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# THE WIDESPREAD FAILURE OF PRODUCTION UNITIZATION IN US OIL FIELDS: A STRATEGIC EXPLANATION

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## ABSTRACT

This paper examines unitization of oil production in common pool oil fields. We argue that strategic consideration rather than asymmetric information may be the primary reason for the persistent and widespread failure of unitization in U. S. onshore oil fields. It is shown that, despite large gains in field wide rent, unitization may cause losses to the participating leases unless the scale of unitization is sufficiently large. Further, given other firms' decisions on whether to unitize or not, a firm is always better off by staying out. The inability of the unitized unit to capture the gain that it generates, together with the rewarding nature of staying out, may be the primary reason for the continuing and widespread failure of unitization.


## INTRODUCTION

Ever since petroleum was first found in the U. S. in the middle of 19th century, serious common pool wastes have plagued oil production. Under the common law rule of capture, the property rights to oil are only assigned upon extraction. When multiple firms compete for migratory oil in a common pool reservoir, each has an incentive to drill competitively and drain oil from its neighbors. Competitive production leads to excessive drilling, unnecessary surface storage, overextraction and reduced ultimate oil recovery. For example, in 1914, the U.S. Bureau of Mines estimated annual losses from competitive extraction at $50 million, approximately one-quarter of the total value of the U. S. production; the Federal Oil

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Conservation Board (1926, p.30; 1929, p.10} estimated recovery rates of only 20-25 percent with competitive extraction, while 85-90 percent was possible with controlled withdrawal.

The general solution to the common pool problem, unitization of production, has long been recognized in the industry: as early as 1916, the U. S. Bureau of Mines called for uni- tization of oil fields; in 1924, the Federal Oil Conservation Board also specifically endorsed unitization. Under unitization, a single firm, the unit operator, is selected to produce in a part of or in the entire reservoir with the net rent shared by all leases participating in the unitization. When an entire oil field is unitized, the unit operator becomes the sole residue profit claimant who maximizes the fieldwide rent. The common pool losses can then be completely eliminated. Even if the production is partially unitized in an oil field, the number of independent operating firms is reduced and the production concentration is increased, and thus the common pool losses can be alleviated. Despite the consensus on the large gains of unitization, private crude oil producing firms have generally failed to unitize U.S. oil fields. For instance, Bain (1947} reports only 12 fully and 138 partially unitized fields out of some 3,000 U.S. fields sampled. Libecap and Wiggins (1985a} find that as late as 1975 neither Oklahoma nor Texas, two leading oil producing states, had as much as 40 percent of production unitized. The question, then, is why is there the persistent and widespread failure of unitization? This paper provides an answer.

We argue that private firms' strategic consideration is responsible for the widespread failure of production unitization. Unitization changes the competition structure in extraction and internalizes the externality of oil extraction among the unitized leases. On one hand, this increases the production concentration and the fieldwide economic rent. On the other hand, lease operators participating in unitization become less aggressive in production relative to those outside unitization. As a result, a lease that is outside of a unitized unit enjoys a bigger share of output and rent than one that is inside. In fact, a lease gains more by not participating in unitization. This creates an incentive for a lease to stay out. Moreover, unless the scale of unitization is sufficiently large, the output shares of the unitized leases can fall so much that it dominates the gain due to the increase in fieldwide rent. In that case, not only does all the gain from unitization go to the nonunitized leases, but also the participants of unitization incur net losses. We argue that the inability of the unitized unit to capture the gain that it generates, together with the rewarding nature of staying out are the main reasons for widespread failure of production unitization. The results are analogous to losses due to mergers under Cournot competition. Salant, Switzer and Reynolds (1983) demonstrate that mergers of firms in a homogeneous product Cournot oligopoly may cause losses to the firms that participating in mergers. They argue that, after a merger, its participants as a group become less aggressive in competition and as a result incur losses in market share. Despite the fact that the aggregate profit in the market increases after a merger, firms involved in the merger may incur net losses in profit. The profit share of merging firms may shrink so severely that it dominates gains from the increase in the aggregate profit.

Some other arguments have been advanced to explain the failure of unitization. For example, McDonald (1979) and others have suggested that hold-out strategies, which firms employ in an attempt to strengthen their bargaining power and increase their shares of unitized rents, may block the unitization agreement. This explanation is however more suitable for the delay rather than persistent failure of unitization that exists in the U.S.A simple hold-out strategy is beneficial to a player only if there is a final agreement and the player's share increases because of the hold-out. Without an agreement, hold-out is a useless strategy. Firms are obviously better off by taking a smaller share of the gain of unitization than nothing from holding out permanently. Our analysis is related but distinct from the hold-out explanation. First, it reveals that participants of unitization as a group may incur a net loss in rents compared to the pre-unitization case. This alone provides an incentive for private firms not to participate in unitization. In such circumstances, unlike what the hold-out strategy explanation implies, there is no gain to be divided by participating firms. Second, even if participants gain from unitization when the scale of it is sufficiently large, non-participating leases gain even more. Thus, that a firm chooses not to participate in unitization is because staying out is itself an individually profitable strategy and not because it will be able to enhance the firm's bargaining power in share negotiations.

