10th COMMONWEALTH MINING AND METALLURGICAL CONGRESS

OPENING CEREMONY AND PLENARY SESSIONS

Canada, 1974

CONTENTS

FOREWORD

As the world's largest multi-mineral producing nation, Canada was a fitting host to the Tenth Commonwealth Mining and Metallurgical Congress. The mining industry responded with an exceptional display of the current programs in the mines, mills and metallurgical plants throughout the country.

A forthcoming Proceedings volume will record the general aspects of the Congress and will contain details of the various tours. This publication which contains the opening ceremony and the plenary sessions is being prepared to make the timely and important information available without further delay.

The general chairman Dr. John Convey presided at the inaugural meeting. He gave the opening address, and introduced the various speakers. Official welcomes were extended from the Canadian Institute of Mining and Metallurgy by its president W. M. Gilchrist, the Canadian people by the Honourable Donald S. Macdonald, Minister of Energy, Mines and Resources, and the Commonwealth Council of Mining and Metallurgy by Sir Ronald Prain.

The technical chairman was V. A. Haw assisted by R. B. Toombs, Dr. W. G. Jeffery, and Dr. W. M. Tupper. They arranged a comprehensive program with speakers of international stature covering three areas of major concern in today's mineral industry.

On the topic of energy, M. King Hubbert discussed world resources; F. D. McFadzean spoke on international trade and price trends; and A. E. Pallister followed with the present and future energy picture. On the subject of mineral resources, Dr. Duncan R. Derry outlined world resource adequacy and W. Vogely spoke from the point of view of conservation, recycling and substitution. Marne Dubs, director of Kennecott Copper Corporation's Ocean Resources Department outlined the potential mineral supplies expected from the oceans. In relating to trends in mineral resources development, H. Ronald Fraser discussed the changing government-industry relationship, and the effect of foreign investment was explained by A. Broches. The session concluded with a presentation by I. S. Litvak and C. J. Maule on government participation in mineral exploration and development projects.

GENERAL CHAIRMAN'S WELCOME

BY JOHN CONVEY*

Ladies and gentlemen, as general chairman of the Tenth Commonwealth Mining and Metallurgical Congress it is indeed an honour and pleasure for me to welcome you officially to the opening plenary session of the Congress.

Today the minerals industry exists in a mixed-up world whose main characteristic is accelerated change, or one wherein the future becomes so rapidly the past. Associated with the changes of the modern age, there exists a formidable challenge for the minerals industry to produce the ever expanding needed minerals of fuels, metals and non-metallics. The rush of events which today's pace of change inspires prompts us to recognize and respect many of the awesome challenges that confront us. Anticipating and measuring change and determining what impact it may have on the minerals industry and the business activity it supports are tasks which command our attention and understanding.

An international meeting such as this conference with representatives from thirty-two countries provides us with the unique collective opportunity to compare and recognize problems of common interest to the minerals industry. Through discussion, we may delineate at least partial solutions to these many challenges. With this in mind your congress committee has planned this plenary session for the presentation by internationally known experts on the topics: World Energy Resources, World Mineral Supplies and National Trends in Mineral Resources Development.

Following the plenary session, you may then participate in the many tours and sessions which were planned to provide you with the opportunity of

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*General chairman, Tenth Commonwealth Mining and Metallurgical Congress and senior advisor, Mining and Metallurgy, Department of Energy, Mines and Resources visiting and examining a good sampling of the Canadian mineral industry. I sincerely hope that participation of the delegates, both your Canadian hosts and the visitors from many countries, will provide us all with a valuable and memorable experience.

It is now my pleasure to introduce to you the gentlemen whose ready support proved to be a primary factor in the development of the Tenth Commonwealth Mining and Metallurgical Congress.

Your host is the Canadian Institute of Mining and Metallurgy. Its members and respective branches provided the main stream of support for the Congress. The Institute is represented by its president W.M. Gilchrist, president of Eldorado Nuclear Ltd.

The Canadian people and the government of Canada are represented by the Hon. Donald Macdonald, minister of Energy, Mines and Resources.

The coordinating group behind the promotion of these Congresses is the Commonwealth Council of Mining and Metallurgy. Representing this council is the chairman, Sir Ronald H. Prain, O.B.E.

The next gentleman is your president of the Tenth Commonwealth Mining and Metallurgical Congress, Alfred Powis, president of Noranda Mines Limited. Should the Congress prove successful, he can accept the credit, but should it fail, then he is capable of taking the blame.

CANADIAN GOVERNMENT WELCOME

BY THE HONOURABLE DONALD S. MACDONALD

Welcome to Canada. As official representative of the Canadian Government, I want to say on behalf of Canadians how pleased we are to have this opportunity to host the Tenth Commonwealth Mining and Metallurgical Congress. Moreover, in my capacity as Minister of Energy, Mines and Resources, I am proud of the opportunity for this assemblage to hear about and see the considerable progress of the Canadian mineral industry, an industry that has placed Canada among the leading world mineral producing nations.

In the course of your sessions in our Capital and as you travel to other parts of this land, I hope that you will take advantage of your visit to become better acquainted with the human as well as the natural resources of our country. Canada is a big country, big enough to touch three oceans, the Atlantic, the Pacific and the Arctic. It stretches almost 4,000 miles from east to west and close to 3,000 miles from north to south. The country is naturally divided into five main regions, each possessing characteristic geological features.

Your trip across our country will show you a land of contrast with mountains, prairies, lakes, rivers, oceans, a cold north, Niagara Falls, red maple trees; a country where you will meet Canadians always happy to welcome you.

It is already 17 years since the Sixth Congress was held in this country. This intervening period has brought significant changes to the world's mineral economy. In Canada, as in most other countries, minerals are seen in terms of industrial development, advancing technology and capital

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*Minister of Energy, Mines and Resources, Ottawa movements. Minerals play an important role in international affairs. They are increasingly significant in the positions adopted by many countries in these times of resource diplomacy.

Many of the nations of the Commonwealth are important producers of minerals. We are meeting at a time of great changes in the world with respect to mineral affairs, and we are all aware that industrial development and the higher standards of living to which all peoples aspire, depend upon raw materials that we extract from the earth and process into usable products. It is hard to imagine today's society without adequate supplies of iron and steel, copper, lead, zinc, aluminum, cement, potash and sulphur as well as the essential mineral fuels that provide our energy requirements.

So the representatives gathered in this hall reflect a dynamic industry - an industry that is as old as the Stone Age, but which is now of utmost importance to the world. The future poses great challenges to the mineral industry because of the ever-increasing size, cost and complexity of projects. New technologies, processes and discoveries will be needed to create reserves from the earth's resources for both traditional and new materials.

While global resources are expected to be sufficient to meet the world's needs in this century, this by no means implies that we should be complacent about the adequacy of resources. Attention to the future is still required by resource managers. We must not forget that each mineral deposit is depleting and non-renewable; each mine eventually comes to an end and therefore the world must be concerned with the best use of its mineral resources.

We should also realize that actions taken by mineral countries have their effect on other parts of the world. In a sense, we are all reliant on the economic health of other nations in this interdependent world. Each country has an interest in ensuring that disruptions are not brought on by its own actions or by those of other resource producers. Each of us has a responsibility in this field.

The future growth of mineral needs will be a challenge to the world mineral industry. In this context, I cannot overstate the potential contribution of all those participating in this Congress.

What could this contribution be? Canada, as other nations, needs informed proposals on its national objectives and the role that resources can most effectively play in attaining them. We need sensitive perceptions on the future world environment within which we must exist. We need to stand back and look at ourselves and examine what we can achieve as opposed to our aspirations.

Each of you could well reflect on the subject of minerals in relation to your particular responsibilities, and then ask how your discipline and expertise can bear on solving mineral problems.

This is part of the message that, as Minister of Energy, Mines and Resources for Canada, I leave with you, wishing that in the course of your meetings there will be many occasions to reflect among yourselves on this challenge.

Once again, a sincere welcome to all of you, ladies and gentlemen, who are honouring us with your presence. Permit me also to add my congratulations to the organizers of this Congress for developing an interesting program that will present an overview of the Canadian mineral industry.

GREETINGS FROM THE CIM

BY W. H. GILCHRIST*

It is indeed a privilege as president of the Canadian Institute of Mining and Metallurgy your official host, to welcome to Canada the Tenth Commonwealth Mining Congress. From the point of view of numbers of delegates it is the best ever and we sincerely hope it will receive equal rating as to content and interest.

In a world in which national interests seem to be so frequently opposed and the resulting problems incapable of solution, the freemasonry of mining, which recognizes no national boundaries, is an invaluable source of comfort and encouragement.

The problems inherent in winning from the earth's crust those elements required for civilization's continued development have no respect for political barriers. However, your great interest in the expanding technology of mining and the potential of new frontiers contributes much to a sense of well-being and the feeling that we can and will break out of the gloom that seems to be so all-pervading at the moment.

It is good to have you in Canada and I sincerely hope that the memory of your visit will be as great a source of pleasure to you as it will be to us in the coming years.

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*President, Canadian Institute of Mining and Metallurgy, and president Eldorado Nuclear Ltd.

COMMONWEALTH COUNCIL JUBILEE ADDRESS

BY SIR RONALD L. PRAIN*

The main purpose of my remarks is to express the thanks of all delegates to this Congress to those who have made it possible. I would like on behalf of all delegates and of the Commonwealth Council to say thank you to the Canadian Institute of Mining and Metallurgy for hosting this Congress, to all those branches of Canadian industry who have supported the Congress so generously, to the Canadian Federal and Provincial Governments for their support and help, to the actual Organizing Committee under Dr. Convey, and to your president, Mr. Powis.

I know from experience that a Congress such as this requires three things: a will to make it a success, financial support, and talent on the part of the organizers. All three have been forthcoming in ample measure for this Congress, and those who are now about to enjoy it are deeply grateful and appreciative. Our appreciation starts right at the beautiful hall - no congress has opened in a more opulent or striking setting.

In addition to extending our thanks to all those I have mentioned, I would also like to extend the congratulations of the Commonwealth Council to those who have organized the massive program which has held out so many attractive options to all those who are attending from overseas. I am confident that this Tenth Congress will be a great success and will long be remembered by those who are privileged to attend.

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*O.B.E. president of the Commonwealth Council of Mining and Metallurgy

It is not my intention, nor indeed my brief, to use this opportunity for a review of the state of the Commonwealth mining and metallurgical industries. However, I think it is not without interest to review, however briefly, some of the changes which have occurred since the Ninth Congress was held in London in 1969. I refer to changes in world affairs which have a special bearing on the mining and metallurgical industries, not only in the Commonwealth but world-wide, and I have identified six main developments which I feel will inevitably engage some of the time of the discussion sessions and which, it seems to me, must be foremost in many of our informal discussions.

First, the last five years have seen a great growth in the spirit of nationalism, not only in the Commonwealth but on a world-wide basis, and not only in the developing countries. I am sure you all know what I mean by the broad term of nationalism. It includes not only the major question of local ownership versus foreign ownership, but also the narrower fields of taxation policy and increased interference by governments in the affairs of the extractive industries. I do not propose to develop this theme, to argue the merits or otherwise of the position adopted by governments, for these will undoubtedly be discussed by others. All I want to do is to identify this subject as one which must be foremost in our deliberations, unlike the situation at our last Congress.

Secondly, we are now in the middle of a world-wide debate on the question of future resources. This debate covers many resources, including food and water, but has a particular emphasis on the mineral resources and to what extent they are finite or otherwise. This, too, is a subject which seems particularly suitable for a Congress of this nature.

Thirdly, the mineral industries are confronted like all other industries by the growing instability of currencies, a world-wide problem, not, of course, peculiar to the mining industry. Far from it - as indeed this problem cuts at the very basis of our economic and social structures. It is naturally of very special relevance to our industry, which is essentially international and world-wide and where the problems of international investment are seen in their most complicated form.

Next, we have experienced since the last Congress the developments in the oil industry and the demonstration of collective producer power with its inevitable implications for similar possibilities in the field of non-fuel minerals.

Next, and arising from the last point, is the situation confronting the mineral and metal industries as a result of the increase in prices of fuel and the repercussions of the whole energy situation. This whole subject is complicated, involved and confusing, but one can say that its implications for the mining industry include questions of costs of production, costs of transportation, future availability of energy, and future demand for various raw materials. The implications include questions of the future costs of metals, and indeed the availability of metals.

Lastly, we have of course since the last Congress run into the problems which are grouped together under the general heading of the environment. The mining and metallurgical industries are particularly affected by the world-wide attention to this subject as evidenced for example by the United Nations conference held in Stockholm in 1972, and by the regulations, sanctions and disciplines which are being forced on industry.

These, then, are six developments which I have picked out as affecting the mining industry. There may be others which you may consider should be included in any inventory of this sort. The organizers of the Congress have arranged sessions which will provide opportunity for discussion on these matters and this alone, I believe, will ensure that this is an interesting and meaningful Congress.

I am speaking, of course, as chairman of the Commonwealth Council. Some of you may remember that at the Ninth Congress I gave a history of the Council and of its purposes and objectives. It has not been realized by everyone, I believe, that this year is the 50th anniversary of the birth of the Commonwealth Council. This Canadian Congress may rightly be termed the Jubilee Congress. The main purpose remains the organizing of these Commonwealth Congresses from time to time, and you may be expecting to hear what is proposed for the 11th Congress. I am not in a position to make a definite announcement on this matter, for we are talking of 1978, and in a fast-changing world it is not possible to make hard and fast arrangements so far in advance. However, I can say that the Council is studying the possibility of holding the 11th Congress in the Far East, and this would be in line with the hopes expressed at the Ninth Congress. The pursuit of such an objective creates more complicated problems than in previous Congresses, but the Council is pursuing its studies, and I cannot say more at the present time. It is possible, though I would not want the Council to be held to any special time-table, that we may be able to come to some definite decision by the end of 1974.

Finally, if I may end on a personal note, I have informed our Council that I wish to retire as chairman at the end of this year. I have reached the point of retirement from the industry, and I feel that the chairman of this Council must be someone who is active in the mining industry. I have held the position of chairman since 1961, when I succeeded the late Lord Bailleau, and I have been closely concerned with the organization of four Congresses. I want to thank the Council and its constituent members for the help and co-operation which has been forthcoming at all times and to say that it has been a great privilege to be allowed to preside over the affairs of the Council over this period of years.

I am glad to be able to say that the Council has invited as my successor, and he has accepted the invitation, Sir Val Duncan. There is no one better known in the Commonwealth or international mining world, and I think we are most fortunate that he is prepared to succeed me. He regrets that he cannot be here today, but on your behalf and that of the Commonwealth mining industry, it gives me much pleasure to welcome him to this office as from January, 1975.

Thank you.

CONGRESS PRESIDENTIAL ADDRESS

BY ALFRED POWIS*

It gives me great pleasure to welcome you to the Tenth Commonwealth Mining and Metallurgical Congress, and to Canada.

We were last honoured by this group in 1957 when the 6th Congress was held here in Canada; prior to that, Canadians hosted the 2nd in 1927. We are pleased to have as friends and visitors to our country such a highly trained and widely experienced group and we are particularly pleased to be meeting here on the 50th anniversary of the 1st Congress held in London in 1924.

These Congresses are held under the authority of the Commonwealth Council, and this one is at the invitation of the Canadian Institute of Mining and Metallurgy. The objectives of these Congresses are straightforward - to provide an opportunity for mining engineers, metallurgists, geologists, scientists and others concerned with the mineral resources and mineral industries of the British Commonwealth to meet and to communicate on matters of common interest. During this next month, we will be travelling together and building the understanding and personal contacts upon which good communication is based.

We begin with some common heritage as members of that loose amalgam of 32 countries, the Commonwealth. To some non-members, the Commonwealth may seem tenuous and transitory, being a family of member states that depends on functional co-operation rather than formal organization for its vitality.

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*President Tenth Commonwealth Mining and Metallurgical Congress, and president and chief executive officer, Noranda Mines Ltd.

This, in fact, was the finding of the Commonwealth heads of government when they met in Ottawa in August 1973. Our communication and co-operation at this Congress can make a significant contribution to greater international understanding, and materially aid in the finding of solutions to the problems relating to our industry.

Meetings such as this stress the value of strengthening practical co-operation among Commonwealth member countries and among the larger world community. There are 35 countries represented at this congress; a total of 720 delegates with 235 from Commonwealth countries and the remaining 485 representing non-Commonwealth countries. We are pleased to have so many guests from outside - Angola, Belgium, Chile, Colombia, Czeckoslovakia, France, Germany, Indonesia, Japan, Mexico, Norway, Rhodesia, South Africa, Surinam, Switzerland and the United States.

The nature of this Congress is not such that it lends itself to resolutions or ultimate solutions. Rather, our objective is to apply the knowledge in our field to the identification of those technical problems which, if left unattended, could develop into crises. Having communicated these observations and conclusions to each other, we can then return home and attempt to convey the message to our respective governments for their consideration and action.

Our work this next month is certainly cut out for us; although all the problems of our industry cannot be identified in that time, we can make progress together in our discussions and deliberations.

I will not summarize the Congress program as you will already have given it careful study prior to arrival, but I would like to refer briefly to its structure. You will have noted that the number of formal meetings has been kept to a minimum. This is the result of the Committee's decision to emphasize visits to mining operations, many of which are in remote areas and thus require some time spent travelling.

Formal meetings are restricted to three plenary sessions. In choosing the topics: "Energy resources", "World mineral supplies", and "National trends in mineral resource development"; the object was to deal with issues of a broad, vital and current interest to all those attending. The speakers on these subjects are highly qualified in their fields. From them, with your participation, we can increase our knowledge and understanding of these issues, to help forestall problems in the future. This material will provide a common basis for discussion during our travels.

The Canadian mining industry is proud of its achievements, its technology, and particularly its people. We are delighted to have this opportunity to show our operations and to introduce many of our people to so many highly-qualified friends from other countries. And on a personal note, I am pleased and honoured that in the various tours planned are included fifteen operations managed by members of the Noranda group of companies.

The growth of the Canadian mining industry since the Second World War has been remarkable, with the value of production today being about nine times greater than in 1945. In the 1960's alone, the value of production nearly tripled. As a result, unlike other primary sectors, direct employment in mining has been increasing at a rate close to that for the economy as a whole, and greater than for most other industries. The employment increase, however, has been less than the growth in production as the level of output per employee has been increasing rapidly and is now about three times that of our economy as a whole. This productivity increase has resulted in large measure from heavy capital expenditures which, in recent years, have reached close to 10% of the Canadian total.

While Canada's mineral endowment is extensive and diversified, it is not uniquely rich or large. Our share of world mine production is greater than our share of proven reserves or geological potential. The main reason for the rapid growth is that Canada has benefited from a substantial share of the world's exploration and development effort having occurred here. For example, during the 1960's it has been estimated that over 80% of the exploration effort in the non-Communist countries was concentrated in the relatively developed countries, with 70% in only four of them - Australia, Canada, South Africa and the U.S.

Canada has received a very favourable share of the world's exploration effort because of the existence of a strong industry and a hospitable political attitude toward mining. In turn, this has led to more rapid development of new discoveries than has been the case in many other parts of the world, where much higher rates of return have traditionally been required on new mine development. For example, a study by the U.S. Bureau of Mines indicates that average annual earnings on U.S. investments in mining in Canada returned less than 10% from 1954-67 compared with 25% in Latin America.

In any event, the Canadian industry has grown to the point where it is now the world's third largest producer of mine products, ranking after the United States and the U.S.S.R. Mining and related metallurgical operations account directly for over 4% of the Gross National Product, and due to its heavy expenditures for goods and services and its downstream activities, a further 8% of the GNP is dependent on the industry. For example, the industry accounts for about 40% of all freight traffic in Canada and is responsible for most of our production of sulphuric acid and phosphate fertilizers.

The industry directly employs about 250,000 people, some 3% of the labour force, but because of its linkages with other sectors of the economy it is thought to provide the basis for employment of a further 12% of the labour force. About 80% of our output is exported, providing about a quarter of Canada's total export earnings. Also of significance in the Canadian context is the fact that our mining industry is internationally competitive, without the need for subsidies or protection despite relatively high wage levels. It is one of the very few sectors of our economy where productivity exceeds that of the United States.

Canada is a large country, a fact which becomes readily apparent when one has to move commodities by truck, rail or water to distant refineries or markets. Then the breadth of Canada, and its great depth from its southern border to its northern extremeties, becomes awesome. And yet our small population is largely concentrated in a ribbon of settled land four thousand miles long and two hundred miles wide along the U.S. - Canada border.

You will see some of this populated strip, but we hope in your visits to more northern communities you will become aware of the unique social contribution made to Canada by the mining industry. Many of these populated areas were once considered of no value but were subsequently developed, opened up and made viable by the discovery and working of a mineral deposit. Mining has been an essential force in pushing back the frontiers of Canadian settlement. Since mining is a truly national industry, its effects have been felt from coast to coast. The tours arranged for this Congress will take participants from Bonaventure Island on the east coast to Sandspit on the west, from Hamilton in the south to Clinton Creek in the Yukon.

Everywhere visited, the economic activity generated by the industry will be obvious. While a successful mine multiplies its impact throughout the economy, it also leads to still more mineral development as companies reinvest revenues in exploration and further development. In turn, new communities result from this growth. Mining means people, settlement, a new social structure where once there were none. New mining communities are carefully planned so that families may enjoy a pleasant life style of their own choosing. The beauty of the natural surroundings and the opportunity for outdoor activity are virtually unlimited. These are permanent towns where families settle down and enjoy a high quality of life with a high material standard of living.

The establishment of new productive industry in areas other than those where rapid urban and industrial growth are already occurring is the unique contribution to Canada of its resource industries. In turn, the mine and the miner require a host of supplies and services both from local and distant sources - rail and road services, electric power, communications networks, radio and television, entertainment and recreation are all needed and attracted to the area. The establishment of a new mining community leads eventually to the development of a diversified and vibrant population centre.

Thus, mining has played and is playing an important role in the development of Canada both from a demographic and economic point of view. This role should continue to be important in both the continued improvement in our national standard of living and the development of our frontier areas.

As yet, I would be less than honest if I were to leave the impression either that the mining industry in Canada has an unclouded future or that its role is universally appreciated by our politicians and citizens. We face serious problems - problems that threaten the industry's future - and since many of these are relevant to the industry throughout the Western world it may be useful to dwell on them briefly.

Because of the intensive level of exploration in this country, particularly during the past 25 years, most of the easily discovered deposits have been found. While enormous potential remains, this is in the remote areas of the country or at greater depth, resulting in much more expensive exploration. It has been estimated, for example, that in recent years nearly three times as much has been spent on exploration for each new mine discovered in Canada as in Australia. In addition, of course, higher capital and operating costs in the remote areas of the country require a higher grade of ore for a deposit to be economically viable. Thus, the odds against exploration success in Canada are lengthening.

Another problem is that, despite vigorous and successful attempts to increase productivity, the operating cost structure is deteriorating in relation to other parts of the world. Despite statistically high unemployment levels, the industry has difficulty in attracting and retaining a full labour complement in spite of its good working conditions and very high wages. More and more Canadians seemingly prefer to live and work in the large urban centres rather than in the more remote areas. Heavy capital and operating costs for environmental control also reduce our cost competitiveness relative to many other countries.

An extremely serious problem for a capital intensive industry such as mining is the incredible rate of inflation in construction costs. Despite price increases for mine products, there are examples of successful existing operations which could not be developed economically at today's construction costs. As you know, preparation of a credible feasibility study necessary to attract the capital to develop a new orebody is normally complicated by the uncertainty associated with market and technical risks. Today, the problem has been enormously compounded by rising material and equipment costs and by an undisciplined and unreliable construction labour force which make accurate estimates of capital costs almost impossible.

Despite these problems, the Canadian mining industry today appears healthy and prosperous as the result of strong world demand and high prices for its products. However, much of the industry's present level of profitability reflects inflationary gains and is illusory, since if the assets employed were valued in current dollars, present rates of return would barely be satisfactory. Nevertheless, this current image of prosperity has created its own problems in terms of public and political perceptions of the industry.

At the root of the problem is the repeated assertion that the mining industry earns excessive profits from the extraction of non-renewable resources belonging to the people, and that an inadequate proportion of these profits are returned to the people in the form of taxes. The result has been a reversal of past Canadian policies which worked so well - of tax incentives for the exploration and development of resources. The recent federal tax reform legislation, which eliminated most of these incentives, was bad enough. But now various provinces, which control a high proportion of our natural resources have themselves been imposing savage new taxes and royalties to increase their revenues from the industry. In effect, the mining industry has been caught in the middle of a squabble over tax revenues between the federal and provincial governments, with the result that the private sector will in future have difficulty in earning a reasonable rate of return on most new mining ventures.

When coupled with all the other problems facing the industry, the result of the punitive provincial action is what could be expected. The level of exploration for new mines in most parts of Canada has declined significantly in recent years and has not recovered in line with the industry's increased profitability. Inevitably, this has led to a decline in the number of new discoveries and in the amount of new mine development. In 1974, new investment by the mining industry will continue the declining trend of the past few years, unlike almost all other sectors of the economy. What therefore appears inevitable over the next few years is stagnation of the Canadian mining industry or at best a level of growth very much less than it could be.

There is a school of thought in Canada which argues that a decline in the relative importance of mining would be a good thing. It is alleged that past national policies designed to stimulate investment, such as tax incentives, have fostered capital intensive industries like mining at the expense of other sectors of the economy. It is said that industries like mining have paid very little in taxes, have created very little employment, have exported most of their production in raw form, and have contributed to foreign domination of the economy. The conclusion is that we need a national industrial strategy which will divert capital from primary industry to the secondary manufacturing and service sectors where many more jobs will be created per unit of investment.

Virtually all of the premises underlying this philosophy are demonstrably false. They ignore the international character of mining capital, the real employment effects of the industry, and the fact that capital intensive industries are the ones most likely to provide the quality of employment and level of income Canadians demand. They fail to come to grips with the question of what other viable industries could be created to take the place of mining. They mistake the extent of further processing, the level of taxation and the degree of foreign domination. Perhaps most importantly, they ascribe to the philosophy that the national role of producer of basic raw materials is one of weakness, while recent events have demonstrated that instead it is a source of strength. Nevertherless, this philosophy has undeniably had an impact on public policy towards the industry in Canada.

Two of the problems relating to the public perception of mining in Canada merit additional comment, particularly since they are not unique to this country. They are the problems of foreign ownership and further processing.

There is considerable preoccupation in Canada with the question of foreign ownership of our industry, which has recently led to the enactment of new federal legislation to control foreign takeovers and new investments. The mining industry is often cited as one which is overwhelmingly foreign controlled, based on official statistics which have been fragmented and highly misleading. For example, these statistics have been used to imply that 80% of our smelting and refining capacity is foreign controlled, when in fact an overwhelming proportion of it is owned by companies the majority of whose shares are held by Canadians.

Leaving aside the question of desirability of foreign investment, the public perception of the situation in Canada is simply wrong. This is not to argue there is not an important degree of foreign ownership in our mining industry. There is, and foreign capital has made a decisive contribution to the industry's growth. The real point is that there is also a substantial and healthy Canadian component which owns over half of the industry overall and whose relative importance has been growing. In the years ahead, our nervousness about foreign capital is likely to result in an accelerating growth in the relative importance of the Canadian-owned component. This will not be achieved without considerable cost, however, in terms of a significant reduction in the amount of foreign capital which would otherwise have flowed into Canada for exploration and development.

As for the second problem, a great deal of concern is expressed over the degree to which Canadian mine products are processed prior to export. This stems from a feeling that we are exporting mine products in their rawest possible form, foregoing the benefits which ought to accrue to us in terms of employment and value added through upgrading to metals and to manufactured products. Like many of our other public perceptions this one is fundamentally, although not completely, inaccurate.

In terms of processing concentrates to metals, the issue is not relevant to a large number of mine products and really boils down to nickel, copper, zinc and lead. During the 1960's there was a marked increase in the proportion of these metals exported in concentrate form as the rapid growth in mine production was not matched by a corresponding increase in smelting and refining capacity. This in turn resulted from a variety of competitive problems including our high construction and wage costs, our distance from a supply of sulphuric acid and metal markets, and tariff structures which discriminate against metal as opposed to concentrate exports. Nevertheless, there was a substantial increase in smelting and refining capacity in the 1960's, and for the balance of this decade it is likely to grow considerably more rapidly than mine production capacity.

In terms of manufacturing, there exists in Canada a viable metal fabricating industry, based on our mine products, which supplies the domestic market and exports to a considerable extent. However, our ability to make further progress in this area is really limited to very few mine products, and then only if significant changes in the tariff policies of our major trading partners can be negotiated. Thus, while scope for further processing of mine products in this country exists, it is really very much more limited than popularly supposed and, to the extent that this is economically viable, the available opportunities are in the process of being exploited.

I have dwelt at some length on the particular problems of Canada's mining industry because, while some of them may be unique to us, many of them appear to have a degree of universality. While there will be differences in emphasis, I feel sure that many of our guests from other countries share similar concerns.

A recent survey of the Canadian economy observed that "no matter where we look, the conditions and assumptions that were so familiar in the post-war era have come apart, leaving a future that is unpredictable and confusing. In short, the comfortable status quo established in the early 1950's has disappeared, and it has yet to be replaced by a new set of familiar, and hence predictable, relationships. We are sailing into uncharted waters". The study goes on to point out that, while economic conditions have always been subject to change, the breadth and depth of the current changes in international institutions and relationships, and in fundamental attitudes, are such that this period is one of profound historical significance. It asks "whether Canadians and the world in general can adapt to the disappearance of the status quo or whether their actions will become defensive, leading to inaction and, eventually, chaos".

These observations seem particularly appropriate to the mining industry throughout the Commonwealth. Certainly, the rules of the game are changing so rapidly that the temptation to sit on the sidelines until the situation is clarified seems at times overwhelming. Even if all other problems are ignored, the possibility that the only cure for spiralling inflation may be an economic and financial collapse is frightening. With its long lead times, high risks and other special characteristics, the mining industry needs a reasonable degree of stability in terms of the institutional, fiscal and economic framework within which it operates. This stability simply does not exist today.

One aspect of this instability is the growing involvement of governments in mining, as illustrated by the fact that governments were involved in ownership of only 2½% of non-Communist copper production in 1960 compared with close to 50% today. This trend has been partly the result of growing hostility towards multinational corporations. But this is by no means the whole answer, as shown by the determination of certain Canadian provinces to participate in future mine development irrespective of the nationality of the corporation which would otherwise have undertaken the project. These trends call into question the future role of privately-owned corporations, both multinational and national, in the further development of the world mining industry.

If governments could effectively and efficiently provide the world's needs for mine products, presumably only the shareholders would care if privately-owned corporations were displaced. However, there are serious reasons for questioning whether governments can really replace the privately-owned corporation. No more effective mechanism for mobilizing the required management, technology and capital is in place or in sight in the western world. Moreover, there is a real question as to whether the preoccupations and motivations of most governments are compatible with the exploration for, and development of, new orebodies.

If, as seems probable, the limited capital available to a government is applied to immediate and pressing social needs, a viable orebody may lie undeveloped almost indefinitely. If, on the other hand, the terms under which private capital is permitted to invest in such an orebody are too onerous, it may be converted to waste rock. Under these conditions, a stalemate develops with the added result that the exploration vital to the further development of the industry will not take place. There are a number of examples of this sort of problem in the world today. Governments may be able to operate mines after they have been found and developed by private capital, although even this is not without its difficulties. However, in general their role is simply incompatible with the requirements of basic exploration and development.

There is a misconception that the recent shortages of raw materials are a permanent phenomenom, as the world is on the verge of running out of non-renewable resources. Perhaps this is true of petroleum products, but if so it is for reasons having no application to most commodities. Ours is a highly cyclical business. We have been through many shortage and surplus cycles in the past, and we will again.

There is enormous remaining potential for new discoveries and mine development throughout the world. The mere existence of this potential, however, is not enough. There must somehow or other be the will and the incentive to mobilize the management, skills, technology and capital needed to find and develop these resources. Given this, there need be no permanent shortage of mine products in the world in the foreseeable future.

The world will continue to change and the clock cannot be turned back. The challenge the mining industry faces today is to help establish a new set of ground rules under which it can continue to make its essential contribution to the development of the world economy. Tax laws are needed which are fair to both the host countries and those who take the risks and provide the needed capital and expertise. If governments wish to participate in the ownership of the mines, they should also be prepared to participate in the very substantial risks involved in the initial exploration and development - or alternatively, they should pay a price related to the value of the resources developed if they choose to come in later.

At the same time, we must recognize and be prepared to deal with the problems faced by governments, which have to be sensitive to the aspirations and perceptions of the people they represent. Concerns regarding foreign domination, further processing, environmental damage, excessive profits and depletion of non-renewable resources - whether valid or not - are very real for any government if they are shared by a large number of their electorate. Too, we must never forget that wide fluctuations in the demand and price for our products, while uncomfortable for the mine operator, can be devastating to the economy of a country which depends heavily on their production.

While we face a great many problems, none of them are insurmountable. Their solution requires new and innovative approaches which satisfy the legitimate aspirations of all parties. There is probably no single right answer. Rather, it seems likely that each situation will have to be dealt with on its own merits, requiring a high degree of sensitivity and flexibility of approach.

Today, the mining industry does not depend only on the traditional skills. The ranks have been expanded to include not only a wide variety of engineering and scientific talents but also professionals in many other fields such as administration, labour, finance, marketing and communications. The industry comprises an extraordinarily talented and effective group of people with the ability and flexibility to adapt to whatever changes in direction and emphasis may prove necessary. For this reason, despite the problems, solutions will be found and the future remains bright.

Hopefully, this Congress will be of great benefit in helping to identify these problems and making a start towards possible solutions. It is also hoped that all delegates will thoroughly enjoy touring our country. It is our great pleasure to have you here as guests.

WORLD ENERGY RESOURCES

BY M. KING HUBBERT*

ABSTRACT

The earth is essentially a closed material system consisting of the 92 naturally occurring chemical elements, all but a minute fraction of which are nonradioactive and hence obey the laws of classical chemistry. With regard to energy, the earth's surface is an open system through which there occurs a continuous flux of energy; as a result, the mobile materials of the earth's surface undergo either intermittent or continuous circulation.

The three principal sources of this energy flux are: (1) solar radiation at the rate of 174,000 x 10^{12} thermal watts; (2) geothermal energy conducted and convected to the earth's surface at a rate of 32 x 10^{12} watts; and (3) tidal energy from the earth-moon-sun potential and kinetic energy at a rate of 3 x 10^{12} watts. In addition, within an accessible depth of about 10 kilometers below the earth's surface are stores of thermal energy, chemical energy of the fossil fuels, and nuclear energy.

During the last two million years, the human species has risen to dominance among the world's animals by inventing means for controlling these energy and material resources. Our modern industrial civilization has been the direct result of exploiting the large energy supplies represented by the fossil fuels. These fuels, however, are finite and exhaustible. World petroleum production will probably reach its culmination during the decade 1990-2000 and coal production during the century 2100-2200 A.D.

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Among other sources of energy appropriate for large-scale industrial uses, waterpower is a large source but inadequate as a replacement for the fossil fuels. Geothermal and tidal power are useful in special cases but are still smaller sources than waterpower. Nuclear fission energy using breeder reactors is a larger source than the fossil fuels, but in a world of social and political unrest it represents a hazard of unprecedented magnitude. Fusion energy based upon the deuterium-deuterium reaction is potentially almost limitless, but controlled fusion has not yet been achieved. In addition to these, the only source of energy of the appropriate magnitude is solar radiation. By a proper utilization of thermal, electrical, chemical, and pipeline technologies already existent, there is promise that a small fraction of the solar energy in the world's areas of brilliant sunshine could supply all the world's needs for industrial power in perpetuity.

The rise of industrialization has occurred principally during the last century; exponential growth rates commonly have been in the range of 4 to 8% per year and have had doubling periods of 8 to 16 years. For ecological as well as for resource limitations, such rates of growth can only be ephemeral. In fact, the world is now in transition from its exponential growth phase into a state essentially of nongrowth. Although this does not impose insoluble technological or biological problems, it will profoundly affect the basic tenets of our contemporary exponential-growth culture and its associated institutions. It appears, therefore, that one of the foremost problems confronting human society today is how to make the cultural transition from exponential growth to a near steady state by the least catastrophic progression.

The earth's energy system

According to the discoveries in the Olduvai Gorge in Tanzania by the late Louis S. B. Leakey and M. D. Leakey and the associated radioactive dating, our ancestors or their near relatives had begun to use crude stone tools by at least 1.7 million years ago. From that time until the present the exploitation of the earth's mineral resources has been a continuous and increasing enterprise, until today the world's industrial civilization more than any prior civilization is almost totally dependent upon the utilization of minerals and energy in unprecedented amounts. The purpose of the present paper is to focus attention on one aspect of this development, namely, the progressively increasing human utilization of energy, the approximate magnitudes of the energy supplies available, and the prospects for the future when viewed on a longer time scale of human history than is customary.

The significance of energy in terrestrial affairs can best be appreciated when we consider that the totality of events on the earth comprise but two interrelated processes, a circulation of matter and an associated degradation of energy. As regards materials, the earth is essentially a closed system consisting of the 92 naturally occurring chemical elements, all but a minute fraction of which are nonradioactive and obey the laws of conservation of matter and nontransmutability of the elements. With regard to energy, the earth's surface is an open system through which there occurs a continuous influx, degradation, and outflux of energy. As a consequence, the mobile constituents of the earth's surface undergo either intermittent or continuous circulation.

The nature of the total energy system is indicated graphically in Fig. 1. The system consists of two parts: (1) certain static quantities of energy-the fossil fuels, nuclear energy, and geothermal energy which are stored in the upper part of the earth and are here shown beneath the horizontal bar; and (2) a dynamic flux of energy shown in the flow diagram in the upper part of the figure.

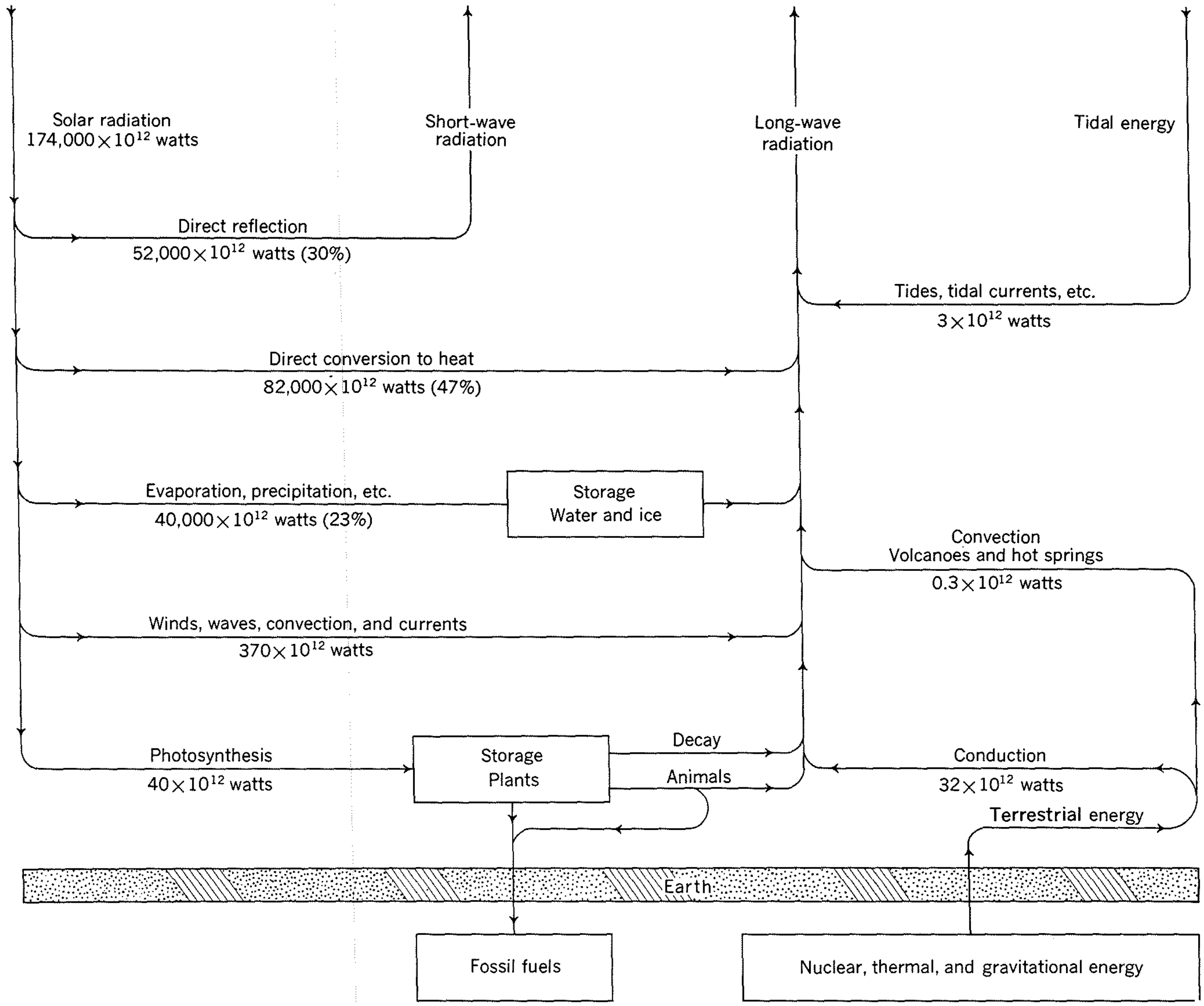

Fig. 1 - Energy flow sheet for the earth (Hubbert, 1974a, Fig. 1).

