ESSAYS ON THE ROLE OF INFORMATION IN NATURAL RESOURCE EXPLORATION AND DEVELOPMENT

Thesis by

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ABSTRACT

Because natural resource exploration and development are inherently risky undertakings, information can be a valuable commodity in these processes.

A survey of the literature concerning information and resources is contained in Chapter 1, and the areas of interest for this thesis are introduced.

Aspects of the role of information early in the exploration process are considered in Chapter 2, as the public and private provision and valuation of exploratory information are examined. The role of information in market performance is not independent of the allocation institutions under consideration, so several are examined. Furthermore, the role of publicly provided information as a remedy for problems in information provision is critically evaluated. It is shown that if the publicly provided information is not perfect, its potential for eliminating, or even reducing, private overvaluation can not be assured.

Next, in Chapter 3, consequences of the joint provision of resources and information are examined in the context of problems of information inexcludability. This essay presents the case in which more than one firm owns land in a geologically related area. Each firm can provide valuable information to the other, and each firm recognizes this predicament. The problem is developed first

as one of noncooperative play of a two person game, with particular attention then given to the theory and performance of cooperative institutions for sharing the resource, information. This essay is not merely an abstract conjecture, for such cooperative institutions are quite common in the oil industry.

Finally, in Chapter 4, the observation that information is a valuable commodity in natural resource markets is once again combined with the fact that such information is often produced jointly with the oil and gas product to demonstrate that price controls on petroleum properties can produce unintended results. This follows from the alteration in firm optimal extraction paths when price controls are present.

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CHAPTER 1

INFORMATION IN RESOURCE EXPLORATION AND DEVELOPMENT: INTRODUCTION AND SURVEY

I. INTRODUCTION

Information, in a world of uncertainty, can be a valuable commodity. That is, individuals and/or firms, when faced with uncertainty, are often willing to pay in order to receive information about the state of the world. While such information could be data about future demand, about the distribution of prices in a market, or about possible changes in technology, these papers are concerned specifically with information about natural resources: the amount of oil located under a particular tract of land, the richness of a copper vein, or the sulfur content of a coal resource. While the objective existence of these facts is not random, man's knowledge of them is imperfect, so the convention that they represent uncertainty is adopted. Because of the author's own knowledge and interest, the primary focus of the survey will be petroleum resources.

One reason individuals or firms may value information is that they are risk averse and are willing to pay to reduce or eliminate uncertainty. More important for this analysis is that risk _neutral_ individuals or firms can value information, for when production costs must be incurred _ex ante_ (that is, before the true state of nature is revealed), expected profits can be increased when better information is available.

If valuable information were just another commodity, like apples or oranges, the standard economic theorems (Arrow, 1951) in which Pareto optimum is achieved by a competitive market would hold (these theorems utilize conditions that production sets are convex and that there are no externalities in production or consumption). However, there are at least four important characteristics of information, including especially resource information, which violate certain assumptions of the fundamental theorems and which have required the development of a distinct "economics of information."

First, there are typically economies of scale in the production of information (see Arrow, 1974). To tell the first oil company whether a promising geological structure exists below a particular tract will typically cost a large initial sum. To transfer this information to all other oil companies will cost some smaller additional amount for reproduction costs. When there is the case of a large inital fixed cost with a small, constant marginal production cost, the convexity conditions used in the welfare theorems are violated. In a competitive market for this information, the marginal optimality conditions require that price equal the constant marginal production cost. However, no firm can earn nonnegative profits at this price because of the large fixed costs. In the long run, the firms would leave the industry and the information would not be produced, perhaps even when it could make some or all persons and/or firms better off.

Efficient production of information could also be achieved by a perfect price discriminating monopolist. Even aside from the distributional issues (the monopolist would extract all the benefits from the information) a second feature typical of information poses a severe problem: it is difficult to establish property rights in information. As has been pointed out in both Arrow [1974] and Montgomery and Quirk [1974] once a monopoly information firm sells information to a single buyer, that purchaser becomes a potential competitor, destroying the first firm's monopoly position (notice that this is more of a problem where information does not lose its value as time passes; a week old newspaper depreciates more than a week old aerial photograph of physical terrain). Although it may seem to be the natural approach, addressing this problem through copyrights or patents has not proven to be easy.

The third problem, which is especially typical of information about natural resources, is nonexcludability. An oil firm which drills a test well and then continues field development is tipping off everyone else who has observed its actions. As Arrow [1974] noted, "The very use of information in any productive way is bound to reveal it, at least in part." Peterson [1975] and Stiglitz [1975] have explored this information externality as it relates to petroleum exploration. Peterson provides figures which confirm Arrow's contention in that successful exploration activity on one tract tends to drive up the value of other tracts which might be geologically related.

Each of the three facets of information discussed in the preceding paragraphs (indivisibility, inability to define property rights, and inexcludability) leads to the same qualitative conclusions: the private marketplace will tend to underproduce information relative to the social optimum. Hirshleifer [1971], however, demonstrated that the divergence between private and social value can go the other direction: the private value of information can be greater than its social value, with too many resources spent on producing information. The most famous illustration is the amount of resources spent at the racetrack by participants attempting to win the bet on the fastest horse. There are other economic examples of this phenomenon: the typical conditions are that the information is being utilized in mechanisms of redistributing resources from one person to another rather than in creating additional total wealth.

II. THE LITERATURE ON THE ROLE OF INFORMATION IN NATURAL RESOURCE EXPLORATION AND DEVELOPMENT

While the special characteristics of information markets have necessitated an "economics of information" (Hirshleifer and Riley, 1979), surprisingly little has been written about the application of this general topic to natural resource exploration and development. This cannot be because the subject is of trivial importance. Virtually every oil firm employing more than a few persons has geologists and geophysicists and their support staffs to produce and process resource information. The Oil and Gas Journal reports that in 1977 oil companies spent over a billion dollars on geophysical information activity.[1]

The best general reference on the role of information gathering and evaluating oil drilling decisions is Grayson [1960].

There are many types of information available to the oil firm: aerial photos, rock samples, seismic surveys, data from other drilling activity in nearby areas, etc. Not even actually drilling a well, logging it, and placing it in production will give an absolutely certain profile of the oil resource. Thus, rather than being a continuous production process, the Grayson view depicts information decisionmaking as a series of discrete choices, nodes on a decision tree. At each point, the firm decides whether or not to purchase the next bunch of information. If it does not purchase the next information, the firm may still proceed in the oil exploration or development process, perhaps purchasing other types of information along the way. At each decision point, the firm will purchase information if the value to the firm of the information is greater than the cost. In determining the value of information, the firm, as depicted by Grayson, uses essentially the same process which is defined more formally in Quirk [1976].

The most extensive treatment of a resource information problem in the economics literature has been with regard to information and the bidding for U.S. offshore oil leases. In this literature, it should be noted, pre-sale resource information can be shown to affect market structure in two distinct ways. First, the information may have social value. Secondly, however, competitive sealed bidding as an institutional arrangement can create conditions in which information has particular private value to firms. The focus of the bidding literature has been on conditions of "asymmetric information." As will be shown, the form of the information asymmetry varies widely.

Hughart [1975] uses a game theoretic framework to develop conditions in which a sealed bid competitive auction leads to Hirshleifer-type private overinvestment in information. Hughart's model can be summarized as follows:

1) There are two risk neutral firms, one of which, A-Co., has access to more information (say an additional seismic test) than the other firm, B-Co., (this is the source of the information asymmetry). This is quite similar to Wilson [1967].

2) The extra information available to A-Co. classifies all tracts as either "good" or "poor." The mean value of good tracts is G, of poor tracts P, and of all tracts together M. The proportion of all tracts which are good is g, $G > M > P > 0$, and $M = gG + (1 - g)P$.

3) "A-Co.'s bid function has as its sole argument the outcome of the geophysical test. B-Co.'s bid function has as its argument the A-Co. bid function."

4) Both firms are aware of the above description of the situation, and of all the relevant parameters (G, M, P, g).

It is easy to see why, in this model of the bidding process, the expected outcome is <u>not</u> that each firm bids its own expected valuation of each tract. Suppose, for example, that there are two tracts, one disclosed to A-Co. as good, the other disclosed to A-Co. as poor. A-Co. would, if bidding true expected valuations, bid G on the good tract and P on the poor tract. B-Co. would bid M on both tracts. The result would be a disaster for B-Co., for it would win the auction on the bad tract and lose the auction on the good tract. Furthermore, this would not be a Nash equilibrium situation, for A-Co. could improve its profits by sumbitting a bid of $M + \varepsilon$ on the good tract.

The Nash equilibrium solutions generated by Hughart entail a random bidding strategy by A-Co., with positive expected profits, and nonpositive expected profits for B-Co. Thus, there is in this model a direct incentive for firms not to be the less informed in the bidding. The result is a systematic incentive for firms who hope to remain in the bidding to acquire more information, even when that is socially wasteful.

An additional result of Hughart's model is that the proportion of economic rent capture by the government (selling the tracts) grows as uncertainty decreases.

Hughart's model generates a kind of curse on B-Co.: it wins the bad tracts and loses the good tracts. In a pathbreaking article, Capen, Clapp and Campbell [1971] derive a type of "winners' curse" which states that "in competitive bidding, the winner tends to be the player who most overestimates the tract value." This conclusion also comes from a model with asymmetric information, but the asymmetry takes a different form than in Hughart. Recall that in Hughart's model, only on the "poor" tracts was the winning bidder the one who overestimated the tract's true value. This distinction can be traced to the different types of information asymmetry. In Hughart, one firm is "more informed" that the other (B-Co. would be willing, ex ante, to trade places with A-Co.). In the Capen, Clapp and Campbell piece, each firm is viewed as drawing a random variable from the same distribution. That is, no one firm has any <u>more</u> information than another, but the information is noisy -- it consists of a signal which is a random variable with a joint probability distribution with the true value of the tract. The firms estimate the value of the tract conditional upon the informational signal they have received. As Capen, Clapp, and Campbell, and later Klein [1976], point out, the expected value of the highest (i.e., winning) bid derived from this random signal is higher than the expected value of the tract even if the signal itself is unbiased. The winner in this model is always cursed, and the rational bidder will reduce his bid by some positive amount from its own true expected value of the tract (based upon the random signal). Klein's extension is to demonstrate that there is a direct incentive for the formation of joint ventures, as the bid based upon the average of the estimates of the members of the joint venture is more accurate than the result if the members bid separately.

The most recent work in the Capen, Clapp, and Campbell tradition is Reece [1978] and [1979]. Reece is most concerned with the effects of reducing uncertainty upon the distribution of rent between the government and the winning bidder, and thus, like Hughart, must explicitly consider the Nash equilibrium which one expects from a particular institution. Utilizing a computer analysis, the first order conditions for a firm's optimum were solved to obtain the equilibrium rents obtained by the government. With some estimates as to real world fixed costs and signal variance (assumed to be log normal) the resulting calculations indicate that as uncertainty (defined as the variance of the log of the signal) declines, the proportion of total possible rent which returns to the government approaches 1.

The Reece papers directly incorporate a feature of offshore oil drilling which Hughart, Capen, et al. and Klein do not consider, namely that there will typically be fixed costs associated with drilling and developing an oil resource after the leases are awarded but before the random variable is known. In a world of fixed costs of drilling, another feature of many of these models needs to be carefully considered: the oil companies do not, as is often described, obtain information in the form of the value of the tract; they obtain information on the physical structures. Without fixed drilling costs, it is reasonable to assume a transformation exists between information about how much oil is present and the value of the tract. However, with ex ante drilling costs, the value of the tract depends on how much information is available. The very process of conducting a seismic survey can increase ex ante the value of the tract.

To summarize the various papers on offshore oil bidding Table 1 classifies each of the four articles discussed here according to three questions: 1) Which type of information asymmetry is employed: different firms have different amount of information, so some are better informed than others (Type I), or different firms each have a single draw of a random information signal from an identical underlying distribution (Type II)? 2) Do the authors include fixed costs of drilling? 3) Do the authors explore the

TABLE 1

	Type of asymmetry	Fixed costs of drilling?	Nash equilibria considered?
Hughart	Type I	No	Yes
Capen, Clapp and Cambell	Type II	No	No
Klein	Type II	No	No
Reece	Type II	Yes	Yes

question of Nash equilibria?

III. ISSUES IN RESOURCE INFORMATION ADDRESSED IN THIS THESIS

The essays presented here address three different aspects of the role of information in natural resource exploration and development.

Aspects of the role of information early in the exploration process are considered in Chapter 2, as the public and private provision of pre-drilling exploratory information are examined. The divergence between public and private valuation of exploratory information reflects the issues raised by Hirshleifer and the competitive bidding literature (as discussed in section I of this chapter). Market structure and the role of information in market performance are not independent of the allocation institution under consideration. There are ways, other than by an auction procedure, in which the rights to explore and drill for oil could be allocated. As the institutions vary, the role of information may change. Therefore, in Chapter 2, public and private valuation of information in other institutional settings are evaluated. Furthermore, the role of publicly provided information as a remedy for some information provision problems is critically examined. It is shown that if the publicly provided information is not perfect, its potential for eliminating, or even reducing, private overvaluation cannot be assured.

Next, in Chapter 3, consequences of the joint provision of resources and information are examined in the context of problems of information inexcludability. This essay presents the case in which more than one firm owns land in a geologically related area. Each firm can provide valuable information to the other, and each firm recognizes this predicament. The problem is developed first as one of noncooperative play of a two person game, with particular attention then given to the theory and performance of cooperative institutions for sharing the resource information. This essay is not merely an abstract conjecture, for such cooperative institutions are quite common in the oil industry.

Finally, in Chapter 4, the observation that information is a valuable commodity in natural resource markets is once again combined with the fact that such information is often produced jointly with the oil and gas product to demonstrate that price controls on petroleum properties can produce unintended results. This follows from the alteration in firm optimal extraction paths when price controls are present.

FOOTNOTE FOR CHAPTER 1

1. Oil and Gas Journal, vol, 77 No. 21, May 21, 1979, p. 100.

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CHAPTER 2

THE VALUE OF INFORMATION IN RESOURCE EXPLORATION: THE INTERACTION OF STRATEGIC PLAYS AND INSTITUTIONAL RULES

I. INTRODUCTION

One characteristic of the search for the production of many natural resources is the uncertainty facing firms in the exploration process. Because exploring firms typically must make expenditure decisions before the true state of nature is revealed, perhaps even before the right to produce the resource is allocated, information can be a valuable commodity to the risk neutral firm, and to society. Typical of this early-stage information gathering is the tremendous number of tests, surveys, and analyses performed by oil corporations before the first wildcat exploratory well is ever begun.

In Chapter 1 of this thesis, several aspects of information (indivisibility, inability to define property rights, inexcludability) which can cause a private, competitive market to produce a suboptimal amount of information were examined. In addition, as was shown by Hirshleifer [1971], private competitive markets may have agents which value information so as to lead to private <u>overinvestment</u> in information. This difference in valuation can occur because private purchasers take account not only of the value of the information in increasing the total of expected profits, but also of the potential for privately informed firms to adapt their own actions in a manner which merely serves to redistribute resources away from others. Such information expenditures, aimed solely at redistribution, are, from society's point of view, a wasteful use of resources.

It is undoubtedly true that these three observations about information (information can be valuable; private markets may, in some cases, underproduce information; private markets may, in other cases, lead to an overinvestment in private information) have motivated interest in publicly provided information about natural resources. This discussion has been particularly prominent in the literature concerning the auctioning of offshore oil drilling rights by the U.S. government. Hughart [1975], for example, specifically suggests some type of government information gathering and announcement program as a remedy for problems in private information markets. The United States government, through N.A.S.A., has already entered this domain with Landsat (an earth images satellite which has been used extensively in resource photography [Short, 1977]). Also recently under consideration is a newer technology satellite, Stereosat, which would provide stereographic earth resources images.

The evaluation of existing and potential government information gathering projects, as well as optimal pricing decisions for the information if it is gathered, raises certain fundamental questions about public valuation of information. Some of these issues will be addressed in this chapter in the context of information about natural resources.

First, in section II, a model of decisionmaking about information purchase in natural resource exploration is presented. Then, in section III, the valuation calculus of a competitive market (in which there are no private over-or under-investment problems) is more fully explored.

Often, models of information gathering posit the existence of a single type of information. The reality of natural resource exploration is that there are many types of information, ranging from aerial photographs (such as are provided by the Landsat satellites), to ground surveys, seismic maps, exploratory drilling, etc. Therefore, in section III, information valuation in the context of a multi-source world will specifically be considered.

In section IV, the divergence between private valuation of information and its social value is examined. It will be demonstrated that such overinvestment can occur in situations other than the auction processes where it has already been described.

In section V, it is confirmed that publicly providing information <u>may</u> have value in that it acts as a remedy to private overinvestment. Such a desirable effect cannot always be expected; in fact, it will be shown that public provision of information can, in some circumstances, create incentives for private overinvestment where none otherwise existed.

II. MODELS

As was described in the introduction, often in the remainder of the paper it will be assumed that the resource firm must decide <u>ex ante</u> whether or not to incur some fixed development cost (such as the cost of drilling). These <u>ex ante</u> fixed costs are very important in defining the value of information. For convenience, <u>ex post</u> variable production costs and multi-period extraction paths will not be explicitly included.

It will be shown that the value of information differs according to the institutions used to allocate production rights on a given tract among several firms. In section III, an "institutionless" idealized competitive market will be examined. In section IV the value of information in some models analogous to "real world" institutions will be explored.

The model of firm information choice will be similar to that protrayed in Grayson [1960]. There are assumed to be some number, say J, types of information available. Firms make discrete choices whether or not to buy one or more packages of information (a group of aerial photographs, a seismic survey, etc.). When a firm declines to buy any more information, it may either be abandoning the prospect or proceeding directly to development. It will also be assumed that the firms view the types of information as being offered in some unambiguous ordering (1, 2,..., J), determined exogenously. In considering whether to make information purchase type j, $1 \leq j \leq J$, the firm will be assumed to act as though it realizes that it will act optimally from steps $j + 1$ to J (so the firm is faced with a dynamic programming problem).[1]

At all times, it will be assumed that the firms are risk neutral and interested in maximizing expected profits.

III. THE VALUE OF INFORMATION IN A COMPETITIVE ENVIRONMENT

This section explores the social value of information in competitive circumstances. The term competition is meant to indicate a world in which a competitive firm owns the rights to explore for and produce minerals in a particular area. Also, in this world there are assumed to be no private distributive gains from information [Hirshleifer, 1971]; rather, all gains in expected profits to the firm are assumed also to be net additions to the total well-being of society. The value of information, both to the firm and to society, will be the difference in expected profits with and without that information being available.[2]

As a first pass, the case in which $J = 1$ (i.e., in which firms have access to no other information except that under consideration) is examined. The following definitions will be useful:

x is the amount of resource in place. x is unknown to the firm, and will be considered by the firm to be a random variable

s is a signal, a random variable realized from information source

S is the set of all possible realizations of s

$w(x,s)$ is the joint p.d.f. of x and s

$h(s)$ is the marginal probability of s

$f(x)$ is the marginal probability of x

$g(x|s)$ is the conditional probability of x given s, constructed according to Bayes' rule

K is an *ex ante* development decision, $K \varepsilon \{0,1\}$. (For example, $K = 0$ means don't drill, $K = 1$ means drill.) Where a subscript I is used, as in K_I, this is intended to denote specifically the decision when some information I is available. Likewise, K_N specifically denotes that the information is not available. With no subscript, K denotes either case.

F is the fixed cost associated with $K = 1$.

P is the price of the resource.

If the firm decides to drill, it will incur only the fixed cost, F. Variable extraction costs are assumed to be zero. Under this assumption, the firm will extract all of the resource, and profits, $\hat{\pi}$, will be $Px - F$. If the firm decides not to drill, further profits are zero.

