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Oil Field Unitization: Contractual Failure in the Presence of Imperfect Information

By STEVEN N. WIGGINS AND GARY D. LIBECAP*

Private contracting is a solution to problems of production and exchange when transactions costs are low, but if they are high, contracting may be less successful (Ronald Coase, 1960; Oliver Williamson, 1976; Victor Goldberg, 1976). Accordingly, incorporation of transactions costs into economic analysis is necessary to determine when private contracting will be effective and when it will not. There has been, however, little empirical analysis, based upon testable theories, of the impact of transactions costs on contracting. This paper presents such an analysis, and shows that imperfect information can seriously limit the effectiveness of private contracting. The case considered is the widespread failure of private crude oil producing firms to unitize U.S. oil fields to reduce rent dissipation. Rent dissipation follows as multiple firms compete for migratory oil in common oil pools. Competitive production leads to excessive wells and surface storage, higher extraction costs because subsurface pressures are inefficiently depleted, and reduced overall oil recovery. Unitization is the obvious private contractual solution to rent dissipation. Under

unitization a single firm is selected to develop the reservoir with net returns shared by all parties, including firms that would otherwise be producing. As early as 1916, the U.S. Bureau of Mines called for unitization of U.S. oil fields; yet, by 1947, Joe Bain found only 12 fully unitized fields out of some 3,000 U.S. fields sampled (p. 29).¹ Our forthcoming paper (1985) shows that as late as 1975 neither Oklahoma nor Texas, two leading producing states, had as much as 40 percent of production from field-wide units.

We argue that the principal causes of contractual failure are imperfect and asymmetric information that prevent agreement on lease values and hold-out strategies of firms to increase their share of unit rents.² This study is based on an empirical analysis of unitization contracting in seven oil fields. Our data are from trade journals and company records, including detailed engineering studies, estimates of parameters affecting lease values, unit share allocation formulas, and votes on shares. Besides these quantitative data, the company files include minutes of negotiations on bargaining strategy and let-

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¹In 1914, the U.S. Bureau of Mines estimated annual losses from competitive extraction at \$50 million, approximately one-quarter of the total value of U.S. production. In 1924, the Federal Oil Conservation Board was organized to review wasteful oil extraction, and it specifically endorsed unitization.

²Stephen McDonald (1979, p. 137) and others have pointed to hold-out strategies by firms for increased shares of unitized rents which block agreement. Our analysis reveals that this explanation is incomplete. A simple hold-out strategy could be employed by any firm, and it would be unrelated to structural advantage or the stage of field development. Yet, we find there are systematic differences, based upon structural conditions, across firms in the willingness of firms to join units. Further, we find that unitization contracts can be successfully completed late, as fields near depletion, or very early before production heterogeneities among firms are known.

ters regarding votes, lease parameters, and estimated gains from agreement.³ From this unusually rich data source we construct a detailed analysis of negotiations on the seven fields and isolate the causes of contractual failure. Section I outlines the general contracting problem. Section II develops a simple theory of contracting in the presence of imperfect information, and Section III provides the empirical analysis.

I. The Contracting Problem

A. Contracting in General

Coase, Goldberg, Williamson, and others have argued that transactions costs can seriously disrupt private contracting. Goldberg and Williamson, for example, explore cases where *ex post* information asymmetries cause contracting to fail when complete contingent claims contracts cannot be written. Contingent updates are difficult to incorporate when new information does not arrive symmetrically across agents. Coase examines a different case where large numbers of parties prevent contracts from being written. In this paper we explore a third and potentially more important cause of contractual failure, *ex ante* information problems that occur during contract negotiation. In unitization contracting there are only a small number of firms involved, typically fewer than 15, so that large numbers problems frequently associated with transactions costs are not encountered. Further, firms do not rely on later events to reveal more accurate information to update contracts. Instead, the unitization bargaining problem occurs before contract execution and centers on the establishment of once-and-for-all unit shares. Dispute focuses on differences in lease value estimates, since lease values determine unit shares. Differences in value estimates arise because of general uncertainty regarding res-

ervoir dynamics and information asymmetries among the bargaining parties. Those disputes block consensus on unit shares, and contribute to contractual failure.

The structural characteristics that lead to contractual failure in unitization are also present in many other contracting contexts. In unitization, bargaining disputes regarding the relative values of leases to be included in the unit lead to a breakdown of negotiations for a sharing formula. It is clear that these same factors are common in other settings, where it is asserted that contracting will provide an efficient, low-cost solution to problems of allocation and exchange. A conceptually similar problem is contracting between firms and workers in team production, when monitoring is imperfect (Richard Startz, 1983). Another related case is private contracting between consumers and firms to reduce pollution. In both cases it is difficult to determine the *ex ante* contribution of each party to production, and, if successful, the contract changes the nature of production so that *ex post* adjustments are not generally feasible. These cases suggest that empirically untested optimism regarding the power of private contracting in the presence of imperfect information may be unwarranted and that more systematic analysis is needed.

B. Contracting for Unitization

Unitization raises field rents by increasing oil recovery and reducing production costs compared to common pool production. Common pool conditions arise as multiple firms extract oil from the same reservoir. Land owners grant firms access to the reservoir through leases, and fragmented land ownership results in numerous firms exploiting the pool. Each is motivated to competitively drill and extract oil. Within the reservoir, oil is migratory, and property rights to it are assigned only upon extraction. Rapid production by a firm lowers subsurface pressure around its wells, stimulating oil immigration, which increases its share of total output. In the aggregate, these production strategies raise marginal extraction costs and reduce total recovery. High extraction rates deplete natural gas throughout the field, making oil

³The company records are from one of the largest producing firms in the United States. We were granted access to their unitization files. For reasons of confidentiality we cannot reveal the names of the bargaining firms on the seven fields examined in the paper.

more viscous and forcing costly artificial lift and injection of natural gas and water to raise pressure. Further, as natural gas leaves solution, pockets of oil become permanently trapped. With unitization these problems can be mitigated by having only a single firm develop the field with net revenues shared by all firms.

The division of net revenues is the central issue in unitization negotiations. The sharing formula is specified at unit agreement, and it assigns *once-and-for-all* shares of unit rents. A permanent share assignment is required because reservoir dynamics and relative lease production potential are fundamentally altered under unitization. Under unit management some wells are plugged and others are converted to gas injection to maintain pressure. No direct production occurs from these leases, and the oil originally below them is extracted elsewhere. Further, widespread injection of natural gas and water increases pressure in certain parts of the field, altering oil migration patterns. Because of these technical changes in the dynamics of production, unit shares must be based on *pre-unitization* estimates of lease values, and share negotiations cannot be reopened later to adjust for new contingencies.