Here we deal with two different entities, energy and power. The stored energy is measurable in terms of the International System unit of energy, the joule. The flux of energy has the dimensions of [energy/time] and thus is measurable in a unit of power, the joule/second or the watt. In the flow diagram the unit used for power is 10^{12} thermal watts.

Into the earth's surface environment are three major influxes of energy: (1) that from the solar radiation intercepted by the earth's diametral plane; (2) the heat flux to the surface from inside the earth; and (3) the tidal energy influx from the combined potential and kinetic energy of the earth-moon-sun system. The approximate magnitudes of these three influxes in the unit of 10^{12} watts are:

Solar	174,000
Geothermal	32
Tidal	3

The relative magnitudes of the three influxes are especially significant, that from the sun being about 5,000 times the sum of the other two. Of the solar energy influx, approximately 30%, the albedo, is directly reflected into outer space and exercises no influence on the earth. The remaining 70%, or approximately 120,000 x 10^{12} thermal watts, is captured by the earth. At this rate the cumulative energy from solar power influx during each month is approximately equivalent to that of the world's initial supply of the fossil fuels. Because cumulative solar energy increases continuously with time, the largest source of energy, past, present, or future, available to the earth is solar radiation.

Of these influxes, that from geothermal sources transforms immediately into heat at the ambient temperature. That from tidal sources is first exerted mechanically in creating oceanic tides and currents and then by mechanical friction is degraded into heat. The 120,000 x 10^{12} watts of the solar influx captured by the earth undergoes degradation along several different channels into low-temperature heat. A part of this is absorbed directly as heat by the atmosphere, the oceans, and the ground. Another fraction produces the atmospheric and oceanic circulations, and a part evaporates, circulates, and precipitates water in the hydrologic cycle. Finally a very small fraction, 40 x 10^{12} watts, is captured by the green leaves of plants and supplies the energy for the process of photosynthesis whereby the common inorganic materials H_2O and CO_2 are synthesized into carbohydrates according to the basic equation,

$$\text{Radiant energy} + CO_2 + H_2O \rightarrow [CH_2O] + O_2,$$

where $[CH_2O]$ represents the unit building block in a series of increasingly complex carbohydrates.

The energy required for photosynthesis is thus stored chemically. The energy flux in this channel, despite its small size, is especially significant because it is the sole source of energy for the physiological requirements of the entire biological system. By the opposite reaction of oxidation,

$$\text{organic matter} + O_2 \rightarrow H_2O + CO_2 + \text{heat.}$$

The end product of all the energy fluxes shown in Fig. 1, with one small but important exception, is heat at the ambient temperature of the earth's surface. This low-temperature heat is then reradiated into outer space by long-wavelength thermal radiation.

The exception to the complete oxidation of organic materials is the minute fraction of such materials that is buried in peat bogs and other oxygen-deficient environments where complete decay is impossible and the energy is conserved. Such processes have been occuring over long periods of geologic time, and the preserved organic materials have been buried under great thicknesses of sedimentary sands, muds, and limes and have become our present stores of fossil fuels.

Geologic and human time scales

To appreciate the mangitude and brevity of the principal human activities with regard to the earth's energy resources, it is important that two separate time scales and their relation to one another be understood. The first of these is the geologic time during which the earth's concentrations of minerals and of the fossil fuels have occurred; the second is the very much briefer period of human history during which these supplies are being dissipated.

The span of geological history is shown graphically in the four bar charts of Fig. 2. The top chart represents the period of 4.5 billion (10^9) years, as determined by radioactive dating of meteorites, since the catastrophic astronomical event which created the solar system must have occurred. This span is divided into a longer period, the Precambrian Era, extending from the origin of the earth to the Cambrian Period, about 570 million years ago; and

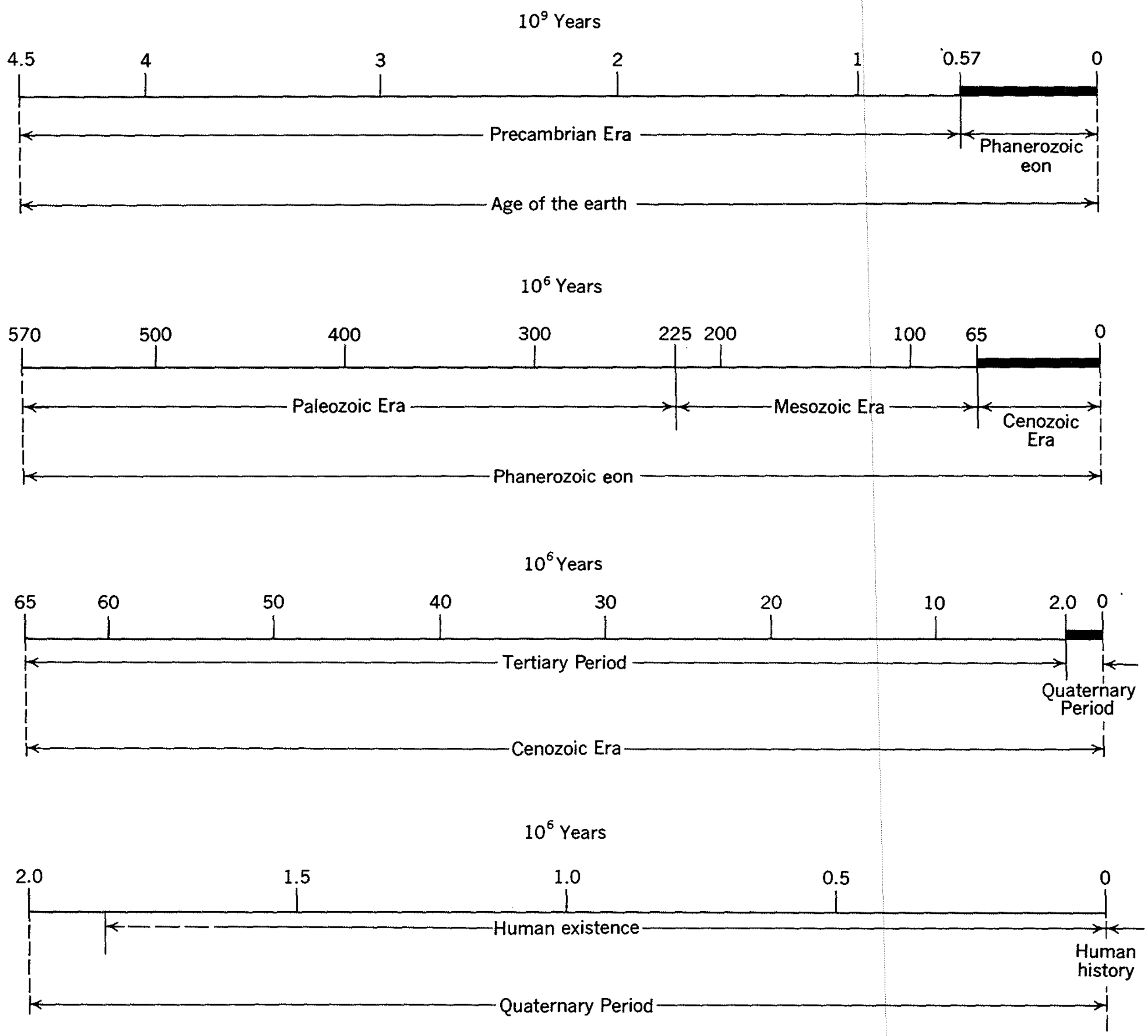

Fig. 2 - Time scales for the history of the earth (Hubbert, 1974a, Fig. 2).

a shorter period, the Phanerozoic eon, extending from the beginning of the Cambrian Period to the present.

The succeeding bar charts represent successive enlargements of the most recent division of each preceding chart. The second chart is an enlargement of the Phanerozoic eon, showing its subdivision into the Paleozoic, the Mesozoic, and the Cenozoic Eras. The third chart is an enlargement of the Cenozoic Era into the Tertiary and the Quaternary Periods, and finally, the last chart represents the Quaternary Period, comprising the last two million years of geological history. The Quaternary Period is the time during which the human species evolved into its present form and arose to dominance. On the Quaternary chart, the width of the vertical line at the extreme right represents approximately the last 5,000 years of human history.

A large part of the earth's metallic ores were accumulated in the Canadian, the Baltic, and other ancient shields during the Precambrian Era. The fossil fuels accumulated during the Phanerozoic eon. The oldest gas field so far discovered is in Australia in upper Precambrian rocks, about 600 million years old. Oil and gas fields are found in rocks of all geological ages from the Cambrian, 570 to 500 million years ago, to the Pleistocene of the last million years in coastal Louisiana. Abundant coal deposits, those of Great Britain, western Europe and eastern and central North America, were formed during the Mississippian and Pennsylvanian Periods-the Carboniferous 345 to 280 million years ago. Abundant subbituminous coal deposits were formed during the Mesozoic Era, and lignites during the Cenozoic. Finally, peat deposits, the first stage in coal formation, are accumulating at present.

What is most important for present purposes is to appreciate the extreme brevity of the human time span in the totality of geological history. In one important respect, all the bar charts of Fig. 2 are misleading. They all terminate at the present and thus create the impression that we are at the end of geological history. A more accurate view would be that we are probably nearer the middle and that geological history will probably continue for some additional billions of years into the future. Hence the activities of the human species at present are just as much a part of geological history as those of the dinosaurs during the Mesozoic, and, like the dinosaurs, there is every reason to expect that the human species will not exist forever.

Man's conquest of energy

The rise of the human species during the last two million years has been characterized by an inventiveness in the capture and utilization of an ever larger fraction of the ambient energy supply. By means of tools and weapons the food supply could be increased. By means of clothing and housing, regions of colder climate could be occupied. By control of fire roughly a million years ago, the energy of wood not previously available became a major addition to the human energy supply. By means of the domestication of plants and animals, 8,000 to 10,000 years ago, a greater fraction of contemporary solar energy was channeled through the ecological system into human uses. Then, in Anatolia about 5,000 years ago, the smelting of nonferrous metals, using the energy of wood, began, and the smelting of iron about 1,500 years later.

New channels of the energy flux in the form of inanimate power were tapped by the ancient Egyptians when they used the power of wind to drive their sailing ships on the Nile. The power of water was used by the Romans for the driving of small grist mills.

The net effect of all of the foregoing developments was to increase the human population, both in areal density and in geographical range. However, these advances occurred with such extreme slowness that the population was more than able to keep pace with developments. Consequently, the energy utilized per capita increased but slightly, probably not much more than about twice the energy of the food consumed.

Release from this constraint was not possible until a much more concentrated source of energy than any hitherto known became available. This occurred about nine centuries ago in the vicinity of Newcastle-upon-Tyne in northeast England, when it was discovered that certain black rocks found along the seashore, and hence known as "sea coals," would burn. From this initial discovery the digging of coal began as a continuous enterprise, and coal mining in the vicinity of Newcastle-upon-Tyne, with the exception of a few weeks recess in the spring of 1974, has continued to the present.

Time here does not permit a review of the technological evolution which inexorably came about as the result of the mining of coal, except for the mention of a few high points. The demand for coal increased until coal mining rapidly spread to all of the principal coal basins of Great Britain and to the Continent. The need for ever larger pumps led to the development of Newcomen's atmospheric engine in 1712, the James Watt improvements half a century later, and finally to application of the engine to rail and water transport near the beginning of the nineteenth century. A paralled use of coal was for metallurgical purposes, first for blacksmithing and then, early in the eighteenth century, for the production of metallurgical coke in place of charcoal for the smelting of iron.

Exploitation of the fossil fuels

Data on the annual rate of world coal production prior to 1860 are difficult to assemble. During the first eight centuries of coal mining only scattered production statistics are available, but enough exist to show that the average rate of growth in the world coal production, principally in Great Britain, prior to 1860 was close to 2% per year, the production rate doubling, on the average, every 34 years. From 1860 to the present, however, data on annual production do exist, and those for coal and lignite are shown graphically, plotted on an arithmetic scale, in Fig. 3. By 1860 the world annual production of coal and lignite had reached 138 million metric tons per year. By 1970 this had increased to 3,000 million, or to 3 billion (10^9) metric tons per year.

What is most informative about the data of Fig. 3 is the contrast in magnitude between the world coal production since 1860 and that before. It will be noted that the production rate increased at a nearly uniform exponential growth rate until World War I. Then, from World War I to the end of World War II, there was a slowdown and finally a renewed higher rate since World War II.

Another way to appreciate the contrast between the magnitudes of coal mining since 1860 and that previously is to consider the cumulative production. By 1860 this amounted to about 7 billion metric tons; by 1970 it had reached 139 billion metric tons. Of the latter figure, approximately the first half was produced during the nine-century period prior to 1940; the second half during the 30-year period since 1940.

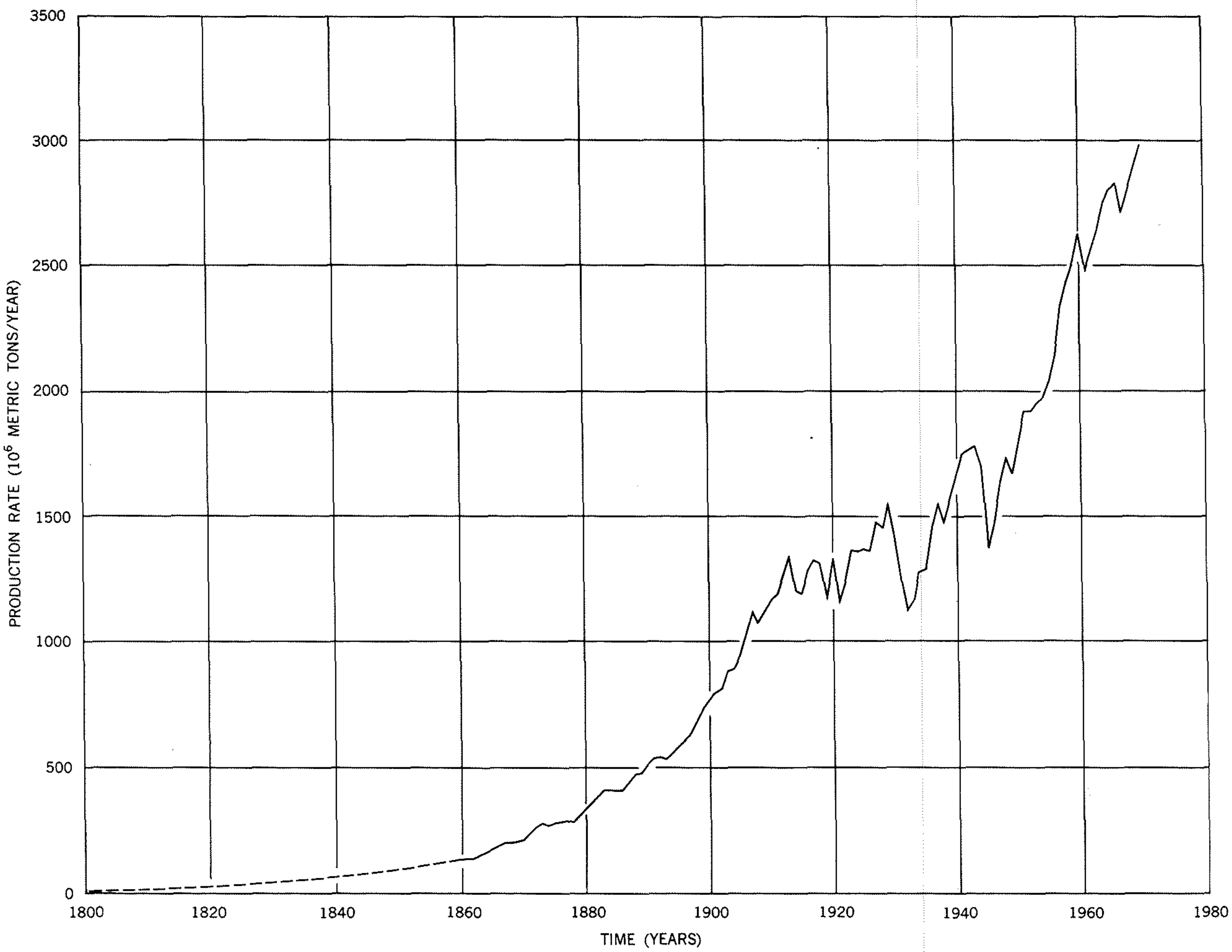

Fig. 3. World production of coal and lignite (Hubbert, 1974a, Fig. 3).

Another aspect of the growth in coal mining since 1860 is seen when the data shown in Fig. 3 are replotted on a semilogarithmic scale for which straight-line segments indicate periods of uniform exponential growth, or doubling in equal intervals of time. Such a plotting is shown in Fig. 4, where three such intervals are seen. During the first, extending from 1860 to World War I, the production rate increased at an average rate of 4.19% per year, with a doubling period of 16.5 years. For the period comprising the two World Wars and the intervening depression, the growth rate dropped to 0.79% per year with a doubling period of 88 years. Then, after World War II, an intermediate growth rate of 3.0% per year and a doubling period of 22.9 years was resumed.

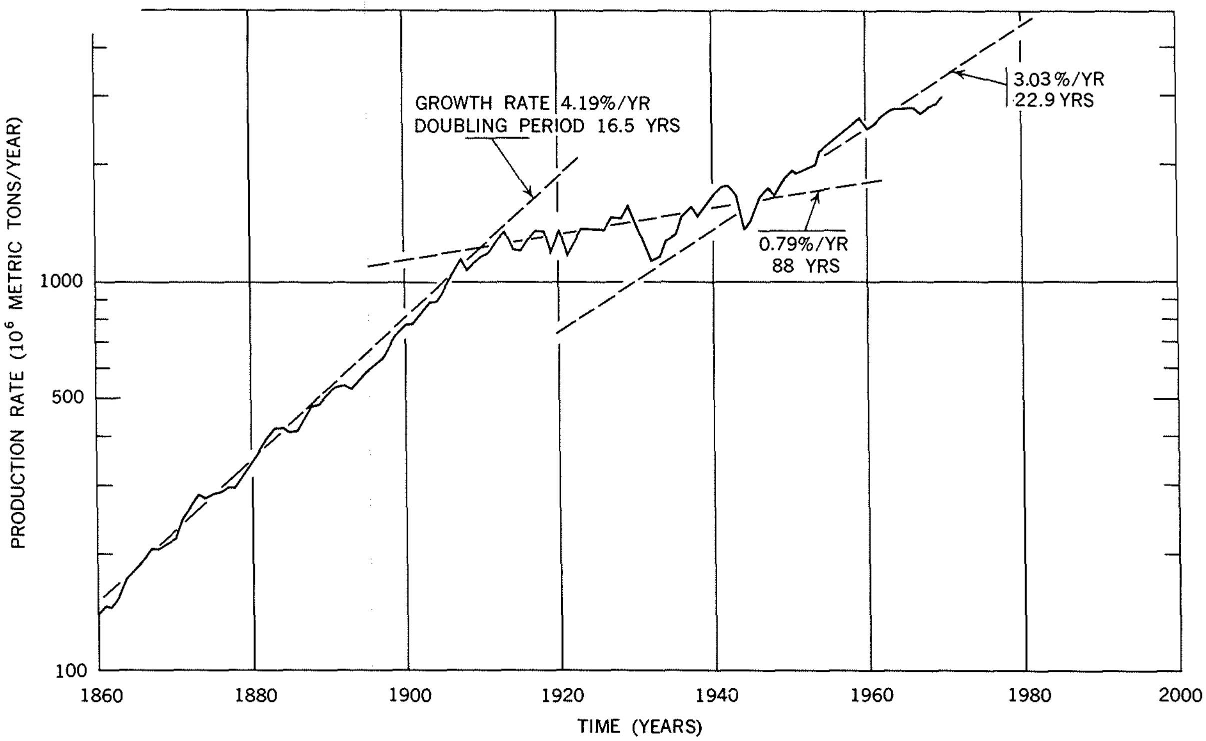

Fig. 4 - World production of coal and lignite, semilogarithmic scale (Hubbert, 1974a, Fig. 4).

World production of the second major fossil fuel, crude oil, is shown on an arithmetic scale in Fig. 5. Although small amounts of oil were produced earlier in China and Burma, crude oil production as a continuous enterprise began in Romania in 1857 and in the United States in 1859. Figure 5 shows the growth of annual production from near zero in 1880 to 16.5 billion barrels per year by 1970. By the end of 1973, the production rate had reached 20.3 billion barrels per year.

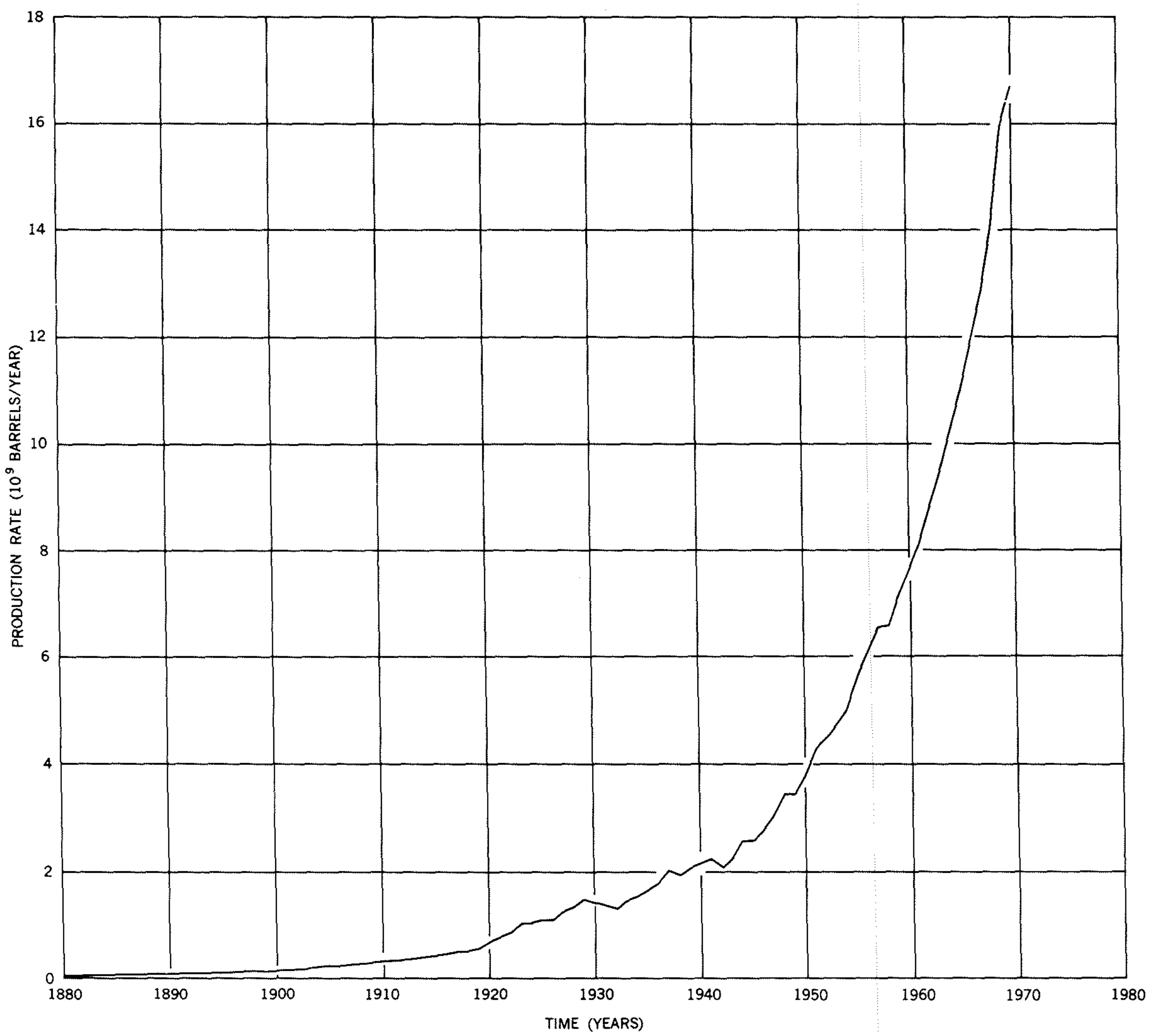

Fig. 5 - World crude oil production (Hubbert, 1974a, Fig. 5).

In Fig. 6 the crude oil production data are shown plotted on a semilogarithmic scale. From 1870 to 1890 the growth rate of production increased somewhat faster than subsequently. Then, after 1890, with only a slight aberration from 1920 to 1940, the production rate followed an almost unbroken exponential straight line to the present, having a sustained average growth of 7.0% per year and a doubling period of 9.8 years.

A characteristic of uniform exponential growth in the production rate is that the cumulative production has the same doubling period as the rate of production. This is borne out by the cumulative data. By the end of 1963 the cumulative world crude oil production amounted to 150 billion barrels; by the end of 1973, 10 years later, it had reached 299 billion

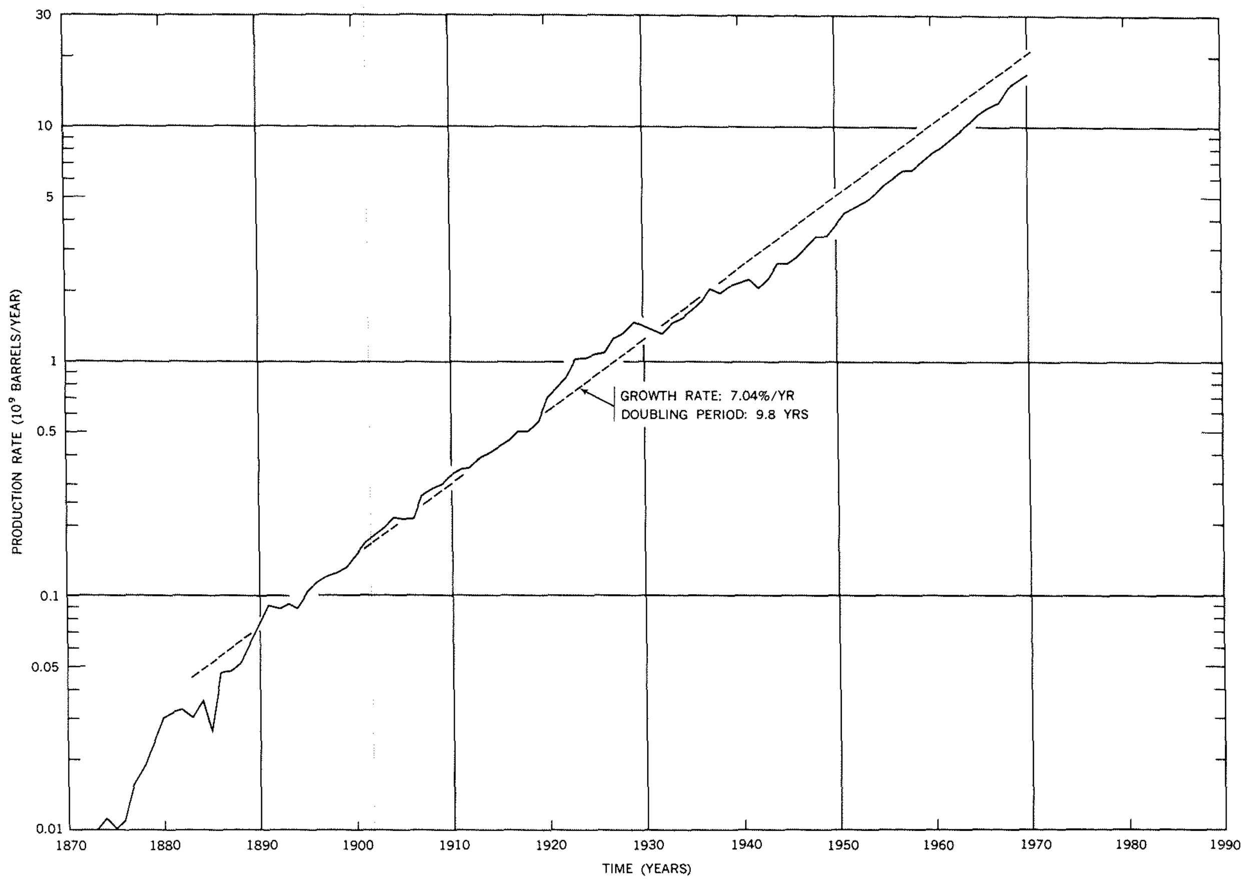

Fig. 6 - World crude oil production, semilogarithmic scale (Hubbert, 1974a, Fig. 6).

barrels, barely less than double that of 1963. To a close approximation, the amount of oil produced during each of the last several decades is equal to all the oil produced prior to that time.

No direct comparison between coal and oil as sources of energy is possible as long as annual coal production is given in metric tons and oil in U.S. barrels. A comparison can be made in terms of the heats of combustion of the respective fuels as shown in Fig. 7. The lower curve is the energy equivalent of coal and lignite; the shaded area is the additional energy of crude oil; and the upper curve is the sum of the two.

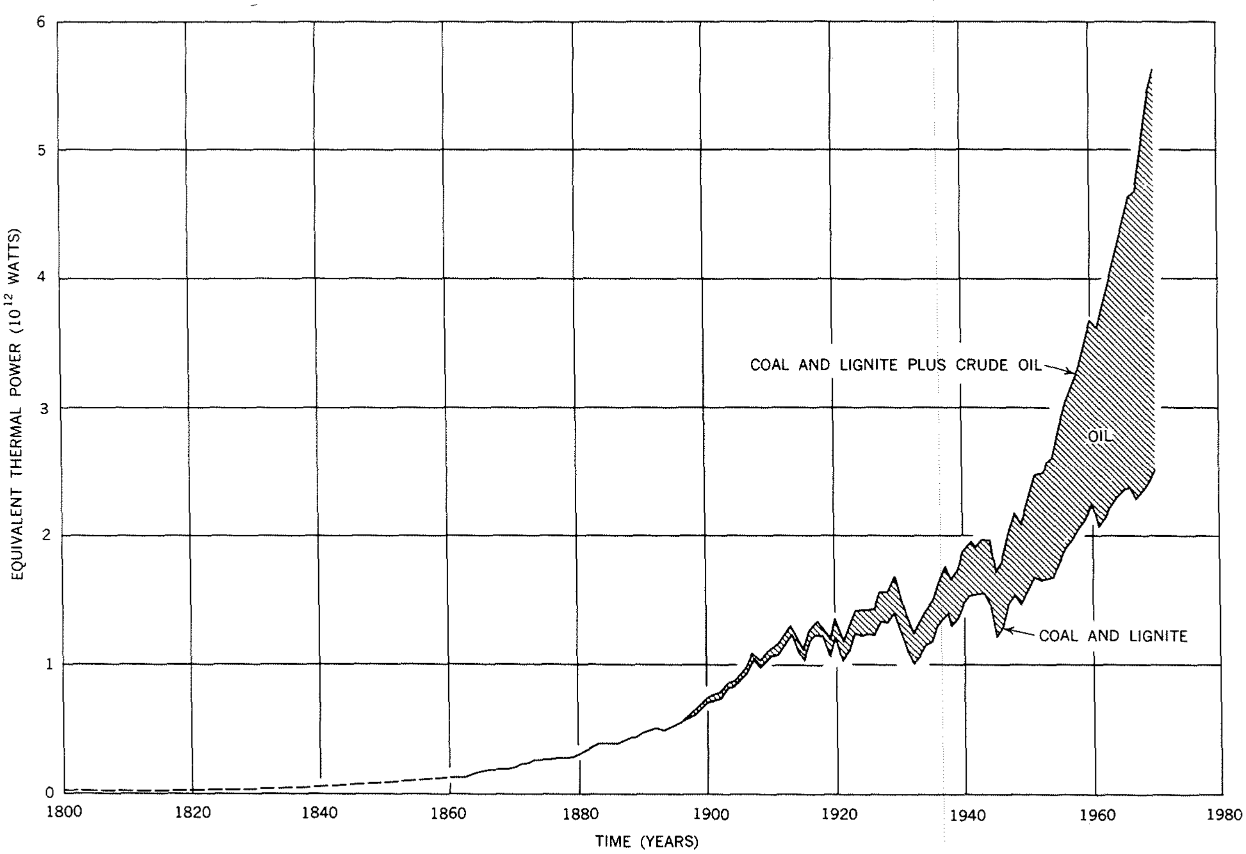

Fig. 7 - World energy production from coal and lignite plus crude oil (Hubbert, 1974a, Fig. 7).

What is significant here is that prior to 1900 the energy contribution of crude oil was insignificant compared with that of coal. Subsequently, the energy contribution of crude oil increased continuously with respect to that of coal until at present the energy from crude oil exceeds that from coal. Were the energy contributions of natural gas and natural-gas liquids to be added to that of crude oil, the petroleum fluids would by now account for about two-thirds and coal only one-third of the total rate of energy production from the fossil fuels.

Complete production cycles for the fossil fuels

When considering the production-rate curves of coal and of crude oil shown in Fig. 3 and 5, one can hardly fail to wonder about the future of such activities. How much longer can such exponential growth rates be maintained and what are the subsequent possibilities?

To obtain approximate answers, account needs to be taken not only of the time scales discussed but also of the processes involved in the utilization of the fossil fuels. With regard to the time scales, we must contrast the hundreds of millions of years required for the accumulation of the fossil fuels by geological processes with the centuries required for their exploitation and exhaustion. The principal utilization process is indicated by the energy and material flow sheet for the fossil fuels shown in Fig. 8. After being taken from the ground the fuel undergoes combustion by chemical reaction with atmospheric oxygen. The material combustion products are the gases, principally CO_2 and H_2O, but including some carbon monoxide and nitrous oxides plus the impurity SO_2, and solid constituents such as ash which return to the ground. The chemically stored energy is released as the heat of combustion. A part of this goes directly to the lowest temperature of the environment. Another part, in the case of heat engines, is converted to mechanical and thence into electrical energy, and eventually back to heat at environmental temperature, after which it is radiated to outer space. Thus, in the combustion of a fuel, the material constituents remain on the earth as gases or solids; the energy, after a series of degradations, leaves the earth. Hence, energetically, the fossil fuels are absolutely exhaustible.

The same geological processes that produced the fossil fuels are still in operation, but because of their extreme slowness no significant addition to the present stores of the fossil fuels may be expected to occur within the few centuries required for the exhaustion of the fuels. Therefore, in effect, the exploitation of the fossil fuels amounts to a continuous withdrawal from an initially fixed and finite supply.

These facts provide the basis for various methods of estimating the time scale during which the fossil fuels may be able to serve as major sources of industrial energy. The complete cycle of production of such a fuel, whether in an individual deposit, in a larger region, or in the entire world, consists of the following sequence of events. The production rate, dQ/dt, begins at zero and then increases exponentially during a period of development. Following that, the growth rate slows down and the production rate, after passing one or more maxima, declines gradually to zero as the resource is exhausted. This sequence of events constitutes the complete cycle of the

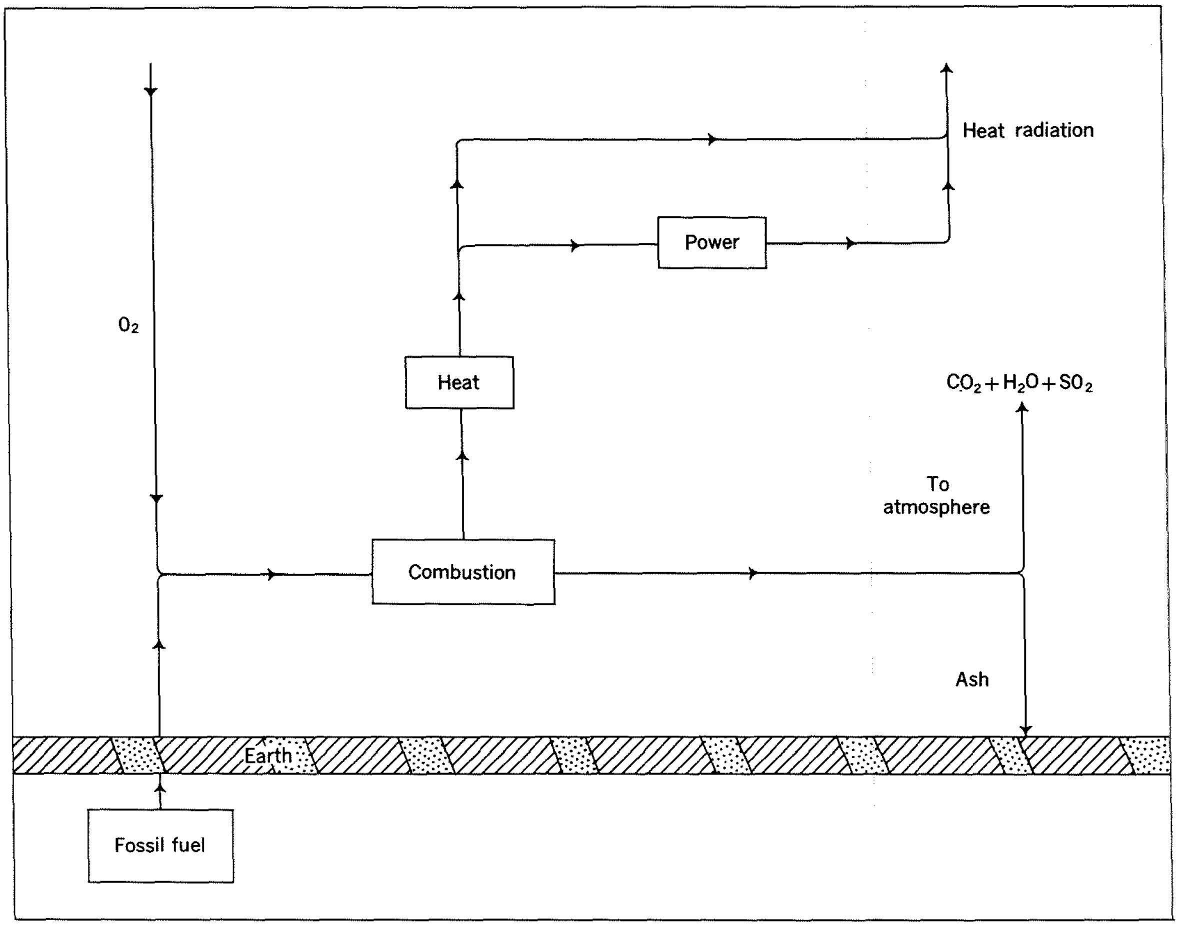

Fig. 8 - Flow sheet for the energy utilization of a fossil fuel (Hubbert, 1974a, Fig. 15).

exhaustion of a fossil fuel in any given region.