The analysis in this paper is also related to the influential work of Libecap and Wiggins (1984, 1985a, 1985b), which stresses the effect of asymmetric information on the contractual failure of unitization. The division of net revenue is the central issue in unitization negotiation. Libecap and Wiggins argue that, general uncertainty and asymmetric information can block consensus on the value estimates and hence on output shares of leases. This causes the contractual failure of unitization. While their reasoning is compelling in some cases, it is not in others. For instance, in many US onshore oil fields, the acreage per lease is very small (For example, in Long Beach field of California, over 220 operators are scattered over a proven area of about 1200 acres. On average, a lease is only 6 acres in size. Usually, the size of a typical U.S. onshore oil field is a few thousand acres and that of most leases is 50 acres or less.) It is difficult to argue that, in such cases, there are enough general uncertainty and asymmetric information on the geological conditions to cause significantly different value estimates for adjacent leases. According to Libecap and Wiggins's arguments, we should then observe voluntary unitization among small adjacent leases. However, the empirical evidences (Bains, 1947; and Libecap and Wiggins, 1985, for example) suggest the contrary. Libecap and Wiggins implicitly assume that the value of a lease is determined by the exogenous geological, parameters. However, we argue that the value of a lease is not entirely determined by the exogenous geological parameters but partly determined by key endogenous factors such as the degree of production concentration and the number of wells in the entire field. The migratory nature of underground oil and the common law rule of capture make oil extraction a common property problem. It is the effects of these endogenous factors that are the focus of this paper. The analysis reveals that the failure of unitization can persist even under certain and symmetric information. This paper provides an alternative or complementary explanation to that of Libecap and Wiggins.

One point to keep in mind is that this analysis intends only for the early stage of oil production, the primary recovery stage, in which oil is driven out of the ground by natural subsurface pressure. The secondary recovery stage, in which costly artificial lifting technologies (Pumping or injection of water or natural gas to drive oil to the surface) have to be employed to expel oil to the surface, is a different issue. The nature of artificial lifting technologies requires more cooperation of producing firms in the field, making unitization more likely. Issues of secondary recovery are, however, out of the focus of this paper.

To simplify the analysis, we assume that an oil field consists of a perfectly connected common pool without the stratification and separating faults. Thus, oil can potentially flow to any corner of the field. Without a doubt, this is an oversimplification of the reality but it captures the essence of the common pool problem.

The paper proceeds as follows. Section 2 provides a brief discussion of oil production technology. Section 3 presents an analysis of the competition in extraction. Section 4 analyzes leaseholders' decisions regarding unitization. Section 5 concludes.

## 1. THE EXTRACTION TECHNOLOGY IN A COMMON POOL

Before analyzing the competition in extraction and unitization of production, we first discuss the oil production technology based primarily on Ben-Zvi (1985), which conducts an excellent survey on oil production technology.

## The Extraction Rate

Oil reservoirs are usually compressed between a layer of natural gas and a layer of water. The underground pressure drives the oil to the surface when the surrounding formation is punctured by wells. The instantaneous extraction rate depends on the geological and fluid parameters of the reservoir formation and the number of wells in the field. Given the geological and fluid characteristics of an oil reservoir, the extraction rate is proportional to the difference between the wellhead pressure and the underground pressure, and is a concave function in the number of wells (See Muskat (1937) and Allain (1979) for details.). That is,

$$q(t) = \eta\Phi(N)(p(t) - p_{\omega}(t)) \qquad (1)$$

where $q(t)$ is the instantaneous extraction rate; 1] is a parameter which measures the effect of geological and fluid characteristics of the reservoir; $N$ is the number of wells in the field and $\Phi(N)$ is a concave function in $N$; $p(t)$ is the underground pressure; and $p_{\omega}(t) \geq 0$ is the wellhead pressure.

Theoretically, operators can control the extraction rate by choosing $p_{\omega}(t)$. Since we are mainly interested in competitive production, we assume that wells produce at full capacity, i.e. $p_{\omega}(t) = 0$ To simplify the analysis, we also assume that $\Phi(N) = N^{\frac{1}{d}}$ , where $d > 1$ approximates the degree of concavity of the instantaneous production function with respect to the number of wells. The extraction function then becomes:

$$q(t) = \eta N^{\frac{1}{d}} p(t) \qquad (2)$$

### 1.1 The Pressure Depletion Dynamics

Unlike many other exhaustible natural resources, the ultimate recovery of oil depends on the time path of output. With a high extraction rate, the ratio of natural gas and water to oil extracted increases, leading to a premature loss in subsurface pressure. Due to the loss in pressure, the natural gas dissolved in the oil leaves the solution, reducing the oil's mobility and leaving significant reserves permanently trapped. It is very costly to extract oil once the pressure is exhausted. Hence, characterizing the behavior of $p(t)$ is an important issue in oil production. The rate of change in $p(t)$ is generally believed to be a function of both the extraction rate, $q(t)$, and the pressure, $p(t)$. We adopt the following functional form for the rate of change in $p(t)$:

$$\frac{dp(t)}{dt} = \alpha q^{b}(t)p^{-a}(t) \tag{3}$$

where $\frac{dp(t)}{dt}$ is the rate of pressure depletion; $\alpha$ is a constant; and $a + 2 > b > 1$, measures the degree of the convexity of the rate of pressure depletion in terms of the extraction rate, where $a > 0$. Notice that this functional form implies that there is no pressure depletion if no oil is extracted. The pressure declines as extraction starts. Moreover, the marginal pressure loss increases with the extraction rate.

#### *1.1.1 The Ultimate Recovery*

The ultimate recovery, Q, is defined as

$$Q = \int_0^{00} q(t)dt \tag{4}$$

Solving for $dt$ in equation (3) yields

$$dt = -\frac{1}{\alpha} q^{-b}(t)p^{a}(t)dp \tag{5}$$

Substituting equations (2) and (5) into (4), we have

$$Q = UN^{\frac{1-b}{d}} = UN^{-s} \tag{6}$$

where $U = \frac{\eta^{1-b} p(0)^{2+a-b}}{\alpha(2+a-b)}$, and $s = \frac{b-1}{d}$.

