ARE ENERGY RESOURCES INEXHAUSTIBLE?

Presentation By

Thomas L. Neff
Massachusetts Institute of Technology

November 11, 1985

to

The 1985-86 Seminar
"Global Energy Prospects: Supply-Side Issues"

International Resources Programme
THE LONDON SCHOOL OF ECONOMICS AND POLITICAL SCIENCE

INTRODUCTION

I am honored to lead off this seminar series dealing with an important--as well as recurrently problematic and frequently paradoxical--topic: the prospects for global supply of energy resources. To begin this season's discussion, my charge is to answer a question that is both trivial and profound, both theoretical and practical: in what sense are energy resources exhaustible? The frequent answer to this question--whether in economic journals, in private investment decisions, or in public policy--is that energy resources are, in fact, exhaustible and that their exploitation is an inexorable downward progression with the heavy shadow of future scarcity cast backward onto life today.

This conviction is so rational and so pervasive that any sensible person would hesitate to question the common definition of the problem of energy resource exploitation. However, there are both theoretical and empirical reasons to do so. In my talk, I will first examine traditional approaches to the question of resource scarcity, focusing on the explicit or implicit assumptions underlying them. Following this, I will then look at how well these assumptions, and the resulting predictions, deal with our actual experience with energy resources. This discussion stresses examples from international uranium supply, because the issues here are particularly clearly drawn, and from oil and natural gas. In the final section, I will try to draw out the implications of the discussion for how we might better think about the exploitation of energy resources. My presentation draws on ongoing work at MIT and I am indebted to my colleagues, and especially to Prof. M. A. Adelman, for their contributions to thinking and rethinking natural resource issues and for collaborations over the years.

THE RESOURCE EXHAUSTION PARADIGM

The conviction that conventional resources are "exhaustible" in some important sense appears to rest on a series of believeable observations and eminently plausible assumptions. We first consider this as a physical question and then as an economic proposition.

The Physical Paradigm At the level of the mine, reservoir, field, or mineral play, it is evident that there will for each be a finite (but somewhat uncertain) amount of material that may ultimately be extracted. It is also evident that as extraction proceeds to greater depths, lower grades, or more difficult conditions for extraction, unit costs will rise. These observations also appear to remain true as one works outward to the set of known deposits that constitute demonstrated reserves. At any given time, reserves constitute an apparently fixed stock, whose depletion horizon is commonly only two or three decades away at current consumption levels. In the past, this "depletion" horizon has often been of concern to both industry and policy-makers and has, needlessly in most cases, driven many policy decisions.

Of course, experience has repeatedly demonstrated that the reserve horizon recedes in time, the result primarily of exploration and development investments that move material from the less-certain category of resources to the more-certain category of reserves. While at least some have become more sophisticated about this process, however, there remains a generalized--and even more seductive and enduring--conviction. This is that ultimate resources are themselves limited. The ontogeny of this idea seems modern, reflecting the closing in this century of historic geographic frontiers, the concern--peaking in the 1970s--about "limits to growth," and the impending depletion and increasing costs of particular historically important energy resource environments. If one adds to this idea the apparently rational assumption that the largest and highest grade natural resource deposits are being found first, the stage is well set for the global depletion paradigm. It is only a small, but perhaps mistaken, step from here to the conviction that we are running out.

In passing, let me raise--but not answer--two questions. The first is whether we can patch up the fixed stock notion for reserves to reflect the dynamic process of reserve additions, or whether some other intellectual construct might prove more satisfying, or at least less dangerous. The second concerns whether we really know where we are on the physical depletion path: are we finding and depleting the best first; are we in the last decades of oil, gas or uranium, or only in the first century of the millenium? A look at reality may at least suggest answers.

The Economic Paradigm Many of the physical assumptions, and questions, about the nature of the energy resource problem appear to carry over into the economic treatment of these resources. The economic study of non-renewable resources has a long and insightful history, beginning in the last century with the notable work of Jevons. But the modern theory stems largely from the seminal work of Harold Hotelling in 1931. With few exceptions, the economic problem definition has remained that stated by Hotelling: how optimally to allocate a fixed stock--seen globally or for an individual mineral asset owner--of a depletible resource over time. The basic intertemporal equilibrium solution, under competitive market conditions, requires that price (minus marginal cost, which Hotelling assumed constant) over the depletion period rise at the discount rate.

This is an intuitive result: if I can sell an increment of resource today for a price higher than the discounted present value of what I could sell it for in the future, then I should do so and invest in other assets that will give me that return on the larger amount; conversely, if I cannot sell at the calculated optimal price today, it is wise to sit on the increment until its market value appreciates. The result of this behavior should be the stabilized optimal exploitation path. In contrast to static equilibrium markets, prices in markets under the threat of scarcity should reflect a premium for that scarcity--what can be thought of as a "user cost," or scarcity rent, to be added to extraction cost, a measure of the opportunity cost of selling now rather than later, when scarcity will be more forcefully felt. Under these assumptions, there are two important conclusions: the first is that prices today will be higher than if resources were unlimited and higher than simple extraction costs would suggest; the second is that net prices should rise exponentially over time from this higher level. In our later confrontation with reality, we will ask whether either of these is true, and, if true, whether scarcity is responsible. To be certain of the answers, we must consider not only the economics of resources but the resourcefulness of economists in stretching the scarcity paradigm.

Hotelling himself, and a large number of subsequent contributors, elaborated and extended the basic idea that the shadow of resource exhaustion can be seen in price and production paths today. Some of these modifications deal with changes within the basic fixed stock idea: the effects of monopoly (to raise the initial prices but slow the rate of production); the consequences if extraction cost decreases over time due to technical advances or increases with extraction rate or cumulative extraction (as might occur, for example, when one goes gradually to lower and lower grades); effects of uncertainties in estimates of the size of the fixed stock or production costs; influences of resource or extraction severence taxes; shifts or uncertainties in demand; and other modifications.

The second class of questions about the basic depletion paradigm concerns behavioral and comparative utility issues. Does the discount rate for private holders of reserve assets match that for society generally--would private holders exploit too rapidly? How do decisions by one asset holder, or prospective holder, relate to those made by others? How do common property issues (e.g., public lands, pollution, or carbon dioxide buildup) enter? How might desires to diversify the risk of holding only one kind of asset alter the exploitation decisions of a natural resource holder? How do larger issues of economic growth or interfuel and interfactor substitution interact with depletion rates and prices? What about intergenerational equity?

The third group of efforts begins to test the actual boundaries of the fixed stock idea, though virtually all consider this more as a perturbation than as a fundamental revolution. For example, the existence of a high-priced backstop technology will change the boundary conditions on exploitation and alter the depletion path. Hotelling recognized that exploration will extend exploitation and a number of subsequent theoretical efforts have elaborated on this. Investment in exploration <u>will</u> add to reserves. However, if there are ever decreasing returns on such investment--the case if one assumes that the best grades are always found first, the basic depletion and scarcity picture is not changed in fundamental qualitative ways. Large investments today to add costly low grade reserves that would not be exploited for years are not justified, though the prospect of later increasing exploration and development investments <u>will</u> reshape the precise path traced out by prices and production over the entire period. But as long as declining grades and rising marginal costs characterize the underlying resource, as well as discovered reserves, the problem simply becomes one of more complex optimization on the allocation of scarcity.