When no information is available, the expected profits of the firm are given by expression (1).

$$\max_{K_N \varepsilon \{0,1\}} \int_0^\infty \hat{\pi}(x,K) f(x)dx \qquad (1)$$

Consider, however, the situation when information is available to the firm (it will be assumed that the firm knows $h(s)$ and $g(x|s)$). In this case, the firm observes s before deciding whether to set K equal to 0 or 1. Therefore, the expected profits for the firm with information can be written as expression (2).

$$\int_S \max_{K_I \varepsilon \{0,1\}} \int_0^\infty (\hat{\pi}(x,K) g(x|s)dx)\ h(s)ds \qquad (2)$$

The value of information to this form is precisely (2) - (1). To see that this is always nonnegative, notice that we can write (1) as

$$\max_{K_I \varepsilon \{0,1\}} \int_S \int_0^\infty (\hat{\pi}(x,K) g(x|s)dx)\ h(s)ds$$

Comparing this with (2) it is clear that the information expands the choices available to the firm; it is always free with the information to act as before, but it is provided with new opportunities to optimize.

There is a special case of the above derivation which is of interest: the case of perfect information. The case of nondiscrete outcomes will be derived here. Calculating the value of perfect information may be useful in that it provides an upper bound on the value of less than perfect information.

With perfect information, every realization of the information signal, s, discloses with certainty that exactly one possible state of the world, x, exists. In fact, we can rescale S so that S = X, the possible range of x. That is, a signal s can be thought of, by definition, as an amount of resource. In this case, the value of information is given by expression (3)

$$\int_0^\infty \max_{K_I \varepsilon \{0,1\}} [\hat{\pi}(x,K_I)] f(x)dx - \max_{K_N \varepsilon \{0,1\}} \int_0^\infty \hat{\pi}(x,K_N) f(x)dx \tag{3}$$

Notice, however, that having received the information, the firm will set K = 1 (drill) for all revealed resource amounts x such that $Px \geq F$. Define x* as x such that $Px^* \equiv F$. Then, (3) can be rewritten as (3') if the decision of the firm without information is K = 1 (drill anyway) and as (3") if without information the tract would not have been developed (K = 0). (The general combination of the two cases is given by (3"').)

$$\int_{x^*}^\infty \hat{\pi}(x,1) f(x)dx - \int_0^\infty \hat{\pi}(x,1) f(x)dx, \text{ if } K_N = 1 \tag{3'}$$

$$\int_{x^*}^{\infty} \hat{\pi}(x,1)f(x)dx \qquad \text{if } K_N = 0 \tag{3''}$$

$$\int_{x^*}^{\infty} \hat{\pi}(x,1)f(x)dx - \max\{0, \int_0^{\infty} \hat{\pi}(x,1)f(x)dx - F\} \tag{3'''}$$

The value of perfect information in the particular model of this section can be expressed in an even more revealing way in expression (4) (when $K_N = 1$) and expression 5 (when $K_N = 0$).

$$-\int_0^{x^*} (Px - F)f(x)dx \geq 0 \quad \text{by definition} \tag{4}$$

$$\int_{x^*}^{\infty} (Px - F)f(x)dx \geq 0 \quad \text{by definition} \tag{5}$$

Expression (4) represents the expected savings from not drilling an otherwise unprofitable tract. Expression (5) represents the expected profits from drilling a profitable structure which, without the information, would have been passed over.

In evaluating one information source, however, there is the possibility that it will not be the only information available for purchase by the firms. In terms of this model, it is necessary to consider cases in which $J \geq 2$.

To capture these new difficulties, an example incorporating two sources of information will be presented. As will become apparent, the extension to more than two sources poses no conceptual problems but is certainly extremely messy. Consider a world in which the competitive form of this section already has available some information I_1 at a cost C_1. As before, the value of another information source, I_0, will be defined as the change in expected profits due to its availability, but with the first information source available in both cases. As will be shown, the information I_0 is valuable not only because it provides information about the resource, but also because it provides new information on which to evaluate the purchase of the first information. There is the possibility that without the new information, I_1 is purchased, yet after having observed the information from I_0, the firm chooses to forego buying I_1, and hence C_1. As Short [1977] noted in an earlier evaluation of the Landsat program by a U.S. oil company, "Major savings in the initial (reconnaissance) stages of exploration are indicated and further savings are suggested for later stages: for example, a reduction in the number of seismic lines that might otherwise have been planned." There is also the possibility that the information I_0 will lead the firm to purchase I_1 in situations in which I_1 would <u>not</u> otherwise be bought. These two possibilities merit a formal examination.

In defining analytically the value of information I_0 (again assumed to be utilized before existing information I_1), the following definitions will be helpful:

s_0	is a signal from I_0; it is a random variable
s_1	is a signal from I_1; it is a random variable
S_0	is the range of s_0
S_1	is the range of s_1

$z(x,s_1,s_0)$ is the joint p.d.f. of x, s_1, s_0

$f(x)$ is the marginal probability of x

$r(x|s_1)$ is the conditional probability of x on s_1

$g(x|s_0)$ is the conditional probability of x on s_0

$p(x|s_1,s_0)$ is the conditional probability of x given both s_1 and s_0

$q(s_1|s_0)$ is the conditional probability of s_1 given s_0

$h(s_0)$ is the marginal probability of s_0

$t(s_1)$ is the marginal probability of s_1.

As was stated above, an important feature of I_0 will be that after the firm receives s_0, it may then perform a new calculus to determine whether to purchase I_1 at cost C_1.

Therefore, define the following two subsets of S_0, Ω_1 and Ω_0, as follows:

$$\Omega_1 = \{s_0 | \text{additional value of } I_1 \text{ (given } s_0) \geq C_1\}$$

$$\Omega_0 = \{s_0 | \text{additional value of } I_1 \text{ (given } s_0) < C_1\}$$

That is, if the firm observes $s_0 \in \Omega_1$, it will proceed to buy some I_1 information; otherwise, it will skip I_1 and go directly to the next choice, optimal K. Using the notation just developed, the value of the new information is given by expression (6).

$$\begin{aligned}
&\int_{\Omega_1}\left[\int_{S_1}\max_{K\varepsilon\{0,1\}}\int_0^\infty \hat{\pi}(x,K)P(x|s_1,s_0)dx\; q(s_1|s_0)dS_1 - C_1\right]h(s_0)ds_0 \\
&\quad + \int_{\Omega_0}\max_{K\varepsilon\{0,1\}}\int_0^\infty \hat{\pi}(x,K)g(x|s_0)dx\; h(s_0)ds_0 \\
&\quad - \max\left\{\left[\int_{S_1}\max_{K\varepsilon\{0,1\}}\int_0^\infty \hat{\pi}(x,K)r(x|s_1)dx\; t(s_1)ds_1 - C_1\right],\right. \\
&\quad \left.\max_{K\varepsilon\{0,1\}}\int_0 \hat{\pi}(x,K)f(x)dx\right\} \qquad (6)
\end{aligned}$$

Expression (6) consists of three terms. The first two define the expected value of the resource with I_0. The last term is the value of the resource without I_0 (which is the greater of the values when I_1 is and is not purchased given that I_0 is unavailable).

An interesting special question to pursue at this point is the following: if I_1 would be purchased absent I_0, under what conditions is $\Omega_0 \neq \phi$; that is, when will public provision of I_0 provide a cost saving by eliminating otherwise purchased I_1?

By definition, the requirement is that there exists some $s_0{}^* \varepsilon S_0$ such that

$$\begin{aligned}
&\int_{S_1}\max_K\int_0^\infty \hat{\pi}(x,K)p(x|s_1 s_0{}^*)dx\, q(s_1|s_0^*)ds_1 - C_1 \\
&\quad < \max_K\int_0^\infty \hat{\pi}(x,K)g(x|s_0^*)dx
\end{aligned}$$

The following theorem provides an intuitive sufficient condition for this to hold, but demonstrates that it is not necessary.

Theorem 1

To insure that public provision of I_0 eliminates all social value to purchasing I_1 regardless of the cost, C_1. The following is sufficient but not necessary:

$$p(x|s_1,s_0) = g(x|s_0) \ \forall \ s_1 \ni q(s_1|s_0) \neq 0$$

■

The proof of the Theorem is contained in the Appendix. In general, Theorem 1 says that I_0 will eliminate all social value for the purchase of I_1 when I_0 is "better" than I_1 in that receiving s_1 in addition to s_0 does not add anything to one's knowledge about the probability of x. An interesting special case is that in which s_0 reveals with certainty the true value of s_1.

As was mentioned previously, even with only two types of information, expression (6) is rather complicated. The same conceptual argument applies when $J \geq 3$ types of information are available, but deriving the expression grows even more cumbersome. The important point is that the new information not only may have value on its own but may also provide gains from an optimal readjustment of the purchase of other categories of information already available.

Two simple, discrete probability examples of the two category case should be useful. These examples demonstrate that if the marginal value calculations of I_0 are made assuming no changes in the purchase of I_1, then these valuations of I_0 are incorrect.

Example III-1: Without I_0, I_1 is purchased.

Let there be four possible states of the world, each occurring with probability 1/4: 0 pounds of ore, 1/2 pound of ore, 3/4 pound of ore, 4.75 pounds of ore. The price of ore is \$2/pound, and the fixed development costs are \$2. There is initially available, at a cost of \$.20, perfect information I_1, over the states of the world. With no information at all, the value of the tract is

$$1/4(\$0) + 1/4(\$1) + 1/4(\$1.5) + 1/4(\$9.50) - \$2 = \$1.$$

With the information I_1, at a cost of \$.20, the value of the tract is

$$3/4\ (\$0) + 1/4\ (\$7.50) - \$.20 = \$1.675,$$

so I_1 would be purchased. Next, suppose that the firm is offered free information I_0 which, with certainty, separates the tract into a worse category (0 pounds or 1/2 pound) or a better category 3/4 pound or 4.75 pounds). Note that, since I_0 adds no new information if I_1 is at hand, I_0 will always be considered first by the firm.

If the signal from I_0, s_0, says that the tract is bad (0 pounds or 1/2 pound), the gross additional value of I_1 is

$$[1/2(0) + 1/2(0)] = (0) = \$0,$$

which is less than \$.20, so the perfect information, I_1, would not be bought. In terms of the formal model, an I_0 signal of "bad" is an element of Ω_0.

However, if the I_0 signal says that the tract is good, (3/4 pound or 4.75 pounds), the gross additional value of I_1 is

$$[1/2(0) + 1/2(\$7.50)] - [1/2(\$1.50) + 1/2(\$9.50) - \$2]$$
$$= \$3.75 - \$3.50 = \$.75$$

which is more than \$.20, so the perfect information would be bought. Again, in terms of the formal model, a "good" signal from I_0 is an element of Ω_1.

Therefore, the total value of the tract, with both I_0 and I_1 available is

$$1/2[\$0] + 1/2[1/2(\$7.50) + 1/2(\$0) - \$.20] = \$1.775$$

so the net marginal benefit of I_0 when I_1 is available is \$.10. As was noted above, if the marginal value calculation of I_0 had assumed that there would be no changes in the purchases of I_1, the marginal additional value of I_0 would have been incorrectly calculated as zero.

Example III-2: Without I_0, I_1 is not purchased.

Again, let there be four possible states of the world, each occurring with probability 1/4: 0 pounds of ore, 1/4 pound of ore, 3/4 pound of ore, 1 pound of ore.

Ore sells for \$1 per pound, and ex ante fixed development costs are \$.40.

There is initially available, at a cost of \$.15, information, I_1, which correctly separates the states of the world into two possible categories

(1 lb, 3/4 lb) or (1/4 lb, 0 lbs).

Without I_1, the expected value of the tract is \$.10. With I_1, purchased at \$.15, the expected value of the tract is

$$1/2(\$0) + 1/2(1/2(\$.60) + 1/2(\$.35)) - \$.15 = \$.0875.$$

So the information would not be purchased.

Suppose that the firm is offered free information, I_0, which correctly separates the tract into the following two categories

(1,1/4) or (0,3/4).

Suppose the realization of I_0, S_0, is that $x \varepsilon (0,3/4)$. With no further information, the expected value of the tract is zero; however, the expected value of the tract (given that $x \varepsilon (0,3/4)$ with the purchase of I_1 at \$.15 is

$$1/2(\$0) + 1/2(\$.35) - \$.15 = \$.025.$$

So, at \$.15 the information will be purchased.

Although it may appear strange that I_0 separates (1,1/4) from

(0,3/4), the example is not far-fetched. Consider the case of a geologic structure described by two characteristics, α and β. (For example, in petroleum exploration there are characteristics such as type of structure, faulting, porosity, permeability, etc.). Suppose information about each characteristic can be either favorable (+) or unfavorable (-). A return matrix for the four combinations could look like Figure 1. In the particular example in this section, α and β would be independent variables each with equal likelihood of producing a positive or negative signal. In such an example, I_1 distinguishes favorable from unfavorable on the β characteristic, while I_0 does the same for the α characteristic.

IV. THE PRIVATE VALUE OF INFORMATION

The previous section has dealt with an idealized competitive market in which all gains to the competitive firm also represent a gain to society. Hirshleifer [1971] has demonstrated that even when markets are competitive, the value of private information can be independent of the social value of the information. Even in a world in which the social value of information (as defined by (2) - (1) in section III) is zero, any one firm or individual might benefit from private knowledge of the true state of the world. Such information, although not increasing the total wealth of society, could allow an individual or firm to take advantage of less knowledgeable agents. A familiar, everyday example (from Montgomery and Quirk [1974]) is the case of horse race gambling: the total well-being of society will probably be little affected by the knowledge of which horse is the fastest, yet

FIGURE 1

		β	
		+	−
α	+	1	1/4
	−	3/4	0

bettors are individually willing to spend a considerable amount on "inside information" from the paddock.

Hirshleifer's arguments for redistributional effects of information were originally couched in terms of the competitive market. Since his work, other authors have shown that particular "real world" resource allocation institutions create an environment for smaller private incentives for redistributional gain. One of the most notable institutions so examined involves a natural resource: the competitive sealed bid auctions for offshore U.S. oil leases (see especially Wilson [1967], Hughart [1975] and Reece [1978]. A more detailed overview of these articles is contained in Chapter 1). The sealed bidding institution can foster incentives for individual firms to purchase information even when such information is not socially valuable (in the sense that ex ante fixed cost decisions can be affected by the availability of the information, as was described in section III).

An example of the incentives for private information purchase in a model which incorporates sealed bidding and fixed cost drilling technology will be developed in this section. Because information can be made available in contexts besides the auction procedure adopted by the U.S. for offshore oil drilling, in this section two other conceivable "real world" institutions also will be considered:

i) face to face bargaining with a preselected firm; and
ii) noncompetitive leasing.

Competitive Sealed Bid Auctions

Hughart [1975] demonstrated a model in which even when information is socially valueless, firms participating in a competitive sealed bid leasing program can have private incentives to purchase information. Here it will be demonstrated that analogous results still hold when fixed production costs and socially valuable information are introduced. The following assumptions are from Hughart's work:

1) There are two risk neutral firms A-Co. and B-Co.
2) There are N tracts of land to be leased separately in N sealed bids, competitive auctions. Before any information is available, both firms agree that, with probability g, a given tract is "good" (it contains X_G resources) and and with probability (1 - g) it is "poor" (it contains X_P resources). Call the price of the resource P.

Unlike in Hughart's model, suppose that there is a fixed drilling cost, F. The following additional assumptions will be utilized here:

3) The expected amount of resources on a given tract is $X_M = g(X_G) + (1 - g)X_P$
4) $P \cdot X_M = F$, so that with no information, each tract would be just marginal.
5) $P \cdot X_P < F$, so that a tract known to be "poor" will not

be developed, and prior perfect information is socially valuable in the amount $(1 - g)(PX_P - F)$.

6) Both firms know g, X_G, X_P, P.

Now, suppose that A-Co. has private access to the prior, perfect information. Unlike in Hughart's model, information is not directly about the value of the tract; rather, information is obtained on the physical characteristics, X_G or X_P, of the tract. In fact, the expected value of any tract is ex ante higher for A-Co. than for B-Co.

First, note that the assumed information asymmetry will be maintained by A-Co. If A-Co. gives the perfect information to B-Co., the resulting equilibrium outcome will result in each firm receiving zero profits, as each bids zero on the poor tracts and bids $(q \cdot X_G - F)$ on the good tracts. If A-Co. keeps the information private, it knows that B-Co. can never bid any positive amount for either tract because B-Co. would then only win the valueless properties. A-Co. can guarantee itself a strictly positive expected profit, while B, at best breaks even.[3]

The penalties of being ill informed and the profits of being the best informed provide an incentive for each firm, if given the opportunity, to purchase the private information (and not transfer it at marginal reproduction cost). From society's point of view, this is an overinvestment in private information, a waste of resources.

Direct Negotiations with a Pre-chosen Firm

Consider a country, B, which has chosen to distribute its mineral leases via face to face negotiation with a preselected firm, A. Assume that both are risk neutral, and that there exist two possible states of the world, each with probability 1/2 (recognized by both parties).

$$X_1 = 1{,}000{,}000 \text{ pounds/ore}$$
$$X_2 = 10{,}000{,}000 \text{ pounds/ore}$$

It will be assumed that all ore is sold in one year at a net price of $20/pound. In this example, suppose that there are no fixed costs of production, so information is "socially valueless" in the sense of section III. The question to be explored here is whether firm A will find information privately valuable.

The total of expected profits from this resource is

$$1/2(\$20 \text{ million}) + 1/2(\$200 \text{ million}) = \$110 \text{ million}$$

Suppose that, after face to face negotiations, the government of B and firm A agree that B will receive expected profits of $65 million, payable either in a resource payment or in royalties on the remainder not given as resource payment. (A resource payment is an agreement in which the first "y" pounds of production, where "y" is a prearranged amount, is given directly to the leaseholder.) With no further information, A's expected profits are $45 million.

Suppose that A were offered perfect, private information about the resource X. How would this affect A's profits?

If A knows before hand that X_1 (X = 1,000,000 pounds of ore) will occur, he can offer B a payment schedule with no resource payment and a royalty of 13/22 of the output. B will be satisfied, as this plan's expected profits are

$$1/2(13/22 \times \$20 \text{ million}) + 1/2(13/22 \times \$200 \text{ million}) = \$65 \text{ million}.$$

A's sure return, knowing that X_1 will occur, is

$$9/22 \times \$20{,}000{,}000 = \$8.18\overline{18} \text{ million}.$$

On the other hand, if A knows that X_2 will occur, he can offer B a resource payment of one million pounds and a royalty of one half of the remainder of the output. Again, B views its expected profits as:

$$1/2(\$20 \text{ million}) + 1/2(\$20 \text{ million} + 1/2(\$180 \text{ million})) = \$65 \text{ million}$$

while A knows that its profits will be

$$1/2(\$180 \text{ million}) = \$90 \text{ million}.$$

Therefore, the expected profits for A operating from a full information position are

$$1/2(\$8.18\overline{18}\text{ million}) + 1/2(\$90\text{ million}) = \$49.09\overline{09}\text{ million}$$

That is, perfect information has a value to A of $\$4.09\overline{09}$ million. A would do well to spend up to this amount to achieve an expected redistributive gain. From the view of increasing the total expected profits of the economy, such expenditures are wasteful. With no fixed costs of production, the same production decision (to open the mine) will be made regardless of the outcome of the effort to acquire information.[4]

Lottery with an Aftermarket

The United States Department of Interior's Bureau of Land Management is authorized to award prospecting permits (which carry a preference right for leasing) on a first come, first served basis.[5] In practice, a public deadline is set, and all applications received are considered to be simultaneously submitted. The winner is then chosen by a public drawing. The preference right leases may be transferred, so in theory (and apparently in practice)[6] there is an aftermarket for them.

This section will concentrate on the lottery feature of this institution. Once the leases are awarded, the further potential value of information, public or private, will depend upon how the market is organized. The previous examples (competitive, bidding, direct negotiation) could easily be applied to the aftermarket. Its role as a secondary market causes no major analytical problems.