A graphical representation of an idealized complete cycle is shown in Fig. 9 in which the production rate, dQ/dt, is shown plotted on an arithmetic scale as a function of time. A fundamental property of such a diagram is that the area beneath the curve to any given time is a graphical measure of the cumulative production to that time; the total area beneath the curve for the complete production cycle, as time increases indefinitely, is the ultimate amount, Q_∞, of cumulative production.

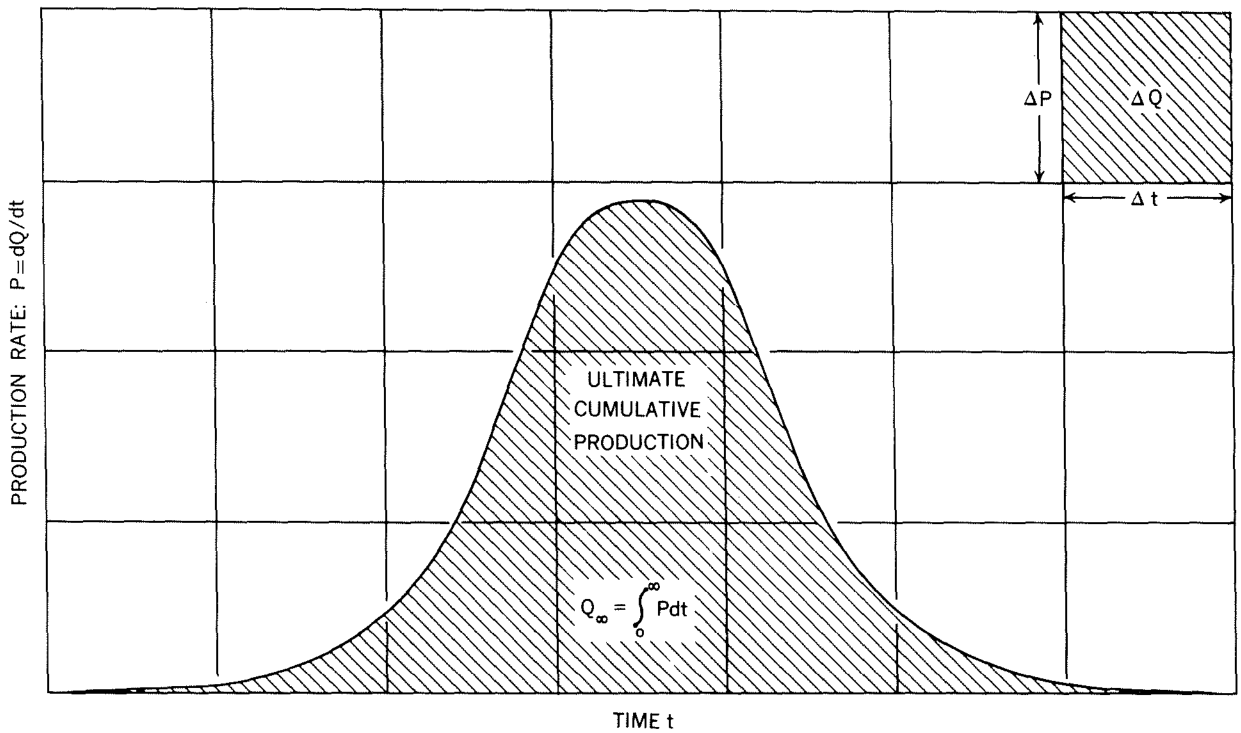

Fig. 9 - Mathematical properties of arithmetical graph of production rate P versus time t for the complete production cycle of an exhaustible resource [Hubbert, 1956, Fig. 11. Reproduced by permission from API, Drilling and Production Practice (1956)].

A graphical scale for this area is afforded by the ΔP-Δt grid square of the coordinate system used, where ΔP is the element of production rate comprising the vertical dimension of the grid square and Δt the time interval for the horizontal dimension. Then, as

$$\Delta P = \Delta Q/\Delta t,$$

where ΔQ is the quantity produced in time Δt, by transposition,

$$\Delta Q = \Delta P \times \Delta t, \qquad (1)$$

so that the area of a single grid square becomes a scale for the measurement of cumulative production. In particular, if the ultimate magnitude of the cumulative production is Q_∞, then the number n of grid squares that can be subtended by the complete-cycle curve must be

$$n = Q_\infty/\Delta Q. \qquad (2)$$

Hence, if after a period of development in a given region an estimate of the magnitude of Q_∞ can be obtained, the number of grid squares beneath the complete-cycle curve is prescribed and the curve must be drawn subject to this constraint.

Such a curve is not unique as to shape, but a family resemblance exists between all such curves that is technologically possible. The principal latitude of choice may be the height of the peak in the production rate. If the complete-cycle curve has a higher peak, its time span will be shortened; if a lower peak, its time span will be lengthened.

During the initial exponential-growth phase of the production cycle, such as the world crude oil production shown in Fig. 5 and 6, there is a strong human tendency to extrapolate the continuation of this phase into the future and to obtain very large estimates of future production rates and of cumulative production. The use of the technique illustrated in Fig. 9 exercises a sobering constraint upon an otherwise unbridled use of the imagination.

Complete cycle for world coal production

To apply the foregoing technique to the world production of coal, we require an independent estimate of Q_∞, the ultimate amount of coal that will be produced. Fortunately, the quantity of coal in a given geological basin is comparatively easy to estimate. Coal occurs in discrete seams or strata which often are continuous for tens or hundreds of kilometers horizontally and which frequently crop out on the surface. By means of surface geological mapping, supplemented by logs of a few widely spaced drill holes, it is possible to make a reasonably accurate estimate of the quantity of coal in the basin, classified as to thickness and depth of the seams. From this information, in conjunction with the technology of mining, reasonably good estimates can be made of Q_∞ for the given basin.

Paul Averitt, who for a number of years has been in charge of such studies for the U.S. Geological Survey, has recently published estimates of the initial coal in place in both the United States and the rest of the world, and of the amount of recoverable coal on the basis of an assumed extraction of 50% of the coal in place (Averitt, 1969). Averitt's estimates of the recoverable coal occuring in beds 12 in. (0.30 m) or more thick to depths of

6,000 ft (1,200 m) or less, in the major geographical areas of the world, are shown graphically in Fig. 10. In this the horizontal dimension from left to right is a cumulative measure of the coal. The vertical columns represent different geographical regions and the vertical scale is in percentages. Hence, the areas of the respective columns are proportional to the initial recoverable coal of those regions.

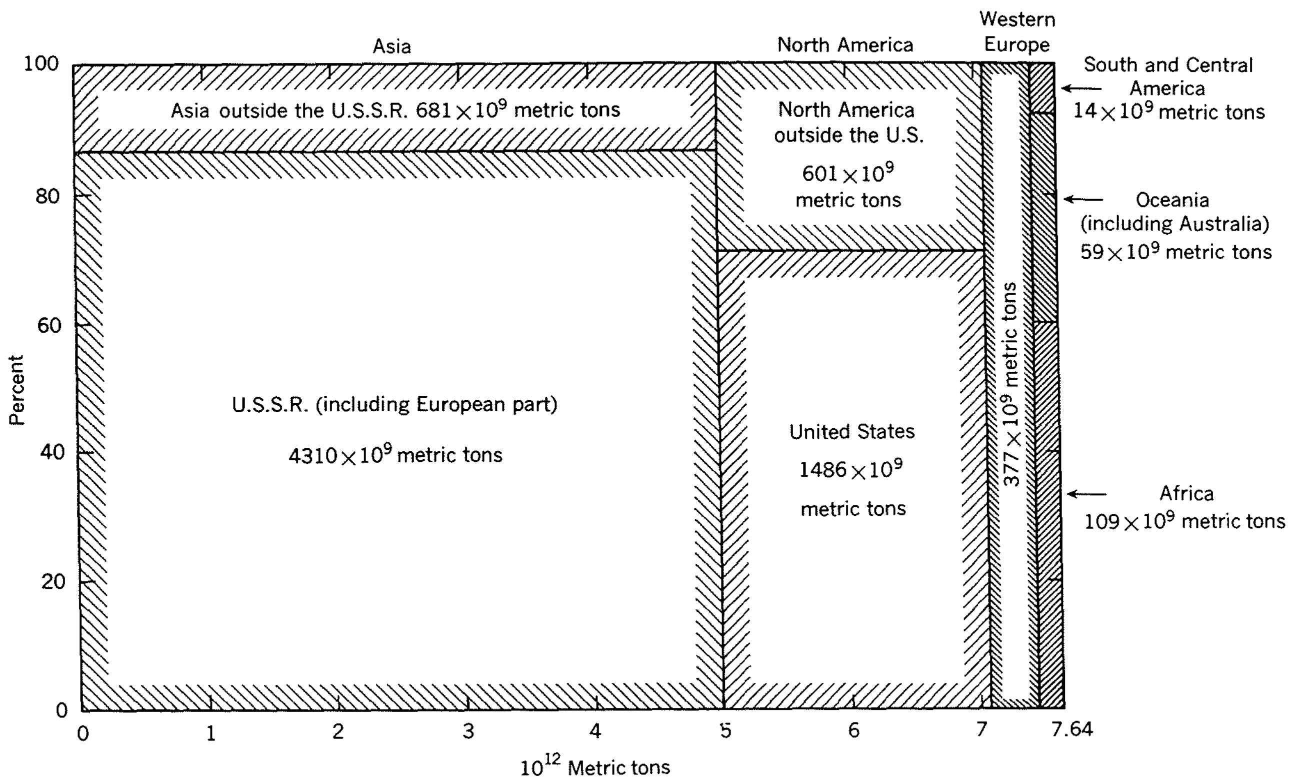

Fig. 10 - Estimates of initial world resources of recoverable coal in beds 12 in. or more thick occurring at depths of 6,000 ft or less (Based on Averitt, 1969, table 8, p. 82).

The estimate of Q_∞ for the world is 7.64 trillion (10^{12}) metric tons, of which 65% is in Asia (principally the U.S.S.R.), 27% in North America, 5% in western Europe, and only 3% in Africa, South and Central America, Australia, and the neighboring Pacific Islands.

In view of the fact that beds of coal as thin as 1 ft (0.3 m) or as deep as 6,000 ft (1,200 m) are not readily recoverable by present mining technology, Averitt (1972) has recently estimated that the initial amount of recoverable coal in the United States in beds 28 in. (0.7 m) or more thick and 1,000 ft (300 m) or less deep was about 390 billion metric tons. Coal beds within these ranges are amenable to extraction by present mining technology.

Averitt's reduced figure for coal in the United States is about one-fourth of his higher figure shown in Fig. 10. Assuming that a comparable reduction would apply to his earlier estimates for the world, a reduced plot of recoverable coal for the world is shown in Fig. 11. Here the value of Q_∞ is reduced to about 2 trillion metric tons.

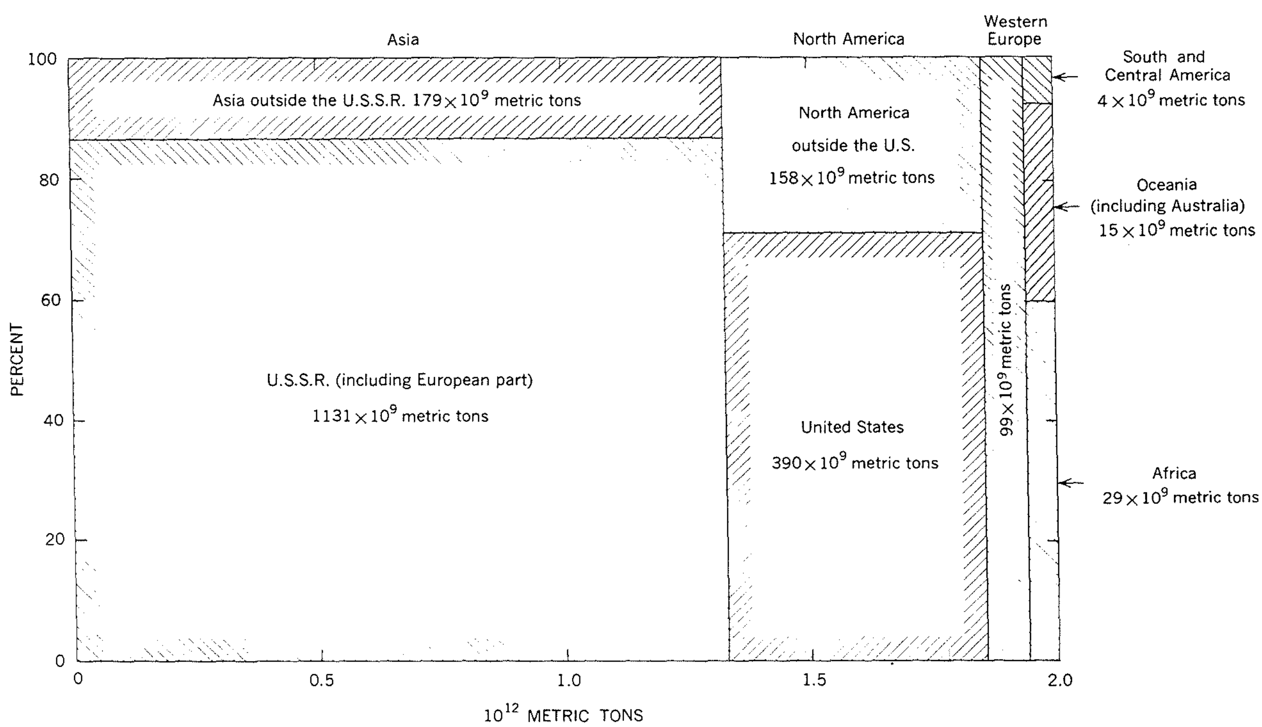

Fig. 11 - Estimates of initial world resources of recoverable coal in beds 28 or more in. thick occurring at depths of 1,000 ft or less (Based on Averitt, 1972, Estimates for the United States).

Using these two values, 7.6 x 10^{12} and 2 x 10^{12} metric tons, for the initial world resources of recoverable coal, two complete-cycle curves for the world coal production are shown in Fig. 12. It must be emphasized that these two curves are unique only as to area. The upper curve is based on the larger value 7.6 x 10^{12} metric tons for Q_∞, and a peak production rate of about three more doublings or an eightfold increase over the present rate. If the peak should be higher the time span would be shortened. The lower curve is based upon the value of 2 x 10^{12} metric tons for Q_∞, and only a threefold increase in the production rate. Should the production rate have an eightfold instead of a threefold increase, this curve would be very much shortened in time.

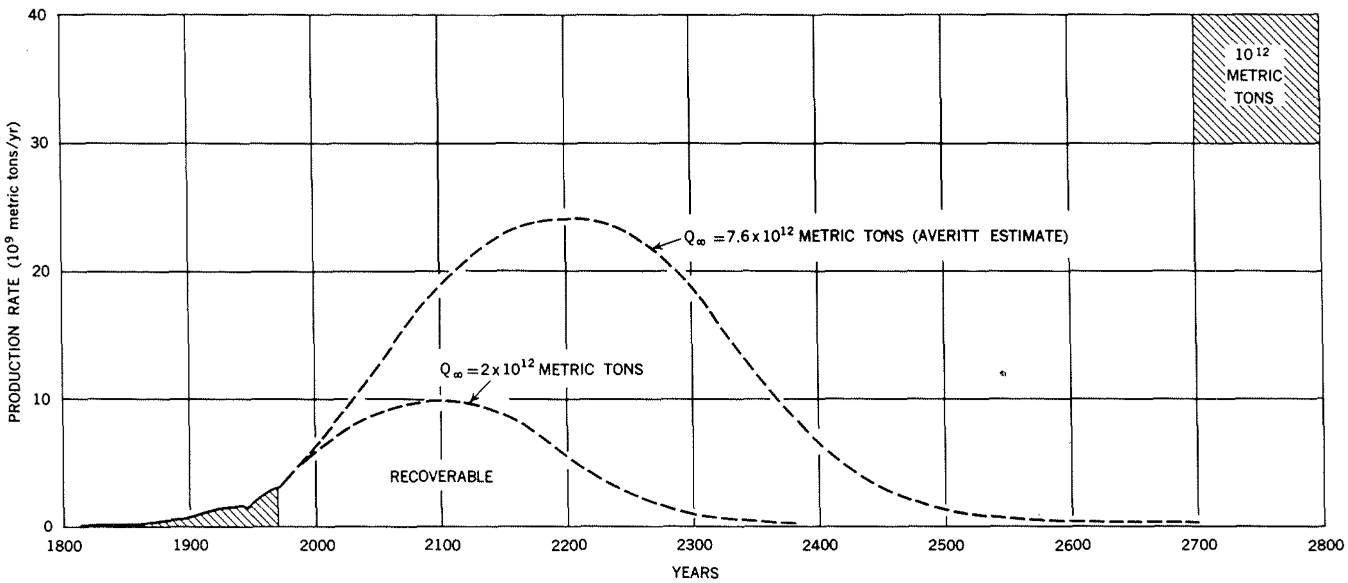

Fig. 12 - Two complete cycles of world coal production based upon Averitt's higher and lower estimates of initial resources of recoverable coal (Hubbert, 1974a, Fig. 21).

These two curves give a reasonably good idea of what we may expect concerning the time scale of future coal production. The total time span for the complete cycle of coal production may be quite long, but this is of little significance because it will take about 1,000 years to produce the first 10% of Q_∞ and possibly another 1,000 years to produce the last 10%. Of much greater significance is the length of time required to produce the middle 80%. From Fig. 12, this will probably not exceed about three centuries, the peak occurring at about the year 2200 if the larger figure for Q_∞ is valid. For the smaller figure for Q_∞, this time span for the middle 80% may be as short as one or two centuries.

Estimation of future discoveries of oil and gas

Because of the nature of geological occurrences of exploitable deposits of petroleum liquids and gases, the estimation of the quantities ultimately to be recoverable in a given region is much more difficult than corresponding estimates for coal. Accumulations of oil and gas occur in the pore spaces of granular, vuggy, or fractured sedimentary rocks, which are otherwise filled with water. Oil or gas accumulations accordingly are retained in positions of minimum potential energy in a rock-water environment, the deposits being in equilibrium between the impelling forces exerted upon the oil or gas by the surrounding water and the constraints to migration afforded by fine-textured or impervious rocks.

In horizontal extent, oil or gas accumulations range from a few hundred meters to as much as about 250 kilometers in maximum horizontal dimensions. In depth, recoverable oil is found from as shallow as 100 meters to as deep as about 6 kilometers. At depths greater than about 6 kilometers liquid petroleum appears to be unstable, but natural gas accumulations are being exploited from depths as great as 7.5 kilometers.

The exploration for petroleum involves such above-ground activities as geological mapping and geophysical mapping by the gravity meter, the airborne magnetometer, and the reflection and refraction seismograph. This is supplemented by such subsurface activities as drilling and testing, geological correlation by means of drill cuttings, and by the use of electrical and other types of geophysical well logging. It is a truism of petroleum exploration, however, that the only tool that actually discovers oil or gas is the drill.

In estimating future discoveries of petroleum, essentially only two procedures are available. In a primary area there is no a priori basis for knowing within wide limits how many accumulations of oil or gas a given region ought to contain, or about how much oil or gas per unit volume of sediments such a region may be expected to yield. The estimation of the ultimate production for such a region must therefore be based upon the cumulative experience of the results of exploration, drilling, and production.

In the early stages of exploration and drilling in a primary petroliferous region, the probability of success of exploratory drilling is at a maximum. As exploration and drilling proceed, however, and the larger and shallower accumulations have been discovered, the probability that any particular exploratory well will be successful declines more or less negative-exponentially with the cumulative amount of drilling. From such a decline curve, reasonably good estimates can be made of the ultimate cumulative discoveries on the basis of the discovery record of past drilling.

The petroleum potentialities of a secondary region, even in advance of drilling, can be crudely estimated on the basis of geological analogy. Thus, suppose that an undrilled secondary region B has been found by geological and geophysical mapping to resemble a primary area A which has already been found to be rich in petroleum. By analogy, it is inferred that region B will eventually be found to contain comparable amounts of petroleum per unit of area or volume to those of area A. As secondary areas are developed these preliminary estimates can be refined by the methods applicable originally to primary areas.

For the entire world, the most intensively explored major oil-producing region is that of the conterminous United States and its adjacent continental shelves. Also, until 1974, the United States has been throughout its history the leading oil-producing country in the world. Therefore, the United States has been the principal primary producing area and has frequently been used as a standard in the estimation of undeveloped secondary areas. For this reason it will be informative to estimate the ultimate amounts of oil and gas which the United States will produce as a partial basis for corresponding estimates for the rest of the world.

In 1956 the author was invited to present a broad-brush review of world energy resources before a meeting of about 500 petroleum engineers under the auspices of the American Petroleum Institute, in San Antonio, Texas. In preparation for this paper (Hubbert, 1956), it was found that during the 97 years since oil was originally discovered in western Pennsylvania, a cumulative amount of 52.4 billion barrels of crude oil had been produced. In studying the writings of the leading geologists and others of the U.S.

petroleum industry the consensus was that the amount of oil ultimately produced in the conterminous United States and adjacent continental shelves would amount to about 150 billion barrels. A higher estimate of about 200 billion barrels was made by the Dallas consulting firm of DeGolyer and MacNaughton. Independent checks with exploration and production managers for different areas confirmed that the ultimate quantity, Q_∞, to be produced would probably fall within the range of 150 billion to 200 billion barrels.

Of even more significance than the general agreement upon the foregoing estimates was the almost universal intuitive judgment by petroleum geologists, engineers, and corporate officials alike concerning what these figures implied. Essentially it was this: If, in just less than a century, we have produced only about 50 billion barrels of oil, and if two or three times that amount of oil remains to be produced in the future, then plainly there can be no oil shortages during our life times - during our grandchildren's, perhaps, but not ours.

Contemporaneously, one of the most widely publicized dicta of the public-relations arm of the U.S. petroleum industry was the statement, "The United States has all the oil it will need for the foreseeable future."

Utilizing the technique illustrated in Fig. 9, the chart shown in Fig. 13 was constructed. One square of the grid represents an amount of oil

$$\begin{aligned}\Delta Q &= \Delta P \times \Delta t \\ &= 10^9 \text{ bbl/yr} \times 25 \text{ yr} \\ &= 25 \times 10^9 \text{ bbl.}\end{aligned}$$

Therefore, if we assume the lower figure of 150 billion barrels for Q_∞, the complete-cycle production curve can encompass but six squares of the grid before descending to zero. However, two squares had already been used by the cumulative production to the end of 1955, leaving but four more for the future. When allowance was made for the fact that production-rate curves must decline gradually rather than abruptly, it became impossible to draw the complete-cycle curve in Fig. 13 in a significantly different manner from that shown.

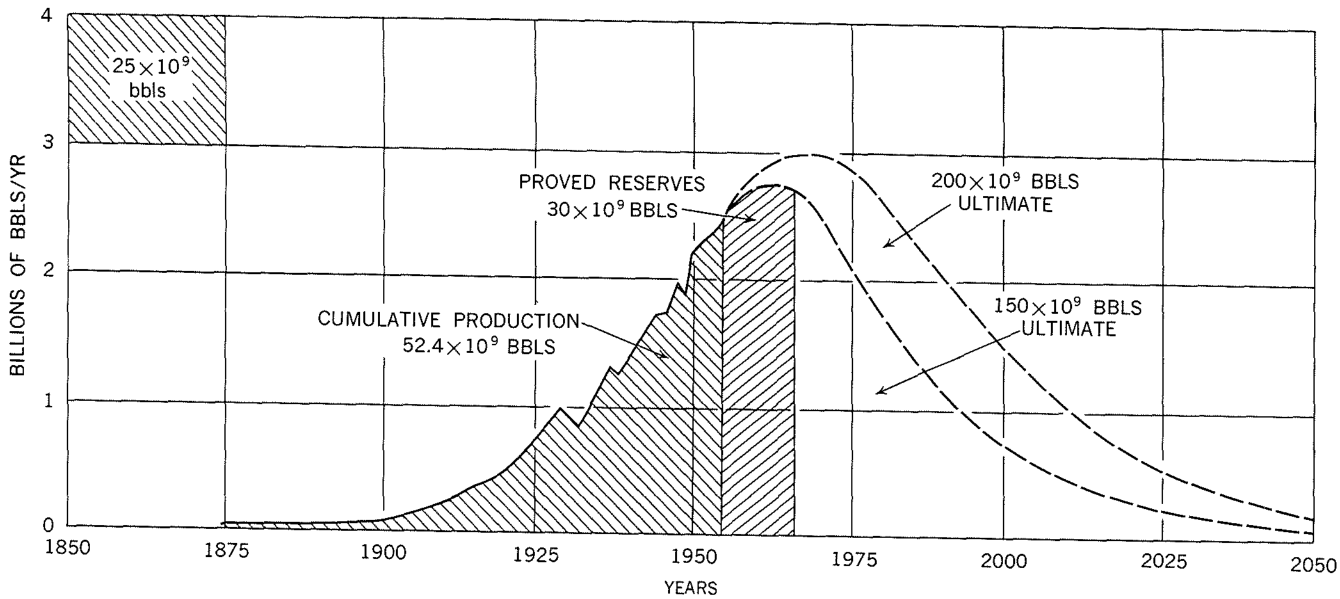

Fig. 13 - Hubbert prediction of 1956 of future production of crude oil in the conterminous United States and adjacent continental shelves [Hubbert, 1956, Fig. 21. Reproduced by permission from API, Drilling and Production Practice (1956)].

It then became evident that if the figure of 150 billion barrels for Q_∞ were approximately correct, the United States would reach its maximum rate of crude oil production in about 10 years, or by about 1966. If the larger figure of 200 billion barrels were used, this would add two more squares under the curve, but these would be principally beneath the declining part of the curve. The date of peak production would be retarded by only about five years. Hence, the general conclusion: If the foregoing estimates for Q_∞ were even approximately correct, the United States would reach the peak in its crude oil production within about 10-15 years after 1956, or between 1966 and 1971.

The initial reaction within the petroleum industry to this conclusion was one of incredulity. However, it soon was realized that the only way this unpleasant conclusion could be avoided would be by increasing the estimates of Q_∞. In particular, if the date of peak production were to be retarded by as much as a few decades, this could not be accomplished by fractional increments to the 1956 estimate; multiples would be required. Significantly, within the next five years, and with insignificant amounts of new information, published estimates for Q_∞ were rapidly escalated - 204, 250, 372, 400 and eventually 590 billion barrels. The last figure, if true, would have retarded the date of the peak in the rate of production until about the year 2000.

The fact that all of the foregoing estimates were semisubjective made it mandatory that methods of estimation based upon objective, publicly available information and explicit methods of reasoning should be devised. One such method involved the record of annual production, for which data have been available since 1860, and the annual estimate of proved reserves by a country-wide industry committee of petroleum engineers. The latter estimates have been issued about March or April of each year since 1937 and give the reserves at the end of the preceding calendar year. Approximate figures for proved reserves, based upon earlier estimates, have been extended back to the year 1900 by the statistical staff of the American Petroleum Institute.

A summation of the annual crude oil production from the year 1860 to any subsequent year gives the cumulative production, Q_p, to that year. The oil proved to have been discovered, Q_d, by any given year may be defined to be the sum of the oil already produced plus the proved reserves, Q_r. Hence, at any given year,

$$Q_d = Q_p + Q_r \tag{3}$$

Figure 14 shows the behavior of these three curves during a complete cycle of production. They are based upon the assumption, which agrees with the evidence thus far, that the complete production cycle for the conterminous United States will be a curve of dQ/dt versus t, having but a single principal maximum.

For the complete cycle, the curve for cumulative production versus time will be an S-shaped curve beginning at zero, rising exponentially for awhile and then passing its inflection point and finally leveling off asymptotically to the ultimate production, Q_∞.

The curve of proved reserves, Q_r, versus time will begin at zero, rise to a maximum about midrange in the complete cycle, and then decline gradually to zero.

The curve of cumulative proved discoveries, Q_d, as a function of time will resemble the curve of cumulative production except that in midrange it will precede the curve of cumulative production by some time interval Δt.

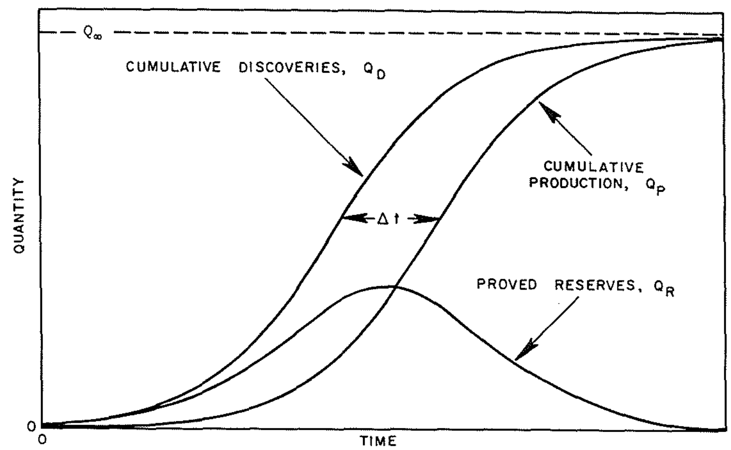

Fig. 14 - Variation with time of proved reserves, Q_r, cumulative production, Q_p, and cumulative proved discoveries, Q_d, during a complete cycle of petroleum production (Hubbert, 1962, Fig. 22).

The time derivative of Equation (3) is

$$dQ_d/dt = dQ_p/dt + dQ_r/dt \tag{4}$$

These derivative curves are shown in Fig. 15.

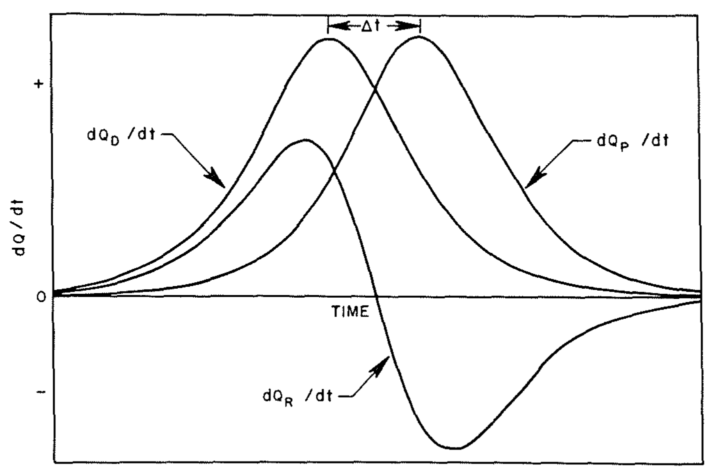

Fig. 15 - Variation of rates of production, of proved discovery, and of rate of increase of proved reserves of crude oil or natural gas during a complete production cycle (Hubbert, 1962, Fig. 24).

Curves of the rate of discovery and of the rate of production are similar except that the peak in the discovery rate precedes that of the rate of production by approximately the time interval Δt. The curve of the rate of increase of proved reserves, dQ_r/dt, has a positive loop while reserves are increasing, crosses the zero line when proved reserves reach their maximum, and has a negative loop while proved reserves are declining. Also, it will be seen from Equation (4) that when reserves are at this maximum, dQ_r/dt is zero. At that time

$$dQ_p/dt = dQ_d/dt \tag{5}$$

that is, the curves of the rate of discovery and the rate of production cross one another, the rate of discovery already declining while the rate of production is still increasing.

In the earlier stages this family of curves is uninformative, but as time advances and successive maxima begin to develop, they provide an increasingly accurate estimate of the stage of advancement of petroleum exploration and production in the complete discovery and production cycle.

In 1962 (Hubbert, 1962) the foregoing method of analysis was applied to the data for the conterminous United States. At that time the rate-of-discovery curve had already passed its peak at about 1957; proved reserves appeared to be at their peak in 1962, and the time-lag Δt was found to be about 10-11 years. This led to the estimate that the peak in the production rate should occur about 10-11 years later than the peak in the discovery rate, or about 5-6 years later than the peak in proved reserves. This would be roughly about 1967-1968, or near the end of the 1960-decade. From a mathematical fitting of the curve of cumulative discoveries (which was 10-11 years more advanced than the curve of cumulative production), it was estimated that the asymptote, Q_∞, would be about 170 billion barrels.

In 1972 (Hubbert, 1974a), with 10 more years of data, the foregoing type of analysis was repeated. The curves of cumulative production, proved reserves, and cumulative proved discoveries are shown in Fig. 16. The proved reserves did pass their maximum in 1962, and the best mathematical fit to the curves still gave 170×10^9 as the best estimate for Q_∞. The derivatives, or rate curves, corresponding to Fig. 16 are shown in Fig. 17, 18, and 19. By 1972 the rate of discovery (Fig. 17) had passed its peak at about 1957 and was well advanced on its descent down the back slope of the curve. The curve of the rate of increase of proved reserves (Fig. 18) was near the lowest point in its negative loop with proved reserves declining at an average rate of about 1 billion barrels per year. The curve of the rate of production (Fig. 19) showed a negative aberration from about 1956 to 1967 and then an

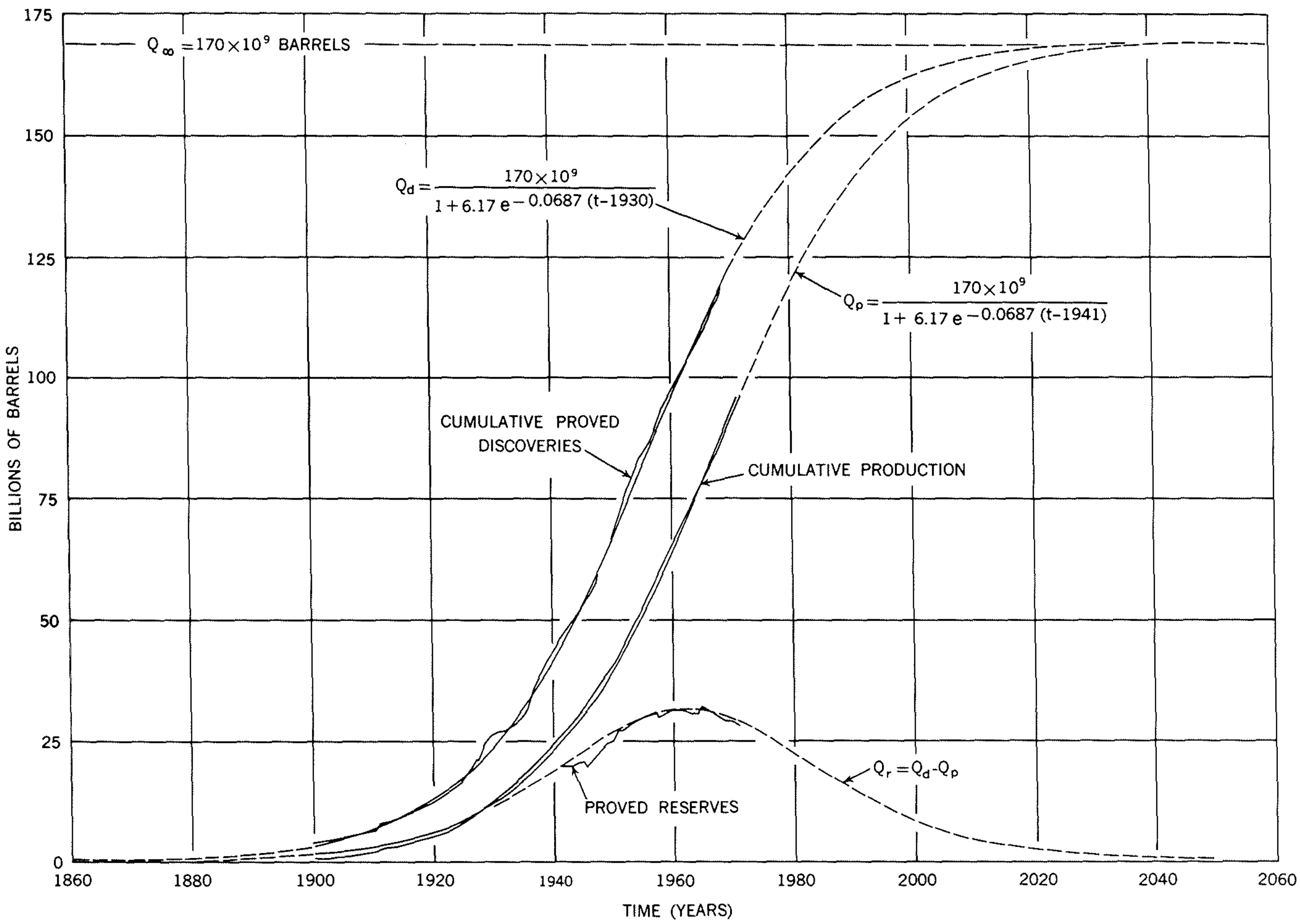

Fig. 16 - Logistic equations and curves of cumulative production, cumulative proved discoveries, and proved reserves for crude oil for the conterminous United States 1900-1971 (Hubbert, 1974a, Fig. 36).

asymmetric positive spike with a peak in the year 1970. These aberrations were evidently due in large part to the Suez Crisis of 1956 and subsequently to the successive Middle East disturbances. The smooth mathematical curve of the rate of crude oil production had its maximum in 1968, in agreement with the estimate of 1962.

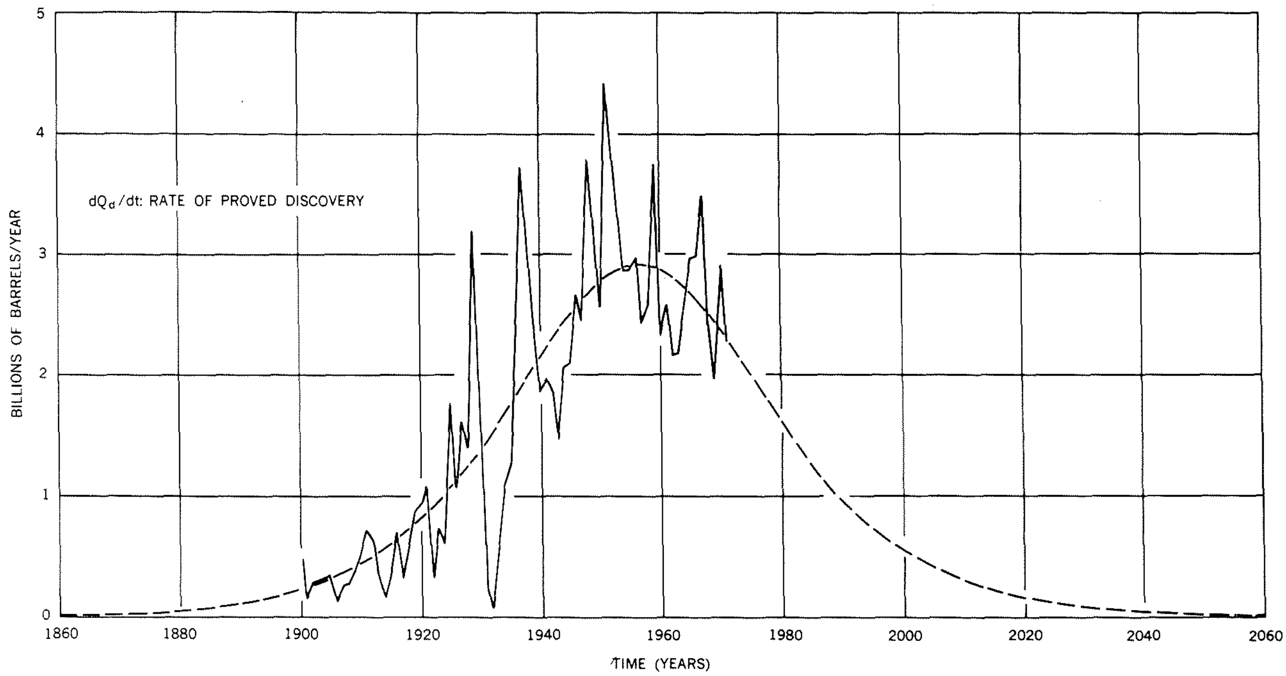

Fig. 17 - Comparison of annual proved discoveries of crude oil in the conterminous United States, 1900-1971, with corresponding theoretical curve derived from logistic equation (Hubbert, 1974a, Fig. 38).