These theoretical developments were motivated in part by practical issues and empirical experience associated with world resource supply, and there have been many theoretical successes. There remain, however, some nagging questions of the type that suggest that all may not be well with the fundamental paradigm. At a number of points in the history of science, basic theoretical structures have been strained by empirical observations that require ever greater, and telltale, efforts to accommodate them within the old framework. The result in such cases has often been a radically new paradigm or theoretical system transcending the old and of greater explanatory and predictive power. This has not usually meant the demise of the old theory but rather new appreciation of the simplified conditions or limitations under which it might give correct results.

Two kinds of troublesome problems confront us in the case of energy resource supply. The first set concerns whether the narrower resource exhaustion problem definition is correct even within restricted application to the real world. The second set concerns whether it is adequately complete. The problem of energy resource supply--the larger subject of this seminar series--involves central complexities of human activity: of laws, governments, institutions and behavior, as well as geology and basic economic phenomena. Both analytical and practical problems are complicated by this duality: those concerned about the adequacy of theory will have many "externalities" to blame; those functioning in the sphere of policy may have in the backs of their minds misleading ideas of the underlying resource problem. The only way I know to improve this situation is to work back and forth between empiricism and theory. It is to this that I now turn.

THE CONFRONTATION WITH EXPERIENCE

As we have discussed, the idea that energy resources are depletible and that this idea is relevant to, and reflected in our experience with these resources, is common, persuasive, and not surprising. What is surprising is that most of the empirical evidence is at best nonsupportive and more often contradictory. In the following, I will look at the evidence in the case of uranium and the nature of the errors repeatedly made in interpreting it. While it might be argued that uranium is somewhat special, this does not appear to be the case, as comparisons drawn from other minerals will show.

We first look at the natural resource perspective as it has developed over time. We then look at the evolution of prices. Finally, we consider how markets, in their several dimensions, have dealt with uranium and other energy commodities.

Resource Perspectives For many years, uranium was considered a geologically scarce resource. Because of its strategic importance, first for nuclear weapons programs and then for an expected exponential growth of commercial nuclear power plants (for which uranium is but a small cost component), massive efforts were made to identify and develop uranium reserves. There was considerable success in this effort: discoveries were made in sandstone and quartz-pebble conglomerate deposits in the U.S., South Africa, Niger, Australia, and Eastern Canada, and later in disseminated desposits in igneous and metamorphic rocks in Namibia, Brazil and the Bancroft area of Ontario. However, ore concentrations were low--below about 0.3 percent uranium oxide, less than a thousand times average crustal abundance. Moreover, extraction looked increasingly costly, with declining grades, smaller deposit sizes, and increasing depths seen as unavoidable facts of future life. By the early 1970s, international estimates of "reasonably assured reserves and resources" provided barely 30 years forward coverage for expected nuclear power demand.

This evidence clearly fit the depletion paradigm and the seduction of most geologists, economists, and policy makers easily followed. The professional literature less than a decade ago is full of articles and analyses demonstrating the inevitable. In the policy sphere, nations committed to multi-billion dollar research and development programs aimed first at extending the use of uranium through plutonium reprocessing and recycle and then, by the 1990s at the latest, breeder reactors. The latter were to free us finally from nature's parsimony.

As it turned out, however, we were not so much captive of nature's limits as of our own in thinking about uranium reserves and resources. We made several mistakes. The first was to believe that the proven reserve horizon reflected more than human unwillingness to invest money in exploration to find material that would not be used for more than thirty years. As we saw earlier, this error in economic logic might be corrected, in theory, by allowing for an investment-induced flow of material from unknown resources to known reserves. However, it would have been difficult to convince many economists that this did much more than drag out the exhaustion process. It turned out to be even more difficult to induce policy makers to take seriously energy materials that could not be proven to exist. This is still difficult.

The second error was even more of a surprise. Despite intensive exploration, all of the deposits of uranium discovered prior to the 1970s were either small or low in grade or, in the case of most U.S. sandstone deposits, both. But, beginning in 1969, a series of discoveries made almost simultaneously in northern Saskatchewan and the Northern Territory of Australia gradually revealed the richness of what were characterized as "unconformity-related" deposits. Ten to one hundred times richer in grade than previous discoveries, some of these deposits were also an order of magnitude larger. Discoveries in other environments also stretched resource horizons in other directions. The most significant of these was found in 1977 at Roxby Downs Station in South Australia. While uranium is present only at a concentration of about 0.07 percent, there is more than a million tonnes of it, coproducible with copper, gold and other minerals. This deposit alone is equal to the world total of reasonably assured reserves and resources assessed only seven years earlier.

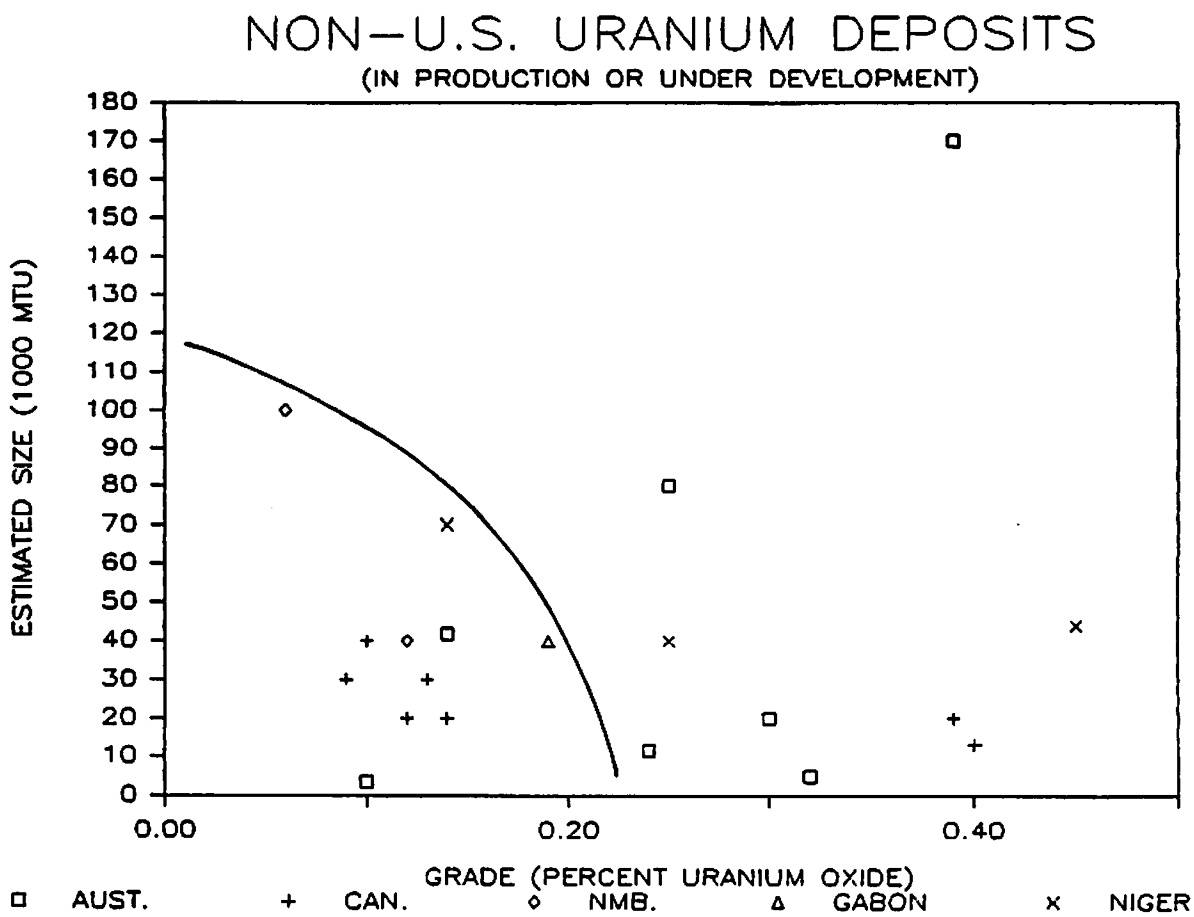
This expansion of resource horizons is shown, in part, in the scatter plot of Chart 1. Each point represents a discovered deposit, positioned according to ore grade and size--rough proxies for cost. Deposits in the U.S., the best-known uranium environment, and the older deposits outside the U.S., virtually all lie in the lower left corner of this diagram. The contour line indicates the progression of knowledge over time: the boundaries have been pushed outward, sometimes with revolutionary speed. In fact, Chart 1 understates this expansion: it would have to be ten times as wide to accomodate new discoveries in Canada and five times as high to include Roxby Downs!