So, consider just the lottery part of the situation. Let X be a lease for which applications are being accepted (for purposes of this paper, the original prospectus permit and the subsequent preference lease right will be considered as one). Suppose that

1) There are N risk neutral potential bidders
2) There are two possible states of the world, which each bidder believes will occur with probability 1/2:
   $X_1 = X_P$ lbs/ore
   $X_2 = X_G$ lbs/ore, $X_G > X_P$
3) Ore sells for \$q/lb; all ore will be sold the first year
4) There are fixed costs of production of \$F
5) $qX_1 - F < 0$, so information is socially valuable
6) There are no costs of participating in the lottery
7) The winner of the lottery may costlessly forfeit if desired.

The winner of the lottery will consider purchasing the valuable information in order to increase expected profits. However, the outcome of the lottery is itself a random event. Knowledge about the true state of X does not change the probability of winning for any participant, nor does it offer any possible reduction in costs from the lottery itself. Therefore, none of the individuals will value any private information before the lottery and the lottery per se induces no wasteful purchase of information.

If Assumption 6 or 7 is modified so that participating in the lottery entails a fixed cost,[6] or if the winner is subject to fees which are unavoidable by forfeiture, then each participant can value private information which allows him to avoid auction costs or lease fees on bad tracts.

V. PRIVATE INFORMATION PURCHASE AND THE VALUE OF PUBLIC INFORMATION

In situations in which more than one firm finds that there is a private value of information, the resulting individual firm decisions on information purchase can be viewed initially as an N-person, noncooperative game. In this section, it will be shown that, in many situations, the resulting model will be a classic prisoner's dilemma. Each firm buys the private information, yet when all firms are purchasers, each firm is worse off than if none bought.

In section III, it was shown that among the benefits of public information is the possibility of making otherwise scheduled information purchase unnecessary. There is a similar principle which applies to private information. Publicly provided information may have benefits beyond its own direct social value if its dissemination eliminates the waste of resources which otherwise would have occurred through overinvestment in private information for redistributive gain. Thus, public (i.e., government) information gathering and announcement are often recommended as a means of eliminating wasteful private duplication (Hughart 1975). In this section, publicly provided information will be examined along with another possible remedy, cooperative information gathering. It will be shown that each has drawbacks. Specifically, however, it will be demonstrated that public information provision not only may fail to alleviate private overinvestment, it may actually make matters worse.[9]

Consider a world consisting of precisely two firms. Because the world consists of only these two firms, define "social well-being" to be the sum of the firms profits. When information has no social value, the maximum expected joint profits of the firms are not increased by information. If obtaining the information represents a cost to the society of $C > 0$, then maximum social well-being requires that C not be purchased. However, when it is the case that a privately informed firm gains some redistributive benefit $y^* > C$ from an ill-informed firm, there is the possibility of private incentives to purchase information. (It will be assumed that if both firms are informed, no redistribution occurs.) These assumptions can be represented by a 2-person game in normal form (Figure 2), in which the entries are profits (represented as changes from the don't buy/don't buy social optimum). The noncooperative dominant strategy equilibrium is (buy, buy) which is strictly Pareto dominated by (don't buy, don't buy), a classic prisoner's dilemma situation.

If cooperative behavior is allowed, no joint information gathering will occur, for the maximum expected joint payoffs occur when no information at all is purchased. The only efficient cooperative behavior is some type of binding agreement that prevents either firm from gathering information.

If both firms are given perfect public information,

FIGURE 2

		FIRM B	
		Don't buy info	Buy info
FIRM A	Don't buy info	0, 0	-y*, y* - C
	Buy info	y* - C, -y*	-C, -C

then there is no longer any incentive for further overinvestment in that particular private information. In fact, public information which is "better" in the sense of Theorem 1 in section III will, by a proof identical to that of Theorem 1, eliminate that particular private incentive to overinvestment. Thus, the "social maximizer" attempting to maximize the joint expected profits of the firms, would consider two policies: i) an institution which prevents any information gathering at all (at some cost Cs_1): or ii) public information provision (at some cost Cs_2). Neither policy is valuable in and of itself, but each may prevent the waste of resources, 2C, on private information.

Next, consider a case in which the information <u>is</u> socially valuable in that it increases joint expected profits by $w > C$. Of course, if both firms privately purchase the information at cost C, resources are wasted. Assume that if one firm is perfectly informed, while the other is not, the informed firm obtains all the social benefits, w, plus some net redistributive transfer $u \geq 0$. If both firms are perfectly informed, each receives some share, α or β, of w, where $\alpha + \beta \leq 1$. Then, assuming $\alpha w - C > 0$ and $\beta w - C > 0$, the game matrix can be represented by Figure 3.

Again, when $\alpha w - c \geq -y$, overinvestment in information is still the dominant strategy equilibrium with total payoffs $(\alpha + \beta)w - 2C$. In this case, however, optimal joint expected profits can be achieved by voluntary, cooperative information gathering by the firms, as the social optimum is not (don't buy, don't buy) but rather either (don't buy, buy) or (buy, don't buy), with payoffs $(w - C)$.

FIGURE 3

FIRM B

		Don't buy	Buy
FIRM A	Don't buy	$0, 0$	$-y, w + y - C$
	Buy	$w + y - C, -y$	$\alpha w - C, \beta w - C$

Providing better public information also eliminates the incentives for private information purchase.

A strong caveat is in order at this point. The assumption of a society of only two firms excludes the case of efficiency losses from cartel behavior by the two firms, or a redistribution away from other parties. In a world of more than two firms, competitive behavior would require that cooperation be limited strictly to the process of gathering information. The extent to which firms can cooperate on information gathering and not be able to collude in other aspects is an open question.

To see the problems which potential collusion can cause, a third model will be presented in which there is a third, passive player in the game. The payoffs to the third person are a function solely of the actions of the two firms. As in the bidding model, this player might be a government holding a lease auction. It will be assumed that information is socially valuable (and that society's well-being is defined as the sum of profits to the two firms and to the passive third party). If neither firm is informed, neither makes any profits and some "uninformed" return, w, accrues to the third party. However, suppose that if some information is gathered at cost C, there is a higher level, w*, in expected total profits. If both firms are informed, each firm captures ε of the informed profits, w*, and the third party receives $w^*(1 - 2\varepsilon)$. (It will be assumed that $1/2 \geq \varepsilon \geq 0$.) If only one firm is informed it receives a transfer $y^* \geq 0$ from the other firm, as well as some other fraction $0 \geq \delta \geq 1$ of the informed return, w*. It is reasonable to believe that, as in the bidding model, it is better to be the only one informed, so let $\delta w^* + y^* > 2\varepsilon w^*$. The payoff matrix is presented in Figure 4, with the third entry in each cell representing the "third party." Overinvestment in private information will be a dominant strategy only when: i) if both firms are informed, each one's share of the total profits less the cost of purchasing the information is greater than the penality to being the only one uninformed ($\varepsilon w^* - C \geq -y^*$); and ii) if only one firm is informed, its redistribution from the uninformed firm plus its additional share of the informed total profits is greater than the cost of the information ($\varepsilon w^* + y^* - C \geq 0$).

Consider voluntary cooperative behavior on the part of the firms. The total of profits to the two firms is i) the informed firms increment from the informed total profits less informations costs ($\delta w^* - C$) when only one firm buys the information; ii) zero, when neither firm buys the information; or iii) the total of the two firms' share in total profits, less twice the information costs ($2\varepsilon w^* - 2C$) when both purchase the information. If the share of the only informed firm in the higher level of profits is greater than the information costs ($\delta w^* > C$), then the firms will find their cooperative strategy is to purchase the information once, then act towards the third party as though (don't buy, buy) or (buy, don't buy) is their strategy, and finally to arrange appropriate side payments. In terms of the bidding model, this means that the firms' cooperative behavior must include cooperative information purchase and a collusive bidding strategy identical to the one that

FIGURE 4

		FIRM B	
		Don't buy	Buy
FIRM A	Don't buy	$0, 0$ (w)	$-y^*, \delta w^* + y^* - C$ $([1 - \delta]w^*)$
	Buy	$\delta w^* + y^* - C,$ $-y^*$ $([1 - \delta]w^*)$	$\varepsilon w^* - C, \varepsilon w^* - C$ $([1 - 2\varepsilon]w^*)$

would occur in the (don't buy, buy) or (buy, don't buy) noncooperative case. If the firms jointly purchase information but bid competitively against each other on the basis of that information, the returns are ($\varepsilon w^* - C/2$) to each firm and ($[1 - 2\varepsilon]w^*$) to the government.

If the firms are constrained in their possible cooperation so that only cooperative information gathering (not collusive bidding strategies) is allowed, then each would prefer that outcome ($\varepsilon w^* - C/2, \varepsilon w^* - C/2$) to the result of double purchase ($\varepsilon w^* - C$, $\varepsilon w^* - C$), although each could still prefer (0,0) where each firm is prevented from purchasing any information at all. Once again, if "better" public information is provided, the incentives for private purchase of the information disappear.

In the preceding three models, the prescription for publicly provided information might appear to be rather robust: the models let the private information be socially valueless or valuable, and passive third parties do not affect the result. For these conclusions to hold, the provision that the public information be "better" than the private is crucial, as the following examples demonstrate.

Example V-1: In the following, publicly provided information fails to eliminate a strictly positive incentive for overinvestment in private information of another kind.

Let X be an ore deposit. Let there be four possible states of the world, each occurring with probability 1/4:

X_1 = 0 tons $\qquad$ X_3 = 2 tons

X_2 = 1 ton $\qquad$ X_4 = 4 tons

Assume that there are N risk neutral firms, each of which shares the above subjective probability over outcomes, and each of which is endowed with a 1/N share of ownership of the ore depost. Each of the N firms will buy or sell shares in the deposit for the perceived expected value. For purposes of this illustrative example, suppose $N = 2$, and consider the following further assumptions:

i) ore sells for $1/ton

ii) there are no fixed extraction costs; public information has no social value.

Suppose that there is available for private purchase at $.10 perfect information over the true state of the world. Each firm will calculate the value of that private information as follows: with no information at all, the expected value of a 1/2 share in the venture is $.875. On the other hand, the firm must examine its optimal strategy with private, perfect information. If X_1 or X_2 is known, the informed firm can increase its profits by selling its 1/2 share to the uninformed firm at $.8750. If X_3 or X_4 is known, then the informed firm can increase its profits by buying out the partner at $.8750. Therefore, the informed firms expected profits are

$$1/2(\$.875) + 1/4(\$2 - .875) + 1/4(\$4 - .875) = \$1.50$$

The gross value of the information, \$.625, is greater than its cost, so the information has a net positive value. Similar calculations will show that the expected return from being uninformed is \$.25, creating a prisoner's dilemma type situation that leads to information overinvestment. See Figure 5.

Suppose that "the government" distributes, free of charge, public information which would correctly separate the world into two possibilities $\{X_1, X_2\}$ or $\{X_3, X_4\}$. If the public information narrows the possibilities to $\{X_1, X_2\}$, and there is no further information, the expected half-share payoff is:

$$1/2(1/2(0) + 1/2(1)) = \$.25.$$

If a firm has the private information, the expected gross return is (using similar calculations) \$.50. Again, the gross value of the information exceeds the cost, \$.10. The return to being the only one uninformed is zero, so overinvestment in the private information still occurs, as depicted in the game in Figure 6. Likewise, if $\{X_2, X_3\}$ is the revealed pair, the expected payoff chart can be represented by Figure 7. Despite the public purchase of the first information package, the dominant strategy equilibrium is to overinvest in the perfect private information. Therefore, the "government" has invested some C* in public information, yet has not caused any reduction in private investment in information.

One key feature of the previous example is that the private information provides knowledge about the world which the

FIGURE 5

		FIRM B	
		Don't buy	Buy
FIRM A	Don't buy	$.875, $.875	$.25, $1.40
	Buy	$1.40, $.25	$.775, $.775

FIGURE 6

FIRM B

		Buy	Don't buy
FIRM A	Buy	.25, .25	0, 40
	Don't buy	.40, 0	.15, .15

FIGURE 7

FIRM B

		Don't buy	Buy
FIRM A	Don't buy	1.50, 1.50	1.00, 1.90
	Buy	1.90, 1.00	1.40, 1.40

public information does not. Of course one could construct intermediate cases in which public information of one type eliminates some but not all overinvestment in other private information. The other key feature is the pattern of states-of-the-world which the public information will differentiate.

This example suggests that existing private overinvestment can remain unchecked by publicly provided information. In fact, the results can be even worse. In some cases providing some (imperfect) public information can create incentives for wasteful private overinvestment. This observation follows directly from example III-2, in which the presence of one type of information can increase the value of another.

Example V-2: A case in which publicly provided information creates incentives for later private overinvestment.

To see this point, consider a situation similar to the preceding example: let there be two firms sharing in a venture with four possible outcomes:

X_1 = 0 tons $\qquad$ X_3 = .6 tons

X_2 = .45 tons $\qquad$ X_4 = .65 tons

each occurring with probability 1/4. Again assume that

i) ore sells for \$1/ton

ii) there are no extraction costs; public information has no social value.

Each firm will buy and sell shares in the venture for the perceived expected value. What each firm must decide is whether or not to purchase, at a cost of \$.12, information which correctly separates the world into two categories: {0,.45} or {.6,.65}. Without such information, 1/2 of the expected value of the tract is

$$1/2(1/4(0 + \$.45 + \$.60 + \$.65)) = \$.2125.$$

With the information, the gross value of the tract is

$$1/2(\$.2125) + 1/2(\$.625 - \$.2125) = \$.3125$$

So, the gross value of the information is \$.10 and it would not be purchased.

Suppose that public information is released which correctly reveals that the true state of the world is either {0 or .6} tons. Now, 1/2 of the expected value of the venture is \$.15. However, with private information which correctly indentifies {0,.45} or {.60,.65}, the gross value of the tract is

$$1/2\{.15\} + 1/2\{.6 - .15\} = \$.30$$

That is, after the public information is released, there is <u>increased</u> private overinvestment, as a prisoner's dilemma (depicted in Figure 8) has been created.

FIGURE 8

		FIRM B	
		Don't buy	Buy
FIRM A	Don't buy	.15,.15	0,.18
	Buy	.18,0	.03,.03

Thus, when the public information is not perfect, not only may it not work as a remedy to private overinvestment, it may actually generate more wasteful duplicate private purchase than would otherwise have occurred.

These two examples demonstrate that it is not a general proposition that publicly provided information will eliminate private overinvestment in information.

The examples do not themselves indicate any general guidelines for anticipating the "perverse" result that even more private investment can result.

It was noted earlier in this section that when public information is better (in the sense of Theorem 1) than the private information, private overinvestment will be eliminated. When this condition is not true, the results are ambiguous. The following theorem, proved in the Appendix, provides necessary but not sufficient conditions for public information never to create incentives for private investment where none otherwise existed.

Theorem 2

Suppose there are two firms and two types of information: i) I_1 is available for private purchase, and ii) I_o which the government is considering providing publicly, with s being a particular realization of the signal from I_o. Define the following:

V_N^s is the expected gross to one firm if neither purchases I_1, if s is observed from I_o

V_+^s is the expected gross return to the only firm purchasing

I_1 if s is observed from I_o

V^s_- Is the expected gross return to the only firm not purchasing I_1 if s is observed from I_o.

V^s_B is the expected gross return to one firm if both purchase I_1, if s is observed from I_o.

C is the cost of purchasing I.

The following two conditions are jointly necessary but not sufficient to insure that it is always a dominant strategy not to privately purchase I_1 if the government provides I_o.

1) $E(V^s_N) \geq E(V^s_+) - C$

2) $E(V^s_-) \geq E(V^s_B) - C$ □

This theorem says that to insure that no private incentives for overinvestment occur for any realization of the public information, it must be true for each firm that the expected returns from purchasing the information must be less than or equal to the expected returns without the information regardless of the actions of the other firm. Even if this condition holds, "perverse" results can still occur at some realizations of I_o, the public information.

When a prisoner's dilemma (such as has been modelled in this section) exists, firms realize that if they are market participants, their dominant strategy will be to purchase private information. The structure of incentives, therefore, creates a fixed cost to potential resource extraction firms. As fixed costs can pose barriers to entry, the incentives for private overinvestment may have the side effect of making the market less competitive than otherwise. Unfortunately, since public information provision may allow for more, less, or the same expenditures on subsequent private information purchases, the net effect of the public information on the resulting market structure is ambiguous.

The partial equilibrium approach utilized in the examples in this section may overstate the potential for private overinvestment compared to a general equilibrium appraoch. As Montgomery and Quirk [1974] have pointed out, the informed firm which attempts to obtain financing for its transactions in imperfect capital markets may be required to divulge the results of the private information to the source of funds. The extent to which natural resource firms actually face this problem in exploration or pre-auction capital transactions is not explored here.

VI. SUMMARY AND CONCLUSIONS

Information can be a valuable commodity in natural resource exploration, even to the risk neutral firm. It is clear that natural resource firms recognize and procure many types of exploratory information. Such a multi-source information decision problem can be modelled, and the resulting value of information defined. Such a calculus necessarily takes account of the effects of one type of information on the optimal purchase of other types.

The valuation of information by private firms may differ from that of society in that private purchasers may value information in order to obtain strictly redistributional gains. This has been a particular concern with regard to the auctioning of offshore oil leases. In sections IV and V of this paper, it was noted that, while the role of information may differ in contexts other than competitive auctions for oil leases, the problem is not unique to auctioning among real world allocation processes.

Public information provision has been suggested as a remedy for private incentives to overinvest in information. It was shown that, while public information may in some cases eliminate private overinvestment, this is not a general result if the public information is not better than the private. Unfortunately, it is not realistic to believe that a government can release perfect natural resource information, so the problems of overinvestment remain. As an aerial photograph would not reveal with certainty the presence of oil, the potential would exist for further private investment in other types of information, such as seismic or magnetic surveys, even with publicly provided information.

APPENDIX FOR CHAPTER 2

Proof of Theorem 1

Again, the theorem states that

$$p(x|s_1,s_0) = g(x|s_0) \;\forall\; s_1 \ni q(s_1|s_0) \neq 0.$$

is sufficient but not necessary to insure that I_0 eliminates all value to I_1 . Note that if public provision of I_0 eliminates the further incentive to purchase I_1 when $C_1 = 0$, it certainly eliminates that incentive if $C_1 > 0$. Therefore, consider the case of the expected profits from having I_1 (given that I_0 has been revealed to be S_0^*) when the cost of $I_1 = 0$. These expected profits are given by expression (A-1).

$$\int_{S_1} \max_K \int_0^\infty \hat{\pi}(x,K)p(x|s_1,s_0^*)dx\; q(s_1|s_0^*)ds_1 \tag{A-1}$$

By the condition of the theorem, one need consider only $s_1 \in \{s_1|q(s_1|s_0^*) > 0\}$. Call this set $\hat{S}$. Then (A-1) becomes (A-2).

$$\int_{\hat{S}} \max_K \int_0^\infty \hat{\pi}(x,K)p(x|s_1,s_0^*)dx\; q(s_1|s_0^*)ds_1 \tag{A-2}$$

Again using the condition, one can substitute $g(x|s_0^*)$ for $p(x|s_1,s_0^*)$ and obtain (A-3).

$$\int_{\hat{S}} \max_{K} \int_0^{\infty} \hat{\pi}(x,K)g(x|s_0^*)dx \; q(s_1|s_0^*)ds_1 \tag{A-3}$$

But the middle part of (A-3) is independent of s_1, and so can be brought outside the integral sign to give (A-4).

$$\max_{K} \int_0^{\infty} \hat{\pi}(x,K)g(x|s_0^*)dx \int_{\hat{S}} q(s_1|s_0^*) - \max_{K} \int_0^{\infty} \hat{\pi}(x,K)g(x|s_0^*)dx \tag{A-4}$$

Expression (A-4) is precisely the value of expected profits without purchasing any additional information I_1. Since I_1 has not increased expected profits at all, it is valueless. The choice of s_0^* was arbitrary, so the result holds regardless of the outcome of information I_0.