Equation (6) shows that the ultimate recovery declines with the total number of producing wells in a common pool. When there is only one well $(N = 1)$, the ultimate recovery reaches its maximum, where $Q = U$. Thus, $U$ is the maximum recoverable oil reserve. The decline rate of the ultimate recovery is measured by $s$, which characterizes how fast the gross rent (ultimate recovery) decreases with the number of wells. Notice that, when $s = 0$ (or $b = 1$), the ultimate recovery is independent of the number of wells. The Federal Oil Conservation Board (1926, P.30; 1929, p. 10) estimated that the ultimate recovery at competitive extraction is about 30% of that under controlled withdrawal. Since the number of wells under competitive extraction is usually many times greater than that under controlled withdrawal, it can be inferred that $s$ is a number between zero and one, and perhaps relatively close to zero. We therefore assume that $0 \le s < 1$.

## 2. COMPETITION IN EXTRACTION

Now, we are ready to analyze the competition of extraction in a common pool oil field. Consider a simple setting where $L$ independent leaseholders in a common pool field compete for oil by simultaneously choosing their optimal extraction strategies. The migratory nature of oil and the common law rule of capture give each firm an incentive to drill and drain oil from its neighbors. Once a well is drilled, it will be used to produce at full capacity. Otherwise, except for the integer problem, a rational firm would not drill the well in the first place since drilling is costly. Extraction strategies are therefore reduced to simply choosing the number of wells drilled.

In order to further simplify the analysis, the following assumptions are made:

A1: The drilling cost function is assumed to be $D(N) = NC$, where $C$ denotes the marginal cost of drilling a well and $D$ is the total drilling cost.

A2: The crude oil market is assumed to be perfectly competitive. We also assume the expected crude oil price to be constant over time. Without loss of generality, the expected oil price is normalized to be one.

A3: The discount rate is assumed to be zero.

In assumption Al, we implicitly assume that all wells in the same oil field have the same drilling cost. Assumption A2 is not unreasonable. First, in addition to numerous world oil producers, there are in the U.S. alone thousands of oil fields and many times more independent operating firms. Thus, oil producers in a relatively small oil pool face approximately a competitive market unless they mainly supply for a relatively independent local market. Second, in making leasing decisions, the relevant oil price is the expected future price. It is not uncommon to assume the expected oil price to be constant in the future. Assumption A3 is obviously an oversimplification of reality. However, it helps to make a tedious derivation tractable. Under a zero discount rate, the present value of oil production becomes the ultimate recovery. A nonzero discount rate does not affect the main results of the paper but only complicates the derivation.

Let $N_l$ denote the number of wells a typical lessee *l* chooses to drill, where $l = 1,2,\ldots,L$. Then, the total number of wells in the common pool is $N = \sum_{l=1}^{L} N_l$. Assume that all wells produce at the same rate. Lessee *l's* output share and instantaneous extraction rate are then $\frac{N_l}{N}$ and $\frac{N_l}{N} q(t)$ respectively, where $q(t)$ is the total instantaneous extraction rate in the common pool. Lessee $l's$ net return is the present value of its revenue flow minus the drilling cost, that is

$$\pi_l = \int_0^{\infty} \frac{N_l}{N} q(t) dt - N_l C$$

$$= \frac{N_l}{N} Q(N) - N_l C \tag{7}$$

Taking as given other lessees' number of wells, lessee $l$ chooses $N_l$ to maximize her net return. The first order condition yields

$$\frac{\partial \frac{N_l}{N}}{\partial N_l} Q(N) + \frac{N_l}{N} \frac{dQ(n)}{dN} - C = 0. \tag{8}$$

In the left hand side of the above equation, each of the three terms represents a different effect of drilling an extra well on lessee $l's$ profit:

the first term measures the gain due to the subsequent increase in lessee $l$'s output share; the second term measures the loss due to the decrease in ultimate recovery; and the third term measures the loss due to the increased drilling cost. The first order condition describes the state where these three effects are balanced.

Rewriting equation (8), we have

$$U((N-N_l)N^{-(2+s)} - sN_l N^{-(2+s)}) - C = 0. \tag{9}$$

Notice that the $N_l$ that solves equation (9) is independent of the subscript $l$. That is, $N_l$ is the same for $l = 1,2,\ldots,L$. Denote the equilibrium number of wells per lease by *n*. Then, $N_l = n$ and $N = nL$. Multiplying equation (9) by *L* and solving for *N*, we have

$$N = [\frac{1-\frac{s+1}{L}}{c}]^{\frac{1}{s+1}} \tag{10}$$

for $L > s + 1$, where $c = \frac{C}{U}$ is the relative marginal drilling cost of a well. Then,

$$n = \frac{1}{L}[\frac{1-\frac{s+1}{L}}{c}]^{\frac{1}{s+1}}, \tag{11}$$

and,

$$Q(N) = UN^{-s} = U[\frac{1-\frac{s+1}{L}}{c}]^{-\frac{s}{s+1}}. \tag{12}$$

Then, the field-wide gross return, denoted by $\Pi$, is

$$\Pi = (Q(N) - CN)$$

$$= (1+s)UL^{-\frac{1}{s+1}}(\frac{c}{L-(s+1)})^{\frac{s}{s+1}}. \tag{13}$$

Similarly, lessee $l's$ gross return, denoted by $\Pi_l$, is

$$\Pi_l = \frac{1}{L}(1+s)UL^{\frac{1}{s+1}}(\frac{c}{L-(s+1)})^{\frac{s}{s+1}}]. \tag{14}$$

**Proposition 1**: Under AI-A3, the following results hold:

( a) both the ultimate recovery of oil and the aggregate gross return of the common pool decreases with the number of independent production leases;

(b) the value of a lease decreases with the number of independent leases in the common pool field;

The proof of Proposition 1 can be easily obtained by differentiating equation (11) to (14).

