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Extraction cost, scarcity rent and institutional choice: Three reflections of resource scarcity

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EXTRACTION COST, SCARCITY RENT AND INSTITUTIONAL CHOICE
THREE REFLECTIONS OF RESOURCE SCARCITY

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ABSTRACT

Resources are provided by nature and they may be very scarce or very abundant relative to the quantity demanded. When resources are scarce, scarcity may be reflected in rising extraction costs and high rents. When resources are abundant, that may be indicated by common property or other non-traditional arrangements to govern resource use.

As production of both scarce and abundant resources accumulates over time, economists are challenged to predict changes in costs, rents and institutions. This dissertation proposes models and empirical analysis, of specific mineral and water resource industries, to begin to improve the understanding of resource price trends and the ability to forecast events based upon those trends.

The logic explaining the sequence of chapters in this dissertation is as follows. A model of institutional choice, in California water districts, takes priority in Chapter Two. Given the institutional background, resource extraction costs are most directly affected by the characteristics of resources being extracted and by resource prices. Accordingly, a mine investment model is presented in Chapter Three which emphasizes the impact of an important resource attribute, deposit volume, upon project cost and outputs in U.S. copper mines. This model is then used as
one component of the rent model in Chapter Four. The rent model relates long run changes in extraction costs to mineral scarcity rents.

Each chapter may also be read as an independent analysis of a specific public policy problem. Chapter Two addresses the impact of proposed legislation to end flat rate water sales in California water districts. Chapter Three forecasts the impacts of a trade embargo upon U.S. copper production. Chapter Four evaluates copper, coal and oil extraction cost trends and suggests that these trends are not a cause for policy concern.
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CHAPTER 1

EXTRACTION COST, SCARCITY RENT AND INSTITUTIONAL CHOICE:
THREE REFLECTIONS OF RESOURCE SCARCITY

I INTRODUCTION

One of man's oldest economic problems has been running out of accessible and high quality resources. In ancient times, growing societies faced a constant need to seek more distant water supplies, explore thinner seams of mineral ore and plant crops in poorer soils. In more recent times this problem has continued behind a comforting veil of technological change. The source of this problem is both a growing demand and a limited supply of high quality resources. The physical trace of this problem is the movement from more to less preferred resources at the margin of production. This movement is termed increasing scarcity.

This dissertation evaluates methods to forecast the impact of increasing scarcity upon three important policy variables - resource extraction cost, scarcity rent and institutional choice. Much of the practical interest in resource economics is due to the hope that these variables will move in a predictable fashion as production of scarce resources proceeds and as better quality resources are used up. If this hope is realized then changes in these
variables may be forecast and public policy and private investment strategies may be more efficiently crafted.

Methods used to forecast changes in these policy variables vary according to the adequacy of data about available resource stocks. Given sufficient resource data, it is often possible to directly estimate changes in institutional choice, extraction cost and rent. When resource data is poor, future trends in extraction costs and rents may be inferred from past trends. Trend data used for this purpose are often termed scarcity measures.

In addition, inferences may be drawn about the efficiency of future resource use, by comparing past adjustments to scarcity of the policy variables with "optimal" adjustments following some type of efficiency criteria. Programming or other optimal resource use models are commonly used to estimate efficient adjustments, using standard economic efficiency criteria.

If resources may be divided into two groups — abundant (low cost, bulky) resources and scarce (high cost, manageable) resources, the following hypothesis is proposed to describe the effect of an increase in resource demand. Institutional practices for managing abundant resources will move toward more market-like arrangements and, for scarce resources, extraction costs, will increase and rents will equal the present value of the increase, as if markets were
perfect. This is the unifying hypothesis of this dissertation.

Chapter one introduces subjects raised in this dissertation which tend to support this hypothesis. The chapter is divided into six sections. Following this introduction, section two describes models of the relationship between resource scarcity and the three policy variables. Section three describes the use of the policy variables to measure resource scarcity. Section four discusses resource use efficiency inferred from changes in the policy variables. Section five contains a brief overview of the remaining chapters in the dissertation and section six concludes this chapter.

II SCARCITY AND THE THREE POLICY VARIABLES

Information about the supply of resources available for current and future use may be used to predict increases in extraction cost, as resources are more intensively used, the equilibrium rent, compatible with those rising costs, and institutions which prevent rent (consumer or producer surplus) dissipation. This section describes the various models and model assumptions used to make such predictions.
Institutional Change

Institutional arrangements, including markets, property rights and contracting arrangements, govern the production and exchange of resources. Institutional arrangements may change over time, as resources become scarce and resource prices increase. Among other things, the relationship between scarcity and institutions is conditioned by the transaction costs of different institutions and the motivations underlying the social choice of institutions (Coase 1937; Demsetz 1964).

Transactions costs include the costs of defining and enforcing institutional arrangements such as markets, property rights and contracts. A variety of factors, including resource attributes, affect transactions costs. For example, many studies indicate that dispersed, unevenly distributed, hidden and fugitive resources are particularly expensive to define and enforce as private property. Hence, grazing land, oil and gold deposits, water resources and fish are often treated as open access or common property rather than as private property resources (Anderson and Hill 1975; Umbeck 1977; Libecap and Wiggins 1985). These same resource attributes raise the transactions costs of private contracting and monitoring of resource production and sales. This explains why the adjudication (unitization) of gold, oil and groundwater extraction and the metering of water
sales is not more widespread (Anderson and Hill 1975; Umbeck 1977; Libecap and Wiggins 1985; Randall 1982; Bowen 1982).

Much of the property rights and markets literature suggests that institutions naturally evolve in the direction of efficient arrangements, and there are many historical examples to back up this suggestion. Previously open access resources, such as land, minerals and water in the early American west, became private property or more carefully controlled common property, after the value of those resources rose (Demsetz 1967; Anderson and Hill 1975; Libecap 1978; Mathews 1986; Issac 1987).

However, the public choice and monopoly power literature indicate other motivations for institutional change besides efficiency (Williamson 1985). For example, voting can generate "inefficient" non-market practices, such as public irrigation districts and excessive public water storage (Buchanan and Tullock 1962; Smith 1980; Gardner 1983). Voting may also bring about markets when that practice is not efficient. The analysis of district water sales techniques, in Chapter Four, describes an instance where institutions may be forced to adapt inefficient market-like practices.

Resource Extraction Cost

Resource attributes affect the cost of resource extraction during the discovery, extraction, refinery and
delivery phases. Attributes may be classified in a number of ways; important attributes include resource concentration, variability, accessibility and deposit volume.

Resource deposit volume has an important impact upon project output and project sequencing and thus upon project costs. Most resources cluster into deposits of finite volume. This limits the total output possible from a given deposit and raises resource production costs from that deposit (Alchian 1959). Over time, this also implies that the path of resource production costs will be largely determined by the sequencing of projects, from one deposit to the next.

There are two basic models used to describe the impact of deposit volume limits upon project output — declining output and fixed output models. Early economic models (of the mine) emphasized that limits on the volume of deposits implied declining output, assuming a fixed resource price and no capacity constraints (Gray 1914; Scott 1953). More recent models, including capacity constraints, suggest that output will remain fixed until much of the deposit has been extracted (Crabbe 1982; Cambell 1980; Cremer 1979). Capacity constraints suggest, as a modeling simplification, that marginal resource production costs may be considered roughly constant up to the capacity limit and infinite thereafter.
Most applied studies in this topic area deal with the mining of minerals. Typically in these studies, mine output is assumed to be fixed and various methods are used to predict the mine capacity (Zimmerman 1977; Bradley 1982). However, the accuracy of these forecasting methods has not been well demonstrated. Chapter three of this dissertation presents a simple, fixed output mine model, which is compatible both with the economic theory of costs and outputs and with existing mine capacity data (Alchian 1959).

Other economic models are used to describe the development sequence of several, fixed volume deposits. The standard result obtained from these models is that deposits are developed in order of extraction cost so that extraction cost rises over time (Herfindahl 1967; Solow and Wan 1976; Lewis 1982). This result, often termed the least-cost-first rule, is obtained assuming a partial equilibrium framework, a fixed extraction technology and a set of projects that may be ranked in order of extraction cost. Other models have been proposed which indicate circumstances where the least-cost-first rule may not apply (Kemp and Long 1980).

Most mineral and water applications of sequencing models assume least-cost-first behavior and estimate the rate of increase in extraction costs given that behavior. (Moncur and Pollock 1988; Rosenkrantz 1979; Zimmerman 1977; Pindyke 1978; Nordhaus 1973; Lof and Hardison 1966). It remains an open question whether the least-cost-first rule
is a valid empirical description of mineral and water project sequencing (See Dale 1990).

**Resource Rent**

The relationship between resource scarcity and rent forms the core of much of the modern literature on exhaustible resource use. Many different models of exhaustible resource use have been specified (Hotelling 1931; Dasgupta and Heal 1979). Those models which assume perfect certainty and complete markets, usually characterize the equilibrium rent as everywhere equal to the present value of subsequent increases in extraction cost caused by the increasing scarcity (Heal 1976; Hanson 1980; Fisher 1981; Slade 1982). This characterization is sometimes termed the present-value-cost rule.

Other models suggest how uncertainty, incomplete markets and institutional constraints may complicate the relationship between extraction costs and rent (Dasgupta and Heal 1979; Gilbert 1979; Peterson 1975). Nevertheless, most applied studies accept assumptions about certainty and complete markets and forecast rents from resource stock data and the present-value-cost rule (Nordhaus 1973; Pindyke 1976; Moncur and Pollock 1988). Unfortunately, there are few historical studies of resource extraction cost and rent paths to confirm this relationship in practice.
III MEASURING RESOURCE SCARCITY

Concern with the adequacy of the earth's resources to sustain economic and population growth, and ignorance about available resource stocks, have led to efforts to measure resource scarcity. The prescribed economic measure of resource scarcity is the resource rent which, like any price, is determined by the intersection of supply and demand for the resource. When demand is increasing, or supply decreasing, the rent on marginal resources is termed Hotelling rent. It can be shown that Hotelling rent, and other measurements of resource scarcity, are effectively forecasts of resource extraction cost increases.

Resource rent may be defined in terms of extraction cost variations resulting from quality variations in the resource stock and quality variations in resources extracted over time. The quality of resource stocks varies substantially. There are rich and poor soils, high and low grade mineral deposits and accessible and distant water supplies. Usually, high quality resources can be replaced by low quality resources at a cost. Following this principal, nineteenth century agricultural economists determined that the rent on a given parcel of cropland equaled the difference between its unit growing costs and unit growing costs on the worst quality parcel in production (Ricardo 1960). Generalizing, this finding implies that
resource rent and resource production cost differentials are equivalent measures of resource scarcity, assuming static demand. Resource rent under static conditions is often termed Ricardian Rent.

Growing demand or resource non-renewability cause a movement over time from more to less favored resources, because less favored resources tend to be saved for future production. The rent paid for marginal resources in this case, represents future demand for the resource and reflects a kind of dynamic scarcity.

Using standard market assumptions, it can be shown that the Hotelling rent equals the present value of future increases in extraction cost caused by the movement from more to less favored resources (Chapter 4). For example, given zero discount rates the Hotelling rent on a parcel equals the difference between its unit extraction cost and the extraction cost of the worst quality parcel extracted in the future. Because discount rates are not zero, the Hotelling rent is the discounted difference in cost. Roughly speaking, the Hotelling rent is simply a discounted Ricardian rent.

It is the concern with growing demand, and limited resource stocks, that has motivated efforts to measure the increasing relative scarcity of resources such as fisheries, minerals and water. In these circumstances, the Hotelling rent is generally the recommended measure of resource
However, vertical integration in production and incomplete property rights to many resources create difficulties using Hotelling rent as a scarcity measure. Market rent data may not be available, under vertical integration, and available data may be distorted, with incomplete property rights. This has motivated a search for alternative scarcity measures which approximate the rent.

The ideal alternative would be a direct prediction of future resource extraction cost increases, discounted to present value. Theoretically this prediction would be equivalent to rent. In practice, a lack of resource stock data, as well as uncertainty about cost functions and expected demand, limit direct predictions of extraction cost trends. More often, economists use scarcity measures, including unit extraction cost trends and proxies for the Hotelling rent, to infer future extraction cost increases.

Past unit extraction cost trends are perhaps the most widely cited index of resource scarcity. An extrapolation of the trend provides at least one estimate of future costs. Unit extraction costs have been calculated for a number of extractive resources in the United States between 1870 and 1975 (Barnett and Morse 1963; Barnett 1979). These calculations indicate that unit extraction costs for most resources have been falling continuously and many economists
have concluded that resources are not now scarce and there is little cause for concern over future scarcity.

Objections to this conclusion and to past unit cost as a scarcity index are mainly two. First, unit cost trends are a function of technological improvement as well as resource quality and the unit cost trend may reflect past technological improvement rather than a lack of past scarcity (of high quality resources). Second, at best unit cost trends reflect changes in past resource quality not future changes, which may be quite different.

Proxies for the Hotelling rent have been suggested as scarcity measures, including the unit resource price and resource exploration costs. General conclusions about resource scarcity are difficult to draw from these suggested indexes. The price of most resources in the United States has been falling since 1870, a trend which has further encouraged economists in the belief that resources are not scarce (Barnett and Morse 1963; Barnett 1979). However, the price of most resources contains a large, often predominant, unit cost component to which criticism of the unit cost index applies.

In some circumstances marginal exploration costs for a resource firm are equal to the rent. This finding has been used to justify using exploration cost in place of Hotelling rent as a measure of scarcity (Fisher 1981; Halvorsen and
However, the lack of marginal exploration cost data for many resources constrains the use of this measure. A serious objection to rent and rent proxy measures of scarcity obtains for open access or partially controlled access resources such as fisheries and water. The rent for such resources tends to become dissipated and therefore may not even approximately measure scarcity. In this case, the trend in resource costs or perhaps marginal expenditures on property rights definition might provide a surrogate measure of resource scarcity. Recall that property rights definition tends to increase as unit extraction costs rise and marginal resource quality declines (Anderson 1983). Conceptually this measure has intriguing possibilities but data considerations would probably constrain widespread application.

IV THE EFFICIENCY OF RESOURCE USE

Many economic models of institutional choice and resource pricing suggest criteria for evaluating the efficiency of institutional and resource price responses to scarcity but strong assumptions limit the practical application of these criteria. For example, models of institutional change indicate that scarcity and rising resource costs will encourage a shift from common property to private property — assuming low transactions costs and
social choice motivated toward economizing (Anderson 1983). Similarly, Hotelling-type resource extraction models indicate that rising resource extraction costs will generate rents, to efficiently raise prices and slow resource consumption, assuming low transactions costs, pervasive markets and profit (efficiency) minded firm owners.

Policy makers may evaluate the efficiency of resource use with such models by showing that the models successfully explain observed patterns of institutional choice, extraction costs and rents. When this occurs, it follows that the observed patterns are consistent with the models assumptions, including the assumption of efficient resource use. This raises the possibility that existing choice mechanisms and markets are efficient, following standard welfare economic theorems, and that state interference will be counterproductive.

Inferences about efficiency are only suggestive. Inefficiency cannot be demonstrated by a divergence between the predictions of optimal resource use models and observed behavior. Apart from possible data and estimation error, a divergence may be explained by transactions costs which make open access, and other market distortions, nevertheless efficient. Nor is efficiency demonstrated by a successful explanation of behavior. A close correlation between observation and prediction may be explained by the prevalence of markets which happen not to be efficient due
to high transactions costs. This suggests that analysis of the resource institutions and transactions costs is required to obtain convincing evidence of efficient resource use.

Models of institutional change, termed transactions cost models, explicitly incorporate the tradeoff between the benefit and transactions cost of markets. Ideally, transactions cost models may be used to evaluate the efficiency of an institutional practice, but this usage is rare because transactions costs data is difficult to obtain. In practice, transactions cost models have often been used, in and of themselves, to tighten the standard applied to justify state intervention as a cure for market failure. Following this standard, market failure is not sufficient grounds for intervention unless the benefit of the intervention outweighs the transactions cost of the cure (Buchanan et. al 1980). The analysis in Chapter Two suggests this is a one-sided use and biased use of transactions cost models.

There have been few efforts to use Hotelling type resource extraction or other optimizing models to explain historical cost and rent patterns, or to infer resource use efficiency, with these data and models. In general, these studies have had some limited success explaining market cost and rent patterns (Heal and Barrow 1980; Stollery 1983; Farrow 1985; Miller and Upton 1985).
Measurements of long run resource scarcity indicate that resource costs and prices in the United States have been constant or have fallen since 1870 (Barnett and Morse 1963; Barnett 1979). These findings have led many economists to question the market efficiency assumptions used in standard extraction cost and rent models. This has helped to motivate and guide theoretical analysis into the effects of uncertainty, open access and other market imperfections upon on resource extraction, as possible explanations for the decline in mineral costs and prices (Dasgupta and Heal 1979).

IV DISSERTATION OVERVIEW

Chapter Two analyzes the impact of resource scarcity upon institutional choice. The example chosen is the choice of water sales technique by urban water districts in the Central Valley of California. Many districts in the Central Valley continue to sell water to customers on a flat rate or communal basis. The model developed in the chapter is used to predict the increase in volumetric sales resulting from an increase in the average cost of water supplies to a District. However, the focus of the chapter is upon the efficiency of local district choice of water sales technique.
Inferences about resource use efficiency are at best suggestive, never conclusive. While the tendency among economists is often to assume efficient those institutions which evolve toward market solutions and those markets which behave competitively, this is not always the case. When transactions costs are high, markets may be inefficient and efforts to force institutions to behave like markets may indicate rent seeking.