To see that the condition in the theorem is not necessary, consider the following example:

Let X take on, with equal (1/4) probability, one of four states

X_1 = 0 pounds/ore
X_2 = 1 pound/ore
X_3 = 19 pounds/ore
X_4 = 20 pounds/ore

Suppose ore sells for \$1/pound, and that fixed mining costs are \$10. Let I_1 be perfect, sure information about the true state of X. Let I_0 correctly separate the world into two categories:

Good: $X = \{X_3 \text{ or } X_4\}$

Bad: $X = \{X_1 \text{ or } X_2\}$

Simple calculations will show that regardless of the cost of I_1, there is no value to purchasing it after I_0 is provided. Yet, the condition of the theorem is violated.

Proof of Theorem 2

For each realization s of the public information I_0, the following game matrix is created:

		Firm B	
		Don't Buy	Buy
Firm A	Don't Buy	V_N^s, V_N^s	$V_-^s, V_+^s - C$
	Buy	$V_+^s - C, V_-^s$	$V_B^s - C, V_B^s - C$

If, for the realization s, "Don't Buy" is a dominant strategy, then the following two conditions must hold:

$$V_N^s \geq V_+^s - C \text{ ; and} \tag{A-5}$$

$$V_-^s \geq V_B^s - C \tag{A-6}$$

It follows that if "Don't Buy" is a dominant strategy for all realizations of the public information, I_0, then the expectations of the expressions (A-5) and (A-6) must yield the same inequalities:

$$E(V^s_N) \geq E(V^s_+) - C \qquad \text{(A-7)}$$

$$E(V^s_-) \geq E(V^s_B) - C \qquad \text{(A-8)}$$

To see that (A-7) and (A-8) are not sufficient conditions, consider Example V-2. Had the public information revealed instead that one of {.45 or .65} was the true state of the world, then the payoff matrix for the private information problem would be as follows:

		FIRM B	
		Don't Buy	Buy
FIRM A	Don't Buy	.275, .275	.225, .205
	Buy	.205, .225	.155, .155

Not purchasing the private information is a joint dominant strategy equilibrium. Yet, combining this result with the similar numbers from figure 8, the following relationships obtain:

$$E(V^s_N) = .2125 \geq .1925 = E(V^s_+) - C$$

$$E(V^s_-) = .1125 \geq .0925 = E(V^s_B) - C$$

The two necessary conditions of the theorem hold, yet Example V-2 demonstrates that private investment incentives are created at one realization of the public information.

FOOTNOTES FOR CHAPTER 2

1. The problem can be elaborated to allow the firm to choose the most profitable from among the J! possible sequences of J types of information.

2. It is assumed that all firms' probabilistic expectations over the information are consistent with their expectations directly over the states of the world. That is, if a firm believes that (with probability 1/2) $X = 0$, and (with probability 1/2) $X = 1$, then it must also believe that perfect information about X will reveal $X = 0$ and $X = 1$ each with probability 1/2.

   This approach to the value of information involves *ex ante* optimization. For a discussion of the distinction between *ex ante* and *ex post* optimality, see Starr [1973]

3. In this special example, the equilibrium concept which is used is the Nash equilibrium. For example, when both firms are informed the following strategy

   $(P \cdot X_G - F)$ on good tracts

   No bid on poor tracts

   when used by each firm is a Nash equilibrium. Likewise, when A-Co. alone is privately informed, the following bidding strategy is a Nash equilibrium for A-Co.: 0 on good tracts; No bids on bad

B-Co.: No bids at all

Expected profits A-Co. = $Ng(P \cdot X_G - F)$

Expected profits B-Co. = 0

Hughart's model incorporates a slightly more complicated leader/follower equilibrium. This is explained more fully in Chapter 1. Hughart's assumption of common knowledge by all firms of the other assumptions is maintained.

4. This example shows that private overinvestment incentives occur even outside a system of sealed bidding for oil leases. It is not designed to be a definitive description of such a bargaining problem, which could have strategic behavior on both sides at many levels.

5. 43 C.F.R. §3511 and 43 C.F.R. §3520

6. 43 C.F.R. §3506 and <u>Oil and Gas Journal</u>, Vol. 77 No. 24, June 11, 1979, pp. 34-35.

7. According to the <u>Oil and Gas Journal</u> (op. cit.) the filing fee for noncompetitive leasing onshore is $10. In addition, there is a $1/year lease rental fee.

8. The approach taken in this chapter draws upon insight from Ferejohn and Noll [1978].

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CHAPTER 3

COOPERATIVE INSTITUTIONS FOR INFORMATION SHARING IN THE OIL INDUSTRY

I. INTRODUCTION

Finding and producing petroleum is an inherently risky undertaking. In such an environment of uncertainty, information can be a valuable commodity.[1] There are several ways in which an oil firm can obtain information about a prospect. There are well defined markets in which certain scientific measurements or records can be obtained (aerial photographs, seismic surveys, the labor market for geologists and geophysicists, etc.). But it is also true that the actual drilling, logging, coring, and producing from a subsurface structure can provide information.[2]

An important feature of petroleum exploration and development is that information obtained about one geological feature is often useful outside of a particular drilling site. Such information can give a better picture not only of a portion of a potential stratum but also of the entire reservoir and even of entirely separate prospects with similar geological features. Thus, there are many opportunities for an oil company, through its own information gathering procedures, to obtain information valuable to others. In this respect, as one firm, X, has a commodity (information) which another firm, Y, values, there is the possibility of mutually beneficial exchange. Oil field information often also has the property of "non-excludability" in which one firm is unable to prevent another firm from sharing in the valuable information if they do not agree upon terms of exchange.

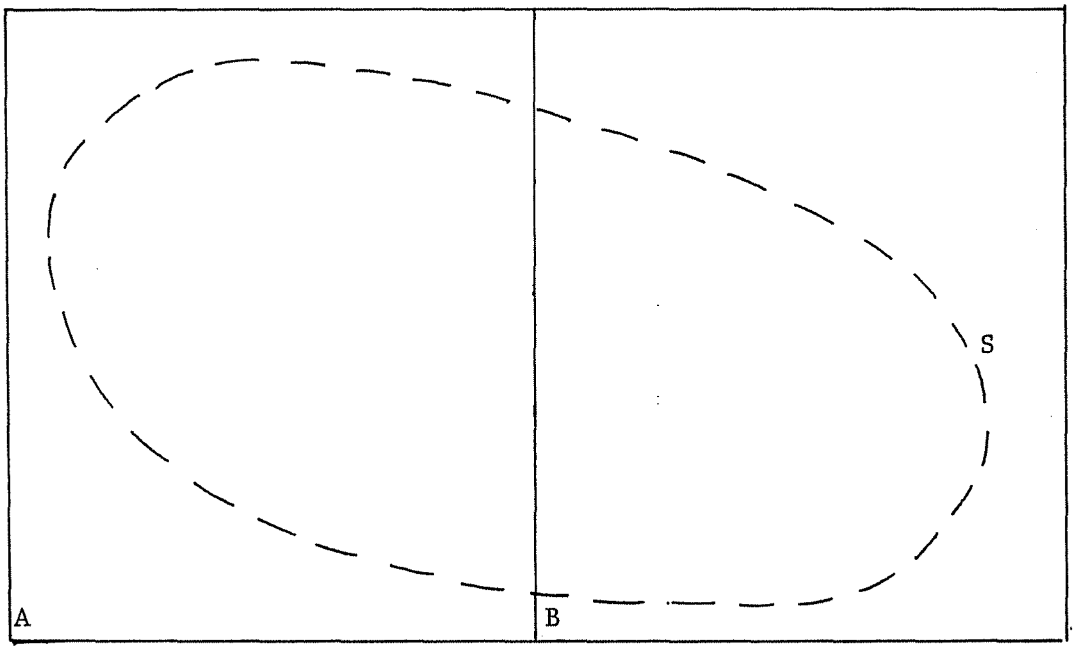
Information is thus often a public good. For example, while a firm may be able to keep the results *per se* of a seismic survey private, if the firm acts upon the information in some particular way, say, by commencing drilling on a wildcat prospect, the firm may "tip off" others.[3] Likewise, the results of completed test drilling may not easily be kept secret. It is typically observed that successful discoveries on one lease will drive up the value of surrounding acreage.[4] This is an indication that the first discovering oil firm, if it does not already own all the relevant adjacent acreage, is giving away valuable information to others. In fact, the mere initiation of drilling activity on land previously thought to be worthless should increase the value of the mineral rights of surrounding land by the capitalized value of the information. In these cases, surrounding lease owners are in the position of being "free riders" off the first person to begin drilling.

This paper is concerned with a special case of such information externalities, namely those in which there is more than one firm owning "informationally related" prospects and in which each firm has the opportunity to be a free rider in receiving information paid for by another. A simple example is depicted in Figure 1. The dotted line indicates the boundaries of a geological formation which has two tracts, A and B; each tract is owned by a different firm. Suppose that drilling a well on either property yields valuable information about both. Furthermore, suppose that the information obtained through drilling is not excludable, so the owner of A can gain information if drilling takes place on B, and vice versa. If the external information flows are valuable, the model represents a conflict of interest which can be modeled in the framework of game theory. This game theoretic model of two firms and "nature" is essentially the one employed by Stiglitz [1975].

Using this game theoretic model, it is easy to show that when the conflict takes the form of a noncooperative, variable sum game, a suboptimal outcome can result. However, the more important part of this paper will be to examine the role of some "real world" institutions which Grayson calls "trading" arrangements (Grayson [1960]). These institutions will be described in more detail in a later section, but the essential feature which will be modeled here is that they transform the noncooperative game to a cooperative game with side payments. In some instances the existence of these trading arrangements allows the players to reach an optimal outcome.

In an earlier paper, which does not specifically consider the existence of these trading institutions, Peterson argues that the presence of information externalities in exploration suggests the need for government subsidies (Peterson [1975]).[5] A similar

FIGURE 1



argument was made by Stiglitz (1975). To the extent that cooperative information sharing institutions ameliorate effects of the externality, the need for government assistance is no longer indicated. However, it will be shown in this paper that the voluntary trading arrangements are not a cure-all. There are circumstances in which suboptimal results can still occur. This paper will attempt to distinguish the conditions in which the private trading institutions will fail from those in which they will be more successful. Particular attention will be paid to those cases in which all firms realize that they will be strictly better off by playing the game cooperatively. When this is true, the existence of trading agreements suggests that their evolution is a natural or expected institutional adaptation.

II. THE NATURE OF THE PROBLEM

Referring again to Figure 1, consider a tract of land under which there is a geological structure S. Suppose that the surface projection of S (represented by the dotted line) is divided in terms of ownership between two different tracts, called here A and B, which have different owners. Because of this overlap, it will be assumed that the two tracts are informationally related[6] and that each owner has precisely two ways of obtaining information about its own tract: i) drilling a wildcat exploration well that produces nonexcludable information, or ii) free-riding off of the information provided if the other firm drills a wildcat exploration well.

Such information overlaps are common in oilfield exploration. The problems caused by the resulting externality are well recognized. There is no question that the oil industry observes and acts upon the information externally. From the nineteenth century until today, the "oil scout," whose job is to gain such information, has been a recognized job description, although the methods employed have changed to some extent. In 1882, the owners of a Pennsylvania well nicknamed "646" fenced the drilling site and surrounded it with armed guards. Yet, "with oil scouts dangling from every available tree and bush, the flow of news from '646' grew every day" (reported in Williamson and Daum [1959], pp. 390-393). In the 1950s, oil scouts from different companies but assigned to the same geographical region would often compare notes. The uncooperative would sometimes find themselves the target of a "scout check," a weekly meeting in which each oil scout reported to the group what he had found out.[7]

It is also clear that the oil industry recognizes the potential gains from directly cooperating in the drilling/information gathering process. For example, John R. Kennedy [1976] remarks that "if we ignore the wildcat-contribution problem we invite either bankruptcy or the near termination of exploratory drilling" (p. 88). Grayson [1960] has described certain cooperative institutions, broadly called trading institutions, in which the value of the information externalities are specifically considered by the participants. Four commonly used institutions are:

1) the "dry hole contribution" in which one firm agrees to drill a well, and another agrees to pay the first a prearranged amount of money if the well turns out to be a dry hole.

2) the "bottom hole contribution" in which a contribution is paid regardless of the outcome of the well that X has agreed to drill.
3) the "acreage contribution" which is like 1) or 2), but acreage, rather than money, is exchanged.
4) the "joint venture" in which the firms combine their operations over the tracts.

These categories are neither exhaustive nor mutually exclusive, as these and other features can be permuted to fit the nature of the deal at hand.

Clearly, these institutions differ from one another in many ways, not the least of which is the manner in which they share their risks. For this paper, however, they will be collapsed into a general, abstract cooperative institution in which the firms agree to behave in a certain prescribed manner, and in which there may be an exchange of something of value between them. The question to be addressed is whether these cooperative institutions completely remedy any potential market failure caused by the externality.

The game form which will be used to model the firms' conflict will consist of two players (firms A and B) each with two strategies : i) drill an exploration well today (D); or ii) hold out until tomorrow (ND). The firms will be assumed to be expected profit maximizers. The "payoffs" of the games will be discounted expected profits. The normal form representation of the game is depicted in Figure 2. Relationships among the values of the entries in the payoff matrix will be set according to different axiom sets in order to create different games.

The payoffs to the firms are discounted expected profits. From the very beginning it has been posited that oil exploration is a risky undertaking. Implicit, then, in the 2 X 2 normal form representation of the games is an expanded game in which "nature" is a player via a random variable, Θ, which describes the presence or absence of oil. In this model, information about Θ comes only through drilling into the reservoir.

To illustrate the role of "nature's" play, consider the following example in which there are two states of the world: Θ_1 in which there is oil under both tracts and Θ_2 in which there is oil under neither tract.

Let: V_0^j be the discounted stream of earnings to firm j of a successful well drilled today.

V_1^j = the discounted stream of earnings to firm j of a successful well drilled tomorrow.

C_0^j = the cost to firm j to drill a well today.

C_1^j = the discounted cost to firm j of drilling a well tomorrow.

Φ_1 = prob. of Θ_1, $(1 - \Phi_1)$ = prob. of Θ_2.

Then, referring back to Figure 2, the expected payoffs to firm A can be calculated as follows:

FIGURE 2

		B	
		D	ND
A	D	$E\Pi_A(D,D)$; $E\Pi_B(D,D)$	$E\Pi_A(D,ND)$; $E\Pi_B(D,ND)$
	ND	$E\Pi_A(ND,D)$; $E\Pi_B(ND,D)$	$E\Pi_A(ND,ND)$; $E\Pi_B(ND,ND)$

$E\Pi_j(i,k)$ = optimal discounted expected profits of firm j when firm A uses strategy i and firm B uses strategy k.

$$E\Pi_A(D,D) = E\Pi_A(D,ND) = \Phi_1(V_0^A) - C_0^A$$

$$E\Pi_A(ND,D) = \Phi_1(V_1^A - C_1^A) + (1 - \Phi_1)(0) = \Phi_1(V_1^A - C_1^A)$$

$$E\Pi_A(ND,ND) = \Phi_1(V_1^A) - C_1^A$$

The structure of $E\Pi_A(ND,D)$ is important. By waiting until the other firm has drilled, firm A can avoid the cost C_1^A of drilling a structure known to be dry. The same relationship holds for firm B if it waits until firm A has drilled.

Other, more complicated models of uncertainty are possible (continuous outcomes, or the possibility that one well will be dry while the other produces). The concept of the calculation of expected profits for each strategy choice remains the same.

Each of the noncooperative games will be considered in terms of existing solution concepts from the literature on game theory. It is hoped that this will capture the outcomes which a player (firm) would reasonably expect to occur if the games are noncooperative. This expected noncooperative outcome, a type of threat point, will be compared with the possible outcomes when the same games are played cooperatively, with side payments. When the analogous solution concepts, or "reasonable" outcomes, of the cooperative game present the opportunity for both players to have strictly higher expected payoffs than at the noncooperative outcome, these trading institutions are a rational response to the information externality.

III. THE NONCOOPERATIVE GAME

The general model of the preceding section can be transformed into specific types of games by choosing specific assumptions about the relationships among the payoff entries. In this section, four such relationships will be introduced as maintained assumptions. These four postulates define the two-period feature of the problem and specify the nature of the value of the information. With this set of maintained assumptions, five specific two-person games are formed by adding more detailed structure on the preferences of the players for acting today rather than tomorrow. One of these five games is that presented also by Stiglitz [1975].

In analyzing these noncooperative games, an attractive behavioral assumption is that individuals will not play dominated strategies (if such exist). This assumption allows a direct analysis of "reasonable" outcomes in two important cases. First, if each player has a unique dominant strategy, then this assumption leads immediately to the intuitively obvious outcome, the dominant strategy equilibrium. Likewise, suppose that all but one of the players has a unique dominant strategy. The player without a dominant strategy knows, from the above assumptions, the choices of others. Therefore, it is reasonable to assume that he will play a best response.

While this behavioral assumption seems intuitive (for example, the dominant strategy equilibrium is present in the confess/confess outcome in the prisoner's dilemma), it is not, by itself, a solution concept. There does exist at least one formally developed solution concept which is motivated in an analogous fashion: the "solution in the weak sense" of Luce and Raiffa [1957]. A more detailed exposition is presented in Appendix I. For the remainder of the body of this paper, however, the important feature of the solution in the weak sense is that (by reducing the game through eliminating dominated strategies), joint dominant strategy equilibriums and dominant strategy/best response equilibriums are solutions.

Using the solutions in the weak sense (where it exists) as the concept of a reasonable outcome of noncooperative play, it will be shown that nonoptimal outcomes can occur in three of the five possible specific games to be developed.

Formally, then, the following four assumptions will be maintained:

A1: There are two firms.

A2: Each firm realizes that if they both hold out (ND) until tomorrow, each will have to make a "drill/don't drill" decision based solely upon its own actions.

As will be pointed out in a later section, restricting the analysis to two firms, as opposed to N firms, does eliminate the possibility of one firm "free-riding" while others sign an information sharing agreement.

A3: If one firm drills today (D), its profits are unaffected by whether or not the other firm drills. This assumption requires that:

$$E\Pi_A(D,D) = E\Pi_A(D,ND) \quad \text{for firm A}$$

$$E\Pi_B(D,D) = E\Pi_B(ND,D) \quad \text{for firm B}$$

Because the analysis here is focused on the exploration stage, and in order to isolate the effects of the information externality, the potential production externality effects during field development are ignored by this assumption.

A4: Information is socially valuable in that the maximum of joint discounted expected profits occurs through sequential drilling (either (D,ND) or (ND,D)), and the information is privately valuable in that each firm would, if holding out, prefer to receive it than not.

That information is socially valuable can be seen to be a restriction on the relationship between revenues and costs in periods 0 and 1. The assumption requires that the maximum of discounted joint expected profits is either

$$\Phi_1(V_0^A) - C_0^A + \Phi_1\ (V_1^B - C_1^B) = (\text{A drills first and B observes } \theta):$$

or

$$\Phi_1(V_0^B) - C_0^B + \Phi_1(V_1^A - C_1^A) = (\text{B drills first and A observes } \theta).$$

Information is privately valuable in that

$E\Pi_A(ND,D) > E\Pi_A(ND,ND)$; and

$E\Pi_B(D,ND) > E\Pi_B(ND,ND)$.

With the preceding four maintained assumptions, there are five different game types which can be formed by introducing specific restrictions on the firms' preferences for drilling today versus drilling tomorrow.

Game 1: HOLDOUT/HOLDOUT

Consider the following assumptions:

A5: Given that the other firm holds out, a firm is indifferent between drilling today and holding out until tomorrow, i.e.

$E\Pi_A(D,ND) = E\Pi_A(ND,ND)$ or

$E\Pi_B(ND,D) = E\Pi_B(ND,ND)$

A6: Given that the other firm drills, a firm would rather hold out and receive the information than drill.

$E\Pi_A(ND,D) > E\Pi_A(D,D)$, or

$$E\Pi_B(D,ND) > E\Pi_B(D,D)$$

The axiom structure [A1, A2, A3, A4, A5, A6] for both firms yields the normal form represented in Figure 3. Holding out (ND) is a dominant strategy for each firm, so (ND, ND) is a dominant strategy equilibrium. (ND, ND) is also the only strong Nash equilibrium and the solution in the weak sense.