Proposition 1 (a) states two separate claims regarding the ultimate recovery and the aggregate rent respectively. The ultimate recovery of oil declining with the number of leases can be said to be an oil extraction phenomenon, resulting from the underground pressure depletion dynamics of oil production. That a large number of independent leases cause low economic rent, however, is the usual outcome associated with common property problems. Here, the number of leases measures the degree of production fragmentation. More leases represent a lower degree of production concentration, which results in a higher rent dissipation.

Given the result in (a), (b) is straight forward (more leases share a smaller fieldwide rent.). Interestingly, it implies that as long as one of the landowners grants additional leases, a lease belonging to other landowners will be of a lesser value even though nothing else has changed.

## 3. PRODUCTION UNITIZATION

Unitization of production refers to a system under which a single firm is selected to produce in a part of or in the entire reservoir with the net return shared by all participants of unitization, including firms that would otherwise be producing. Unitization of production in the entire reservoir is called field-wide unitization, otherwise, it is called partial unitization. Unitization internalizes at least part of the externality of oil production involving multiple firms in a common pool and therefore could mitigate the rent dissipation problem. Given the consensus of oil industry on the gain of unitization, the widespread failure of unitization is indeed puzzling. In this section, we try to show why unitization may still fail despite its apparent potential gain even under perfect and symmetric information.

Production unitization generates the most benefit before any drilling occurs. After independent lessees drill wells, even though unitization may reduce the number of wells used to produce oil and in turn increase total oil recovery, a lot has already been wasted in costly drilling. In this section, we first examine the incentives of production unitization right after the discovery of oil and before wells are drilled. Then, we will discuss the case in which wells have already been drilled.[1]

### 3.1 Production Unitization before Drilling

Consider a perfect common pool reservoir in which there are initially $L$ independent lessees. Imagine that before any drilling occurs, $l + 1$ lessees form a single production unit with the net return equally shared by all participants, where $0 \le l \le L-1$. The remaining $L-l-1$ other lessees behave independently. Notice that $l = 0$ represents the case of the outright failure of unitization while $l = L-1$ the case of fieldwide unitization. It is convenient to refer to the lessees participating in unitization as 'insiders' and the lessees that continue to behave independently as 'outsiders'. Then, what are the payoffs of unitization to insiders and outsiders?

Denote by $\pi^u(L,l)$ and $\pi^{nu}(L,l)$ the net return to a typical insider and outsider respectively. Denote by $\pi^0(L)$ the net return to a typical lessee prior to unitization. From the equilibrium results in production competition, we have

$$\pi^0(L) = \frac{1}{L}Q(N(L)) - CN(L))$$

$$= \frac{1+s}{L}[UL^{-\frac{1}{s+1}}(\frac{c}{L-(s+1)})^{\frac{s}{s+1}}] \qquad (15)$$

$$\pi^u(L,l) = \frac{1}{(l+1)(L-l)}(Q(N(L-l)) - CN(L-l))$$

$$= \frac{1+s}{(l+1)(L-l)}[U(L-l)^{\frac{1}{s+1}}(\frac{c}{L-l-(s+1)})^{\frac{s}{s+1}}] \qquad (16)$$

and

$$\pi^{nu}(L,l) = \frac{1}{L-l}(Q(N(L-l)) - CN(l-l)$$

$$= \frac{1+s}{L-l}[U(L-l)^{-\frac{1}{s+1}}(\frac{c}{L-l-(s+1)})^{\frac{s}{s+1}}]. \qquad (17)$$

Equation (15) follows directly from the equilibrium results of the competition in extrac- tion. Prior to unitization, an insider has the same net return as a typical lessee in the $L$ independent lessees equilibrium. Equation (16) reflects two of our assumptions: (i) under unitization, the $l+1$ insiders form a unit and thus behave exactly like an independent outsider, resulting in a $L-l$ lessees equilibrium; and (ii) the net return of the unitized unit is equally shared by all the insiders. Equation (17) follows from the $L-l$ lessees production equilibrium.

Denote by $\Theta(L,l)$ the change in net return to a typical insider resulting from unitization. Then by definition,

$$\Theta(L,l) = \pi^u(L,l) - \pi^0(L)$$

$$= \frac{1+s}{(l+1)(L-l)}[U(L-l)^{-\frac{1}{s+1}}(\frac{c}{L-l-(s+1)})^{\frac{s}{s+1}}]$$

$$-\frac{1+s}{L}[UL^{-\frac{1}{s+1}}(\frac{c}{L-(s+1)})^{\frac{s}{s+1}}]. \qquad (18)$$

For any given number of lessees $L$ prior to unitization, equation (18) can be used to determine whether unitization is profitable for the insiders. Insiders lose in unitization if and only if $\Theta < 0$. The $\Theta(L,l)$ function can be used to derive the following results:

**Proposition 2:** (i) Field-wide unitization is always profitable for insiders; (ii) Unitization always raises the fieldwide rent; (iii) There exists a number $\bar{l}$ such that insiders incur net losses in rent due to unitization if $l < \bar{l}$; (iv) There exists a number $\hat{l}$ such that rents of insider declines with the scale of unitization when $l < \hat{l}$

(See Appendix for Proofs).