For uranium, at least, the notion that the best is found and used first and that exploitation is an inevitable progression from bad to worse, seems untrue. The depletion paradigm may adequately describe individual mines or well-defined territories or even environments (such as U.S. sandstones). But the leap to global generalization--from what we may know perhaps too well to the unknown and unknowable--seems dangerous indeed.

Of course, one might argue that uranium is unique and immature among energy resources. A particularly seductive explanation is that we may just be in the early stages of its exploitation, that reserves should increase and prices fall for awhile before we begin to encounter the inevitable countervailing pressures of depletion. Of course this is ultimately true--the earth is finite. But how do we know where we are in this progression? Everyone thought they knew and they were wrong.

What mechanisms lie behind the "irrational" progression of discovery? There appear to be several. But in part the problem seems to

Chart 1


NON—U.S. URANIUM DEPOSITS
(IN PRODUCTION OR UNDER DEVELOPMENT)
ESTIMATED SIZE (1000 MTU)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0.00
0.20
0.40
GRADE (PERCENT URANIUM OXIDE)
AUST.
CAN.
NMB.
GABON
NIGER

be success. Success in particular environments seems to blind exploration elsewhere. Discoveries, and massive investments, in eastern Canada may have contributed to failure to find much richer deposits in the west. Intense focus on sandstones in the U.S. may have limited geologic vision not just in the U.S. but worldwide. The history of exploration investment appears to bear this out. Well over half of all investment has been in the U.S., about twelve percent each in Canada and France, and much smaller investments elsewhere. As we will discuss later, there are other reasons, but, whatever they are, investment patterns appear to have little relationship to underlying resource potential or to discoveries.

Have we done better with other energy resources? We may think we have, but the evidence is far from compelling. Exploration investment patterns for oil and gas are similar to those for uranium; we have been looking predominantly and expensively in our own backyards. And we have been developing extremely expensive production capacity when we know or suspect that there are much less costly deposits. Kuwait, looking for natural gas for domestic use, stumbled across a wholly new oil field with reserves that appear greater than the North Sea and the Alaska North Slope put together. New discoveries in the Middle East, in the Llanos of Colombia, and elsewhere continue to suggest that the world supply curve leaps about erratically. Our understanding of natural gas derives largely from oil exploration, rather than from confident systematic assessment, and is subject to the same observations about geographic priorities as oil.

Prices If uranium, or other energy resources, could be considered as truly scarce, one would expect to see some evidence of long-term upward price trends reflecting that scarcity. Several studies in the last decades looked at a century of mineral price evidence and found no such upward drift. This set off a great discussion. There are, of course, many reasons why prices might not directly reflect scarcity. Theoretically, it is not price but rent that measures scarcity, and rent is pretty hard to observe. Practically, one might argue that oligopoly kept prices higher in early years of the price series while technical advances reduced extraction costs, and therefore prices, in later years, leading to a leveling of what might otherwise be a long-run upward trend. This is all plausible. However, one may be bothered about two things. The first is a general discomfort when one cannot find a nonrenewable resource commodity whose price has moved consistently upward (perversely, some renewable resource prices have risen). The second is that recurrent question about the explanatory value of a depletible resource paradigm that requires constant correction or appeal to extenuating circumstances.

For a while, it appeared that energy commodities might be the exceptions that proved the rule. Oil, gas, and uranium prices all went spectacularly up in the 1970s. Chart 2 shows the behavior of real uranium prices (corrected for inflation) since 1950. Prices surged to historic highs in the mid to late 1970s. However, prior to this time they had fallen by a factor of three--with the low reached in early 1973--and since the boom they have again fallen to the lowest level on