Chapter Two recounts efforts by the State government to force water districts to sell water on a volumetric basis. Despite such efforts, the low cost of water supply in many of these districts, and the high cost of water meters required to sell water on a volumetric basis, indicate that communal water use may be efficient. Moreover, cross sectional analysis of water districts indicates that current district sales practices are correlated with water supply costs, suggesting that districts choose to adopt volumetric pricing when it is efficient to do so. This finding supports the unifying hypothesis of the dissertation. The analysis in the chapter concludes that State intervention, while perhaps politically expedient, would be economically inefficient.

Despite the potential for paradoxes of this sort, competitive and widespread markets are usually considered a sign of efficient resource allocation and efficient resource allocation is usually considered an indication of
competitive and pervasive markets. On this basis, the analysis in Chapters Three and Four of mineral extraction rates indicates that mineral extraction rates are efficient and that open access or other potential barriers to efficient resource use are not prominent.

Chapter Three is focused upon issues involved in estimating the cost of extraction from a mineral deposit. Costs are affected by two types of resource attributes — resource concentration or accessibility and deposit volume. Elementary engineering explains why extraction costs are inversely related to concentration and accessibility. (More effort is required to obtain and refine dispersed or deep resources). The treatment of deposit volume is more interesting from an economic perspective.

Economists have long hypothesized that extraction cost is inversely proportional to production volume (Alchian 1959). The extraction of mineral deposits provides a good case for analyzing this hypothesis because the production volume of a mine is naturally limited by the size of the mineral deposit. The model used in Chapter Three reveals the importance of discounting, planned extraction rate and mine capital cost in determining the cost of extraction from a deposit. Discounting increases a deposit owners incentive to extract rapidly but the cost of mine capital, and the fixed deposit volume, makes rapid extraction expensive. The model simultaneously estimates the planned extraction rate
and the extraction cost which maximize the mine owners' profits.

The model is used to estimate the planned extraction rate and cost which maximize the expected profits of several existing copper mines, using price and cost assumptions thought similar to those facing copper deposit owners in the past. The estimated rate of extraction compared closely with the rate chosen by past copper deposit owners. This comparison is consistent with the efficient resource use and perfect market assumptions in the model and supports the unifying hypothesis of the dissertation. The comparison also helps defend the forecasts of copper extraction costs and rates reported in the Chapter. This forecasts are based upon extensive U.S.G.S. data about known but un-mined copper deposits in the United States.

Lacking information about available resource stocks, extraction costs may be inferred from scarcity measures such as rent data or past unit extraction cost trends. A model developed in Chapter Four proves that rent equals the present value of expected future increases in extraction cost caused by a decline in the quality of remaining mineral resources. The model assumes perfect markets and efficient resource allocation.

Historical rent and resource quality data were collected and used to illustrate this relationship between rent and extraction costs in practice. A reasonably close
comparison was found between historical rents and subsequent extraction cost increases in U.S. coal, copper and oil markets. This finding, like that made in Chapter Three, is consistent with the efficient resource use and perfect market assumptions in the model and thus supports the dissertation's unifying hypothesis. The finding justifies the application of rent as a scarcity measure when rent data is available. Forecasts of future extraction costs are reported in Chapter Four, which have been extrapolated from current rent data.

V CONCLUSION

As production of resources accumulates over time, applied economists are challenged with trying to forecast changes in costs, rents and institutions. Three types of forecasts are distinguished. When there is data about available resource stocks, econometric procedures may be used to estimate changes in institutions, costs and rents. Without resource data, it is common to use time series cost and rent data, termed scarcity measures, to infer future extraction cost trends. Finally, inferences about resource use efficiency may be drawn, by comparing past adjustments to resource scarcity, in institutions, costs and rents, to adjustments predicted by optimal resource use models.
The following chapters in this dissertation provide examples of the three types of forecasts. Chapter Two analyzes the efficiency of institutional choices made by local water districts and provides a model to predict future changes. Chapter Three develops a mine investment model used to forecast changes in extraction cost and planned rates of extraction due to variations in deposit volume and mineral price. Chapter Four provides a model which is used to evaluate the accuracy of rent as a measure of past resource scarcity and to predict future extraction cost increases caused by resource scarcity.
CHAPTER 2
TRANSACTIONS COSTS AND METERING OF
URBAN WATER USE IN CALIFORNIA

The analysis in Chapter Two illustrates the impact of resource scarcity upon institutional choice. The example chosen is the choice of water sales technique by urban water districts in the Central Valley of California. Many districts in the Central Valley sell water to customers on a flat rate basis at a time when many policy makers advise sales on a volumetric basis, to conserve water.

A transactions cost model is developed in this chapter to examine the district choice of water sales practice. The model assumes that districts maximize net consumer benefits when choosing between a flat rate or volumetric sales option. A switch from the flat rate to the volumetric option tends to lower water use and increase transactions costs — primarily the cost of installing water meters and billing customers. Hence, the net benefit of the switch varies according to the expected decline in water use, the cost of metering and the cost of water.

The model is used to explain the observed pattern of flat rate and volumetric sale practices in the Central Valley of California and to predict the increase in volumetric sales resulting from an increase in the average cost of water. A logistic regression analysis of this data indicates that local water cost explains much of the variation in water sale practices in the Central Valley, as predicted by the model. The logistic equation is used to forecast the transition to volumetric sales which would occur given higher water costs. This analysis suggests that volumetric sales will predominate when local water costs rise above $175 per acre foot.

The analysis in this chapter is unusual in that an attempt is made to quantify the transactions costs and the benefits of a change to volumetric pricing. Most transactions cost studies tend to be qualitative or comparative, rather than quantitative in nature (Williamson 1985). A benefit-cost analysis of this data suggests that flat rate sales in the Central Valley are an efficient response to low cost water and expensive water meters. Efforts to mandate volumetric sales in those districts may indicate political rent seeking. This analysis only considers the direct costs of water and meters to districts.
Broader considerations, such as the volume and quality of return flows and possible underpricing of water, are not dealt with and could modify this conclusion.

I INTRODUCTION

The Central Valley of California encloses a broad band of rich farmland and a number of cities. A peculiarity of the cities of the Central Valley is that most water services are not metered, that is, most urban water users pay a flat monthly fee for an unlimited supply of water. In essence, these residents share the city water supply much like Swiss cantons share grazing areas.

Communal, or more accurately communal and incompletely metered, water systems in the Central Valley have become the focus of increasing State controversy in recent years as pressures upon limited State water supplies have grown. The communal water system is attacked by those interested in water conservation as inherently inefficient because it provides users little incentive to conserve water. Indeed, several studies have indicated that per-capita water use in cities with communal water systems is much higher than water use in cities with metered systems. In response to these pressures, the California State legislature has proposed and may soon act upon bills to force State municipalities to meter individual service connections.
Many cities have lobbied strongly against such legislation. Sacramento, a prime example, has the largest communal water system in the State. Sacramento’s preference for the communal water system is enshrined in it’s city charter, which forbids residential water service meters. Representatives of Sacramento regularly attend hearings of the State Water Resources Control Board, a state agency responsible for regulating such matters, and lobby against mandated water meters.

The continuation of communal water systems in Central Valley cities, at a time when water is becoming increasingly scarce in many other areas, is therefore the focus of much policy interest. However, of perhaps equal interest are the many cities in the Central Valley which meter some or all service connections. For example, both Bakersfield and Fresno, the second and third largest cities in the Valley, meter a minority of their service connections and many, perhaps most smaller cities meter all service connections.

The adoption of water service meters, by some cities, and the communal water systems, by other cities, provides a unique opportunity to observe and measure the determinants of this type of institutional choice. This chapter proposes a model of urban water district behavior which explains the pattern and extent of incomplete water metering in Central Valley cities. The chapter is divided into five sections. Following this introduction, section two briefly summarizes
the relevant transactions cost and institutional choice literature. Section three presents a model which predicts the extent of water metering in a water district and suggests a testable hypothesis of this model. An econometric analysis of data from urban Central Valley water districts is used to illustrate the model in section four. The concluding section five, contains a brief discussion of the policy implications of the analysis.

The model presented in this paper assumes that the district choice for incomplete water metering is an efficient response to water metering transactions costs. To the degree this model is supported by the data on water metering in the Central Valley, caution is advised against regulations which impose water meters to improve water use efficiency.

II BACKGROUND LITERATURE

Incomplete water metering may be characterized as non-standard market practice (most goods are sold on a volumetric rather than communal basis). Transactions cost economics has provided a useful perspective for explaining non-standard practices as means to economize on the transactions costs of the market (Coase 1937; Demsetz 1967; Williamson 1985). The existence of the firm, non-standard modes of organization, such as vertical integration, and
non-standard sales methods, such as block booking and tie-in sales, have all been explained as measures to economize on transactions costs (Coase 1937; Williamson 1985; Kenny and Klein 1983).

Meters represent part of the cost of measuring the amount of water that is sold. This cost, termed measurement cost, represents one type of market transactions cost. Non-standard practices often evolve in cases where measurement costs are particularly high. For example, the high costs of measuring the individual contributions of members of teams may shape the organization of work and firms (Alchian and Demsetz 1972; Ouchi 1980). Similarly, large effort required to determine the value of complex goods offered for purchase may explain the existence of tie in and block booking. For example, Kenny and Klein have suggested that excessive measurement cost associated with diamond purchases may be avoided by the practice of block booking (Kenny and Klein 1983). In this chapter, communal water use is explained as a practice to economize on water use measurement cost.

Communal water use may also be explained as rent seeking or perhaps as the outcome of historical accident. Non-standard practices which economize on transactions costs may evolve over time due to natural selection processes (Alchian 1950; Fama 1980; Jensen 1983). However, when resources are owned collectively, rent seeking and
inefficiencies in decision making may impede this process (Buchanan and Tullock 1965). Most water districts in the Central Valley are public and decision making is collective.

Rent seeking and collective decision making in the formation and management of water districts has been blamed for a variety of perceived inefficiencies (Weatherford 1982). For example, the formation of public and often inefficient water districts has been explained with a median voter model in cases where water use among district voters is skewed such that the majority may gain a differential advantage in water rates and land values at the expense of the minority by going public (Smith 1983). A similar model might be used to explain the existence of communal water systems in the urban Central Valley water districts. Districts with a sufficiently skewed water use distribution, might choose communal water use because a majority within the district would benefit even though the district as a whole suffer net economic loss.

Another "explanation" of communal water use is that it is the adventitious outcome of numerous historical, legal, social and other forces peculiar to the Central Valley (Granovetter 1985). Following this "explanation", Central Valley water use practices are historically determined and unlikely to respond predictably to a single economic change, such as high water costs.
The model used in this chapter assumes that communal water use is a result of economizing rather than rent seeking or historical accident. This assumption is supported by the compatibility of the model predictions with the pattern of water use practices in the Central Valley.

III A TRANSACTIONS COST MODEL OF WATER SALES PRACTICES

The Central Valley contains many residences within many urban water districts. Each district chooses the number of residential water service connections within the district to be fit with meters, termed here the metering coverage ($p_i$). There are $I$ districts, denoted by $i$, $i = 1 \ldots I$, and $J$ residences within each district, denoted by $j$, $j = 1 \ldots J$.

For simplicity, the following assumptions are made about district water demand and supply. Individuals in all districts have identical demand (benefit) schedules for water ($W(q)$). The demand schedule is a decreasing monotonic function relating the volumetric price ($c_i$) and the quantity demanded ($q$) such that

$$\frac{\partial W}{\partial c_i} < 0.$$  

Demand intersects the quantity axis at some finite value ($q_2$) and approaches the price axis asymptotically. Water supply to each district exhibits constant returns and costs.
per unit for acquisition, delivery and disposal. The cost of meter installation and billing to each resident \( k_j \) in each district varies according to residential location. The distribution of meter costs across residences is the same in all districts.

Each district \( i \) has two options for selling water to each resident \( j \) — a share option \( (S_{ij}) \) and a meter option \( (R_{ij}) \). Under the share option, a resident is charged a flat fee for water per time period and consumes \( q_2 \) units of water. Under the meter option a resident is charged a volumetric fee, based upon quantity consumed, and consumes \( q_i(c_i) \) units of water, a variable quantity less than \( q_2 \) (See Figure 2.1).

Under both options district water revenues equal district costs. Under the share option the district delivers \( q_2 \) units of water and charges a flat fee \( (q_2 \times c_i) \) to cover the water acquisition and delivery costs. Under the meter option, the district delivers \( q_i(c_i) \) units of water, an amount less than \( q_2 \), and charges a volumetric price for that water totalling \( c_i \times q_i \) and assesses an additional fee \( (k_j) \) to cover the cost of meter installation and billing\(^1\).

\(^1\) In practice, it is common for districts to monitor their system to detect leakage and, presumably, unauthorized water transfers. While one might expect the costs of such monitoring to be lower, in districts with 100% residential metering, none of the water districts interviewed mentioned this as a significant consideration in their metering choice.
Figure 2.1
Water Demand, Excessive Water Use
and Dead Weight Loss Under Different Options For
Distributing Water
The model assumes no additional monitoring to limit the water use of metered and un-metered residents.

The district chooses to maximize net benefits summed across all residences within the district. As the problem is defined, the district chooses between \( S_{ij} \) and \( R_{ij} \) for each resident so as to maximize net benefits to that resident. The district chooses \( S_{ij} \) when \( S_{ij} > R_{ij} \) and the meter option when \( S_{ij} < R_{ij} \).

Since

\[
S_{ij} = \int_0^{q_2} W(q) dq - c_i q_2
\]

\[
R_{ij} = \int_0^{q_i} W(q) dq - c_i q_2 - k_j
\]

it is apparent, after differentiating (1) and (2) with respect to \( c_i \) and simplifying, that

\[
\frac{\partial S_{ij}}{\partial c_i} = -q_2
\]
An increase in the cost of water decreases option $S_{ij}$ net benefits more than it decreases option $R_{ij}$ net benefits. Given free water ($c_i = 0$) and some positive metering cost $k^*$, equations (1) and (2) indicate that option $S_{ij}$ will always be preferred to option $R_{ij}$, (assuming $S_{ij} > 0$). As $c_i$ is increased indefinitely, eventually some cost $c^*$ will be reached where

\begin{equation}
\int_0^{q_2} W(q) \, dq - c_i^* q_2 - \int_0^{q_1} W(q) \, dq - c_i^* q_1 - k^*
\end{equation}

and $S^*_{ij} = R^*_{ij}$. If $p^*$ of the residences in the district have metering costs below $k^*$, it is apparent from (5) that $p^*$ percent of the district residences in this example will have metered service connections and $1 - p^*$ will have share service connections.

Similarly, equations (1) and (2) indicate
(7) \[ \int_0^{q_i} W(q) \, dq - c_{\text{avg}} q_i = \int_0^{q_i} W(q) \, dq - c_{\text{avg}} q_i - k^{**} \]

for some \( k^{**} \), where \( c^{**} > c^* \). From (5) it can be shown that \( k^{**} > k^* \), which implies that over \( p' \) of the district residences will be metered given cost \( c^{**} \). Therefore, it follows in general that

\[ \frac{\partial p}{\partial c_1} > 0 \]

always assuming \( S_{ij}, R_{ij} > 0 \).

IV EMPIRICAL APPLICATION AND DATA ANALYSIS

The model is used to explain the pattern of residential metering shown by water districts in Central Valley urban areas. Empirical analysis required the collection of primary data. Phone interviews were conducted with representatives of urban water districts in the Central Valley. The respondents supplied \( p_i \), the proportion of metered connections in the district, \( c_i \), the unit water cost charged customers, \( g_i \), water use per resident and \( n_i \), district population. (Recall that average cost is assumed constant so that average and marginal cost are equivalent). Selected water districts were asked to supply \( k_i \), the average cost of metering service connections, including the costs of meter installation and meter reading and billing.
These data were used to supplement and update information published in a California Department of Water Resources bulletin and covering 57 urban areas in the Central Valley watershed (DWR 1984). Of these 57 areas, complete water use, metering and water price data were available for only 41 areas. These areas were included as observations in the regression analysis.

These data are analyzed using two techniques. First, the data are used to indicate the minimum water cost needed to justify residential metering and maximize net benefits, assuming average metering costs in a district and efficient water district choice of metering coverage. Second, the data are used in a logistic regression to estimate the actual change in metering associated with the change in water costs across districts in the Central Valley. A comparison between "efficient" and actual metering permits analysis of the motivation explaining district water metering choice.

Benefit Cost Criteria For Choosing Between Water Sales Options

The switch from option S to option R represents a trade off between the benefits and the costs of metering. When a meter is installed, water use drops but metering costs become positive. Hence, the net benefit of the switch
varies according to the expected drop in water use, the value of the drop in water use and the cost of metering.

The 57 urban districts which provided at least partial data may be split into three groups, group one, including districts where all residents have water meters, group two, including districts where no residents have water meter meters and group three, including districts where some residents have meters and some residents do not have meters. These three groups contain 21, 13 and 23 districts respectively in our sample (Table 2.1 contains a partial sample of these districts).