A similar result obtains if A5 is replaced by

A7: Given that the other firm holds out, the firm would rather hold out itself, i.e.

$$E\Pi_A(D,ND) < E\Pi_A(ND,ND) \text{ or}$$

$$E\Pi_B(ND,D) < E\Pi_B(ND,ND)$$

This may occur because the firm's development policy would require expensive "holding" of this resource if explored today, or because the firm is waiting for valuable information from another source.

In the structure [A1, A2, A3, A4, A6, A7] for each firm, (call it game 1') (ND,ND) is the dominant strategy equilibrium, as well as the only Nash equilibrium and the solution in the weak sense. (See Figure 4). This is essentially the game form discussed by Stiglitz [1975].

FIGURE 3

GAME 1

		B D	ND
A	D	r,s	r,t
	ND	u,s	r,s

with

$t > s$

$u > r$

EXAMPLE

		B D	ND
A	D	1,1	1,3
	ND	2,1	1,1

FIGURE 4

GAME 1'

		B	
		D	ND
A	D	r,s	r,t
	ND	u,s	p,q

$t > q > s$

$u > p > r$

EXAMPLE

		B	
		D	ND
A	D	1,1	1,5
	ND	3,1	2,2

GAME 2

Suppose the relationship between drilling today and drilling tomorrow when the other firm holds out is changed from A5 to A8:

A8: Given that the other firm doesn't drill, the firm prefers drilling today to drilling tomorrow i.e.

$$E\Pi_A(D,ND) > E\Pi_A(ND,ND) \text{j or}$$

$$E\Pi_B(ND,D) > E\Pi_B(ND,ND)$$

That is, absent the possibility of receiving a free good (information), the firm prefers to drill today. This could be due to costs of waiting such as lease payments, renegotiation deadlines, etc. However, when assumption A6 still holds, any waiting costs must be small enough so that the firm will still prefer to hold out if it knows that it will receive valuable information. If this modification holds for only one firm, while the other firm is described by A5 or A7, rather than A8, the axioms [A1, A2, A3, A4, A5 or A7, A6] for A, and
A[1, A2, A3, A4, A6, A8] for B
result in a normal form game such as in Figure 5.

The choice facing firm B is now seemingly more complicated. If A drills today, B would rather hold out; if A holds out, B would rather drill. However, a simple behavioral assumption

FIGURE 5

GAME 2

		B	
		D	ND
A	D	r,s	r,t
	ND	u,s	r,z

with

$u > p \geq r$

$t > s$

$s > z$

EXAMPLE

		B	
		D	ND
A	D	1,1	1,1.4
	ND	2,1	1, .4

is that firm A will never drill today, because A's dominant strategy is to hold out. Under the assumption that this is a game of complete information,[11] B recognizes A's dominant strategy, and chooses his best response, D. Therefore, (ND,D) is the solution in the weak sense.

GAME 3: BATTLE OF THE SEXES

If A8, rather than A5, holds for each firm, the analysis becomes substantially more complicated. The general form is represented in Figure 6 along with a more illustrative numerical example.

Neither player has a dominant strategy. There are three Nash equilibria: (D,ND) and (ND,D) are strong Nash equilibria, and there is a weak Nash equilibrium in mixed strategies (in the example in Figure 6, the mixed strategy equilibrium is (probability of D = 1/2 probability,of ND = 1/2) played by A and B).

Formally, because the Nash equilibrium pairs are neither equivalent nor interchangeable, this game is not solvable by any of the standard solution concepts. This is an intuitive result. Because the Nash equilibria are not equivalent, simply restricting attention to the set of equilibrium points does little to remove the element of conflict from the game. Because the equilibria are not interchangeable, there is no guarantee that the players in the noncooperative setting can reach an equilibrium point even if they want to. In fact, the maximin strategy dominates the

FIGURE 6

Game 3

		B	
		D	ND
A	D	r,s	r,t
	ND	u,s	w,z

with

$r > w$

$s > z$

$t > s$

$u > r$

Example

		B	
		D	ND
A	D	1,1	1,2
	ND	2,1	0,0

mixed equilibrium strategy. Of course, the disappointing truth is that the joint maximin outcome (D, D) is not in equilibrium.

There is one other possible way to describe the outcome of this noncooperative game. One can suppose that, given the absence of a well defined solution in the standard sense, each firm simply attempts to maximize its expected payoff based upon some subjective probability distribution over the strategy choices by the other firm. We will return to the problems such a situation can cause in a later section.

GAMES 4 and 5:

Finally, there is the possibility that for one firm A8 holds but not A6. Rather, the value of the drilling information to one firm is not enough to persuade it to hold out, even if it knows that the other firm intends to drill. This is expressed as A9[8].

A9 : $E\Pi_A(ND,D) \leq E\Pi_A(D,D)$ for firm A, or

$E\Pi_B(D,ND) \leq E\Pi_B(D,D)$ for firm B.

If this is true for only one firm, say firm A, the result is as in Figures 7 and 8, represented by the axioms

For A: [A1, A2, A3, A4, A8, A9]

For B: [A1, A2, A3, A4, A6, and either A5, or A7 (Game 4) or A8 (Game 5)].

FIGURE 7

GAME 4

		B	
		D	ND
A	D	r,s	r,t
	ND	u,s	w,z

$u < r$

$w < r$

$s < t$

$s \leq z < t$

$u > w$

EXAMPLE

		B	
		D	ND
A	D	1,1	1,1.2
	ND	.9,1	.1,1.1

FIGURE 8

GAME 5

B

		D	ND
A	D	r,s	r,t
	ND	u,s	w,z

$r > u$
$r > w$
$s < t$
$s > z$
$t > z$
$u > w$

EXAMPLE

B

		D	ND
A	D	1,1	1,1.2
	ND	.9,1	.1,.5

Firm A has a dominant strategy to drill today. Firm B, which has either a dominant strategy not to drill (Game 4) or a contingent strategy (Game 5) therefore holds out. These games are solvable in the weak sense (D,ND).

Table I summarizes the nature of each of the five games according to whether the assumptions imply that the firm has a dominant strategy to drill today, a dominant strategy to hold out, or a contingent strategy (drill if opponent doesn't drill today, hold out if opponent drills today).

IV. THE NONCOOPERATIVE GAMES AND THE QUESTION OF OPTIMALITY

In the previous section, it was shown that by altering the assumptions over the firm's preferences, five different game forms are possible. In only two of these (games 4 and 5) will the optimal drilling pattern necessarily be a result of noncooperative exploration choices.

One of the maintained assumptions was that the information had "social value" in that the joint maximum of expected profits occurs when one of the firms drills today, the other observes the information and makes a decision on drilling tomorrow. Clearly, then, in games 1 and 1', in which a nonsequential drilling strategy (ND,ND) is the solution, the noncooperative play does not reach an optimum. In game 2, a sequential drilling strategy does occur at the solution in the weak sense, but the result may not be optimal because the solution may be to drill the wells in the wrong order. For example, the firm which should efficiently "hold

TABLE I

		Firm B		
		"D" Dominant	Contingent	"ND" Dominant
Firm A	"D" Dominant	Not Admissible	Game 5	Game 4
	Contigent	Game 5	Game 3 (Battle of the sexes)	Game 2
	"ND" Dominant	Game 4	Game 2	Game 1 or Game 1' (Holdout/ Holdout)

out" may face penalties on its lease if exploratory drilling does not commence. The payoff matrix might look like Figure 9. In this example, the solution is (ND,D). However, the optimal staggered drilling order is (D,ND). Only in Games 4 and 5 is the solution to noncooperative play optimal. (A proof of this is shown in Appendix II).

Finally, Game 3 has no solution in the weak sense, and therefore there is no guarantee the noncooperative would necessarily achieve the joint optimum.

V. THE THEORY AND STRUCTURE OF COOPERATIVE DRILLING GAMES

Each of the four proposed cooperative arrangements may be appropriate under different circumstances. If the noncooperative result is that both firms hold out, a dry hole contribution, bottom hole contribution, or acreage contribution could induce one firm to drill. For the other cases, a joint venture or a combination of proposals might be suggested.

Yet the two critical characteristics of any cooperative play of the drilling game are that i) the firms are allowed the opportunity to communicate and coordinate their drilling strategy and ii) the firms can make "side payments" that is, transfers of case or acreage ownership.

The total net profit to each firm from a coordinated drilling strategy will be the profit from its own property plus the net total of all side payments (which may be positive or negative).

FIGURE 8

		B	
		D	ND
A	D	1.4, .9	1.4, 1.2
	ND	1.6, .9	1.4, .8

Thus, there are two important choices to be made in the cooperative play of the game: i) the drilling strategies to be chosen, and ii) the side payments to be arranged.

The theory of cooperative game solutions is built upon two fundamental concepts: i) the coalition, and ii) the characteristic function. Let I be the set of all players. A coalition C is a subset of I which agrees to a joint strategy. The characteristic function of a game, call it V(S), is a set function mapping subsets of I (coalitions) into the real numbers. The characteristic function denotes "the joint payoff which the members of any given coalition ($S \subseteq I$) would achieve if they did cooperate among themselves but did not cooperate with the remaining players" (Harsanyi, 1977, pp. 213). A characteristic function has the properties that $V(\emptyset) = 0$ (where $\emptyset$ is the empty set), and

$$V(R \cup S) \geq V(R) + V(S) \quad \forall R,S \subseteq I$$

(That is, two groups can always do at least as well by acting together as by acting separately.)

For the two person drilling games in this paper, the concern is with V(A), V(B), and V(A + B). V(A) and V(B) are the payoffs each firm would get by acting alone. As has been shown in the previous section, however, this concept is neither simply nor unambiguously defined. Many game theorists have adopted the convention that V(i) is person i's maximin value, that is, how much the one person coalition of i can guarantee if all other players (firms) turn against him. (See, for example, Von Neumann and Morgenstern [1953], pp. 538-564.) The question that needs to be asked here is how this general adoption of the maximin concept squares with some of the "reasonable" outcomes presented in the previous section. Unfortunately, all is not well as the following lemmata (about two person games) demonstrate:

Lemma 1: Let α^* be a dominant strategy for player j; then, α^* is also a maximin strategy.

Proof: If α^* is not maximin $\exists$ some strategy pair (α,β) such that $E\Pi_j(\alpha,\beta) > E\Pi_j(\alpha^*,\beta) \rightarrow\leftarrow$.

Lemma 2: Let (α^*,β^*) be a dominant strategy equilibrium. Then, for each player j,$E\Pi_j(\alpha^*,\beta^*) \geq \hat{V}(j)$ if $\hat{V}(j)$ is the maximin characteristic function.

Proof: If, say, $\hat{V}(A) > E\Pi_A(\alpha^*,\beta^*)$ then $\exists$ a strategy α such that $E\Pi_A(\alpha,\beta^*) > E\Pi_A(\alpha,\beta^*) \rightarrow\leftarrow$.

Lemma 3: Let (α^*,β^*) and $\hat{V}(j)$ be defined as in Lemma 2. It can be true that for both players, $E\Pi_j(\alpha^*,\beta^*) > \hat{V}(j)$

Proof: Consider

		B	
		D	ND
A	D	10, 10	4 ,2
	ND	2, 4	2 ,2

$\hat{V}(A) = \hat{V}(B) = 4$

$\alpha^* = D,\ \beta^* = D$

$E\Pi_A(D,D) = E\Pi_B(D,D) = 10$

Lemma 4: If A has a dominant strategy α^*, and $\hat{\beta}$ is B's "best response," $\hat{\beta}$ need not be B's maximin strategy.

Proof: Consider

		B	
		D	ND
A	D	100, 10	100, 4
	ND	4, 0	4, 4

$\alpha^* = D,\ \hat{\beta} = D,$ but B's maximin strategy is ND.

Lemma 5: If the pair (α',β') is the "solution in the weak sense," $E\Pi_j\ (\alpha',\beta') \geq \hat{V}(j)\ \forall j$ where $\hat{V}(j)$ is the maximin value.

Proof: Suppose $\hat{V}(A) > E\Pi_A(\alpha',\beta')$. Then, $\exists\ \alpha \ni E\Pi_A(\alpha',\beta') < E\Pi_A(\alpha,\beta')$. But, then, (α',β') is not an equilibrium in the reduced game $\nrightarrow$.

Lemma 6: Let α',β', & $\hat{V}(j)$ be defined in Lemma 5, then it is possible that for both players $E\Pi_j(\alpha',\beta') > \hat{V}(j)$

Proof: Consider

		B	
		D	ND
A	D	100, 5	80, 4
	ND	4, 0	4, 4

(D,D) is the solution in the weak sense.

$\hat{V}(A) = 80 < E\Pi_A(D,D) = 100$

$\hat{V}(B) = 4 < E\Pi_B(D,D) = 5$

All of the games developed in the previous section, except Game 3, have either dominant strategy equilibria or solutions in the weak sense (a dominant strategy equilibrium is also a solution in the weak sense). The maintained behavioral proposition of this paper is that if both players see that the cooperative play makes them better off, then the cooperative institutions are a "natural response."

However, this leaves a key conjectural ambiguity. How does player A believe that player B will respond? In the context simply of noncooperative play, the reasoning behind solutions such as the solution in the weak sense suggests that if firm A has a dominant strategy, firm B recognizes this, and (despite any preplay threats) B believes A will ultimately choose to play his own dominant strategy. As was previously mentioned, however, when dealing with cooperative games, the reasoning typically begins with the concept of the best someone can do if everyone else turns against him.

As was demonstrated in Lemma 5, the divergence between the maximin characteristic function and the weak solution is asymmetric. The payoff at the solution in the weak sense is always at least as great as the maximin characteristic function. This is intuitive. No player will ever consider a "reasonable" outcome one which pays <u>less</u> than the same player would guarantee himself regardless of the outcome of others. However, as shown in Lemma 6, there is the possibility that the outcome at the solution in the weak sense pays each player <u>more</u> than the maximin characteristic function value.

The problem for this analysis is that by underevaluating V(i), one runs the risk of overstating the potential for cooperative play. Therefore, the following alternate characteristic function, $V°(S)$, for games with a solution in the weak sense, is proposed:

- $V°(\emptyset) = 0$
- $V°(j) = E\Pi_j(\hat{\alpha},\hat{\beta})$ where $(\hat{\alpha},\hat{\beta})$ is the solution in the weak sense of the noncooperative game, $(j = A,B)$.
- $V°(A \cup B)$ = the maximum of joint profits obtained from an efficient drilling schedule.

(Note that $V°(S)$ fulfills the conditions that

$$V°(\emptyset) = 0$$

$$V°(R \cup S) \geq V°(R) + V°(S) \quad \forall S \subseteq I).$$

In terms of the drilling games developed in the previous section, the potential for cooperative institutions occurs when each firm sees itself being better off at the outcome of cooperative play then at the "reasonable outcome" of noncooperative play. In the setting of cooperative games, the first criterion which will be adopted for a "reasonable" outcome is that it is in the "core." That is, let $X = (E\Pi^*_A, E\Pi^*_B)$ be a vector of final net expected profits to the firms. X is in the core if

i) $E\Pi^*_A + E\Pi^*_B = V(A \cup B)$

ii) $E\Pi^*_A \geq V^\circ(A)$

iii) $E\Pi^*_B \geq V^\circ(B)$

The previously developed restriction on the definition of the bargaining mechanism can be formally stated as a second criterion on a proposed outcome X.

If $X = (\Pi^*_A, \Pi^*_B)$ and

$$\Pi^*_A + \Pi^*_B > V^\circ(A) + V^\circ(B)$$

then $\Pi^*_A > V^\circ(A)$; $\Pi^*_B > V^\circ(B)$

That is, both firms will be made strictly better off when cooperative play produces greater joint expected profits than noncooperative play. Other "fair" properties of bargaining mechanisms are discussed in Harsanyi and Luce and Raiffa. A specific example of a bargaining scheme is given by Kennedy.

Because of the implicit bargaining procedure, the possibility of an extended bargaining game (see Luce and Raiffa pp. 140-143) must be addressed. In an extended bargaining game, the firms would list moves in the noncooperative game as binding threats, say d_A and d_B. Then the outcome (d_A, d_B) would become the threat point for the bargaining mechanism. In Harsanyi's terms, the noncooperative threat game becomes "dependent" on the bargaining game. However, it will be assumed here that firms cannot make binding threats. In Harsanyi's terms, the noncooperative conflict game is "independent" of the bargaining game. The "threat point" or expected outcome will be determined strictly by the noncooperative play as outlined in the previous section, and not by any preplay nonbinding threats made by the firms.[9] So, for games 1, 1', 2, and 4 the "solution in the weak sense" will still be considered the expected noncooperative outcome.

VI. A SUMMARY OF INCENTIVES FOR COOPERATIVE DRILLING

In the four games with a weak solution in noncooperative play, the important policy conclusion is that the incentives for cooperative information sharing ($V°(A \cup B) > V°(A) + V°(B)$) occur precisely when the expected result of noncooperative play is inefficient. Furthermore, when this occurs there is some outcome in the core (chosen by a bargaining mechanism) that makes both firms strictly better off than noncooperative play. If activating these institutions is costless, then the existence of the information externality is not *per se* an argument for an exploration subsidy in these cases.

When the maximin characteristic function, call it $\hat{V}(S)$, is used in lieu of the characteristic function based on the solution in the weak sense, $V^{\circ}(S)$, this implication runs only in one direction: when the solution is nonoptimal, firms recognize the gains from joint action. However, in Game 4, Figure 7, (D,ND), is the solution in the weak sense but $\hat{V}(A \cup B) > \hat{V}(A) + \hat{V}(B)$. That is, cooperative behavior is indicated where none is needed.

However, there is still the case of Game 3 which has no solution. It is quite possible that no reasonable characteristic function exists for this game. In the example in Figure 6, if the maximin value is the "threat point" payoff, $\hat{V}(j)$, then each firm will recognize the potential gains from cooperative play, as $\hat{V}(A \cup B) > \hat{V}(A) + \hat{V}(B)$. But (D,D) is not an equilibrium, and it is not unreasonable to suspect that there are conditions in which one expects a greater payoff. However, suppose we create a function $V'(j)$ which is the amount j "expects" to receive from noncooperative play (with j's expectation based upon his own subjective evaluation of his opponents strategy). There is always the possibility that each firm is (incorrectly) convinced that it can bluff out the other; each plays the strategy ND, and $V'(A) + V'(B) = (2) + (2) > V(A \cup B)$ (the efficient outcome).

Neither firm would initiate cooperative play, and a promoter attempting to put together a deal would be frustrated by the firms' attitudes. In such a situation, noncooperative play leads to a suboptimal result, but private cooperative action would fail.

VII. HISTORY AND DEVELOPMENT OF THE INSTITUTION

The date on which two oilmen first exchanged information for something else of value will probably continue to be lost in history. However, the evidence indicates that such contracts have been common for at least sixty years, and perhaps much longer. Contractual resource exchange has been part of the oil industry from the very beginning, all the way back to Col. Drake's well in Titusville, Pennsylvania, in 1859, although the contracts on that well do not appear to be connected to an information externality.

Oilmen began to pay more attention to the information externality as they developed more sophisticated theories of oil location. After the birth of the oil industry in 1859, persons looking for oil soon realized that there were ways of spotting new wells other than by drilling on known oil seeps or as close as possible to an existing well. For example, Williamson and Daum [1959], in describing the oil location theories of a Mr. Angell, show how acting upon his theory (essentially that oil is located in veins, like coal) required that Mr. Angell gain information from other leaseholders:

> Starting with information from his own three producing wells at Belle Island, in 1867, some eighteen miles below Franklin on the Allegheny River, Angell began a tedious process of collecting fragmented information about other wells at different locations: depths, differences between upper surfaces of the different sand rocks, their thickness, quantity, and quality of oil showings in the second sand, and texture of third sand rocks. At Foster Station, about nine miles north of Belle Island by river, he found striking similarities with his own wells. In 1868 and 1869 he hired a professional surveyor to aid him, and in the following year, in partnership with Frederick Prentice, he leased or purchased all land on the line he formulated between Belle Island and Foster Station.