Most of proposition 2 can be vividly illustrated by Figure 1, in which $\pi^u(L,l)$ and $\pi^0(L)$ are plotted against *l*. $\Theta(L,l)$ is distance between these two curves. $\pi^u(L,l)$ is U-shaped in *l:* falling initially, reaching the minimum at $\hat{l}$ and then starting to increase. When *l* reaches $\bar{l}$ the insiders' net return come back to the preunitization level. Thus, $\bar{l}$ defines the minimum scale of profitable unitization for its participants.

The most important message from proposition 2 is that even though unitization always increases fieldwide rent, it may cause net losses to its participants unless the scale of unitization is sufficiently large. The requirement of large scale may hinder unitization since private contracting involving many agents can be difficult due to high transaction costs (Coase,1960; Williamson, 1976; Goldberg, 1976). Nonetheless, it is far from convincing that the large-scale requirement is enough to cause such a persistent and widespread failure of unitization. After all, there always exists unitization with sufficiently large scale, which generates gains for its participants.

Obviously, whether a lessee joins unitization or not depends also on the opportunity costs. The alternative to participating in unitization is staying out of it or being an outsider. A comparison of the profit of an insider and that of an outsider reveals the following results:

**Proposition 3:** (i) Unitization always raises outsiders' profit; (ii) An outsider makes a higher profit than an insider; (iii) The difference in profit between an insider and outsider increases with the scale of the unitization; (iv) It is not profitable for an outsider to join a unitized unit if there are more than $\widetilde{l}$ leases prior to unitization, where $\widetilde{l} = \max\{6, 3 + (\frac{2-s}{1-s})^2\}$.

(See Appendix for proofs.)

Unitization reduces the number of independent leases and therefore increases the field- wide economic rent. Yet, insiders may incur losses in net returns. The reason is that unitization commits its participants to a lower extraction rate and in turn smaller shares of output and rent, the effect of which may dominate the gain in fieldwide rent for insiders. Indeed, unless unitization covers a sufficiently large fraction of all lessees, outsiders will capture all the gains from unitization and more, leaving insiders worse off in comparison to the pre-unitization case. Furthermore, outsiders always earn more profits than insiders, and the relative differences increase with the scale of unitization. Therefore, given other lessees' actions, a lessee is always better off by staying independent. The rewarding nature of staying out of a unitization scheme, together with the inability of the unitized unit to capture the gain it generates, clearly makes unitization difficult to succeed.

Proposition 2 and 3 together provide an explanation as to why there can be persistent and widespread failure of unitization in common pool oil fields under common law rule of capture even though merits of unitization is universally known. They also imply that: (i) if unitization is successful, it involves a large fraction of leases in an oil field; (ii) once a unitized unit is formed, it will most likely fail to expand; and (iii) the more independent leases in an oil field, the less likely is unitization.

Participation in a partial unitization may result in losses to a lease. On the contrary, staying out is always more beneficial to a lease if there is ever a partial unitization. It is irrational for an independent lease to voluntarily participating in unitization, which dooms the chances of voluntary production unitization. The only effective public policy is therefore mandatory field-wide production unitization.

### 3.2 Production Unitization after Competitive Drilling

Imagine that $L$ independent lessees in a common pool oil field engage in competitive production and have just finished drilling in the fashion we describe in section 3. To capture the potential gains of unitization, $l + 1$ lessees decide to form a single production unit with the net return equally shared by all participants, where $0 \leq l \leq L-1$. The remaining $L-l-1$ other lessees behave independently. We continue to refer to the lessees participating in unitization as 'insiders' and the other lessees as 'outsiders'.

Prior to unitization, the insiders as a group have $(l+1)n$ wells drilled and each outsider has $n$, where $n = \frac{1}{L}[\frac{1-\frac{s+1}{L}}{c}]^{\frac{1}{s+1}}$ (see equation (11)). After unitization, the insiders and the outsiders have to decide whether existing numbers of wells are optimal for themselves. If not, they have to decide how many wells to use if they have too many existing wells, or how many new ones to drill if they have too few. Let $n_0$ and $n_u$ be the numbers of producing wells for a typical outsider and the unitized lessees, respectively. Then, the total number of producing wells, $N = (L-l-1)n_0 + n_u$.

After unitization, the first order condition for profit maximization for outsiders becomes (see Equation (9))

$$U((N-n_0)N^{-(2+s)} - sn_0N^{-(2+s)}) = 0. \tag{19}$$

for $n_0 < n$. And,

$$U((N-n_0)N^{-(2+s)} - sn_0N^{-(2+s)}) - C = 0. \tag{20}$$

for $n_0 \geq n$. Similarly, the first order condition for profit maximization for insiders becomes

$$U((N-n_u)N^{-(2+s)} - sn_0N^{-(2+s)}) = 0 \tag{21}$$

for $n_u < (l+1)n$. And,

$$U((N-n_u)N^{-(2+s)} - sn_u N^{-(2+s)}) - C = 0. \qquad (22)$$

for $n_u \geq (l+1)n$.

However, equation (22) never holds. If it does, then equation (20) also holds. 'Then, $n_0 = n_u > (l+1)n$ and the total number of wells is greater than $Ln$. However, since the number of independent producers after unitization $L - l < L$, the total number of wells in the symmetric equilibrium like that in Section 3 should decrease. It is a contradiction. We summarize this result in the following lemma.