Unit shares are based on estimates of lease values, but general uncertainty and asymmetric information block consensus on value estimates and, hence, shares. The parameters influencing lease values and unit shares include current and cumulative oil and gas production, number of wells, surface acreage, bottom hole pressure, gross acre feet of pay (volume of the producing formation), net acre feet of pay (nonporous and non-oil-bearing rock is subtracted from the gross measure), and remaining reserves (original oil-in-place less cumulative production). The first four parameters are directly observable and uncontroversial. The last four parameters describe reservoir characteristics under each lease, and provide more complete information on lease potentials. These are estimated from well logs and production histories, and require highly subjective interpretation by geologists and engineers. The need for subjective interpretation using arbitrary procedures leads to serious disputes. For ex-

ample, it was noted during negotiations in the Western RKM unit in Texas that: "The Engineering Committee could not agree upon oil reserves for a large number of tracts in the unit area because of the poor quality and interpretive nature of the available basic data" (Letter, Western RKM Unit File, Company Records).

The information problems that limit the number of parameters that can be used in allocation formulas is further illustrated in the calculation of remaining primary oil reserves. This parameter is a principal component of nonunitized lease value because it is an estimate of oil that may be produced from the lease under competitive production. It establishes a benchmark against which the value offered under unitization can be evaluated. Yet, remaining primary reserves are estimated using simple ordinary least square (*OLS*) regressions on specific functional forms that are often inaccurate. For example, in unsuccessful unit negotiations on the Wasson field in 1971, ultimate primary recovery (cumulative production plus remaining primary reserves) was estimated at 48 million barrels. This was based on production decline curves inferred from a production history of 36 million barrels; thus, it was estimated that one-quarter of the field's primary reserves remained. In 1978 negotiations were reopened after 2 million additional barrels had been produced. Ultimate primary was reestimated at 43 million barrels. A 6 percent change in output led to new information and a revision of remaining reserves estimates by approximately 50 percent (Wasson Unit File, Company Records).

Because of the subjective nature and wide variation in estimates of subsurface parameters, negotiating parties rely upon a small set of objectively measurable variables, but they are likely to be poor indicators of lease value. The problem is illustrated in Table 1 with regression estimates of output per acre using objective parameters for leases on three fields. Output per acre is a key determinant of lease value. In all three fields there remains a large, unexplained residual variance in the estimates due to inherent variation in reservoir quality and differences in the stage of development among leases that are not re-

TABLE 1—REGRESSIONS OF OUTPUT PER ACRE^a

	Independent Variables:			Statistics		
	Intercept	Cumulative Output/Acre	Wells/Acre	Mean	SE _R	Coefficient
Goldsmith/Landreth	28.23 (9.79)	.036 (.0063)	38.87 (196.46)	68	46	68
North Cowden	40.19 (35.19)	.0083 (.0012)	618.69 (1471.58)	85	33	39
Prentice Northeast	2.45 (11.15)	.045 (.0062)	2602.88 (911.15)	116	39	34

^aDependent variable: Output per acre; standard errors are shown in parentheses.

flected in measurable parameters. For example, mean output per acre on Goldsmith/Landreth is 68 barrels with a standard error of the regression (*SE_R*) of 46 barrels. Similarly on North Cowden mean output is 85 barrels with *SE_R* 33, and on Prentice mean output is 116 barrels with *SE_R* 39. With so much unexplained variation in lease productivity there are ample grounds for disagreement about how long production differences will persist and whether they will grow larger or smaller over time. It is important to note that in such disputes the subjective judgment of a firm's engineers, who are familiar with individual well performance, provides an important source of *private* information about lease values. These judgements, however, are not easily verified by other parties, and accordingly, are difficult to incorporate into the unit allocation formula.

The problems of estimation and extrapolation for static structural characteristics are compounded in the estimation of dynamic reservoir performance characteristics, which are central to the negotiation of relative unit shares. Efforts to predict future performance are typically *ad hoc*. For example, predicted future production is often a simple extrapolation of past production with little systematic account taken of the pattern of water encroachment or other key variables. Such predictions are sensitive to the specific functional forms chosen. Companies often have differing, and strong, opinions about the correct estimation procedure, when choices may reallocate millions of dollars, and there is no generally accepted standard. The result is that consensus cannot be achieved on future

lease output. Such an agreement, however, is necessary for successful unit share negotiations.

These problems are particularly important for highly productive leases that are constrained by prorationing output quotas under state regulation. To estimate the well's future producing capability, it is necessary to have observations of the rate of production decline, which varies substantially across leases. On highly productive leases, producing the maximum regulated allowable, however, such observations are not available. Hence, the data at which the decline will begin and its rate must be based on the subjective opinions of engineers and geologists, which are open to dispute. Below we review cases where such problems impede unit agreements because parties cannot agree on potential future production. These information problems are central to the failure of private contracting.⁴ We now develop a formal theory for analyzing unitization contracting.

⁴ The unitization contracting problem is summarized by Raymond Myers:

The principal obstacle to full, voluntary agreement is the problem of dividing the proceeds of production. If development of the area sought to be unitized is complete, ... some lessors and leases may be inclined to rely on the possibility that... the entire production from their land will be more valuable than an undivided interest in production from a much larger unit. If development of the pool is relatively complete, there is frequent acrimony as to the respective shares of production to be given owners of interest in favorable parts of the structure and owners of interests in less favorable areas... [1967, p. 108]

II. Theory: Contracting for Unification Agreements

This section presents a simple, testable model of a firm's decision to join a unit. The decision is made so as to maximize the expected present value of the firm's lease(s). There are two central features of assessing the relative values of oil leases that lead to contractual failure. One feature is that each firm has access to better information concerning the highly uncertain value of its own leases than do other firms in the field. It is assumed that at least a portion of this private information cannot be successfully communicated.⁵ A second key aspect is that firms differ regarding the transformation of raw data into value estimates, and there is no absolute standard that can resolve differences. Either of these information problems is sufficient to cause the observed contractual breakdown, and both appear to be empirically important.

Let the raw, publicly available information concerning lease i be a vector of random variables x_i and the privately available information be random variables z_i . Firms have the incentives to develop procedures to share information. As discussed above, however, it is unlikely that these mechanisms will be perfect in equilibrium and so we assume that z_i is not empty. Finally, let respective maps to value estimates be the functions g and h :

$$(1) \quad \hat{V}_p^i = g(x_i);$$

$$(2) \quad \hat{V}_j^i = h(x_i, z_i),$$

where \hat{V}_p^i and \hat{V}_j^i are random variables that correspond to the public and private estimates of the value of lease i . The simple

form taken by (1) and (2) belies the potential complexity of the process under consideration. For example, the vector x_i contains objective data on production and information each firm reveals about the characteristics of its leases. Accordingly, misrepresentations concerning lease characteristics are also included in the x_i , though they may be completely discounted and not affect \hat{V}_p^i . Similarly, if firms truthfully reveal a characteristic, but it is not believed because it cannot be verified, that information also will not affect \hat{V}_p^i , but it will affect \hat{V}_j^i . On the other hand, if firms lie regarding lease characteristic j , and the lies are believed, then z_j^i will be the difference between the true value of the characteristic and the value x_j^i believed to be true by other parties. In this case the misrepresentations clearly influence \hat{V}_p^i . A related case is if firms truthfully reveal only favorable information, then z_i consists of the unfavorable information held back; x_i will not include unfavorable data available only from the firm, if the firm cannot be induced to reveal it. There are also other possibilities. Hence, while (1) and (2) take a simple form they admit the full range of value estimation problems due to asymmetric information. It is convenient to assume, for now, that both information sources are unbiased:

$$(3) \quad E(\hat{V}_p^i) = E(\hat{V}_j^i) = V_i,$$

where V_i is true lease value and $E(\)$ is the mathematical expected value. In principal, of course, either or both estimation procedures may be biased as discussed above. The simplifying assumption in (3) is that the estimation rule, (1), can correct for these potential biases. This assumption is made solely to illustrate that contracting conflicts can occur even when actors have rational expectations with respect to lease values. As it turns out, this assumption can be relaxed easily, but this would only complicate the exposition while adding little additional insight. Conflict over estimated lease values and unit shares is the heart of the contracting problem analyzed below, and it is not critical whether the conflict is due to inherent uncertainty about values or because of unrecognized biases in the estimation of lease values.