One historian of early day oil exploration places the development of the formal information trading institution as it is known today at about the turn of the century in what were then the newer oil areas of the Southwest. The following quote is from this informal history by Tait [1946] (pp. 133-134):

> To make the great number of discoveries from 1905 to 1929 required not only ingenuity and daring, which the wildcatter had always possessed, but something more; namely, a new mode of financing wildcat wells. Most of the pioneering from the Kansas River to the Rio Grande was done by men operating on a well worn shoestring.... This new method of financing was called checkerboarding, and the man who devised it in its embryonic form was James E. O'Neil....As soon as he appreciated the vastness of the Southwest, Jim O'Neil concluded that when the oil game crossed the river, as men used to express the migration from southeastern Illinois to Kansas, Oklahoma and Texas, it entered an empire where new methods of leasing and development were essential. Whole counties out here had never had a well,a nd there was nothing to indicate whether there was oil. To lease and pay rental on all of them would obviously have bankrupted even the Standard [for whom O'Neil worked]. O'Neil devised the

> custom of leasing scattered farms and ranches, say six sections in all out of the thirty six in a township, and so distributed that the company was likely to be in on any drilling play that was started thereabouts. The map of such a township, once O'Neil's land and lease men had finished their work there, looked like a checkerboard. Next step was for the company to offer to put up money to help anyone who wished to drill in the neighborhood, sometimes putting it up as a payment without condition, sometimes as dry hole money to be paid by the company only if the well were unproductive.

Tait indicates that these institutions were developed between 1905 and 1929. In fact, two important court cases from 1929 serve to document that such contracts were considered to be common by the early 1920s. The exposition of facts in Atlantic Oil Producing Co. v. Masterson[11] discusses a contract signed in Februrary, 1923, and notes (at p. 481) that:

> the contract sued on what is called a 'dry hole' or information contract. It is a type of contract, quite common in the business of oil production, under which one who drills a test well on a lease in which he is interested receives contributions either in money or acreage from owners of adjoining lands or leases, the object of the contribution being to secure the benefit of information to be derived from the drilling of a test well near their own holdings.

Similarly, the court in Hoffer Oil Corporation v. Carpenter,[12] a breach of contract suit invoving a 1925 information sharing agreement, called such an exchange "an everyday transaction."

These two cases are more than convenient evidence of the existence of a particular type of contract. The opinions of the courts deal with important legal questions about the standing of contracts covering trades of information; had the decisions been different, information trading contracts would have almost certainly become much less common.

In the <u>Atlantic</u> case, the defendant, Masterson, failed to undertake all the drilling that was specified in the contract, thus denying Atlantic the information that the contract promised. Atlantic sued for damages to cover the costs it had incurred by obtaining the desired information by drilling a well on its own property. While the lower courts agreed that the defendant had breached the contract, they rejected the contention of Atlantic that it was entitled to recover the cost of drilling a well on its own property. Instead, the lower courts awarded Atlantic only "nominal damages." (The term "nominal damages" refers to token amounts of money awarded to a plaintiff when the court agrees that the defendant has breached, but rejects the plaintiff's claim for damages. The significance of nominal damages is primarily symbolic.) Atlantic appealed the award of only nominal damages to the Fifth Circuit Court of Appeals. The circuit court ruled against Atlantic, saying (at p. 482):

> It cannot reasonably be supposed that the parties contemplated the drilling of a well on appellant's 20 acres at the expense of the appellees, for in that event appellant would have been the sole owner of the well as well as of any oil that might have been produced therefrom.... Appellant failed to get the information it contracted for, and it would seem to follow that the damage it sustained was the value of that information. If under an information contract, such as this is,

> one contributing owner could recover the cost of drilling the test well, every other such contributing owner could do the same. The rather startling result would be that the driller of the test well would be liable to each contributor for the full cost of drilling.

The opinion in the Atlantic case correctly recognized that the test well produced joint products: one, the oil to be produced, was essentially a private good; the second, the information from the well, was a good which benefited both concerns. The judges also correctly distinguished between the value of information to a particular individual and the cost of providing that information for both.

An even more important case is Hoffer, for in a set of circumstances similar to that in the Atlantic case, a company breaching an information sharing contract, Hoffer, argued that no damages at all could be awarded, based on the following two assertions (at pp. 590-591):

> First, that no benefit would have accrued to Carpenter as a direct, natural, and proximate consequence of the drilling of such test well, and that, therefore, no general damages can be recovered....
>
> Second, that the completion of such test well might have disclosed oil and gas in paying quantities or might have resulted in a dry hole, and therefore the benefits to be derived from the completion of such well were too uncertain and speculative to afford any basis for the recovery of damages.

The first of Hoffer's arguments denies the value of the information externality. The second disputes the economic argument that information, although purchased to ameliorate uncertainty, does have a well defined ex ante valuation. Had the court accepted Hoffer's claims, the effect would have been to develop a legal view of information that denied its economic significance. However, Hoffer lost in the lower courts and, after an appeal, the Tenth Circuit Court also ruled against Hoffer. First, the court dispatched the claims that the information had no value, and that it was "speculative" (at pp. 591-592):

> Such information was of substantial value to Carpenter, who owned leases on land adjacent to the leases upon which the well was contracted to be drilled. That the drilling of the well might have produced a dry hole and afforded unfavorable geological information does not, as contended by counsel for the Oil Corporation (Hoffer), render the damages resulting from the failure to furnish such information so speculative as to prevent recovery. Contracts for such information are always made prospectively. Persons situated as was Carpenter in the present case realize that such information may indicate their land will produce oil and gas in paying quantities, or it may indicate otherwise. Nevertheless, they are willing to pay a substantial consideration therefor , because it is of benefit to such persons to make reasonably certain that which is uncertain, in order that they may act prudently in future expenditures in development of their land for oil and gas.... In the development of unproven oil land, well managed oil companies employ high salaried and competent geologists to make investigations and give their reports and opinions based thereon. Likewise, oil operators constantly make contracts such as the contract in the instant case, by which they contribute, in cash or in valuable leases, a portion of the cost of a test well in return for a log of such well and the information which such test discloses. These facts compel the conclusions that such information has a substantial value.

Having disposed of the argument that no damages could be awarded because the information was valueless, the court then proceeded to refute the contention that damages were too "uncertain" to be awarded (thus confirming that the information had a well-defined ex ante valuation) (at p. 593):

> It is, of course, impossible to determine what facts and geological information the drilling of the oil well would have disclosed, and whether the information would have indicated that the land on which Carpenter's leases were located would produce oil in paying quantities. We have demonstrated, we believe, that such information, in any event, would have been valuable to Carpenter. Furthermore, as stated above, contracts for such information are always made prospectively.
>
> The information can be obtained only by drilling, and such drilling costs substantially the same amount, whether the result is production of oil and gas in paying quantities or a 'dry hole.' Therefore, the damages must be based upon the value of the services rendered in obtaining the information, and not upon the value of the information after it is obtained....

Although the court disagreed with each of Hoffer Oil Company's points, Carpenter did not win a complete victory. Like the Atlantic Oil Company, Carpenter had requested damages based upon the cost of drilling a test well on his own property. The court relying upon the decision of the Atlantic case, ruled against Carpenter on this point saying (at p. 591):

> The cost of drilling the well is not, in our opinion, the true measure of damages. Carpenter had no interest in the land upon which the oil well was to be drilled. The well, when completed, and the oil, if any, belonged wholly to the Oil Corporation. Because of these facts, Carpenter would have received no direct benefit from the well itself, as

> distinguished from the information which the drilling of the well would have disclosed.... If he were compensated damages to the extent of the full cost of the well, it would give him the equivalent of an oil well on his own land, from which he would receive the benefit of the service for which he had contracted, and in addition, the oil well itself and any oil and gas that might be produced.

The court awarded Carpenter, as noted above, the value of the service in obtaining the contracted-for information. The court decided that such value should be based upon

> what a reasonable person owning land adjacent to the lands on which another proposes to drill such a test well similarly situated and of similar oil bearing potentialities as the land of the parties in the instant case would ordinarily pay by way of contribution to the cost of such a test well and the geological information which the drilling thereof would disclose (p. 593).

The recommended method of calculating the damages follows from the fact that, unlike those cases in which the breach of contract involves a good which can be valued in markets other than the contract at issue, this case involved a strictly bilateral market with the specific good being unique to the particular situation. This made the correct amount of damages difficult to ascertain. However, having established liability and rejected the argument that the damages were too speculative to be recovered, the court was following established precedent in ruling that recovery of damages is not voided merely because they are difficult to calculate. In endorsing the use of testimony by experts (apparently the procedure that had been followed in the lower courts) the court was approving an attempt to estimate the value of the damages by consulting those who were themselves familiar with such bilateral markets and the goods (information) exchanged there.

Thus, the information sharing contracts which are the topic of this paper not only have been around a long time, they have been recognized by the courts and the oil industry to have been commonplace for at least fifty to sixty years. The narrative by Tait gives at least a plausible explanation as to why one individual (in this case, O'Neil) would incur the costs of institutional innovation. The fact that the Southwest did indeed contain large reserves of oil and gas undoubtedly helped to popularize the institutions. The court cases of the 1920s helped overcome the post agreement coordination of problems that apparently were giving rise to breach of contracts for sharing information costs. Therefore, in analyzing the present use of this institution, the historical record permits the maintained assumptions that pre-play start up problems and post-play enforceability questions can be ignored.

VIII. EVIDENCE RELATING TO THE USE OF INFORMATION SHARING CONTRACTS

In the historical survey of section VII, the basic structure of the theoretical model is confirmed: i) there exists an information externality in petroleum exploration; ii) cooperative institutions for overcoming the suboptimality of noncooperation have developed in instances corresponding closely in structure and rationale to those cases in which the theory predicts that cooperation would be viewed as beneficial to all potential participants. Mr. James E. O'Neil, for example, apparently believed that absent his offer for dry hole money, no other parties would drill on the neighboring parcels, and he was himself under no constraints to drill immediately. Such a situation is described by Game 1 or Game 1'. It was shown that, certainly by the early 1920s, information sharing contracts were a common device in planning petroleum exploration.

The more important policy questions, however, exist not in showing that a lot of people did use these contracts, but rather in identifying and addressing any instances in which the private information sharing arrangements might not have worked very well. The theoretical basis for failure has been presented earlier in this chapter, in the exposition of the "battle of the sexes" type drilling game; yet the possibility of failure was conjectural, for it depended upon the decision strategy of persons involved in such a situation. Unfortunately, the data to best test the conjecture is, understandably, nonexistent. If certain tracts should be explored via the information sharing institutions but are not, then no records of this failure will likely exist. That is, the existing data base on the trading institutions (as meager as it is) still represents evidence from the successful application of the contracts. To obtain exact "success ratios" would require a denominator representing the total of all sites on which exploratory wells should have been drilled with cooperative information sharing. A direct measure of this would entail evaluation of all unexplored properties in the geographic area under consideration (probably the entire United States), a formidable task.

Therefore, the approach adopted here is to seek to find indirect tests of the operation of information sharing. Yet, even when data do exist, they have other limitations. For example, there are many different types of trading institutions, and most data sources typically cover only some of them. Furthermore, even though these sharing arrangements are and have been common, they need not be transacted on a formal or standardized basis. While the American Association of Petroleum Landmen does endorse certain standard forms, informal bargaining can and does occur. The participants may trade cash, acreage, royalties, motorcycles, oilfield pumps -- anything forming a basis of value in exchange. These trades may be recorded on the standard AAPL forms, on a letterhead, or perhaps even more informally.[13]

Despite these major shortcomings in the data base, it is possible to turn to the "real world" oil industry and find out more about how information trading arrangements do and don't work.

The most readily available source of information is talking to the persons who work with exploration on a day-to-day basis, or going to the journals where they talk to each other. For example, one will find that the late 1950s and early 1960s are described by oilmen as a period of relatively successful use of the information sharing institutions. In 1961, petroleum landman John H. Folks told the American Association of Petroleum Geologists:

> There are certain features concerning dry hole contributions under serious consideration today which should result in uniform thinking.... This (effort) is being made in the belief that the 'sharp trading' days are rapidly vanishing. There appears everywhere a clearly defined trend that the vast majority of management wants to bear the true burden in acreage evaluation. (Folks, 1957)

During the same time period (late 1950s and early 1960s) many in the oil industry apparently felt that there was an "unwritten law" that if a company had acreage near a wildcat, the company would contribute dry hole money.[14]

The basis for firm behavior articulated as a series of norms about "unwritten laws" or "true burdens" can be explained quite easily by the theoretical model of this chapter: what is being observed is precisely the case that all parties recognize and act to obtain the benefits of cooperative play of the game. The comments of Mr. Warren Taylor [1962] that firms during the period were more willing to shelve exploration plans suggests that the "waiting costs" described in section III were low, and that drilling games of types 1, 1', and 2 were common. Not surprisingly, these are the games in which the theory suggests that the benefits from cooperation exist and are most easily recognized.

More recently, the U.S. Bureau of the Census has collected data since 1973 on "test hole expenditures" (see Table II). These numbers show a drop of 46% in the real level of onshore test hole contributions from 1973 to 1974, coincident with the large OPEC crude oil price increases. This raises an interesting question: since one should expect more exploration with higher crude oil prices, does this drop in test hole expenditures say anything about the functioning of information sharing institutions?

There are several hypotheses to be considered. On the one hand, as was noted above, this data series may not be a good indicator for all information sharing, since it covers just dry hole contributions and bottom hole contributions, and specifically excludes any form of acreage contribution. Some oilmen say that in the 1970s the proportional use of agreements other than dry and bottom hole money has increased.[16] On the other hand, a large, unexpected increase in crude oil prices could change the type of drilling game facing the participants, and the theoretical model of this paper suggests that this could alter the use of the information sharing agreements. This change would occur for the following reasons. The drilling games in section IV differ from one another primarily in the preference of the firms for drilling today or tomorrow; that is, whether they have a dominant strategy to wait, a contingent choice, or a dominant strategy to drill today. When there are few or no waiting costs (as it was argued was the case in the 1950s and 1960s) many firms have a dominant strategy to "hold out" and games of types 1, 1', and 2 are common. If waiting

TABLE II

TEST HOLE EXPENDITURES
Million $ (Real 1967 $)

Year	Onshore	Total
1973	9.92	10.37
1974	5.35	6.03
1975	7.88	10.48
1976	9.27	12.73
1977	10.97	18.02

Source: United States Bureau of the Census "Annual Survey of Oil and Gas", 1973-1977. Figures deflated by the Consumer Price Index.

costs increase, more firms find that their drill/don't drill choice becomes contingent. As waiting costs further increase, more firms find that drilling today becomes a dominant strategy.

One of the most common examples of a waiting cost actually takes the form of a penalty for not drilling today; this occurs because firms typically must drill before a certain date, or face renegotiation of the lease. When oil prices have taken a large and unexpected jump, leaseowners who leased before the unexpected increase would presumably demand much more favorable terms from the leaseholding firms at renegotiation. Therefore, the OPEC price increases can be viewed as potentially increasing the proportion of games of types 3, 4, and 5 in the set of potential sites for exploration.

An increase in the proportion of either of these types of games could lead to fewer information contracts, although for different reasons. In sections V and VI it was shown that cooperative institutions may fail in the "battle of the sexes" game (Game 3). If these become more common, the failure rate of the institution might also increase. If there are more of Game 4 or Game 5, the contracts are not needed to achieve a pareto optimum. (In fact, it is possible that waiting costs increase to the point that a drill/drill dominant strategy, not allowed in the theoretical model of this paper, results.)

There are, then, at least three possible explanations (not mutually exclusive) to explain the observed decrease in the amount of test hole expenditures from 1973 to 1974; i) increased waiting costs created more "battle of the sexes" games, leading to increasing failure of cooperative information sharing to achieve optimal drilling; ii) increased waiting costs created more drilling games in which the information contracts were not needed; iii) the data series itself does not represent all information sharing, as contracts other than dry hole or bottom hole money took up the slack.

Evidence supporting possibility (iii) has already been mentioned. And, (i) and (ii) cannot be directly tested because of the unobservability of the key parameters. However, there are some indirect tests to show more about what was going on in 1974. First, consider the following identity:

$$W_{C_t} + W_{NC_t} \equiv W_t \tag{1}$$

where W_{C_t} = exploratory wells drilled using information sharing contracts in time t

W_{NC_t} = exploratory wells drilled in time t in which information sharing contracts were not needed

W_t = total exploratory wells drilled in time t.

Since, as can be seen from Table III, W_t increased from 1973 to 1974, the following observation obtains:

Observation: If the decline in test hole expenditures from 1973 to 1974 does, in fact, represent a decline in W_{C_t}, then W_{NC_t} must have increased; that is, the number of wells drilled without the necessity of information sharing went up.

This observation suggests that at least some of the

TABLE III

NEW FIELD WILDCAT EXPLORATORY WELLS

Year	Number
1960	7320
1961	6909
1962	6794
1963	6570
1964	6632
1965	6182
1966	6158
1967	5271
1968	5205
1969	5956
1970	5069
1971	4462
1972	5086
1973	4989
1974	5652
1975	6004
1976	5840
1977	5101
1978	6505

(For source and explanation of data, see Footnote 16.)

increase in waiting costs translated into more drilling situations in which contracts were not needed to promote drilling today.

Although the above observation supports possibility (ii), it does not rule out possibility (i), that there was an increase in failures of the institution during the period. A more difficult indirect test is needed for possibility (i). Consider another identity:

$$W_t + F_t \equiv S_t \qquad (2)$$

where F_t = the number of "failures," i.e., potential wells which should have been drilled, but were not, because of a failure to get the firms to cooperate in information sharing.[17]

S_t = sites, or the total number of exploratory oil wells which should have been drilled in time t.

The unobservability of the sites data is the primary problem encountered in an empirical test of possibility (i). However, there exists another, observable data series which can serve as a proxy for S_t. This observable, obtainable data series is the amount of leased but unexplored acreage in period t, denoted here as A_t (see Table IV).[18] A_t is, in some sense, a measure of the exploratory margin stock from which certain sites will be chosen for exploration, that is

$$S_t \doteq \beta_t A_t \qquad (3)$$

TABLE IV

ESTIMATED LEASED BUT UNPRODUCTIVE ACREAGE

Year	Amount (in acres) x 10^6
1960	397.852500
1961	387.336000
1962	366.082493
1963	342.527495
1964	338.372611
1965	326.987969
1966	306.498942
1967	299.967832
1968	298.399764
1969	306.903800
1970	306.202192
1971	309.113722
1972	325.185371
1973	339.219754
1974	356.355384
1975	360.207548
1976	354.588004
1977	359.625163
1978	373.598201

(For source and explanation of data, see Footnote 17.)

The parameter β is indexed by t because the relationship between A_t and S_t need not be constant over time. Expression (2) can be combined with (3) to obtain (4), below:

$$W_t + F_t = \beta_t A_t \tag{4}$$

It will now be established that there are certain conditions under which A_t can be a useful substitute for S_t. Consider a time period in which, because there are no radical changes in the underlying economic parameters, the nature of the exploratory margin sites S_t with respect to the drilling games presented here is stable, so that the number of wells which should have an information sharing contract is proportional to S_t, or

$$(W_{C_t} + F_t) = \alpha(S_t) \tag{5}$$

Notice that this stable relationship rules out the type of change which is explicit in explanation (ii) above. Then posit that

$$W_{C_t} = \gamma(\alpha S_t) = \psi S_t \tag{6}$$

that is, the success rate of the information is a constant, γ. Then again combining expressions yields

$$W_t = \psi S_t + (1 - \alpha) S_t = \mu(S_t)$$

and then

$$W_t = \mu\beta_t A_t.$$

That is, the number of wells actually drilled, W_t, can be stated as a proportion of unexplored acreage, A_t. If the parameter β_t, relating sites to acreage is constant, then empirically it should be observed that

$$W_t = bA_t$$

or, wells drilled are proportional to acreage. The anecdotal comments of the oil industry about the late 1950s and early 1960s (mentioned earlier in this section) suggest that the period was one in which the underlying game structure was static. This conjecture is also supported by the slow, steady decline of crude oil prices. Thus, the period of the late 1950s and early 1960s would appear to be a prime target to observe a stable, constant relationship between exploratory wells and unexplored leaseholdings. If such a relationship is observed, the conjecture of a stable wells/acreage relationship will be adopted as a working hypothesis for a test in more recent periods.