The average cost of water in group one was $202 per acre foot (af) and the average cost of water in group two was $118/af. The average annual water use per residence in groups one and two was .77 af and 1.04 af respectively. As a first approximation, these data suggest that a switch from an S to an R option, to a resident in a district where the cost of water was $202/af, would decrease water use .27 af. This .27 af may be termed excessive water use because it has a marginal value less than its marginal cost. An un-metered residence will always have some excessive water use because each resident acts as though his marginal cost of water were zero.
Table 2.1
Metering Practices, Water Cost and Water Use in Selected Central Valley Cities

<table>
<thead>
<tr>
<th>City</th>
<th>Proportion Metered (% Services)</th>
<th>Average Cost Water ($/acre foot)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Cost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avenal</td>
<td>100</td>
<td>414</td>
</tr>
<tr>
<td>Huron</td>
<td>100</td>
<td>326</td>
</tr>
<tr>
<td>Oroville</td>
<td>72</td>
<td>388</td>
</tr>
<tr>
<td>Grass Valley</td>
<td>100</td>
<td>280</td>
</tr>
<tr>
<td>Stockton</td>
<td>100</td>
<td>250</td>
</tr>
<tr>
<td>Dixon</td>
<td>100</td>
<td>227</td>
</tr>
<tr>
<td>Placerville</td>
<td>100</td>
<td>226</td>
</tr>
<tr>
<td>Yuba City</td>
<td>50</td>
<td>218</td>
</tr>
<tr>
<td>Brentwood</td>
<td>100</td>
<td>212</td>
</tr>
<tr>
<td>Vacaville</td>
<td>100</td>
<td>210</td>
</tr>
<tr>
<td>Tehachapi</td>
<td>100</td>
<td>209</td>
</tr>
<tr>
<td>Williams</td>
<td>100</td>
<td>202</td>
</tr>
<tr>
<td><strong>Middle Cost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Niles</td>
<td>100</td>
<td>199</td>
</tr>
<tr>
<td>Antioch</td>
<td>100</td>
<td>197</td>
</tr>
<tr>
<td>Lindsay</td>
<td>100</td>
<td>189</td>
</tr>
<tr>
<td>Willows</td>
<td>50</td>
<td>168</td>
</tr>
<tr>
<td>Redding</td>
<td>100</td>
<td>180</td>
</tr>
<tr>
<td>Tracy</td>
<td>100</td>
<td>183</td>
</tr>
<tr>
<td>Coalinga</td>
<td>5</td>
<td>181</td>
</tr>
<tr>
<td>Dos Palos</td>
<td>100</td>
<td>179</td>
</tr>
<tr>
<td>Red Bluff</td>
<td>50</td>
<td>166</td>
</tr>
<tr>
<td>Bakersfield</td>
<td>20</td>
<td>140</td>
</tr>
<tr>
<td>Marysville</td>
<td>30</td>
<td>134</td>
</tr>
<tr>
<td>Fresno</td>
<td>13</td>
<td>124</td>
</tr>
<tr>
<td>Manteca</td>
<td>100</td>
<td>121</td>
</tr>
<tr>
<td>Selma</td>
<td>31</td>
<td>120</td>
</tr>
<tr>
<td>Turlock</td>
<td>0</td>
<td>117</td>
</tr>
<tr>
<td>Visalia</td>
<td>20</td>
<td>116</td>
</tr>
<tr>
<td>Roseville</td>
<td>0</td>
<td>115</td>
</tr>
<tr>
<td>Chico</td>
<td>38</td>
<td>107</td>
</tr>
<tr>
<td>Clovis</td>
<td>0</td>
<td>103</td>
</tr>
<tr>
<td>Colusa</td>
<td>100</td>
<td>101</td>
</tr>
<tr>
<td><strong>Low Cost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sanger</td>
<td>100</td>
<td>99</td>
</tr>
<tr>
<td>Lodi</td>
<td>0</td>
<td>96</td>
</tr>
<tr>
<td>Davis</td>
<td>0</td>
<td>92</td>
</tr>
<tr>
<td>Shafter</td>
<td>0</td>
<td>83</td>
</tr>
<tr>
<td>Merced</td>
<td>40</td>
<td>74</td>
</tr>
<tr>
<td>Sacramento</td>
<td>0</td>
<td>71</td>
</tr>
<tr>
<td>Mt Shasta</td>
<td>0</td>
<td>68</td>
</tr>
<tr>
<td>Woodland</td>
<td>0</td>
<td>56</td>
</tr>
<tr>
<td>Modesto</td>
<td>0</td>
<td>55</td>
</tr>
</tbody>
</table>
The value of a drop in water use to a resident equals the avoided cost of the resident's excessive water use. The cost of excessive water use is termed dead weight loss (dwl).

Assuming a linear demand for water between $200/af and $0/af, the dead weight loss (dwl) associated with the .27 af excessive water use is $54 (See Figure 2.1). Since demand is linear, half the cost of excessive water use by an unmetered residence is dead weight loss (dwl) (See Hanke 1982). Using these same assumptions, the dwl associated with water costing $150/af is about $30, the dwl associated with $100/af water is about $14, and the dwl associated with $50/af water is about $4.

Seven urban water districts provided cost data based upon recent or on-going metering programs (Table 2.2). These data indicate that metering costs within a district are quite variable and suggest that the distribution of metering costs is bimodal, reflecting the difference between the costs of retrofitting meters into older residences and installing meters in new residences. Based upon these data, the annual cost of meter installation, reading and billing is estimated to average $36.79 for a retrofit and $11.74 for a new residence meter (Table 2.2).
Table 2.2
Cost of Meter Installation, and Meter Reading and Billing

1. Survey Results

<table>
<thead>
<tr>
<th>Municipal Utility</th>
<th>Meter Installation</th>
<th>Reading and Billing (Annual Cost)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Retrofit</td>
<td>New</td>
</tr>
<tr>
<td>Chico</td>
<td>$150.00</td>
<td>$70.00</td>
</tr>
<tr>
<td>Fresno</td>
<td>$170.00</td>
<td>$55.00</td>
</tr>
<tr>
<td>Redding</td>
<td>$65.00</td>
<td></td>
</tr>
<tr>
<td>Sacramento citizens</td>
<td></td>
<td>$129.00</td>
</tr>
<tr>
<td>Sacramento County</td>
<td>$520.00</td>
<td>$5.26</td>
</tr>
<tr>
<td>Stockton</td>
<td>$150.00</td>
<td>$70.00</td>
</tr>
<tr>
<td>Denver Water Dept.</td>
<td>$433.38</td>
<td>$70.00</td>
</tr>
</tbody>
</table>

2. Average Cost

|                         | $260.00 | $66.00 | $3.22 |

3. Annual Cost to Install (Amortized over 15 yr life @10%) $33.57 $8.52

4. Total Cost (Including Reading and Billing Cost) $36.79 $11.74
A switch from option S to option R is warranted only when avoided dwl is greater than acquired metering costs. The estimates above suggest this to be the case on average for retrofit metering, only when the cost of water is above $175/af. Avoided dwl exceeds the cost of new residence metering when the cost of water is over $80/af.

Logistic Regression Analysis of Water District Choices

Benefit-cost criteria might assist district residents to choose between options S and R for distributing water. An econometric analysis was done to determine whether similar benefit-criteria affect this choice in practice. Specifically, a logistic recession was run to estimate the change in metering proportion associated with a unit change in water costs across districts in the Central Valley.

The logistic regression estimates the metering-water cost relationship (equation 8) assuming a function of the form

$y = b_1 + b_2 c + e$  

where $b_1$ and $b_2$ are variables to be estimated, $c_i$ is a vector of district average water cost, $e$ is the error term having a zero mean and weibull distribution and $y$ represents the logistic transformation of $p_i$ equal to
\( y = \int \frac{p - \frac{1}{n}}{1 - p - \frac{1}{n}} \quad \text{if } p_i = 1 \)

in order to perturb the data from the boundary conditions (Cox 1970). Recall that \( p_i \) is the proportion of residences in a district with water service connections that are metered and \( n \) is the number of observations in the regression sample. Equation (9) may then be estimated using ordinary least squares (Cox 1970).

These factors entered into the regression of distinct metering proportions:

\[
\begin{align*}
  y &= -2.99 + 0.033 (c_i) \\
  &\quad (-33) \quad (4.5) \\
  R^2 &= 0.34
\end{align*}
\]

41 observations
t statistics in parenthesis
variables as defined in text
The estimated coefficient and t statistic in the regression equation indicates that the water cost variable is positive and significant, as predicted by the model. Accordingly, the equation may be used to predict the long run increase in metering caused by changes in the water cost. For example, the equation indicates a 25% metering proportion given $80/af water and indicates a 65% metering proportion, given $175/af water. In this range, a $95 increase in the cost of water is associated with a 40% increase in metering.

It is noteworthy that district choice of metering options, as summarized in the regression equation, is compatible with the benefit cost criterion for maximizing district net benefits, presented in the example above. Recall that these criteria indicate that retrofit metering is uneconomic, given below $175/af water, and new residence metering is uneconomic, given below $80/af water, assuming average costs for retrofit and new residence meters.

In other words, district metering in the Central Valley is probable (65%), when the benefit cost criterion indicates metering existing residences is economic, and district metering is not probable (25%), when benefit cost criterion indicates metering new residences is not economic. This comparison between metering practice and metering benefits and costs, suggests that water districts choose metering proportions largely on efficiency grounds. It is generally
not correct to accuse water districts of inefficiency merely because district residences are not metered.

IV CONCLUSION

Metering proportions of Central Valley water districts are explained using a model which postulates maximization of District net benefits. Predictions of metering proportions, based upon this model, are compatible with the empirical data. These findings suggest that share water systems in the Central Valley are an efficient response to low water costs.

These findings also suggest that legislative effort to end share water systems may be misguided. More fundamental inefficiencies in California water use, such as uncertain water rights, hinder water sales between districts and may keep Central Valley water prices artificially low. Legislative effort might be more effective if it were directed to solve these fundamental problems rather than to impose water meters upon Central Valley water districts.

The analysis in this chapter illustrated the impact of resource scarcity upon an institutional practice in the water supply industry. A transactions cost model was developed and used to predict the increase in volumetric sales in urban water districts occurring due to an increase in the cost of water. The model was also used to judge the efficiency of current and proposed practices. The analysis concludes that urban water districts choose water sales
techniques efficiently and that districts will voluntarily choose volumetric sales techniques when water costs increase.

The next chapter considers the impact of resource scarcity upon extraction costs. In that study the institutional structure is assumed to include perfect and pervasive markets.
CHAPTER 3
MINE CAPACITY AND MINERAL PRICE

The last chapter analyzed changes in institutional choice resulting from increased resource scarcity. This chapter examines the effect of scarcity upon resource extraction costs and the planned rate of extraction. The example chosen for analysis in this chapter is the mining of copper deposits in the United States.

The chapter introduces a model to determine the planned rate of production from a resource deposit and applies the model to the U.S. copper industry to estimate changes in aggregate planned copper production as a function of the copper price. Most models used to estimate aggregate resource production take the planned rate of production from deposits as exogenous (Rosenkrantz 1979). The model developed in this chapter solves for the planned rate of production endogenously. The model expands on the cost and output postulates of Alchian (1959) and provides empirical support for these postulates using the U.S. copper industry data.

Standard investment theory is applied in the model to examine the choice of the planned rate of extraction from limited volume resource deposits. A setting is analyzed in which the total production volume from any site is fixed by the size of the resource deposit at that site. Capital investment at the site is not re-deployable and input and output prices are known and fixed over the production period. In addition, the operating cost of resource production is assumed to be fixed, up to the planned rate of production (mine capacity), and infinite thereafter. Finally, competition is assumed to be perfect, resource owners maximize profits and resource property rights are perfectly enforced. Within this setting, the planned rate of resource extraction is a fully endogenous solution of the model.

Properties of this solution are investigated to determine changes in the planned rate of production caused by variation in operating cost, investment cost and output price parameters. Most significantly, the planned rate of production from any deposit is found to increase at a decreasing rate, given incremental increases in the output price, ceteris paribus.

The finding is illustrated with data describing mined and yet-to-be mined copper deposits in the United States. First, operating and capital costs are estimated for these deposits, as functions of resource quality parameters, including mineral concentration and deposit depth. These estimates are derived from industry operating and capital
cost functions. Next, model is used to estimate the planned (profit maximizing) rate of production for each deposit for several output price scenarios. A close match is observed between the calculated production rate for mined copper deposits and the mine capacity (rate of production) chosen by the owners of those deposits, given plausible assumptions about mine owner price expectations. Finally, the planned rate of production is aggregated across all deposits and plotted as a function of output price. An "aggregate medium run copper supply curve" is obtained, indicating the elasticity of planned production to changes in the expected long run output price of copper. This empirical example suggests that doubling the output price, from $1 to $2 per pound copper, would triple aggregate planned copper production in the United States.

I INTRODUCTION

Two key questions about the effect of losing critical foreign mineral supplies are these: (1) How high would mineral prices rise? (2) What new domestic supplies would then become available? To help answer the second question, the Geological Survey and the Bureau of Mines of the U.S. Department of the Interior have investigated the availability of low-grade domestic mineral resources. The underlying notion is that if prices rise, some additional high-cost, low-grade resources will probably be mined.

This chapter investigates an additional way in which mineral production could increase — the most economic scale of operation could change, e.g., new and existing mines would be planned at larger optimal capacities. These factors could have a sizable effect on mineral supplies in the interim investment period (the 5-40 years between
initial investment and closure of the mine). Except for Bradley (1980), this combined effect has been largely overlooked in the literature.

This chapter estimates the sensitivity of mine capacity to expected price changes with a simple financial model of mine investment. The model represents an extension of Alchian's (1959) formulation of costs and outputs. Part two describes Alchian's work and related literature. Part three presents an investment model of a mine. Part four includes an economic estimation of mine capital and operating cost equations which are used in part five as part of an empirical test to see how well the model approximates industry investment practice. The sensitivity of U.S. copper mine capacity to long run price change is illustrated in part six. Finally, the sensitivity of U.S. mine capacity to long run price change is illustrated. The conclusion drawn from this exercise is that long run price changes will affect optimal mine capacity and U.S. mineral supply.

II BACKGROUND

The analysis in this chapter builds upon the theory of production costs and output formulated by Alchian (1959). That formulation sets forth a number of propositions about the shape of the firm's cost function. Specifically, total and marginal production cost of a firm are (always) an
increasing function of the rate of production, volume held constant and marginal cost is a falling function of volume of output, rate held constant.

In this chapter, two corollary propositions are proposed which follow closely those made by Alchian and which have special application to the mineral industry. These propositions concern the relationship between the optimal rate of production, the unit price and the production volume. The optimal rate of production is defined as the rate which maximizes firm (or project) profit under conditions of certainty and perfect competition. The first corollary proposition is that the production rate is an increasing function of the unit price. The second corollary proposition is that the production rate is an increasing function of the volume.

Mining, particularly copper mining, provides a good illustration of the Alchian and corollary propositions, because mine production volume is fixed by the deposit size, the mine production rate is generally fixed by the mine capacity and the unit price is largely competitively determined and, for copper, relatively stable in past decades. Copper and other mineral resources cluster into deposits of a given size so that the volume of a mine production run is set by nature. The Alchian propositions suggest that the total and marginal costs of mining large
deposits will be lower than the total and marginal costs of mining small deposits, other things equal.

The rate of production from a mine is largely set by its mine capacity, which is planned in the initial stages of mine investment. This is because mines are notably capital intensive. Capital intensity, in exploration, investment in infrastructure, overburden removal and construction of mining and milling plants helps to explain why mineral extraction is constant and near planned capacity over most of the mine life and does not decline over time (Campbell 1980; Hartwick and Olewiler 1986; Bradley 1980).

Finally, mining of copper and most other minerals in the United States is reasonably competitive and the mineral unit price is little affected by a change in the rate of production from any one mine. Moreover, copper industry prices were remarkably stable between 1950 and 1975 so that rational and adaptive price expectations over the period were similar (Herfindahl 1959; Fisher et al 1971). In this case, the corollary propositions about costs and outputs proposed in this chapter suggest that the planned capacity of a mine will be positively correlated with the expected unit price and with the deposit volume.
A simple mine investment model is proposed which analytically relates mine capacity to deposit attributes, such as grade, reserves, and depth, and to the metal price. The model is used to determine optimal mine capacity and the impact of price and deposit volume changes. The model requires simplifications and the usual underlying assumption that what is ignored is less important than what is emphasized. It ignores the effects of nonuniform ore grade, changing reserve estimates, and variable mine production over the life of the mine. The model assumes the following:

1. Deposit reserves (tonnage) (R) and grade (G) are correctly estimated. The total volume of copper in the deposit (V) is equal to RG.
2. The reserves are of uniform grade.
3. Costs of all inputs and prices of outputs are fixed and known.
4. Mine output is a constant proportion of mine capacity. It does not change over the life of the mine.
5. The mine owner has unchallenged property rights to the deposit. The owners' objective is to maximize profits.

These assumptions emphasize the only remaining choice variable — mine capacity (Q). The ex ante choice of mine
capacity determines annual mine output, mine life (T), and mine revenues. Given a market with fixed copper price (P), discount rate (r), per-unit operating cost (C), and per-unit annual capacity cost (K), the net present value of all operating profits is

$$\int_{t=0}^{T} (P - C) Q e^{-rt} dt = (P - C) Q \frac{1 - e^{-rT}}{r}$$

Because mine output is a constant proportion of mine capacity, the life of the mine is determined to be V/Q. Therefore, the profit maximization problem is

$$\max_{Q} X = (P - C) Q \left( \frac{1 - e^{-r \frac{V}{Q}}}{r} \right) - KQ$$

This function is maximized at $\frac{dX}{dQ} = 0$, giving the optimal mine capacity ($Q^*$). At that point, the marginal cost of adding new capacity would just equal the marginal revenue of selling more copper sooner. If capital and operating costs are constant, equation 1 can be solved for $Q^*$ with the approximation procedure described in the Appendix. When operating and per unit capital costs are not constant, equation 1 cannot be solved explicitly for $Q^*$. 

50
The corollary propositions proposed in this chapter may now be defined in terms of the investment model. These propositions are

\[
\frac{\partial Q^*}{\partial P} > 0
\]

\[
\frac{\partial Q^*}{\partial RG} > 0
\]

Following, a two-step procedure is used to estimate optimal capacity for copper mines. First, capital and operating cost functions are estimated as functions of mine capacity, as well as of deposit attributes. Second, given mine capital and operating cost functions and an expected ore price, the optimal (i.e., profit-maximizing) mine capacity can be calculated using an iterative procedure.

