisions which, like the management-incentives argument above, reflects his own

[5]The Bureau of Land Management (BLM) of the Department of Interior prepares a pre-sale evaluation of each tract offered in OCS auctions; these presale estimates (PSE) are available for auctions beginning May 1968. Although PSEs are lower bounds on price, not an expected price, they provide a common scale for the bids on disparate OCS tracts. See Bieniewicz (1980).

[6]The capital asset pricing model (CAPM)—Sharpe (1964), Lintner (1965), Mossin (1966)—implies that stock prices will have no risk premium. Friend and Westerfield (1981) refute this no-risk-premium implication. They conclude that "the most theoretically plausible [explanation] is that the implicit CAPM assumption of zero transaction and information costs may not be acceptable even as a first approximation. . . . investors may in general concentrate on a relatively small set of marketable assets so that residual risk measures may be as important as, or more important than, systematic risk (beta) in explaining individual asset returns." (p. 314)

[7]Masson (1971) surveys the form of executive compensation (largely stock options and other payments contingent on net worth) and does not address the issue of risk aversion. Yet his regression results imply risk aversion—decreasing absolute risk aversion and constant relative risk aversion—in that a fractional power, $2/3$, on total financial return to the executive increased the confidence level of his hypothesis tests slightly compared with a power of unity (p. 1284 note 8).

[8]Lewellen (1971) found that after-tax executive compensation for large U.S. manufacturing firms for both chief executives and the top five executives was primarily from (1) stock-based remuneration, (2) dividend income, and (3) capital gains with (4) fixed dollar remuneration being relatively minor in comparison. In particular, over the period 1954–1963 the average annual ratio of $[(1)+(2)+(3)]/(4)$ ranged from 2.123 to 7.973 for chief executives and from 1.753 to 8.669 for the top five executives in large U.S. manufacturing corporations (pp. 89–90). Moreover, these executives, on average, had large stock holdings in their own corporations—$341,437 to $3,033,896 during 1954–1963—and were not active sellers (p. 79). Since these ratios and averages were increasing, reaching their highs in 1962 and 1963, the inference of risk aversion on the part of executives and their firms in our sample period 1968–75 seems particularly apt.

risk aversion. A straightforward extension of this argument covers the case where one or a few stockholders form a coalition to command a significant portion of the outstanding shares, elect directors, and force the management to act in their best interest, and, hence, to reflect their risk aversion. The implicit assumption in this argument is that individuals with sufficient equity in a firm to participate in its decision making will have such a large portion of their wealth in the firm that they will not be able to sufficiently diversify the balance of their portfolio; hence, they will not be risk neutral with respect to the firm's performance (see note 6).

If the controlling stockholders' portfolios were risk-insulated from the impact of a single firm's performance, it would be true that firms would be impelled to make risk-neutral choices. Since risk-neutral firms would require lower rates of return on risky projects, such firms would have a competitive advantage over risk-averse firms tending to eliminate risk-averse behavior among publicly held firms. However, this scenario could hold only if major stockholders' portfolios were ex ante immune—i.e., sufficiently diversified—to the effects of any firm's risky investment choices. Moreover, it follows that if stockholders wanted management to make profit-maximizing choices rather than maximizing a risk-averse objective function, management incentives would not be contingent claims on the firm's market value (see note 8).

Therefore, we assume that the firm determines its bids so as to maximize the expected value of a thrice-continuously differentiable function, *F(P(W))*, of its portfolio of assets, *P(W)*, constrained by its current net worth, *W*. Risk aversion is equivalent to the concavity of the firm's objective function,

$$F' \equiv \frac{\partial F(P(W))}{\partial W} > 0, \qquad [1]$$

$$F'' \equiv \frac{\partial^2 F(P(W))}{\partial W^2} < 0. \qquad [2]$$

Following the Arrow-Pratt theory of risk aversion, risk aversion is conceptually measured in terms of two indexes, absolute risk aversion (R_A),

$$R_A \equiv \frac{-F''}{F'}, \qquad [3]$$

and relative risk aversion, (R_R),

$$R_R \equiv \frac{-WF''}{F'}. \qquad [4]$$

The two principal behavioral hypotheses of the Arrow-Pratt theory are decreasing absolute risk aversion and increasing relative risk aversion, respectively:

$$\frac{\partial R_A}{\partial W} < 0, \qquad [5]$$

$$\frac{\partial R_R}{\partial W} > 0. \qquad [6]$$

These risk-aversion hypotheses imply that a risk-averse firm will require a higher rate of return, ζ, from a risky investment than the riskless yield, *r*, demanded by a risk-neutral investor:

$$\zeta = (1 + \delta)r, \qquad [7]$$

where δ is the risk premium which depends on *W* in accordance with [5] and [6].[9]