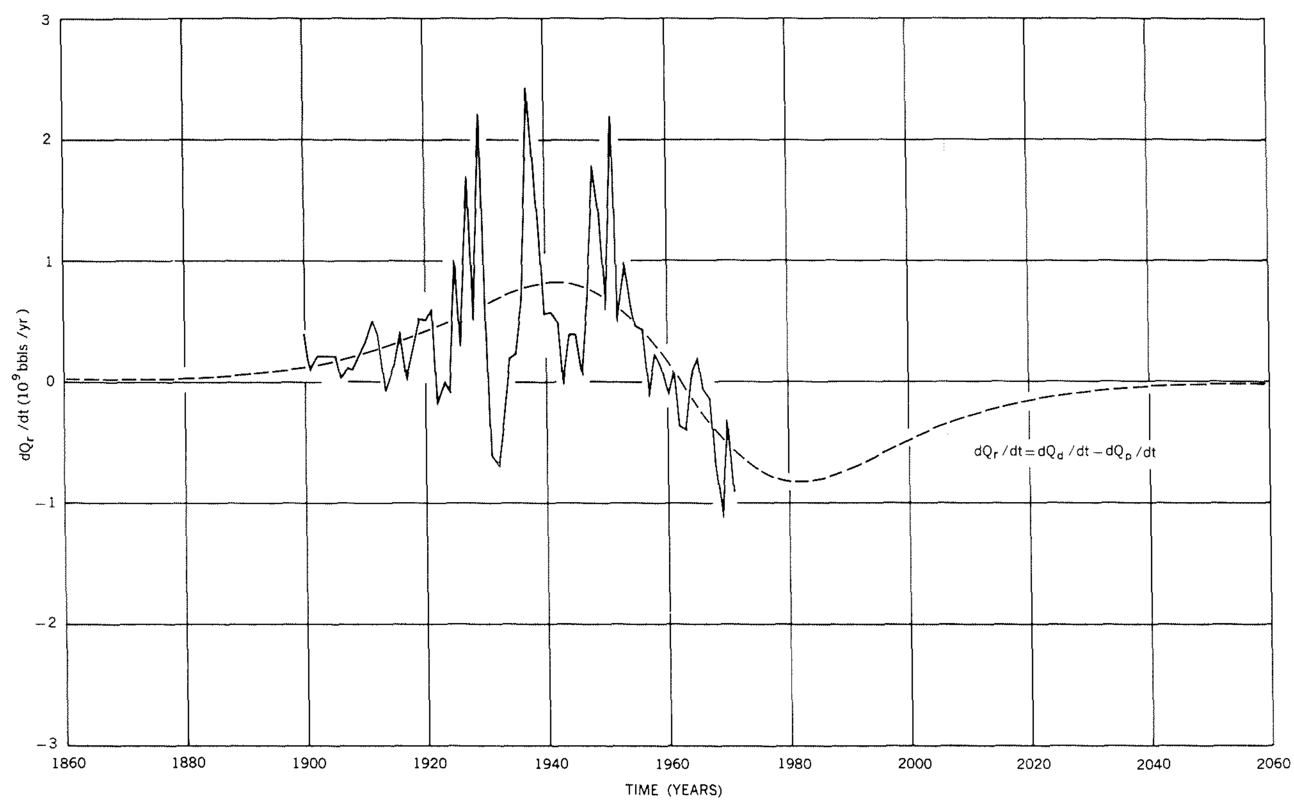

Fig. 18 - Comparison of annual increases of proved reserves of conterminous United States, 1900-1971, with theoretical curve derived from logistic equations (Hubbert, 1974a, Fig. 40).

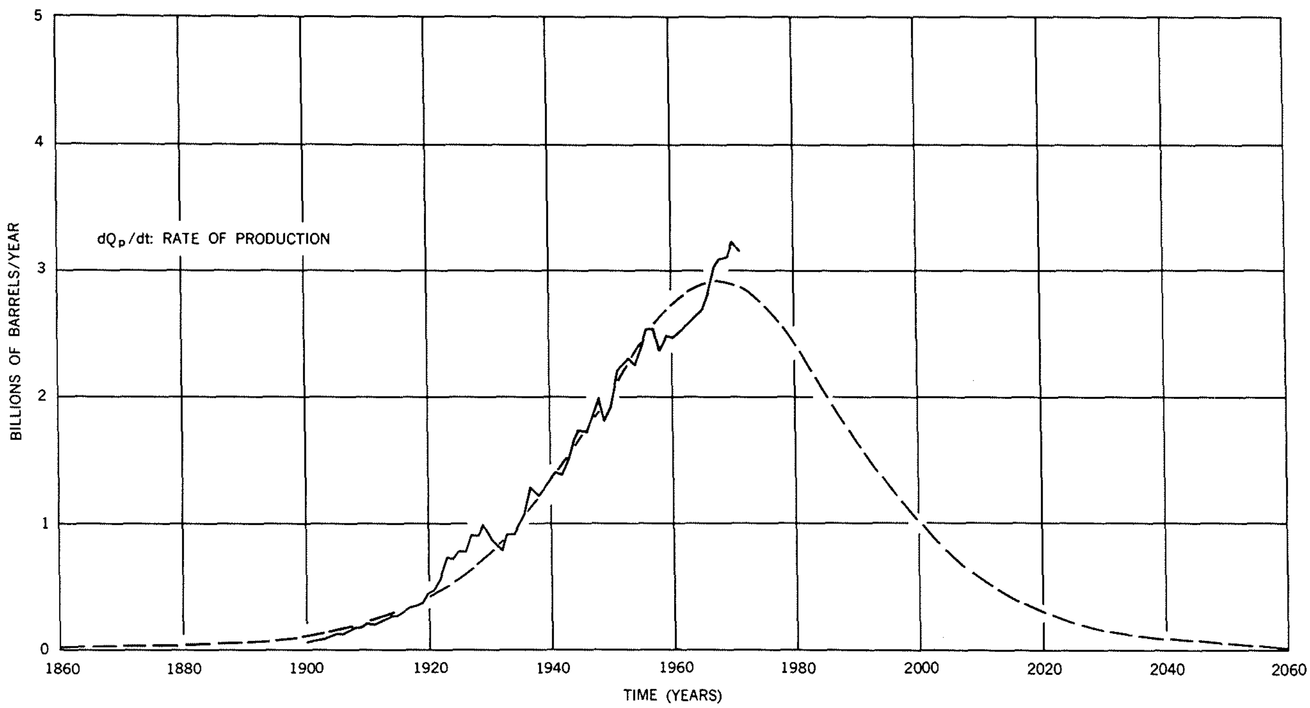

Fig. 19 - Comparison of annual crude-oil production in conterminous United States, 1900-1971, with corresponding theoretical curve derived from logistic equation (Hubbert, 1974a, Fig. 39).

Discoveries per foot of exploratory drilling

A different method of estimation is based upon the fact that in any given region the easier and often the larger discoveries are made early in the cycle. Then, as exploratory drilling continues, the undiscovered accumulations continuously decrease in number while increasing in depth and obscurity. The result is that the probability of discovery by a given amount of exploratory drilling declines in a negative-exponential manner as exploratory drilling progresses.

These facts suggest a means of analysis whereby the average amount of oil discovered per unit depth of exploratory drilling, dQ/dh, is plotted as a function of cumulative depth, h. Figure 20 shows the discovery record for crude oil as a function of cumulative exploratory drilling in the conterminous United States and adjacent continental shelves from 1860 to 1972. By 1972 the cumulative depth of exploratory drilling amounted to 1.7×10^9 ft, or to 17 units of 10^8 ft each. The heights of the separate columns represent the average number of barrels per foot discovered during each 10^8-ft unit of

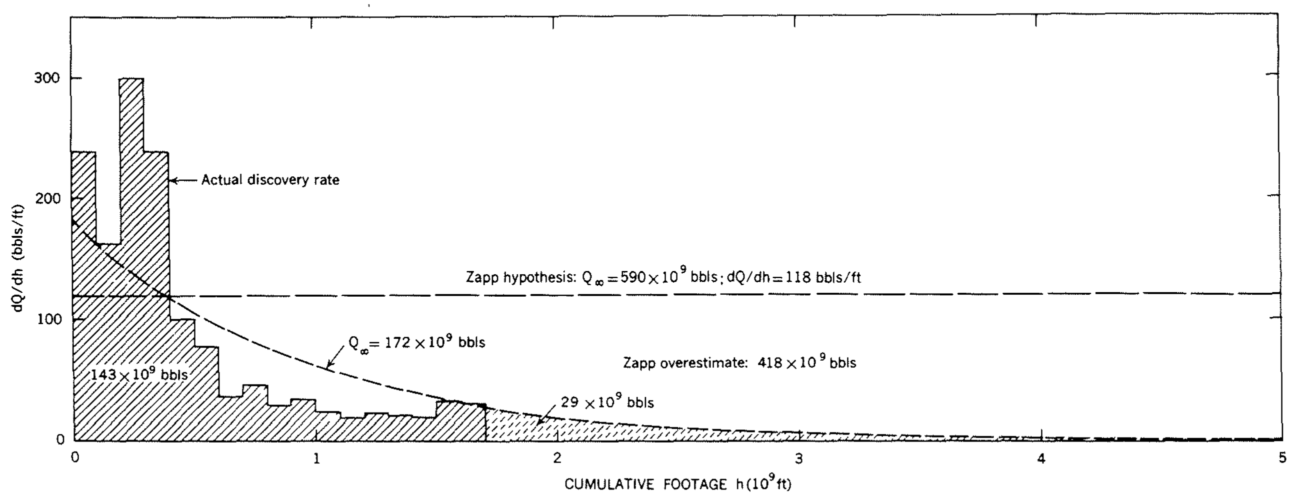

Fig. 20 - Estimation of ultimate crude oil production of conterminous United States by means of curve of discoveries per foot versus cumulative footage of exploratory drilling, and comparison with Zapp hypothesis (Hubbert, 1974a, Fig. 50).

drilling, their areas the quantities of oil discovered. The total shaded area is a measure of the total quantity of oil discovered from 1860 to 1972. The total amount of oil discovered by 1972 was estimated to be about 143 billion barrels. This is the sum of cumulative production plus proved reserves plus an additional amount of recoverable oil in known fields not yet included as proved reserves.

During the first 10^8-ft of drilling, which required the 60-year period from 1860 to 1920, the success ratio was high, averaging 240 bbl/ft. During the second interval, which included most of the 1920-decade, discovery was becoming more difficult and the rate dropped to 161 bbl/ft. Then, during the third interval, extending from about 1928 to 1936, a maximum rate of 300 bbl/ft was reached. This interval included the accidental discovery of the 6-billion barrel East Texas field, which alone accounted for 60 bbl/ft. It was also the period during which reflection seismology, the gravity meter, and electrical well logging were introduced. Then, following the third interval, we see a precipitous decline to about 30 bbl/ft by the time the 17th interval was reached.

It is significant that this decline after the mid-1930's occurred during the period of the most intensive research and development in methods of exploration and production in the history of the petroleum industry. This decline in discoveries per foot versus cumulative footage of exploratory drilling is roughly a negative-exponential decline. Hence, in order to estimate the future discoveries, a negative-exponential decline curve needs to be determined which most nearly agrees with the data. Such a curve would be one which equalizes the excesses and defects in the discovery rate, and passes through the point 30.2 bbl/ft at $h = 17 \times 10^8$ ft.

The decline curve satisfying these conditions is shown by the dashed line in Fig. 20. It passes through the point $dQ/dh = 181.6$ bbl/ft at $h = 0$, and 30.2 bbl/ft at $h = 17 \times 10^8$ ft, and has a decline rate of 10.55% for each 10^8 ft of drilling. Extrapolating this decline curve into the future at the same rate of decline gives an estimate of 29 billion barrels for future discoveries with unlimited future drilling. Adding this to the 143 billion barrels already discovered gives a total of 172 billion barrels as an independent estimate for Q_∞. This is in very close agreement with the figure of 170 billion barrels obtained by the previous method of analysis.

The complete cycle of crude oil production, based upon the estimate of 170 billion barrels for Q_∞ for the lower 48 States and adjacent continental shelves, is shown in Fig. 21. By the end of 1971 cumulative production amounted to 96 billion barrels, and reserves of recoverable oil from fields already discovered were estimated from the analysis of discoveries per foot to amount to an additional 47 billion barrels. This left 27 billion barrels (or 29 billion if Q_∞ is taken to be 172 billion barrels) for future discoveries.

From this it appears that of the estimated 170 billion - 172 billion barrels of oil ultimately to be recovered from this area, probably more than 80% will be from fields already discovered by the end of 1971.

The time required to produce the middle 80% of Q_∞ is also significant. This is the approximately 67-year period from about 1932 to 1999. Hence, a child born in the 1930's, if he lives a normal life expectancy, will see the United States consume most of its oil during his lifetime.

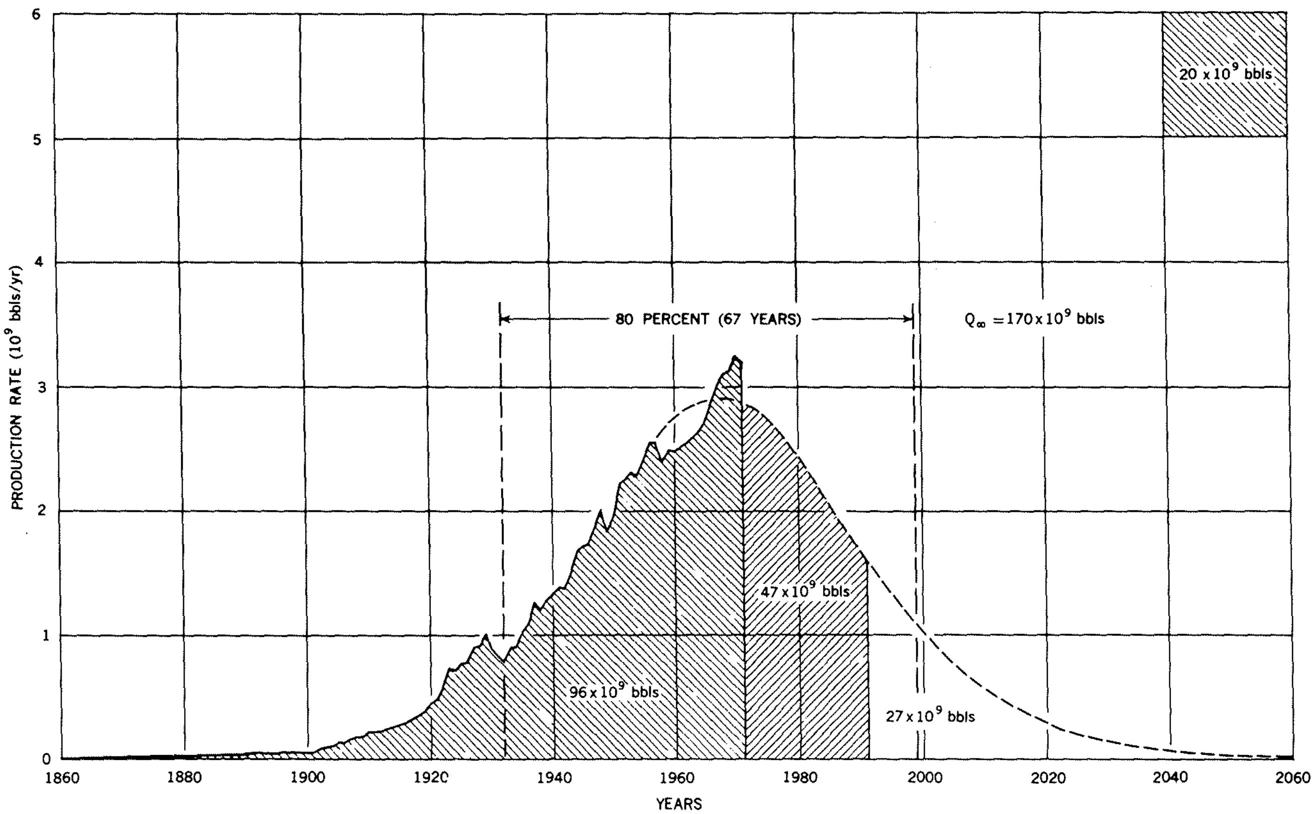

Fig. 21 - Complete cycle of crude oil production in conterminous United States as of 1971 (Hubbert, 1974a, Fig. 51).

Estimates of U. S. natural gas and natural-gas liquids

In the 1962 report (Hubbert, 1962), the natural-gas estimate was obtained by adding to the cumulative discoveries to 1962 an estimate of future discoveries based on the ratio of recent gas to oil discoveries applied to the prior estimate of future discovery of crude oil. When a current gas-oil ratio of 6,250 ft^3 of gas per barrel of crude oil was used, it gave a value for Q_∞ for natural gas of 958 trillion ft^3; when a higher future ratio of 7,500 ft^3/bbl was assumed, an estimate of 1,053 trillion ft^3 resulted. These were rounded off to 1,000 trillion ft^3.

The date at which proved reserves of natural gas would reach their maximum was estimated to be 1969, and the date of peak production rate was 1976-1977.

The corresponding estimates obtained by a comparable study as of 1972 were the following:

The value of Q_∞ obtained from the prior oil estimate and the gas-oil ratio was still 1,000 trillion ft^3. However, a higher figure of 1,103 trillion ft^3 was obtained from an analysis of discoveries per foot versus cumulative depth of exploratory drilling. A median figure of 1,050 was adopted as the best present estimate. Whereas in 1962 the peak date for proved reserves of natural gas was estimated to be 1969, it actually occurred in 1967. The date of the peak in the production rate will not be known until after it has been passed, but it now appears to be very close to the present - 1973 to 1974.

Natural-gas liquids are the components of natural gas which when separated from the mixture are liquid under surface temperatures and atmospheric pressure. Currently, approximately one barrel of natural-gas liquids is obtained from each 30,000 ft^3 of natural gas produced. Cumulative production of natural-gas liquids by the end of 1971 amounted to 13.4 billion barrels; an additional 21 billion barrels was estimated to be recoverable from the future gas production of 636×10^{12} ft^3. Adding these two figures gives an estimate of about 34 billion barrels for Q_∞ for natural-gas liquids.

Complete cycle for U. S. production of petroleum liquids

When the figure of 34 billion barrels for Q_∞ for natural-gas liquids for the conterminous United States is added to the prior estimate of 170 billion barrels for crude oil, we obtain a figure of 204 billion barrels for total hydrocarbon liquids. On the basis of this figure, the complete production cycle for petroleum liquids is shown in Fig. 22. This curve reaches its maximum in 1970, and the time required to consume the middle 80% is the 61-year period from about 1938 to 1999.

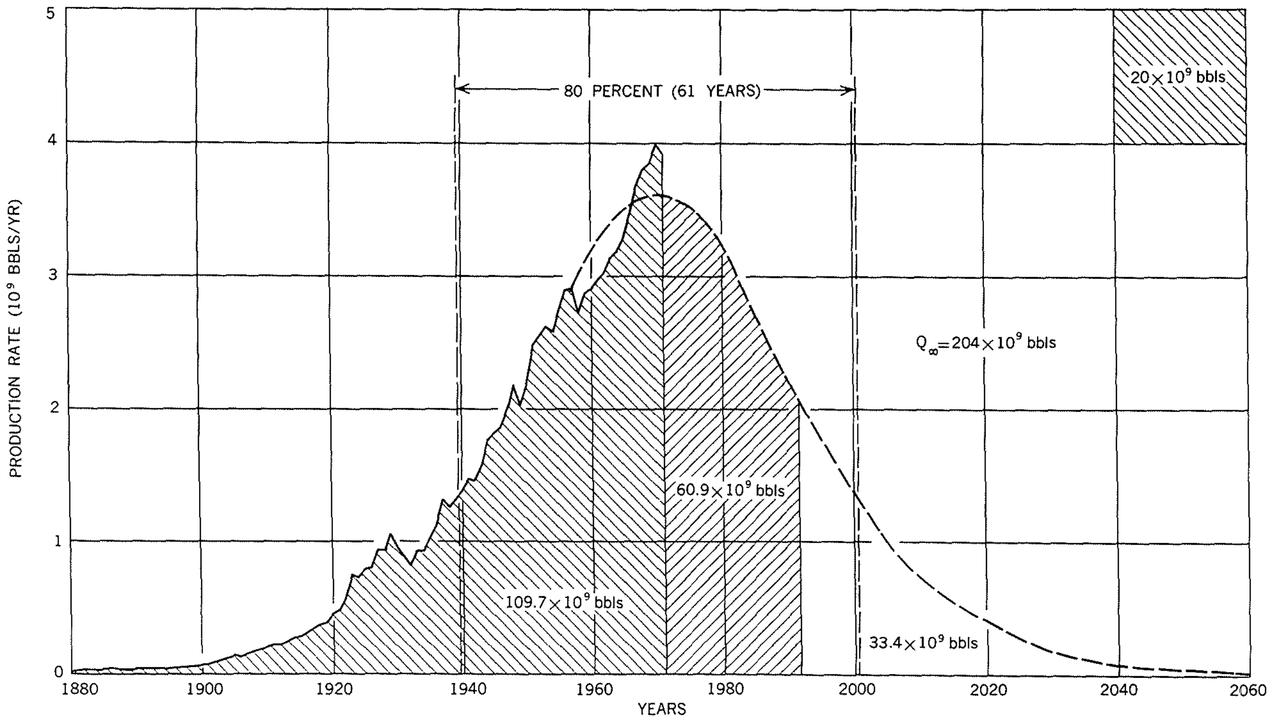

Fig. 22 - Estimate as of 1972 of complete cycle of petroleum liquids production in the conterminous United States (Hubbert, 1974a, Fig. 66).

Complete cycle of world crude oil production

The estimation of Q_∞, the ultimate cumulative crude oil production, for the world involves the combined use of the two methods outlined previously: (1) estimation by geological analogy for undrilled sedimentary basins, and (2) estimation of the ultimate production in regions already partially exploited on the basis of prior drilling and discovery experience.

Principally during the last 30 years, the petroleum industry has extended its exploratory activities to the entire world, both the land areas and the oceanic shallow seas and continental shelves. During this period successive estimates have been made by petroleum geologists, principally those with international oil companies, of approximately how much crude oil will ultimately be produced in the entire world. Table 1 gives a summary of such published estimates made during the period 1949 to 1973. The earlier estimates, based upon less complete information on land and giving little allowance for drilling offshore, were understandably lower than the more recent estimates. Disregarding the first three estimates in Table 1, the last 15 range from 1,200 billion to 2,480 billion barrels and average 1,840.

Table 1. Estimates of ultimate world crude oil production

Year	Author	Organization	Quantity (10^9 bbl)	Reference
1949	L. G. Weeks	Standard Oil Co. (N.J.)	1,000	Weeks, 1949
1949	A. I. Levorsen	Stanford University	1,500	Levorsen, 1949
1953	L. W. MacNaughton	DeGolyer and MacNaughton	1,000	MacNaughton, 1953
1958	L. G. Weeks	Standard Oil Co. (N.J.)	1,500	Weeks, 1958
1959	L. G. Weeks	Standard Oil Co. (N.J.)	2,000	Weeks, 1959
1962	M. King Hubbert	National Academy of Sciences	1,250	Hubbert, 1962
1965	T. A. Hendricks	U. S. Geological Survey	2,480	Hendricks, 1965
1967	W. P. Ryman	Standard Oil Co. (N.J.)	2,090	Cited in Hubbert, 1969, table 8.2
1968	- - - - - -	Shell	1,800	Warman, 1971
1968	L. G. Weeks	Consultant	1,870*	Weeks, 1968a, b
1969	M. King Hubbert	Nat'l. Acad. Sci. - Nat'l. Res. Council	1,350-2,000	Hubbert, 1969
1970	J. D. Moody	Mobil Oil Corporation	1,800	Moody, 1970
1971	H. R. Warman	British Petroleum Co. Ltd.	1,200-2,000	Warman, 1971
1971	L. G. Weeks	Lewis G. Weeks Associates Ltd.	1,950**	Weeks, 1971
1972	J. D. Moody and H. H. Emmerick	Mobil Oil Corporation	1,800-1,900	Moody and Emmerick, 1972
1972	Richard L. Jodry	Sun Oil Co.	1,952	Cited in Hubbert, 1974a, table 9
1972	H. R. Warman	British Petroleum Co. Ltd.	1,800	Warman, 1972
1973	Wim Vermeer	Shell	1,930	Vermeer, 1973

*85% of petroleum liquids estimate of 2,200 x 10^9 bbl.
**85% of petroleum liquids estimate of 2,290 x 10^9 bbl.

For present purposes the approximate distribution of the ultimate recoverable crude oil resources by major geographical areas is shown in Fig. 23. This figure is based upon an unpublished study by Richard L. Jodry (Hubbert, 1974a, Fig. 67 and table 10) of Sun Oil Company which he has permitted me to use with the understanding the estimates are attributable to him personally but do not necessarily represent the views of Sun Oil Company. Jodry's study involved a detailed analysis of every potential petroleum producing area in the world. The estimates for separate areas add up to a total of 1,952 billion barrels for the whole earth. Regional estimates by other authors give approximately the same geographical distribution of the world's petroleum resources as those estimated by Jodry.

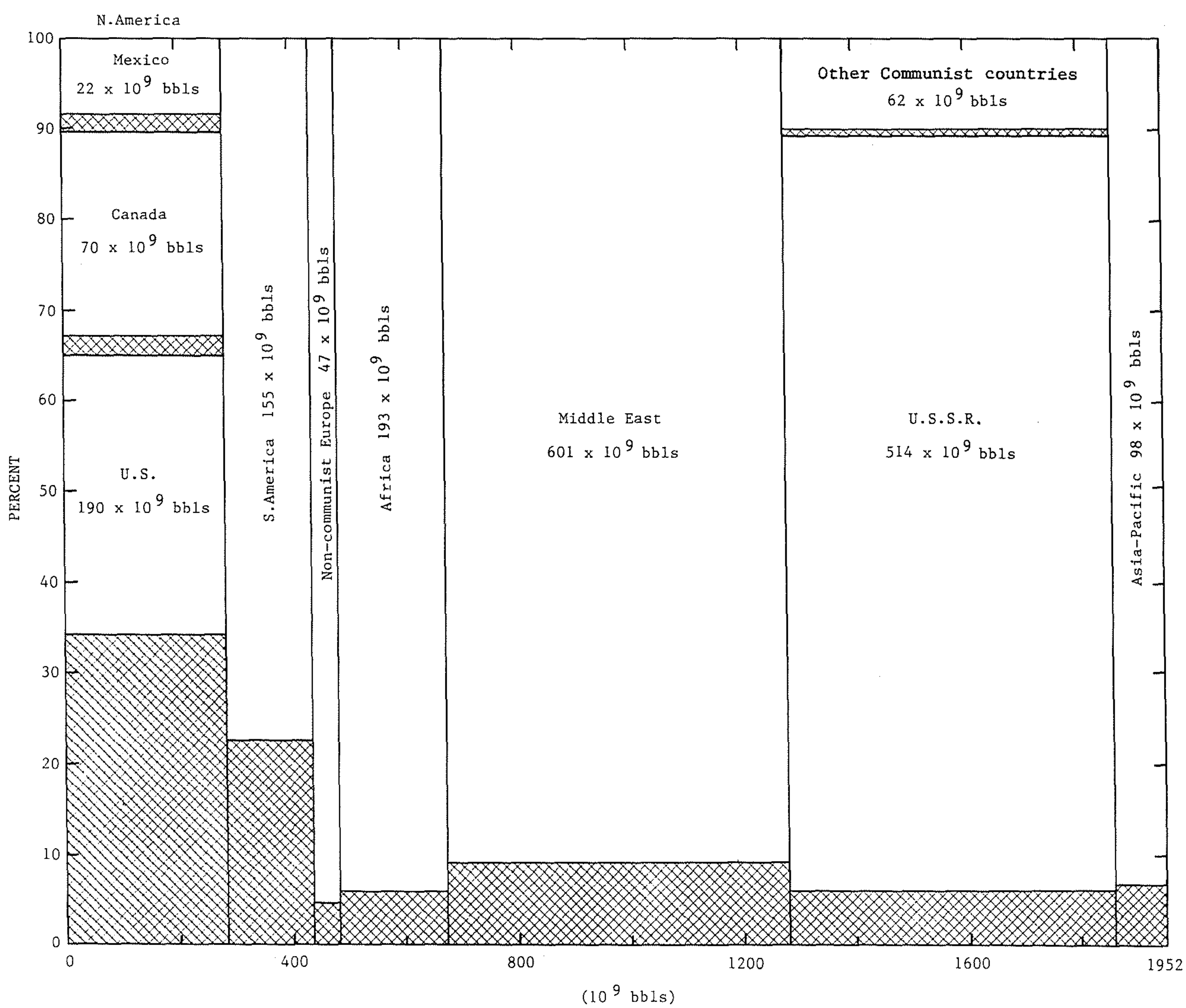

Fig. 23 - Graphical representation of Jodry estimate of world ultimately recoverable crude oil. The shaded areas at the foot of each column or sector represent quantities already consumed (Hubbert, 1974a, Fig. 67).

In Fig. 23 the horizontal scale represents the cumulative amount of oil for separate regions. The areas of the vertical columns are proportional to the estimated oil resources for the separate regions. The shaded area at the base of each column or sector represents the quantity of oil already produced.

Two principal results are obvious from Fig. 23 by inspection. First, the North American column, of which the United States accounts for about two-thirds, represents only about 15% of the world's total crude oil resources. Second, the bulk of the world's remaining petroleum resources are to be found in the Middle East, Africa, and the U.S.S.R. It is especially significant that the United States with only about one-tenth of the world's initial oil resources is the world's largest consumer of oil, and, until 1974, has been the largest producer of oil of any country in the world. It is unavoidable, therefore, that the United States should be the leading major country in the exhaustion of its petroleum resources.

The complete cycle of world crude oil production, based on a round figure of 2,000 billion barrels for Q_∞, is shown in Fig. 24. The figure assumes an orderly growth and decline in petroleum production. It is possible, of course, that because of political and economic disturbances the orderly growth could be curtailed. This would have the effect of distorting the curve, making it flatter on top and extending the declining part further into the future. For a normal undisturbed cycle of production, the peak production rate will probably occur between the years 1990 and 2000. The time required to produce the middle 80% of Q_∞ is estimated to be only about 56 years, extending from about 1967 to 2023. According to this, a person born about 1970 should, with a normal life span, see the world consume the bulk of its petroleum during his lifetime.

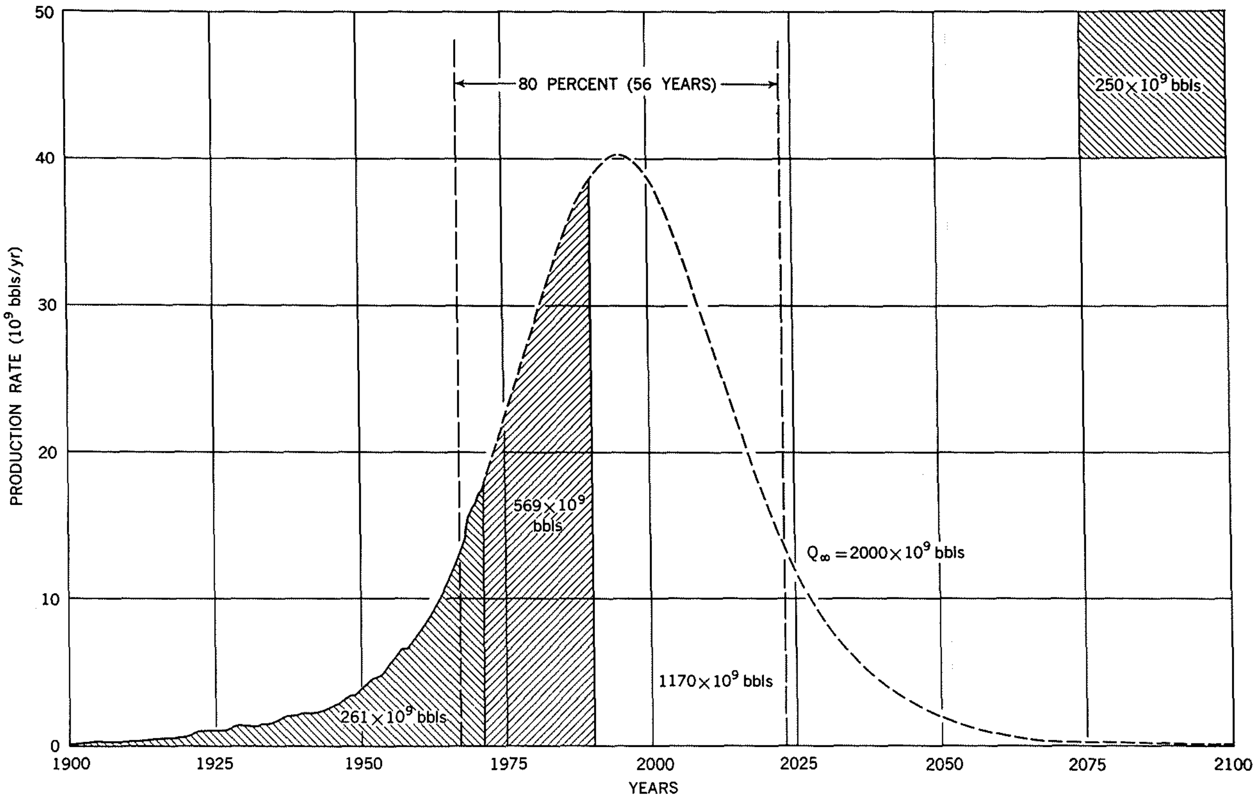

Fig. 24 - Estimate as of 1972 of complete cycle of world crude oil production (Hubbert, 1974a, Fig. 68).

World resources of natural gas and natural-gas liquids

Because of lack of transportation facilities a large fraction of the natural gas produced in association with oil production in the nonindustrialized regions of the world is flared at the sites of production. About as good an estimate as can be made of the world's potential supply of natural gas and natural-gas liquids is to assume that the ratio of natural gas to crude oil and of natural-gas liquids to natural gas will have about the same average values worldwide as in the United States.

For the United States the ratio of the estimated ultimate amount of natural gas to the ultimate amount of crude oil is approximately

$$\frac{1050 \times 10^{12} \text{ ft}^3}{170 \times 10^9 \text{ bbl}} = 6{,}200 \quad \text{ft}^3/\text{bbl}.$$

The corresponding ratio of natural-gas liquids to crude oil is

$$\frac{34 \times 10^9 \text{ bbl}}{170 \times 10^9 \text{ bbl}} = 0.2.$$

Assuming, roundly, a figure of 2,000 x 10^9 bbls for the world's ultimate recoverable crude oil, and the above ratios, we obtain as an estimate for natural gas

$$2.0 \times 10^{12} \text{ bbl} \times 6.2 \times 10^3 \text{ ft}^3/\text{bbl} = 12.4 \times 10^{15} \text{ ft}^3,$$

or roundly, about 12,000 trillion ft^3.

For natural-gas liquids the corresponding estimate would be 0.2 x 2,000 billion barrels of crude oil or about 400 billion barrels. Hence, based upon a figure of 2,000 billion barrels for crude oil, the world's ultimate supply of petroleum liquids would be about 2,400 billion barrels, or about 2,200 if the average estimate of 1,840 billion barrels for crude oil is accepted.

Other fossil fuels

Space here will permit only brief mention of other fossil fuels. These comprise principally the heavy oil or tar sands and the oil shales.

Heavy-oil sands. - The largest and best known deposits of heavy oil sands are the Athabasca and other deposits in northern Alberta, Canada, and an extensive deposit in the Orinoco Valley in southeastern Venezuela. Large-scale exploitation by open pit mining of the Athabasca deposit began in 1966 by the Great Canadian Oil Sands Ltd., and projects by other companies are about to begin. The most recent estimates of the amount of synthetic crude oil obtainable from these deposits are those of Scott (1974):

	(10^9 bbl)
Oil-in-place	625
Extractable:	
by mining	38
by in-situ methods	110
Total	148

According to Scott, 70 barrels of synthetic crude oil are obtainable from 100 barrels of raw oil. Hence, the total synthetic crude oil obtainable from these deposits would be about 104 billion barrels.

According to a recent staff report in the Oil and Gas Journal (1973) a heavy oil belt, roughly 85 km wide and 600 km long, extends east-west along Venezuela's Eastern Basin. This lies north of and parallel to the Orinoco

River. About 84% of this occurs in four main areas from west to east: Gorrin-Machete, Altimira-Iguana-Zuata, Santa Clara-Hamaca, and Cerro Negro. The average net pay thickness is about 82 meters in the first area and about 100 meters in each of the other three. The gravity of the oil is about 8°-12° A.P.I. The oil-in-place is estimated to be about 700 billion barrels of which 10%, or 70 billion barrels, is considered recoverable.

According to a more recent account (Oil and Gas Journal, 1974b) new data indicate that the belt is larger than it was first thought to be. It extends farther south and closer to the Orinoco River, and the sands are thicker than originally estimated. The average gravity is now said to be 8°-10° A.P.I.

According to these figures, the recoverable oil from this source may amount to as much as 100 billion barrels of raw crude oil, or about 70 billion barrels of synthetic crude oil.

Oil shales - Unlike heavy-oil sands which contain highly viscous liquids, the oil shales contain varying amounts of solid hydrocarbons, principally kerogen. Upon being heated in a test tube the kerogen from this shale distills off as a dense amber-colored vapor and then condenses on the cool wall of the tube as a liquid.

A worldwide study of the known occurrences of oil shales was published in 1965 by Duncan and Swanson of the U. S. Geological Survey and a condensation of their results is given in Table 2. This gives a rounded total of 5,300 billion barrels of shale oil in shales having contents within the range of 5-100 U.S. gallons per short ton of shale. Of this, however, these authors regarded only about 190 billion barrels as being recoverable under 1965 conditions.

The best known, and among the richest of the world's oil shale deposits are those of the Green River Formation of Eocene age in Wyoming, Colorado, and Utah in western United States. An engineering study of these deposits has recently been made by a Task Group of the National Petroleum Council (Natl. Petroleum Council, Oil Shale Task Group, 1972). Table 3 gives the estimates by this group of the recoverable oil (based upon 60% recovery).

Table 2. Known shale oil resources of world land areas

	Recoverable under 1965 conditions	Marginal and submarginal		
Grade (US gal/ton)	10 - 100	5 - 10	10 - 25	25 - 100
Continents	Oil content (10^9 barrels)			
Africa	10	small	small	90
Asia	20	ne	14	70
Australia and New Zealand	small	ne	1	small
Europe	30	ne	6	40
North America	80	2,200	1,600	520
South America	50	ne	750	small
Totals	190	2,200	2,400	720

ne: No estimate.
Source: Duncan and Swanson (1965).

The categories of decreasing favorability are listed as Classes 1, 2, and 3. Class 1 comprises beds at least 30 ft thick having an average oil content of at least 35 gal/ton. Class 2 comprises shales containing beds at least 30 ft thick and having an average oil content of at least 30 gal/ton. Class 3 comprises shales comparable to those of Class 2 only less well defined or more inaccessible. The total recoverable oil from these three classes in the three separate deposits amounted to 188 billion barrels. Of this, however, only the 20 billion barrels of the Class 1 deposits of the Piceance Basin in western Colorado were considered exploitable at present.