CHART 2

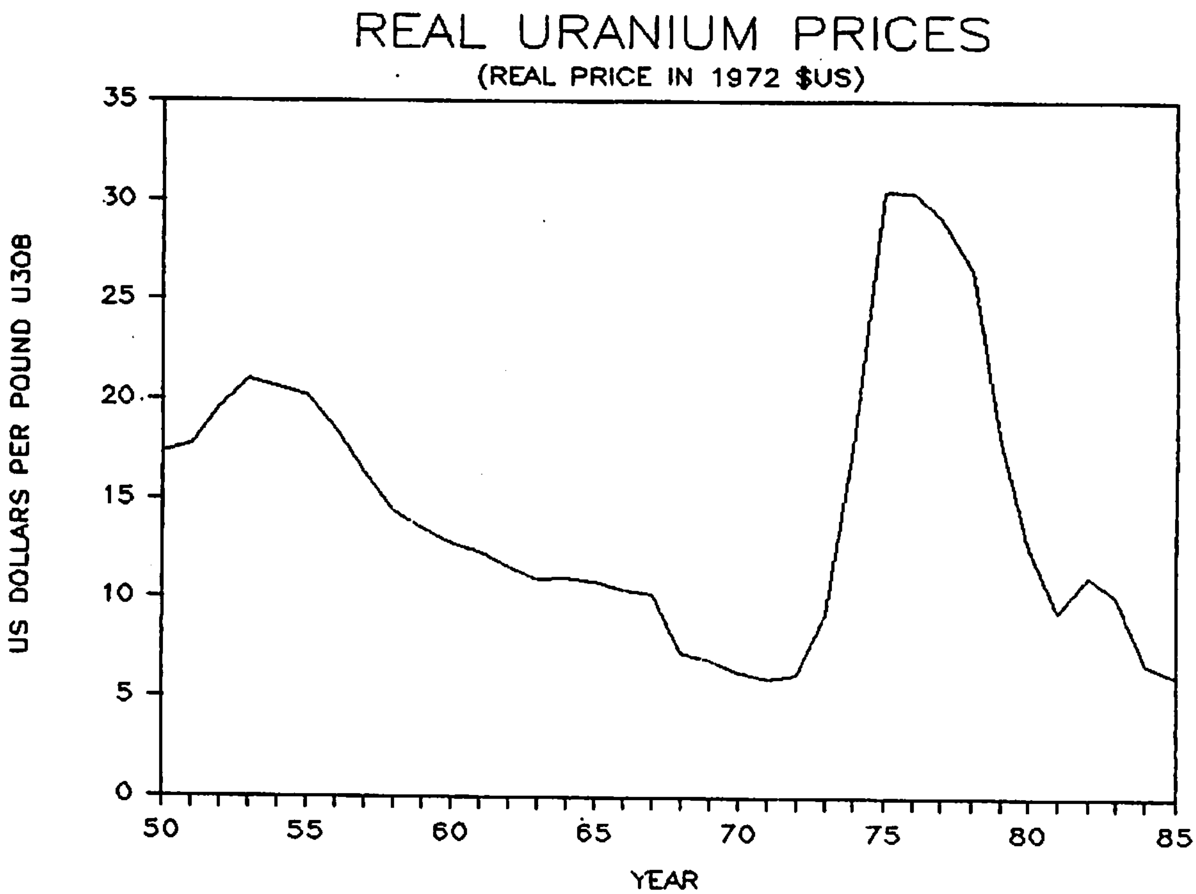
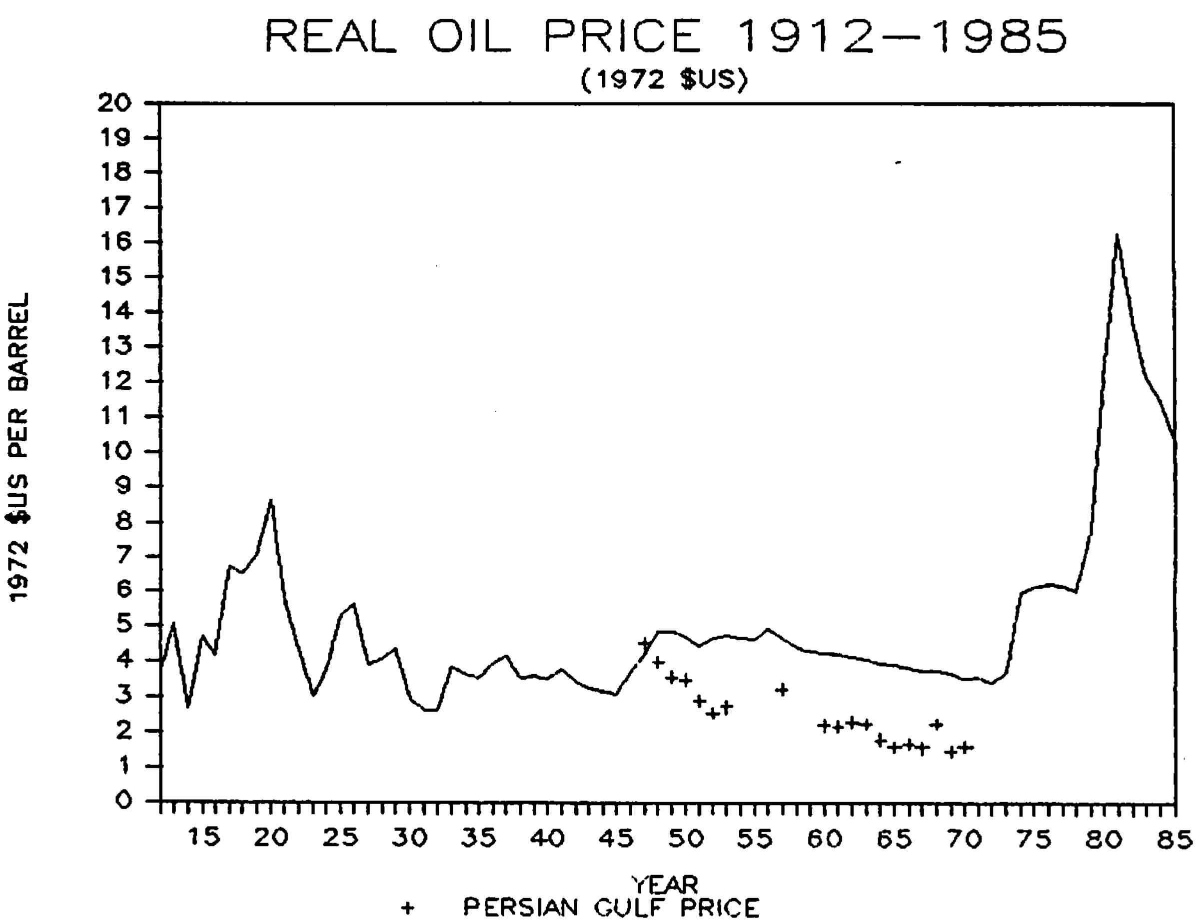

REAL URANIUM PRICES
(REAL PRICE IN 1972 $US)
US DOLLARS PER POUND U308
35
30
25
20
15
10
5
0
50
55
60
65
70
75
80
85
YEAR

CHART 3


REAL OIL PRICE 1912—1985
(1972 $US)
1972 $US PER BARREL
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
YEAR
+ PERSIAN GULF PRICE

record. In any explanation of this price history the shadow of exhaustion would be difficult to see.

It is interesting to compare the uranium price series with the similar, but more extended history for posted real oil prices in the U.S. Chart 3 is an updated version of the data M.A. Adelman showed here last Spring. Again there is an evident price slide until the early 1970s, one that would be more pronounced if one looked at posted Persian Gulf prices (shown) in the era of U.S. price controls. Then there were the price explosions. Since the peak in 1980, real prices have retreated; how much more they may do so is one of the larger questions of the day. The recent falloff, to historic lows, in uranium prices makes one wonder: is it possible that oil is only lagging uranium in its fall?