Since the outcome of a risky project is not completely under the firm's control, its only means of raising the anticipated yield is to lower the price it offers for the risky asset relative to the actuarially expected values. The risk premium depends not only on the riskiness of the project—i.e., the second and higher moments of the probability distribution of its yield—but also on the firm's wealth and the diversification of its portfolio. With respect to wealth, [5] implies that, ceteris paribus, a wealthier firm will require a smaller risk premium on a specific risky asset than a smaller firm. With respect to diversification, [6] implies that, ceteris paribus, wealthier firms will invest less in risky assets *relative to their wealth,* than smaller firms. A further implication of [6] is that, if the covariance of yields is positive, then the larger the total quantity of risky projects relative to the

[9]For details, see Arrow (1970, pp. 98–105); the specific proposition that risky assets must bear a higher return if a risk averter holds them is developed on p. 99. For a discussion of the contrary view on relative risk aversion, see Samuelson (1977).

wealth of the firm, the higher will be the risk premium.[10]

Postulating that all firms are risk averse and controlling for differences in their makeup—i.e., wealth, specialization in petroleum production, joint bidding history with other firms, etc.—implies that each firm will bid only a fraction of any tract's actuarial value and that comparing the bids of a cross section of firms, wealthier firms will bid a larger fraction of the actuarial value than less wealthy firms. This fraction depends on the firm's wealth, the consortium share the firm undertakes in the bid, and the firm's total bids in the auction relative to its wealth. Define

- σ ≡ Uncertainty, variability, or riskiness of tract's value;
- α ≡ Share in bid chosen by the firm;
- β ≡ Fraction of the actuarially expected net value of tract bid by the firm;
- ρ ≡ Proportion of the firm's net worth at risk in total bids on this and other tracts offered in the same auction;
- V ≡ Actuarially expected value of tract net of royalties, exploration, development, and production costs.

Then, the fraction of the tract's actuarial value that the firm offers in its bid depends inversely on the risk premium embodying the Arrow-Pratt risk aversion hypotheses, [5] and [6], as follows:

$$\beta_j = \beta(\alpha_j ; \sigma_j , V_j , \rho, W), \qquad [8]$$

$$\frac{\partial \beta_j}{\partial \sigma_j} < 0, \qquad [8.1]$$

$$\frac{\partial \beta_j}{\partial \alpha_j} < 0, \qquad [8.2]$$

$$\frac{\partial \beta_j}{\partial V_j} < 0, \qquad [8.3]$$

$$\frac{\partial \beta_j}{\partial \rho} < 0, \qquad [8.4]$$

$$\frac{\partial \beta_j}{\partial W} > 0. \qquad [8.5]$$

Ceteris paribus, [8.1] is implied by risk aversion—i.e., the more variable the anticipated outcome, the higher the required yield; [8.2], [8.3], and [8.4] are implied by relative risk aversion—the larger the risky commitment for a given level of wealth, the higher the risk premium[11]; and [8.5] is implied by decreasing absolute risk aversion—holding risk and commitment constant, the higher the wealth, the smaller the risk premium.

III. TESTS OF THE MODEL OF RISK-AVERSE BIDDING BY FIRMS ON OCS TRACTS IN THE GULF OF MEXICO IN AUCTIONS DURING 1968–75

We assume that each firm is risk averse as specified in [1]–[8], and that it chooses its bid so as to maximize its objective function $F(P(W))$, where $P(W)$ is the portfolio of assets which will include those risky assets—OCS leases—acquired in the auction. It is important to emphasize that we are not testing a theory of the firm's optimization; rather, assuming optimization under risk aversion, we attempt to isolate how the *subjective* valuation of risky assets varies with wealth, liquid assets, consortium history, and degree of petroleum production specialization. We assume that the firms are otherwise identical and obtain their *objective* or actuarial valuations by similar techniques from samples drawn from unbiased lognormal distributions of each tract's value, [Reece (1978), 371]. Moreover, we ignore strategic considerations which would induce the firms to bid other than their subjective valuation based on presumed knowledge of the number of competing bidders opposing them on each tract.[12]

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[10]For a detailed theoretical development of these propositions in the context of OCS bidding, see Ramsey (1980a, Chapter V).

[11]An obvious implication of hypothesis (8.2) is that risk-averse firms will be willing to pay a higher price jointly for a tract as part of a joint bid than they would individually in a solo bid—i.e., the smaller α, the larger β—a point overlooked in testimony offered to the Congressional Committee investigating joint bidding in OCS auctions (U.S. Congress (1976, pp. 448–95)).