Data on W_t and A_t are available for 1960 to 1969 (Tables III and IV). The year 1969 was chosen as the cutoff date because, from a reading of the oil industry literature and an initial examination of the data, tax and regulatory changes in 1970 appear to have dramatically affected the drilling calculus. Therefore, the following linear regression model was estimated:

$$W_t = \hat{a} + \hat{b}A_t$$

A small intercept $\hat{a}$ and a good regression fit would suggest a confirmation of the hypothesis of a stable well/acreage relationship. In fact the estimated parameters are:

$\hat{a} = 490.87$ $(t = .527)$

$\hat{b} = 17.32$ $(t = 6.3)$

$R^2 = .8325$, $\bar{R}^2 = .8116$.

The actual and predicted values for W_t are listed in Table V.

The estimated intercept is relatively small in magnitude (about 8% of the mean W_t) and statistically insignificant. This and the respectable $\bar{R}^2$ and predicted values for W_t lead to the acceptance of the following working hypothesis:

> In a period of relatively stable crude oil prices (and other economic variables such as taxes, regulations, etc.), the proportionality factor between S_t and A_t is relatively constant.

The above working hypothesis allows a quite limited and tentative test of the performance of the voluntary information sharing arrangements in the period around 1974. Even though test hole expenditures declined from 1973 to 1974, the number of new field wildcats increased. Thus, the key question is whether the number of

TABLE V

Year	$\hat{W}_t$	$W_{t\ \text{actual}}$
1960	7381.68	7320
1961	7199.53	6909
1962	6831.35	6794
1963	6423.45	6570
1964	6351.48	6632
1965	6154.29	6182
1966	5799.43	6158
1967	5686.31	5271
1968	5659.15	5205
1969	5806.44	5956

wells increased "enough." If the answer is yes, possibility (i), that the failure rate increased, is refuted. If the answer is no, possibility (i) is supported. Unfortunately, attempting to match 1974 drilling activity to the data from 1970 to 1978 is not valid because crude oil prices were most assuredly not stable in the period. It is, in fact, the large and unexpected jump in those prices which motivates this examination.

However, the institution of U.S. price controls on domestically produced "new oil" (a category which includes oil from new field wildcats) did keep crude oil prices in that category relatively stable from 1974 to 1978. This is useful, because the data in Table II show that test hole contributions began to increase after 1974, reaching pre-embargo levels. Therefore, if the period 1975 to 1978 can be marked as one of returning to normal, the drilling of new field wildcats in 1974 can be compared to that which would be "expected" by observing the data from 1975 to 1978.[18] This can be done as follows: the "working hypothesis" stated above is employed, and a wells/acreage regression is estimated for the years 1975 to 1978. The results from the regression are used to "post forecast" an expected number of new field wildcats for 1974, and the predicted level $\hat{W}_{1974}$, is tested statistically against the actual value. When this procedure is followed, the following results are obtained:

$\hat{W}_{1974} = 5919.32$

$W_{1974(\text{actual})} = 5652$

Error 267.32

t-statistic on error = 3.68

A one tailed t test shows the error to be significant at $\alpha = .05$.

The importance of restricting this kind of estimation to a period in which the assumption on the stability of b_t can reasonably be thought to hold can be seen by running precisely the same test using all the years from 1960 to 1978 (excluding 1974). While, as in the more limited test of 1975-1978, actual drilling for 1974 is lower than predicted (the point estimate of the error is actually larger than the first test), the t-statistic on the error is insignificant:

W_t 1974 actual	5652
$\hat{W}_t$ 1974	6177.29

error 625.29

t on error: 1.10

The details of the two regressions are reported in Table VI.

The paradox of this simple test, then, is that it requires a stable environment, yet such periods of stability over the period of interest are short (only four years in the one case). To approach the problem with the availability of a more robust data series, b can be assumed to vary systematically as a function of the structure of the economic environment. The argument presented here has been that oil and gas prices are an important determinant of the structure, affecting both β_t in expression (3) and α (the

TABLE VI

REGRESSIONS RELATING WELLS DRILLED TO ACREAGE

Years:	1975-1978	1960-1978 (ex. 1974)
Intercept:	-6289.4215	-355.1425
	(4.00)	(.244)
Slope:	34.26	18.612
	(7.90)	(4.36)
$\bar{R}^2$:	.9533	.51
N:	4	18
1974 prediction error:	267	625.29
t on error:	3.68	1.10

relationship of the exploratory margin to the drilling games) in expression (5). Therefore, the following relationship was estimated for 1962 to 1978 (excluding 1974) using ordinary least squares:

$$\frac{W_t}{A_t} = a_o + a_1 P_t + a_2 P_t^2 + a_3 DUM_t$$

where P_t is a real after-corporate-tax price index for oil and gas, (see Table VII) and DUM_t is a dummy for the years after 1969 (when changes in personal income tax laws and the oil import tariff program went into effect). The results of the regression are presented in Table VIII.

The regression estimates were used to compute a prediction for W_t/A_t for 1974, which can be compared with the actual 1974 figure:

1974 predicted	16.679213
1974 actual	15.86
error	.819213
t on error	.8131

Using the actual acreage level for 1974, the 1974 error translates to approximately 292 wells, which is similar in magnitude to the 261-well shortfall predicted by the 1975-1978 test. However, the t-test on the error from the more inclusive regression is highly insignificant.

Thus, while the qualitative results of these tests support

TABLE VII

ADJUSTED REAL OIL AND GAS PRICE INDEX

Year	Index
1962	.413
1963	.406
1964	.399
1965	.390
1966	.381
1967	.376
1968	.363
1969	.353
1970	.361
1971	.392
1972	.423
1973	.533
1974	1.000
1975	1.053
1976	1.034
1977	1.009
1978	.995

TABLE VIII

Variable	Value	t statistic
constant	21.01881	
P	-8.605432	- .55232
P^2	7.665373	.705247
DUM	-3.399538	-5.566899

$\overline{R}^2 = .72282$

N = 16

D.W. = 2.0469

F = 14.03886

the hypothesis that too few wells were drilled in 1974, there is not sufficient evidence to conclude that the error is significantly different from zero. Consequently, while there is support for explanation (i) from the direction of the error, the alternative hypothesis that the cooperative institutions worked as well in 1974 as in other years cannot be rejected.

In summary, the empirical evidence for the successful application of the cooperative institutions is abundant. The motivations for cooperative behavior developed in the theoretical section of this paper are reflected by the real world development and operation of the institutions.

The theory developed here was also shown to be meaningful in that it generates testable hypotheses about real world behavior. Specifically, there is the possibility that the cooperative contracts will fail under certain circumstances. While the data needed to directly test the failure rate are almost nonexistent, a sharp drop in reported dry hole and bottom hole contributions in 1974 is suspect. There is some support for each of three possible explanations for this drop: i) failure of the cooperative arrangements, ii) decreased necessity for the agreements, and iii) changes away from dry hole and bottom hole contributions to other forms of agreements. The third possibility is supported anecdotally by conversations with persons in the oil industry; the second is necessarily true if the number of agreements did decline, because exploratory drilling increased in 1974. The first possibility was tested indirectly, and while it was supported by the direction of the predictions, the alternative hypothesis that

(i) was not a factor could not be rejected.

IX. AN EVALUATION OF DIFFERENT POLICIES FOR DEALING WITH THE INFORMATION EXTERNALITY

It is clear that, absent any cooperative or collective action, suboptimal exploration patterns may occur. The existing cooperative information sharing contracts, discussed at length in this chapter, as well as other proposals, such as drilling subsidies, address this problem. These programs can be evaluated in light of the theory and empirical evidence reported in this chapter. The evaluation presented in this section will cover four points: i) whether or not the policy is better than doing nothing at all; ii) whether or not the policy is optimal; iii) how one policy compares with or relates to another; and iv) problems of implementation.

First, consider the cooperative information sharing arrangements which are extant in the oil industry. Within the structure of the model as presented in this paper, the information sharing contracts are better than no action at all. Using the theory of cooperative games and the characteristic function based upon the solution in the weak sense (section VI), it is evident that cooperative institutions never induce firms to take action which is pareto dominated by noncooperative play. On the other hand, the theory predicts that there will be situations of successful cooperation to improve outcomes from the noncooperative solution. That this does, in fact, occur is confirmed overwhelmingly by the empirical evidence from the oil industry. The use of these agreements is robust and widespread.

The cooperative institutions, however, may not be ideal. Theoretically, the potential failure of the cooperative arrangements in a battle-of-the-sexes game was noted, and some evidence to support this possibility was presented in section VIII. Furthermore, there is evidence that, as the number of firms goes from two to greater than two, the problems of coordinating and negotiating larger group public goods decisions become more acute (Kennedy, [1976]). The modern institutions involved with cooperative agreements also demonstrate a strong tendency to adapt in order to capture more gains from cooperation. This can be seen in the evolution of the tradition that "cooperators" receive better information (electric logs, core samples, etc.) than those "hanging from every tree." The adaptation is also evident in the "scout check" meetings of the 1950s, and in the switch from money towards acreage and even more elaborate trading agreements in the 1970s.

Finally, the fact that so many institutional details and hardware have been put in place makes these trading institutions very accessible to potential participants.

Among the other solutions suggested for dealing with the problem of information externalities is a program of government drilling subsidies.

For each of the games in which suboptimal noncooperative play could result, there would exist a particular Coase-type subsidy for achieving optimality. For example, consider a version of Game 3 as depicted in Figure 6. Optimality can be achieved by paying either firm A or B a $\$(1 + \varepsilon)$ subsidy, while paying the other firm nothing. The subsidized firm would drill, the other firm would hold out. An optimal subsidy scheme must be selective both with regards to the firm and as to the drilling situation at hand. Different firms in different locations would have to be paid different amounts. The information requirements of such a program would be immense, if not impossible.

Another possible type of subsidy would be a simple, blanket national subsidy for exploratory drilling. As can be seen from the discussion above, a uniform subsidy could not achieve optimality, More important is the fact that such a policy would not necessarily be better than doing nothing at all. In Games 4 and 5, for example, noncooperative play achieves an optimal staggered drilling plan which could be frustrated by a drilling subsidy available to each firm. Furthermore, if a uniform subsidy were added with the cooperative drilling arrangements still being used, the subsidy could frustrate the contracts in situations where optimality might otherwise have been achieved. The key point is that the nonoptimality of noncooperative behavior derives not merely from "too little" exploration, it can also be a result of improperly sequenced information, a problem which a blanket subsidy cannot handle properly.

These three policies do not exhaust the list of potential solutions. The possibility of the application of newly created incentive compatible institutions to guide petroleum exploration is an important topic for further research. Such institutions might include, but would not be limited to, aspects of joint ventures or field unitization applied at the exploration stage.

X. SUMMARY AND CONCLUSION

The nature of petroleum exploration patterns in this country has led to situations in which the information provided by drilling is a public good. With a game theoretic model of drilling decisions, it has been shown that noncooperation can lead to suboptimal outcomes. Public policy discussions of methods of handling this problem should take account of the common use of cooperative arrangements to share information in exploratory oil field drilling.

It was shown theoretically that under several reasonable conditions, private cooperative institutions are a natural result of the derived two person drilling game. The predicted success of the drilling institutions in such cases is mirrored by its common and successful application in the real world.

The theory also predicts that the cooperative sharing arrangements might fail to insure optimal behavior from firms if a "battle-of-the-sexes" game situation is present. There is theoretical and empirical evidence to suggest that such failures may have increased in 1974, but the lack of data permits only an indirect test which yields ambiguous statistical results.

Other suggestions have been offered for dealing with the information externality. For example, there exists (in each case) an appropriate selective subsidy to achieve optimality. However, the more easily implemented general or blanket subsidy has drawbacks which could make matters worse than doing nothing at all. For the moment, the small implementation problems and proven instances of success (even if the nature of failures is unknown) argues well for the private cooperative arrangements. More research into alternative collective decisionmaking processes is needed.

APPENDIX I

The basis for the solution in the weak sense of Luce and Raiffa ([1957], pp. 106-109) is the stronger solution concept, the "solution in the strict sense." To examine the solution in the strict sense, some preliminary definitions are needed.

Define a strategy pair (α,β) to be jointly inadmissible if there exists another strategy pair (α',β') such that each player prefers the outcome at (α',β') to that at (α,β). An outcome which is not jointly inadmissible is jointly admissible.

If (α^*,β^*) is an equilibrium pair, and $(\hat{\alpha},\hat{\beta})$ is also an equilibrium pair, then the equilibria are interchangeable if $(\alpha^*,\hat{\beta})$ and $(\hat{\alpha},\beta^*)$ are also equilibrium strategy pairs. The equilibria are equivalent if they yield the same payoffs.

A noncooperative game has a solution in the strict sense if:

i) there exists an equilibrium in the set of jointly admissible strategy pairs; and

ii) all jointly admissible equilibria are both interchangeable and equivalent.

These conditions impose desirable properties of coordination and lack of conflict on candidates for "solution" to the game. However, they are strong enough that nonexistence is a real problem. The familiar prisoner's dilemma does not have a solution in the strict sense. In fact, the very concept under investigation here, the possibility that "reasonable outcomes" occur at pareto suboptimal points, precludes the existence of a solution in the strict sense.

The solution in the weak sense imposes the same conditions i) and ii) on the reduced game which occurs when players eliminate dominated strategies. As in a prisoner's dilemma, the solution in the weak sense can occur at a non-pareto outcome.

For the two-person, two-pair strategy games of this paper, it is important to note the following:

1) A dominant strategy equilibrium is a solution in the weak sense (it is the only strategy in the reduced games, so it is trivially an interchangeable, equivalent equilibrium in admissible pairs, thus a solution in the strict sense of the reduced game).

2) When one firm plays a dominant strategy, α', and the other firm plays a best response, β', the pair (α',β') is the solution in the weak sense. (Again, trivially, (α',β') is admissible in the reduced game, and it is the only equilibrium in the reduced game.)

Dominance in this paper is used in the following sense: α dominates α' if and only if

$$[E\Pi_j(\alpha,\beta') \geq E\Pi_j(\alpha',\beta')] \quad \forall\beta'$$

with > holding for at least one β'. α is a dominant strategy if it dominates all other strategies.

APPENDIX II

Lemma: The solution in the "weak sense" of games 4 and 5 is the social optimum.

Proof: The games are

		B	
		D	ND
A	D	r,s	r,t
	ND	u,s	w,z

$u < r$

$w < r$

$u > w$

$s < t$

$s \gtrless z < t$

The solution is (D,ND).

$t > s$ so (D,D) cannot be an optimum. Likewise $r > u$ rules out (ND,D). Finally $r > w$, $t > z$ eliminates (ND,ND).

FOOTNOTES TO CHAPTER 3

1. When production decisions must be made ex ante, information can be used to improve production choices in a way which increases expected profits. (See Hirshleifer, 1971).

2. In fact, the complete profile of the structure may not be known until the entire production history of the well is complete, if then. But, Kennedy [1976] says, "Any wildcat has some value.... At the very worst, they establish that yes, the granite is indeed only 300 ft. below the surface, and everybody can now drop their acreage in the area and get on with better things. At the very best, a significant new discovery is made, and everybody can now start hustling for rigs and tubular goods."

3. See especially Arrow [1974].

4. Peterson [1975] gives an example from the Alaska North Slope.

5. In a later paper, Peterson [1978] mentions these institutions in a footnote, but does not incorporate them in his analysis.

6. This paper will not consider the more general topic of production externalities between the properties.

7. Personal communication with petroleum geologist Robert L. Isaac.

8. "Complete" information is defined here to mean that each player knows the strategies and associated payoffs available to the other players.

9. Given A3 and A4, if A5 or A7 holds rather than A8, A9 cannot hold. To see this, consider A's payoffs

		B	
		D	ND
A	D	r	r
	ND	u	w

A5 or A7 $\Rightarrow w \geq r$.

A4 $\Rightarrow u > w$

$\Rightarrow u > r$ which contradicts A9.

It is also true that given A3, if A9 holds for both firms, then A4 cannot hold. Consider

		B	
		D	ND
A	D	r,s	r,t
	ND	u,s	w,z

By A9 $r \geq u$, $s \geq t$. By A4 (the second part) $u > w$, $t > z$ and (D,D) is the social maximum $\rightarrow\leftarrow$.

10. Kennedy relates that the principal difficulties he has experienced in dry hole contribution bargaining were: "1. Operators proposing a test will have generally tried to argue a gross exaggeration of the value of the test to owners of surrounding acreage, while at the same time pretending to ignore its value for their own acreage in the area outside the drilling unit.

2. Nonoperator acreage owners around the proposed test have carried on a similar charade, pretending to virtual indifference as to whether the well is drilled, yet perversely insisting on its great value to acreage owners in the drill site unit."

Kennedy's article is, in fact, an exposition of a particular bargaining mechanism, based on distance from the drill site.

11. 30 F.(2d) 481

12. 34 F.(2d) 589

13. Personal communication with Harry L. Sprinkle, Executive Vice President of the American Association of Petroleum Landmen (AAPL).

14 Personal communication with Robert L. Isaac.

15. Personal communication with Harry L. Sprinkle and Robert L. Isaac.

16. There are several measures of the amount of exploratory drilling. The data series reported in Table III is the "new field wildcat" count from the American Association of Petroleum Geologists, reported periodically in the Association's Bulletin. These numbers do not comprise the whole of what the AAPG classifies as "exploratory" wells, which includes new field wildcats, but adds outposts, extension wells, and deep and shallow tests. Roughly speaking, these latter categories are "exploratory" in that wells are not directed towards a known pool, but they are located on or near land with known oil producing capabilities. The new field wildcats are expressly those searching out new oil fields.

Likewise, there are several methods of assigning an acreage measure to a given year. This data series, reported annually in the periodical The Oil Producing Industry in Your State (published by the Independent Petroleum Association of America), is measured as of January 1 of a given year. These data could have been assigned to the year just starting or the year just ending. As wells are drilled throughout the 12-month span, when economic conditions can change, the data reported here are the mean of the beginning and ending acreage for any given year.

17. The only drilling failures which will be considered here are those resulting from the failure of the cooperative information sharing institutions, i.e., the possibility of an otherwise profitable well not being drilled because of a mechanical failure or bad weather will not be considered.

18. For some producers, the marginal revenue of "new oil" was above its price in 1974 and 1975 because of the released oil program of the federal government, in which the production of a barrel of new oil "released" another otherwise price-controlled barrel of old oil from the price limit.

19. The price index used here was constructed as follows: nominal oil and gas prices were adjusted for changes in the maximum corporate tax rate, the percentage depletion allowance, and the investment tax credit according to the formula:

$$\frac{P_{NOM}(1 - u(1 - DA))}{1 - \gamma(itc)}$$

where P_{NOM} = nominal price

u = corporate income tax rate

DA = percentage depletion allowance

γ = proportion of oil and gas investments eligible for the investment tax credit (γ was estimated to be about 15 percent)

c = the investment tax credit

(see Brannon [1975] and Cox and Wright [1975]).

In 1975, the depletion allowance was repealed for all but independent oil producers of less than or equal to a certain amount of barrels per day. The criticial amount declined in stages from 2,000 b/d to 1,000 b/d from 1975 to 1980. The Oil and Gas Journal [1975] estimated that initially 150 firms would be made ineligible. The approach used here was to take the proportion of wildcats drilled by other than the 200 largest companies (for 1977, this figure was about 60 percent (U.S. Bureau of the Census [1977])) and multiply by the percentage depletion amount. The proxy .13 thus calculated was used for 1975 to 1978.