⁵The exact amount of information that can be communicated is a complex theoretical problem. Since firms have an incentive to selectively reveal only favorable information about the value of their leases, there will be some degree of imperfection in communication. Moreover, as described in the text, lease values estimates are influenced by firm-specific management policies, the details of which are difficult to reliably convey to other firms.

Finally we assume that unit shares will be based upon public estimates of lease values:

$$(4) \quad S_i = \hat{V}_p^i / V^*$$

where $V^* = \sum \hat{V}_p^i$. This assumption is not central to the analysis and is used only to close the model.⁶ Any alternative assumption regarding share assignment will yield the same qualitative results for the analysis so long as public value estimates influence final share assignments.⁷ We will refer to (4) as the allocation rule. Given that the allocation rule will be the one offered the firm in unit negotiation, we can now characterize firms' decisions to join the unit.

The firm's objective in considering whether to join is to maximize the expected present value of its leases with respect to the date it joins the unit, t_u , and it may choose never to join. Formally, we have

$$(5) \quad \text{Max}_{t_u} E_f(PV_i) \\ = E_f \left\{ \int_{t_0}^{t_u} \pi_n(t) s_n^i(t) e^{-rt} dt \right. \\ \left. + \int_{t_u}^T \pi_u(t_u, t) s_u^i(t_u) e^{-rt} dt \right\},$$

where PV_i = the present value of lease i , t_u = the time the lease is put in the unit, π_n = the stream of nonunitized net revenues from the field, s_n^i = lease i 's share of nonunitized net revenues, π_u = the stream of unitized net revenues from the field, s_u^i =

lease i 's share of unitized production, T = field life, r = the common discount rate for all firms, and $E_f(\cdot)$ represents the firm's expectations. Differentiating (5) with respect to t_u , we derive the necessary first-order condition for the firm to join the unit at a particular time:

$$(6) \quad E_f \left\{ \left[\pi_n(t) s_n^i(t) - \pi_u(t) s_u^i(t_u) \right] e^{-rt} \right. \\ \left. + \int_{t_u}^T \left[\frac{\partial \pi(t_u, t)}{\partial t_u} s_u^i(t_u) \right. \right. \\ \left. \left. + \pi_u(t_u, t) \frac{\partial s_u^i}{\partial t_u} \right] e^{-rt} dt \right\} = 0.$$

Rewriting (6) we have

$$(7) \quad E_f(\alpha_i + \eta l_i) = E_f(\beta_i - s_i \lambda_i),$$

where $\alpha_i = \pi_n(t) s_n^i(t) e^{-rt}$,

$$\beta_i = \pi_u(t) s_u^i(t_u) e^{-rt}, \quad l_i = \partial s_u^i / \partial t_u,$$

$$\eta = \int_{t_u}^T \pi_u(t_u, t) e^{-rt} dt, \quad s_i = s_u^i(t_u),$$

$$\lambda_i = \int_{t_u}^T \frac{\partial \pi_u(t_u, t)}{\partial t_u} e^{-rt} dt < 0.$$

The separation of l_i from the integral is appropriate since shares are fixed at the time of unitization. α_i represents the firm's instantaneous nonunitized net revenues, and ηl_i represents the gain in unitized share the firm expects to receive if there is delay in unit formation. β_i represents the firm's instantaneous share of unitized net revenues, and λ_i represents the firm's share of lowered field rents caused by delayed unitization.

Since $\sum_i l_i = 0$ and $\sum \alpha_i \leq \sum \beta_i - \sum l_i$, there are aggregate incentives to unitize, but the division of the increased rents determines whether or not an individual firm will have incentive to join. Before considering reasons why, according to the model, certain firms will delay joining, let us rule out some other reasons for delay that are inconsistent with the model. Suppose the sharing rule is the number of wells, then the firm will not delay

⁶Given (4), the economic content of (3) follows without loss of generality. Since $\sum S_i = 1$ by construction, the average share must be unbiased. Selective revelation or distortion of facts, then, is a zero sum game that can only increase the variance in the assigned shares about the true "fair" shares, i.e., those that would be assigned if V_i rather than \hat{V}_p^i were in the numerator of (4). Hence, if (3) fails, and the estimates are biased, rather than using the terminology "variance" below, "Mean Squared Error" should be substituted and similarly for higher moments, but otherwise the analysis is unchanged.

⁷For example, if unit shares in equilibrium were an increasing but strictly concave function of \hat{V}_p^i , because small firms can force concessions from large firms, the analysis below still applies.

unit formation merely to drill more wells absent disagreement over the number of wells it *can* drill. If all parties agree on the number of wells that can be drilled on a lease and if there is no desire to change the way in which wells enter the allocation rule, then the potential number of wells will enter \hat{V}_f^i and \hat{V}_p^i in precisely the same way, and there will be no need to delay unitization until the wells are actually drilled. Similar reasoning applies to any other strategic advantage of one party; so long as other parties recognize the valuation consequences of the advantage, it becomes immediately incorporated into the allocation rule, and delay is unnecessary.

There are other reasons, however, why the left-hand side of (7) may be greater than the right, in which case the model predicts that the firm will prefer to delay unit formation. A firm may wish to delay unit formation if its private value estimates exceed public value estimates, $\hat{V}_f^i > \hat{V}_p^i$, and if the firm expects the public estimate to be revised upward as more information on lease value becomes available. Differences between public and private information can occur for two reasons: (i) the functions g and h differ so that the mappings from raw data to value estimates are not the same; and (ii) there is private information, z_i , that causes the firm to believe public estimates are inaccurate. If the firm believes that the function g , used to map known data to value estimates, seriously underestimates its leases' future productive potential, then the firm will have incentive to delay unit formation by withholding its leases in the expectation that subsequent production data will cause an upward revision in assigned shares. Further, the firm's engineers and geologists have access to company records, the accuracy of which cannot be verified by outsiders. If these records cause them to believe that future lease output (value) has been underestimated ($\partial h / \partial z > 0$), then there will also be incentive to delay unit formation to await future production information that will be expected to increase \hat{V}_p^i .