[12]While these questions of strategy have been the focus of recent investigations of OCS auctions, these pa-

The firm must decide simultaneously its bid on a particular tract, whether to form a consortium and its share in it, its bids on other tracts in the same auction, and the proportion of total net worth to be allocated to bids in the auction. Hence, to test propositions about the firm's bids requires a system of equations rather than one. The estimated system consists of the following three equations:

$$B_{ij}^* = \tau_0 + \tau_1 A_{ij}^* + \tau_2 R_i^* + \tau_3 W_i^* + \tau_4 V_j^* + \tau_5 P^* + \tau_6 M^* + \tau_7 O^* + \tau_8 U_{ij} + \tau_9 T + \sum_{k=1}^{7} \tau_{k+9} X_k + e_1^*, \qquad [9.1]$$

$$A_{ij}^* = \psi_0 + \psi_1 R_i^* + \psi_2 W_i^* + \psi_3 I_i^* + \psi_4 V_j^* + \psi_5 L_i^* + \psi_6 J_i^* + \psi_7 D_j^* + \psi_8 S_j^* + \psi_9 U_{ij} + \psi_{10} T + \sum_{k=1}^{7} \psi_{k+10} X_k + e_2^*, \qquad [9.2]$$

$$R_i^* = \chi_0 + \chi_1 W_i^* + \chi_2 I_i^* + \chi_3 L_i^* + \chi_4 P^* + \chi_5 M^* + \chi_6 O^* + \chi_7 T + \sum_{k=2}^{5} \chi_{k+7} X_k + e_3^*, \qquad [9.3]$$

where

- B ≡ Ratio of bonus bid to the government's presale evaluation, (β);[13]
- A ≡ Percent share by firm in the bid, (α);
- R ≡ The sum of all bids on this and other tracts by the firm in this auction in ratio to its wealth, (ρ);
- W ≡ Firm's net worth—constant dollar value of outstanding common stock or common stockholders' equity;
- I ≡ Index of firm's specialization in crude petroleum production;
- V ≡ Presale estimate of tract's value per acre by BLM;
- L ≡ Ratio of firm's liquid or cash assets to net plant;
- J ≡ Index of shared bidding experience by consortium members;
- S ≡ Size of tract in acres;
- D ≡ Depth of water in tract in feet;
- P ≡ Real price of Arabian crude oil per barrel;
- M ≡ Index of the real price of oil machinery price;
- O ≡ Index of the real oilfield wage;
- T ≡ Time trend—months beginning with first auction May 1968;
- U ≡ Proportion of the observed bid which has been offered by firms included in the data set; and
- X ≡ Dummy variables.

Asterisks indicate natural logarithms; a firm is identified by the index i, the specific tract by the index j, and e_1, e_2, e_3 are stochastic residual terms. The construction of these variables and their sources are discussed in the Appendix.

The bidding equation, [9.1], directly tests the implications of [8.1]–[8.5]. Of course, given the simultaneity of the bidding decision, the consortium decision, A, and total bids, R, must also be treated as endogenous. Of the right-hand variables in system [9], the signs of the coefficients of A, V, R, and W are predicted by the hypotheses [8.2]–[8.5]. In particular, decreasing absolute risk aversion predicts a positive coefficient on W in [9.1] and [9.2], while increasing relative risk aversion predicts a negative coefficient for W in [9.3]. The variables M and O reflect the expected costliness of development and produc-

pers have typically assumed the bidding firms to be identical (Reece [1978], 370); thus, our approach ignores questions of strategy on individual bids and pursues the effects of different characteristics of firms on their bids. Of course, the firms' bids must depend on their awareness that the higher the fraction (β_j) of the tract's actuarial value (V_j) offered, the greater is the likelihood of winning; without this dependence there would be no incentive for any firm or consortium to bid its subjective evaluation $\beta_j V_j$, since it would expect to win as often with a tiny bid as with a large one. Thus, it would offer a lower bid if it believed that would be sufficient to outbid its opponents; see Reece (1978, 370, 372–74), Smith (1981). Ramsey (1980*a*, Chapter IV) discusses the strategic implications of the expected number of competing bidders and reviews the literature on this approach.

[13] The firm does not know the government's evaluation and sets its bid based on its own evaluation which is not observable. The government's presale evaluation, however, is a proxy for the firm's unobservable appraisal.

tion in real terms and price theory predicts negative coefficients. For the riskiness of the OCS tracts three dummy variables assess aspects of riskiness (see below); their negative coefficients in [9.1] are predicted by [8.1].

A consortium in system [9] is described by three variables: *A*, the observed bidding firm's share; *J*, an index of the observed firm's previous joint bids with its current partners; and *U*, the percent of the bid offered by firms in our data set. The greater is *J*, the lower would be information costs and uncertainty associated with the bid and the more desirable would be the partnership; hence, *J* should have a positive coefficient in the *A* equation, [9.2]. There is no a priori prediction for the sign of *U* although the firms in our data set—i.e., firms listed on the New York or American stock exchanges and those nonlisted (OTC) firms for which we could obtain data—are almost certainly larger than those not included. Since such nonincluded firms would be smaller and perhaps differently organized or privately held, their participation (necessarily in a consortium in the proportion (1-U)) might lower bids or affect consortium choices, but not in a strictly predictable way.