IV OPERATING AND CAPITAL COST FUNCTIONS FOR OPEN PIT MINES

An overview of open pit mining will help to clarify the relation between the ore deposit and open pit mining costs. Open pit mining is begun by stripping the earth off the top of the ore deposit to allow open access to large earth-moving machinery. Usually, a mill is set up nearby which has equipment to concentrate the ore to a high enough grade to be taken elsewhere for refining. The mill is
considered a part of the mine complex in this study. Hence, the major investments necessary to start open pit mining include the cost of stripping the earth that covers the deposit and the cost of the mine and mill equipment used to excavate and concentrate the ore. Operating expenses are largely made up of labor, fuel, and other costs required to operate the equipment in the mine and mill.

The division between capital and operating costs is usually somewhat arbitrary. For example, stripping to uncover ore takes place both before and after mining is underway, so the costs of stripping might be classified as either operating or capital cost. The division between mine and mill costs in each category is also somewhat arbitrary; in this chapter mine and mill costs are aggregated.

Capital and operating cost equations are estimated below on 16 open pit mines opened or planned for development after 1960.² The major factor determining both capital and operating costs is the amount of rock that must be moved and processed to obtain the finished metal. Mine capital costs are largely spent on pre-production stripping of earth off

²The mine cost data set includes mine cost and mine deposit information for copper properties scattered throughout the country, but concentrated in Arizona, Utah, and New Mexico. This mine cost data was generated by mine engineers of the Bureau of Mines. They gathered existing cost statistics for operating mines and selected appropriate mine designs and mine cost estimates for undeveloped properties. Several properties with high environmental mitigation costs were omitted along with three high-cost properties in Alaska. The remaining set represents a cross-section of typical modern open pit copper mines.
the top of the deposit. The amount of pre-production stripping needed to recover a given amount of metal is the ratio of the pre-production strip ratio (ratio of earth stripped to ore mined) and the ore grade (percent of metal in the ore).\(^3\) A plausible unit capacity-capital cost function is, therefore, of the form

\[
K = A_1 + A_2 \left( \frac{\text{strip ratio}}{\text{grade}} \right).
\]

Due to possible economies or diseconomies of scale, unit capital costs may also be affected by mine capacity \(Q\). In addition, a dummy variable is added to distinguish older developed mines from new or planned mines.\(^4\)

These three factors entered in the final regression of capital costs

\[
K = 0.885 + 0.258 \left( \frac{\text{strip ratio}}{\text{grade}} \right) + 0.623 \times 10^{-8} Q - 1.74 \text{(mine age)}
\]

\[
(2.5) \quad (5.6) \quad (2.0) \quad (-4.7)
\]

\(R^2 = 0.82\)

Mean of \(K = 1.79\)

Standard error of regression = \$.64\)

16 observations

(t statistics in parentheses)

\(^3\)The production strip ratio was used as a proxy for the pre-production strip ratio because pre-production strip data were not available.

\(^4\) Mine and mill capital costs of older mines in the Bureau of Mines figures reflect 1978 "depreciated" values and not initial costs. All cost figures were from Bureau of Mines data.
Definition of Variables:

\[ K = \text{Capital costs (mine and mill) per pound annual copper capacity (1978 dollars)} \]
\[ \text{Strip ratio} = \text{Ratio of material removed to ore mined} \]
\[ Q = \text{Mine and mill capacity in pounds of copper/year} \]
\[ \text{Mine age} = \text{Dummy variable equal to 1 if the mine is developed (2 years or older) and 0 if the mine is new or planned.} \]

The regression shows that the estimated costs are predicted by the strip ratio, grade, and mine capacity. The t statistics are useful for comparing the relative explanatory power of the independent variables. By this standard, strip ratio/grade is the most important variable, followed by mine age. The coefficient of Q indicates that diseconomies of scale occur in mine capacity formation.\(^5\) This is probably a result of the long construction period necessary to complete large mine developments and the high

\(^5\) In contrast, a 1972 study estimated that the costs of increasing capacity in Chilean open pit copper mines rose only by the \(0.941\) power of the capacity. See (Jarpa 1972). Another study of Canadian copper mines reached similar conclusions, leading the author to speculate why mines do not have larger capacities (Bradley 1979). My work suggests that diseconomies of scale of mine capacity is the answer. These diseconomies were not evident in earlier studies which disregard the cost of capital held idle during mine construction.
cost of capital held idle during that period. For example, a study of Arizona copper mines indicates that it required an average of only 1.75 years to construct mines between 18,000 and 44,000 MT annual capacity and over three years to construct mines between 80 and 80,000 MT annual capacity (Burgin 1976).

Operating costs are largely a function of the amount of rock moved and separated per pound of metal concentrated, as are capital costs. Because economies of scale may also apply to mine operations, mine capacity \( Q \) is also of importance.

The estimated mine and mill operating cost equation was

\[
C = 1.81 + .165 \left( \frac{1}{\text{grade}} \right) + .0427 \left( \text{strip ratio} \right) - .0984 (\log Q)
\]

\( R^2 = .81 \)

Mean of \( C \) = $.48

Standard error = $.09

16 observations

(t statistics in parentheses)

The estimated coefficients and t statistics confirm expectations that operating costs are primarily a function of ore grade and, to a lesser degree, mine strip ratio. In contrast with the capital cost regression, the estimated
coefficient of Q in this regression suggests that there are economies of scale in open pit mining operations.⁶

After the ore is milled, the resulting mineral concentrate is shipped to industrial smelters and refineries where it is processed into the finished metal product. The concentrate from most mills is of a relatively uniform grade, and the costs of further processing do not differ greatly between mines. The costs of transporting the concentrate, then smelting and refining it, range from about $.20 to $.30 per pound of copper.⁷

V A TEST OF THE MODEL

Mine capacity and operating cost equations were used to test the financial optimizing model for mine capacity of the 15 deposits that became major open pit mines in the United

---

⁶ The only contrasting study I could find was a 1979 study of mine operating costs. This analysis of four open pit copper mines in the United States estimated the following mine and mill operating cost regression: Mine Cost (in 1972 dollars) = -36.19 -23.27 (Grade) + 2.11 (Strip ratio) -.21 (Ore Recovery Percentage). See (Foley 1978). Several years of mine operating cost observations used in the regression analysis, adding to a total of 17 observations. The coefficients were all significant.

⁷ In a 1977 study, these costs were estimated between $.24 and $.26 per pound of copper (Winters 1977).
States after 1950. The procedure followed was to first estimate total capital and operating costs for a given mine capacity. The present value of the cost of this mine capacity was calculated from equation 1, with \( P \) equal to 0. This cost was re-estimated for successively larger mine capacities. These calculations produced a graph of average costs and marginal total costs for each deposit (Figure 3.1).

The profit-maximizing capacity of each deposit is the point where the price (\$0.75 per pound of copper prices in 1978 dollars) and the marginal total cost curve intersect. The profit-maximizing (or least-cost) capacity of the 15 deposits was compared with the real mine capacity of those deposits (Table 3.1).

The results of this simulation exercise were encouraging. All but a few of the estimated optimal capacity figures came close to the reported capacity figures of the 15 U.S. open pit mines tested. Most were within 10 to 20% of reported capacity.

---

8 I used a Bureau of Mines input cost indexing method to backdate the 1978 (1) capital and (2) operating cost estimates, and (3) the smelter, refinery and transportation charges. Pre-1975 costs were calculated at between 77 and 81% of 1978 costs (Speckley 1980).

9 The average price of copper between 1950 and 1978 was \$0.75 per pound (in constant 1978 dollars). This is assumed to be a good proxy for the expected long run price (\( P \)) in the mine profit function.
Figure 3.1
Average and Marginal Cost of Mine Capacity

Cost per pound of copper

$.75

Marginal total cost of mine capacity

Average total cost of mine capacity

Profit-maximizing capacity

Mine capacity (1000 MT of copper per year)
Table 3.1
U.S. Open Pit Copper Mine Capacities

<table>
<thead>
<tr>
<th>Mine</th>
<th>First Year of Production</th>
<th>Mine Capacity of Actual &amp; Potential (mt of Copper)</th>
<th>Sources</th>
<th>Estimated Optimal Capacity ** (mt of Copper)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bagdad, AZ</td>
<td>1927</td>
<td>65,000</td>
<td>EMJ</td>
<td></td>
</tr>
<tr>
<td>Inspiration, AZ</td>
<td>1915</td>
<td>54,000</td>
<td>EMJ</td>
<td></td>
</tr>
<tr>
<td>Metcaif, AZ</td>
<td>1975</td>
<td>85,000</td>
<td>EMJ</td>
<td>106,000</td>
</tr>
<tr>
<td>Mineral Park, AZ</td>
<td>1964</td>
<td>18,000</td>
<td>GS</td>
<td>20,100</td>
</tr>
<tr>
<td>Mission San Xavier, AZ</td>
<td>1961</td>
<td>49,000</td>
<td>EMJ</td>
<td>47,000</td>
</tr>
<tr>
<td>Morenci, AZ</td>
<td>1942</td>
<td>113,000</td>
<td>EMJ</td>
<td></td>
</tr>
<tr>
<td>New Cornelia, AZ</td>
<td>1917</td>
<td>45,000</td>
<td>GS</td>
<td></td>
</tr>
<tr>
<td>Palo Verdi, AZ</td>
<td>1979</td>
<td>26,000</td>
<td>GS</td>
<td>36,000</td>
</tr>
<tr>
<td>Pima, AZ</td>
<td>1957</td>
<td>54,000</td>
<td>EMJ</td>
<td>51,000</td>
</tr>
<tr>
<td>Ray, AZ</td>
<td>1911</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sierrita, AZ</td>
<td>1973</td>
<td>91,000</td>
<td>EMJ</td>
<td>62,000</td>
</tr>
<tr>
<td>Silver Bell, AZ</td>
<td>1954</td>
<td>22,000</td>
<td>EMJ</td>
<td>38,000</td>
</tr>
<tr>
<td>Twin Buttes, AZ</td>
<td>1954</td>
<td>68,000</td>
<td>GS</td>
<td>62,000</td>
</tr>
<tr>
<td>Butte, MT (Berkeley Pit)</td>
<td>1955</td>
<td>91,000</td>
<td>EMJ</td>
<td>88,000</td>
</tr>
<tr>
<td>Chino, NM</td>
<td>1912</td>
<td>59,000</td>
<td>EMJ</td>
<td></td>
</tr>
<tr>
<td>Continental Surface, NM</td>
<td>1968</td>
<td>22,000</td>
<td>GS</td>
<td>20,000</td>
</tr>
<tr>
<td>Tyrone, NM</td>
<td>1973</td>
<td>86,000</td>
<td>EMJ</td>
<td>80,000</td>
</tr>
<tr>
<td>Bingham, UT</td>
<td>1900</td>
<td>200,000</td>
<td>EMJ</td>
<td></td>
</tr>
<tr>
<td>Esperanza, AZ</td>
<td>1959</td>
<td>14,000</td>
<td>EMJ</td>
<td>11,000</td>
</tr>
<tr>
<td>Peacock, AZ</td>
<td>1911</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safford Inspiration, AZ</td>
<td>1974</td>
<td>20,000</td>
<td>GS</td>
<td>32,000</td>
</tr>
<tr>
<td>New Ruth, NV</td>
<td>1970</td>
<td>45,000</td>
<td>GS</td>
<td>29,000</td>
</tr>
<tr>
<td>Yerinton, NV</td>
<td>1961</td>
<td>30,000</td>
<td>GS</td>
<td>39,000</td>
</tr>
</tbody>
</table>

* EMJ = Engineering and Mining Journal, June 1978; GS = Geological Survey

** The figures shown are the profit-maximizing capacity or the capacity associated with minimum average cost, whichever is larger. The capacity of each mine was estimated from the mine profit equation 1, which was solved in an iterative fashion to maximize mine profits over Q. The copper price used to calculate revenues was $.75 in constant 1978 dollars. We used a 13% discount rate. The by-product and copper grades, deposit tonnage and strip ratio figures of the deposit were taken from Bureau of Mines and Geological Survey data files. All grades and tonnages used were original, or were extrapolated back to original figures. Twenty-six cents was added to operating costs to cover transportation, smelting and refining charges. By-product credits were subtracted from operating costs. Credits were determined from the quantities of gold and silver produced with each pound of copper from a deposit valued at their average price over the 10 years just before mine production. The by-product recovery factor was assumed to be 85%. 

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Given the simplified nature of the model’s assumptions, cost equations, and price expectations, the fit between estimated and reported capacity was surprisingly close (Figure 3.2.). This close fit suggests that the simple investment model may be used to estimate mine capacity of undeveloped deposits.\textsuperscript{10}

**Potential Mine Capacity of Undeveloped Deposits**

Thirty-one undeveloped copper deposits in the United States are thought to have potential to become open pit copper mines—when the copper price rises high enough.\textsuperscript{11} These deposits vary considerably in size, grade, and strip ratio as do their estimated mining costs. In general, the estimated costs of these deposits are higher than the costs of the developed deposits in Table 3.1.

Each of the 31 deposits has a minimum cost mine capacity ($Q_{\text{min}}$), which corresponds to the low point on its average total cost curve (Figure 3.3). The capacity of these deposits can be ranked in order of average mining cost ($AC_{\text{min}}$). A cumulative minimum cost capacity curve can then be derived (Figure 3.4, dotted line).

\textsuperscript{10} Deposits typically have both a proven reserve and a larger, ultimate reserve figure. Only the proven reserve figures were used here which implies that the estimates of optimal capacity may be conservative.

\textsuperscript{11} Data for these deposits were collected from Geological Survey and Bureau of Mines files.
Figure 3.2
Actual and Estimated Mine Capacity

Actual mine capacity (1000 MT of copper per year)

Estimated mine capacity ($Q^*$) (1000 MT of copper per year)
Figure 3.3
Average and Marginal Total Cost of Mine Capacity Curves

Mining capacity (metric tons of copper per year)
Figure 3.4
Potential Capacity Supply Curve

Price per pound of copper

Mine capacity (1000 MT of copper per year)
Each horizontal segment of the cumulative minimum cost capacity curve represents the $Q_{\text{min}}$ capacity of one or more copper deposits. If every deposit were developed into a mine with capacity $Q_{\text{min}}$ when the expected price was at or above $AC_{\text{min}}$, the curve would show the total increased capacity from these deposits for a particular expected copper price. However, because the expected price is frequently above $AC_{\text{min}}$, the mine capacity of the deposit will be above $Q_{\text{min}}$ — at some higher profit-maximizing capacity $Q^*$.

The same procedure followed to test the model was used to estimate the capacity $Q^*$ and the corresponding average cost of the undeveloped copper deposits over four expected prices. The $Q^*$ capacities of these deposits were ranked in order of average mining cost, and the cumulative maximum profit capacity curve was derived (Figure 3.5, solid line). As can be noted, the cumulative maximum profit capacity curve is always outside the cumulative minimum cost capacity curve; this indicates that new mines will generally not be built at the $Q_{\text{min}}$ capacity. The evidence presented in Figure 3.5 suggests that price increases could generate large increases in the planned capacity of undeveloped mines. Table 3.2 illustrates the price elasticity of several of the larger undeveloped deposits.
Figure 3.5
Potential U.S. Copper Capacity
From Known Open Pit Properties

Price per pound of copper
$2.00
$1.50
$1.00
$0.75
$0.50

Mine capacity (1000 MT of copper per year)
1000
2000
3000
4000
5000

Present mine capacity
Increase in present mine capacity
New mine capacity $Q_{min}$
Increase in new mine capacity
Price-induced increases in capacity
Optimal Capacity of Existing Mines

Price increases could also affect the capacity of existing mines. The Q* mine capacity figures of the major U.S. open pit copper mines illustrate the effect of price increases on the capacity of developed mines (Table 3.3). Several of the deposits do not show signs of expansion because the remaining reserves are not large enough to support additional capacity. Table 3.3 clearly indicates that price increases may induce large capacity increases at existing mines. Comparison of the totals in Tables 3.2 and 3.3 indicates that the effect on existing capacities would apparently overshadow the effect on new mines.