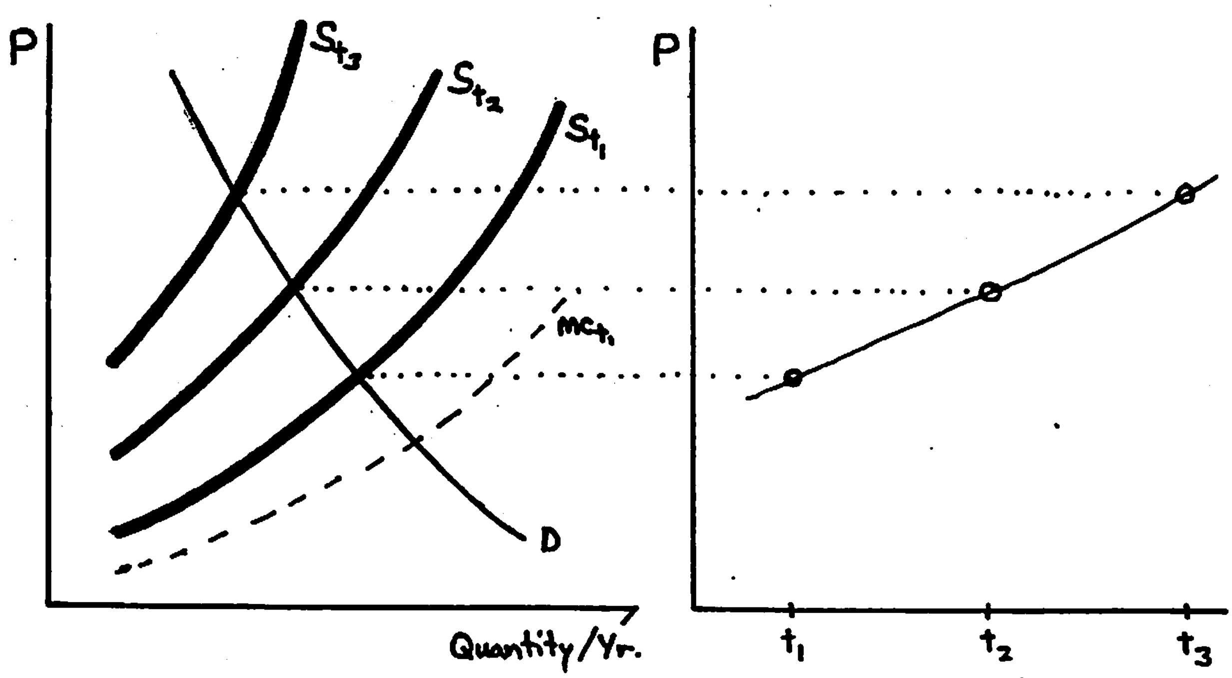
The evolution of prices is clearly more complicated than the simple exhaustion paradigm suggests. In the case of uranium, and more recently oil, unexpected changes in demand obviously play a role in altering expected price paths. But in the current context, the more important observation is that both short- and long-run supply curves are strongly affected by the resource and discovery perspectives we have sketched. They are also affected by geopolitical factors and by collective expectations. These facts have enormous, but often confused, implications for decisions made by energy firms, consumers, and by makers of public policy.

In the following brief discussion, I will try to untangle resource and geopolitical issues by looking--in quite simplified and I hope transparent ways--at short-run and long-run supply profiles. Short-run supply curves provide us with snapshots at given times of how much might be produced at various prices during a given period (say, a year). We will be interested in how the short-run supply picture changes over time, due to competing forces of depletion and discovery, and in the implications for prices. In order to look at the geopolitical issues--and at the massive uncertainties and risks present in energy resource exploitation--I will then look at long-run supply.

First consider the conventional scarcity view of the world. According to the fixed stock exhaustion idea, the short-run supply curve should, over time and as depletion occurs, move upward and leftward--as shown in Chart 4. The position of the curve today (at t_1) and its movement over time (to t_2 and t_3) would depend on the presumed scarcity rent: prices for a given quantity would in general be higher than the marginal cost of extraction at the given level of output (the dashed line). The supply curve receives contributions from a spectrum of deposits with a variety of different grades and average costs. Under competition, each deposit (or subdeposit) would be produced at an output level that matched marginal costs across deposits (we ignore, for the present purpose, complications that may occur, such as when the production rate of a deposit affects the amount ultimately recoverable). At later times, more of the fixed stock is used up and prices for any given output level will rise, moving the whole curve upward and leftward. The corresponding price profile is shown to the right in Chart 4. If the demand curve shifts up and outward over time (as a result, say, of economic growth), the price rise will be even steeper. This

CHART 4

EVOLUTION OF SHORT-RUN SUPPLY UNDER DEPLETION



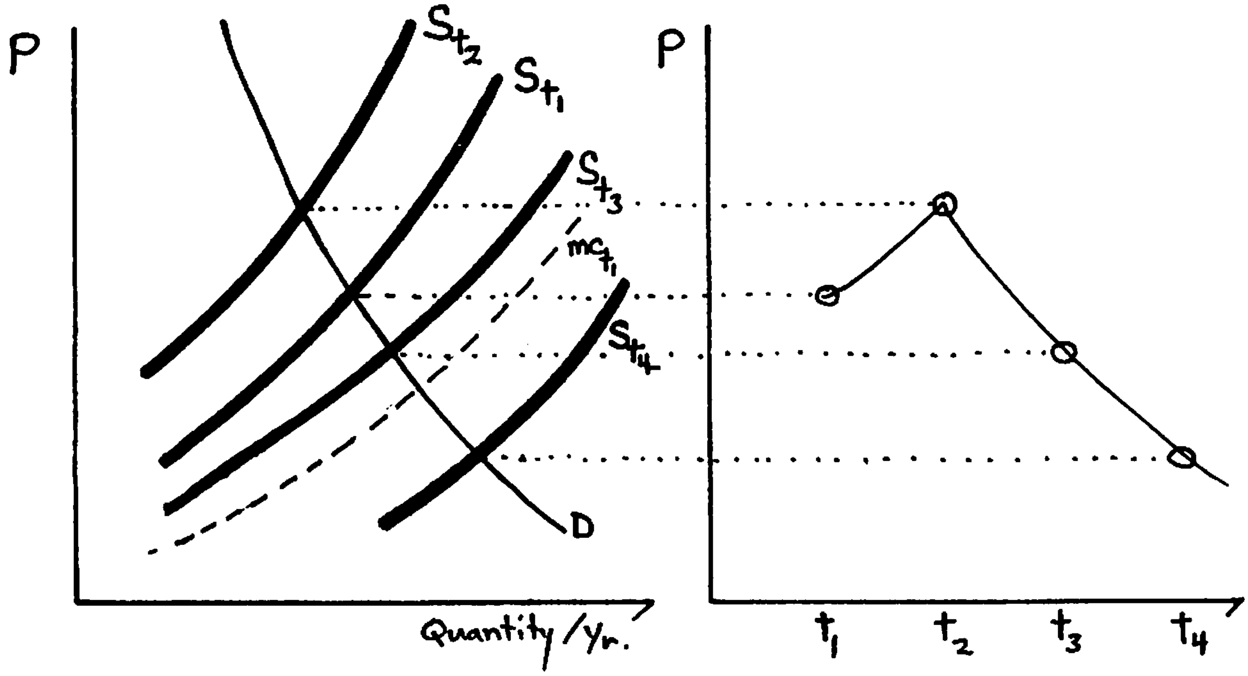
picture of prices has historically been quite seductive, and--as repeated surveys of future price expectations show--still resides in many minds.