**Lemma 1:** Post unitization, the insiders as a group will not drill any new wells.

**Lemma 2:** In equilibrium, (a) when the share of the leases unitized $\beta > \frac{1}{1+s}$, the unitized leases will use some of but not all of their existing wells to produce and will not drill new wells, and the outsiders will use all of their existing wells and will drill new wells; (b) when $\beta \leq \frac{1}{1+s}$ the unitized leases will use all of their existing wells but will not drill new wells, and the outsiders will also use all of their existing wells and will not drill new wells,

(Proof in Appendix)

When $\beta \leq \frac{1}{1+s}$, unitization has no effect on production pattern, profits and oil recovery, since insiders and outsiders will use all of their existing wells to produce and will not drill any new wells. In such cases, unitization is irrelevant economically.

When $\beta \leq \frac{1}{1+s}$, equations (20) and (21) hold. Solving these equations jointly, we have

$$N = [\frac{1 - \frac{s}{L-l-1}}{c}]^{\frac{1}{s+1}} \qquad (23)$$

and

$$n_u = \frac{1}{1+s}[\frac{1 - \frac{s}{L-l-1}}{c}]^{\frac{1}{s+1}} \qquad (24)$$

and

$$n_0 = \frac{1}{L-l-1}\frac{s}{1+s}[\frac{1-\frac{s}{L-l-1}}{c}]^{\frac{1}{s+1}} \tag{25}$$

From equation (23), we have $N = [\frac{1-\frac{\frac{s}{L}}{1-\beta}}{c}]^{\frac{1}{s+1}}$ Thus,

**Lemma 3:** When, $\beta > \frac{1}{1+s}$, the total number of producing wells in the field decrease after unitization.

**Proposition 4:** (i) Field-wide unitization increases oil recovery and each individual lessee's profit; (ii) When, $\beta \leq \frac{1}{1+s}$, unitization does not generate any benefits or losses for both insiders and outsiders; (iii) When, $\beta > \frac{1}{1+s}$ the total oil recovery increases; (iv) It is not profitable to unitize for the insiders unless the fraction of unitized lease is sufficiently big ($\beta >> \frac{1}{1+s}$).

(Proof in Appendix)

After competitive drilling occurs, small scale unitization ($\beta \leq \frac{1}{1+s}$) does not have any effects on production pattern, oil recovery and economic rent. It is economically irrelevant and unnecessary. Yet, potentially beneficial unitization ($\beta > \frac{1}{1+s}$) will still fail without policy intervention, for reasons similar to those of unitization before the competitive drilling occurs.

In summary, unitization may increase oil recovery and field wide economic rent. How- ever, lessees participating in the unitization may not share the gains or even suffer net loses from unitization, regardless unitization occurs before or after drilling costs have sunk. Without policy intervention, unitization will fail in general.

## CONCLUSION

This paper examines strategic reasons for the widespread failure of unitization in common pool oil fields. It is shown that, despite the large gain associated with concentrated oil extraction, unitization may cause losses to the participating leases. Further, given other firms' decisions on whether to unitize or not, a firm is always better off by staying out. The inability of the unitized unit to capture the gain it generates together with the rewarding nature of staying out may be the primary reason for the continuing and widespread failure of unitization. The potential gain from unitization is larger when unitization occurs prior to competitive drilling. When wells have been already drilled, small-scale unitization does not increase oil recovery and total economic rent. Potentially beneficial unitization with large scale does not happen because the unitized lessees suffer losses in the process.

The analysis in this paper has some policy implications. The externalities of unitization (insiders do not capture all the gain of unitization) make it a classical case for government intervention. Without some form of encouragement for participating in unitization (or penalties for not participating), the private incentive to unitize production is lower than the social one, leading to a complete or partial failure of unitization. Mandatory field-wide unitization is possibly the only effective policy leading to unitization whether the drilling costs have sunk or not.

Several different policies regarding unitization coexist in the U. S. onshore oil fields. For instance, on federal lands, firms can obtain leases for up to twenty years under the Mineral Leasing Act, but the aggregate acreage held by a firm cannot exceed 246,000 acres. If firms agree to unitize their leases, however, the leases are automatically extended for the life of the unit, and they are exempt from the statutory acreage limit. In Texas, there are no explicit policies for unitization except that unanimous agreement for the formation of a unit is required before the Texas Railroad Commission will approve it. Oklahoma has a compulsory unitization statue. If 63% of the operators (weighted by acreage) agree to unitization, the law allows the Oklahoma Corporation Commission to force all leaseholders on a reservoir to join (1945 Oklahoma Sess. Laws at 162). The impact of policy differences is evident. By 1948, Wyoming federal land had 58% of its production under unitization, whereas the Oklahoma share was 9% and Texas had no production under unitization (Libecap and Wiggins, 1985b).

A similar analysis can be applied to landownership consolidation through land purchasing. The reasons that cause the failures of production unitization are also likely to cause the failure of landholding consolidation. Moreover, the structural characteristics that lead to the failure of unitization are also present in many other common property problems.

## APPENDIX

**Proof of Proposition 1:**

Differentiating equation (12) and simplifying, we have

$$\frac{dQ}{dL} = -\frac{s}{L^2} U[\frac{1 - \frac{s+1}{L}}{c} - \frac{2s+1}{s+1} < 0$$

that is, the ultimate oil recovery decreases with the number of leases.

Both $L^{-\frac{1}{s+1}}$ and $(\frac{c}{L-(s+1)})^{\frac{s}{s+1}}$ decrease with $L$. Thus, from equation (13), II decreases with $L$. That is, the field wide rent decreases with the number of the leases.

$\Pi_l$ is simply $\frac{\Pi}{L}$. Since we have shown that $\Pi$ decreases with $L$, $\Pi_l$ will decrease with $L$ at a higher rate. Q. E. D.