VI DISCUSSION

The total potential open pit copper supply is the sum of the present and potential capacity at existing open pit mines and the potential capacity at 31 undeveloped deposits (Figure 3.5). Several sources of new copper supply are not considered in the total potential supply. These include (1) underground mines and undeveloped deposits that would be mined underground, (2) low-grade extensions of the open pit and underground mines and deposits, and (3) copper resources not evaluated by the Bureau of Mines or the Geological Survey.
Table 3.2

Estimated Mine Capacity of Undeveloped U.S. Copper Deposits at Varying Prices*

<table>
<thead>
<tr>
<th>Deposit</th>
<th>$0.75</th>
<th>$1.00</th>
<th>$1.50</th>
<th>$2.00</th>
<th>$1.00-2.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper Basin, AZ</td>
<td>0</td>
<td>45,000</td>
<td>77,000</td>
<td>98,000</td>
<td>117</td>
</tr>
<tr>
<td>Florence C., AZ</td>
<td>0</td>
<td>0</td>
<td>111,000</td>
<td>161,000</td>
<td>---</td>
</tr>
<tr>
<td>Helvetica East, AZ</td>
<td>56,000</td>
<td>91,000</td>
<td>120,000</td>
<td>162,000</td>
<td>78</td>
</tr>
<tr>
<td>Helvetica, AZ</td>
<td>0</td>
<td>0</td>
<td>14,000</td>
<td>18,000</td>
<td>---</td>
</tr>
<tr>
<td>Vekol Hills, AZ</td>
<td>0</td>
<td>29,000</td>
<td>53,000</td>
<td>65,000</td>
<td>124</td>
</tr>
<tr>
<td>Lights Creek, CA</td>
<td>0</td>
<td>0</td>
<td>64,000</td>
<td>107,000</td>
<td>---</td>
</tr>
<tr>
<td>Ely Spruce, MN</td>
<td>0</td>
<td>53,000</td>
<td>95,000</td>
<td>120,000</td>
<td>118</td>
</tr>
<tr>
<td>Heddleston, MT</td>
<td>0</td>
<td>0</td>
<td>37,000</td>
<td>49,000</td>
<td>---</td>
</tr>
<tr>
<td>Stillwater, MT</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>25,000</td>
<td>---</td>
</tr>
<tr>
<td>Hillsboro, NV</td>
<td>0</td>
<td>16,000</td>
<td>30,000</td>
<td>38,000</td>
<td>137</td>
</tr>
<tr>
<td>Kirwin, WY</td>
<td>0</td>
<td>40,000</td>
<td>57,000</td>
<td>70,000</td>
<td>75</td>
</tr>
<tr>
<td><strong>Total Capacity</strong></td>
<td>56,000</td>
<td>276,000</td>
<td>678,000</td>
<td>912,000</td>
<td>231</td>
</tr>
</tbody>
</table>

* The numbers in the columns refer to the profit-maximizing capacity Q* of each mine. When the price was below the AC min, the corresponding Q* was assumed to be 0.
## Table 3.3
Estimated Mine Capacity of Existing Mines at Various Prices

<table>
<thead>
<tr>
<th>Mine</th>
<th>1978 Annual Capacity</th>
<th>Expected Price (1978 dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$1.00</td>
<td>$1.50</td>
</tr>
<tr>
<td>Bagdad, AZ</td>
<td>65,000</td>
<td>(65,000)</td>
</tr>
<tr>
<td>Inspiration, AZ</td>
<td>54,000</td>
<td>52,000</td>
</tr>
<tr>
<td>Metcalf, AZ</td>
<td>85,000</td>
<td>118,000</td>
</tr>
<tr>
<td>Mineral Park, AZ</td>
<td>18,000</td>
<td>(18,000)</td>
</tr>
<tr>
<td>Mission San Xavier, AZ</td>
<td>49,000</td>
<td>71,000</td>
</tr>
<tr>
<td>Morenci, AZ</td>
<td>113,000</td>
<td>114,000</td>
</tr>
<tr>
<td>New Cornelia, AZ</td>
<td>45,000</td>
<td>(47,000)</td>
</tr>
<tr>
<td>Palo Verdi, AZ</td>
<td>26,000</td>
<td>50,000</td>
</tr>
<tr>
<td>Pima, AZ</td>
<td>54,000</td>
<td>(54,000)</td>
</tr>
<tr>
<td>Ray, AZ</td>
<td>86,000</td>
<td>169,000</td>
</tr>
<tr>
<td>Sierrita, AZ</td>
<td>91,000</td>
<td>(91,000)</td>
</tr>
<tr>
<td>Silver Bell, AZ</td>
<td>22,000</td>
<td>(22,000)</td>
</tr>
<tr>
<td>Twin Buttes, AZ</td>
<td>68,000</td>
<td>(68,000)</td>
</tr>
<tr>
<td>Butte, MT (Berkeley Pit)</td>
<td>91,000</td>
<td>117,000</td>
</tr>
<tr>
<td>Chino, NM</td>
<td>96,000</td>
<td>102,000</td>
</tr>
<tr>
<td>Continental Surface, NM</td>
<td>22,000</td>
<td>(22,000)</td>
</tr>
<tr>
<td>Tyrone, NM</td>
<td>86,000</td>
<td>91,000</td>
</tr>
<tr>
<td>Bingham, UT</td>
<td>231,000</td>
<td>(231,000)</td>
</tr>
<tr>
<td>Esperanza, AZ</td>
<td>14,000</td>
<td>(14,000)</td>
</tr>
<tr>
<td>Peacock, AZ</td>
<td>7,000</td>
<td>16,000</td>
</tr>
<tr>
<td>Safford Inspiration, AZ</td>
<td>20,000</td>
<td>(20,000)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1343.0</strong></td>
<td><strong>1582.0</strong></td>
</tr>
</tbody>
</table>

* Numbers in parentheses indicate a mine capacity at or below the 1978 mine capacity. To calculate the capital and operating costs and net mine life (RG/Q*) of the new mine capacity, 1978 (not original) deposit tonnages were used. On the average, the per-unit capital cost of the new capacity was a little higher and the operating cost of the mine a little lower than the costs of the original capacity. Ten-year (1972-1982) average gold price ($220 per oz.) and silver price ($7.50 per oz.) were used to value the by-products of the mines.
Only about half of the properties known to the Bureau of Mines and the Geological Survey are considered open pit properties. The other half would probably be mined with underground techniques. The underground properties are generally smaller, however, and represent a smaller potential for new capacity. Only about 20% of present U.S. copper mine capacity comes from underground mines, and this share seems likely to shrink in the future. To evaluate explicitly the potential capacity from these properties would require capital and operating cost equations for underground mines.

Another important source of new supply could be the low-grade extensions of major copper deposits. Most copper deposits are surrounded by low-grade mineral ore zones. If prices rise and make it economically viable, the capacity at some mines would increase to include mining these low-grade extensions. Without specific data on these low-grade zones, their impact on optimal capacity is difficult to assess.12

Lastly, but perhaps most importantly, additional sources of mineral supply are less well known or poorly explored copper deposits. For example, Geological Survey copper specialists estimate that perhaps 10 or 20 copper deposits are known to the copper industry, but information about them is not available to the Geological Survey.

---

12 Several individuals have tried to simulate the effect of changing deposit grade on copper mining (Bradley 1979).
Additional exploration would be need to bring most of these deposits to the point where they can be developed into mines.\footnote{13}{Dennis Cox of the Geological Survey, personal conversation.}

VII CONCLUSIONS

The major points raised in this chapter are these: (1) The mine capacity at existing mines is consistent with predictions based upon an extended Alchian formulation concerning production costs and outputs; (2) changes in the expected mineral price through price supports or changes in the terms of international trade would change existing and planned mine capacity; and (3) these changes in mine capacity can be predicted with the simple financial model of mine capacity presented in this chapter.

Although some of the future copper supply could come from new and as yet unassessed resources, in an emergency these resources could not be relied upon to supplement traditional sources of supply. The only relatively sure and quick supply of new mine capacity would have to come from known mines and deposits. Price-induced increases in planned or existing mine capacity could be substantial, with increases of 100 to 200\% above existing capacity possible if the ore price were guaranteed at a high enough level.
Notes for Chapter 3

In order to solve equation 1 explicitly for Q*, an empirical approximation of the following expression is used

\[ \frac{1 - e^{-r \frac{V}{Q}}}{r} \]

Fit to 73 values of Q and RG from Bureau of Mines copper mine data, approximating functions are shown below for two discount rates:

- \[ 6.78 + .0064 \frac{V}{Q} - 14.79 \frac{Q}{V} \text{ for } r = .15 \]
- \[ 10.26 + .182 \frac{V}{Q} - 31.192 \frac{Q}{V} \text{ for } r = .05 \]

The following table compares values of the exponential function and its empirical approximation at the 5% and 15% discount rates:

<table>
<thead>
<tr>
<th>Mine Life (V/Q) in Years</th>
<th>Mine Life (V/Q) in Years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>4.42</td>
</tr>
<tr>
<td>[ \frac{1 - e^{-r \frac{V}{Q}}}{r} ] r = 0.5</td>
<td>3.52</td>
</tr>
<tr>
<td>( d_1 + d_2 \frac{V}{Q} + d_3 \frac{Q}{V} )</td>
<td>4.77</td>
</tr>
<tr>
<td>[ \frac{1 - e^{-r \frac{V}{Q}}}{r} ] r = 0.15</td>
<td>3.85</td>
</tr>
<tr>
<td>( d_1 + d_2 \frac{V}{Q} + d_3 \frac{Q}{V} )</td>
<td>4.77</td>
</tr>
</tbody>
</table>

As can be seen by comparison of the columns, within the relevant range of mine lives and interest rates the functions track one another closely. Given this approximation, the profit equation 1 can be rewritten as

\[ X = (P - C)Q \left[ d_1 + d_2 \frac{V}{Q} + d_3 \frac{Q}{V} \right] - KQ \quad (2) \]
Assuming fixed unit capital and operating costs, the derivative of mine profit \( X \) with respect to \( Q \) can be solved explicitly for optimal mine capacity \( Q^* \):

\[
Q^* = \frac{K - (P - C) d_1}{2(P - C) d_3} V \quad \text{when} \quad \frac{dX}{dQ} = 0
\]

Differentiating this equation with respect to \( P \) gives

\[
\frac{\partial Q^*}{\partial P} = -\frac{V d_1 [2(P - C) d_3 - 2d_3 V(K - (P - C) d_1)]}{[2(P - C) d_3]²}.
\]

Since the denominator is a squared term and thus positive, we are only concerned with the numerator. The numerator simplifies to

\[-2Vd_1 d_3 [(P - C) + \frac{K}{d_1} - (P - C)] = -2Vd_3 K\]

This term is also positive because reserves times grade \((RG)\) and the average cost of capacity \((K)\) are positive and \(d_3\) is negative. Note that \(d_3\) is negative for 5 and 15% discount rates. Thus, profit-maximizing mine capacity, as approximated by equation 2, is positively correlated with the expected ore price.

The sensitivity of mine capacity to the ore price is a function of the discount rates, capital costs, and deposit size of the mine in question. For example, if capital costs were $2.00 per pound of copper, operating costs were 25 cents per pound of copper, the deposit were 50,000,000 pounds of contained copper, and the discount rate were 5%, than an increase in the copper price from $.75 to $1.75 per pound increases optimal capacity from
In this case, a dollar rise in the expected price translates into a 60% rise in the optimal mine capacity.
CHAPTER 4

FORECASTING MINERAL SUPPLY FROM MINERAL RENT DATA

In the last chapter a static investment model was presented to clarify the relationship between mineral price, extraction cost and mineral quality at the mine or firm level, in the short run. In this chapter, an optimal control model of exhaustible resource use is applied to clarify the long run relationship between mineral price or rent and extraction cost at the industry level.

A standard first order condition of that model, which indicates the time rate of change of rents, is reformulated to reveal an important practical application of the theory. Given restrictions upon mineral markets and the extraction cost function, rent data may be used to forecast changes in extraction costs resulting from resource depletion.

Chapter four develops this application of the theory of exhaustible resources, and illustrates the application, using historical mineral industry rent and extraction cost data. This illustration supports the use of mineral rents to guide forecasts of mineral extraction cost.

An important contribution of the chapter is to clarify what is meant by exhaustible resource scarcity. Past studies have suggested that rent is an index of resource scarcity. This paper goes further and argues that rent is a market forecast of extraction cost changes and, properly understood, may be used to make statistical forecasts of extraction cost. Statistical forecasts of U.S. coal, copper and oil extraction costs, following the method proposed in this chapter, suggest that future rates of extraction cost increase will be similar to rates experienced in the past and that there is no special reason for policy concern at this time.

I INTRODUCTION

Resource scarcity has been a recurrent public concern for at least two centuries. In the nineteenth century, Malthus predicted population limits from scarcity of arable land (Malthus 1806) and Jevons foresaw the end of the

This recurrent concern was exacerbated by widespread resource price inflation in the 1970's and early 1980's, and helped to motivate policy measures to limit resource consumption. These measures include precautionary measures, such as the National Environmental Policy Act, as well as proposals to tax domestic consumption and to restrict resource exports. In effect, these measures were designed in part to delay increases in resource extraction costs accompanying high grade resource depletion.

Though extraction cost increases due to depletion are feared, they are by no means inevitable for most privately owned resources. Applied economists have tried to demonstrate this point with a variety of sophisticated econometric forecasts of extraction costs and prices. Rarely do these forecasts indicate rapid cost escalation, but much of the general public and many policy makers remain unconvinced. The complexities of the techniques and inadequate verification of the forecasts may contribute to this skepticism.

This chapter forecasts copper, coal and oil mineral extraction costs, using simple extrapolations of mineral rent data. The technique is well supported by economic
theory, has been verified using historical copper, oil and coal rent and extraction cost data and is easy to explain to policy makers. For these reasons, this technique is advised as an alternative to more complicated econometric forecasts.

This chapter is divided into six parts. Part two, following this introduction, describes background literature supporting rent extrapolation to forecast mineral extraction costs. Part three presents the model relating rent and extraction cost for exhaustible resources. Part four uses the model to explain the pattern of extraction costs and rent in copper, oil and coal resource markets during the last century. Part five forecasts future extraction costs of these minerals and briefly discusses policy measures to limit resource consumption. Part six concludes the chapter.

II BACKGROUND LITERATURE

General concerns with scarcity and extraction cost escalation have led to a search for quantifiable measures to forecast scarcity. These measures include physical indices, past cost and price trends and dynamic econometric models. Earth scientists have often suggested various physical indices of scarcity, including the ratio of anticipated mineral reserve stocks to consumption and the ratio of mineral crustal abundance to consumption to give a general indication of future cost increases (See Brobst 1979;
Nordhaus 1974). These indices indicate something about the quantity of the resource that is available but little about the economic costs of extracting that resource (Fisher 1982).

Some economists have used past trends in resource extraction costs and prices to evaluate future costs and prices (Barnett and Morse 1963; Barnett 1979; Johnson and Bell 1978). However, these trends indicate the cost of past resource use, they may indicate little about the cost of future resource use.

Other resource economists have used engineering cost curves to estimate future extraction costs. Engineering cost curves include geologic and engineering estimates of the quantity of resource available at different economic costs of production (See for example: Rosenkrantz 1977; Bieniewski et. al. 1971). These curves are often coupled with estimates of demand in econometric models to predict future cost and price trends (Nordhaus 1973; Zimmerman 1981; Roumasset, et. al. 1985). Unfortunately, there is much uncertainty about the cost curves and demand estimates, used in these models, and verification of model output is often inadequate.

On theoretical grounds, probably most resource economists favor in-situ resource rents as a measure of future resource scarcity. Rents provide a market estimate of future extraction cost increases which, in theory, takes
into account perceptions about future reserves, changes in extraction technology and trends in demand (Fisher 1979; Brown and Field 1978, Solow and Wan, 1976, and Dasgupta and Heal 1979).

Three practical problems have argued against the use of rents as a measure of future cost increases due to scarcity. The first has been the fact that resource rent data is not fully available. This problem has been addressed recently by several economists, who concede the point for some minerals and resources (but not others) and advocate the use of proxies for rent, such as the marginal cost of exploration when full rent data is not available (Devarajan and Fisher 1982; Stollery 1983; Livernois 1988; Miller and Upton 1985). The work in this chapter suggests that sample rent data may be obtained for many important minerals.

The second problem is skepticism about the accuracy of rents as a scarcity index or as a tool to predict future extraction cost increases. Many of the assumptions required in economic models used to support rents as a scarcity index, including perfect information about resource stocks and universal markets, are violated in practice. Faulty assumptions could distort the relationship between rents and extraction cost. Unfortunately, there have been a few studies which have examined the relationship between rents and extraction cost in the past, and these have usually been rather narrow or indirect in focus (Devarajan and Fisher 1982; Stollery 1983; Livernois 1988; Miller and Upton 1985). The work in this chapter suggests that sample rent data may be obtained for many important minerals.
The third problem is that resource rents do not indicate the shape of the extraction cost path. For example, the same rent may be associated with a long run convex, concave or linear future cost path. For some policy purposes, it is important to know the shape of the cost path and such information is needed to verify the past association between rent and extraction cost.

The analysis in this chapter suggests that the general functional form of the future extraction cost path can be specified from rent trend and other data. Then, given a specification for the extraction cost path, the rate of cost increase along that path is calculated from rent data.

This cost estimation technique is verified against a sample of rent and cost data from U.S. mineral markets in part four. There, the technique is shown to provide a reasonably close estimate of past changes in extraction cost caused by depletion in those markets. The technique is based upon a model of resource extraction described below.

III THE MODEL

This section describes a model which relates mineral rents and extraction costs. Standard first order conditions are derived from the model and used to obtain expressions defining the equilibrium time paths of mineral rents and
prices. The expression defining the rent path is reformulated to reveal an important relationship between the current value rent and future changes in unit extraction cost caused by depletion. Depletion is defined here as a decline in mineral ore quality.

The expressions obtained from the model for the rent and price paths are difficult to interpret in the general case. However, restrictions placed upon the extraction cost function allow a clearer description of the rent and the price path. The description of rent derived in this fashion has an important practical application. In some instances rent data may be used to predict future changes in extraction cost. Equations are obtained to make such predictions assuming logarithmic, exponential and linear extraction cost paths.

The Derivation of Rent

The model developed here is a modification of models due to Slade (1982) and Schultz (1974). In this model, perfect markets and foresight are assumed. In presenting the model, the following notation will be used.

\[ Q(t) \]
\[ g(t) \]

is the output of refined product in the extractive industry at time \( t \),

is the quality of ore mined at time \( t \), including such attributes as mineral grade
and deposit volume. Extraction is ordered by ore quality such that better quality ore is mined first,

\[ W(Q) \]

is the benefit or willingness to pay for \( Q \),

\[ C(Q,g,t) \]

is total extraction and processing cost. Total cost depends on the level of output, time (a measure of technological change in the industry) and the quality of ore \( g \) extracted. Extraction cost increases as \( g \) decreases,

\[ f(g) \]

is the density of refined product available of quality \( g \). The total amount of refined product in ore quality between \( g \) and \( g + \Delta g \), is approximately \( f(g) \Delta g \), \( g \leq g \leq g + \Delta g \), \( r \) is the discount rate,

\[ T \]

is the termination date of resource extraction.