These information problems aside, the firm may also decide to delay joining, if holding out will alter the allocation rule, (4), through concessions from the other parties since de-

lay causes aggregate losses. Theoretically, then, firms may hold out in an attempt to delay unit formation either due to differences in value estimates, where $\hat{V}_f^i > \hat{V}_p^i$, or because they want to alter the allocation rule. If the firm expects the incremental gains in assigned share from new information and strategic bargaining to offset the firm's share of losses in field value due to delay, the firm will not join. Formally, the firm will not join if

$$(8) \quad E_f(l_i) > (\beta_i - \alpha_i - s_i \lambda_i) / \eta,$$

where $E_f(l_i)$ is the firm's expectation of the change in its unit share due to delay.

The special case where instantaneous profits are the same under open and unitized production, $\beta_i = \alpha_i$, yields intuitive insight into the problem. In this case, (8) implies

$$(9) \quad \frac{E_f(l_i)}{s_i} \equiv \frac{\partial s_u^i}{\partial t_u} / s_i > \frac{-\lambda_i}{\eta} \\ = - \int_{t_u}^T \frac{\partial \pi_u(t_u, t)}{\partial t_u} e^{-rt} dt \\ \left/ \int_{t_u}^T \pi_u(t_u, t) e^{-rt} dt. \right.$$

In words, if the firm's expected percentage gain in share exceeds the percentage loss due to delayed unitization, the firm will not join.⁸ There exists an expected share revision, l_i^* , which just creates an equality in (9) and is the dividing line between firms that want to join and those that want to delay. Because the right-hand side of (9) is strictly positive, the threshold value l_i^* must also be strictly positive. The probability that the firm will wish to delay, then, is the probability that $E_f(l_i) > l_i^*$. Because both estimates of value are unbiased, $E_f(l_i)$ will have zero mean, and the probability that it exceeds l_i^* will

⁸Strategic bargaining aside, a necessary condition for (9) to hold is that the firm's private information leads to higher expected lease value than that based on public information.

depend critically upon the uncertainty of the public value estimates. As more lease information becomes known, \hat{V}_p^i collapses around V_i , and the returns to waiting for more favorable information vanish. Hence, the probability that $E_f(l_i) > l_i^*$ decreases monotonically with the reliability of public estimates of lease value.

Assume that $E_f(l_i)$ is normally distributed with zero mean and variance σ , and define $p(J)$ as the probability that lease i will join at time t ; then

$$(10) \quad p(J) = p\{E_f(l_i) \geq (\beta_i - \alpha_i - s_i \lambda_i) / \eta\} \\ = \Phi(\psi / \sigma),$$

where Φ is the normal distribution function and $\Psi \equiv (\beta_i - \alpha_i - s_i \lambda_i) / \eta$. As the variance σ declines, the probability of joinder increases.

Figure 1 illustrates the impact of more precise public value estimates on the probability that a lease will join. The figure shows the density function for the firm's expectation of the change in share, $E_f(l_i)$, and the mean is equal to zero since both estimates of value are unbiased. As the variance of public estimates of lease value declines, the probability to the right of the threshold change in share, l_i^* , declines and the probability of joinder rises.^{9,10}

This leads to an important implication that leases with more uncertainty regarding their value will be less likely to join units early in negotiations. We show below that these leases tend to be those with the longest productive lives and the greatest estimated values. Over time, greater information on lease values becomes available, uncertainty

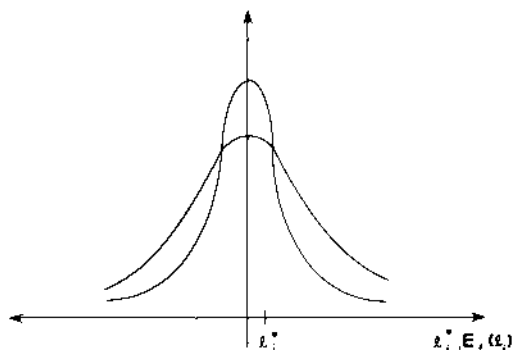


FIGURE 1

declines, and public and private estimates of lease values collapse around the true value. Accordingly, the model implies that unitization contracts are more likely to be completed late in the primary productive life of the reservoir.

Another factor affecting the probability of delaying unit information is the location of the threshold l_i^* itself. A major influence on this threshold l_i^* is the size of the firm's holdings on the field (see (9)). As size increases, the firm will bear a larger share of the cost of delayed unitization. Hence, for a large firm to postpone joining, the expected share increase from delay must be larger, moving l_i^* to the right. This implies that very large firms on a field are more likely to join early.

Finally, a firm may delay joining for strategic bargaining reasons as we have noted above. In such cases the firm attempts to extract share concessions as a means of gaining ratification of unitization. In such circumstances the firm expects a positive $E_f(l_i)$, *ceteris paribus*.

There are other potentially important contracting problems. First, there will be some opportunity for the unit operator to take advantage of his position due to imperfect monitoring by other firms. Opportunism provides additional incentive for the operator to put his leases in the unit, but is a source of concern to other firms. A second problem we have referenced above is the case where a firm not only delays, but decides not to join the unit when it is finally formed. The firm's

⁹This generalizes beyond the normal density to any mean-preserving spread for any density so long as probability weight is being taken from $[0, l_i^*]$ and placed to the right of l_i^* .

¹⁰Other factors affecting $E_f(l_i)$ are the rate of change of the public information stock and strategic bargaining. The arguments in the text apply, *ceteris paribus*, for a given rate of change of these variables. To ease exposition the example chosen is where there is zero expected share change due to strategic bargaining.

decision rule under these circumstances is

$$(11) \quad \int_{t_u}^T \pi_n^i(t) e^{-rt} dt \\ > \int_{t_u}^T \pi_u(t) s_u^i(t_u) e^{-rt} dt.$$

In this case an all-or-nothing offer is being made by the unit to the firm to, effectively, play a positive sum game. The offer made must reflect what the firm can achieve independently or it will not play. Further, if the offer exceeds by any amount what the firm can achieve independently then, in general, it will accept.¹¹ We show below that certain firms systematically refuse these offers. Empirically, they are not offered greater shares to join after the unit is formed. In this case there must be disagreement regarding what the firm can independently achieve. Central to the firm's viability outside the unit is whether or not it has a large enough segment of the field to operate effectively as a separate entity. This is particularly important for secondary oil recovery. With secondary recovery, injection of natural gas or water increases pressure and would drive oil to adjacent areas unless the firm drilled injection wells along the perimeter of its leases. Hence there are substantial effective economies of scale for these secondary recovery projects. For small acreage, the added costs of injection wells would likely swamp any gains from separate secondary recovery. Therefore, a firm with large contiguous acreage will be better situated to remain independent of the unit if his private information suggests that his leases have higher values than public information suggests.

One task of the empirical analysis in Section III is to separate, where possible, the contracting problems due to information issues from those arising from a simple hold-

out strategy. The empirical observation that some firms choose to remain permanently out of a unit allows us to comment on hold-out strategies. Hold-out behavior is unlikely to be a major factor in the firm's decision not to join when a unit is formed, since firms who refuse to join are not later offered more favorable shares. Hence, holding out to increase one's share is not the motivation. Further, holding out to free ride on secondary recovery projects is also not empirically important. Firms that hold out often form their own subunits with neighboring firms, and cooperatively drill water injection wells along boundaries common with the unit to prevent oil migration between secondary recovery projects. This suggests that a firm's decision not to join is more complex than strategic bargaining to raise rental shares.