Table 3. Reserves of recoverable oil from the Green River Formation, Colorado, Utah, and Wyoming

Location	Shale-oil reserves: at 60% recovery (10^9 bbl)			
	Class 1	Class 2	Class 3	Total
Piceance Basin, Colo.	20	50	100	170
Uinta Basin, Colo. and Utah		7	9	16
Green River Basin, Wyo.			2	2
Total	20	57	111	188

Source: National Petroleum Council, Oil Shale Task Group (1972).

Consistent with this appraisal, the Department of the Interior has recently made several leases of blocks of land of about 5,000 acres each in the Piceance Basin to several petroleum industry groups. One of the largest of these is the Colony Development Operation, a joint-venture consortium comprising Atlantic-Richfield Co., Shell Oil Co., Ashland Oil Inc., and Oil Shale Corporation, under the management of Hollis M. Dole, former Assistant Secretary of the Interior for Mineral Resources. This was to be a 50,000 bbl/day mining and extraction operation.

According to the Oil and Gas Journal (1974a), Colony has recently been forced to suspend its plans for plant construction because of inflation and other difficulties. The cost of the extraction plant, which would have been $450 million in 1973, has inflated to more than $800 million for completion in 1977.

This is indicative of only some of the difficulties in the extraction of oil from shale. Twenty plants with capacities of 50,000 bbl/day each would be required to achieve a daily oil production of 1 million barrels, and this would be barely significant in meeting the present U. S. rate of oil consumption of about 17 million bbl/day. In any case, the additional energy obtainable from heavy oil sands and from shale appears at present to be but a minor fraction of that obtainable from coal and from crude oil, natural gas, and natural-gas liquids. At present a figure of 200 billion barrels appears to be a liberal allowance for the ultimate world production of synthetic crude oil from heavy oil sands and oil shale.

Summary of fossil fuels

On the basis of the foregoing review, Table 4 gives the approximate magnitudes, and their energy contents, of the world's initial supply of recoverable fossil fuels. In this table Averitt's (Averitt, 1969) higher estimate of 7.6×10^{12} metric tons for the world's recoverable coal has been used. This includes beds as thin as 1 ft (0.3 m) thick occurring at depths of 6,000 ft (1.8 km) or less. Were the coal resources to be limited to beds 28 in (0.71 m) thick and 1,000 ft (300 m) or less deep, the coal estimates in Table 4 would be reduced to about 2×10^{12} metric tons.

If the larger estimate is used, coal and lignite account for about 89% of the total energy content of the fossil fuels. Most of the remainder is accounted for by petroleum liquids and natural gas, each accounting for a little more than 5% of the total supply of energy from the fossil fuels.

The significance and brevity of the fossil fuel exploitation in human history can best be appreciated if the complete cycle of production of energy from the fossil fuels is plotted graphically on a time span extending from 5,000 years in the past to 5,000 years in the future - a span well within the range of prospective human history. Such a plotting is shown in Fig. 25. The Washington-Monumentlike spike having a middle 80% span of about three centuries represents the whole epoch of the fossil fuels. It is true that the production rate may taper off for 1,000 years in each direction, but the bulk of the initial supply will probably be consumed within the three centuries from about 2000 to 2300 A.D.

Although this represents but a brief interval in human history, the exploitation of the fossil fuels has been principally responsible for the rise

Table 4. Approximate magnitudes and energy contents of world's initial recoverable fossil fuels

Fuel	Quantity	Energy per unit	Energy content (10^{21} Joule	Percent
Coal and lignite	7.6 x 10^{12} metric tons	3.05 x 10^{10} joule/metric ton	232	88.9
Petroleum liquids	2.4 x 10^{12} bbl	5.91 x 10^{9} joule/bbl	14.2	5.4
Natural gas	12.4 x 10^{15} ft	1.09 x 10^{6} joule/ft^3	13.5	5.2
Tar sands and Oil shale	200 x 10^{9} bbl	5.91 x 10^{9} joule/bbl	1.2	0.5
		Totals	261	100.0

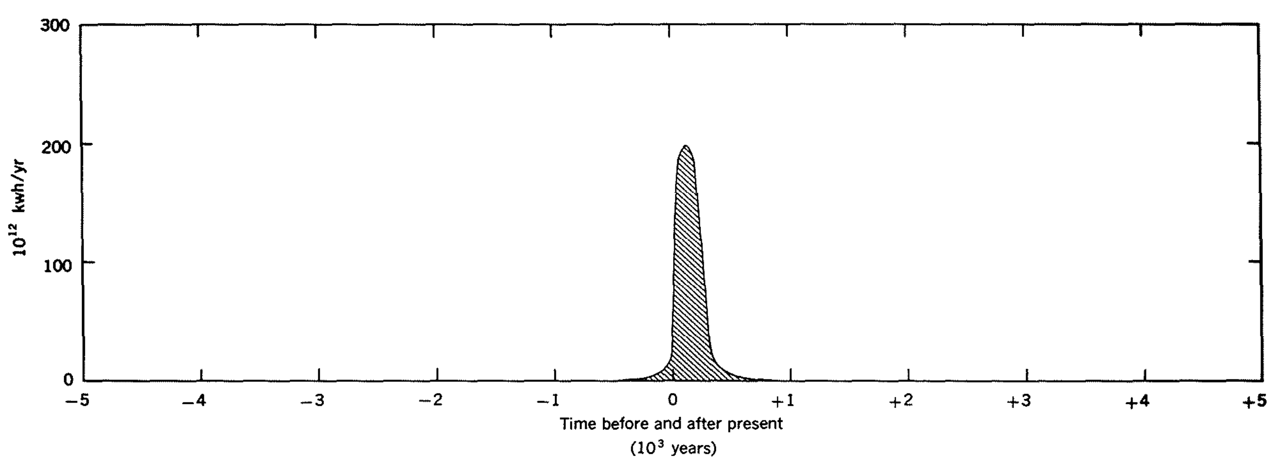

Fig. 25 - The epoch of fossil fuel exploitation as seen on a time scale of human history from 5,000 years ago to 5,000 years in the future (modified from Hubbert, 1962, Fig. 54).

of the world's modern industrial civilization. At the same time it has been the most disturbing influence ever experienced by the human species during its entire existence.

Other sources of energy

In view of the fact that the fossil fuels can only suffice for at most a few centuries as a major source of energy in a highly industrialized world, prudence demands that attention should now be given to the acquisition of other sources of energy of comparable magnitudes. For such sources we refer again to Fig. 1. In the energy flow sheet the channels that are already in various stages of development are those of waterpower, wind power, and tidal power. Among the stored forms of energy other than the fossil fuels, we have geothermal energy and nuclear energy.

Waterpower

Of the foregoing sources of industrial energy, waterpower is one of the more attractive. During the last century, because of the development of electrical means of generation and distribution of power, waterpower has become a source of industrial power second only to the fossil fuels.

The potential and developed waterpower capacities of the various major geographical regions of the world are given in Table 5. The total potential capacity is about 3×10^{12} electrical watts, of which about 8.5% have already been developed. The most completely developed regions are the highly industrialized areas of North America, Western Europe, the USSR, and the Far East. The regions having the largest potential waterpower are Africa, South America and Southeast Asia, which are also the least industrialized regions of the world.

A graphical representation of the growth of waterpower development is shown in Fig. 26.

For comparison, the world's present total energy consumption for industrial purposes is about 6×10^{12} thermal watts, or about twice the potential magnitude of waterpower. Hence, although waterpower is potentially very large, it is not large enough to replace the fossil fuels as a source of industrial power. Waterpower is also confronted with another difficulty when considered on a time span of a few centuries. Most waterpower developments

Table 5. World potential and developed waterpower capacity

Region	Potential power[a] (10^3 MW)	Percent of total	Developed[b] capacity, 1967 (10^3 MW)	Percent developed
North America	313	11	76	23
South America	577	20	10	1.7
Western Europe	158	6	90	57
Africa	780	27	5	0.6
Middle East	21	1	1	4.8
Southeast Asia	455	16	6	1.3
Far East	42	1	20	48
Australia	45	2	5	11
USSR, China, and satellites	466	16	30	6.4
World	2,857	100	243	8.5

Sources: [a] Francis L. Adams, 1961
[b] U.S. Federal Power Commission, 1967

involve the building of large dams and the storage of water in large reservoirs. These reservoirs from their inception become the repositories of streamborne sands and muds, and the time required for their complete fill-up is commonly only a few centuries. After a reservoir is filled with sediments it is no longer of much use for the generation of power. For this reason, even waterpower may not be able to serve as a nearly constant source of power for more than a few centuries.

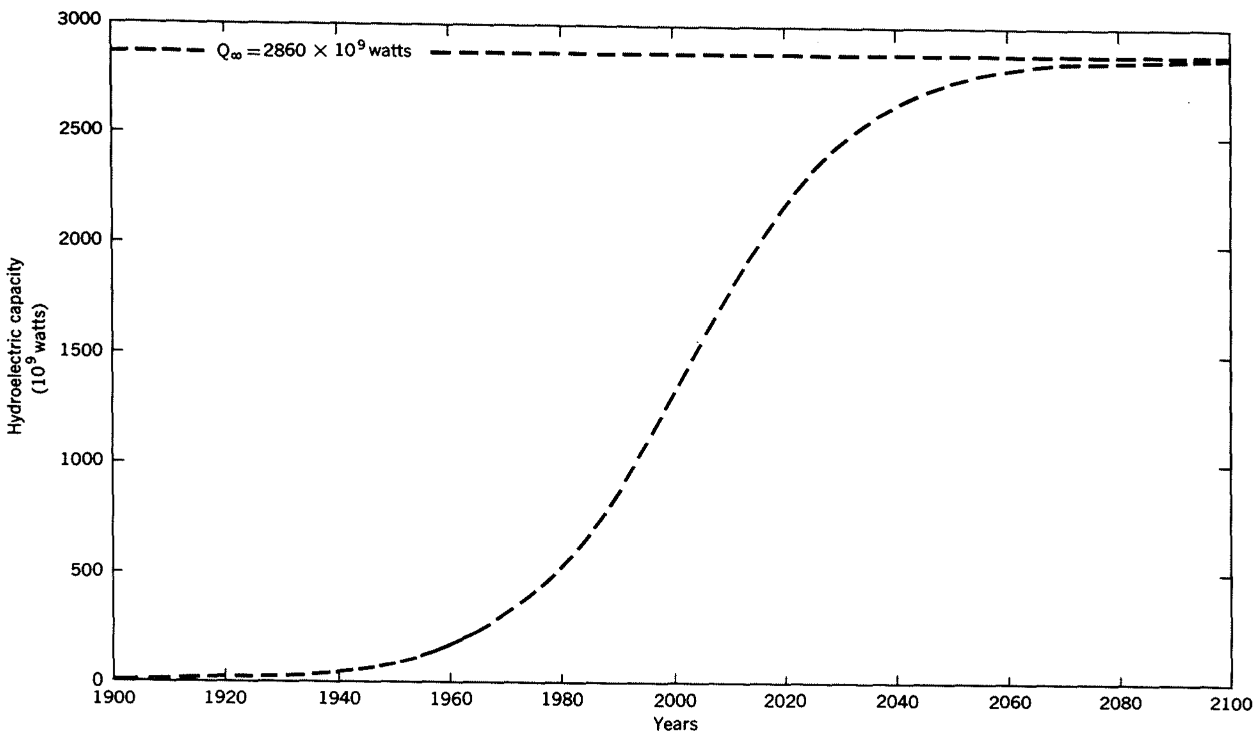

Fig. 26 - Potential and developed hydroelectric capacity of the world (Hubbert, 1972, Fig. 22).

Tidal power

Tidal power is closely related to waterpower except that it is derived from the alternate filling and emptying, at the semidiurnal period of 12 hours and 24.4 minutes of the lunar day, of a bay or estuary that can be enclosed by a dam. When a tidal basin is enclosed, the maximum power obtainable would be by a flow cycle that permitted the basin to empty and fill during brief periods about high and low tides. For such a cycle the maximum work potentially obtainable per cycle from one high tide to the next would be

$$W = pgSR^2, \tag{6}$$

where p is the density of the water, g the acceleration of gravity, S the area of the tidal basin, and R the tidal range.

The average power for the complete cycle would therefore be

$$P = W/T = pgSR^2/T, \tag{7}$$

where $T = 4.46 \times 10^4$ sec is the tidal period. A small augmentation of this can be accomplished by pumped storage near the crest of the tidal cycle.

In engineering calculations, a range of 8 to 20% is commonly assumed as the fraction of the maximum potential power that may be realized in practice. However, in the French La Rance establishment, the power realized is reported to approach 25% of the theoretical maximum.

From Equation 7 it is seen that the power obtainable from a tidal basin is proportional to both the area S of the basin and to the square of the tidal range R. Therefore, the favorable sites for tidal power are along coasts where tides of large amplitudes occur and where coastal configurations exist which permit the enclosure of large tidal basins by dams. There is, accordingly, an ambiguity in estimating potential tidal power, depending upon how large a basin it may be practical to dam.

With these limitations in mind, a summary of the world's more favorable tidal-power sites, and the maximum potential power, is given in Table 6. Included are individual sites having potential power capacities in the range from 2 to 20,000 MW each. These have a total maximum potential power capacity of 64,000 MW, which is about 2% of the world's potential waterpower capacity of 3×10^{12} watts.

Small tidal mills of at most a few tens of kW capacity each have been built along the Atlantic coast of Europe since the 11th century, but only now are large tidal-electric power installations beginning to be built. The only large tidal-electric plant so far built is that by the French on the Rance estuary on the Channel coast of France. This began operation in 1967 with an initial capacity of 240 MW and a planned extension to 320.

In 1969 a small experimental tidal plant of 0.4 MW capacity on the Kislaya Bay 80 km northwest of Murmansk was announced by the Soviet Union.

The largest potential tidal power region in the world is the Bay of Fundy in northeastern United States and southeastern Canada. In 1956 the Canadian and United States governments requested the International Joint Commission to make a comprehensive study of the feasibility of developing the power of Passamaquoddy Bay on the U.S.-Canadian boundary. The system favored in this study was a two-pool system having a 300 MW installed capacity

Table 6. Tidal power sites and maximum potential power[a]

Locality or region	Average potential power (10^3 kW)	Potential annual energy production (10^6 kWh)
North America Bay of Fundy (Nine sites)	29,027	255,020
South America Argentina San Jose	5,870	51,500
Europe England Severn estuary	1,680	14,700
France (Nine sites)	11,149	97,811
U.S.S.R. (Four sites)	16,049	140,452
Totals	63,775	559,483

[a]Sources: Trenholm, 1961; Bernshtein, 1965.

and an annual energy production of 1,843 million kWh. However, it was concluded that the cost of the power produced would be prohibitive with respect to that of power from other sources.

By an agreement of August 1966, the governments of Canada and of the Provinces of New Brunswick and Nova Scotia established a five-man Atlantic Tidal Power Programming Board and a complementary five-man Atlantic Power Engineering and Management Committee for a study of the economic development of tidal power from the Bay of Fundy. In its final report (Atlantic Tidal Power Engineering and Management Committee, 1969), the three most favorable sites were selected by this Committee. These, designated as 7.1, 7.2, and 8.1, were respectively Shepoy Bay in New Brunswick, Cumberland Basin on the New

Brunswick-Nova Scotia boundary, and Cobequid Bay in Nova Scotia. For these sites it was estimated (Table 7, p. 80) that 16,847 million kWh of energy could be obtained annually, using double-acting turbines and auxiliary pumping during high tides. This would correspond to a mean power production rate of 1,922 MW.

It appears, therefore, that as the costs of fossil fuels rapidly increase the cost disadvantage of tidal power is disappearing, and accelerated development of power from this source may soon be anticipated.

Windpower

Windpower is probably the oldest source of nonbiological energy used by man. Sailing ships on the Nile are depicted in ancient Egyptian temple drawings. From that time until about a century ago, when windpower was supplanted by energy from fossil fuels, windpower continued to be the principal source of energy for ship propulsion. On land, the windmill was developed in the Middle East about the 9th century and reached its culmination within the last century as the source of power for grist mills in Europe, for pumping water in the Netherlands, for crushing sugar cane in the West Indies, for pumping water from wells on farms and ranches in the United States, and for small household electric generating sets.

Windpower on land as at sea has been largely displaced by either the internal combustion engine or by electric power from utility networks. As costs rapidly escalate and as fossil fuels become increasingly scarce, serious attention again is being directed to the development of wind-electric systems for both small-and large-scale generation of electric power.

At present no estimate is available as to how large the potential wind power from favorable sites may be but in the aggregate it can be very large. If modern technology of aero and electrodynamics is utilized there is no obvious reason why large-scale wind-electric power cannot be developed.

Power from ocean currents and from oceanic temperature differences

Very large quantities of energy are stored in the oceans in the form of the kinetic energy of ocean currents and thermal energy. The kinetic energy of currents can be converted into mechanical and electrical power by means of underwater turbines analogous to windmills on land. Likewise, thermal energy can be converted into mechanical power by means of heat engines provided a suitable difference of temperature exists.

One of the largest and best known ocean currents is that of the Gulf Stream, a major part of which passes through the Strait of Florida between the Florida Peninsula and the Bahama Islands. The width of this channel between Miami, Florida, and Bimini is about 80 km. If we restrict our attention to velocities of 0.9 m/sec or more, the Gulf Stream due east of Miami, Florida, has a width of about 60 km, a maximum depth of 800 m, and a cross-section area of 28 km^2. The energy flux through this cross section is the kinetic energy of the water passing a fixed surface in one second. The kinetic energy of a cubic meter of water is proportional to the square of its velocity, and the number of cubic meters of water passing through the cross section in one second is proportional to the velocity Hence, the energy flux per second through the cross section is proportional to the cube of the velocity. The cube root of the mean of the cubes of the velocities over the face of the cross section is about 1.53 m/sec. The energy flux can be found from the equation,

$$\begin{aligned} P &= mv^2/2 = \rho A v^3/2 \\ &= (10^3 \text{ kg/m}^3)\ (28 \times 10^6 \text{ m}^2)\ (1.53 \text{ m/sec})^3/2 \\ &= 50{,}000 \text{ MW} \end{aligned}$$

where P is the energy flux in watts, m is mass in kg, ρ is the density in kg/m^3, A is area in m^2, and v is velocity in m/sec. If all of this could be converted into electric power, the result would be equivalent to fifty 1000 MW power plants. It is unlikely, however, that as much as 10% of this flux could be so converted. In that case the maximum power obtainable from this current would probably not be more than about 5,000 MW, or the equivalent of four large steam plants on land.

A comparable problem to that of extracting the kinetic energy from an ocean current is that of extracting its thermal energy. Differences in temperatures of 25° to 30°C between waters at the ocean surface and those at several hundred meters depth are common in the tropics, and a heat engine can work between the higher and lower temperatures. However, for an upper temperature of 30°C and a lower temperature of 0°C the maximum possible efficiency of a heat engine is only about 10%, and an actual achievement probably would not be more than about 5%.

The problem in utilizing this thermal energy is thus twofold: (1) the low thermodynamic efficiency because of the small temperature difference, and (2) the large amount of water that must be processed per unit of mechanical or electrical energy obtained.

When consideration is given to the magnitude of the equipment that must be installed to achieve a significant amount of power, such as 1,000 MW, from either ocean currents or ocean temperature differences, and when further consideration is given to the problem of maintenance of such equipment in a hostile marine environment, the development of either of these sources of power at present does not appear practical in comparison with other sources.

Geothermal energy

The possibility of extracting power or useful heat from geothermal energy results from the fact that the temperature beneath the earth's surface increases as depth increases at an average rate (as determined from many measurements in drillholes) of about 25° C/km. The deepest wells so far drilled are about 10 km deep. At such a gradient the temperature in the earth above that at the surface would increase linearly from 0° at the surface to 250°C at a depth of 10 km. This corresponds to an average excess temperature of 125°C. The volumetric specific heat of rocks is about 0.6 cal/cm^3-^{o}C, or 2.5 x 10^6 joules/m^3-^{o}C. From these data the total amount of heat stored in the upper 10 km of the earth at temperatures in excess of surface temperatures is found to be about 3.8 x 10^{26} calories, or 1.6 x 10^{27} thermal joules.

The average rate of heat conduction to the earth's surface is about 1.5×10^{-6}(cal/sec)/cm^2, or 6.3×10^{-2} watts/m^2. For the entire earth surface this amounts to 32×10^{12} watts (Fig. 1).

Because of the very low thermal conductivity of rocks large-scale industrial use of the above basic heat content of the outer part of the earth does not appear promising. However, in many parts of the world, superposed on this basic heat system are local areas for which considerably higher geothermal gradients exist and hence higher temperatures at shallower depths. These gradients and temperatures are associated with igneous magmas or volcanic rocks which have risen from much greater depths to the vicinity of the earth's surface. Associated with the volumes of higher temperature rocks are circulating ground waters which may be present either as abnormally hot water or as steam. Such hydrothermal systems are at present the sources of geothermal energy amenable for the generation of thermal-electric power.

In Table 7 are listed the sites and installed electric power capacity of the world's geothermal-electric plants as of 1974. The earliest use of geothermal steam for power generation was in 1904 at Larderello, Italy. At present, the combined electric capacity in Italy from two geothermal fields amounts to 384 MW, which is somewhat less than half the capacity of one modern steam-power plant. By now, the largest installation in the world is that of The Geysers in California. This began in 1960 with a small experimental 11.0 MW plant. Subsequently, the capacity has been continuously increased to a 1974 figure of 502 MW; probable future increases will bring the capacity to perhaps 900 MW or more. The third largest installation is that of Wairakei, New Zealand; it has a capacity of 160 MW. This began operation in 1958. By 1974 the total world capacity of geothermal-electric power amounts to just less than 1,200 MW, which is about equivalent to the capacity of a single large modern steam-electric plant.

Concerning the potential ultimate magnitude of geothermal-electric power, the most promising areas are those that have high-temperature water or steam at depths of less than 10 km. It should be understood that the heat in these localities is that convected to shallow depths by molten igneous rocks. Such stores of heat are accordingly finite in magnitude. The

Table 7. World geothermal generating capacity, 1974

Country	Field	Electrical capacity, MW Vapor-dominated system	 Hot-water-dominated system	 Total
Italy	Larderello	358.6		358.6
	Monte Amiata	25.5		25.5
United States	The Geysers	502		502
New Zealand	Wairakei	160		160
	Kawerau		10	10
Japan	Matsukawa	20		20
	Otake		13	13
Mexico	Pathé		3.5	3.5
	Cerro Prieto		75	75
Soviet Union	Pauzhetsk		5	5
	Paratunka		0.7	0.7
Iceland	Namafjell		2.5	2.5
	Totals	1,066.1	109.7	1,175.8

Sources: White, 1973, Table 1; Pacific Gas and Electric Company, 1973.

exploitation of this heat for power purposes is in effect a mining operation, and thermal sources are as exhaustible by mining as are the more familiar deposits of metallic ores.

Extensive studies of the approximate magnitude of the world's hydrothermal sources have been made by Donald E. White (1965, 1973) and by L. J. P. Muffler (1973), both of the U. S. Geological Survey. White's most recent estimate (White, 1973, p. 91) is that world geothermal power, under present prices and technology, is unlikely to exceed 30,000 MW. For the United States he estimates the total geothermal-electric energy under these conditions at about 600 MW centuries. This would be equivalent to one 1,200 MW power plant operating for 50 years. For the world, his maximum estimate is within the range of 2,000 to 4,000 MW centuries.

For comparison, the total potential world waterpower capacity is about 3×10^{12} watts, which is equivalent to 3,000 plants of 1,000 MW each. Assuming that these figures are reliable within an order of magnitude, we obtain a reasonably good appraisal of geothermal power. It is very attractive in favorable sites, such as that of The Geysers. It is limited in time, however, and in magnitude it is small, being the order of one-hundredth or one-thousandth of the world's potential water power. The energy represented by 4,000 MW centuries is about 1.3×10^{19} thermal joules, which is about 10^{-4} of the energy of recoverable fossil fuels.

Nuclear energy

Nuclear energy is obtainable from two contrasting nuclear phenomena, the fissioning of certain isotopes in the heavy end of the atomic mass range and the fusion of isotopes of hydrogen into helium on the light end of the range.

Fission power

For fission power, the heavy elements of initial interest are uranium and thorium, elements 92 and 90, respectively, in the numerical scale of the 92 naturally occurring chemical elements. Natural uranium consists of two isotopes, uranium-238 and uranium-235, which occur in the ratio of 140 atoms of U-238 to 1 of U-235. Of these two isotopes only U-235 is fissionable under nonextreme environmental conditions. Upon encounter with a stray slowly-moving or thermal neutron, an atom of U-235 absorbs the neutron and then undergoes spontaneous fission. The fission products consist of the nuclei of two atoms of chemical elements somewhere in the midrange of the atomic number scale, and two or three (averaging 2.1) free neutrons. These neutrons, upon encounter with additional atoms of U-235, cause further fissioning, which under suitable conditions leads to a sustained chain reaction. This may be either uncontrolled and explosive as in a fission bomb, or a controlled and sustained reaction as in a fission powerplant.

The energy released by the fissioning of 1 gram of U-235 amounts to 8.2×10^{10} joules. This is 0.96 of a MW day. It is also equivalent to the heat of combustion of 2.7 metric tons of bituminous coal or to 13.7 barrels of crude oil. The energy released per unit mass by the fissioning of uranium is thus about 3 million times greater than that of the most energetic chemical reactions.

Figure 27 shows schematically the nature of the controlled, steady-state chain reaction in a fission powerplant operating on U-235 as fuel. If U-235 is "burned" as fuel, highly radioactive fission products accumulate as the "ash" or waste, and the heat generated may be used to drive a conventional steam-electric power plant.

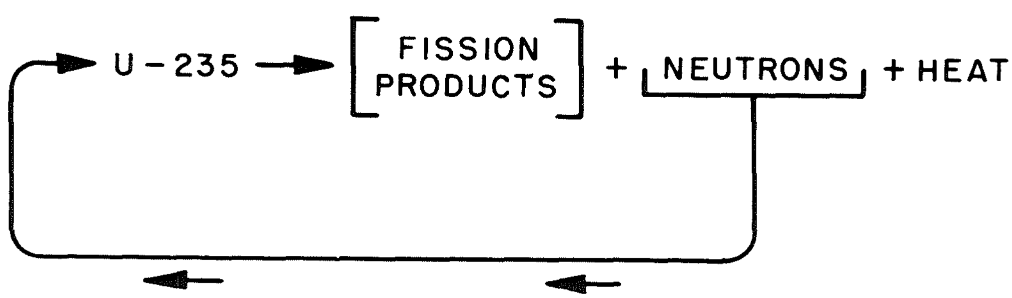

Fig. 27 - Schematic representation of nuclear power reaction involving the fissioning of U-235 [Hubbert, 1956, Fig. 25. Reproduced by permission from API, Drilling and Production Practice (1956)].

In practice, however, pure U-235 is not available as fuel. Instead, either natural uranium consisting of only 0.7% of U-235, or else slightly enriched uranium containing about 3-4% of U-235 is used as fuel. The remainder of the uranium is U-238.

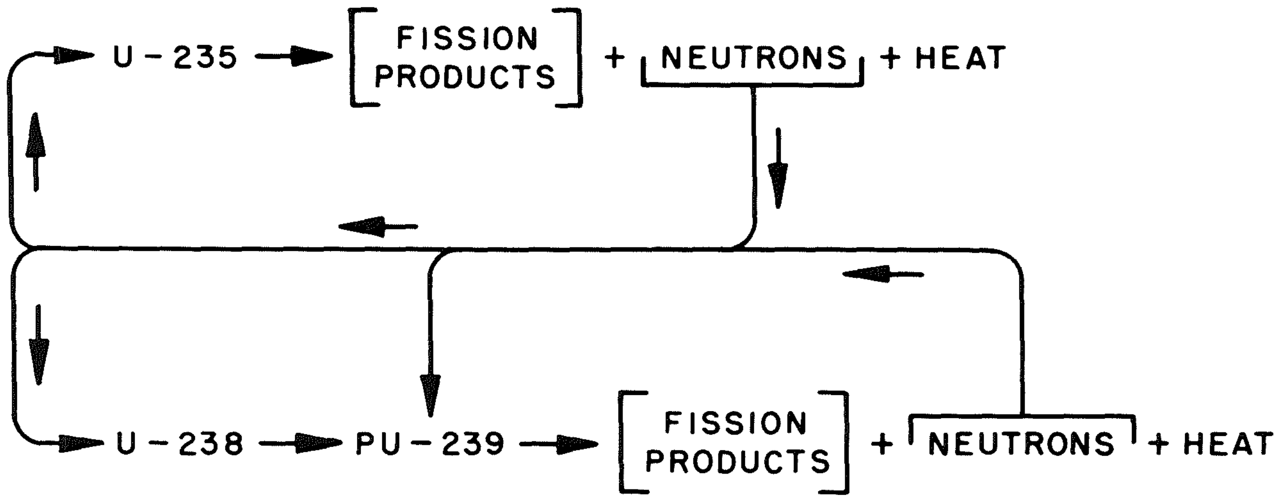

Fig. 28 - Schematic representation of.breeder reaction for U-238 [Hubbert, 1956, Fig. 26. Reproduced by permission from API, Drilling and Production Practice (1956)].

Figure 28 is a schematic flow diagram of a reactor containing both U-235 and U-238. In such a reactor the slow neutrons cause the fissioning of the U-235 fuel. However, some high-velocity or fast neutrons also occur; one of these upon encounter with an atom of U-238 may be captured. Then the following nuclear reactions ensue:

$$\text{Uranium-238} + 1 \text{ neutron} \rightarrow \text{uranium-239} \rightarrow \text{neptunium-239} \rightarrow \text{plutonium-239}$$

Plutonium-239, like uranium-235, is fissionable and so is usable as a nuclear fuel. If the ratio of the plutonium produced to the initial fuel consumed is between 0 and 1, the reactor is called a converter; if greater than 1, it is a breeder.

Conversion and breeding can also be accomplished using common thorium (Th-232) instead of U-238. In this case the end product derived from thorium is the fissile isotope uranium-233. Accordingly, U-238 and Th-232 are known as fertile materials which, although not themselves fissionable, can be converted into fissile materials by conversion or breeding.

Large-scale nuclear power, based almost entirely on the burning of U-235, is already a "fait accompli". During the incredibly short time since the achievement of the first chain reaction at the University of Chicago on

December 2, 1942, and the 23 years since the first electric power was generated at Arco, Idaho, on December 20, 1951, nuclear power plants have evolved in size to units of more than 1,000 electrical megawatts (MWe). Geographically, 33 separate countries have a total, as of July 1974, of 145 operable nuclear reactors with a combined capacity of 55,000 MWe. Of these reactors, 49 having a combined capacity of 31,700 MWe are in the United States (King, 1974, p 5). The present rate of growth in nuclear power capacity in both the United States and the world is approximately 35% per year with a doubling period of only about two years.

The principal question of present interest pertains to the potential magnitude of nuclear power, and in particular, how it compares in magnitude with the fossil fuels. All rocks contain small concentrations of uranium and thorium. Granite, the most abundant near-surface rock of the earth, contains on the average about 4 grams of uranium and 12 of thorium per metric ton. Above this base level, rocks of wide regional extent contain uranium in the range of 50 - 100 g per metric ton. Finally, much rarer high-grade deposits contain uranium in the range of 2 - 3 kg per metric ton.

These latter high-grade deposits are what constitute the uranium ores for the present U-235-burning reactors. Minable ores at present are those that can be worked at a price level of less than \$10/lb U_3O_8. In a joint report the Organization for Economic Cooperation and Development and the International Atomic Energy Agency (1973) have made a country-by-country review of world uranium resources exclusive of the U.S.S.R., eastern European countries, and China for which no data were available. These estimates include "reasonably assured resources (reserves)" and "estimated additional resources" in two price ranges, less than \$10/lb U_3O_8 and \$10 to \$15/lb U_3O_8. The summary results of this review are given in Table 8. The reasonably assured resources and the estimated additional resources in each price range amount to about 1.5×10^6 metric tons of uranium, with an estimated total of 3×10^6 metric tons.

In the same report the estimates of cumulative requirements of uranium until the year 1990 range from $1,045 \times 10^3$ to $1,713 \times 10^3$ metric tons.

Table 8. World[1/] resources of high-grade uranium

	Resources		
Price range ($/lb U_3O_8	Reasonably assured resources (reserves)	Estimated additional resources	Totals
	(10^3 metric ton U)		
Less than 10	866	916	1,782
10 - 15	680	632	1,312
Totals	1,546	1,548	3,094

1/ USSR, Eastern Europe, and China not included

Source: Joint Report by the Organization for Economic Cooperation and Development and the International Atomic Energy Agency, 1973, Table 1.

Granted that additional discoveries of uranium will be made in the future, these estimates nonetheless provide a reasonable order of magnitude of the world resources of U-235. One metric ton of natural uranium contains 7.0 kg of U-235. Therefore, the U-235 content of 3 x 10^6 metric tons of uranium would be 2.1 x 10^4 metric tons. The energy released by the fissioning of 1 gram of U-235 is 8.2 x 10^{10} joules. Therefore, that represented by 2.1 x 10^4 metric tons, or 2.1 x 10^{10} grams of U-235 would be 1.7 x 10^{21} joules. Comparing this with the energy contents of the fossil fuels given in Table 4, it is seen that the energy obtainable from the U-235 content of the estimated world resources of the high-grade ores is of the order of 6% of the 3 x 10^{22} joules represented by petroleum and natural gas, or 0.7% of the 2.6 x 10^{23} joules of all the fossil fuels. When this is considered in conjunction with the rate of growth of nuclear power, it appears that if the nuclear reactors continue to be dependent on U-235 for fuel, a shortage of reserves will probably occur by the year 2000, and the time during which nuclear power could be a major factor in world energy requirements would probably be less than a century.

Breeder reactors

If this consequence is to be avoided it is mandatory that the present generation of burner reactors be replaced by breeders. Utilizing a feed stock of U-235 and U-238, breeders with a conversion ratio greater than 1 convert U-238 to fissile plutonium. The doubling period of a breeder reactor is the time required for the fuel inventory to be doubled. This doubling time is expected to fall within a range of about 8 to 20 years. In principal, therefore, using breeder reactors, it should become possible to consume nearly all of natural uranium or thorium instead of just the rare isotope U-235.

Several small experimental breeders have been built and operated in the United States since 1951. Also breeders of intermediate size have been built or are under construction in the United Kingdom, France, Japan, West Germany, and the Soviet Union. In the United States a 350 MWe demonstration liquid-metal fast breeder reactor is being built at Oak Ridge, Tennessee, with a scheduled completion date in the early 1980's.

Assuming a complete replacement of the present generation of burner reactors with breeder reactors, the energy supply from uranium and thorium would be increased by a large ratio, due principally to the possibility of utilizing the much more abundant intermediate-grade ore deposits.

Figure 29 is a map of the United States showing the approximate extent of the principal known deposits of uranium and thorium. The high-grade deposits currently being mined are in the western United States - the Colorado plateau, the Wyoming basins, the northern Rocky Mountains, and the Texas coastal plain. Intermediate-grade deposits of large extent and magnitude are found in the phosphate rocks of the northern Rocky Mountains and Florida, the lignites of North Dakota, the Cretaceous Pierre Shale in the Black Hills region,

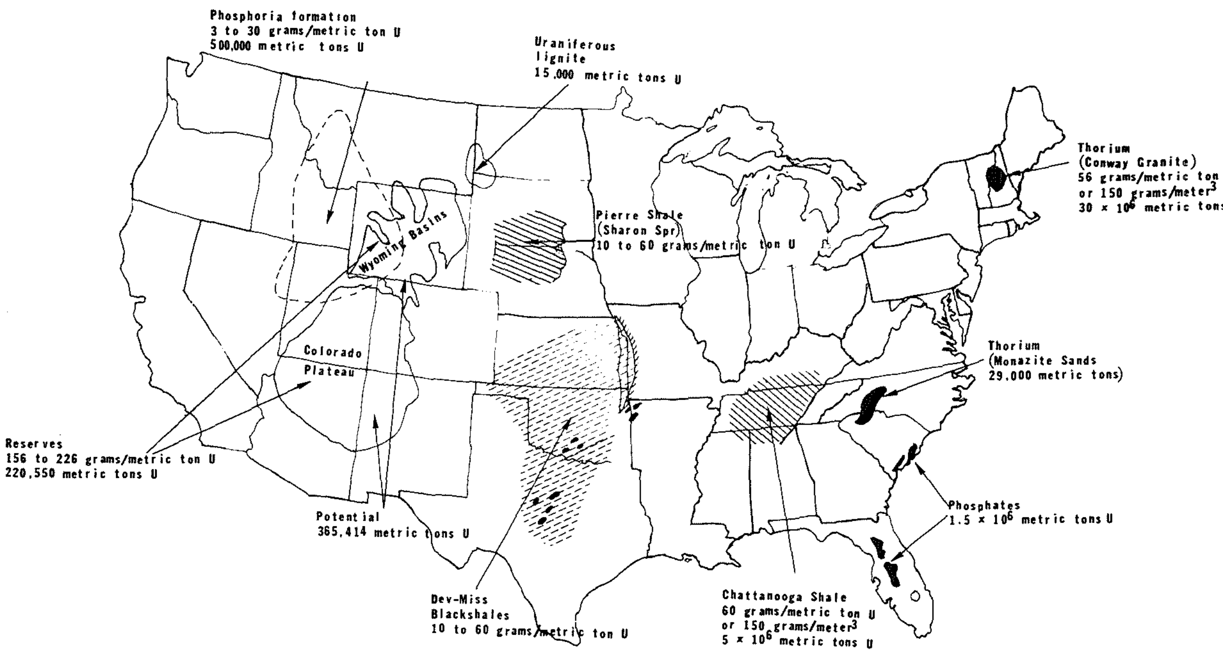

Fig. 29 - Major uranium and thorium deposits in the United States

and the Devonian Chattanooga Shale which crops out along the western border of the Appalachian Mountains in eastern Tennessee and neighboring States, and underlies at minable depths most of the northeastern States west of the Appalachian Mountains.

For a sense of the magnitude of the energy involved, in the outcrop area of the Chattanooga Shale in eastern Tennessee there is a stratum, the Gassaway Member, about 5 meters thick which has a uranium content of 60 g per metric ton (Swanson, 1960, p 4). Assuming that 50% of this could be recovered and used as fuel for breeder reactors, the energy obtainable from an area about 40 km square would be equivalent to all the fossil fuels in the United States. When the total extent of such low-grade deposits is considered, it becomes evident that fission energy is potentially orders of magnitude larger than the fossil fuels.

Hazards of fission power

Offsetting these favorable aspects of nuclear-fission power are the hazardous aspects. Two of these are technological; a third is social and political. The technological hazards arise from the possibility of industrial accidents ranging in magnitude from trivial to catastrophic. A second hazard is associated with the radioactive fission products resulting from the spent fuel. Two of these, strontium-90 and cesium-137, with half-lives of 28 and 34 years, respectively, are particularly dangerous physiologically and require roughly 1,000 years to decay to an innocuous level. When these products are being continuously generated by an exponentially expanding nuclear-power industry, mankind is confronted with a formidable problem of perpetual care for millenia into the future.

In a world of sustained social stability, there would be little doubt that the foregoing hazards could be managed technologically in a satisfactory manner. Unfortunately, as terroristic activities demonstrate daily, we do not have a world of social and political stability, and therein lies the greatest hazard of all.