In order to apply the risk aversion theory across firms and consortia, observable characteristics which differentiate them—*W*, *I*, *L*, *J*, and *U*—must be controlled. While the focus of the paper is on the effects of net worth, *W*, the extent of specialization in crude oil and natural gas production, *I*, is important since it indicates both an expertise in evaluating OCS assets and a preference for them relative to alternative investments. Hence, *I* obviously should have a positive coefficient in the *R* equation, but its impact on the consortium choice, *A*, is not a priori clear. Conversely, a larger *L* reflects a relatively more risk-averse firm, ceteris paribus; thus, we expect negative coefficients on *L* in the *A* and *R* equations.

A time trend, *T*, and the real price of crude petroleum—the uncontrolled world price, *P*—also were included. If the structure of the system changed over the eight years of observations in a way not captured by the explanatory variables and dummies (see below), the coefficients on *T* would be significant. The in world oil prices would imply a positive coefficient for P in both [9.1] and [9.3] if the government's presale evaluations generally underestimated the OCS tracts' anticipated values.

The other coefficients in [9.2] also are implied by [8.1]–[8.5]. *A* is a measure of risk bearing; consequently, since higher *A* indicates higher risk bearing, its dependence on the explanatory variables parallels the pattern for *B*. Thus, by [8.4], the riskier the portfolio of other bids, the lower will be *A*; hence, *R* should have a negative coefficient. By declining absolute risk aversion, [3] and [8.5], *W* should have a positive coefficient. The presale estimated value, *V*, has an indeterminate sign: higher *V* is a less risky venture, but for a given *A* requires a larger proportional commitment of the firm's net worth (less diversification). Finally, *S* and *D* are quantitative measures of the tract's riskiness and should have negative coefficients.

Dummy variables were included to absorb two types of shifts in the sample space. First, cross-sectional dummies were used to account for characteristics which differentiate the bidding firms or tracts to an extent that precluded the assumption that they had been drawn from the same populations; dummies distinguish major from minor oil firms (*X*2), subsidiaries from parent firms (*X*7), and frontier from drainage tracts (*X*1).[14] Second, time-series dummies were included to absorb structural shifts due to events which changed the rules or payoffs of the auctions; dummies were used to isolate the impacts of the lowering of the depletion allowance (*X*3), the ending of the depletion allowance for majors (*X*4), the OCS development injunction following the Santa Barbara Channel blowout (*X*5), and oil price controls (*X*6) (which also

[14]A drainage tract is a tract adjacent to a producing tract; hence, it is a high likelihood, low-risk prospect. Note that last these two dummies do not appear in the total bids equation, [9.3]. The drainage tract dummy (*X*1) would be inappropriate since it refers to an individual bid in the auction, not to the total amount bid on all tracts; the subsidiary dummy (*X*7) also refers to the specific lease and again is not relevant to R which is the sum of bids by the parent and *all* is subsidiaries in the auction.

coincided with the period beginning with the OPEC embargo).

The coefficients of the dummies have, in some cases, ambiguous signs. Theory does not predict, for example, that majors ($X2$) will bid differently than nonmajors (but, see note 3) or that subsidiaries ($X7$) will bid differently than parent firms. Others carry straightforward predictions. $X1$ indicates a less risky tract so that, by [8.1], bids and consortium shares should be higher; conversely, $X5$ and $X6$ indicate a decrease in the security of lessees' property rights and $X3$ and $X4$ indicate less tax shelter on receipts so that bids, bid shares, and total bids should be smaller. The increase in domestic petroleum property values due to the OPEC embargo will be picked up by the coefficient of the price variable, while the coefficient of $X6$ will reflect the reduction in lease value due to oil price controls.

An observation of this system is a vector whose elements are the jointly dependent, independent, and predetermined variables specified above. The data set covers the bids, solo and joint, by a subset of firms for tracts in the Gulf of Mexico offered in 17 auctions from May 1968 through July 1975; this sample was used in order to include similar tracts offered under consistent rules: all are in the Gulf of Mexico, BLM released its presale evaluations after each auction, and the leases were offered in auctions without restrictions on joint bidding. The subset of bidders included was determined by the availability of financial data on the bidding firms; this set included 103 parent firms which bid on their own or through subsidiaries and were involved in 89% of the 14,963 bids offered during the eight-year period. A sample of 3,434 bids offered on 977 tracts was drawn.[15] All data are standardized—expressed as logs of ratios to their means. This sample was used in estimating the system [9] by means of the three-stage-least-squares routine of the SAS package.

The results of this estimation are displayed in Table 1 for the quantitative variables and in Table 2 for the qualitative or dummy variables. The variables are listed down the left-hand margin—in Table 1 first the jointly dependent variables and then the independent or predetermined variables. Across the top are the dependent variable names which indicate the equation being estimated; two wealth definitions were employed—respectively, the book value of common stock equity and the market value of common stock, each in real terms, as deflated by the implicit GNP deflator. At the foot of Table 1 are the $\bar{R}^2$ and F-statistics for each equation's second-stage estimates and the weighted-R^2 for the system estimations.