The theoretical discussion leads to a number of hypotheses to be tested in the empirical analysis in Section III:

1: As fields age, public and private information sources converge, making agreement on an allocation rule more likely.

2: Firms with large, scattered holdings on a field will be more willing to join and will also be more flexible in voting on allocation rules.

3: Similarly, firms with large blocks of contiguous acreage are more likely to withdraw and form separate units.

4: Leases where there is greater uncertainty of public estimates of lease value will be less likely to join a unit. It will be shown that high-output leases fit into this category.

5: Negotiation of allocation rules for assigning unitized rental shares will be constrained by disputes over estimates of structural characteristics.

6: Allocation rules must assign once-and-for-all shares, with no contingent updates.

7: Finally, the unit operator will be more likely to place a given lease in the unit, *ceteris paribus*.

The empirical analysis addresses the evidence concerning each of the (alternative) hypotheses. The discussion will generally be organized by hypothesis number.

¹¹ This decision is made recognizing that the firm will not be later offered a more favorable share. Such an offer would require a general renegotiation of shares, which is not possible. In this case, an all-or-nothing offer is made by the unit to the firm.

III. Contracting on Seven Fields

The empirical bases for the study are unitization negotiations on seven Texas and New Mexico oil fields. Descriptive statistics for these fields and their unit negotiations are provided in Appendix A. Our examination of unitization contracting begins with a quantitative analysis of firms' decisions to place particular leases in the unit on the three oil fields for which we have sufficient data. The fields are North Cowden, Goldsmith/Landreth, and Prentice Northeast.¹² The theory presented above establishes the following partial derivatives for the probability that a given lease will be placed in a unit.¹³

$$(12) \quad J_{i,k} = f(A_i, C_{i,k}, Q_{i,k}, w_i, \varepsilon_{i,k})$$

$$f_1 > 0, f_2 < 0, f_3 < 0, f_4 > 0,$$

¹²The North Cowden field was discovered in 1930 and negotiations for the unit began in 1958 as the field neared depletion of primary reserves. An Engineering Committee was formed to collect parameter data from operators for assigning shares and to estimate gains from secondary recovery. In 1960 the committee estimated that recovery would increase by 100 million barrels, a gain of \$285 million in 1960 prices (Minutes, July 28, 1960, North Cowden Unit File, Company Records). Nevertheless, 19 of the 31 operators eventually withdrew part or all of their leased acreage, and a smaller unit was not formed until 1966, eight years after negotiations began. Contracting for the Goldsmith/Landreth unit began in 1961, but conflict over unit boundaries delayed work by the Engineering Committee until 1963. Four of the 10 operators bargaining for the unit withdrew leases in disagreement over allocation rules. Additionally, after a formula was finally agreed upon one firm withdrew eight more leases due to a dispute over secondary recovery plans. The final unit was not formed until October 1965. The Prentice field was discovered in 1951, and unit negotiations began in early 1954. Despite predictions that early unitization would substantially increase recovery, negotiations faltered, and were abandoned between 1956 and 1959. At that time the largest operator in the field attempted to reopen negotiations. By 1963 it was clear that field-wide unitization was not possible, and in late 1963 three units were formed, nearly ten years after negotiations were opened; the Northeast and Southwest units were operated by one firm and the central unit was operated by another.

¹³Strictly speaking, the hypothesis that $f_3 < 0$ requires evidence (to be presented below) that increases in

where $J_{i,k} = 1$ if lease k of firm i is placed in the unit, zero otherwise; A_i is firm i 's total acreage in the field; $C_{i,k}$ is firm i 's acreage contiguous to lease k ; $Q_{i,k}$ is the current output per acre on lease k ; $w_i = 1$ if firm i is the unit operator, zero otherwise; $\varepsilon_{i,k}$ is the error term; and where $f_1 = \partial f / \partial A_i$, and similarly for f_2, f_3 , and f_4 . This equation can be used to test hypotheses 2, 3, 4, and 7. The assumption above that $E_f(I_i)$ is normally distributed, and the binomial nature of the dependent variable requires a Probit estimation procedure for the joinder equation. Empirical results are presented in Table 2, part A. All coefficients are of the right sign and most are significant. Thus, the results generally provide strong support for the four hypotheses.

We have argued that firms with very productive leases will not place those leases into the unit. There is generally greater uncertainty about their value and disagreement over their share in the unit. The regression coefficients in Table 2, part A, are consistent with this notion. All of the output per acre coefficients are significant at the 10 percent level, and two are significant at the 1 percent level. Moreover, in Appendix B we show that there is greater uncertainty regarding predicted output levels for high output leases. We do this by regressing current output on all known structural characteristics and then examining the residuals. Those leases where uncertainty is highest will have the largest residual variance after adjusting for all factors known to affect output. We show that those leases with the highest output have larger unexplained (residual) variance. According to the theory, this should increase the probability that such leases will be withheld from the unit. The results of the estimations in Table 2 strongly support this hypothesis.

Qualitative evidence also indicates that the pattern of withholding very productive leases is consistent on all seven fields, despite ag-

lease output lead to greater uncertainty in value estimates.

TABLE 2^a

	Intercept	Unit Operator	Lease Output per Acre	Firm Acres Contiguous to Lease	Total Firm Acres
A. Probit Estimations of Joinder Decisions ^b					
North Cowden	-.51 (.34)	11.7 (34.2)	-.0051 (.0032)	-.00096 (.00025)	.00050 (.00024)
$\chi^2 = 54.57$					
Goldsmith/Landreth	2.70 (1.01)	13.6 (13.5)	-.0118 (.0040)	-.0061 (.0014)	.00061 (.00063)
$\chi^2 = 39.49$					
Prentice Northeast	.736 (.569)	4.94 (74.6)	-.0062 (.0028)	-.0130 (.0044)	.0120 (.0042)
$\chi^2 = 33.18$					
B. Voting Patterns on Empire Abo Unit ^c					
	9.67 (2.74)				.0066 (.0025)
$F(1,11) = 7.16$					

^aStandard errors are shown in parentheses.

^bDependent variable = 1 if lease is placed in unit; 0 otherwise.