But now consider what happens if new discoveries are made and developed in the future. If these discoveries have costs comparable to those already being developed or to be developed in the future, they will --at a minimum--slow the rise of the short-run supply curve. If such discoveries change perceptions of future scarcity, this may even reduce the scarcity rent that people are willing to pay, causing the supply curve to drop as time goes on. If discoveries are large enough, or have low enough costs, they may move future short-run supply curves strongly to the right. This is shown in Chart 5, along with the evolution of prices over time. As indicated, depletion of existing stocks may for a period move the supply curve upward and to the left, with prices rising; next, indications of new discoveries (or, equivalently, improvements in extraction technology) may alter expectations of depletion and erode rents, resulting in a drop in the supply curve and in prices; finally, additions to production from new reserves may shift the supply curve far to the right and prices down even more.

Uranium is perhaps the most dramatic example of how new discoveries can push supply curves to the right and prices down. There is another way this can happen; we will come to the Persian Gulf shortly. In general, the evolution of energy supply and prices over time depends on the unpredictable balancing of two countervailing forces: the depletion of known reserves versus increasing knowledge and the movement of previously unknown resources into the accessible reserve category.

CHART 5

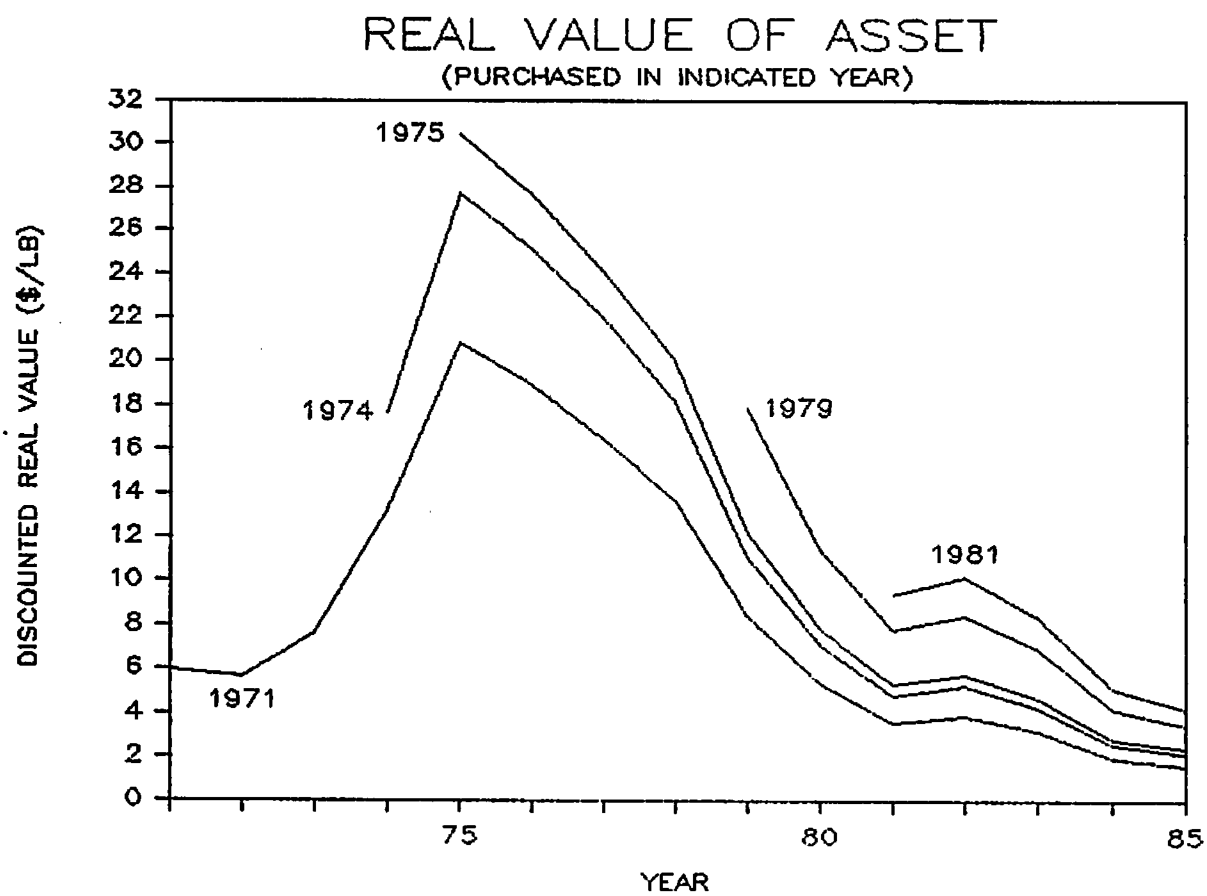
DISCOVERY VERSUS DEPLETION--A DYNAMIC PERSPECTIVE



This dynamic picture--which emphasizes increasing knowledge rather than looming exhaustion and a flow of material rather than a fixed stock--is helpful in understanding how the supply outlook and prices can change even under competitive conditions. It also has significant implications for energy resource industries and for public policy regarding these resources. If one believes in the exhaustion paradigm, there may well be circumstances under which delay in extraction can result in increases in the net discounted present value of one's holdings. This idea works in the same direction as the notion that energy reserves might best be held for the future, when they may be more valuable in non-economic as well as economic ways. What emerges from the dynamic picture, and I believe from the history of energy resource supply to date, is that the decision to defer involves potentially enormous downside risks.

This risk is quite demonstrable in the history of uranium. Consider a decision to buy or hold uranium or in-ground uranium assets at different points in the time series shown in Chart 2. Historically, very large purchases and investments were made during this time, especially in the mid-1970s when prices were high. In hindsight, however, virtually all such actions can be seen to have had negative net real present value when they were made, based on any reasonable discount rate. Chart 6 shows such a calculation for purchases in five particular years; it is assumed that purchase was made at the given year's price and that its value in future years was assessed at that year's real price, discounted

CHART 6


REAL VALUE OF ASSET
(PURCHASED IN INDICATED YEAR)
DISCOUNTED REAL VALUE ($/LB)
YEAR
1971
1974
1975
1979
1981
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
75
80
85

(at ten percent annually) back to the year of purchase. The discount rate, which could be changed without altering the main point, accounts for what one might expect from an investment of average riskiness; such an average investment would be represented by a horizontal line in Chart 6.

It was only if one bought uranium or reserves in the very early 1970s, and sold them before about 1979, that one could have made more than by simply putting the money in a portfolio of projects representing the general investment market. Those who bought earlier, or in 1975 or later, and those still sitting on their reserves, have seen the value of their holdings plummet. The same may be said of many oil and natural gas reserve holders.