**S.O.C. of the extraction game:**

$$\frac{\partial^2 \pi_l}{\partial N_l^2} = sN^{-(2+s)} - (2+s)(N - (1+s)N_l)N^{-(3+s)} < 0$$

**Proof of Proposition 2:**

(i):

$$\Theta(L, L-1) = \frac{1}{L} Uc^{\frac{s}{s+1}}[1 - L^{-\frac{1}{s+1}}(L-s-1)^{-\frac{1}{s+1}}] > 0$$

(ii):

Denote by $\Pi^{\omega}$ the fieldwide rent. Then, $\Pi^{\omega} = U(L-l)^{-\frac{1}{s+1}}(\frac{c}{L-l-(s+1)})^{\frac{s}{s+1}}$.

$$\frac{\partial \Pi^{\omega}}{\partial l} = \Pi^{\omega}[\frac{1}{(s+1)(L-l)} + \frac{s}{(s+1)(L-l-s-1)}] > 0.$$

(iii):

$$\Theta(L,l) \geq 0 \Leftrightarrow$$

$$F(L,l) = (L-l-s-1)^{-\frac{s}{s+1}}(L-l)^{-\frac{s+2}{s+1}} - (l+1)L^{-\frac{s+2}{s+1}}(L-s-1)^{-\frac{s}{s+1}} \geq 0$$

$$\frac{\partial^2 F(L,l)}{\partial l^2} = \frac{(s+2)(2s+3)(L-l)^{-\frac{3s+4)}{s+1}}}{(L-l-s-1)^{\frac{s}{s+1}}(s+1)^2}$$
$$+ 2s(s+2)(s+1)^{-2}(L-l)^{-\frac{2s+3}{s+1}}(L-l-s-1)^{-\frac{2s+1}{s+1}}$$
$$+ \frac{s(2s+1)(L-l-s-1)^{-\frac{3s+2}{s+1}}}{(s+1)^2(L-l)^{\frac{s+2}{s+1}}} \geq 0$$

for $0 \leq l < L-s-1$.

Therefore, *F(L, l)* is convex in *l* for $0 \leq l < L-s-1$.

And,

$$\frac{\partial F(L,l)}{\partial l}\Big|_{l=0} = (\frac{s+2}{L(s+1)} + \frac{s}{(L-s-1)(s+1)} - 1)L^{-\frac{s+2}{s+1}}(L-s-1)^{-\frac{s}{s+1}} < 0$$

for $L > s+3$.

It easy to check that $F(L,l)\big|_{l=0} = 0$ and $F(L,l)\big|_{l \to L-s-1} > 0$.
Then, there exists $0 < \bar{l} < L-s-1$ such that $F(L,\bar{l}) = 0$. Since *F(L,l)* is convex in *l* for $0 < l < \bar{l} < L-s-1, F(L,l) \leq 0$ for $l < \bar{l}$.

(iv):

$$\Theta(L,l)\big|_{l=0} = 0$$

and,

$$\frac{\partial \Theta(L,l)}{\partial l}\Big|_{l=0} < 0$$

Therefore, insiders incur losses when *l* increases from zero. Since $\Theta(L,l)$ is smooth in *l*, therefore, there exists $\hat{l} > 0$ such that $\frac{\partial \Theta(L,l)}{\partial l} < 0$ if $l \leq \hat{l}$. Q.E.D.

**Proof of Proposition 3:**

(i):

$$\frac{\partial \pi^{nu}(L,l)}{\partial l} = \pi^{nu}(L,l)\left(\frac{s+2}{(s+1)(L-l)} + \frac{s}{(s+1)(L-l-s-1)}\right) > 0.$$

(ii) and (iii):

$$\pi^{nu}(L,l) - \pi^{u}(L,l) = l\pi^{u}$$

(iv):

$$\pi^{u}(L,l+1) > \pi^{nu}(L,l)$$

$$\Leftrightarrow \tfrac{1}{l+2}(L-l-1)^{-\frac{s+2}{s+1}}(L-l-s-2)^{-\frac{s}{s+1}} > (L-l)^{-\frac{s+2}{s+1}}(L-l-s-1)^{-\frac{s}{s+1}}$$

$$\Leftrightarrow$$

$$l+2 < \left(\tfrac{L-l}{L-l-1}\right)^{\frac{s+2}{s+1}}\left(\tfrac{L-l-s-1}{L-l-s-2}\right)^{\frac{s}{s+1}}$$

Notice that $\left(\tfrac{L-l}{L-l-1}\right)^{\frac{s+2}{s+1}}\left(\tfrac{L-l-s-1}{L-l-s-2}\right)^{\frac{s}{s+1}} < \left(\tfrac{L-l-s-1}{L-l-s-2}\right)^{2} = \left(1+\tfrac{1}{L-l-2-s}\right)^{2}$.

Define $y(L,l) = l+2-\left(1+\tfrac{1}{L-l-2-s}\right)^{2}$.

$\frac{\partial^2 y(L,l)}{\partial l} = \frac{2}{(L-l-s-2)^4} - \frac{4(L-l-s-1)}{(L-l-s-2)^4} < 0$, that is, $y(L,l)$ is strictly concave in $l$, for $l < L-s-2$.

It is easy to check that, for $L \geq 6 > 5+s, y(L,l)\big|_{l=0} > 0$; and, for $L \geq 3+\left(\tfrac{2-s}{1-s}\right)^{2}$, $y(L,l)\big|_{l=L-3} > 0$.

Then, if $L \geq\cong \max(6, 3+\left(\tfrac{2-s}{1-s}\right)^{2}), y(L,l) > 0$ for $l \leq L-3$. Q.E.D.