The problem is to choose a time path for extraction rates that will maximize the discounted stream of current and future benefits minus costs. The extraction rate at time \( t \), \( Q(t) \), is equal to the rate of change in ore quality, \( \dot{g} \), (where a dot over a variable denotes its time rate of change) times the density function, \( f(g) \) (the refined product available at that ore quality). Therefore, choosing an extraction rate is equivalent to choosing the rate of change of ore quality. We thus wish to maximize
\[ (1) \quad \max_{\mathcal{Q}} \int_{0}^{T} \left[ W(\mathcal{Q}) - C(\mathcal{Q},g,t) \right] e^{-rt} \, dt \]

subject to the production relationship

\[ (2) \quad Q(t) = \mathcal{Q}(t)f(g). \]

The optimal control problem can be solved by introducing the costate variable, \( \rho(t) \), and forming the Hamiltonian, \( H \).

\[ (3) \quad H = e^{-rt} \left[ W(Q) - C(Q,g,t) \right] - \rho(t). \]

The first order conditions for an interior maximum of (1) are

\[ (4) \quad H_{\mathcal{Q}} = e^{-rt} \left[ W_{\mathcal{Q}} f(g) - C_{\mathcal{Q}} f(g) \right] - \rho(t) = 0 \]

and

\[ (5) \quad \dot{\rho} = H_{\mathcal{Q}} = e^{-rt} \left[ W' f' \mathcal{Q} - C_{\mathcal{Q}} - C_{\mathcal{Q}} f' \mathcal{Q} \right]. \]

Since \( W'(Q) = P(Q) \) is the inverse demand function and if we let \( \lambda(t) = \rho(t)e^{rt}/f \) then upon rearranging (4) we have

\[ (6) \quad P = C_{\mathcal{Q}} + \lambda \]

or \( \lambda(t) = P(Q) - C(Q,g,t) \) so that \( \lambda \) is the rent or marginal value of the resource in the ground.

Notice that

\[ \dot{\lambda} = \dot{\rho} e^{-rt}/f - \lambda f' \mathcal{Q}/f + r\lambda \]

or

\[ (7) \quad \dot{\lambda} - r\lambda = \dot{\rho} e^{-rt}/f - \lambda f' \mathcal{Q}/f \]

Using this with (5), (6) and the fact that \( W' = P \) we find

\[ (8) \quad \dot{\lambda} - r\lambda = -C_{g}/f. \]

Integrating both sides of this differential equation from 0 to \( t \) and rearranging we obtain
Letting $t = T$, assuming $\lambda_T = 0$ (when a substitute resource becomes available) and rearranging we obtain

\begin{equation}
\lambda(0) = \int_0^T e^{-rs} \frac{C_g}{T} \, ds
\end{equation}

The expression $C_g/f$ is the change in total cost due to depletion (a change in $g$) per unit of refined product extracted (of quality $g$). Let this expression be termed depletion cost. Accordingly, rent in (9a) equals discounted future increases in depletion cost.

To determine the path of prices in this model we differentiate (6) to obtain

\begin{equation}
\dot{P} = \dot{C}_Q + \frac{\dot{\lambda}}{T} \\
= \dot{C}_Q + e^{rt} \frac{\dot{P}}{f} + re^{rt} \frac{\rho}{f} - e^{rt} \frac{\rho f'}{f} + \frac{\lambda f'}{f}.
\end{equation}

Substituting (5) into this and using (6) we get

\begin{align*}
\dot{P} &= \dot{C}_Q + P \dot{g} f' \frac{f'}{f} - C_g \dot{g} f' \frac{f}{f} \\
&\quad - C_g \dot{f} f' \frac{f}{f} - \lambda f' \dot{g} \frac{f}{f} \\
&\quad - \lambda \dot{f} \dot{g} f' \frac{f}{f} \\
&\quad + \lambda \dot{g} f' f (C_Q + \lambda) \\
&\quad + \dot{C}_Q - C_g f' f + r \lambda.
\end{align*}

The expressions for the price path and the rent ($\lambda(0)$) are difficult to interpret without making simplifying
assumptions about the extraction and processing cost function. Assume that marginal cost, \( C_Q \), is constant for a given ore quality and state of technology and is an additive function of its arguments such that

\[
C = [h(g) + k(t)]Q.
\]

In this case

\[
\dot{C}_Q = h'g + \dot{k} \quad \text{and} \quad C_g = h'(g)Q
\]

then substituting in (11) gives

\[
(12) \quad \dot{P} = h'g + \dot{k} - h'Q/f + r\lambda.
\]

However, \( h'g = h'gf/f = h'Q/f \) so we have

\[
(13) \quad \dot{P} = \dot{k} + r\lambda.
\]

Price equals marginal extraction cost plus rent and the rate of change of price is equal to the rate of change of cost, due to changes in technology, plus the discount rate times rent. Given sufficient technological change, such that \( |k| > r\lambda \), prices will fall.

Also using (11a)

\[
C_g = h'(g)Q
\]

but since \( Q = f(g) \dot{g} \), this gives

\[
C_g/f = C_g/Q \dot{g} = h'(g) \dot{g}.
\]

Thus (9a) becomes
Rent is now a function of the derivative of marginal extraction cost with respect to ore quality, changes in ore quality, the discount rate and the termination data for extraction. Hence, rent may be estimated given values for $h'(g)$, $\hat{g}$, $r$ and $T$. ¹⁴

Rent indicates scarcity in (14) in the following manner. Let $g_y$ and $g_z$ be the quality of ore for minerals $y$ and $z$ respectively. Similarly, $C_y'$ and $C_z'$ are the cost functions and $\lambda_y$ and $\lambda_z$ the rents for minerals $y$ and $z$ respectively. Suppose now that $\lambda_y > \lambda_z$ and that $C_y'$ and $C_z'$ do not intersect. It follows that $C_{g_y}/f > C_{g_z}/f$ and or $T_y > T_z$. The termination date of extraction is likely to be very distant for most minerals. (There are few historical examples of a mineral for which extraction has everywhere terminated). If we assume that $T_y$ and $T_z$ are infinite then unambiguously

$$C_{g_y}/f > C_{g_z}/f.$$ ¹⁴

¹⁴Note that without technological change, i.e. $k(t)$ is constant, $C_Q = h(g)$ and $C_Q = h'(g)\hat{g}$ and

$$\lambda(0) = \int_0^T e^{-rs} C_Q ds$$

In this special case rent equals discounted future increases in marginal extraction cost.

85
If in addition we assume that $C = [h(g) + k(t)]Q$ and hold $k(t)$ constant, then as before

$$C^{y}_{g,y}/f = h'(g_{y})g_{y} = \dot{C}_{Q}^{y}$$

and

$$\dot{C}_{Q}^{y} \geq \ddot{C}_{Q}^{y}.$$  

In some instances it may be possible to forecast the general shape of depletion cost or the marginal extraction cost path over time, from rent path $\dot{\lambda}$, resource demand $Q$, or mineral density function $f(g)$ information (Roumasset and Chakravorty 1989). In such instances, it is possible to forecast the depletion cost or marginal extraction cost time path $[h'(g)g]$ along that path from rent data as described below.

**Rent Paths Corresponding to Depletion Cost Paths**

Assume three general time paths of depletion cost—concave to the origin, convex to the origin, or linear. Many economists feel that depletion cost for most minerals will be concave (Hanson 1980). This feeling is based in part upon the tonnage-grade distribution observed for minerals which is skewed toward greater mineral abundance at lower ore grades (Singer 1978).

Hanson (1980) has demonstrated that the scarcity rent declines in every period before $T$ when depletion cost is continuous and strictly concave to the origin such that

$$h'(g)g < 0 \rightarrow \dot{\lambda} < 0.$$
Let us approximate depletion cost as a (concave) logarithmic function such that

\[ -\xi(t) = \xi(0) + a \ln(t), \]

where \( \xi(0) \) (for notational convenience) now denotes an initial cost position, \( \ln(t) \) is the natural log of time and \( a \) is some constant. (Recall that \( C \) will denote the time path of marginal extraction cost if technology is held constant)\(^{15}\). Therefore \( \dot{\xi} = a/t \), where \( \dot{\xi} \) is depletion cost, and

\[ (16) \quad \lambda = \int_1^T \frac{a}{t} e^{-rt} \, dt \]

If \( r \) is set to .1 in this equation and \( T \) approaches infinity

\[ (17) \quad \lambda = 1.82 \, a, \]

\[ (18) \quad a = \lambda/1.82 \]

and

\[ (19) \quad \dot{\xi} = (\lambda/1.82)/t. \]

Since \( t \) is known, depletion cost can be estimated from rent data if the cost path may be approximated as a logarithmic function.

Some geologists and economists believe that the most probable time path of depletion cost is convex to the

\(^{15}\)The depletion cost and the time path of extraction cost are equivalent when marginal cost is constant for a given grade and when technology is held constant. In this case \( C_0' = h'(g)g = C_g/f \).
origin. This belief is due, in part, to the perception that the costs of processing ore sharply increase beyond some lower ore quality "mineralogical threshold" (Slade 1982; Brobst 1979).

Roumasset and Chakravorty (1979) have shown that rents increase when the cost path is convex, prior to a price path inflection point, where

\[ (20) \quad \lambda > 0 \text{ if } \dot{\xi} > 0 \text{ and } \dot{\xi} < r \lambda. \]

Let us approximate the convex depletion cost path over time as

\[ C(t) = C(0) e^{it} \]

where \( C(0) \) is an initial period cost and \( i \) is the average annual rate of growth associated with that cost. Then

\[ \dot{\xi} = iC(0)e^{it} \]

and

\[ \lambda = i \int_0^T C(0)e^{it}e^{-rt}dt = \frac{i}{1-r}[e^{(1-r)t} - 1]C(0) \]

When \( T \) is large and \( i \) is less than \( r \), rent can be approximated by
Therefore

\[ (21) \quad \lambda = \frac{1}{t-1} \epsilon(0) \]

Therefore

\[ (22) \quad i = \frac{\lambda r}{\epsilon + \lambda} = \frac{\lambda r}{P} \]

and

\[ (23) \quad \dot{\epsilon} = \frac{\lambda r}{P} C(0) e^{\frac{\lambda t}{P}} \]

Since \( P \) is known (23) implies that the rate of cost increase can be estimated from rent data, if the cost path is convex and may be approximated as an exponential function.

Finally, the depletion cost path may be linear. This implies that the depletion cost path over time may be approximated as

\[ \epsilon_t = \epsilon(0) + xt \]

where \( x \) is the average annual increase in cost associated with a given path. Then

\[ \dot{\epsilon} = x \]

and
\[ \lambda = g \int_0^T x e^{-rt} dt = \frac{x}{r} (1 - e^{-rt}). \]

When \( T \) is large, rent may be approximated by

\[ (24) \quad \lambda = \lim_{T \to \infty} \int_0^T x e^{-rt} dt = \frac{x}{r} \]

Therefore

\[ (25) \quad x = \dot{c} = \lambda r \]

When the cost path is linear over time, the rent is constant as shown in (24). Moreover, the annual increase in cost can be estimated from rent data, as shown in (25).

IV MODEL ILLUSTRATION

The model is used to explain the pattern of rent and depletion cost data from anthracite coal, bituminous coal, oil and copper markets over the past century. The explanation is given in three steps. First, sample rent data for these minerals are presented for selected years between 1900 and 1980. Trends in the rent data are used, in one case, to predict the convexity, concavity or linearity of depletion cost, following equation (15). Then rent data are used to predict a rate of cost increase, along different assumed cost paths, following equations (19), (23) and (25).
Next, the rate of cost increase \( (\dot{c}) \) is measured for each mineral. These measurements were obtained from historical ore quality data and econometric cost functions. The ore quality data indicates trends in deposit volume, grade and depth of mines opened between 1900 and 1980 and provide a measure of \( \dot{g} \) over the period. The econometric functions sum the different indices of ore quality into a single index and provide a measure of \( h'(g) \) over the period. The econometric functions represent 1970's cost data and technological relationships so that \( h'(g) \) must be assumed constant.

Finally, the predicted cost increase is compared with the measured cost increase. The close fit between predicted and measured costs supports the use of the mineral model to predict trends in extraction cost caused by resource depletion.

Rent Data and Predicted Cost Increases

Past coal, copper and oil rent data are presented in Table 4.1. The rents are shown as a percent of the current price, following industry practice, and as a dollar per unit output, in parenthesis. These data were obtained from a variety of sources, cited in the Table, to represent the in-place value of marginal (newly mined) deposits, net of exploration and extraction costs, for the time periods indicated.
The anthracite coal data include five rent samples, spaced at roughly ten year intervals, between 1900 and 1950. These rents decline in each interval, a pattern consistent with a concave cost path following equation (15). The bituminous, petroleum and copper data suggest the general magnitude of rents paid for those minerals, but are insufficient to indicate a particular cost path. However, many analysts have estimated that bituminous coal, petroleum and copper costs follow a convex path (Pindyke 1978; Zimmerman 1977; Roumasset et. al. 1983).

In the table, anthracite coal costs are estimated assuming a logarithmic path and bituminous coal, petroleum and copper costs are estimated assuming both exponential and linear cost paths. The exponential cost path estimated for anthracite coal is included for comparative purposes. For all minerals, the average rent in a period is used to estimate the rate of cost increase (depletion cost), following equations (19), (23) and (25).

Anthracite and petroleum rents as a percent of the price, are considerably larger than bituminous and copper rents. Anthracite rents range between 10 and 30 percent of the price, during the 1900 to 1923 period, and corresponding petroleum rents vary between 12 and 50 percent, during the 1929 and 1955 period. Bituminous coal and copper rents are below 9 percent in all years and locations cited.
The anthracite and petroleum rents indicate increases in anthracite cost between 1.0 and 2.5 percent (prior to 1923) and increases in petroleum cost between 2.1 and 4.5 percent annually, following equation (19). By comparison, bituminous and copper rents suggest bituminous and copper cost increases under .7 percent per year (See Table 4.1).
Table 4.1
Rent Data and Predicted Cost Increase

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Years</th>
<th>Rent % ($1977 $)</th>
<th>Predicted Rate of Annual Cost Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Exponential (€)</td>
</tr>
<tr>
<td>Anthracite Coal</td>
<td>1900</td>
<td>20-30 (1.93-2.89)</td>
<td>$2.5 C(o) e^{0.5t}$</td>
</tr>
<tr>
<td></td>
<td>1913</td>
<td>16-25 (1.77-2.77)</td>
<td>$2.0 C(o) e^{0.2t}$</td>
</tr>
<tr>
<td></td>
<td>1923</td>
<td>10 (1.96)</td>
<td>$1.0 C(o) e^{1.0t}$</td>
</tr>
<tr>
<td></td>
<td>1939</td>
<td>6 (1.03)</td>
<td>$0.6 C(o) e^{0.6t}$</td>
</tr>
<tr>
<td></td>
<td>1940-50</td>
<td>3-5 (.61-1.01)</td>
<td>$0.4 C(o) e^{0.4t}$</td>
</tr>
<tr>
<td>Bituminous Coal</td>
<td>1900</td>
<td>9 (.67)</td>
<td>$0.5 C(o) e^{0.5t}$</td>
</tr>
<tr>
<td></td>
<td>1936, 1940</td>
<td>4-5 (.39-.50)</td>
<td>$2.5 C(o) e^{0.5t}$</td>
</tr>
<tr>
<td>Petroleum</td>
<td>1929-40</td>
<td>40-50 (2.40-3.00)</td>
<td>$4.5 C(o) e^{4.5t}$</td>
</tr>
<tr>
<td></td>
<td>1950-55</td>
<td>12-30 (.91-2.28)</td>
<td>$2.1 C(o) e^{2.1t}$</td>
</tr>
<tr>
<td>Copper</td>
<td>1960</td>
<td>4-8 (.06)</td>
<td>$0.6 C(o) e^{0.6t}$</td>
</tr>
</tbody>
</table>

Sources:

a Roberts, 1901, p. 55
b Norris, 1913, p. 355
c Wing and Black, 1925, p. 867
d Papst, 1940
e Edward Fox, Retired President of the Philadelphia and Reading Coal and Iron Company, personal communication
f Jessie Core, Retired Vice President, Coal Mining Operations, U.S. Steel, personal communication (West Virginia mines)
g Fisher and James, 1955, p. 372 (West Virginia mines)
h Subhash Bhagwat State Geologist, personal communication (Illinois mines)
i Bain, 1943, p. 83
j McDonald, 1963, p. 32; Magill, 1981, p. 179
k Beasley, Harris, and McFarlane, 1981, pp. 91, 97, 147

Additional information is listed by commodity in the appendix.

Note: The predicted rate of cost increase was calculated using equations 9, 12, and 14. The market rent data, shown in the table, was usually given as a percent of price and had to be converted into dollar figures using average price data for the period in question. The discount rate (r) was assumed to be 0.1.
These rent data are used to derive linear depletion cost predictions, for bituminous coal, petroleum and copper, following equation (25) and logarithmic depletion cost predictions, for anthracite coal, following equation (19).

Mineral Ore Quality Data

Quality indices differ in importance among minerals because of different factors affecting the ease with which minerals are found or mined. Coal, oil, and copper have three indices of quality in common: deposit grade, size, and depth. Deposit findability, another index of resource quality, is more important for oil resource quality than it is for copper and coal.

The size of oil and copper deposits is important because large deposits are easier to find and cheaper to develop and to exploit than small deposits. Coal deposits are usually spread over large areas so that total resource size is not as critical a cost variable. However, the thickness of the coal seam mined varies greatly and may affect coal mine productivity more than any other single variable (Young and Anderson 1952; Zimmerman 1981).