The estimates in Table 1 manifest several immediate impressions and a number of subtler ones. First, wealth is a significant explanatory variable in all three equations so that, in particular, the hypotheses of decreasing absolute risk aversion and increasing relative risk aversion are not rejected.[16] Second, consor-

[15]Only one independent observation exists in a joint bid since the bid is agreed upon by all consortium members. The observed bidder for each consortium was selected by random number. All solo bids by firms in our subset are included in the sample. The log linear form of [9] was specified because there is abundant evidence that OCS bids tend to be distributed exponentially. See Markham (1970, 128), Dougherty-Lohrenz (1977), Reece (1978, 371), and Ramsey (1980*a*, chapters I, II). Nonetheless, this leaves open the question of whether the log of the ratio of bid to PSE is log-normally distributed. Tests for lognormality led to omission of three suspect subsets of bids: (1) tracts arbitrarily assigned PSEs of the Department of Interior's minimum acceptable bid of $25/acre (MAB); (2) tracts assigned PSEs lower than MAB; (3) tracts reoffered in the July 1974 "junk sale" (see Sullivan and Kobrin [1980]). Omitting the 884 bids on these tracts with suspect PSEs resulted in a sample of B observations for which lognormality was not rejected.

[16]There may appear to be ambiguity in the coefficient of wealth in the R-equation and, therefore, in testing for increasing relative risk aversion since wealth appears in the denominator of R as well as in the right-hand side of the R-equation. Note, however, that the increasing relative risk aversion hypothesis also implies $\eta(Q,W) < 1$, where Q is firm's sum of bids in the auction. If Q instead of R were the dependent variable in [9.3], we would predict a positive coefficient on wealth—since risky investment is a normal good—but from [6] a coefficient significantly less than 1. This can be seen by differentiating $R = Q/W$ with respect to W to obtain

$$\frac{\partial R}{\partial W} = \frac{Q}{W^2}(\eta(Q,W)-1),$$

which by increasing relative risk aversion [6] should be negative. Since Q and W are positive, this implies

TABLE 1

ESTIMATED ELASTICITIES (3SLS) OF BIDS, CONSORTIUM SHARES, AND TOTAL BIDS IN 17 AUCTIONS FOR OCS TRACTS IN THE GULF OF MEXICO, 1968–1975

	Variable Type and Definition[2]	Specification of Wealth Variable and Dependent Variable of Estimated Equation[1] — *Book Value* B	*Book Value* A	*Book Value* R	*Market Value* B	*Market Value* A	*Market Value* R
Jointly Dependent:							
(B)	Bid/.PSE						
(A)	Bid share	−0.312			−0.280		
		(6.283)*			(5.879)*		
(R)	Ratio of total bids by firm in same auction to its wealth	0.046	−0.102		0.067	−0.109	
		(0.774)	(3.377)*		(1.103)	(3.654)*	
Independent or Pre-Determined:							
	Intercept	−0.757	0.002	−2.544	−0.687	−0.046	−2.506
		(3.542)*	(0.072)	(21.166)*	(3.234)*	(1.506)	(20.636)*
(W)	Wealth	0.204	0.098	−0.551	0.205	0.123	−0.537
		(5.091)*	(5.064)*	(38.564)*	(4.947)*	(6.390)*	(35.885)*
(I)	Index of petroleum production		−0.013	0.242		−0.025	0.213
			(1.103)	(17.827)*		(2.281)*	(15.670)*
(V)	Presale estimated value per acre	−0.672	−0.017		−0.673	−0.015	
		(36.160)*	(1.780)		(36.155)*	(1.515)	
(L)	Cash/Net Plant		−0.129	−0.131		−0.174	−0.215
			(7.737)*	(5.456)*		(10.026)*	(8.804)*
(J)	Index of prior shared bids		0.028			0.028	
			(39.925)*			(41.221)*	
(S)	Tract size		−0.053			−0.053	
			(1.504)			(1.531)	
(D)	Water depth		−0.075			−0.074	
			(5.092)*			(5.042)*	
(P)	World price of crude oil	1.076		2.331	1.087		2.417
		(5.822)*		(21.333)*	(5.654)*		(21.866)*
(M)	Oilfield machinery price index	−2.477		−14.015	−2.249		−14.234
		(1.383)		(12.490)*	(1.235)		(12.610)*
(O)	Oilfield wage wage index	−16.097		−77.144	−13.922		−73.874
		(2.557)*		(21.647)*	(2.230)*		(20.676)*
(U)	Percent of bid by included firm	−0.214	0.092		−0.241	0.077	
		(2.195)*	(1.941)		(2.502)*	(1.623)	
(T)	Time trend	−0.007	−0.000	0.105	−0.010	0.002	0.102
		(0.697)	(0.002)	(16.962)*	(1.010)	(0.493)	(16.567)*
R^2 (2SLS)		.316	.500	.673	.314	.511	.653
F (2SLS)		94	192	545	93	200	498
Degrees of freedom		3416	3415	3420	3416	3415	3420
Weighted–R^2 (3SLS)			.622			.610	

[1]Absolute value of t-ratio is parentheses; *indicates significance at 5% (2-tail).
[2]Data definitions and sources in Appendix.