**Proof of Lemma 2:**

Lemma 1 establishes that insiders will not choose to drill additional wells after unitization. There are only two other possibilities: insiders use either some or all of their existing wells to produce. When insiders use all of their existing wells to produce, it is trivial to check that $n_0 = n$ satisfies equation (20). That is, outsiders will also use all the existing wells and will not drill new wells. Unitization in this case does not have any effects on the number of producing wells, drilling, profits, and the ultimate oil recovery. When insiders use some of but not all of their existing wells,

$n_u < (l+1)n$, or $\frac{1}{1+s}[\frac{1-\frac{s}{L-l-1}}{c}]^{\frac{1}{s+1}} < (l+1)\frac{1}{L}[\frac{1-\frac{s+1}{L}}{c}]^{\frac{1}{s+1}}$ (using equations (9) and (24)). Simplifying the inequality yields

$$(\frac{1}{1+s})^{1+s} < \beta^{1+s}(1-\beta)\frac{1-\frac{1+s}{L}}{(1-\beta-\frac{s}{L})} \qquad (26)$$

where $\beta = \frac{l+1}{L}$. It is easy to check that $\beta = \frac{1}{1+s}$ is the solution of

$$(\frac{1}{1+s})^{1+s} = \beta^{1+s}(1-\beta)\frac{1-\frac{1+s}{L}}{(1-\beta)-\frac{s}{L}}.$$

.

Since $\beta^{1+s}$ and $(1-\beta)\frac{1-\frac{1+s}{L}}{(1-\beta)-\frac{s}{L}}$ are both increasing functions in $\beta$, the right hand side of equation (26) is an increasing function in $\beta$. Therefore, when $\beta < \frac{1}{1+s}$, the inequality (26) holds, i.e., the insiders use some of but not all of their existing wells.

Totally differentiating equation (20) and simplifying yield

$$\frac{dn_0}{dn_u} = -\frac{N-(2+s)n_0}{N+(L-l-1)[N-(2+s)n_0]} < 0$$

when $L \geq 3$. Therefore, the outsiders drill additional wells when the insiders do not use all existing wells in production. Q.E.D.

**Proof of Proposition 4:**

Proposition 4 (i) is obvious. (ii) is a corollary of Lemma 2 and (iii) is a direct result from Lemma 3.

To prove (iv), we first write each insider's profit after unitization, which is simply the value of their share of oil production because as a group the insiders do not drill any new wells. Thus,

$$\pi^u = \frac{1}{l+1}\frac{n_u}{N}Q(N) = \frac{Uc^{\frac{s}{1+s}}}{L(1+s)B},$$

where $B = \beta[1-\frac{\frac{s}{L}}{1-\beta}]^{\frac{s}{1+s}}$. And,

$$\frac{dB}{d\beta} = [1-\frac{\frac{s}{L}}{1-\beta}]^{-\frac{1}{1+s}}[1-\frac{s}{L}\frac{1}{1-\beta}(1+\frac{s}{1+s}\frac{\beta}{1-\beta})].$$

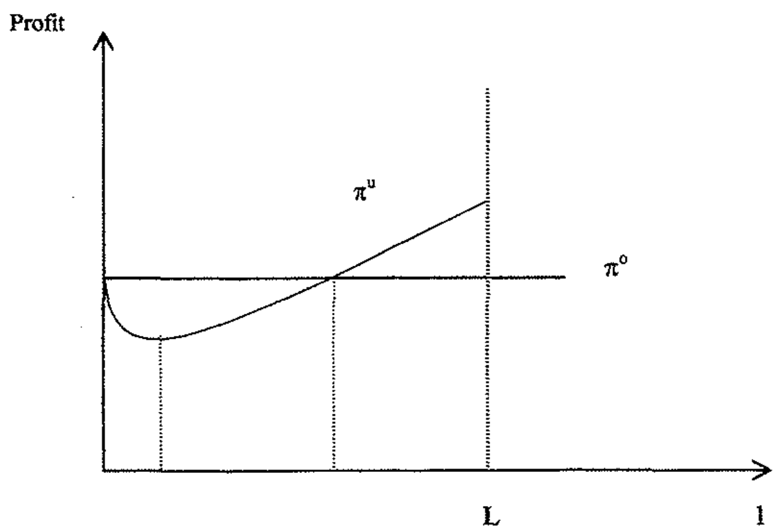
Notice (a) as long as $\beta \leq \frac{L-1}{L}$ (unitization is not field-wide),

$$[1-\frac{\frac{s}{L}}{1-\beta}]^{-\frac{1}{1+s}} > 0 \text{; (b)}$$

$1-\frac{s}{L}\frac{1}{1-\beta}(1+\frac{s}{1+s}\frac{\beta}{1-\beta})$ is an inverse U-shaped curve in $\beta$; (c) it is easy to check that $1-\frac{s}{L}\frac{1}{1-\beta}(1+\frac{s}{1+s}\frac{\beta}{1-\beta}) > 0$ at $\beta = \frac{1}{1+s}$, beyond which the insiders will choose to leave some of the existing wells unused. Therefore, $\frac{dB}{d\beta} > 0$ at $\beta = \frac{1}{1+s}$.

Since $\frac{d\pi^u}{d\beta}$ and $\frac{dB}{d\beta}$ have opposite signs. $\frac{d\pi^u}{d\beta} < 0$ at $\beta = \frac{1}{1+s}$. That is, when the unitization scale is smaller than $\beta = \frac{1}{1+s}$, the unitization does not have any impacts on economic rent and oil recovery. When unitization scale increases from $\beta = \frac{1}{1+s}$, the unitized leases will suffer a loss in profit. Q.E.D.

**Figure 1**



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