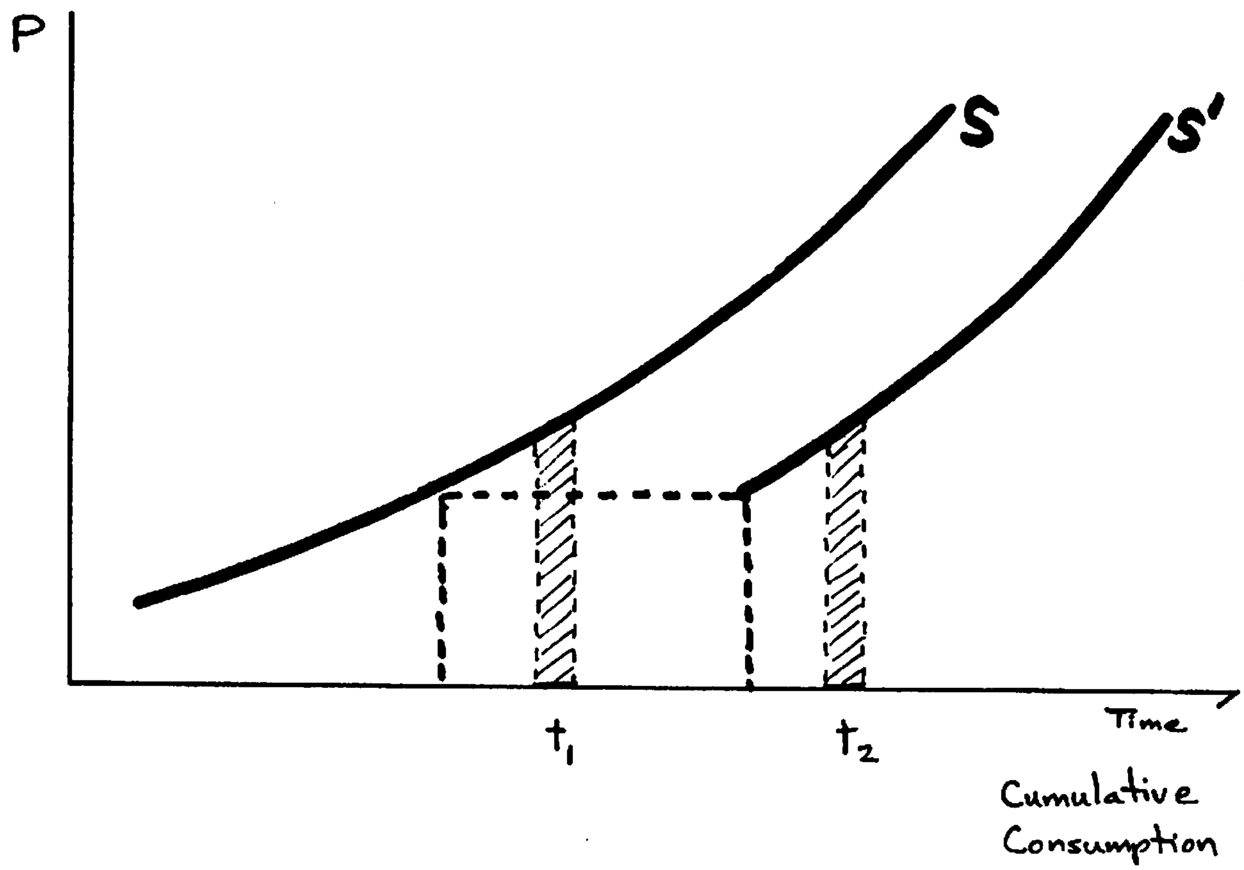
This process of reserve revaluation, generalized to a global scale, can be seen by looking at changes in long-run supply perspectives as they are affected by geological discovery or equivalently--as we shall argue--by geopolitical changes in access to resources and reserves. Let me start with a simple and familiar example. Suppose we inventory the stock of known reserves of uranium, or oil, and classify them in increments according to the prices that would cover the costs of bringing them forth. If we assume, rationally again, that the cheapest is exploited first, we can construct a long-run supply curve, plotting price against cumulative quantity consumed as in Chart 7. As time goes by, cumulative consumption increases, so the horizontal axis is also a time axis, with the scale set by demand and other conditions. (There are some subtleties in the price profile and arraying of reserves relating to time preferences and expections that we will ignore for now.)

Now consider what happens if a new block of low cost reserves is discovered, the case with uranium finds in Saskatchewan, for example. To a first approximation, the effect is to shift the higher cost component of the long run supply curve outward, further off in time and cumulative consumption. This can be quite disturbing to the owners of reserves underlying this component of the supply curve, since the prospective delay in their exploitation is equivalent to the forced economic depreciation of the reserve assets, a potentially severe reduction in their present value. In the U.S., for example, holders of high-cost reserves are seeking restrictions on imports of foreign uranium that would, in effect, help restore the value of their reserve assets. Similar stories can be told about the earlier imposition of U.S. oil import restrictions and actions taken elsewhere in the world regarding oil, natural gas and coal. Governments do act to preserve private asset values and associated jobs.

As I mentioned earlier, there are two ways in which supply curves can be shifted. One is through discovery. The other is through changes in the conditions of access to low-cost resources and reserves that we know (or strongly suspect) exist. Nature and geopolitics thus play the same game; both can isolate us from access to new and potentially low cost resources. Geopolitical shifts, as well as exploration and discovery, can bring new material into the energy supply picture. The

CHART 7

SHIFTS IN LONG-RUN SUPPLY



most obvious case of this is the Persian Gulf. While industrial nations are exploring, developing and producing from relatively high-cost environments elsewhere in the world, there are immense pools of low-cost material in a politically unstable region for which access has been limited by the OPEC nations, and by the dependency fears of consumers.

As with the possiblity of new low-cost discoveries, this is an intrinsically unstable situation. At any time, new increments of low-cost reserves may become more accessible, with the same effect on supply, prices, and reserve asset valuation as those uranium discoveries in Saskatchewan.

TOWARD A NEW PARADIGM

It is here that we come to a need to redefine the question posed in the title of my talk. In both theoretical and practical ways, the scarcity paradigm must be replaced by a supply paradigm. And that new paradigm must integrate two major and interactive elements: a more realistic view of the economics of energy resource exploitation and better understanding of the role of legal, institutional and geopolitical forces in shaping and reshaping supply. This is the subject of this year's entire seminar series and I shall not try to anticipate all of the issues. It may be useful, however to identify the key observations and questions pointing the way to a more satisfying, and perhaps more successful, perspective on energy and other non-renewable natural resources.

The first requirement is to find a replacement for the fixed stock notion as the operative framework for analysis: while any given deposit is finite, and while the earth is finite, neither of these ultimate facts provides an adequate basis for explaining supply; the world we must deal with is somewhere, unknowably or unpredictably, between these extremes. As we have seen, intellectual progress with the fixed stock idea has apparently gone as far as it can: while we have transcended the naive focus on fixed stocks of reserves (most of which have been depleted several times over in this century), we seem to have leapt too quickly to a more global, but still problematic, emphasis on the stock of resources. The common problems seems to arise from the focus on physical stocks rather than flows and from assumption of implicit certainty rather than explicit uncertainty.