Once the adjusted prices were obtained, they were deflated using the Consumer Price Index. (Another regression using a series deflated by the A.P.I. cost-of-drilling index was not as successful and is not reported here.) Finally, the adjusted and deflated prices series were converted to a Laspeyres price index using 1974 reserve additions and discoveries for each as the base year weights (American Petroleum Institute [1975]).

Finding a nominal price series to be used as a basis was straightforward for oil. For years 1973 and before, the average wellhead price of crude oil (American Petroleum Institute [1975]) was used. For 1974 and later, the appropriate federally regulated price ceiling for oil from exploratory wells was used (source: the U.S. Department of Energy Monthly Energy Review, various issues).

The task of choosing the appropriate nominal price for natural gas was much more difficult, because throughout the period under study, there was not one but several markets to which new reserves of natural gas could be dedicated: the regulated interstate market and the various unregulated intrastate markets. From the pattern of reserve dedications, it appears that prices in the intrastate markets surpassed the interstate ceilings in the late 1960 or early 1970s (Breyer and MacAvoy [1974]). Therefore, the average of i) Permian Basin (Texas) and ii) Southern Louisiana area federal price ceilings for new dedications was used for the period 1962-1970. Finding the appropriate intrastate prices for use from 1971 to 1978 was particularly difficult. For the years 1975 to 1978, the U.S. Department of Energy Monthly Energy Review reported detailed figures on intrastate gas prices; again, for this series an average of Texas and Louisiana prices was adopted. For the years 1971 to 1974 the following figures were estimated:

1971	30¢/MCF
1972	43¢/MCF
1973	72¢/MCF
1974	$1.15/MCF

These numbers represent very rough extrapolations based on reports in various issues of the Oil and Gas Journal (August 21, 1972, p. 34; November 27, 1972, p. 40; December 25, 1972, p. 47; January 15, 1973, p. 40; January 29, 1973, p. 85; February 5, 1973, p. 35; November 11, 1974, p. 29).

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CHAPTER 4

PETROLEUM PRICE CONTROLS WHEN INFORMATION IS A JOINT PRODUCT

I. INTRODUCTION[1]

Federal regulations which set maximum price schedules for crude oil production are, without a doubt, a major reason for the recent increased interest in the effects of pricing policy on resource production. The papers of Burness [1976], Montgomery [1977] and Lee [1978] demonstrate that, due to the intertemporal nature of the fixed resource problem, price controls, even those which appear to be "nonbinding" in a static sense, will lead to altered production schedules by profit maximizing, competitive firms. In general, whether price controls lead to earlier or later resource depletion depends upon the rate of change of the spread between the world and controlled prices. Montgomery, based upon estimates of price behavior and of physical properties of oil fields, calculated that "if domestic oil producers had not been subject to price controls, and if they extrapolated recent OPEC pricing behavior, current (1977) U.S. oil production would be lower than it is now under price controls" (p. 52). The comparative statics of price controls is presented in Appendix I.

Standard economic theory suggests that when price controls alter the production of some good X, other goods which are related to X through production techology or market demand will also be affected. This paper will show that there is another way in which production decisions on seemingly unrelated deposits can be biased by the existence of price controls on one of them. This occurs if (i) the property under price controls produces information as a joint product with the resource, and (ii) there is a jointness of information between the two properties, and (iii) the existence of fixed costs of beginning development on the non-controlled property allows the availability of information to affect total equilibrium profitability conditions.

Existing work has focused on the effects of price controls on the production schedule of the directly controlled commodity. Yet, such controls may distort economic signals to owners of other resources and serve to alter their production decisions. There are many obvious ways in which price controls on one commodity, X, can directly distort the production of another good, Y. First, X and Y may be joint products, or their production may entail common costs. Likewise, the demand for X and Y may not be independent. For example, the market for natural gas is connected in both respects to crude oil production. In some fields, natural gas and crude oil are joint products. And, natural gas and crude oil derivatives are imperfect substitutes for many fuel purposes. Finally, the ceiling on X may vary with production of Y (see Smith and Phelps [1978]).

There is also the possibility that regulations are written so as to bring Y under controls even though it is a different resource. For example, the most striking aspect of U.S. federal regulations has been the rather severe set of price controls placed on "old" oil, oil from "properties" already in production at the beginning of the OPEC price increase. Other U.S. production has either remained free from controls, or has been placed under a much higher ceiling price. Presumably, the controls on old oil are an attempt to strip away intramarginal rent from owners of crude oil with lower marginal production costs. However, "property" was defined by the Federal Energy Administration to be "the right to produce domestic crude oil which arises from a lease or from a fee interest."[2] Yet, given input prices, production costs are determined by physical properties of the particular reservoir. But if two reservoirs are covered by the same lease, production from them is classified together for purposes of determining old oil levels, even if production from one is substantially more expensive than from the other. On the other hand, if one reservoir extends beyond the "property" boundary, its oil can legally be produced at two different prices. The F.E.A. (now Department of Energy) has considered proposals to base the determination of old oil upon reservoir limits, but has dropped the idea because of the "enormous administrative problems associated with determining the limits of thousands of different reservoirs."[3]

This paper examines one other manner in which production schedules may be interdependent. Production from the price controlled site may produce joint products: the resource, and information valuable to the production from another site. The next section presents a model in which it is reasonable to expect that changes in the flow of the external information from one site will affect the production at another.

II. INFORMATIONALLY RELATED PRODUCTION

Now consider specifically crude oil production. The basis for analysis, following federal procedures, will be the oil "property." Assume that the output of each property is identical in all physical aspects and that there are no differences in transportation costs. Let there be a single oil price trajectory, $\tilde{P}_t$, which is known and is determined exogenously (say, by a perfectly elastic supply price announced by the OPEC cartel). Furthermore, let the physical production functions of the oil from each property be independent. This second assumption is not made because it is necessarily a good description of reality. Rather it was noted in the last section that problems can be caused by production interdependence. The purpose of this section is to demonstrate some potential distortions which can exist even in the absence of direct production jointness.

Next, suppose that there are two properties, X_s and X_v. X_s is a property already in production and which is subject to a price ceiling, so its output schedule differs from that absent price controls. (Again, the mathematical derivation which shows that the X_s output schedule can be changed by price controls is presented in Appendix I.) Let X_v be a property not subject to price controls, and perhaps not yet even in production. By the above assumptions, the price of the X_v output, $\tilde{P}_t$, and its production costs are unchanged. Nevertheless, there is the possibility for the price controls on X_s to affect the production decisions for X_v. Suppose there is a jointness of information between the two properties (in that production data from X_s also provide information about X_v), and that there are fixed costs of beginning well development. If this is true, the availability of production data information from X_s can affect the total optimization conditions governing the commencement of development of X_v, as well as other production decisions based on knowledge about X_v. If price controls on X_s alter the X_s production schedule, the flow of external information about X_v will also be changed. The change in the information about X_v can affect production decisions there.

One special case of such an interaction is of particular interest: the case in which X_v is not yet in production, and in which the decision to be made is when to commence production. Because of the fixed development costs, and with the knowledge of the nature of the external information from X_s, the owner of X_v may wish to wait to make a decision regarding the development of X_v until information dependent on a certain amount of total production from X_s is received. As the flow of information from X_s is altered by price controls, the optimal decision date at X_v may also vary. Even though price controls on X_s have not altered the price or costs at X_v, they have affected the total profitability conditions for commencing development. Specifically, if production from X_s is speeded up, the owner of X_v may hasten the date for deciding upon its initial development.

These results are vacuous if there is not such an interdependence between production at X_s and X_v, either because analogy comparisons are not valid, or because such information is not related to the production schedule. It was demonstrated in Chapter 3 that information interdependencies do exist, in that case at the level of the drilling of the first well on a property. Furthermore, it appears that firms do use historical production data from more mature properties in estimating reserves at other prospects. In the Petroleum Exploration Handbook by Moody [1961] the use of "analogy" reserve estimation is discussed:

> Production statistics and reservoir data are available on older fields, thus enabling the geologist or engineer to calculate actual cumulative recoveries in barrels per acre or barrels per acre-foot for any given field or reservoir. Nothing is of more value to the estimator than historical knowledge of a similar reservoir. However, these statistical yardsticks should not be used as a substitute for judgment, but as tools to make judgment more accurate. (pp. 14-18)

In particular, cumulative recovery data, focusing on the pressure of the "drive" in the formation, are said to be useful in reserve estimation.

It should be noted that the information from X_s about X_v may be, but need not be, a message which is external to a firm. If the message is not external to a firm (because the same firm owns both properties) it should be argued that in planning production from X_s, the value of message about X_v is included in the calculations. In Appendix II, it is demonstrated that the result that price controls alter production incentives for the X_s property remains, although under some circumstances the way in which production is rescheduled may vary if the information is included in the calculations.

This theoretical exposition has been presented in terms of "development." Using this terminology is not meant to exclude activities which are commonly called "exploration," and to the extent that oil firms make the same information - sensitive calculations in timing of oil exploration, the same conclusions are applicable. Price controls can affect the pattern of exploration on non-controlled prospects if the timing of the exploration relies upon information generated as a joint product of the (altered) production schedule of the price controlled wells.

III. APPLICATION TO RECENT EVENTS

From its inception, the U.S. crude oil price control program has had multi-tier pricing as a central feature. From 1973 to January 1976 this took the form of a price ceiling of $5.03 per barrel on old oil and world market prices for other production. By January 1976, the average price for uncontrolled oil was $12.99 per barrel. Beginning in February 1976, an upper tier price ceiling, initially $11.47 per barrel, was imposed on previously uncontrolled crude oil production. (Low production "stripper" well oil is exempt from price controls.) As of 1978, about 37.54% of total U.S. crude oil production remained controlled as "old oil" (although both ceilings rose slightly during 1976-1978).[4]

The theoretical results of this paper, when considered in light of these regulations, suggest that if price controls altered the production schedules from old oil wells, exploration and production decisions on uncontrolled (later upper tier) properties also could have been affected.

By definition, old oil is produced from properties already in production in 1973. Further, areas that are most likely to be informationally related are proximate either physically or in type of structure. That is, among the uncontrolled (upper tier) properties, those most likely to be developed differently along the lines of the joint information model of this chapter are those located in the more mature producing areas. Oil activity on uncontrolled properties in more unknown or unusual areas would be the least likely to be informationally related to altered information streams from "old" oil fields.

If Montgomery is correct and the U.S. price control program served originally to accelerate production and development from price-controlled properties, then one would suspect (based on the model in the previous section regarding the commencment of drilling activity) that the oil exploration activity which followed higher prices for uncontrolled (upper tier) oil was relatively more concentrated in and around mature producing areas than otherwise would have been the case. (Likewise, exploration initially should have been less heavily focused on frontier or exotic properties.) There is some scattered evidence to support this hypothesis. Over the period 1972 to 1977, the "success rate" of oil exploration (defined as the proportion of exploration wells completed as producers) rose to an all time high of 26.97 percent,[5] while the percentage of all new field discoveries estimated to have reserves of greater than one million barrels fell sharply,[6] suggesting a shift to less risky, lower payoff areas of exploration.

Frederiksen [1978] documents that these trends were reflected also in a drop in the exploration "finding rate" (barrels of oil equivalent found per new field wildcat foot drilled). Frederiksen points out that the data sources[7] do not distinguish between truly "dry" holes and those with small but unproductive amounts of hydrocarbon, so that the increase in the success rate may simply reflect the reclassification of marginal new fields by higher prices and not a shift in drilling patterns. However, restricting attention to "new field" wildcats (as opposed to those which seek extension of or new pools in old fields), one observes similar increases in the success rate. Yet Frederiksen reports that historically the percentage of new field discoveries which have been abandoned as unprofitable within one year has been quite small (an average of .9 percent between 1970 and 1973, and an average of .3 percent between 1974 and 1976). Therefore, for this one important exploration category, simple reclassification does not appear to be responsible for the observed increases in the success rate.

These data are not intended to build a conclusive case that information flows are the only possible reasons for such observations. Frederiksen, for example, considers several other explanations for the apparent shift towards less risky exploration projects: stripper well pricing policy, availability of oil field supplies, price expectations, etc. These data are intended to suggest that future research on exploration patterns in the period 1973 to the present is one area in which the model of information as developed in the previous sections of this paper may be helpful.

IV. CONCLUSION

There are many ways in which price controls on one oil property can bias the production decisions at a second property. The direct effects through production and demand dependence are straightforward. There are undoubtedly other areas, such as changes in price expectations or gaming against the controls themselves, which still need to be examined. This paper has shown that the distortion of information flows is also a possibility. While no attempt has been made to quantify or rank the various effects, it seems that the use of inter-property analogy in petroleum exploration is considered important by petroleum geologists. Recent experiences in U.S. oil exploration provide some unusual data which are consistent with the hypothesis developed from this paper.

APPENDIX I

The following is adapted from Burness [1976] and Montgomery [1977].

Let

$\tilde{P}_t$ = world oil price trajectory, determined exogenously

P_c = controlled price of domestic crude oil (assumed constant over time)

define $\alpha_t \equiv (\tilde{P}_t - P_c)$

Rewrite $\tilde{P}_t$ as $P_c + \alpha_t$

γ = market discount rate

x_t = production of petroleum in period t

$C(x_t)$ = production costs, $c' > 0$, $c'' > 0$

X_t = resource remaining in period t

The problem for the expected profit maximizing firm can be considered a problem of optimal control. In the case of price control, the problem is

$$\max_{x_t} \int_{t_0}^{T^1} \left\{ P_c x_t - C(x_t) \right\} e^{-\gamma t} dt$$

subject to $\dot{X}_t = - x_t$

The Hamiltonian to be formed is

$$H^1 = \left\{P_c x_t - C(x_t)\right\} e^{-\gamma_t} - \lambda_t^1 x_t$$

the necessary conditions are

a.i) $$\frac{\partial H^1}{\partial x_c} = 0 = P_c - C'(x_t) - \lambda_t^1 e^{\gamma t}$$

$$\Rightarrow \quad P_c - C'(x_t) = \lambda_t^1 e^{\gamma t}$$

a.ii) $$\frac{\partial H^1}{\partial x_t} = -\dot{\lambda}_t^1 = 0$$

a.iii) $$\lim_{t \to T^1} \left\{\left(P_c x_t - C(x_t)\right) e^{-\gamma t} - \lambda_t^1 x_t\right\} = 0$$

Likewise, the expected profit maximizing problem for the firm that receives the uncontrolled price for its output will act to

$$\underset{x_t}{\text{Max}} \int_{t_o}^{T^2} \left\{(P_c + \alpha_t) x_t - C(x_t)\right\} e^{-\gamma t} dt \quad \text{subject to } \dot{X}_t = -x_t$$

The Hamiltonian is

$$H^2 = \left\{(P_c + \alpha_t) x_t - C(x_t)\right\} e^{-\gamma t} - \lambda_t^2 x_t$$

and the necessary conditions are

b.i) $$\frac{\partial H^2}{\partial x_t} = 0 = (P_c + \alpha_t) - C'(x_t) - \lambda_t^2 e^{\gamma t}$$

$$\Rightarrow \quad (P_c + \alpha_t) - C'(x_t) = \lambda_t^2 e^{\gamma t}$$

b.ii) $\frac{\partial H^2}{\partial x_t} = -\dot{\lambda}_t^2 = 0$

b.iii) $\lim_{t \to T^2} \left\{ \left((P_c - \alpha_t)x_t - C(x_t) \right) e^{-\gamma t} - \lambda_t^2 x_t \right\} = 0$

Since the firm faces the same resource constraint in each case, there must be at least one point at which the production schedules intersect. Denote x_{tc} as production at time t with controls, x_{tw} as production at time t when the firm faces world prices. Totally differentiating a.i and b.i results in

$$\dot{x}_{tc} = \frac{-\gamma\left(P_c - C'(x_{tc})\right)}{C''(x_{tc})} \qquad \text{A.I.1}$$

$$\dot{x}_{tw} = \frac{\dot{\alpha} - \gamma\left(P_c + \alpha - C'(x_{tw})\right)}{C''(x_{tw})} \qquad \text{A.I.2}$$

Let $\hat{t}$ be one such time at which the production schedules intersect, so $x_{\hat{t}c} = x_{\hat{t}w} = x_{\hat{t}}$. At time $\hat{t}$

$$\dot{x}_{\hat{t}c} - \dot{x}_{\hat{t}w} = \frac{-\dot{\alpha} + \gamma\alpha}{C''(x_{\hat{t}})} \qquad \text{A.I.3}$$

which is positive, negative, or zero as γ is greater than, less than, or equal to $\frac{\dot{\alpha}}{\alpha}$, the proportionate rate of change of the difference between the world price and the price ceiling. If $\dot{x}_{\hat{t}c}$ is less than $\dot{x}_{\hat{t}w}$, the price control production schedule intersects the market price production schedule from above. If $\frac{\dot{\alpha}}{\alpha}$ is always greater than

γ, the rate of interest, there will be only one intersection point. In this case, production under price controls is initially greater than in a free market, and resource exhaustion occurs sooner. If the relationship between $\frac{\dot{\alpha}}{\alpha}$ and γ varies, but $\frac{\dot{\alpha}}{\alpha}$ is greater than γ at the first intersection point, then production rates before that point are greater under price controls, but the ultimate exhaustion date may be sooner or later.

With a two-tier price control (such as is applied to "old" and "new" oil) a similar result obtains. The first $\bar{x}$ production in each period is subject to the price ceiling P_c. Then $\alpha \cdot \bar{x}$ acts as a "franchise" tax, creating an incentive to shift production schedules forward.

APPENDIX II

Suppose the firm recognizes that production from X_s yields another good, information. Denote $f_c(x_t)$ as the value of information received from production x_s at time t when there are price controls. Let $f_w(x_t)$ be the value when there are no price controls. At time $\hat{t}$, defined as in Appendix I as a time at which the production schedules intersect, the analagous equation to A.I.3 is

$$\dot{x}_{\hat{t}c} - \dot{x}_{\hat{t}w} = \left[\frac{-\gamma\Big(P_c - C'(x_{\hat{t}})\Big) - \gamma\Big(f_c'(x_{\hat{t}})\Big),}{C''(x_{\hat{t}}) - f''_c(x_{\hat{t}})}\right] - \left[\frac{\dot{\alpha} - \gamma(P_c + \alpha - C'(x_{\hat{t}}) - \gamma\Big(f_w'(x_{\hat{t}})\Big)}{C''(x_{\hat{t}}) - f''_w(x_{\hat{t}})}\right]$$

If price controls do not change the value of the information, perhaps because (as was assumed in section III) $\tilde{P}_t$ is exogenous, then

$\dot{x}_{\hat{t}c} - \dot{x}_{\hat{t}w} = \dfrac{-\dot{\alpha} + \gamma\alpha}{C''(x_{\hat{t}}) - f''(x_{\hat{t}})}$ which yields exactly the same conditions as A.I.3 as long as $C''(x_{\hat{t}}) > f''(x_{\hat{t}})$. The usual assumption about marginal cost is that $C''(x_{\hat{t}}) > 0$. And it also would be reasonable to believe that the marginal information value of production does <u>not</u> increase without bound as the production from the property increases, so that by some point $f''(x_{\hat{t}}) \leq 0$, making $C''(x_{\hat{t}}) > f''(x_{\hat{t}})$ seem to be a reasonable condition.

FOOTNOTES TO CHAPTER 4

1. This is a revised version of the paper of the same title appearing in the May 1980 issue of Land Economics 56, No. 2.

2. 41 Federal Register 4940, February 3, 1976.

3. 41 Federal Register 4938, February 3, 1976.

4. The U.S. Department of Energy, Monthly Energy Review, May 1979.

5. Oil and Gas Journal, July 16, 1979, p. 40.

6. Oil and Gas Journal, July 16, 1979, p. 41.

7. Both the Oil and Gas Journal and Frederiksen use a data base of the American Association of Petroleum Geologists.

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