High-grade copper or high-Btu coal is desirable because it is easier to mine and process per unit of final product. Grade varies more among copper deposits than among coal seams or oil fields and therefore tends to be a more accurate index of the quality of copper than of coal or oil.
Deep deposits are more difficult to find and to mine than shallow deposits. For example, to find and develop deeper oil fields, deeper and more expensive wells must be drilled. The average depth of oil wells in the United States has almost doubled since 1920, and coal and copper mines have also become deeper over time.

For a variety of reasons, the cost of finding oil and gas has increased because of depletion. In fact, oil depletion is often measured by changes in the exploration drilling success ratio (Hubbert 1969). The cost of finding other minerals, such as copper and coal, however, probably has not increased much because of depletion. Canadian figures indicate that copper and other hard rock mineral exploration costs are typically only 2-3 percent of revenues and that the value of minerals found per exploration dollar has changed little for some time (Cranstone 1980, 10). Because most coal fields in the United States were explored and mapped long ago, coal exploration is relatively unimportant. Therefore, estimates of quality changes here include changes over time in exploration cost for oil but not for copper and coal.

**Anthracite Coal**

Perhaps the best example of the depletion of any major U.S. mineral resource is the production history of anthracite — the highest grade heating coal. For much of
the 19th and 20th centuries, large quantities of anthracite were mined from a relatively small area in eastern Pennsylvania. As mining progressed, the average anthracite coal seams were thinner and deeper (Table 4.2); mine productivity fell and costs of mining rose.

Including waste left in discarded mines, more than 12.2 billion tons of anthracite have been consumed since 1860.\footnote{Assumes 30 percent coal recovery before 1900 and 50 percent after.} Currently, nearly 40 percent of the original resource, or more than 60 percent of the reserve base, has been depleted (U.S. Dept. of Commerce 1975; Westerstrom 1975).

\textbf{Bituminous Coal Quality}

The depletion of eastern bituminous coal has been more gradual than the depletion of anthracite coal. Average underground coal seams in key eastern coal states have not, as a rule, become thinner. In four eastern coal mining states average underground seams are slightly thicker than in earlier mines (See Table 4.3).
Table 4.2

Anthracite Coal Depletion

<table>
<thead>
<tr>
<th>Year</th>
<th>Cumulative Production (million tons)</th>
<th>Average Seam Thickness (feet)</th>
<th>Average Mine Depth (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1892</td>
<td>838</td>
<td>9.0</td>
<td>360</td>
</tr>
<tr>
<td>1902</td>
<td>1,389</td>
<td>7.8</td>
<td>390</td>
</tr>
<tr>
<td>1912</td>
<td>2,195</td>
<td>7.0</td>
<td>400</td>
</tr>
<tr>
<td>1922</td>
<td>3,075</td>
<td>6.6</td>
<td>415</td>
</tr>
<tr>
<td>1930</td>
<td>3,701</td>
<td>6.3</td>
<td>420</td>
</tr>
<tr>
<td>1980</td>
<td>5,400</td>
<td>3-4</td>
<td>NA</td>
</tr>
</tbody>
</table>

Sources: Walter and Lesher 1925, 661; Tryon, Read, and Heald 1937, 3. Figures for 1980 seam size from correspondence with Edward Fox, retired president of the Philadelphia and Reading Coal and Iron Company.
Table 4.3
Underground Mine Seam Thickness
In the Major Coal States

<table>
<thead>
<tr>
<th>Number of Observations in 1977</th>
<th>Sample</th>
<th>Average Seam Thickness</th>
<th>New Underground Mines</th>
<th>(feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1920</td>
<td>1950</td>
<td>1977</td>
<td></td>
</tr>
<tr>
<td>Illinois</td>
<td>6.25</td>
<td>(3.0%)</td>
<td>7.1 (31%)</td>
<td>7.0 (45%)</td>
</tr>
<tr>
<td>Indiana</td>
<td>5.1</td>
<td>(7.1%)</td>
<td>5.8 (53%)</td>
<td>6.0 (99%)</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>5.1</td>
<td>--a</td>
<td>5.1 (25%)</td>
<td>4.4 (54%)</td>
</tr>
<tr>
<td>Ohio</td>
<td>4.7</td>
<td>(11.0%)</td>
<td>4.7 (60%)</td>
<td>4.7 (70%)</td>
</tr>
<tr>
<td>West Virginia</td>
<td>5.3</td>
<td>--</td>
<td>5.1 (9%)</td>
<td>3.9 (20%)</td>
</tr>
<tr>
<td>Kentucky</td>
<td>4.42</td>
<td>--</td>
<td>4.1 (18%)</td>
<td>4.7 (56%)</td>
</tr>
<tr>
<td>Virginia</td>
<td>5.2</td>
<td>--</td>
<td>4.8 (9%)</td>
<td>5.5 (39%)</td>
</tr>
</tbody>
</table>

Sources: 1920, Hotchkiss et al. 1939, 64, 103-106; 1950, Young and Anderson 1952, 4; and 1977, Benson and Doyle 1978.

Note: Figures in parentheses refer to percent of strip mine production in total.
      a No entries when percentages were insignificant.
The increase in average underground mine seam thickness in some states is a reflection of a change to strip mining. In 1920, eastern strip mining was limited to Ohio, Indiana, and Illinois. Later, strip mining grew in importance and by 1977 only one state mined less than 30 percent of its coal from strip mines. The new strip mines replaced the thin-seam underground coal mines. States with little strip mining had declining average seam sizes. In contrast, the decline in quality of new strip mines after 1946 was quite rapid. This decline is measured by the change in the overburden-to-seam-thickness ratio (Table 4.4).

Bituminous coal deterioration is probably best measured by taking together the average change in underground seam thickness and the marginal change in new strip mine overburden-to-seam-thickness ratio. Between 1920 and 1950 the underground seam thickness of established mines in West Virginia, Kentucky, and Virginia (states with little strip mining) fell from around 5 feet to 4.8 feet. The decline in new mine seam thickness during this time was probably slightly more rapid. After 1946 there was rapid quality depletion of the strip mine coal resource but little apparent change in underground coal seams (see Table 4.2). The overburden-to-seam-thickness ratio of new strip mines in the midwest districts (Illinois, Indiana, and western Kentucky) is estimated to have risen from an average of 9.8 to 13.7.
## Table 4.4

Average Overburden-to-Seam-Thickness Ratio of Open Pit Coal Mines^a^

<table>
<thead>
<tr>
<th>State, Region</th>
<th>1946</th>
<th>1950</th>
<th>1977^b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinois (1)</td>
<td>9.6</td>
<td>9.4</td>
<td>16.25</td>
</tr>
<tr>
<td>(46)</td>
<td></td>
<td>(81)</td>
<td></td>
</tr>
<tr>
<td>Indiana (4)</td>
<td>8.9</td>
<td>9.1</td>
<td>13.25</td>
</tr>
<tr>
<td>(50)</td>
<td></td>
<td>(44)</td>
<td></td>
</tr>
<tr>
<td>Kentucky, western (3)</td>
<td>4.9</td>
<td>7.34</td>
<td>13.36</td>
</tr>
<tr>
<td>(32)</td>
<td></td>
<td>(64)</td>
<td></td>
</tr>
<tr>
<td>Kentucky, eastern (2)</td>
<td>7.7</td>
<td>6.9</td>
<td>23.1</td>
</tr>
<tr>
<td>(24)</td>
<td></td>
<td>(72)</td>
<td></td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>6.2</td>
<td>9.0</td>
<td>...</td>
</tr>
<tr>
<td>(640)</td>
<td></td>
<td>(726)</td>
<td></td>
</tr>
<tr>
<td>Ohio (1)</td>
<td>7.0</td>
<td>9.7</td>
<td>15.0</td>
</tr>
<tr>
<td>(197)</td>
<td></td>
<td>(303)</td>
<td></td>
</tr>
<tr>
<td>West Virginia</td>
<td>5.1</td>
<td>7.0</td>
<td>...</td>
</tr>
<tr>
<td>(186)</td>
<td></td>
<td>(244)</td>
<td></td>
</tr>
<tr>
<td>Virginia mines</td>
<td>3.6</td>
<td>8.2</td>
<td>No new</td>
</tr>
<tr>
<td>(15)</td>
<td></td>
<td>(19)</td>
<td></td>
</tr>
</tbody>
</table>


^a Number of mines in parentheses
^b New mines only
Oil Resource Depletion

Oil resource estimates in the United States vary greatly, depending upon the definition of resource. Broadly defined, more than 500 billion barrels of oil resources existed in the United States before oil drilling began in 1859. This estimate includes 300 billion barrels remaining in "depleted" oil fields (Dick and Wimpfen 1980) and another 30-40 billion barrels held in reserve at the end of 1977 (Root and Drew 1979). Less than one-fourth of the total, 118 billion barrels, had been consumed by that time. Some estimates suggest that relatively little oil remains in undiscovered fields in the contiguous 48 states, but there is controversy on this point (Hubbert 1972).

The physical deterioration of the oil resource over time was pronounced. The oil fields being discovered today are much smaller and deeper than the fields found earlier in the exploration progress. Between 1900 and 1945 an average of 200 barrels of oil were discovered for each foot of exploratory drilling. By 1955, the discovery rate had dipped to around 40 barrels per foot, where it remained quite steady (Hubbert 1969).

This two-step national trend combines exploratory data from many oil basins around the country. Detailed information for one large but fairly typical region, the Permian basin in west Texas, is revealing. Drilling in the Permian basin began in 1920 and at first the discovery rate
in the basin was high – more than 1,500 barrels per foot drilled before 1938. It dropped to 600 barrels between 1939 and 1946, and to 430 barrels between 1947 and 1950. By 1960, after 16,000 wells had been drilled, the discovery rate had fallen to 55, and by 1970 it was 30 (Root and Drew 1979). After 1955, the major oil basins in the United States had been largely explored and the national average fell rapidly.

The discovery rate in the United States was high initially because the first fields discovered were larger and closer to the surface than fields discovered later. The average oil field found between 1921 and 1938 in the Permian basin contained 121.2 million barrels of oil equivalent (BOE). The average field found in 1950 contained 23 million BOE and after 1960 only between 1.5 and 4.1 million BOE (Root and Drew 1979). The average depth of exploratory holes in the Permian basin increased from 4,000 to 7,500 feet during this same period. The later fields required less exploratory drilling because of increased knowledge of geology, and the number of exploratory holes drilled per field discovery fell from 18.2 to 6.6 between 1921 and 1975. Oil resource quality in other basins in the United States would exhibit similar trends.

Although U.S. coal resources are far from exhausted, the quality depletion of the higher grade, thicker, and more accessible coal seams is apparent. U.S. coal resources are
currently estimated at 3,200 billion tons (Averitt 1973). This remains after nearly two centuries of coal mining during which some 41 billion tons of bituminous and 5.4 billion tons of anthracite coal were extracted (U.S. Dept. of Commerce 1975). If discarded mine waste is included in the total, more than 95 billion tons have been extracted, or nearly 3 percent of the total coal resource. However, the total depletion of high grade bituminous and anthracite coal within 1,000 feet of the surface has probably approached 10 percent (U.S. Geological Survey 1980).

Copper Quality

Three indices of copper resource depletion have been traced: the fall in new mine ore grade, the decline in deposit tonnage, and the rise in the new mine strip ratio. The steady quality depletion of higher grade copper reserves is evidenced by the decrease in average mining grades from around 2-3 percent before 1900 to 0.55 percent in 1978. This was the result of two trends: The fall in ore grade of existing mines, and the lower-grade reserves in new mines. Grade at the margin is best measured by a decline in new mine grades. Seven new mines opening between 1910 and 1920 had an average ore grade of 2.1 percent copper. Sixteen new
mines opening between 1970 and 1980 had an average ore grade of .79 percent copper.¹⁷

Another significant trend was the falling copper mine reserve tonnage. The 7 major copper mines that opened between 1910 and 1920 each had an average reserve of 3,600,000 metric tons (MT) of contained copper. The 16 mines that opened after 1970 had, on average, only 1,000,000 MT of copper in reserves (Cox 1981). The depth of mines also has increased. The mine strip ratio measures the waste rock mined per unit of ore obtained in mining. Deeper deposits usually have higher strip ratios. The average strip ratio of open pit mines in 1915 was around 1.9 (Leong, Erdreich, and Burritt 1940) and for mines opened after 1950 was 3.1.¹⁸

**Mineral Depletion Cost Measurements**

The mineral depletion cost trend is a weighted average of the different ore quality indices described above, with weights taken from econometric extraction cost equations. The cost equations and coal, petroleum and copper depletion cost measurements are described in this section.

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¹⁷ Personal correspondence with Dennis Cox of the U.S. Geological Survey.

¹⁸ Information averaged from the U.S. Geological Survey and the Bureau of Mines copper mine data.
Anthracite Coal Costs

Anthracite coal depletion cost is evaluated as a function of changes in new mine seam thickness (ST) over time, as shown in Table 4.4. It is apparent in the table that underground anthracite seam thickness declined as production cumulated over time. It is also apparent that seam thickness declined most rapidly in the first few decades after 1890, when production was high, and declined less rapidly after 1920, as production tapered off.

The depletion cost of anthracite coal between 1940 and 1980 is measured with a cost equation developed for underground coal mines

$$AC = 2567 / [(ST)^{1.107}]$$

where AC is average mine cost and ST is average seam thickness of new mines (Zimmerman, 1981).

This measurement indicates that depletion cost increased by smaller and smaller increments each ten year period after 1880, supporting the earlier prediction of a concave cost path. The cost of mining increased $2.40 per ton between 1892 and 1902. The costs increased $2.20 between 1902 and 1912, $1.30 between 1912 and 1922 and only $.70 between 1922 and 1932.
Bituminous Coal Costs

The depletion cost of bituminous coal in the eastern coal fields can be measured with cost equations developed for open pit and underground mines (Zimmerman 1981):

Open Pit Mines

\[ AC = 0.67 \times (OR)^{1.63317} + 0.96 \]

Underground Mines

\[ AC = \frac{2567}{(ST)^{1.1071}}, \]

where OR is the overburden ratio, ST the seam thickness and AC the average cost of new mines.

These equations can be used along with estimates of changes of coal seam size and overburden-to-seam-thickness ratios to estimate trends in coal depletion costs.

The estimated cost of underground mining increased only slightly from 1920 to 1950—the average in the three states of West Virginia, Kentucky, and Virginia increases from $27.6 to $28.9 or $1.3 per ton. Since this estimate derives from average coal seam figures, it gives a low-bound estimate of depletion cost. The higher cost of strip mining coal fields after 1946 suggests that the coal depletion trend increased at the time. The estimated cost of 1978 fields is $20 per ton higher than the cost of mining 1946 fields. Since this change represents only strip mine depletion, it gives a high-bound estimate of depletion cost. The initial cost advantage enjoyed by strip mine owners
seems to have ended and the trend is back to underground mining (Benson and Doyle 1978).

Oil Costs

The cost of oil depletion between 1936 and 1974 is calculated using a cost model developed to estimate the cost of new oil production in the Permian basin (U.S.G.S. 1980). This model includes a series of tables and diagrams used to determine exploration, development, and operating costs of oil and gas fields as a function of field size and depth. The production costs of average fields found in the Permian basin in 1936 and 1974 are shown in Table 4.5.

The largest percentage increase in costs occurs in the exploration phase of oil production, largely because the size of new fields has decreased. However, exploration costs amount to only 36 percent of total costs. The largest absolute increase in production cost is for field development, which adds $3.27 a barrel to total cost. Oil costs increase $4.14 a barrel over the 30 year period (or about 4 percent a year) due to resource depletion.
Table 4.5
Cost Per Barrel of Oil in the Permian Basin
(1977 dollars)\(^a\)

<table>
<thead>
<tr>
<th></th>
<th>1936-1946</th>
<th>1946-1970</th>
<th>30 year Average oil cost</th>
<th>Annual increase</th>
<th>Costs ($1977)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exploration Cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average cost per barrel</td>
<td>$.12</td>
<td>$1.65</td>
<td>9.2%</td>
<td>.05</td>
<td></td>
</tr>
<tr>
<td>Break even cost per barrel</td>
<td>$.19c</td>
<td>$2.19d</td>
<td>8.7%</td>
<td>.06</td>
<td></td>
</tr>
<tr>
<td><strong>Exploration Plus Development Cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average cost per barrel</td>
<td>$.82</td>
<td>$4.10</td>
<td>5.5%</td>
<td>.11</td>
<td></td>
</tr>
<tr>
<td>Break even cost per barrel</td>
<td>$1.24c</td>
<td>$5.46d</td>
<td>5.1%</td>
<td>.14</td>
<td></td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average cost per barrel</td>
<td>$1.24</td>
<td>$4.51</td>
<td>4.4%</td>
<td>.11</td>
<td></td>
</tr>
<tr>
<td>Break even cost per barrel</td>
<td>$1.87c</td>
<td>$6.01d</td>
<td>4.0%</td>
<td>.14</td>
<td></td>
</tr>
</tbody>
</table>


\(^a\) Field extraction costs were estimated only for oil pools with an average gas content for the size and depth of the pool.

\(^b\) Production discounted at 10 percent rate.

\(^c\) Assumes 20 years taken to deplete field at exponential rate of decline.

\(^d\) Assumes 12 years taken to deplete field at exponential rate of decline.

\(^e\) Includes production and administrative costs.
This estimate is consistent with a similar estimate by Norgaard who concluded that changes in oil resource deposit quality in the United States between 1939 and 1968 increased petroleum development costs at an annual rate of 4.1 percent (Norgaard 1971). The author of that study did not find significant differences in between period rates of depletion cost.