TABLE 2

ESTIMATED COEFFICIENTS (3SLS) OF DUMMY OR QUALITATIVE VARIABLES IN 17 AUCTIONS FOR OCS TRACTS IN THE GULF OF MEXICO, 1968–75

	Specification of Wealth Variable and Dependent Variable of Estimated Equation[1]					
	Book Value			*Market Value*		
Variable Definition[2]	*B*	*A*	*R*	*B*	*A*	*R*
Dummies:						
(*X*1) If drainage tract	0.803 (6.982)*	0.044 (0.743)		0.801 (6.857)*	0.048 (0.816)	
(*X*2) If major	0.095 (1.490)	0.114 (3.311)*	−0.161 (3.162)*	0.114 (1.778)	0.077 (2.278)*	−0.140 (2.737)*
(*X*3) If after depletion allowance lowered	0.577 (2.002)*	0.057 (0.518)	−2.664 (13.933)*	0.667 (2.325)*	0.035 (0.325)	−2.544 (13.269)*
(*X*4A) If after depletion allowance ended for majors and if nonmajor	−0.006 (0.023)	−0.301 (3.749)*	0.840 (4.112)*	−0.020 (0.072)	−0.320 (4.005)*	0.826 (4.023)*
(*X*4B) If after depletion allowance ended for majors and if major	−0.231 (0.797)	0.009 (0.111)	1.498 (7.161)*	−0.252 (0.862)	0.036 (0.481)	1.575 (7.495)*
(*X*5) If after Pacific OCS injunction	1.354 (5.836)*	−0.090 (0.894)	0.496 (2.771)*	1.352 (5.828)*	−0.111 (1.113)	0.445 (2.477)*
(*X*6) If during oil-price controls	−0.907 (4.504)*	0.018 (0.317)	−2.128 (16.399)*	−0.912 (4.386)*	0.036 (0.647)	−2.197 (16.765)*
(*X*7) If subsidiary	−0.166 (3.425)*	−0.036 (1.517)		−0.170 (3.522)*	−0.038 (1.654)	

[1]Absolute value of t-ratio in parentheses; *indicates significance at 5% (2-tail).
[2]Data definitions and sources in Appendix.

tium bidding seems to be a response to the riskiness of the OCS lease bids—*A* rises as wealth increases but falls as the riskiness (depth) of the tract increases. Third, the signs of the coefficients generally accord with the predictions from risk aversion and standard price theory. Moreover, the coefficient magnitudes are similar under the two wealth definitions. Fourth, since the estimation is primarily a cross-section study on micro-data, the $\bar{R}^2$s are quite reasonable—not only the *A*-equations in which about half of the variation is explained but also the *B*-equations in which about one third of the variation is explained. Observe, in this connection, that the time trend variable (*T*) was insignificant in the *B*- and *A*-equations.[17]

Of the hypotheses implied by the Arrow-

implies $\eta(Q,W) < 1$. In terms of the regression system [9], note that

$$\frac{\partial Q^*}{\partial W^*} = \eta(Q,W) + 1 = \frac{\partial R^*}{\partial W^*} + 1.$$

Estimating system [9] with Q^* in place of R^* yielded coefficients for Q^* in [9.3] which fit these predictions: significantly positive, significantly less than unity as predicted by increasing relative risk aversion, and insignificantly different from 1 plus the estimated coefficient on W^* in the *R*-equation displayed in Table 1. Moreover, the other coefficients in [9.3] were not significantly different than those reported in tables 1 and 2.

[17]The *B*- and *R*-equations under both wealth definitions have significant intercepts; however, by construction, regressions on standardized data (i.e., data with means of zero) must have zero intercepts. The explanation is that our data set includes dummy variables and a time trend, neither of which are standardized.

Pratt theory of risk aversion, the most important is decreasing absolute risk aversion—[5] and, more specifically, [8.5]. Other inferences would be vacuous if this hypothesis had been refuted since the risk-sharing argument is contingent on risk aversion and decreasing absolute risk aversion. Hence, the strong, positive significance of wealth (t-statistics of about 5 under each wealth definition) in the B-equation is the crucial empirical result of this paper.

Turning to a more detailed consideration of the consortium decision and its effects on bids, note that the larger the share a firm holds in a bid, the smaller the bid. As can be seen in Table 1, the coefficient of A in the B-equation is significantly negative as predicted by [8.2]. Moreover, the firm's share is larger the larger its wealth, and more proportionally widespread bidding (larger R) is associated with decreased shares. These estimates offer strong support for the risk aversion explanation for joint bidding. Joint bidding apparently substitutes marginally for wealth and credit for firms undertaking relatively large and risky projects. Since such motivations for joint bidding have been explicitly advanced in debates leading to the enactment of laws, in the opinions of the courts, and in other institutional forms of risk bearing—e.g., coinsurance—it is reassuring that empirical results should support this view in OCS lease auctions.