In all burner reactors using natural or slightly enriched uranium a small fraction of the U-238 is converted into plutonium. According to Willrich and Taylor (1974, p 32), in the light-water reactors of the type used in the United States, one atom of plutonium is produced for each two atoms of U-235 that fission. However, a part of this plutonium is also fissioned in the reactor, leaving a net production of about one atom of plutonium for each four U-235 atoms that fission. In a 1,000 MWe light-waterpower station, this corresponds to a net production rate of 250 kg of plutonium per year. Of this, about 80% is fissile Pu-239. The remaining 20% is principally Pu-240 and a small amount of Pu-241. According to the projections of the U.S. Atomic Energy Commission (1973a, Table 3-9), the fissile plutonium to be produced in 1974 from domestic power fuels will amount to 1,000 kg. By 1978 this will increase to 10,900 and by 1985, to 36,900 kg per year. The cumulative production by 1985 is estimated to amount to 199,800 kg.

The hazards posed by this amount of fissile plutonium which must be transported over long distances and processed and stored in many widely separated places, become evident when it is considered that only slightly more than 5 kg were required for the bomb detonated over Nagasaki in 1945, and a bomb can be constructed using as little as 2 kg. The prospects of terroristic activities using illicit plutonium bombs have been painstakingly reviewed by Willrich and Taylor (1974) and by McPhee (1974). Incidentally, Theodore B. Taylor has been one of the principal bomb designers for the U.S. Atomic Energy Commission.

In view of these ominous hazards in the burgeoning proliferation in nuclear-fission electric powerplants and the concomitant real and potential spread of nuclear weapons, it becomes increasingly urgent to develop some alternative source of energy which has the appropriate magnitude but not the objectionable characteristics of fissile nuclear systems.

Fusion

Fusion may possibly satisfy such a need. It was originally shown by Bethe (1939a, b) that the enormous outpouring of radiant energy from the sun and other stars results from a stellar fusion reaction whereby atoms of hydrogen are fused into the next heavier element, helium. The uncontrolled explosive terrestrial achievement of fusion was accomplished when the first hydrogen or so-called thermonuclear bomb was exploded on the island of Eniwetok on November 1, 1952.

Since that time, intensive research has been underway in several countries in an effort to obtain a controlled fusion reaction in the laboratory as a first step toward the eventual achievement of fusion-electric power. The obstacles have proved to be formidable but progress is gradually being made toward the achievement of the extreme conditions of temperature and confinement essential for fusion to occur. At present there is hope that controlled fusion may be accomplished in the laboratory within a decade. Should this be the case, the U.S. Atomic Energy Commission in its Annual Report to Congress of 1973 (1973b) has expressed the conjecture that a demonstration fusion power plant may be put in operation during the 1990-decade.

If it can be achieved, fusion power has many advantages over fission power. It is nonexplosive and it produces no radioactive fission products. Many different fusion reactions are possible. The one that requires the least extreme conditions, and hence the one most likely to be accomplished first, is the so-called D-T reaction. This is the fusion between deuterium and tritium, the isotopes of hydrogen of masses 2 and 3, respectively. Deuterium occurs in sea water in an atomic abundance of approximately 1 atom of deuterium to 6,700 atoms of hydrogen. Tritium occurs naturally in only minute traces. Hence, the tritium for the D-T reaction must be generated by the neutron bombardment of lithium. However, the world's known and estimated resources of recoverable lithium are only about 10^{-9} as abundant as deuterium. Consequently, the fusion energy utilizing the D-T reaction represents an energy supply of about the same magnitude as that of the fossil fuels.

However, if the D-T reaction can be achieved, it will probably not be too difficult to take the next step to the D-D reaction. Assuming that this will be done, the summary fusion equation would be,

$$5\ {}^{2}_{1}D \rightarrow {}^{4}_{2}He + {}^{3}_{2}He + H + 2n + 24.8\ \text{Mev}$$

The energy released per single deuterium atom would be 4.96 Mev (1 Mev = 1 million electron-volts), or 7.95×10^{-13} joules. There are 1.0×10^{25} atoms, or 34.4 grams, of deuterium in one cubic meter of sea water. The fusion of this amount of deuterium would release 7.95×10^{12} joules of heat which is equivalent approximately to the heat of combustion of 1,300 barrels of crude oil or to 240 metric tons of bituminous coal.

A comparison between the fusion energy represented by various volumes of sea water and equivalent amounts of fossil fuels is given in Table 9. In particular, if the deuterium in 1 m^3 of sea water is equivalent to the combustion of 1,300 barrels of crude oil, then 1 km^3 of sea water would be equivalent to 1,300 billion barrels of oil, and 1.5 km^3 would be equivalent to the estimated initial world supply of crude oil. Finally, the deuterium in 32.7 km^3 of sea water would be equivalent to the world's total supply of fossil fuels.

Table 9. Energy potentially obtainable by fusion from deuterium in sea water

Volume of sea water	Energy content (joules)	Crude oil equivalent (bbl)	Coal equivalent (metric tons)
1 m^3	7.95×10^{12}	1,300	240
1 km^3	7.95×10^{21}	$1,300 \times 10^9$	240×10^9
32.7 km^3	2.6×10^{23}	Total energy of the fossil fuels	
Total ocean volume 1.37×10^9 km^3	10.9×10^{30}	Approximately 4.2×10^7 times the world's fossil fuels	

Solar energy

In view of the hazards of nuclear-fission power and of the insufficiencies of water, tidal, and geothermal sources of energy, we again refer to Fig. 1 to see what other possibilities remain. The largest source of energy available to the earth is that from the continuous influx of solar energy. The intensity of this flux outside the earth's atmosphere at the mean distance of the earth from the sun, the solar constant, amounts to 1,363 thermal watts per square meter normal to the sun's rays. For the entire earth, the total power of the intercepted radiation is 174×10^{15} watts, of which about 70%, or 120×10^{15} watts, is effective in terrestrial processes. In quantity, the cumulative amount of this energy is equal every 25 days to the 2.6×10^{23} joules estimated for the world's fossil fuels; in time, this influx has been continuous for billions of years of the geologic past, and the expectations are that it will continue for a comparable period in the future. On cloudless days in local areas a large fraction of the incident radiation - three-quarters or more - actually reaches the earth's surface and is available for potential industrial uses.

Actual and potential industrial uses of solar energy are in two principal categories: (1) small-scale uses such as water heating and space heating and air conditioning, and (2) large-scale power production. While the first of these types of usage may be quite large in the aggregate, such uses are essentially auxiliary to a pre-existing electric-power system derived from other sources of energy. Our present concern pertains to whether solar energy would be capable of being the principal source of large-scale industrial power, replacing the fossil fuels and nuclear sources.

For this purpose the optimum collection areas are the regions of maximum insolation, the arid and desert regions of the earth. A typical example of such an area is afforded by the southwestern part of the United States. During the last two years ground measurements of the total insolation on horizontal surfaces have been made at various points in Nevada by the Desert Research Institute of the University of Nevada (1974). Typical of the results obtained are those at Las Vegas, at $36.3°_N$ where the annual rainfall is less than 30 centimeters.

Continuous measurements were made for a year or more, and then by correlation with Weather Bureau records, extended back for 20 years. The net result was that daily average insolation over this 20-year period amounted to 2.15×10^7 joules per square meter of horizontal surface. This is equivalent to a year-round day-and-night average power input of 250 thermal watts per square meter. On a cloudless day in mid-April a peak mid-day value of 1,045 watts/m^2 was recorded.

Incident solar radiation can be converted into electric power either directly by photovoltaic cells, or indirectly by heat engines. Research and development is underway in the United States on several different types of solar collectors for large steam-electric powerplants that have estimated efficiencies as high as 20%.

The best photovoltaic system uses wafers of single-crystal silicon doped with boron. This has an achieved efficiency of 12%, and a possible improvement to as much as 20%. Silicon photovoltaic solar collectors are used on space craft, but heretofore they have been too expensive by two or three orders of magnitude for industrial power production. However, it has been recently announced by the Tyco Laboratories, Inc., of Waltham, Massachusetts, that a technique has been developed for drawing single-crystal ribbons from a silicon melt which promises to reduce the cost per electrical kw to a level comparable to that of fossil-fuel plants (Hammond, 1974).

To gain some idea of the magnitudes involved in the production of power from solar radiation, consider a region such as that of Las Vegas, Nevada, which has a day-and-night year-round average insolation of 250 W/m^2. Also assume a 10% efficiency of conversion from solar to electrical power by either a thermal or photovoltaic system. This would give an average electric-power density of 25 We/m^2 or 25 MWe/km^2. Hence, a collection area of 40 km^2 would produce 1,000 MWe and a collection area of 9,000 km^2, or slightly more than 3% of the area of Nevada, would produce 2×10^{12} kWh/yr, which was approximately the annual output of the electric-power industry of the United States in 1974.

Using this as a standard of reference, consider the potential of solar energy as a means of meeting the power requirements of the world. At present the world production rate of electrical energy is approximately 6.0×10^{12}kWh/yr, or at an average rate of 6.8×10^5 MWe. Then, at an average rate of 25 MWe/km^2, the solar collection area required to equal the world's present rate of electrical energy production would be 27,000 km^2, or a square area 165 km to the side. Against this, consider the regions of the earth that have little rainfall and intense solar radiation: the southwestern region of the United States and northern Mexico; the Atacama Desert extending north and south along the coast of Chili; southern Argentina; half or more of Australia; southwest Africa; a 2,000 km wide band across the Sahara Desert, the Red Sea, the Arabian Peninsula, the Persian Gulf, and beyond; and finally the desert region extending across Asia from the Caspian Sea to eastern Mongolia. These regions have an aggregate area of approximately 40×10^6 km^2, or one-quarter of the total land area of the earth. Clearly, at 25 MWe/km^2, a small fraction of this could supply all the industrial energy ever likely to be needed.

Two particular difficulties are inherent in the direct utilization of solar energy for the production and distribution of electric power. One of these is the intermittent nature of solar radiation at a given point because of the diurnal cycle and interruptions by prolonged periods of cloudiness. The second is that the areas that are best for solar-electric power generation are commonly remote from the principal areas of power consumption. The first difficulty requires the use of large-scale energy storage facilities; the second involves the large power losses that occur when transmission distances exceed a few hundred km.

For these reasons it appears that the best means of utilizing solar energy will probably not be by the electric-power route, but by a chemical route. Let the energy be collected in the arid or desert regions either thermally or photovoltaically. Then let it be stored locally in a suitable gaseous or liquid chemical vehicle. Obvious examples would be to generate the gas hydrogen from water (H_2O), or methane (CH_4) from the raw materials, water and limestone ($CaCO_3$). Or, if a liquid be perferable, mathanol (CH_3OH) can also be produced from water and limestone.

These chemical vehicles avoid the difficulties not only of intermittent radiation, but also those of long-distance transmission. If existent pipeline technology is used which is second only to water transportation in efficiency, fluids can be transported any required distance overland to centers of consumption.

It appears, therefore, that by means of technology already developed all of the world's industrial energy needs could be met by utilizing only a small fraction of the solar energy from arid and desert regions in conjunction with such abundant material resources as water, or water and limestone.

Ecological aspects of growth

Before concluding, let us again consider the growth phenomena in the production of the fossil fuels as depicted in Fig. 3 to 7 inclusive. In each instance we see the rate of production following a nearly uniform exponential growth curve for a half century or longer, with growth rates of

4 to 8% per year, before beginning to slow down. For each curve except that of world annual production of crude oil, the slowing-down phase has already begun, and for crude oil the incidence of this phase is imminent if it has not already begun within the last year.

Because the fossil fuels are finite and exhaustible, this is an inevitable behavior as illustrated by the complete-cycle curve of Fig. 9. However, suppose that we succeed in making the transition to the virtually inexhaustible sources of energy-solar energy or deuterium-deuterium controlled fusion, would not this remove the prior constraints to growth and permit almost unlimited industrial expansion?

Complementary to such virtually unlimited sources of energy are the resources of the industrial metals. These, with the exception of magnesium from sea water, are invariably obtained from ore deposits in which the respective metals have been concentrated by geological processes. These ore deposits are just as exhaustible as coal or oil deposits. However, unlike the fossil fuels, the metals during use are not destroyed chemically. They are extracted from high-grade ore deposits and ultimately scattered.

Concerning the abundance of metals, citations are sometimes made on the basis of the geochemical abundance of the elements in the earth's crust of the impressive quantities of metals in a cubic kilometer of average crustal rock. One km^2 of such rock has a mass of 2.7×10^9 metric tons. Of this, the aluminum content, with a crustal abundance of 8.2%, would be 220 million metric tons; the iron content of 5.6% would be 150 million metric tons. Similarly, such a volume would contain 200,000 metric tons of nickel, 190,000 tons of zinc, 150,000 tons of copper, and 34,000 tons of lead. Hence, with these impressive quantities of indestructible metals in conjunction with virtually inexhaustible sources of energy, are there any real physical constraints to almost unlimited industrial growth? As we shall see, there indeed are such constraints. Even if we have inexhaustible energy and material resources, there are limits to what the earth itself can tolerate. These constraints are essentially ecological.

The phenomena of exponential growth were probably first appreciated with regard to monetary operations. The increase of a sum of money at a constant rate of interest compounded either continuously or at equal intervals of time, is a perfect example of uniform exponential growth. The principal doubles at equal intervals of time indefinitely. Probably the second group to appreciate exponential-growth phenomena were the biologists who learned well over a century ago that the population of any biologic species from microbes to elephants will, if given a favorable environment, increase exponentially with time in accordance with the equation

$$P = P_o e^{at}, \tag{8}$$

where P_o is the initial polulation, P that after an elapsed time t, e = 2.718 the base of natural logarithms, and a the instantaneous growth rate. This can also be expressed in an equivalent form in terms of the number of doublings,

$$P = P_o \cdot 2^{t/T} = P_o \cdot 2^n, \tag{9}$$

where T is the doubling period of the species and n = t/T the number of doublings during the time t.

A qualitative example of this kind is given in Fig. 30 which shows the growth of the human population of the world since the year 1000 A.D. Note the very slow growth during the five centuries from 1000 to 1500 A.D. and then the subsequent acceleration. The acceleration came about as the result of reduction in death rates due to more favorable circumstances in terms of food supply, advances in medical knowledge, expansion into new geographical regions of the New World, and the increased energy per capita obtained from the fossil fuels.

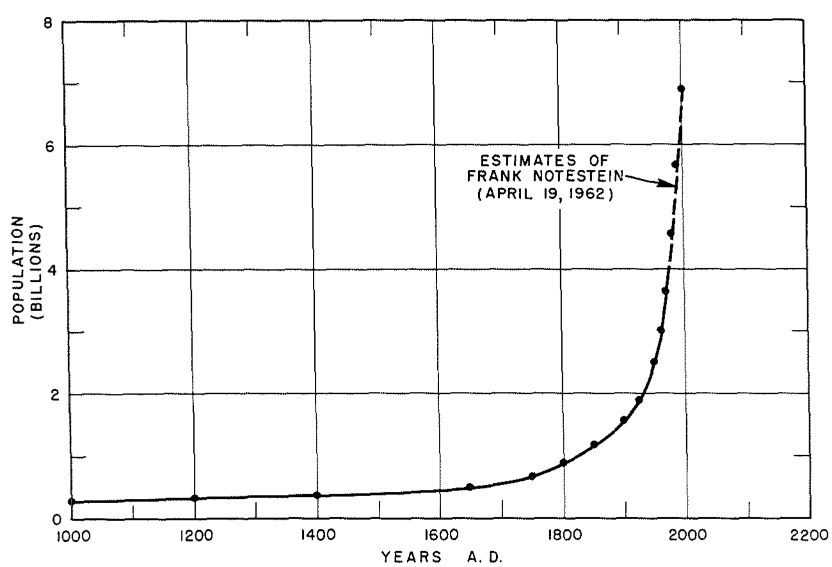

Fig. 30 - Growth of world population (modified from Hubbert, 1962, Fig. 2).

This curve depicts a unique event in the totality of human history. Were the curve to be extended backward in time for a million years, it would remain just above the zero line. The maximum average growth rate during the last million years would be obtained if we make the unrealistic assumption that the biological minimum population of only two existed initially. From this hypothetical minimum the number of doublings required to reach the present world population of 4.0 x 10^9 would be only 31. This would be the maximum number of doublings that could have occurred during the last million years. Hence, the minimum value of the average doubling period would be 1 million/31, or 32,000 years.

During the last five centuries the population has increased 10-fold corresponding to 3.3 doublings, each requiring a shorter period than the one preceding. At present the growth rate has reached 2.2% per year and the doubling period has dropped to 32 years.

Figure 31 shows the same kind of growth in a purely industrial component, namely the growth of world-installed capacity of electrical power stations. The solid curve is a plot of actual data during the last two decades, and the dashed curve is the approximate growth between 1900 and 1955. This growth is occurring at a rate of 8.0% per year and has a doubling period of 8.7 years.

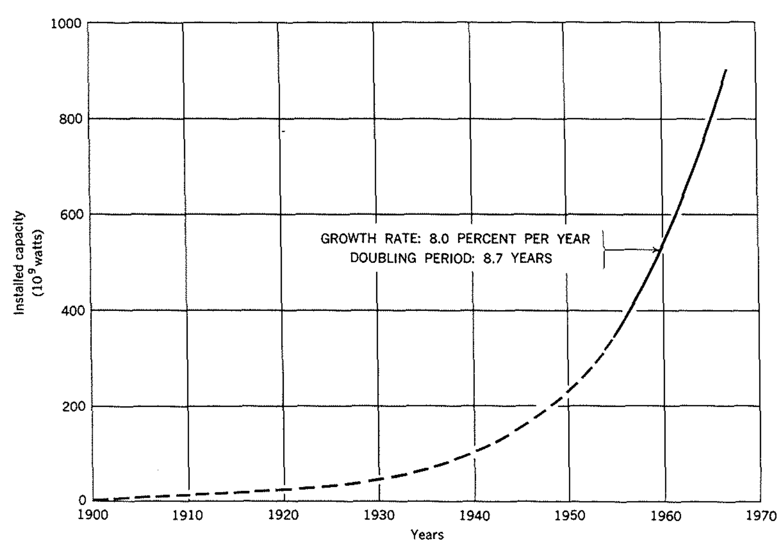

Fig. 31 - World electrical generating capacity (Hubbert, 1971, Fig. 2).

During the last decade, the world population of automobiles and of the passenger miles traveled on scheduled air flights have each also been doubling approximately every 10 years.

The question that these examples raise is this: How many doublings of any biological or industrial component can the earth itself tolerate? A clue to this can be obtained if we consider the classical problem of the wheat and the chessboard. One grain of wheat is to be placed upon the first square and the number repeatedly doubled for each successive square. The number of grains on the first square would be 1, or 2^0; that on the second, 2^1; on the third, 2^2; and on the nth square, 2^{n-1}. Hence, the number of grains on the last or 64th square would be 2^{63}, and the total for the entire board would be twice that amount, or 2^{64} (or to be mathematically precise, $2^{64}-1$).

What volume of wheat would this be? Recently some wheat was obtained and the number of grains in a measured volume counted. From this it was determined that the amount of wheat required would be 2,000 times the world's present annual wheat crop.

Superficially, this may appear trivial; actually its implications are profound. The earth itself cannot tolerate the doubling of 1 grain of wheat 64 times. We noted before that the world automobile population is doubling every 10 years. Suppose we apply the same arithmetic as for the wheat problem to automobiles. Suppose that beginning with 1 automobile, we allow the automobile population to be doubled 64 times, and the resulting cars stacked uniformly over all the land areas of the earth. How deep a layer would be formed? Two thousand km deep. The world automobile population cannot be doubled 64 times.

From such calculations it becomes evident that the maximum number of doublings of any industrial or biological component that is even possible is only a few tens, and in the case of industrial growth most of these have occurred already.

Three types of growth phenomena are illustrated in Fig. 32. In their early stages these three contrasting types of growth are indistinguishable from one another. One is a pure exponential growth curve which is only for mathematical or monetary significance. Money, being a system of accounting of units of debt has no physical constraints against unlimited expansion. The second curve begins exponentially but soon becomes subject to retarding influence which slow its growth rate until it finally levels off to some constant finite quantity. Waterpower and biological populations show this kind of growth. In a large region the development of waterpower capacity increases exponentially for a period and then gradually levels off asymptotically to a maximum as all potential sites are developed. In biology, the growth of a single tree or animal behaves in a similar manner. Likewise, for reasons that we have already discussed, a biologic population can only increase exponentially for a small number of doublings before retarding influences set in. These may be crowding, limitation of food supply, interaction with other organisms, or pollution. In fact more than a century ago it was learned that the exponential-growth phase in a biologic population is an exceptional and transient phenomenon. The normal state of a biologic population, meaning the state that prevails most of the time, is a near-steady state. The response to a disturbance may be either positive or negative. The previously stable population may undergo a transient increase and stabilize at a higher level; or if conditions are unfavorable, it may undergo a transient decrease and then stabilize at a lower level; or else it may decrease to zero and become extinct.

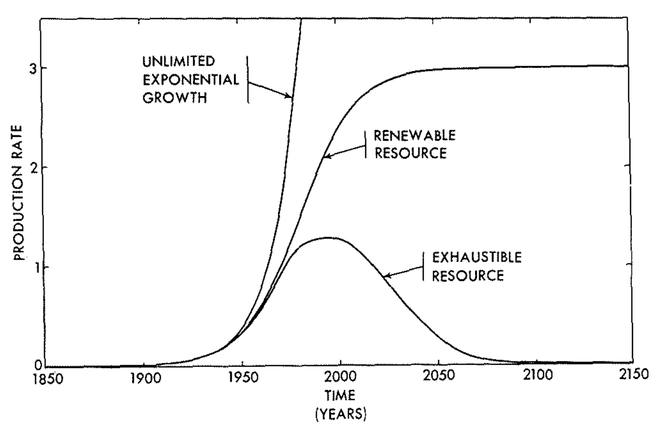

Fig. 32 - Types of industrial and biological growth (modified from Hubbert, 1974b, Fig. 1).

The third curve in Fig. 32 is characteristic of the production rate of any exhaustible resource, as we have already seen in the case of the fossil fuels.

The principles of ecology are further illustrated in Fig. 33. Although ecology may deal with the growth of single populations under controlled conditions, its principal concern has been with the population dynamics of open ecological complexes composed of both plants and animals in their natural settings. In such a system the normal state is one in which all populations, when averaged over a few years, remain nearly stationary or else drift slowly with time. However, the interspecies linkages are such that any disturbance to the population of any given species influences that of each of the others.

Although traditionally ecology has dealt only with biological systems, its basic principles are also applicable to industrial components such as automobiles, airplanes, and powerplants. Witness, for example, the decline of the polulation of horses and mules as the population of motor vehicles rose.

Figure 33 shows the responses of three component populations of an initially stable ecological complex in response to a disturbance. The disturbance proved favorable to Species 1, so its population increased from its initial level and stabilized at a higher level. The altered conditions were unfavorable to Species 3, so its population declined and stabilized at a lower level. The population of Species 2 was barely affected.

For a concrete example, Population 1 could be that of the human species in North America before and after the year 1600 A.D. Population 3 could be that of the American bison. However, in this case it would be difficult to identify Population 2.

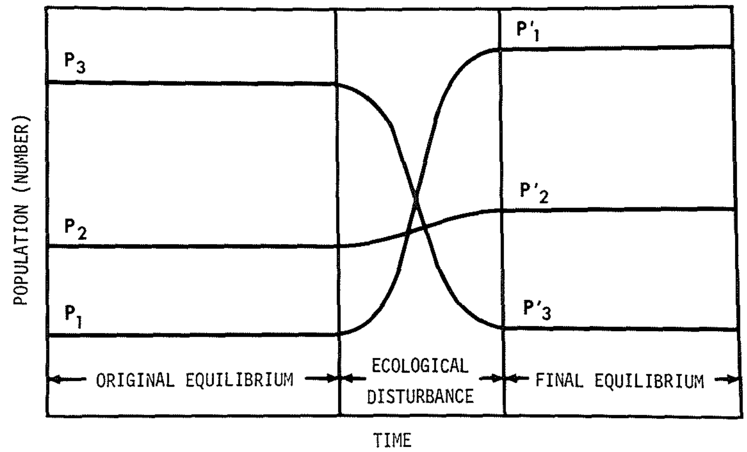

Fig. 33 - Population changes due to an ecological disturbance (Hubbert, 1962, Fig. 60).

Significance to human affairs

From this review of the world's energy resources and their exploitation by the human species, two realizations of outstanding significance emerge. One of these is the brevity of the time, as compared with the totality of human history, during which the large-scale use of energy for industrial purposes has arisen; the other is that with the present potentialities of utilizing solar and possibly fusion energy for industrial purposes, an energy supply promises to become available that should be able to meet all the world's industrial requirements for an unlimited time in the future.

The limiting factors in power production and associated industrial growth are, therefore, no longer the scarcity of energy resources but rather the principles of ecology. The world itself cannot tolerate more than a few tens of doublings of any industrial or biological component. For this reason, it is inevitable that the rate of industrial and population growth that has prevailed during the last century or two must soon cease and some kind of stabilized state must be achieved. Such a state conceivably could be one of maximum energy consumption and maximum population as is indicated by Curves I in Fig. 34. As the earth is already seriously overpopulated, it is far more likely that the population after overshooting will have to adjust to a lower more nearly optimum level indicated by Curves II. Or a cultural decline may occur whereby the population will have to adjust to a primitive low-energy level of existence, as indicated by Curves III.

Regardless of which of these possible courses may actually be followed, it is clear that the epoch of exponential growth can only be a transitory interval of about three centuries duration in the totality of human history. It represents but a brief transitional period between two much longer periods, each characterized by rates of change so slow as to be regarded essentially as a period of nongrowth. This transition from our present position to that of an optimum stabilized state having a high-energy level of operation and a human population adjusted to the earth's area and its resources poses no insuperable technological or biological problems; however, it will entail fundamental adjustments in those aspects of our present culture that depend for their stability upon the continuance of exponential growth.

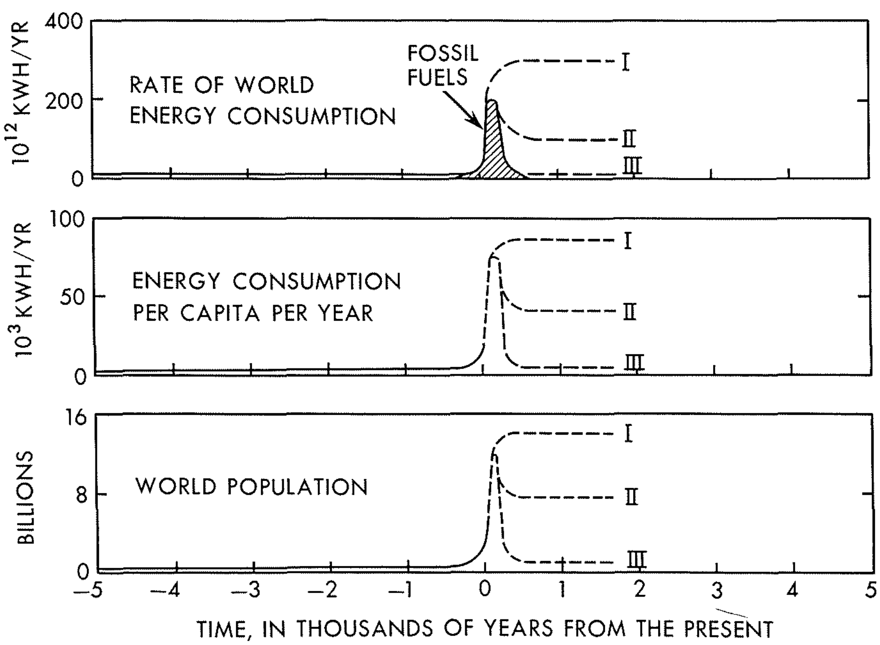

Fig. 34 - Human affairs in time perspective (modified from Hubbert, 1962, Fig. 61).

It appears, therefore, that the foremost problem facing humanity today is that of how to make the transition from our present precarious position on the front slopes of the curves of Fig. 34 to an optimum stabilized state, such as that indicated by Curves II, by the least catastrophic progression. Once this transition has occurred and a culture appropriate to a nongrowth state has been achieved, there is promise that such a state might also provide a climate for the flowering of one of the greatest intellectual advances in human history.

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INTERNATIONAL ENERGY TRADE AND PRICE TRENDS

BY FRANK S. MCFADZEAN*

There is a growing idea that the oil supply crisis is over and that we are again free to consume as much as we please, to go back to our old ways. This is not true. It may never become true. Some of the acute symptons have disappeared and supply conditions are more normal: but there is a big difference between what was normal before the events of last October and what is considered normal now. The crisis has left its legacy.

To my mind, the principal legacy is almost certainly one of permanent change. Change began a long time ago. During the transformation there have been other acute stages of varying importance, such as the first closing of the Suez Canal in 1956, which made it clear how dependent Western Europe had become on cheap oil from the Eastern Hemisphere. Last year it became clear that virtually the whole world had become dependent on oil from that source - not just cheap oil but oil at almost any price.

From the very outset in the international oil industry there were considerable economic pressures towards the integration of the various functions involved. The wayward geography of oil in relation to markets demands it. The search has to go on continuously, oil must be produced, moved - usually over considerable distances - to refineries, turned into products, distributed and sold. It was the economics of competition, not chance, that compelled the oil companies towards integration. This pattern of supply has been followed for over half a century, involving most of the oil in international trade. Competition kept down the cost of oil, gave the industrialized countries abundant supplies and helped oil to reach its dominant position in the supply of energy.

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Indeed, a broad sweep of the energy picture from 1945 to 1972 shows that, while the rate varied from year to year, there was a growth in total energy demand throughout the period. Within that increase, the contribution of solid fuels declined not only as a percentage of the total but also in absolute terms. The bulk of the energy requirements was taken up by oil and gas but more particularly by oil.

The relative cheapness of the final products was the main reason that brought oil into its dominant position. The underlying trends were sometimes obscured by the incidence of excise taxes imposed by the governments of consuming countries. Net of excise duties, however, the oil industry outside North America contained inflation in the sixties and, what is more, up to 1971 realizations for oil products remained below the 1961 level. Several factors resulted in bringing about this situation. In the first place there was the growing appreciation of the magnitude and very low technical costs of the Middle East fields. Next there was the discovery of oil in various countries in Africa - Algeria, Libya and Nigeria. Although produced at much higher technical costs than in the Middle East, the oil enjoyed quality and also transportation advantages to important markets such as Europe and the United States. Moreover a considerable proportion of this oil was in the hands of American independents who, due to import controls, had only limited possibilities of disposing of their production in the United States. Competition to achieve position in non-American markets therefore increased.

Economies of scale were also important contributors to the relatively low oil prices in the sixties. These affected virtually every aspect of the business. In the market place concentration on high-throughput stations, greater use of pipelines, hydrant refuelling, two-and three-shifting of equipment in "blind" and larger drops and many other - in themselves small but in total appreciable - changes produced substantial cost savings. In refining, distillation columns of 20,000 barrels per day gave way to columns of up to nine times this capacity: while in marine transportation tankers of 35,000 deadweight tons have been superseded by vessels in the 200,000 to 350,000-ton range for oil movements on the main supply routes. The question is sometimes raised whether additional economies of scale can contribute towards containing current rates of inflation and the higher prices imposed by oil-exporting governments: but little hope can be held out in this direction.

Economies are of course still possible but the dramatic ones have probably been achieved already: the future ones are likely to be relatively marginal. As an example, the cost of transporting oil from Kuwait to Rotterdam via the Cape of Good Hope by a 210,000-tonner is about one third of the cost of transporting the oil in a 35,000-tonner. In a 620,000-tonner, which is a possible size for the next generation of very large crude carriers, the cost would fall only to about one quarter of the cost of a 35,000-tonner. The larger fall in cost is therefore represented by the jump from 35,000 to 210,000 tonners: the fall for increased size beyond the latter figure becomes progressively smaller. Indeed, it is a fairly fine calculation whether the additional transportation cost-saving in the possible new generation of ships is sufficient to outweigh the cost penalties involved in the reduction of the number of ports capable of receiving the larger ships, their inability to traverse some of the main sea lanes of the world, such as the English Channel and the Straits of Malacca, and the necessity to build additional storage to load and discharge the vessels at acceptable rates.

In addition to the cheapness of oil and its greater convenience in use than some alternative fuels, the question of security of supply also entered the assessments of the consuming countries. The extent of the reserves proven by exploration world-wide - but particularly in the Middle-East - coupled with the flexibility of the industry in surmounting successive crises, engendered a feeling of sufficient confidence in most consuming countries to permit the relative shares of the various forms of primary energy to be determined mainly by market forces. However, even before the onset of last year's troubles the security of supply had already started to weaken. The "shut-in" production potential of the United States - itself the result of pro-rationing but which had proved a useful buffer in successive crises - had virtually disappeared by 1972. The sheer size of the volumes supplied by certain key countries such as Saudi Arabia and Iran was such that the prolonged absence of any one of them from the supply scene could produce considerable problems. Moreover the accumulation of substantial currency reserves by countries such as Libya and Kuwait reduced the pressure on them to maintain output. All these factors, combined with the increasing overtones of oil as a political weapon, had already reduced security of supply before the crisis actually broke.

The same competition and low prices that literally fuelled the post-war rate of economic growth also led to the formation in 1960 of the Organization of Petroleum Exporting Countries (OPEC), and thirteen years later to the confirmation of the political and economic power of the oil-exporting countries. In the years leading up to the crisis, the monopoly power of the oil-exporting countries of the Middle East was developing rapidly and by the end of 1973 oil-exporting governments were able to impose on the rest of the world their own terms. They did so. The events which brought about the change are now well known: cuts in the level of oil production by most Arab countries; embargoes on the shipment of oil to a number of destinations, notably the United States and the Netherlands; a fourfold increase in the posted price of crude oil and in the "take" by exporting governments in the last quarter of 1973; and a substantial increase in the share of those governments in oil produced by the companies, because of the negotiation and renegotiation of agreements on participation. Under traditional supply patterns the balancing of supply and demand had been carried out by the companies.

Demand growth was fairly steady. It was therefore predictable and could be met by regular increases in supply capacity.

These actions by oil-exporting governments damaged the stable framework of international trade in oil.

The full significance of the changed relations has been temporarily obscured by the fact that the steep rise in prices has resulted in reduced demand which, in turn has thrown up excess capacity in tankers, refineries and marketing facilities. The fact is that the close-knit system of co-ordination for both the long term and the short term has been broken. The price of crude oil and the volume available have become dependent on what is agreed at OPEC meetings two weeks before each quarter comes to an end. The uncertainty over planning has made fragile almost any decision over investment in energy, greatly increasing the risk. It has also made precarious the position of all countries importing oil, a commodity vital for almost all sectors of modern economies and constituting some 20% of the value of all international trade.

Let us examine what that change and uncertainty means by looking at the market today, almost a year after oil-exporting governments decided to raise prices and cut back supplies.

Firstly, there is at present a surplus of oil production of around 1-1/2 million barrels a day. This is attributable to falling demand and to the fact that re-stocking after cutbacks has largely been completed.

Secondly, in a normal market situation this surplus would tend to lower prices; but since prices are now determined by oil-exporting governments, there is no reason to believe that this must necessarily follow for the bulk of crude oil moving in international trade.

Thirdly, decisions by governments on price are affected by what happens over sales of government equity oil. At the time of acute shortage, governments increased the third-party sales of their share of the oil produced by the companies, the near-panic exhibited by some buyers resulted in government receiving from third parties higher prices than they did from the oil companies although the volumes were sometimes small. Governments have lately been putting up more oil for auction and in present circumstances the froth has tended to disappear from the market. Failing to achieve a continuation of high prices, some governments have preferred to shut back supply rather than reduce prices to stimulate demand.

Fourthly, the present "easy" supply situation could either continue or, particularly if there is a severe winter, turn into a shortage in a matter of months. The terms on which existing closed-in production will be allowed to re-open, if at all, are unknown. The effect on the oil-importing countries is to compound the insecurity both for volumes and prices.

In the face of this uncertain future, the ability of the oil companies to obtain supplies has been much less flexible. This has led to policies of seizing all reasonable supply opportunities. It has also resulted in high inventories, in spite of the new cost of working capital and of storage.

Negotiations over the participation agreements has still not been finalized. Oil companies have for some months been lifting crude oil from some exporting countries without knowing what they may ultimately have to pay for it. This is because some of the oil is now taken up by governments for sale by them and the extent of the share is in many instances still undetermined. Talks are still going on over how much of this government equity oil will become available to the companies - and at what price.

At the same time, little action has been taken by importing governments. Beginnings, but no more, have been made in two areas: proposals for emergency allocation measures in a possible supply crisis and policies for reducing consumption. But oil-importing and oil-exporting governments have not yet sat down together to discuss the matters of major concern to them both - the future of volumes and price of crude oil.

Indeed, any proposal that this should be done often evokes a hostile reaction from at least some OPEC members. Yet the statesmen among them realize the potential for disruption inherent in the present unstable situation and the need to find some mutually acceptable accommodation if the international trade and payments system - so laboriously built up since the war - is not to be put under intolerable strain. The oil-exporting countries are estimated to have earnings in the current year of some $70,000 - 75,000 million - above their absorptive capacities for goods and services. This is of course the obverse of the current balances-of-payments deficits of the oil-importing countries. Due to various time-lags, the full effects of these - by any standard - massive financial shifts have not yet become manifest, but are likely to do so at an accelerating pace from now on. There is a considerable volume of vague talk about recycling these financial flows to where they are needed: The blunt fact is that in the international monetary system there is no mechanism or series of mechanisms that ensures this will in fact take place. Although many politicians and bankers appear to be aware both of the potential dangers and the various solutions that could - to a large degree - mitigate the probable effects, there seems to be a lack of political will to achieve results. There is a tendency to treat it as tomorrow's problem where prudence would suggest that it is handled today.

Faced with present difficulties and uncertainties both on volumes and prices, the energy industries and the govvernments of the oil-importing countries are considering the development of alternative supply sources. Alternatives, of course, include conventional oil and gas reserves outside the OPEC areas and these - Alaska and the North Sea, for example - are in the process of being developed now, as are improved secondary recovery methods from existing fields. But the increase in prices has been such that energy sources which until recently most of us thought to belong to the next decades have now had their economic horizon brought sharply forward as supplements to conventional oil and gas. Even so, some sources (such as nuclear fusion) still remain visionary and the journey from the scientist to the drawing-board and to everyday life is likely to be a very long one. The bridging period into the new energy environment foreseen by the scientists is likely to witness the development of coal, tar sands, shale and nuclear fission as more substantial contributors to energy demand.

The possibilities and limitations of all of them are constantly changing. Coal is a good example. Although never delineated in any detail, it is estimated that coal deposits are anything from 10 to 40 times the volume of reserves of conventional oil. Moreover from a security point of view the reserves are more widely spread than oil. Big efforts to develop indigenous sources of coal for home consumption in North America and Eastern Europe are expected but a more important feature will be the expansion of the volume of coal entering international trade. Coal can now be delivered from a number of areas into Western Europe and Japan at an estimated range of costs of between $25 and $40 per ton, which makes it competitive with oil for many uses. Moreover technology is advancing rapidly. Coal is no longer merely a fuel for burning as a traditional means of raising steam. A whole new future is opened up by the possibilities of converting coal into oil, gas and other products; even where it is still burned beneath boilers it will be possible to do so with far greater freedom than in the past, because ways are being found of removing both sulphur and ash. The stack-gas scrubber, which is now operating successfully in a refinery in Japan, could be applied to coal-burning boilers. Other advances in technology are making coal easier to mine and transport. The large funds now being spent on research and development are an indication of the future envisaged for coal as a supplementary source of liquid and gaseous hydrocarbons.

The reserves contained in tar sands and shales are also estimated to be considerably greater than the proven reserves of conventional oil. The tar sands here in Canada, provide the equivalent of several hundred billion barrels of oil, half of which is considered recoverable by strip mining and "in situ" methods. The reserves could support an estimated production of 500,000 barrels a day by the mid-eighties, building up to 3,000,000 barrels a day towards the end of the century. Present production from the only plant in operation is of the order of 50,000 barrels a day but there are now more than two dozen companies interested in the development of the Athabasca area. Likewise, interest in the production of oil from shale has been stimulated by current high prices and the research effort into the most economic means of extraction has been accelerated.