^cDependent variable: the number of yes votes by firm in unit balloting (58 ballots).

gregate gains from a field-wide unit. On the Prentice field, a group of the most productive leases were located in the center of the field. After nine years of negotiations, efforts to form a single unit were abandoned because "a common formula could not be negotiated" (Minutes, Operators' Meeting, February, 1963, Prentice N.E. Unit File, Company Records). As a result three units were formed with separate secondary recovery projects. On the North Cowden field, firms with very productive leases voiced opposition to the proposed unit, with one firm asserting "none of the proposed parameters give justice to those leases because of their abnormal producing capabilities" (Letters, January 20, 1959; March 30, 1961, North Cowden Unit File, Company Records). Eight of the firms withdrawing acreage had ten of the most productive leases on the field. Output on those leases for the first six months of 1960 averaged 133 barrels per acre, while the average for all other leases was 79 barrels per acre (Engineering Report, December 1, 1960, North Cowden Unit File, Company Records). One unit proponent reported: "It is extremely difficult to arrive at a single factor which can be said to represent an equitable minimum, since the field is currently under active development and current production

relationships are changing with each month's data" (Letter, February 5, 1960, North Cowden Unit File, Company Records). Similarly, on Goldsmith/Landreth, three firms with unusually productive leases requested that acreage be deleted from the allocation rule. The three leases involved had average output per acre of 233 barrels for the period June 1962 to June 1963; only one other lease on the field had production of 200 barrels per acre, and average output for all other leases was 80 barrels, about one-third that of the withdrawn leases (1963 Engineers' Report, Table 4, Goldsmith/Landreth Unit File, Company Records). On the seven fields, owners of very productive acreage typically stressed that none of the formulas under consideration adequately protected their equity. Despite long negotiations (see Appendix A) and repeated formula adjustments (58 different votes on Empire Abo alone), consensus could not be reached on lease values and unit shares to attract the most productive leases into the unit. Thus, highly productive leases were systematically segregated from less productive leases and, where possible, separate subunits were formed.

When separate subunits were formed, independent secondary recovery projects were undertaken that were typically less effective

than field-wide projects. This indicates that firms could not agree on relative shares, since they were willing to bear higher costs. Moreover, there was no prospect of later renegotiation, and neither party was able to free ride on the other's secondary recovery efforts. Hence, parties disagreed about the relative values of leases, leading to a breakdown in negotiations. These observations suggest bargaining problems that are more complex than a simple hold-out problem.

Hypothesis 1 states that as field-wide primary depletion nears, consensus on unitization is more likely. The qualitative evidence from all seven fields supports this notion. Negotiations on North Cowden took eight years, in part, because some of the field was newly developed, while other parts were sharply declining. Much of the conflict centered on differences between new and older sections of the field. In withdrawing its lease from the unit, one firm notified the unit organizers that "the various parts of the field were simply so diverse that not one formula could satisfy everyone. We wish you every success in forming a unit in the center of the field where everything is more uniform" (Letter, September 4, 1963, North Cowden Unit File, Company Records). Similarly, agreement could not be achieved early in 1967 on Empire Abo when most leases could produce at regulated maximum production. Agreement could not be reached until 1971 as primary production declined.

The regression results in Table 2, part A, also support the notion that firms with large holdings on a given field will support unitization (hypothesis 2). This effect is measured by the total acreage variable, and the coefficients indicate that such firms were more willing to place their leases into the unit. These results are also backed by qualitative evidence. Firms with large holdings frequently made concessions to complete unit agreements. For example, on North Cowden, the largest firm estimated its 1959 output share at 37.5 percent of field production, but was willing to accept a lower minimum unit share of 36 percent (Letter, January 1, 1960, North Cowden Unit File, Company Records). On Goldsmith/Landreth, the concern of the largest firm regarding an increase in

unit costs due to the withdrawal of some leases is reflected as follows: "Although our reserves in the area from which all eleven tracks are eliminated are indicated to be greater... , our costs will undoubtedly be greater due to the requirement of additional injection wells..." (Letter, October 12, 1964, Goldsmith/Landreth Unit File, Company Records).

It was also predicted that firms with large acreage will support more allocation rules than will firms with small holdings. Data for 58 recorded ballots for 13 firms in Empire Abo negotiations allow for quantitative tests. In Table 2, part B, *OLS* regression results are reported for voting on Empire Abo:

$$(13) \quad Y_i = f(A_i; \eta_i); \quad f_1 > 0,$$

where Y_i = the number of yes votes by firm i in the balloting; A_i is firm i 's total acreage on the Empire Abo field; and η_i is the error term with zero mean, and it is assumed that A_i and η_i are independent. The test, then, examines the link between the total number of yes votes in repeated balloting and acreage. The coefficient for acreage is positive and highly significant, and these results are repeated elsewhere. On the Goldsmith San Andres field, the larger operators offered to give more than proportionately in share negotiations to speed the unit. In internal negotiating documents the firms recognized that they had 72.23 percent of current output, but they agreed to an aggregate share of 71.09 percent of remaining primary production under the unit and 67.80 percent of secondary recovery (Letter, October 27, 1961, Goldsmith San Andres Unit File, Company Records).

Firms with limited holdings, on the other hand, were more selective, supporting only specific allocation formulas that emphasized characteristics favoring their leases. For example, on the Slaughter Estate unit, one firm with 4 percent of acreage withdrew because the current output parameter used in the allocation formula supposedly undervalued its two leases. The firm had 2.81 percent of current production, but asserted that it had 3.53 percent of remaining oil reserves based on Engineering Committee estimates.

Two other firms with 4 and 2 percent of acreage, respectively, also threatened to withdraw for similar reasons (Letters, December 26, 1962, June 6, 1963, Slaughter Estate Unit File, Company Records). On Goldsmith San Andres none of the firms consistently voting no on allocation formulas had over 9 percent of field productive acreage. One small firm with only .3 percent of acreage voted no on all formulas offered. These small firms repeatedly called for adjustments in the weights placed on specific parameters to reflect their individual advantages: one firm with 5 percent of acreage and 1 percent of cumulative output called for less weight on the latter; another, with 4 percent of acreage and 2.8 percent of current output wanted current production removed or discounted. On the other hand, the three largest firms with 24, 16, and 15 percent of acreage, respectively, voted yes on all of the allocation rules submitted for consideration (Minutes, January 10, 12, 1962; February 7, 1962, Goldsmith San Andres Unit File, Company Records). In general, in contrast to the case where firms refused the final offer to join, evidence on voting behavior can reflect both information issues and hold-out strategies to increase rental shares.

The regression results in Table 2, part A, also support the notion that firms with large blocks of *contiguous* acreage will permanently withdraw and form their own units (see hypothesis 3, above). The coefficient for contiguous acreage is negative in all three fields and significant in two. On North Cowden, firms with large tracts of contiguous leases withdrew to form separate units. They included the second, fourth, and sixth largest firms by acreage on the field, and the withdrawn leases represented 97, 93, and 71 percent of the total acreage of these firms (Table 2, Engineers' Report, December 1, 1960, North Cowden Unit File, Company Records). On Western RKM, the second largest firm with 26 percent of acreage, all concentrated in the eastern part of the field, withdrew and formed its own secondary recovery unit.¹⁴ The firm argued that the

parameters considered for share assignment "considerably underestimated" its lease values. The firm, along with other adjacent leases, formed its own secondary recovery unit (Letter, May 20, 1964, Western RKM Unit File, Company Records). On Prentice, the primary advocate of separate units had acreage of sufficient size concentrated in the center of the field for secondary recovery to be possible. In contrast, the unusually productive leases that were isolated in the northeast portion of the field finally joined the northeast unit; in part, because they were not large enough to be independently viable. As noted above, these decisions to remain outside a unit must be largely due to information issues and not a bargaining strategy.