Briefly looking at some other results in Table 1, note that the more specialized in petroleum production the firm (as measured by I), the larger the proportion of its net worth is offered at risk in OCS auctions; but the evidence from the two wealth definitions is mixed as to whether more specialized firms take significantly smaller shares in consortia than less specialized firms. Also mixed are the tests of increasing relative risk aversion; while [6] and its implication for R is supported by the estimate coefficient of wealth in [9.3], the implication of [8.4] in [9.1] is not; higher ratios of total bids to wealth do not lower the offered bid.

The cost hypotheses predicted lower bids, lower consortium shares, and less total bids the higher the anticipated exploration, drilling and development costs. Variables which measure anticipated costs are tract size *(S)*, oil machinery prices *(M)*, and oil field wages *(O)*; also, water depth *(D)* is a cost as well as risk factor. The estimated coefficients of these variables imply that while larger tract size does not induce significantly larger consortia, higher oil machinery prices or oilfield wages do cause lower bids (both on individual tracts and in total bids in proportion to wealth), and water depth was a strongly significant inducement to smaller shares.

Finally, consider some illuminating results of the dummy variables reported in Table 2. Drainage tracts ($X1$) drew higher bids than the alternative, riskier wildcat or frontier tracts. The bids of majors ($X2$) were not significantly different than nonmajors, a further refutation of the Gaskins-Vann hypothesis; however, majors took larger consortium shares and put a smaller proportion of their net worth into total bids.[18] The lowering of the depletion allowance from 27% to 22% ($X3$) did not lower bids but did lower total bids. Surprisingly, the court injunction on OCS development in the Santa Barbara Channel following the blowout in 1971 ($X5$), which effectively froze the assets of field developers and operators, was associated with higher rather than lower bids or total bids in the succeeding auctions. Price controls on domestic oil ($X6$) lowered bid levels and total bids, offsetting somewhat the impact of higher long-run energy prices following the OPEC embargo as reflected in the positive coefficients on P, the world price of oil, in Table 1.

IV. CONCLUSIONS AND IMPLICATIONS FOR EFFICIENT POLICIES TO DEVELOP OCS PETROLEUM RESOURCES

We have tested the Arrow-Pratt theory of risk aversion on bids offered in OCS auctions.

[18]Note that optimal bidding strategies take into account the number of expected opponents and the number of bids to be made in an auction (see Smith [1981] and Bieniewicz [1980]). Thus, since the number of bids weighted by shares rises strongly with wealth (we found an elasticity of about .4 under either wealth definition) the winner's curse would imply, ceteris paribus, that they bid lower. It is a measure of the strength of decreasing absolute risk aversion (with wealth) that wealth offsets this tendency of the winner's curse to decrease bids.

The tests performed on OCS lease auctions of tracts in the Gulf of Mexico over 1968–75 would be of interest simply as an application of this theory. However, the results of the hypotheses tests embodied in the regression estimates have policy implications which are of relevance for the management of U.S. petroleum reserves, for regulations governing bidding consortia and price controls.

In particular, we have found that:

> The petroleum-producing firms in our sample are risk-averse decisionmakers so that the ex ante value of OCS leases increases with the firm's wealth and, equivalently, smaller rates of return are required the larger the firm.
>
> Wealthier petroleum firms put a smaller portion of their wealth into additions to their portfolio of OCS leases than do smaller firms.
>
> Consortium formation is largely explained by risk-sharing incentives in the sense that wealthier firms demand larger shares.
>
> Bids are raised by consortium bidding
>
> The major oil firms do not offer lower bids but they do take significantly larger consortia shares (hence, bid in smaller consortia), and they bid less widely than other firms in relation to their wealth.
>
> Increases in the world price of petroleum raise the ex ante value of OCS leases, but price controls lower both bids and the proportions of wealth put at risk in OCS auctions.

These findings have direct significance for the management and development of U.S. offshore petroleum resources both actual and potential.

The Federal Energy Information Administration (EIA) has estimated that over 30% of the undiscovered recoverable U.S. petroleum resources are offshore, and, of course, if real crude oil prices rise above those assumed in their projection, then both the absolute quantity (26 billion barrels) and, perhaps, the offshore proportion may be expected to rise. However, inextricably bound up with this anticipated resource development is the disincentive of the greater risks of operating in extremely harsh environments—e.g., the offshore regions of Alaska and the Atlantic reef—combined with the greater uncertainty of exploration and development in frontier regions as compared with the relatively well-known Gulf of Mexico.