A new urgency has also been brought into a generation of electricity from nuclear power. Even before the oil crisis of last year, the international atomic energy agency forecast a large increase in installed capacity over the next decade. The effect of the crisis has been to reinforce the argument in favour of enlarging or speeding up nuclear programmes both on economic and logistical grounds. This has been particularly marked in Japan, with its heavy dependence on energy imports. Within the next seven or eight years, the United States, Japan and the countries of Western Europe as a whole expect to draw at least one quarter of all their electricity requirements from nuclear power plants.

However, the fact that there are abundant alternative energy sources to supplement whatever level of conventional oil is permitted to be produced must not lull the consuming countries into a complacent feeling that a new dawn is just around the corner. There are two important limiting factors in the development of new supplies, there is, firstly, a long lead-time involved. It applies in varying degree to all the alternatives but let me give one specific example. Shell companies are involved in the establishment of a plant in Athabasca to produce 100,000 b/d of synthetic crude oil - a level of production which cannot be considered very great and which could be absorbed in an industrial complex in a large manufacturing city. If the green light were given to commence operations tomorrow, it is estimated that it will be 1980 before the full level of production will be reached.

Equally important is the vastly increased capital investment per unit of output which is necessary for the new sources of supply compared with the Middle East. Investment required per barrel per day in the Middle East is of the order of $250: in the North Sea, where the industry's technical knowledge to produce in deep and rough waters is being pushed to the limit, the figure is now estimated to lie between $3,500 and $4,000 while here in Canada the investment required to produce one barrel per day from the tar sands would be between $10,000 and $15,000. Compared with the Middle East, the capital requirements of the tar sands is therefore between forty and sixty times greater and single projects costing $1 billion have thus to be faced. Moreover, the combination of long lead-times and inflation could conceivably in the time taken to bring a new project on stream, push a $1 billion project well along the road towards $2 billion.

Although the effects will vary from country to country, for the world as a whole several conclusions would appear to flow from this analysis.

Firstly, within the limits of present technical knowledge, there appears to be no credible alternative to oil in the energy supply balance for the next decade or so.

Secondly, although its percentage contribution may well decrease, there is over the same time-span no credible alternative to oil from the Middle East - two thirds of the world's proven reserves of conventional oil are located there.

Thirdly, consuming countries will require to devote an increasing proportion of their resources to meet the cost of energy supplies, not only as a consequence of the increases in world prices, but also because of the heavier investment necessary to develop alternative supplies.

Fourthly, only the immediate crisis of supply volumes has been overcome: the full balances-of-payments impacts of the price increases have yet to be felt.

There is still an urgent need for more determined effort to reduce some of the extravagant uses of energy. An analysis of fossil fuel consumption in the United States, Japan and Western Europe shows that about half is wasted either in transportation or in the process of converting fuels into more convenient forms of energy. This is due to the low efficiency of the internal combustion engine - petrol 10-18% and small diesel 21% - and the low efficiency of electric power generation at 38%. Electricity for domestic heating is about 30% efficient compared with 70% for gas or oil. Improved insulation and a re-think of some of the energy-intensive automobile exhaust-gas purification measures could also make substantial contributions to a reduction in demand.

Let me conclude with some further observations on price. The era of cheap energy on which so much of the economic expansion of the world was based is probably over. The economies of the importing countries could probably have adjusted themselves to this fact with minimum upheaval if changes had not been precipitate. But the virtual quadrupling of the price of a basic commodity like oil in less than three months must result in a considerable amount of economic disruption: the full extent of this we have yet to witness. Secretary Simon of the United States has expressed the view that oil prices in general - not only the frothy part of market - will come down from their present high levels. This line of argument is supported by the fact that it is quite unique for any commodity not in immediate short supply to be trading at up to eighty times its technical cost of production. Yet the forces which traditionally have undermined prices inflated to this extend by the operation of cartel arrangements are largely absent in the present situation. There is no economic pressure on some of the main exporting countries to increase production to obtain higher revenue. Indeed the limited absorptive capacities of economies such as Saudi Arabia, Kuwait and Libya are such that pressures tend to be the other way round - to retain the oil in the ground rather than produce it. On the evidence available, it is difficult to share the optimism of Secretary Simon.

Yet the governments of most of the major oil-exporting countries have no interest in contributing towards a possible world depression. They could not remain unaffected by the forces that would be released by such an event. However, because not all of them realize - any more than most of the rest of us do, as consumers - the potential injury to the international economy, there is a real danger that the world may drift into a situation that neither the producers nor the consumers wish to arise. A closer dialogue between them becomes more urgent than ever. It may be optimistic to expect it to result in a reduction in prices, but it should at least be possible to cushion the impact by reaching some agreement on a mechanism to channel surplus funds where they are most needed.

One of the outstanding features of the post-war world has been the growing interdependence of the various national economies. But many politicians have failed to grasp the significance of this trend and political institutions have tended to evolve much slower than the underlying economic realities. In spite of warnings of its possibility by some oil companies, the crisis of October 1973 erupted without any intergovernmental agreement on how to allocate oil in periods of artificial shortage. In the absence of any such mechanism the oil companies were forced to fill the vacuum. But the companies were subjected to pressures from various governments to keep them whole at the expense of deeper cuts to other countries. This was a recipe for even greater disruption since it was absurd to think that countries with a more-than-average reduction in supplies would use their scarce resources to bunker ships or aeroplanes belonging to those who suffered no reduction at all in volume.

It is this tendency towards a chauvinistic approach in times of crisis that represents the real danger that confronts us at the present time. In the absence of agreed international action the incidence and effects of the oil price increases and consequent flow of international funds will vary widely between countries.

It is essential that those who enjoy benefits take cognizance of those less well placed and of the wider and more important issues at stake.

ENERGY FOR TOMORROW . . . . AND BEYOND

BY A. E. PALLISTER*

If ever a subject gave scope for a broad brush treatment, spiced with mind-boggling numbers and grand designs, that subject is future energy supply and demand. Even today, we routinely talk of trillions of cubic feet of natural gas, billions of barrels of oil, millions of kilowatts of electricity. The sums of money involved can seem equally astronomical. To cite a single example, the latest estimated cost for the James Bay Hydroelectric project, Canada's largest single energy project at present, is $12 billion -- that is about equal to the 1973 GNP of countries such as Norway, Turkey or Finland.

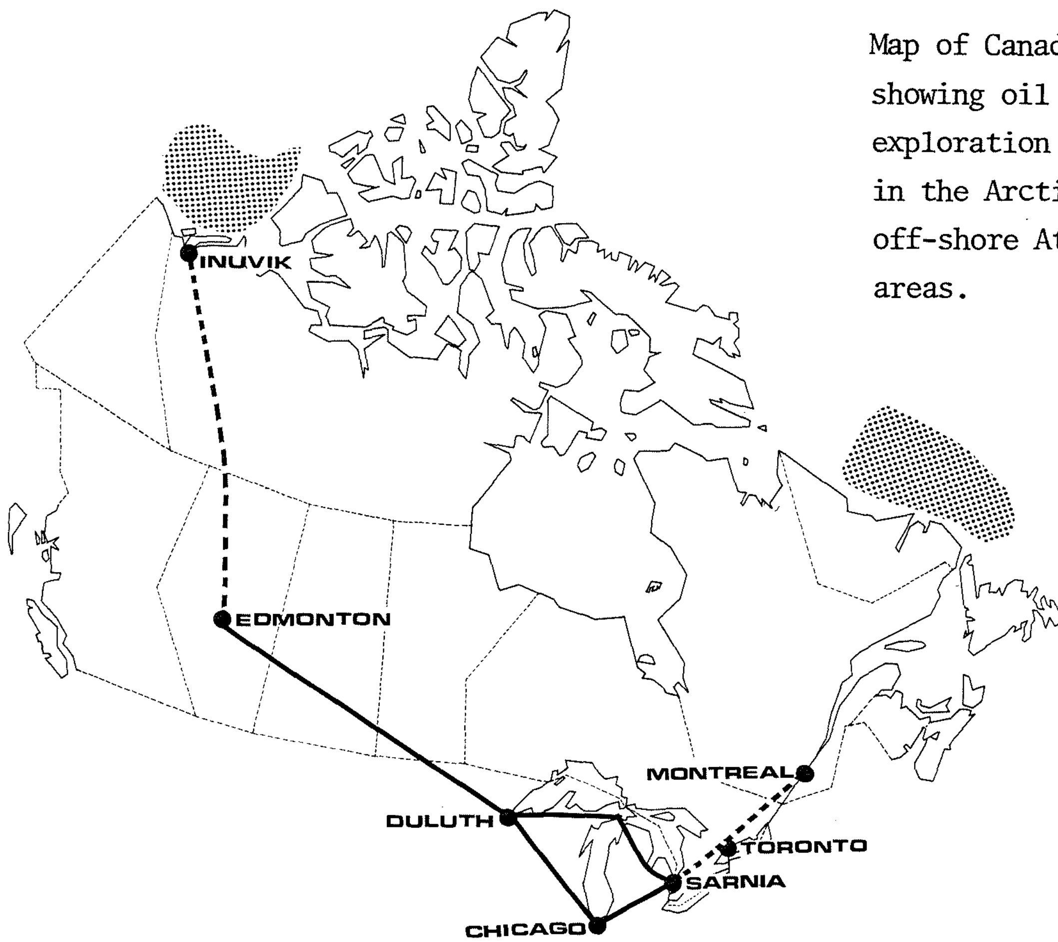
This presentation will provide views on what broad changes are likely or possible in the areas of energy supply from a vantage point which is primarily, but not exclusively, Canadian and technological. Some comments will be inserted on energy demand as a counter-point to those on supply. Although concentrating on Canada, it must be remembered that Canada's energy system is inextricably intertwined with the global system.

What I have to say on policies and on economics will be particularly highly focussed on Canada. I hope to be able to touch on both the immediate and the long range future and to include some ideas which can be held with confidence and some which must be classed as speculative. My perspective is shaped partly by a career involving a close association with the oil and gas industries and partly from my position as vice-chairman of the Science Council of Canada which has had a study on policies for energy R & D underway for about three years now -- studies which obviously have influenced many of my views.

*Vice-chairman, Science Council of Canada and
president, Pallister Resource Management Consultants

Geographical perspective

To set the stage, it may be useful to review briefly some geographical points. Reference will be made to oil and gas exploration activity in the Canadian Arctic and off the Atlantic Coast - the two shaded areas in the map.



Map of Canada showing oil and gas exploration activity in the Arctic and off-shore Atlantic areas.

The distance between Inuvik on the Arctic Coast and Montreal, is about 2,600 miles as the crow flies. The distance along the potential pipeline route via the existing Edmonton to Sarnia pipeline is about 3,500 miles. By comparison, the Labrador Coast is a mere 1,000 miles from Montreal. Since most of Canada's population lives in a narrow strip running from Windsor to Quebec City, the distance which a resource has to travel to the market place is an important consideration. Also, the means chosen to transport the resource may have to operate at both ends of an 80 to 85 Celsius degree range of ambient air temperature. The existing oil pipeline goes through the

U.S., dropping off major exports en route, particularly in the mid-West market area served through Chicago.

Historical perspective

The single most important lesson to be drawn from the history of man's use of energy is that no single source has ever remained dominant; the rise and fall in importance of every form of energy source is something entirely to be expected even though it may be impossible to forecast with much accuracy the time period in which this will come about.

Figure 1
World energy sources - the historical pattern showing percent contribution to total supplies.

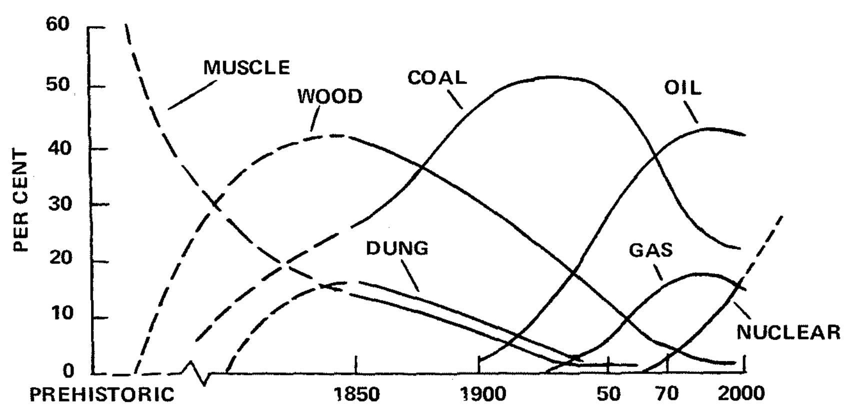


Figure 1, despite omissions such as hydro power, shows some historical data and conjecture in a fairly graphic manner. If such a figure were drawn about the year 2100, it would probably show similar wave patterns recounting the rise of nuclear power, of solar power, of power from thermonuclear fusion, and the decline of fossil fuels (although it would not be surprising to find the decline of coal could be considerably slower than that of conventional oil or natural gas).

The arrival of each new energy form permits substitutions for older sources. Some applications have seen substitutions occur many times; perhaps an extreme example is marine transportation which has used power in turn from muscles, from wind, from steam generated by wood or coal, from oil and recently from nuclear reactors. Substitutions have been dictated historically by two sets of factors -- technological and economic -- and there is every reason to believe that the process will continue. As a case in point, the recent beginning of the substitution of uranium for fossil fuels as a source of electric power has depended on technological developments for its feasibility and on economics for its timing. In addition, we have recently begun to give weight to environmental concerns, and particularly to pollution, in our decision-making; this factor is likely to be increasingly important in deciding on substitutions in the future. Further, the impacts of such intangibles as social concerns surrounding resource developments, aboriginal rights and so forth, will in future have increased effect on the choices of energy resources.

In considering not only substitutions of energy resources but also in developing new sources, we will need to give greater weight to the question of energy balance -- just how much energy must be put into a development to get a new energy source as output. Where the gain is not large, the usefulness of our approach must be questioned.

The present situation

In turning to the present - today plus or minus about a year - short-term trends can be misleading; they may only be the noise associated with the signal of long term trends. Two snapshots of Canada's energy supply and demand situation follow - the first being the energy flow shown in Fig. 2.

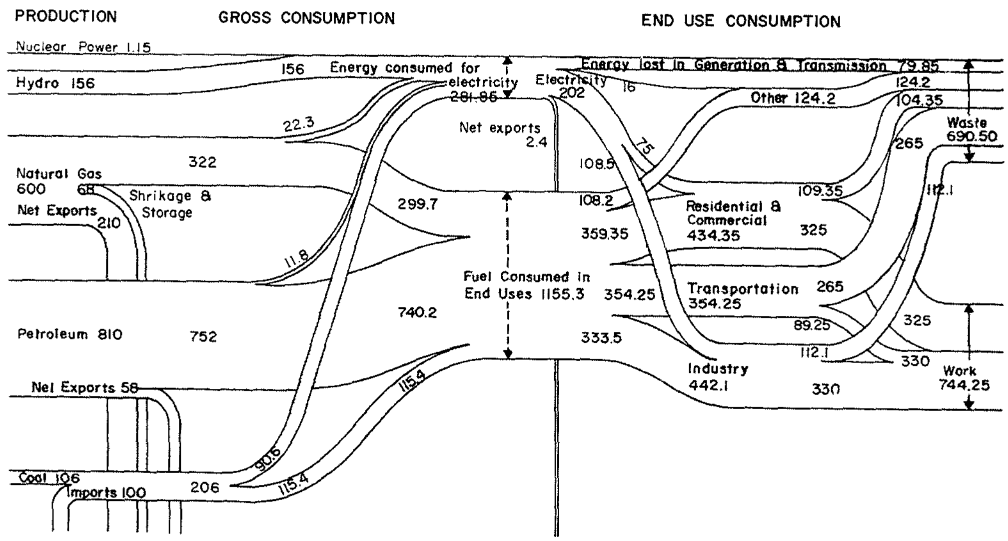


Figure 2 - Canadian energy flow in 1970 is traced from the production of energy commodities (left) to the ultimate conversion of energy into useful work and waste heat (right). Total consumption of energy in 1970 was 1437.15 kWh x 10^{12}. The overall efficiency of the system was approximately 52%. The end use "Other" refers to field and plant use (and/or) fuel and losses (and/or) losses and unaccounted for. It is assumed the energy within this area is all waste. Efficiency of direct fuel use in transportation is taken as 25%; of fuel use in other applications as 75%.

Figure 2 has been called a spaghetti diagram and depicts the flow of energy in Canada for 1970. Energy commodities appear on the left and their ultimate fate (as work or waste) on the right. The key elements to note are

(a) the dominant position of petroleum (more than 50% of all energy used in Canada comes from petroleum and about 75% from petroleum plus natural gas);

(b) the very large proportion of energy which ends up as waste - in the case of Canada about 48% of total usage;

(c) the large role already played by electricity in Canada's energy economy and the significant proportion within that share which is hydroelectric power (about 55% of all of today's electricity in Canada is hydro-generated but this proportion will decline in future).

Table 1 shows a comparison of net per capita consumption of electricity in some OECD countries.

Table 1

Net consumption of electricity

kWh per capita per annum excluding losses
(data for 1971)

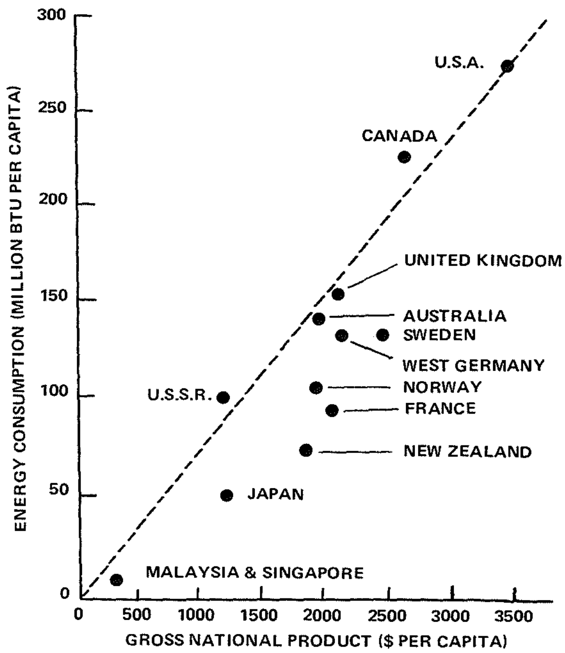
Norway	13,965	Australia	4,224
Canada	9,021	United Kingdom	3,944
United States	7,661	Ireland	1,786

Canada is second only to Norway in this particular ranking.

Figure 3 shows a plot sketching the relationship of per capita GNP to per capita energy consumption for a number of countries. Canada ranks high, partly as a reflection of a high standard of living, but partly also because of climate and geography -- demands for heating and for transportation make up about 45% of current total consumption.

The energy crisis of last winter came as a nasty shock. More properly, it was an oil supply and an oil price crisis. While Canada today is what could be termed numerically self-sufficient in oil production, it does in fact import oil from Venezuela, Africa and the Middle East to serve Montreal and markets east of that city, while exporting an equivalent amount mainly from Alberta, to the U.S. The flows in both directions are currently of the order of ¾ million barrels per day.

Figure 3 - Per capita energy consumption and per capita GNP selected countries 1965.



Some policy questions

An important parameter influencing Canada's present energy situation and national energy policy is the particular political and constitutional system which prevails in the federal state. Both the set of ten provinces and the federal government have areas of jurisdiction which allow them to consider resources or the resource industries, so each has the ability to influence the national stance.

The British North American Act of 1867, which is Canada's constitution, granted ownership of natural resources to the provinces but allocated responsibility for the supervision of trade and commerce - whether interprovincial or international - to the federal government. This particular division of jurisdiction is the source of much of the current political controversy over energy within Canada today.

In a report* published last year, the federal government set out its energy policy objectives. To paraphrase them slightly, they were concerned with

- the provision of adequate supplies of energy at competitive prices
- security of supply
- the encouragement of timely energy resource development
- the exportation of surplus energy supplies under terms beneficial to Canada
- the acquisition of foreign supplies when these are more economic than domestic ones and when this does not seriously damage the security of supply
- the alignment of energy policy with other federal policies, e.g. on environmental quality, on Canadian ownership, and on Canada's posture as a trading nation which has traditionally worked for the lowering of international trade barriers.

In turning to Canada's ten provinces, it is tempting (but an oversimplification) to divide them into producers and consumers of energy. This division is perhaps most relevant in the case of oil and gas where one province, Alberta, is the source and owner of about 85% of all domestic supplies while being the home of about 7½% of Canada's population; in this more limited area, policy objectives of the province of Alberta appear to include:

- the acquisition of a fair return to the province via taxes and royalties, from the exploitation of her resources
- the use of her jurisdiction over energy resources to secure industrial diversification and growth
- the use of her jurisdiction over energy resources to secure improvements in some of the services provided or regulated by the federal government (e.g. transportation). This point may be particularly significant in an era when the province elected no members of the ruling party in the federal government.

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*An Energy Policy for Canada, Phase 1, issued by the Minister of Energy, Mines and Resources, June 1973

Priorities would be rather different in Ontario, home of more than half of Canada's manufacturing activity, where objectives would be focussed around security of supply of imported energy resources (particularly oil, gas and coal) and development of a nuclear generating capacity.

The energy policy arena is currently further complicated by a series of essentially political disputes between the two senior levels of government over their respective rights to set prices, levy royalties and taxes and control development and delivery of energy resources. Also there is a federal-provincial dispute over ownership of any resources which might be found on continental shelves.

Another particular but all-pervasive concern to policy makers is the extensive foreign ownership of companies developing and distributing resources. Fossil fuel reserves are almost entirely controlled by the major multi-national companies, although there are literally hundreds of smaller independent Canadian companies operating throughout the oil and gas business; this gives rise to many problems including some important ones concerning technology and scientific information.

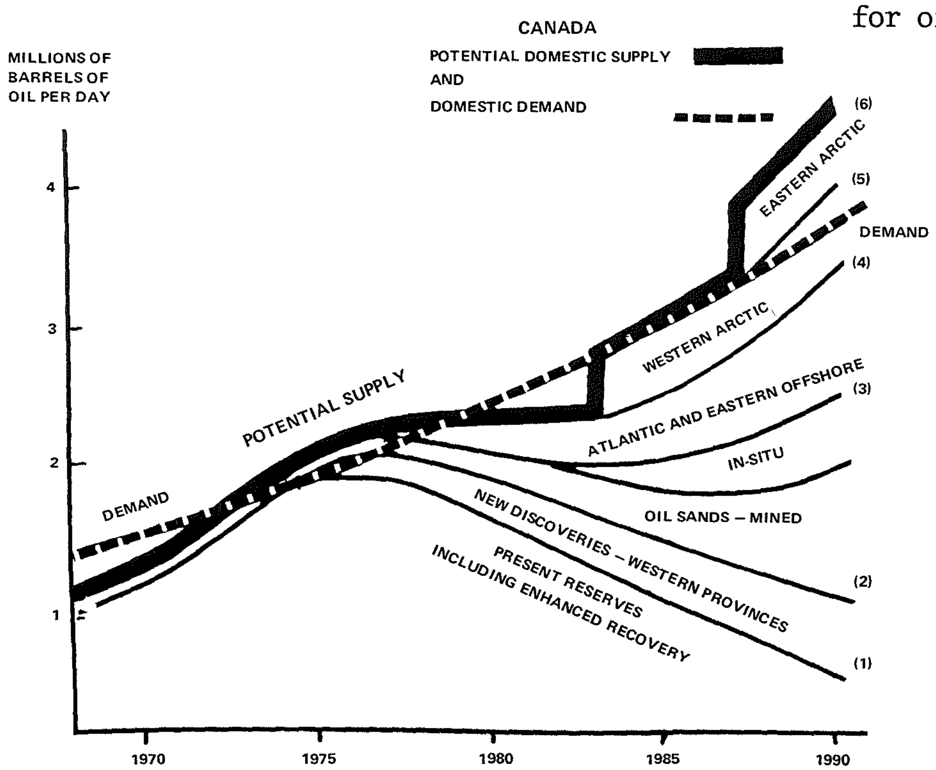
One important example is that the technology necessary to recover Canadian resources being developed principally outside of Canada - Canadian-based R & D in the industries involved is not highly developed and it is doubtful if there truly exists within Canada the complete range of technological capabilities needed to operate in the oil, gas or coal business in the future. Canadian subsidiaries of the multi-nationals are technologically dependent on the parent corporations. Perhaps the single notable exception to this generalization was the development, in the Research Council of Alberta, of a hot-water technology for the extraction of bitumen from the Alberta tar sands, a technology which is now in use in modified form.

Some short-range problems

While the policy issues surrounding Canada's energy supplies present many problems, comments here will be focused on the technological and financial problems to be overcome if Canada is to implement a national energy policy. Amongs short range problems extending to the end of the 80's is Canada's supply of crude oil.

Present day society is dependent on oil as an economical, compact, easily transportable energy source. Despite the possibility for considerable substitution, e.g. hydro or nuclear-generated electricity instead of oil for space heating, oil will remain the dominant energy source for a long time to come. With this in mind, Figure 4 shows a supply and demand projection based on some optimistic assumptions. Even given the optimistically early dates for the availability of oil from what hopefully will be large finds in Arctic and Atlantic offshore areas, and notwithstanding the immense potential of undeveloped sources, there seems to be a period in the early 80's when Canada will become a net importer of oil. If the international price for oil stays at $10 per barrel, then that gap between supply and demand in the 80's could cost us, on a cumulative basis, more than $6 billion on the deficit side of our international balance of trade. It should be in Canada's interest to see that the exploration and technological developments needed to find and deliver to the Canadian market oil from offshore areas and from oil sands, proceed rapidly enough to at least minimize the adverse impact of the indicated domestic shortfall.

Figure 4
Canadian oil supply and demand projection for oil.



It is also important to note that, even though the potential reserves of synthetic oil in the Athabasca oil sands are vast - possibly in the range of hundreds of billions of barrels - oil from that source will still satisfy no more than about 40% of demand by 1990.

A second problem area for Canadian self-sufficiency stems from inadequacies of the internal transportation and distribution systems. A few transportation difficulties are:

1 - There is no pipeline system today to take Western Canadian oil into the markets of Montreal and Eastern Canada, although last winter the federal government announced an intention to extend the existing pipeline from its present terminal at Sarnia to Montreal. This means that Eastern Canada will continue to use essentially imported oil, at least until production begins off the Atlantic Coast.

2 - There is no adequate transportation system for hauling western coal to the markets of Ontario, nor is there the productive capacity to supply those markets, so Ontario Hydro imports millions of tons of U.S. coal annually. The cost of transportation was certainly a significant factor in this case.

3 - The first application to build a pipeline to bring Arctic gas to southern markets is still under consideration; in the next decade or so more than one such pipeline will be needed and an oil pipeline along this route will also be needed by the mid-80's. It must be added that no plans exist today for this oil pipeline.

4 - There are still considerable losses involved in the transmission of electrical energy, and most of the remaining promising sites for hydroelectric generation are long distances from the centre of demand. Some first class work is underway on this problem in Canada, principally at Hydro Quebec's Institute IREQ at Varennes.

5 - There is no effective national electrical system in Canada; much upgrading of the interconnections between provincial systems remains to be accomplished.

Each of these transportation problems is large, but none is insoluble. The even larger problems of oil supply are also important and ultimately, I believe, soluble.

Financial outlook

Perhaps large enough even to overshadow the technological problems of energy production are the high financial investments involved. A few order of magnitude costs for the kinds of projects contemplated are:

- Plants for the Athabasca oil sands and supporting mining operations - \$1 billion each. At least five such plants are already on the drawing board

- Coal mining operations on the scale of an oil sands operation - about \$½ billion

- Nuclear power stations - \$1 to \$2 billion, priced according to size

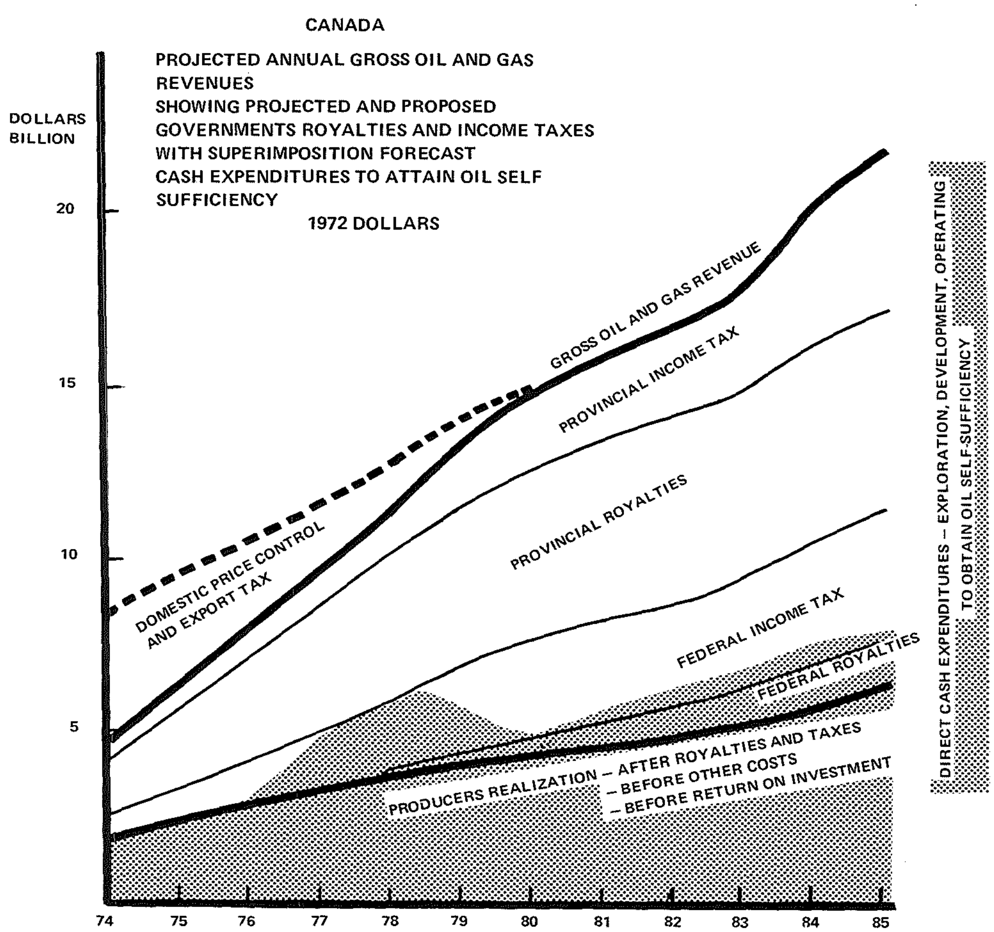
- Oil or gas pipelines from the Arctic Coast - about \$5 billion each

- The James Bay Hydro project - last estimate \$12 billion.

In Figure 5 the revenue has been computed which might be expected from the oil supply configuration shown in Figure 4 (assuming that by 1980 Canada's domestic price for oil will equal the international price) and it is shown how this revenue will be divided. Also shown is a computation of the investment needed to bring about the production required to let Canada be self-sufficient in oil in the period beyond the mid-eighties, using 1972 dollars as far as possible. What is staggering is that this calculation indicates a need for expenditures to quickly exceed \$5 billion annually compared with the current level of \$1.5 billion.

All of this almost literally adds up to a \$64 billion question - where will the investment capital come from to fund Canada's energy developments in the future?

FIGURE 5



Projected annual gross oil and gas revenues showing projected and proposed governments royalties and income taxes with superimposition forecast cash expenditures to attain oil self sufficiency.

An important policy concern in Canada, as mentioned earlier, relates to the foreign-ownership of much of the economy: given this, there will be strong pressures exerted to provide as much of the capital as possible from domestic sources or from borrowing and to minimize the importation of foreign capital in the form of equity. In the case of those projects involving the oil industry, it is certain there will be continuing pressure on governments for a reapportionment of the revenues derived from oil production so that the industry might generate most of its capital internally.

The need for investment capital will be heightened if Canada opts for a policy of oil and gas self-sufficiency. We must be concerned about the price of self-sufficiency since it is unlikely that, for example, the oil from frontier areas will be cheap. Canadians can remember past subsidies to parts of the coal industry which cost several hundred millions of dollars and do not wish to repeat that process in the oil and gas industry. On the other hand an attempted stance of "flexibility" vis-à-vis the question of importation versus domestic production may not provide the climate to attract the long term investment needed to make domestic production in the frontier areas a reality, leaving Canada dependent on imports and on the vagaries of the international price of oil.

What conditions - geological, political and economic - need to be met to make domestic self-sufficiency even feasible?

Geologically, the untapped Arctic and Atlantic Basins must be, as a very minimum, as rich in reserves per cubic mile of sediments as the Western Canadian Basin in Alberta. If the individual pools of oil which make up potential supplies in the frontier areas are not in sufficiently large units - perhaps of the order of a quarter of a billion barrels - they could well be passed by as uneconomic by the oil companies because of development costs involved. With the exception of one small and old field in the North West Territories, there are no proven reserves as yet in the frontiers. The estimates published by the federal government for potential supplies from the frontier areas range as high as 80 billion barrels which compares with the 6 billion barrels believed to exist but still to be found, in the Western Canadian Basin. Unless the supplies in the frontiers occur under the most favourable geological conditions, perhaps as few as 20 billion barrels will ever be brought to market at an economic price. Even this supply, however, will be a vital buffer until major production from the Athabasca deposits is achieved.

Politically, there must be resolution of the current federal-provincial argument over the economic rent to be levied on petroleum resources and its distribution between the two levels of government.

Economically, there must be assurance that a fair share of the revenue from production is returned to the oil companies. Furthermore, the economic conditions in Canada should make new exploration and development at least as attractive an investment as diversification into other, non-resource-based, activities. Most importantly, beyond recycling a share of their revenues, the oil companies must also be in a position to attract additional new investment to finance further expansion of their productive capacity.

Geological constraints cannot be changed but we must seek knowledge of our frontier resource base to determine if self-sufficiency is feasible in terms of availability. Political constraints are man-made and simply have to be overcome in such a way as to obviate economic constraints. This in turn will involve encouraging recycling of old money and attracting new money into the oil and gas industries.

The three principal actors are the province of Alberta, the oil companies and the federal government. By 1985 Alberta could be receiving about $10 billion annually in revenues compared with today's provincial budget running at $1.6 billion. This assumes that the domestic price for oil reaches the international price by 1980 and that royalty rates continue unchanged.

Under the current tax structure, which is under review, the oil companies are recording substantially higher profits and proven reserves have substantially appreciated in value in recent months. On the other hand, the costs involved in replenishing their inventories will be materially higher in the future, and new investment will be needed.

The federal government is faced with its national responsibility to look after its citizens and the economy, and must concern itself with the prospect of a shortfall in domestic oil production in the early 80's which has profound implications both for the security of supply and the balance of payments. Two of the actions which can be anticipated from the federal government are:

1 - Encouragement of exploration and development in federal lands in the Arctic and offshore regions, possibly by using some selective tax incentive and by announcing oil and gas regulations, both designed to promote reinvestment of industry profits and to attract new capital to the frontier ventures.

2 - Launching of the proposed National Oil Company with the mandate which will include the stimulation of production by a wide variety of means including joint ventures with the industrial sector. The National Oil Company would be expected to be influenced by Canadian goals and priorities more than would be the case for a private oil company, and might be expected to take a quite different position

on the appropriate timing for funding of some ventures than would a corporation which is guided by global market forces.

So far the discussion of Canada's oil and gas prospects has been focussed entirely on supplies and on supply policy. The production of oil has grown exponentially to date. This form of growth cannot and must not continue and I hope to demonstrate vividly why.

At the present time, adding the optimistic projections of Canada's potential oil supplies from the Western Basin, the frontier areas and Athabasca, results in the apparently staggering total of 400 billion barrels of potential supply. This is made on the entirely unrealistic assumption that every last barrel can be brought to market.

Canada today is consuming oil at an approximate rate of 640 million barrels per year -- a life index of 625 years for all potential supplies at the present consumption rate. Figure 6 compares two scenarios for the future of that life index. The upper curve represents a "no growth in consumption" scenario; the lower, plunging curve represents the assumption of 5% annual growth compounded. Following the 5% growth curve would slash the life index by a factor of 3 in 20 years - and the 30 years just ended has shown an ability to sustain that kind of growth pattern. An entirely similar figure for the future life index of Canada's potential gas supply could be produced.

The growth scenario is absurd because it would result in reaching annual production rates of several billion barrels a year by the turn of the century. The 5% growth curve must be curbed, the question is how.

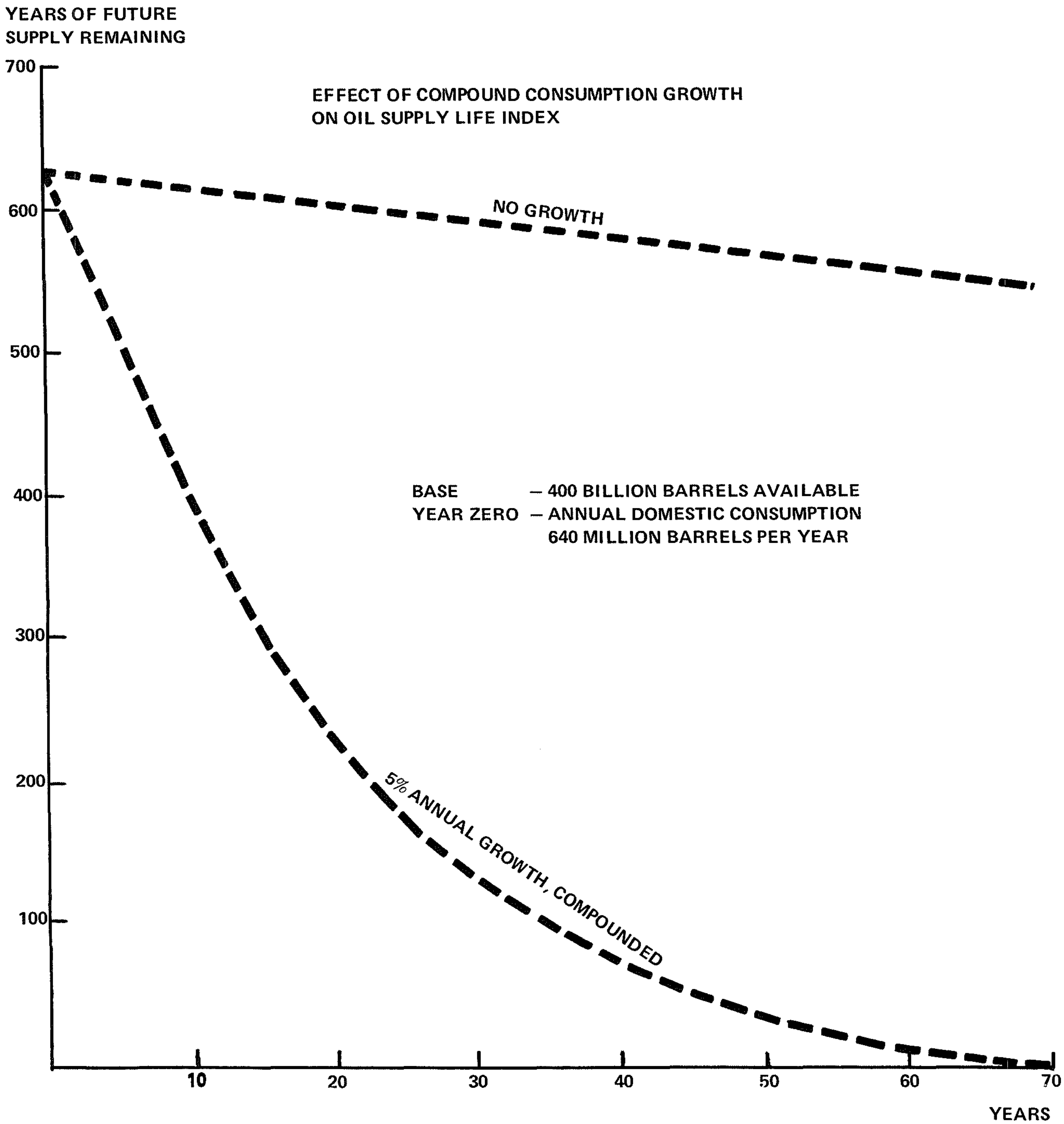


Figure 6 - Effect of compound consumption growth on oil supply life index.