The final coefficients in Table 2, part A, to be discussed are those for the unit operator variable. Hypothesis 7 is that the firm chosen to be unit operator would be more likely to place its leases into the unit. The regression results do not support this view; holding lease productivity, firm size, and contiguous acreage constant, the unit operator is not significantly more likely to place a given lease in the unit on all three fields.

There are two hypotheses not directly addressed by the regression estimates in Table 2. Hypothesis 5 is that the share parameters are limited because they must be based upon public information, and hypothesis 6 states that allocation rules must assign shares for all future periods. Qualitative evidence allows us to examine these hypotheses. The selection and interpretation of formula parameters were the central source of dispute on all seven fields. In general, agreement can only be reached for formulas using parameters that could be measured and interpreted without controversy. This sharply limits contractual flexibility because of the small number of objectively measurable variables and the highly tenuous nature of even modest extrapolations as discussed in Section I. Even simple static structural char-

¹⁴In March 1962, a 26,400 acre RKM unit was planned on the Slaughter field, but was soon dropped in

favor of a smaller 9,911 acre unit. Negotiations continued through 1966. By that time 50 percent of the leases, covering 4,993 acres, had been withdrawn. Most were on the eastern side of the proposed unit, leaving only 4,918 acres in the final agreement.

acteristics, such as the thickness of the reservoir rock and pore space available for holding hydrocarbons, were sources of significant dispute. For example, early in unit negotiations the Engineering Committee on North Cowden reported that data were too sketchy to calculate "a fair and equitable" gross or net pay under each lease (the gross thickness of the reservoir or the thickness net of any nonproductive zones). The Committee only had well cores for 28 of the 733 wells on the field, and it stressed the "meager data and poor quality of available records" (Memo, April 7, 1959, North Cowden Unit File, Company Records). As a result, during the eight years of negotiations for the North Cowden unit, nearly all of the numerous parameter formulas considered were simple convex combinations of current and cumulative output, which were available and reliable for all leases. Attempts to incorporate more sophisticated parameters met with objection due to their subjective nature given the lack of available data: "a disadvantage [of gross pay] is that we are basing a parameter of unitization on the skill or lack of skill in the persons observing the samples. Therefore, there is considerable question as to the consistency of the picks [estimates] between wells, and it would likely be difficult to reach agreement between operators on such data..." (Letter, June 16, 1959, North Cowden Unit File, Company Records). Moreover, remaining reserves could not be estimated in ways acceptable to all operators. The unit operator had access to reservoir data and could have estimated the parameter, but its estimates would have been controversial. Instead, it chose to release the data to the Engineering Committee for parameter calculation. Even so, one small firm hired an outside consultant to calculate its net reserves, and got values double those calculated by the Engineering Committee (Letters, January 9, 1962; March 8, 1963, North Cowden Unit File, Company Records).

Disputes over the measurement of static reservoir characteristics occurred as well on other fields. On Prentice Northeast, the owner of the most productive acreage believed that its reservoir pore space had been badly underestimated. Reconciliation took several

months and finally resulted in an *ad hoc* upward adjustment of 70 percent, and led to a large increase in the firm's unit share. A major information problem was that observations were limited to wells, and the extrapolation method used between wells dramatically altered parameter calculations. For example, a linear versus a log-linear extrapolation of reservoir depth between wells created significant differences in estimated reservoir volume under particular leases. When the reservoir was highly variable or when observations for a large percentage of wells were unavailable, as on Cowden, the issues were extremely difficult to resolve. On Prentice Northeast, the final formula accepted included one observable and measurable variable, current production. Estimates of primary recovery for the leases were made using a variety of techniques, but "Relatively poor agreement between various methods were obtained in many instances. Primary reason for inconsistencies [was] due to a severe lack of control in much of basic data together with inherent uncertainties involved in these type calculations." Core analyses done by differing consulting firms gave dramatically different results (Engineering Committee Minutes; Letter, June 29, 1963, Prentice N.E. Unit File, Company Records). These data problems persisted in 1963, even though Prentice Northeast was fully developed and two-thirds depleted. The inability to precisely estimate reserves at the field level is not a serious obstacle to contracting. Disputes about reserves and future productivity, however, are repeated at the lease level, where they break down share negotiations.

Finally, as predicted in hypothesis 6, the accepted formulas for each unit assigned *permanent* shares. Contingent updates are not feasible because unitization fundamentally changes the pattern of reservoir production. Some wells are plugged, others are converted to injection, and new wells are drilled, completely altering the pattern of migration. Hence, after unitization it is impossible to infer the oil in place or the oil that could have been produced from a given lease. In no case have we encountered a unit where contingent updates were allowed. Evidence of the once-and-for-all nature of the con-

tracts is that the allocation formulas adopted were often multiphase, but established a set pattern of share adjustment, based on data known at the time of agreement. Because unit shares were fixed, those firms most concerned about biases in their fair share calculation due to incomplete information would be reluctant to join, based on existing evidence. We have identified those firms as owners of very productive leases, and their tendency to withdraw from unit contracting has been documented above. If contingent updates were possible, negotiations could allow for temporary shares to entice early agreement with corresponding aggregate gains, and share adjustments could be negotiated as more information became available.

Before turning to the conclusions, it is worth briefly reviewing the hold-out issue. Previous studies of unitization (see, for example, Stephen McDonald) have casually concluded that the primary obstacle to unitization is simple strategic bargaining to increase unit shares, rather than real differences in opinion regarding relative lease values. Clearly an element of both may be present in a given situation, and in many contexts it is difficult to distinguish between "honest" differences and pretended differences to gain an advantage. In the present context, however, there is evidence presented above that shows information problems play a critical role in contractual failure for unitization. The first of these is that the firms' joinder decisions involved a decision to permanently withdraw from the unit. The purpose of a strategic hold out is to gain a more favorable offer later; yet, for all of the decisions represented by the regressions in Table 2, part A, the decisions were once and for all. For these cases, then, strategic bargaining by either party was not the point. Second, a pure strategic hold-out hypothesis also would predict that high- and low-output leases are equally likely to delay the unit or refuse to join. The systematic differences in behavior evident between these groups is inconsistent with a simple hold-out hypothesis, and yet follows naturally from the imperfect information argument. Furthermore, breakdown in unit negotiations often led to the formation of multiple subunits on fields such

as Prentice. Here, the problems of reconciling differences in the value of highly heterogeneous leases were repeatedly cited. The operators, in explaining why they would not (and later *did not*) join a unit, claimed that the heterogeneities could not be reconciled. These same operators, then, contemporaneously formed partial units with other operators having similar, neighboring leases. A hold-out strategy does not explain why these operators would withdraw from one unit and form another.