To the extent that risk is inherent in this environment, it is a cost of production. Our crucial empirical result, the empirical support adduced for declining absolute risk aversion, implies that there are economies of scale in risk bearing. As evidenced by the positive wealth elasticity in the *B*-equation, wealthier firms require smaller risk premia and will, therefore, be willing to take on risky projects at a significantly smaller rate of return than would be acceptable to less wealthy firms. Hence, larger firms are more likely to undertake exploration in high-cost/high-uncertainty areas than smaller firms. Socially efficient leasing policy would encourage the lowest cost producers to undertake these projects, implying that large firms would dominate the Atlantic Reef, Alaskan, and other frontier OCS areas. A corollary is that policies intended to increase the participation of smaller firms must result in higher private yields and lower shares for the federal government.

Wealthier firms have a stronger preference for diversification, proportionally, than do smaller firms. This implication of increasing relative risk aversion, for which we obtained strong empirical support, implies that disallowing joint bids involving more than one major firm in costly, high-risk development regions will raise the anticipated yield (i.e., lower the federal return) necessary to induce such frontier development. Since we have found that consortium bidding raises bids (i.e., lowers the required yield) and that major firms do not in this respect behave differently than other firms, restrictions on joint bidding by majors should be removed.

Generally, we have found that risk-sharing is a sufficient explanation for consortium bidding. While the empirical tests in this paper do not rule out collusive motives, Sullivan-Kobrin (1980) and Millsaps-Ott (1981) both find empirical evidence sufficient to reject the Gaskins-Vann (1976) information hypothesis rationalizing the joint bidding ban. Given the noncollusive nature of joint bidding, the Department of Interior proposal to reduce risk by auctioning larger tracts (Halsey-Ross,

[1980], 65326, 65329–65331) would be an appropriate policy change. By increasing lease size from the usual limit of 5,260 acres to a sufficiently large block to contain an entire geological structure, the risk of discovering petroleum at a boundary would be reduced, and with it the risk of having to share all or most of the return on exploration investment. This externality, which can be internalized by the larger lease size, would require a larger financial commitment from lessees for exploration and induce more consortium bidding. Therefore, to capture all of the benefits of risk reduction of joint bidding, restrictions should be removed.

Overall, we have found that in risky undertakings, firms behave in a risk-averse manner—seeking to raise the rate of return on projects fraught with uncertainty by offering less than their actuarial value, and mitigating uncertainty by a natural form of risk pooling, joint ventures. It follows that policies which impede either of these behaviors are literally counterproductive.

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APPENDIX

Definitions, Descriptions of Variables, and Sources of Data

B ≡ Ratio of bonus bid to BLM presale estimated value (SOURCE: LPR5 TAPE (USGS)).

A ≡ Percentage of bid by observed firm—100 for a solo bid (SOURCE: LPR5 TAPE).

R ≡ Total bids in auction by the observed firm divided by the firm's wealth (SOURCE: LPR5 TAPE and COMPUSTAT or CRSP TAPE).

W ≡ Firm's wealth at the auction date deflated by GNP implicit deflator: *(a)* book value of common equity, or *(b)* market value of common stock (SOURCE: *(a)* COMPUSTATAPE; *(b)* CRSP TAPE).

I ≡ Index of firm's concentration in petroleum production obtained by dividing *(a)* market value at the well-head of 1976 crude oil and natural gas production by *(b)* total net sales in 1976 (SOURCE: *(a)* Atwood, Hersh, Newport (1978); *(b)* COMPUSTAT TAPE).

V ≡ *(a)* Presale estimate of tract's value deflated by GNP implicit deflator divided by *(b)* number of acres in tract (SOURCE: *(a)* data supplied by BLM; *(b)* LPR5 TAPE).

L ≡ Ratio of cash and liquid assets to net plant (SOURCE: COMPUSTAT TAPE).

J ≡ Index of consortium partners' prior shared bidding experience: product of pairwise proportions of previous OCS bids that each consortium member had made jointly with the observed bidding firm. For the initial auction, May 1968, *J* reflected the partners' experience from the first auction in October 1954 through the immediately previous auction in February 1968; for each succeeding auction, *J* was updated to include the previous auctions' joint and solo bidding experience. To avoid zero, a small number, equal to the smallest joint proportion, was used as the lower bound (SOURCE: LPR5 TAPE).

S ≡ Size of tract in acres (SOURCE: LPR5 TAPE).

D ≡ Depth of water in tract in feet (SOURCE: data supplied by BIM).

P ≡ Price of Arabian crude oil/per barrel deflated by GNP implicit deflator (SOURCE: International Monetary Fund, IFS Tape).

M ≡ Ratio of oil field machinery cost index to GNP implicit deflator (SOURCE: Chase Econometrics Databases).

O ≡ Ratio of oilfield wages cost index to GNP implicit deflator (SOURCE: U.S. Department of Labor, Bureau of Labor Statistics. *Employment and Earnings, United States, 1909–78*, p. 24).

T ≡ Time trend: the number of months since the beginning of the sample period at each auction date (SOURCE: auction dates from LPR5 TAPE).

U ≡ Proportion of bid by listed firms (SOURCE: LPR5 TAPE, BIDDER'S NAMES).