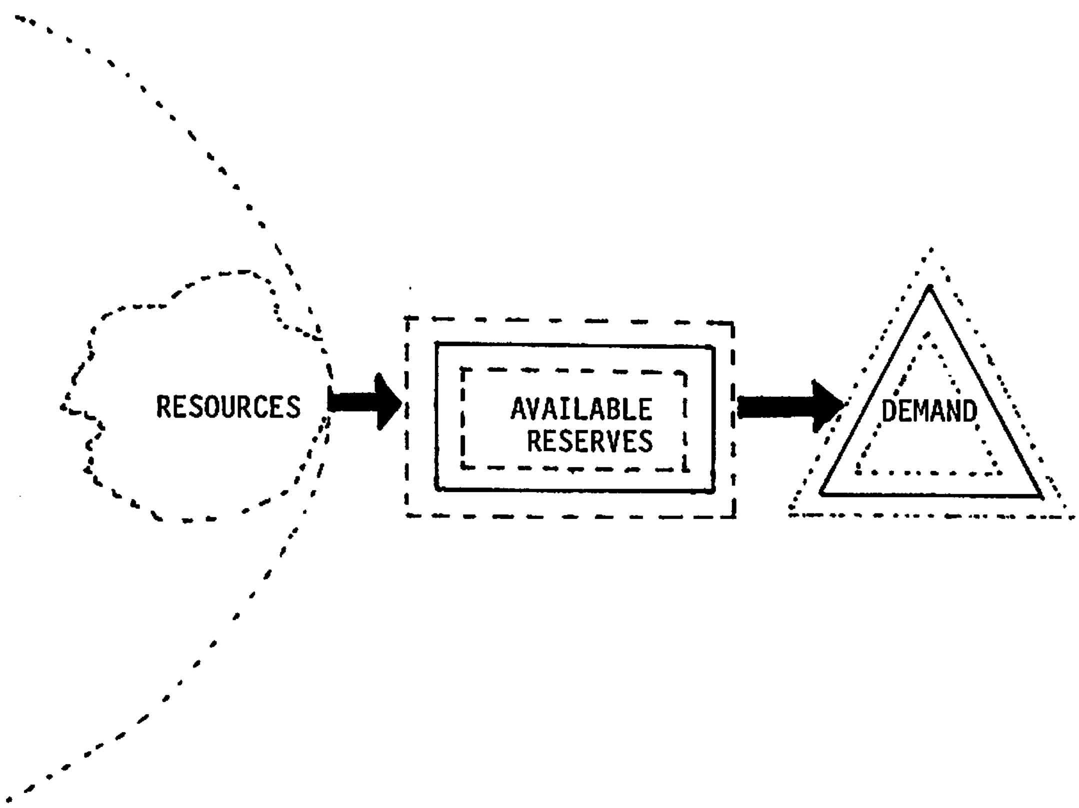
A new paradigm must deal not only provide a better characterization of resources and reserves but, even more importantly, provide insight into the flow from one to the other. In this flow, there are essential interdependencies between stages. For example, the counting of "available" reserves is, in part, an economic process involving prices and price expectations, and, in part, a question of actions taken by political actors; demand plays an important role in both and consequentially affects the size of available reserves. We thus have a systems problem with both important economic and policy dimensions, as well as stochastic elements and essential uncertainties.

An emphasis on systems and flows, rather than stocks, has attractions. It allows us to concentrate on measurable changes (rather than trying to infer, or assume, unknowable quantities); it encourages us to consider how shifts in economic and political forces may affect the flow from resources to consumption; it suggests ways to be explicit about uncertainties; and it allows us to explore interdependencies between processes usually studied independently. Such a system flow paradigm is shown in simple schematic form in Chart 8, where we are interested not just in the characterization of each of the component boxes but also in interdependencies and flows. Such a supply paradigm avoids the remoteness of the scarcity paradigm from what we are most interested in--our linked markets in energy commodities, reserve assets, and resource knowledge.

While adequate models based on this view of supply as flow are still to be developed, it is evident that they will have to deal with the fact that the flow from resources to consumption is fundamentally uncertain; to the extent that there may be equilibrium, it will be unstable. Uncertainty enters at all stages. As we have seen, we not only don't know where we are on whatever ultimate resource depletion curve there may be, but we are very likely sampling different pieces of such a curve at different times and in different places. Except in narrowly-defined regimes of time, technology, and geography, the function describing return on exploration investment--the flow from resources to reserves--seems more likely to be stochastic than smooth. If our

Chart 8

RESOURCES AND RESERVES--AN ALTERNATIVE PARADIGM



examples are any guide, it doesn't even fit within a predictable envelope of depletion.

This uncertain flow from resources to reserves is complicated by high variance in the perceived quantity of available reserves. Resource reserves consist of material that is known and available, given particular economic and policy conditions, and necessary investment. However, these conditions can change rapidly. If prices fall, material at the margins of existing deposits or entire deposits may disappear from reserve lists; if new discoveries prove cheaper, or if expected demand falls, the present value of higher cost material may drop below recovery cost; or if cartels collapse or wars end, access to large volumes of low-cost material may dramatically increase available reserves. Routine government policies toward exploration leasing, fiscal and tax regimes, efficiency standards, and other policies will also affect flows into and out of reserves. Thus, the net flow into and out of reserves is a function of a host of policy and geopolitical variables as well as geology. Not surprisingly, this flow is highly uncertain and can change rapidly.

The high variance in our revised picture of resource supply has profound implications for both private and public actors. For the private sector, the principal focus is on the present value of natural resource projects. From our preceding analysis, it is clear that it isn't just the process of discovery that is risky. Once found, energy resources are very risky assets. In stark contrast to the comfortable world of increasing scarcity, mineral assets can suffer radical changes in value due to processes over which the holder has little control. This calls for new approaches to project evaluation and planning, methods more adept than those offered by conventional payback analysis or even discounted present value techniques. New approaches, that better replicate the structure of risks, policy variables, and contingent claims on future returns, are needed. Conceptually, such approaches may be offered by generalization from modern finance theory, and especially from options theory. It is also calls for new project strategies, emphasising staged decision processes and flexibility. I imagine these would be good topics for the discussion period.

Governments too must be concerned about the variance and risk problem, though on a much broader policy front. The decisions range from what to do about mineral leasing to research and development policy, from domestic economic policy to Middle East policy. Virtually all nations have suffered from the rollercoaster of energy prices and changing asset values described earlier, and most have made major policy errors in anticipating and reacting to events. Indeed, a number of policy actions have contributed to the causes of disruptions. Governments too have been captive of the scarcity idea, the notion that energy prices had nowhere to go but up, and to the extent that they have had a strategy, it has been a sort of naive "prudence": ranging from restraint of energy resource development to costly alternative energy programs. Like the private sector, governments need to recognize the implications--the consequences but also the opportunities--of high variance in energy resource perspectives. They will also need the policy analogue of a strategic options approach to planning.