Third, we have a very interesting set of observations from unitization on federal lands in Wyoming. The federal government actively encourages unitization through policies that facilitate agreement (see our earlier paper).¹⁵ On federal lands, agreements can be reached prior to the drilling of any wells—a period when *private* information about lease characteristics such as well performance will be limited and known lease heterogeneities are minimal. Units formed at this time take less than six months to negotiate, and the percentage of production that is unitized is very high. Further, there is little dispute chronicled in the negotiation records. If, however, the unit is formed later after production has begun, and lease heterogeneities and asymmetric information have emerged, then negotiations take an average of seven years and are frequently acrimonious. Hence, the federal policies work well before asymmetric information and heterogeneities have emerged, but have little impact if agreement is not reached during that period. A simple hold-out strategy cannot easily explain why the commencement of production fundamentally changes the character, speed, and success of unit contracting.

None of this is to suggest that hold outs are an unimportant problem in unitization. Instead, the analysis of this paper shows that information problems play a critical role,

¹⁵ General policy responses to the unitization problem are beyond the scope of this paper. Our forthcoming paper presents analyses of the impact of different unitization policies in Oklahoma, Texas, and federal lands on the speed and extent of unitization. We also offer reasons for sharp policy differences across these political jurisdictions.

and explain much observed behavior that is otherwise difficult to unravel.

IV. Concluding Remarks

Private contracting is a common solution to many problems in production and exchange. When there exists a core of exchange, contracts permit parties to move into the core, and general welfare is improved. Recent analyses of contracting by Goldberg, Williamson, and others, however, have introduced a point of caution—information asymmetries, opportunism, and small numbers bargaining problems can break down the contracting process in cases where there is a need to sequentially update contract terms to reflect changes in the economic environment. These findings limit the range of problems where contracting can be an effective solution in resource allocation.

Our results have more serious ramifications for the general applicability of contracts. The study has analyzed an important empirical setting where private contracting has not been successful. Despite large net gains from unitization, *ex ante* imperfect information and information asymmetries among the negotiating parties regarding lease values prevents consensus on unit shares. These problems exacerbate any hold-out strategies that would otherwise impede agreement. As a result, contracts are often either not completed or are very incomplete with only fragmented units. Even simple once-and-for-all contracts that need little subsequent adjustment systematically break down. While one can think of a variety of hypothetical mechanisms for eliciting the information needed for agreement in an incentive compatible form, they are not observed.

We believe that the informational imperfections and asymmetries that lead to contractual failure in unitization are repeated in many contexts. Examples include labor markets and the problems of evaluating heterogeneous workers and contracting for pollution control. Our analysis suggests that an assumption that private contracting will solve inefficiencies in these areas is unwarranted. Accordingly, close attention by economists

to contracting details in a variety of settings is required for a better understanding of economic processes and events.

APPENDIX

A. Contracting Summary

Table A1 outlines the general contracting conditions for the seven fields examined in the paper. The table reveals the long bargaining time before agreements were reached. Moreover, the table shows that in every case but Empire Abo a subunit was formed, rather than a complete field-wide unit. Empire Abo is on federal land in New Mexico where compulsory unitization rules apply to force nonjoiners into the unit.¹⁶

B. Lease Output and Uncertainty of Lease Value

Here we demonstrate that highly productive leases have more uncertainty regarding their value than do less productive leases. Uncertainty is measured with respect to the publicly available data regarding lease characteristics. Greater uncertainty in public estimates of lease value implies, *ceteris paribus*, a greater probability of relatively large changes in expected share ($E_j(l_i)$). In other words, the probability to the right of l_i^* in Figure 1 is larger. This makes it less likely that the lease will be placed in the unit. We test this proposition regarding high output leases in Section III.

In order to establish greater uncertainty in public estimates of lease value, we examine data concerning current output and all known basic reservoir characteristics. The argument is that inability to accurately predict current output using all known lease characteristics is equivalent to being unable to predict future output and, hence, current value. What we wish to show is that there is greater residual uncertainty regarding current output for highly productive leases than for less productive leases.

¹⁶ Compulsory unitization rules do not exist in Texas; see our forthcoming paper.

TABLE A1

Field	Discovery Date	Date Unit Negotiations Began	Time until Unit Formed	Acreage Under Negotiation	Acreage in Final Unit	Number of Operators
North Cowden	1930	1958	8	30,870	17,503	31
Goldsmith/ Landreth	-	1961	4	10,760	8,985 ^a 7,815	10
Prentice						
Northeast	1951	1954	9	8,500	6,828	-
Western RKM	-	1962	4	16,400	4,918	16
Slaughter Estate	-	1958	5	5,528	5,280	4
Empire Abo	1957	1965	6	11,323	11,323	15
Goldsmith San Andres	-	1959	4	7,199	6,103	27

Sources: Compiled from Unit Files, Company Records.

^a Two reservoirs.

TABLE A2—HETEROSCEDASTICITY REGRESSION

	C	Independent Variables ^a				
		Pore Feet per Acre	Total Feet per Acre	Oil Originally in Place	Wells per Acre	Cumulative Output per Acre
Prentice						
(A)	-1.16 (-.16)	27.74 (.99)	-4.78 (-2.99)	4.43 (.91)	2445 (2.99)	.037 (4.65)
(B)	98.1 (.19)	2114.88 (1.48)	-144.1 (-1.76)	-293.4 (-1.18)	143700 (3.42)	.177 (.42)
Cowden						
(A)	46.1 (1.28)		-1.30 (-1.82)		.009 (6.19)	662 (.45)
(B)	-140 (-.09)		-2.06 (-1.36)		79625 (1.28)	(0.008) (0.138)
Goldsmith						
(A)	28.3 (2.89)				33.7 (.17)	.036 (5.75)
(B)	367.1 (.40)				824 (.04)	1.55 (2.63)

Note: Equation (A): Dependent variable = Output per acre; Equation (B): Dependent variable = Squared residual from Equation (A).

^a *t*-values are shown in parentheses. Independent variables are different across fields solely because of differing data limitations in unit negotiation records. In all cases, the available independent variables used were those not calculated exclusively from current output.

To show this we perform a simple heteroscedasticity test. We first regress current output on *all* known lease characteristics, such as past output, number of wells, and reservoir thickness. We then examine the residuals of this regression. The null hypothesis is that the residuals are homoscedastic, while the alternative is that leases with higher output will have larger residuals than those with lower output. To test for this we estimate a second regression with the squared residuals

from the first regression on the left-hand side and the same set of variables on the right. The null hypothesis is rejected if all variables that are statistically significantly different from zero in both regressions also have the same sign in both regressions.

The regression results are reported in Table A2. For each field the null hypothesis of homoscedastic residuals is rejected at the 10 percent confidence level and for two of the three fields the null hypothesis is rejected at

the 5 percent confidence level.¹⁷ Hence, there is greater residual uncertainty regarding prediction of current output from known lease characteristics for high-output leases than for low-output leases. Thus there are wider confidence bands on public estimates of output for these very productive leases. This increases the probability, *ceteris paribus*, that firms will have private information that causes them to believe that a substantial revision in share will be forthcoming, if the unit is delayed. In a Bayesian sense the strength of the prior, based upon public information, is less. Similarly, it increases the probability that they will not join a given unit because they believe their property is sufficiently undervalued that they can do better on their own. This proposition is tested in Section III.

¹⁷Under the null hypothesis, these tests are unbiased.

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