Copper Costs

Copper depletion costs are measured with the following capital and operation cost equations developed in Chapter 3:

Mine and Mill
Capital Cost = 0.885 + 0.258 (strip ratio/grade) + 0.623 x 10^{-8} (mine capacity)

Mine and Mill
Operating Cost = 0.181 + 0.165 (1/grade) + 0.0427 (strip ratio) - 0.0984 (mine capacity)

The equations are used to estimate the capital and operating extraction costs of copper deposits developed in 1910 and 1980. Several assumptions are made to simplify the calculations (i.e., mine life is fixed at 25 years and copper recovery at 100 percent), and transport and refining costs of $0.26 are added to operating costs. These assumptions and cost equations then are used to estimate the trend in average copper costs for new mines.
Between 1910 and 1980 copper extraction costs increased an estimated $.23 per pound of copper ($0.66 to $0.89 per pound in 1978 dollars) because of quality depletion. The trend implies that the owner of a typical 1910 deposit would have gained an annual cost advantage of 0.4 cents per pound of copper or 0.6 percent relative to other producers simply by holding the deposit in reserve for development in 1980.

The rate of copper depletion between 1915 to 1975 does not appear to have deviated greatly between periods. This conclusion is based on estimates of depletion cost rates between 1915 and 1925, 1925 and 1950 and 1951 and 1975.

Summary

The trends in the depletion cost of U.S. copper, oil, and coal markets are summarized in Table 4.6. In the table, the rate of increase in anthracite depletion cost is measured, assuming logarithmic and, for purposes of comparison, exponential cost paths. The bituminous, petroleum and copper cost trends are measured, assuming both exponential and linear cost paths. It is apparent in the table that petroleum and pre-1911 anthracite were depleted more rapidly than copper and pre-1950 bituminous coal, and anthracite coal after 1912. In addition, anthracite coal resource depletion suggests that depletion cost followed a concave pattern between 1890 and 1940.
Table 4.6
Mineral Depletion Cost Trends

<table>
<thead>
<tr>
<th>Commodity (unit)</th>
<th>Years</th>
<th>Mineral Depletion Cost (Rate of Increase)</th>
<th>Exponential ($)</th>
<th>Logarithmic ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Exponential ($)</td>
<td>Logarithmic ($)</td>
</tr>
<tr>
<td>Anthracite Coal</td>
<td>1892-1901</td>
<td>$1.4 C(t) e^{1.4t}$</td>
<td>$.95/t</td>
<td>.95/t</td>
</tr>
<tr>
<td>(tons)</td>
<td>1902-1911</td>
<td>$1.1 C(t) e^{1.1t}$</td>
<td>.91/t</td>
<td>.91/t</td>
</tr>
<tr>
<td></td>
<td>1912-1921</td>
<td>$.6 C(t) e^{.6t}$</td>
<td>.54/t</td>
<td>.54/t</td>
</tr>
<tr>
<td></td>
<td>1922-1931</td>
<td>$.4 C(t) e^{.4t}$</td>
<td>.47/t</td>
<td>.47/t</td>
</tr>
<tr>
<td>Bituminous Coal</td>
<td>1920-1950</td>
<td>$.09 C(t) e^{.09t}$</td>
<td>.09</td>
<td>.09</td>
</tr>
<tr>
<td>(tons)</td>
<td>1946-1980</td>
<td>$.09 C(t) e^{.09t}$</td>
<td>$.63</td>
<td>$.63</td>
</tr>
<tr>
<td>Petroleum (brl)</td>
<td>1941-1975</td>
<td>$.4 C(t) e^{.4t}$</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Copper (lbs)</td>
<td>1915-1975</td>
<td>$.6 C(t) e^{.6t}$</td>
<td>.004</td>
<td>.004</td>
</tr>
</tbody>
</table>
Summary Comparison

The data in Tables 4.1 and 4.6, suggests a reasonably close correlation between predicted and measured rates of cost increase for all minerals and all assumed cost paths. For example, petroleum and early period anthracite costs are predicted to increase over twice as fast as copper, pre-1950 bituminous and later period anthracite costs. Measurements of these costs, in Table 4.6, suggest that petroleum and early anthracite depletion progressed about twice as fast as copper, pre-1950 bituminous and later period anthracite depletion. This correlation supports the predicted relationship between rent and future depletion cost in equation (14).

The anthracite rent data in Table 4.1 are consistent with an hypothesis of a concave anthracite depletion cost path. This hypothesis is supported by the cost measurements in Table 4.6 which show declining cost increases in every period measured. Assuming a logarithmic cost path, anthracite rent data for 1900 are used to forecast a $4.49 increase in depletion costs between 1900 and 1930. This is almost exactly the increase measured in Table 4.6, following equation (14). (Estimates of cost increases, based upon anthracite data from the other years, are close to measured long run cost increases but overestimate short run cost increases.)
V EVALUATING FUTURE DEPLETION COST

The agreement between predicted and measured depletion cost in the past, supports the model and the use of rent data to forecast future extraction cost. Accordingly, rent data were gathered and depletion cost forecasts were made, and presented in Table 4.7.

Table 4.7
Recent Rent Data and Cost Projections

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Period</th>
<th>Rent</th>
<th>Cost Trend Predictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous</td>
<td>1970-80</td>
<td>10 - 5$^a$</td>
<td>.61-1.93</td>
</tr>
<tr>
<td>Copper</td>
<td>1970-80</td>
<td>0 - .8$^{bc}$</td>
<td>.03</td>
</tr>
<tr>
<td>Petroleum</td>
<td>1965</td>
<td>.22$^d$</td>
<td>(.50)</td>
</tr>
<tr>
<td>Petroleum</td>
<td>1980</td>
<td>.06$^d$</td>
<td>(1.00)</td>
</tr>
</tbody>
</table>

Sources:

- a Jessie Core, Retired Vice President of the Philadelphia and Reading Coal and Iron Company, personal communication. (West Virginia mines)
- b Beasley, Harris, and McFarlane, 1981, pp. 91, 97, 147
- c Slade, 1982
- d Livernois, 1988

Sample bituminous, copper and petroleum rent data were gathered from the literature and from phone interviews with mineral experts. The bituminous coal rent shows a small increases over 1930 and 1940 levels, indicating the higher prices received for energy minerals during the 1970’s and 1980’s. Nevertheless, bituminous depletion costs are projected to grow (exponentially) only between .5 - .9
percent per year. Although based upon a small sample of rent data, this projection is very similar to the cost increase estimated for coal in the highly regarded Zimmerman (1981) coal study.

U.S. copper rents, at the margin, appear to have fallen below historic levels in recent years, and at least one study suggests these rents may be close to zero (Slade 1982). However, copper costs are forecast to rise .4 percent per year, based upon this data.

Petroleum prices and rents have fluctuated greatly in the recent past and future cost projections are accordingly uncertain. In 1980, rent, in constant dollars, probably rose and rent as a percent of price, probably fell from pre-1973 levels. Projected annual cost increases based upon that data, are about .6% per year.

These projected cost trends are below rates measured at times in the past and do not give particular cause for policy concern. Indeed, technological change and input substitution prevented price increases in the past, despite higher rates of cost increase, and continued technological change and will likely curb cost increases for these minerals in the future. There appears to be no special justification for measures to decrease resource use of these minerals at this time.
VI CONCLUSION

An intriguing and central characteristic of natural resources is that their supply is initially ungoverned by man. As exhaustible resources are utilized and become scarce over time, extraction or utilization costs tend to rise. Apart from finding substitutes for the resource or new techniques of extraction, there is little that can be done to prevent this. However, of particular concern to the economist is that resources be used wisely and efficiently, in order to prevent resource costs from rising more rapidly than necessary.

Economic models of institutional choice and resource pricing, presented in this dissertation and elsewhere, raise the hope that institutional reform and rising resource rents will respond, in the face of scarcity, to limit and regulate resource use in an otherwise decentralized setting. For example, given sufficiently low monitoring transactions costs, rising costs may encourage institutional reform and a shift from common property to more carefully metered, private property like arrangements to govern resource use. Similarly, given sufficiently pervasive private markets, rising costs may be anticipated by resource rents, which raise prices and slow resource consumption.

These models help direct inquiry about resource use in an essentially empirical direction. Will transactions costs
check private market formation as scarcity increases? Are markets sufficiently widespread to generate resource rents and regulate resource cost increases? Convincing answers such questions await detailed empirical studies of particular resource industries.

Nevertheless, the evidence presented in this chapter provides a somewhat encouraging, but very incomplete and preliminary response. A model is formulated and a relationship between rents and extraction costs is derived, assuming efficient and complete markets. Rents, in this model, equal the present value of future increases in extraction costs caused by resource scarcity. Rent data, and extraction cost measures are presented which indicate that this relationship, between rents and extraction cost holds, in practice, for at least one set of mineral markets over a variety of assumed cost paths.

This evidence is consistent, on the one hand, with the efficient and complete market assumption of the model and supports, on the other hand, the use of rents as an indexing variable to predict future increases in cost. The efficient and complete market assumption is central to the model and it is encouraging to find evidence consistent with that assumption. This evidence at least maintains the possibility that private markets are pervasive enough, and transactions cost impediments small enough, to permit
efficient orderings of resource prices and restraints on
resource consumption.

Support for the use of rents as a variable to forecast
prices flows directly from the backcasting exercise. Since
rents anticipated cost increases in the past they may do so
in the future. The evidence in this chapter supports the
use of rents, most generally, as a scarcity index equal to
discounted future extraction cost increases caused by
scarcity. Given further assumptions about the cost path,
rents may also be used to project the specific rate and
timing of extraction cost increases. Preliminary rent data
and assumptions about the cost path suggest that mineral
costs are not likely to rise more rapidly in the future than
they have in the past.
The copper, oil, and anthracite coal prices used in Table 1 are from the "preferred series" in Trends in Natural Resource Commodities (Potter and Christy 1962). The bituminous coal prices are from the Minerals Yearbook (Bureau of Mines 1936-1980) published by the Bureau of Mines. The mineral rent data are from the following references:

Copper

Copper rent payments to the government were published by the Geological Survey in 1981 (Beasley, Harris, and McFarlane 1981, 91, 97, 147). Four copper properties on government and Indian lands paid royalties between 4 and 8 percent. One property on Indian lands in Arizona paid a competitively determined rent of around 8 percent of revenues. That property now includes two mines, each with reserves of around 1400 thousand MT copper and grades of about 0.71 percent. These reserves and grades are fairly close to the average for new mines. The other copper properties were smaller and paid rents of between 4 and 5 percent of revenues.

Oil

Pre-1940 oil land plus production rents were estimated by Bain for California (Bain 1945, 83). Figures published by McDonald and Magill indicate that land rents in the United States were around 12 to 13 percent of oil company revenues between 1951 and 1955 (McDonald 1963, 32; Magill 1981, 1979). In addition to land costs, oil companies typically pay production rents of 15 to 18 percent of revenue.

Anthracite Coal

Anthracite rents varied at any one time more than is typical for other minerals. Pains were taken to list the most representative or authoritative figures and, when possible, a range of figures. Rents varied for two principal reasons: (1) contracts were often long term and the royalty payments differed between old and new contracts, and (2) rapid resource depletion caused the mining of both higher and lower quality coal at the same time. Naturally, the higher quality coal commanded a higher royalty. The anthracite data sources are listed by year: 1870 Norris 1913, 355 1900 Roberts 1901, 55 1913 Norris 1913, 355 1923 Wing and Black 1925, 867 1939 Papst 1940, 50. Private correspondence with Edward Fox, and retired president of the Philadelphia and Reading Coal and Iron Company.
Bituminous Coal

Bituminous coal rents varied at any one time principally because transportation costs and initial contract dates differed between coal fields. The rents listed for West Virginia and Illinois illustrates the trends involved in the industry. Year States Source 1936 Illinois, West Virginia Fisher and James 1955, 372 and 1940 1900, West Virginia Private communication, 1940, Jessie Core, retired and vice president, Coal 1970-80 Mining Operations, U.S. Steel 1980 Illinois Private communication, Subash Bhagwat, Illinois state geologist
CHAPTER 5
CONCLUSION

One of man's oldest concerns is the impact of growing demand upon a fixed resource base. As demand for high quality resources grows, there tends to be a movement from more to less preferred resources, and this movement is defined as resource scarcity.

Resource scarcity impacts three policy variables - institutional choice, extraction cost and rent. The impact of scarcity on these variables may be forecast directly, given data about the quality of resource stocks and resource use models, or it may be inferred from trends in such scarcity measures as unit extraction cost and rent. In addition, resource use efficiency may be evaluated by comparing past resource use trends with predictions of optimal resource use models.

If resources may be divided into two groups - abundant (low cost, bulky) resources and scarce (high cost, manageable) resources, the impact of an increase in demand upon resource institutions and markets may be hypothesized as follows. Institutional practices for managing abundant resources will move toward more market-like arrangements and, for scarce resources, extraction costs will increase and rents will equal the present value of the increase, as if markets were perfect.
The different chapters of this dissertation cover subjects which tend to support this thesis. Chapter Two analyses the impact of resource scarcity upon institutional choice. Increasing demand for water in the semi-arid western U.S. is creating pressure for changes in the institutional practices which govern water use. One such practice is the choice of water sales technique by urban water districts in the Central Valley of California. Many districts in the Central Valley continue to sell water to customers on a flat rate or communal basis.

A model developed in Chapter Two can be used to predict the increase in volumetric sales resulting from an increase in the average cost of water supplies to a District. However, the analysis of the Chapter is focused upon the efficiency of local district choice of water sales technique. Paradoxically, the analysis concludes that shared water use is efficient, in many California districts, and State pressure to force a change toward a more market-like volumetric pricing may indicate political rent seeking.

Chapter Three is focused upon issues involved in estimating the cost of extraction from a mineral deposit. Costs are affected by two types of resource attributes — resource concentration or accessibility and deposit volume. Elementary engineering suggests why extraction costs are inversely related to concentration and accessibility. More
effort is required to obtain and refine dispersed or inaccessible resources.

Capital costs, per unit of production, tend to rise the smaller the volume of production. A model is developed in Chapter Three which incorporates the two effects of resource attributes upon extraction costs from a deposit with a fixed volume. In general discounting, planned extraction rate and mine capital cost are all important. Discounting increases a deposit owner's incentive to extract rapidly but the cost of mine capital, and the fixed deposit volume, makes rapid extraction expensive. The model simultaneously estimates the planned extraction rate and the extraction cost which maximize the mine owner's profits.

The model is used to estimate the planned extraction rate and cost which maximize the expected profits of several existing copper mines, using price and cost assumptions thought similar to those facing copper deposit owners in the past. The estimated rate of extraction compared closely with the rate chosen by past copper deposit owners. This comparison is consistent with the efficient resource use and perfect market assumptions in the model and supports the unifying hypothesis of the dissertation. The comparison also helps defend the forecasts of copper extraction costs and rates reported in the Chapter. This forecasts are based upon extensive U.S.G.S. data about known but un-mined copper deposits in the United States.
Information about resource stocks is often unavailable. In this case, future extraction costs may be inferred from scarcity measures such as rent data or past unit extraction cost trends. The model developed in Chapter Four indicates that rent equals the present value of expected future increases in extraction cost caused by a decline in the quality of remaining mineral resources. The model assumes perfect markets and efficient resource allocation.

Historical rent and resource quality data were collected and used to illustrate this relationship between rent and extraction costs in practice. A reasonably close comparison was found between historical rents and subsequent extraction costs in U.S. coal, copper and oil markets. This comparison, like that made in Chapter Three, is consistent with the efficient resource use and perfect market assumptions in the model and thus supports the dissertation’s unifying hypothesis. The comparison also helps justify the use of rent as a scarcity measure. Forecasts of future extraction costs are reported in Chapter Four, which have been extrapolated from current rent data.

It is apparent that the topics chosen for analysis in this dissertation each support a different facet of the unifying hypothesis. A low cost, bulky resource, like water in California, may be treated more like a standard market good as demand for the resource increases. Production of more expensive resources, such as copper and oil, is
largely, but not entirely, handled by standard markets. It appears that costs and rent movements of those resources may be modeled, in the main, as if resource markets were pervasive.

Nevertheless, the unifying hypothesis is more illustrated than carefully supported by the chapter analyses in this dissertation. Additional research topics would help clarify areas only touched upon here. Three such topics will be discussed.

Water metering is studied as a isolated case in Chapter Two and the transactions cost model used in that chapter could probably be generalized to cover a larger variety of institutional practices for handling bulk resources. Many of these practices are categorized, by water and electrical utilities, as demand management tools. These tools include various rate structures, informational campaigns and appliance restrictions. It would be interesting to determine whether such practices can be justified and explained on transactions cost grounds.

Only one of implications of deposit volume was covered in Chapter Three - the impact upon the cost and extraction rate of a single project. Over time, volume restrictions imply a sequencing decision is made to establish the order in which deposits are developed. Sequencing of deposits is one of the more important issues affecting the rate of increase in extraction cost and rent over time. Simple
models have been used to justify a least-cost-first decision rule for choosing deposits but more analysis should be done to determine how closely this rule reflects actual behavior (Dale 1990).

Finally, shocks in the energy and metal industries, occurring over the last two decades suggest modifications to the rent scarcity measure study in Chapter Four. Much of the historical analysis of copper, coal and oil markets in that chapter predated the major resource price and production shocks occurring after 1970. Since that time, resource prices have varied widely and production of many resources has been in the process of shifting to cheaper sources outside the United States. These changes suggest that mineral markets will be characterized by a state of transition for some time. Additional study of transition between equilibrium states in resource markets might improve our understanding of current mineral markets.
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