In its simplest form, Figure 7 shows the necessary change in direction. Instead of allowing demand projections to control supply policies, a course must be followed in which supply projections to a large extent dictate demand policies.

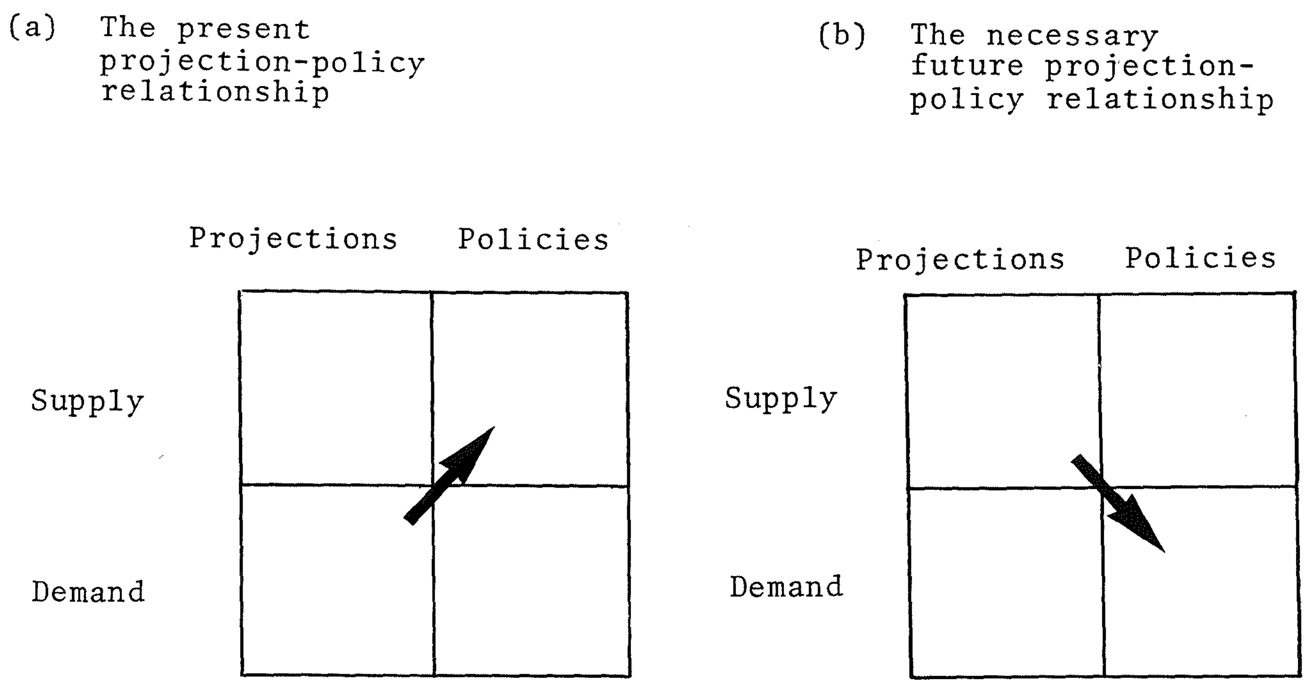
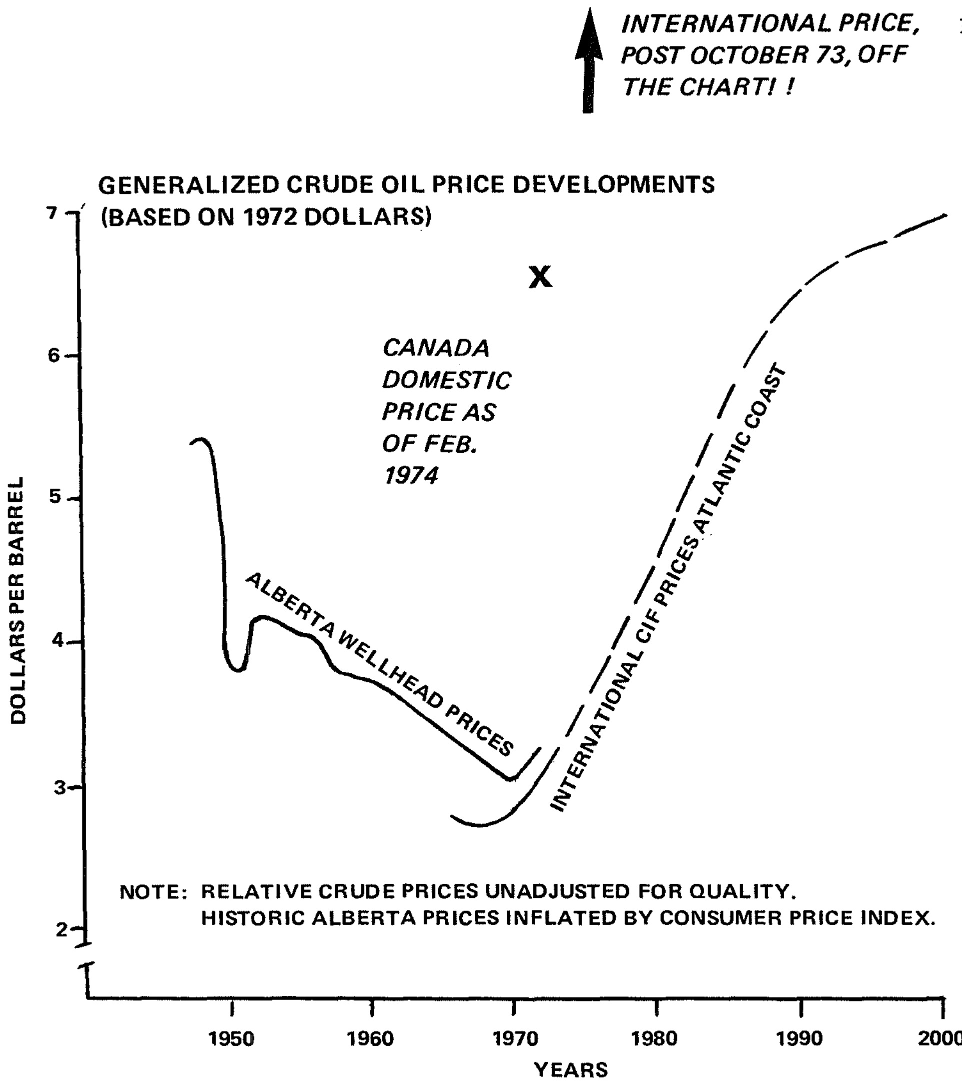


Figure 7 - Future policy will require supply projections to dictate demand policies as in (b) above, apposed to current policy as in (a) above.

The temptation to make more specific financial forecasts will be avoided since this area of forecasting seems even more fraught with uncertainties. In technological forecasting, at least the laws of nature remain fairly fixed, but in financial forecasting the laws of economics and politics play nasty tricks. Just how unexpected these changes can be may be seen on Figure 8 which is a Government of Canada projection of expected oil prices published in June 1973. To this has been added the Canadian domestic oil price as of February 1974 showing that the current international price is well off the chart. The moral should be "Cave Oraculum" -- beware of the oracle!

Figure 8 - Oil price projection made June 73, invalid soon after.



What will be the effect of rising energy prices on our economy?

In the consumer sector, rising prices may act to trim off some excess demand and may lead to buying of more energy-efficient machines and appliances. For example, the traditional North American car and its 10-15 mpg performance is perhaps headed for extinction as North American gasoline prices catch up with those in other parts of the world.

In the manufacturing sector, there must be concern about how increasing energy prices will hit production costs. Fortunately and surprisingly, most industries have a cost structure which is not as sensitive to energy price as previously suspected. Rising energy prices will never be welcome, but they will not be disastrous and perhaps might induce a new thrift which could moderate the growth of demand which, in turn, would tend to make the problems of supply more tractable.

Traditional energy policies throughout the world have been dominated by a concern to ensure the adequacy of supplies in the face of escalating demands. The time is now ripe for the emergence of a new set of energy policies whose aim would be the modulation and even control of demand.

Some emerging prospects

Hope for the future may be derived from what could be called emerging prospects and a variety of long term options. Two areas with very definite emerging prospects are those of oil and gas production and of nuclear power based on the Candu reactor system.

Prospects of finding or developing supplies of hydrocarbons are likely in three locations:

1 - The Canadian Arctic, particularly in the MacKenzie Delta and Beaufort Sea areas;

2 - The Atlantic Offshore, particularly off the Labrador Coast and on the Grand Banks of Newfoundland, and in the Baffin Bay area; and,

3 - The Athabasca oil sands.

The technological challenges facing the developers of Canada's frontier oil are formidable. One of the things needed is the development of a sophisticated technological capability to work in a hostile environment -- the cold, deep ice-infested ocean waters which surround the coasts.

The presence of ice, either as the slowly moving pack ice of the high Arctic or as the dangerously mobile icebergs which cross the Grand Banks of Newfoundland, presents the greatest problem. It must be cold comfort to the man on the oil rig off the Newfoundland coast to be told that, because of the relative shallowness of the ocean there, no iceberg bigger than a million tons is ever likely to come his way. Thought is being given to the possibility of "sub-bottom-completions" for producing wells in frontier zones since conventional rigs could turn the Grank Banks into man's largest pin-ball machine, with the annual migration of several hundred icebergs passing through the region playing the role of the balls. Two years ago some 1587 icebergs got farther south than latitude 48°N, the worst year this century and about four times the normal 360 icebergs which make it that far south.

Developing the full potential of the oil sands will be a challenge which faces Canadian scientists and engineers for many years. Consider the dimensions of the problem. Construction and commissioning of a single 125,000 barrel per day production plant will have to take into account

a - A construction period of at least five years, on a schedule determined by the difficulties of conducting either open-pit mining or in-situ extraction in a location covered by muskeg which is really manageable only in the frozen state;

b - A cost of at least $1 billion per plant;

c - Current difficulties concerning supplies of skilled manpower, both in engineering and trades;

d - Shortages of materials such as steel and mining equipment such as buckets and dragwheels;

and still this output would only be about one sixteenth of the 1974 daily consumption of oil in Canada. Put another way, one additional plant per year coming on stream would only cope with the annual growth in consumption, if the current growth rate is maintained.

What makes the problem bigger is that there is a gap in present technologies; conventional mining techniques are useful to depths of about 150 feet and the in-situ processes now in development show promise of coping with deposits below 600 feet but there are no means today of dealing with the intermediate belt which is 450 feet thick! In addition, present processes need very large volumes of water, and coping with the residual sludge and the SO_2 produced poses a considerable task for environmental managers.

Turning now to nuclear power, the Canadian Candu system with its heavy water moderator and natural uranium fuel has come to the fore on the international stage in the last few years. Pickering, Ontario has the largest single nuclear generating station in the world. Its total output from four reactors is over 2000 MW(e) and its final reactor unit went into service a few weeks ahead of schedule at the end of an eight-year construction program. Its high reliability and high availability have earned it international recognition.

Most of Canada's nuclear development to date has been centered in Ontario and represents the fruits of collaboration between Atomic Energy of Canada Limited, a federal agency and the provincial utility Ontario Hydro, supported by a budding nuclear industry. Today Ontario has an electrical capacity of 16,000 megawatts of which 14% or 2,300 MW are nuclear generated. Ontario has a further 3,000 MW of nuclear capacity under construction, 7,000 MW on order or under negotiation and a target of having about 25,000 MW of nuclear capacity by 1990 at which time nuclear power will generate almost two thirds of the province's electricity.

In addition to this substantial program, two other provinces, Quebec and New Brunswick, have ordered their first commercial nuclear stations. Quebec already has one prototype station operational. Table 2 provides a resumé of expected nuclear development in Canada and suggests that by the turn of the century, almost half of Canada's electricity will be nuclear generated.

Table 2

Installation of nuclear-electric generating capacity in Canada (Megawatts)

Date	Atlantic Provinces	Quebec	Ontario	Prairie Provinces	B.C.	Total
to 1980	-	600	5,500	-	-	6,100
1981-85	1,200	1,200	8,250	600	1,600	12,850
1986-90	1,800	5,600	10,650	1,200	1,600	21,450
1991-95	2,400	14,000	13,200	1,200	4,800	35,000
1996-00	3,000	19,800	25,200	1,800	8,400	58,200
Total	8,400	41,200	62,800	4,800	16,400	133,600
Percent of total electrical generating capacity						
	42	46	63	10	55	46

Some long term prospects

To many people, long range planning is a form of day-dreaming; to our energy systems, it is an absolute necessity because of the very long lead-times involved as shown in the following examples.

- The time from first work to full operation for an oil sands operation using today's open-pit technology is a minimum of five years. For an in-situ operation the lead-time may be between seven and nine years.
- Today the organic-cooled Candu reactor exists as a small-scale prototype; the time to undertake a commercial demonstration to the point where customers could order with confidence, based on some operating experience in a full-scale plant, would be about 12 years.
- Today the net production of energy on a sustainable, controlled basis from thermonuclear fusion has not been demonstrated as experimentally feasible: even the optimists will accept that it will be a probable

minimum of 50 years before fusion could be a commercial power source.

What these lead-times indicate is that if Canada wishes to shape its energy system by the year 2000 and beyond, then the research, development and commercial testing programs should already be underway or at least beginning.

It seems there are three guiding principles which will direct thinking abcut new technologies for the long term:

- More efficient use of energy resources will be wanted in future, so more attention will be paid to conservation-conscious design.
- Dependence will shift from depletable resources to those which are renewable or which in practical terms are not depletable by man's action. This will mean a declining reliance on fossil fuels offset by a growth in reliance on such non-depletables as solar energy or forms of nuclear energy which use as fuels elements whose crustal abundance in accessible forms is so vast as to make miniscule man's capacity to consume it.
- A move away from "environmentally expensive" technologies to those whose associated environmental cost is small.

For Canada beyond the year 2000, it would be hoped that major R & D programs along three distinct paths will be reaching maturity. These programs will involve fossil fuels, nuclear power and some exotic sources of energy.

Fossil fuels

Even after the turn of this century, it is expected that Canada will rely on its reserves of fossil fuels as the source of coveniently transportable energy. To meet such a demand in the face of a diminishing availability of crude oil and natural gas will lead to two primary concerns -- the extraction of oil at all depths from deposits in the Athabasca oil sands and the liquefaction and/or gasification of coal.

Today we are literally only scratching the surface of the tar sands deposits; awaiting the development of in-situ technologies and techniques for exploiting the intermediate zone between 150 and 600 feet, there lie hundreds of billions of barrels of oil. Similarly, potential supplies of coal in Western Canada are vast and hold much promise if a domestic capability is developed to convert them into the low-sulphur liquid or gaseous fuels the market will demand and to distribute them throughout the market.

Nuclear energy

The hallmark of the successful Candu system is its adaptability and it is this trait which allows Canada to look confidently towards nuclear energy as an expanding source in future. While other countries wrestle with the move from thermal to fast breeder reactors and the change from water to liquid-metal coolants, Canada can look to a more evolutionary rather than revolutionary development. Canada could be expected to move first to a commercial size organic cooled Candu, to achieve a higher net station efficiency and to ease the problems of maintenance created by the entrainment of radioactive corrosion products through the primary coolant system which is a complication in water-cooled reactors. Second, I would expect thorium to be introduced into Candu fuel and to operate reactors as "near breeders", without abandoning the thermal neutron regime. Since the natural abundance of thorium is large, such a move will expand immensely nuclear fuel supplies (some enthusiasts say thousands of years).

In parallel with these developments in Candu, further emphasis on the development of uranium mining and extraction technologies might be expected so that use can be made of the huge amounts of uranium available in low concentrations. Although the cost of electricity from Candu plants is quite insensitive to uranium price, no one really wants to have to pay three or four times the present price if not necessary.

Exotic technologies

Five other technologies deserve serious consideration in Canada, some of which may possibly be abandoned after exploratory research while others may eventually flower into major energy sources.

Energy from the sun has many attractions, not the least of which is that the basic resource - radiant energy - is free of charge. The trick lies in using it. Canada's first ventures into solar energy use will likely be related to space heating. New designs of buildings of all types and sizes should be possible, employing solar receptors as the basic source of heat. Beyond this the indirect forms of solar energy which today are referred to, generically, as biomass energy sources may be considered.

In some locations in Canada, particularly in British Columbia, the potential exists of using geothermal energy. There is little domestic experience in this area but New Zealand has. On a local, as opposed to national level, geothermal sources could be important.

Fusion power is one of the glamour areas of "Big Technology" and it is not only because of the high temperatures involved that it has burned many fingers in the past. Any contribution Canada makes to the development of fusion power can be expected to be modest and any real progress will call for an international program. We would need to specialize in some aspect of fusion and the related materials technologies look like an attractive area, particularly because of the potential industrial spin-off from advanced materials research. However, precisely because of the potential for spin-off, this is one subfield of fusion technology likely to have wide appeal in the entire developed world so competition is likely to be particularly tough.

Hydrogen has considerable potential as a means of storing energy and even as a means of transporting it. Developments which would allow, for example, off-peak power from major electric power stations to be used to generate hydrogen which might later be distributed through a pipeline system could be quite attractive.

Many people talk of the products from Athabasca as "synthetic crude", and indeed one of the companies operates under the name of Syncrude, but this is something of an exaggeration since the carbon-hydrogen bond which is the key to petroleum and natural gas energy sources has already been provided by nature. This chemical bond between carbon and hydrogen has shown itself to be the key to producing fuels of high specific energy which are easily usable and easily transportable. The deliberate fabrication of this bond, provided that it can be done with high efficiency, could open up the possibility of transforming energy from one form to another, as well as allowing for storage in an easily transportable form.

One Canadian with a long and successful career as a technological prophet, Dr. W. B. Lewis, has strongly suggested that, given a 5000 MW(e) Candu plant and supplies of fresh water and of limestone, we would be able to produce copious quantities of gasoline at less than today's market price. The scheme seems very attractive and I hope that at least some paper studies are underway to begin to probe the nature of the technological challenge which it would pose.

Summation

By way of summation, let me sketch a scenario of a possible energy future for Canada sometime early in the 21st century and pose as a challenge the need to solve the technological problems which stand in the way of it becoming a reality.

Suppose the principal domestic sources of energy in use are:

- in British Columbia hydro power, natural gas and geothermal power
- in the Prairies coal as a direct source and as a source of gas together with oil from the Athabasca reserves
- in Ontario and Quebec nuclear energy, hydro power, oil from Athabasca, oil and gas from the frontier areas, gas from Prairie gasification plants and the first truly synthetic oil
- in the Atlantic Provinces oil and gas from the continental shelf, supplemented by nuclear power and by hydroelectricity in Newfoundland and Labrador
- across Canada solar energy as an increasingly important complementary source of energy for space and water heating with biomass energy sources in use in some locations and hydrogen becoming a common means of storing off-peak energy.

It might also be expected that the time would be approaching elsewhere for commercial tests of fusion power.

If this scenario is to have any feasibility, these are the technological capabilities which have to be developed in Canada.

(i) to use geothermal energy

(ii) to gasify Canadian coals

(iii) to develop the Athabasca reserves below 150 feet

(iv) to generate hydrogen on a large scale

(v) to use solar energy for space heating

(vi) to produce synthetic fuels based on man-made carbon-hydrogen bonds.

In the meantime, to get us into the next century, we first need an expanded capability

(vii) to develop oil and gas supplies from our frontier regions, and

(viii) in our nuclear program.

In all of these ventures, both the economic and the environmental costs must be acceptable.

In parallel there will be need of a significant improvement in capability and in determination to use energy efficiently and to eliminate substantial waste from the present system.

The need to develop demand policies has been mentioned. It would be folly to believe that demands can be permitted to escalate unchecked and indefinitely. There is need to shape and control demand to make supply problems more tractable.

Few if any of these capabilities will be developed in Canada without determined efforts and unless we start developing a long-range policy.

These then are the dimensions of "le défi canadien"; if we are successful in meeting the challenge, we will truly have an abundance of energy for tomorrow . . . . and beyond.

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WORLD MINERAL RESOURCE ADEQUACY

BY D. R. DERRY*

The summer after next it will be four hundred years since Martin Frobisher led an expedition in three little ships (the largest 25 tons) from London to Baffin Island, the first of three trips in successive summers. These expeditions had two objects, the discovery of a Northwest Passage to the wealth of the Indies and, stressed more in the second expedition, the discovery of gold and silver in the unknown northern regions of the American Continent. The foregoing is relevant to the subject of this address for two reasons: first, this project, or promotion if you will, of Frobisher's in 1576 was the first, not only in North America but in all of what we now call the Commonwealth, that was organized with one of its main objects the search for metals in undeveloped land. It was the first of thousands of mining exploration projects in Canada and Australia and southern Africa and many other parts of the world, led by men prepared to risk their money, and in some cases their lives, in expeditions that were the steps in opening up undeveloped regions.

The second reason is that Frobisher's expeditions were a failure. You can forget the frequently quoted theory that he mistook pyrite, or "fool's gold" for real gold. There is not a shred of evidence for this in the records of these courageous and rather inexperienced explorers. They found heavy metallic material which they called "ore" and, as you all know, visible gold is the exception rather than the rule in gold ore and no one then, any more than today, could tell without assaying whether or not gold was present. The mistake they made was in wishfully accepting the word of one Italian assayer that the first sample contained gold against the insistence of three other assayers that it did not. But the whole project was a total failure, in both objectives. All the shareholders, who included Queen Elizabeth, many

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of her Court, but also many London merchants who could ill afford it, lost their money. Michael Lock, the financial promoter, besides losing his own money, went to gaol and died there. Martin Frobisher avoided gaol but lost his wife's fortune - he had married a rich widow not long before - and she and her children were left with barely enough to live on. He later recovered his reputation and went on to take part in the defeat of the Armada. In being a failure, this promotion leads the ranks of the large majority of exploration projects right up to the present day.

If I may introduce personal experience - over a period of 40 years in the mining exploration business I have been associated, in some capacity, with four discoveries that were viable, but relatively modest orebodies - each project, to the point of discovery costing under $150,000. But I would hate to add up the millions of dollars of other people's money that I have helped to spend on unrewarding projects. This low success ratio is what so many governments of nations, and of provinces or states, forget or conveniently overlook when they concentrate their criticism and their tax legislation on the minority of companies or individuals who succeed.

In a paper on mineral resources of the world I make no excuse for spending the first few minutes talking about rather ancient history. Perhaps if we talked more of history and its implications on our future, and less of facts and figures of exploration costs and returns, we might better catch the attention of those in many countries who make our laws. Certainly we have failed to get the message across so far. And if we fail to get the true picture accepted by our legislators and the public, of the balance between existing resources and the cost of finding and developing them, we are in for temporary and unnecessary famines in a good many metals and minerals.

I will return to the exploration problem later but let us first look at the recorded global resources in relation to the rising rate of consumption. A publication that has received a good deal of public notice is that titled "The Limits to Growth"[1] written by a group at M.I.T. under the sponsorship of the Club of Rome. This was a serious and sobering study of the future of our civilization in which minerals formed only a part. It deserves respect for the part it has played in bringing to the attention of people in many parts of the world the seriousness of the situation, but it appears that the minerals section was written by mineral economists with rather little input from anyone actually exposed to the educational discipline involved in mining exploration. If a similar study to that carried out by the M.I.T. group had been made in 1930 instead of 1970, I am convinced that it would have forecast exhaustion of many of our more vital metals before now. The known reserves at any given date, even taking relatively generous estimates, have a rather limited bearing on resources in the future. Resources beyond known reserves will depend to a varying extent on mining lower grades and in more remote areas. These factors will mean some increase in cost per unit - in constant dollars or loaves of bread - and also, more critically in energy expenditure per unit of metal. Obviously there are limits to how far we can go in money and power expenditure to produce a particular metal and we need to balance the need against the cost in both.

This paper reviews very briefly some of the more essential minerals and metals and is based on figures selected from Table IV in "The Limits to Growth". Comments are made on these figures and any information collected on developments in the four years since the book was written has been added. In Table 1, I have presented the minerals and metals in a different order from that in the original table and have used only certain columns. Column 1 gives the tonnage of reserves as published in the U.S. Bureau of Mines "Mineral Facts and Problems"[2], probably compiled in 1968 or 1969, and used in "Limits to Growth" from which the next three columns are taken. The second column headed "Static Index" gives the number of years in which the reserves would last using current world consumption. Since, however, both population and per capita consumption are increasing at an exponential rate, the third column gives the projected rate of world consumption (and I have used their median figure and not included the high and low estimates) from which a curve is obtained that gives the figures in column 4 headed "Exponential Index", i.e. the number of years the reserves would last assuming this much more steeply climbing curve. Column 5 shows the recently-published global resource figures compiled by the U.S. Bureau of Mines in 1973. Column 6 shows the percentage change in the estimates from 1969 to 1973 but I don't put too much weight on the individual figures because there are often changes in the guidelines and cut-off grades used in the calculations.

TABLE 1

AVAILABILITY OF SOME NON-RENEWABLE RESOURCES

Resource	I 1969 Known Global Reserves	II Static Index (Years)	III Projected Rate of Growth (% per year)	IV Exponential Index Years	V 1973 Known Global Reserves	VI % Change In Reserves
	(US Bureau of Mines)	(from	"The Limits to Growth"	)	(US Bureau of Mines)	
Iron	1.0×10^{11}T	240	1.8	93	2.74×10^{11}T	+ 56.8%
Manganese	8.0×10^{8}T	97	2.9	46	14.7×10^{8}T	+ 83.7%
Chromium	7.75×10^{8}T	420	2.6	95	1.7×10^{9}T	+ 119.3%
Nickel	73.5×10^{6}T	150	3.4	53	70.0×10^{6}T*	- 4.8%
Cobalt	2.4×10^{6}T	110	1.5	60	2.7×10^{6}T	+ 12.5%
Molybdenum	5.4×10^{6}T	79	4.5	34	5.7×10^{6}T	+ 5.0%
Aluminum	1.17×10^{9}T	100	6.4	31	3.6×10^{9}T	+ 20.8%
Copper	308×10^{6}T	36	4.6	21	370×10^{6}T	+ 20.2%
Zinc	123×10^{6}T	23	2.9	18	131×10^{6}T	+ 6.5%
Lead	91×10^{6}T	26	2.0	21	144×10^{6}T	+ 58.2%
Tin	4.3×10^{6}lgT	17	1.1	15	4.2×10^{6}lgT	- 2.3%
Tungsten	1.4×10^{6}T	40	2.5	28	1.4×10^{6}T	No change
Gold	353×10^{6}troy oz	11	4.1	9	$1{,}000 \times 10^{6}$troy oz	+ 183.2%
Silver	5.5×10^{9}troy oz	16	2.7	13	5.5×10^{9}troy oz	No change
Platinum Group	429×10^{6}troy oz	130	3.8	47	624×10^{6}troy oz	+ 45.4%
Coal	5×10^{12}T	2,300	4.1	111	8×10^{12}T	+ 60.0%
Uranium	0.77×10^{6}T (Western World)	NA	NA	NA	1.1×10^{6}T (Western World)	+ 41.5%

*Some changes in categories. This figure is "Resources" which includes 46.2×10^{6} "Reserves".

Iron and ferrous alloy metals

Iron is our most essential metal, not only because it is used far more than any other but because, in the form of alloys, it is the most common substitute for many other metals that become scarce or too costly. It may be noticed in the U.S. Bureau of Mines figure for 1969 that global reserves of contained iron are one hundred thousand million tons and the Exponential Index is 93 years, which would be most serious if true.

I find it hard to believe that our descendants will ever run out of iron. At the present time there are still substantial deposits of high grade - the highest grade significant body of iron ever found in North America lies unworked in Baffin Island. While such deposits, when they justify exploitation, will form a relatively small proportion of world consumption they are indicative of the immense potential tonnage on most continents with the average grade (about 30% iron) of concentrating ores now being worked in Canada and U.S.A. It will cost our descendants more in constant dollars and in energy to mine, concentrate and transport these more remote deposits-but not prohibitively more.

Manganese - In spite of the low Exponential Index relative to iron. manganese is in much the same position, geologically, with large reserves of lower grade at present too remote or too refractory for exploitation. We must also remember that world supplies will be substantially augmented when ocean mining is established since manganese forms the highest proportion of ocean floor nodules.

Chromium shows the same Exponential Index as iron but here again a moderate rise in price in constant dollars would enormously increase reserves as indicated by the apparent doubling of the 1969 figure in four years.

Nickel reserves are particularly sensitive to the cut-off grade used in the calculations. In showing an Exponential Index of 53 years these figures do not include immense tonnages known, but only tentatively explored, of lower-grade sulphide disseminations in widely scattered parts of the world. As in similar situations with other metals discussed, the cost of producing a kilogram of nickel in constant dollars or loaves of bread will be higher but not disastrously higher.

Cobalt - We need have no concern about running out of this metal. When ocean mining begins there will be a massive accumulating surplus as a by-product of recovery of copper and manganese.

Turning briefly to the five basic non-ferrous base metals:

Aluminum, to give the metal its original pronunciation and spelling, has shown greater increase in annual consumption growth (6.4% average in "The Limits to Growth" table) than any other commonly used metal. At the given reserve figure of 1,170 million tons, it gives an Exponential Index of only 31 years. This figure, however, means particularly little in this metal because, while in the future we will probably run out of bauxite, the chances of running out of alumina are impossible in view of its widespread occurrence in a great many surface formations. It should be remembered that even during World War 11, preparations were actually being made to recover alumina from clays in Georgia and studies made for its recovery from nepheline syenite and other high alumina igneous rocks. Clearly aluminum from these sources will cost more per ton but can almost certainly be kept within an acceptable figure.

Copper - The U.S. Bureau of Mines, figure for reserves of copper is 308 million tons and the Exponential Index of "The Limits to Growth" is only 21 years. Over the past few years production has been increasing at slightly over 3% per annum and keeping pace with increased consumption but at a lower rate than the average projected rate of growth of 4.6% given by "The Limits to Growth". In the meantime "Known resources" have increased by 20%. Even if the exponential curve of consumption is as steep as this, and there are reasons to expect some levelling off (as suggested by Sir Alan Cottrell)[3] once the huge electrification of developing countries is accomplished, I believe our great grandchildren would still be able to acquire the resources provided we carry out sufficient exploration in time and follow it up with development. I can see no reason for running out of copper through lack of ores. I can see much more likely restrictions incurred by the increased use of energy per kilo of copper produced and the enormously increased pollution problem both from tailings disposal of treating low-grade ores and air or water pollution from the smelting and refining of the increased quantity.

Zinc - The known global reserves compiled by the U.S. Bureau of Mines in 1969 are 123 million tons giving an Exponential Index of only 18 years, and the 1973 figure is not much higher. Nevertheless, in this metal I think the known reserves figure is particularly misleading when we consider that zinc occurs in two rather distinct but widespread types of deposit-the first associated with copper and the second with lead. Copper-zinc bodies of the volcanogenic (Kidd Creek-Noranda) type are not easy to find unless they reach present surface but they are very widespread, especially in the Archean areas of the world, and there is very little doubt that a great many more will be found in the future. The other type, the sedimentary zinc-lead deposits, show a roughly reliable ratio to volume of Palaeozoic carbonate sediments provided we take large enough areas. For example, the large area of Palaeozoic dominating carbonate sediments extending from southern Canada (where it has no production at all) to southern and mid-western U.S.A. with the main production in several centres of the southeastern States, gives an overall figure of 43 tonnes of zinc in past production plus known reserves per square kilometer of such sediments. There are huge areas of Palaeozoic carbonate sediments almost completely unexplored in the more remote areas of the world. In addition there are tremendous volumes of these sediments carrying zinc in lower percentages than currently being worked or included in these figures but which will play their part when the demand is there - once again at some increase in energy and money costs.

Lead - The outlook for lead (1969 reserve figure of 91 million tons with an Exponential Index of 21 years) is slightly less favourable than zinc as far as occurrence is concerned, partly due to the fact that it does not commonly occur in the volcanogenic deposits with copper and on the average it occurs in somewhat lower quantities than zinc in sedimentary deposits, (38 tonnes per Km^2 compared with 43 in Eastern U.S.A.). "The Limits to Growth" table gives an average projected rate of growth of 2% per annum, but one wonders how long such a growth in consumption can be accepted from the standpoint of atmospheric, water and soil pollution. I suggest restrictions for the latter reasons are likely to come much sooner than any shortage of lead ores.

Tin is the only non-ferrous base metal that I would consider as presenting a serious situation for future availability. Tin is much more "choosey" in its occurrence than any of the other base metals with no substantial production in North America, rather little in Australia, in Africa essentially restricted to Nigeria, and the large proportion of production coming from two areas of the world - the outstanding one being the Malaysian Peninsula and Indonesia and the other Bolivia. In the last 50 years no new tin producing field has been discovered in the non-Communist world nor, evidently, in the U.S.S.R. which is still a net importer of this metal. There is no doubt that demand, and consequently the price, would have been far more extreme had it not been for the major effects of substitution by other metals. Since no new area of tin, at least in the Western World, has been reported, we must take seriously the figures in "The Limits to Growth" tables because, even with modification of the Exponential Index, serious shortages for our grandchildren are suggested.

Precious metals

Gold - As can be seen, gold has the lowest Static and Exponential Index figures but these were based on the fixed price of $35/oz. You can see how much the reserve figure increased once the fixed price was abandoned but it will take a further increase to encourage the discovery and development of new ore.

Silver with a known global reserve in 1969 of 5,500 million ounces (and the same for 1973) also shows a short time before theoretical exhaustion - 16 years at the present rate of consumption and 13 years on the Exponential Index. A part of the increase in orebodies of silver will depend on the corresponding increase in orebodies of which it is a by-product, such as volcanogenic copper-zinc, and certain of the lead-zinc or multi-metal deposits. The possibility of increasing supplies independent of these by-product sources appears, from present knowledge, to be rather limited. I believe, however, that if one could be convinced of a price with a lower limit of $5 in constant dollars, we would see a big increase in new discoveries and development.

Platinum Group - In spite of the large available reserves* of this metal group, showing a higher figure in Static Index and Exponential Index than most metals, I believe we should be more concerned with long-range world supplies of platinum, and to a lesser extent palladium, than for most of the metals I have discussed. I am looking at this from the standpoint of geological occurrence rather than in trying to gauge the accuracy of the forecast increases in consumption both in the automobile industry and atomic power equipment. We may note the fact that under 10% of Western World production is supplied as by-products from the treatment of nickel and related metals. Russian by-product production is much greater. The production of platinum group as primary metals in mining operations is very much restricted geographically, mainly to the South African Republic and to the particular narrow formation - the Merensky Reef but with even larger reserves in the Upper Group chrome seams. Until and unless we find other Merensky Reefs (and there are some suggestions in occurrences recently announced in Montana and Ontario), we must regard the platinum group as presenting one of the more critical outlooks but not for many decades.

Energy minerals

Coal - It will be noted from "The Limits to Growth" figures that at the present rate of use, coal would last the world 2,300 years and using the Exponential Index, 111 years, which is more than the corresponding figure for most metals. Nevertheless, from the geological standpoint, there is more likelihood of coal, together with potash and phosphates, being eventually exhausted than is the case with most metals. There are, of course, immense tonnages of coal of varying qualities in areas like the Arctic regions of Canada even though no exploration specifically for this mineral has been carried out there. The trouble with coal, however, when we consider it from the energy rather than the chemical standpoint, is that if it is very far from regular transportation the energy expended to mine and transport it may be more than it would produce when burned. We must, therefore, regard coal as somewhat like

*S. C. Newman[13] gives a total reserve of 1,330 million ounces from the Merensky Reef and Upper Group chrome seams of South Africa alone, much greater than the U.S. Bureau of Mines global figure.

oil and gas in presenting problems of eventual exhaustion, but a long time ahead.

Uranium - This metal was not included in "The Limits to Growth" table but I have added the figure for Western World reserves in 1969 and a more up-to-date figure from Robertson and Lattanzi[6]. On the basis of projected consumption growth this reserve could be used up in the early 1990's. Uranium is not a scarce metal and I submit that there are adequate supplies in the world to supply any forecast use provided we find and develop them in time and are prepared to pay three or four times the present price (in constant dollars) which price can be accepted without dangerously increasing the cost of atomic energy. The temporary shortage that we may meet in a decade or so will be due to insufficient exploration for uranium during the past five years.

The temporary surplus and resulting low price was initially responsible for keeping uranium exploration at a low tempo but it was showing definite signs of picking up in Canada and Australia when it was brought almost to a halt by government action in both countries. In Canada in 1970, the justifiable action to stop a foreign takeover of a Canadian producer was extended, unnecessarily I believe, to restricting equity by a foreign company (or companies) to one-third, even in an operation that resulted exclusively from its own exploration. This policy announcement had a remarkably rapid effect in damping down uranium exploration. In Australia still more drastic action by the government has left mining companies uncertain of bringing existing orebodies into production and thus leaving little incentive to look for more.

The encouragement of national independence in critical metals is a laudable goal but in both these countries this concern has grown into something of an obsession that is harmful to the nations themselves and to the future world supply.

In running over some of the more essential metals - and coal - I have tried to show that the projection of exponential curves against known or assumed reserves (which are based on present prices relative to costs) gives misleading answers in most cases. I do not believe we will reach exhaustion of metals, with very few exceptions, in any foreseeable future, and I would quote Dr. V. MacKelvey[7], Director of the U.S.G.S., John S. Carmen[11] of the U.N., John Evans[8] and others as supporting this view. Naturally if the population expansion of the world continues at the present rate we could be running out of nearly everything, but I think that we would be running out of food, water, and perhaps oxygen, before we ran out of most metals.

This is not to say that we should not make every effort to check, and eventually reverse, the present increasing, extravagant and wasteful per capita consumption of metals and energy in developed countries - expecially in North America. If the present increase in consumption of metals were to continue unchanged, the problems of pollution production and energy consumption would, as brought out in an excellent paper by David B. Brooks[5] of the Canadian Department of Energy, Mines and Resources, be much more probable restrictions than would the sources of metals.

There is, however, a more immediate danger and that is the probability of temporary (but over periods of years) "famines" in certain metals that could be avoided. These are metal famines resulting from insufficient exploration and development. Uranium is an obvious example in this regard but there are dangers of shortages in many of the other metals in the relatively short term resulting in part from the policies and regulations of some countries.

In the present context the matter of fair treatment of mining companies and their shareholders is only indirectly material. What is directly material for any nation, and for the world, is to ensure that we use the most effective method of carrying out exploration for new mineral reserves. In free enterprise countries this has been done first by individual prospectors, syndicates and small companies and more recently increasingly by the major mining companies and some petroleum companies. This was all at no direct cost to the taxpayer other than that of operating geological surveys that provided the base for mineral exploration. The syndicates and small mining companies responsible for a large proportion of discoveries prior to 1950 have almost disappeared from the scene due to a combination of increased costs of modern exploration, complex regulations on financing and increased taxation of the profits of the minority who are successful. Within the last couple of years new combination of federal taxes and expanding royalties or taxes imposed by states or provinces have discouraged the larger companies from spending as much on "grassroots" exploration as is needed to maintain reserves.

Recently I carried out an informal survey of 26 mining companies that have been among the most active in the mining exploration field in Canada. The results, as seen in Figure 1, show a decrease of 33% between 1971 and 1974 in the constant dollar expenditure on "grassroots" exploration, i.e. looking for new mines rather than proving or expanding previous discoveries. If smaller companies were included, the drop would be seen to be more severe.

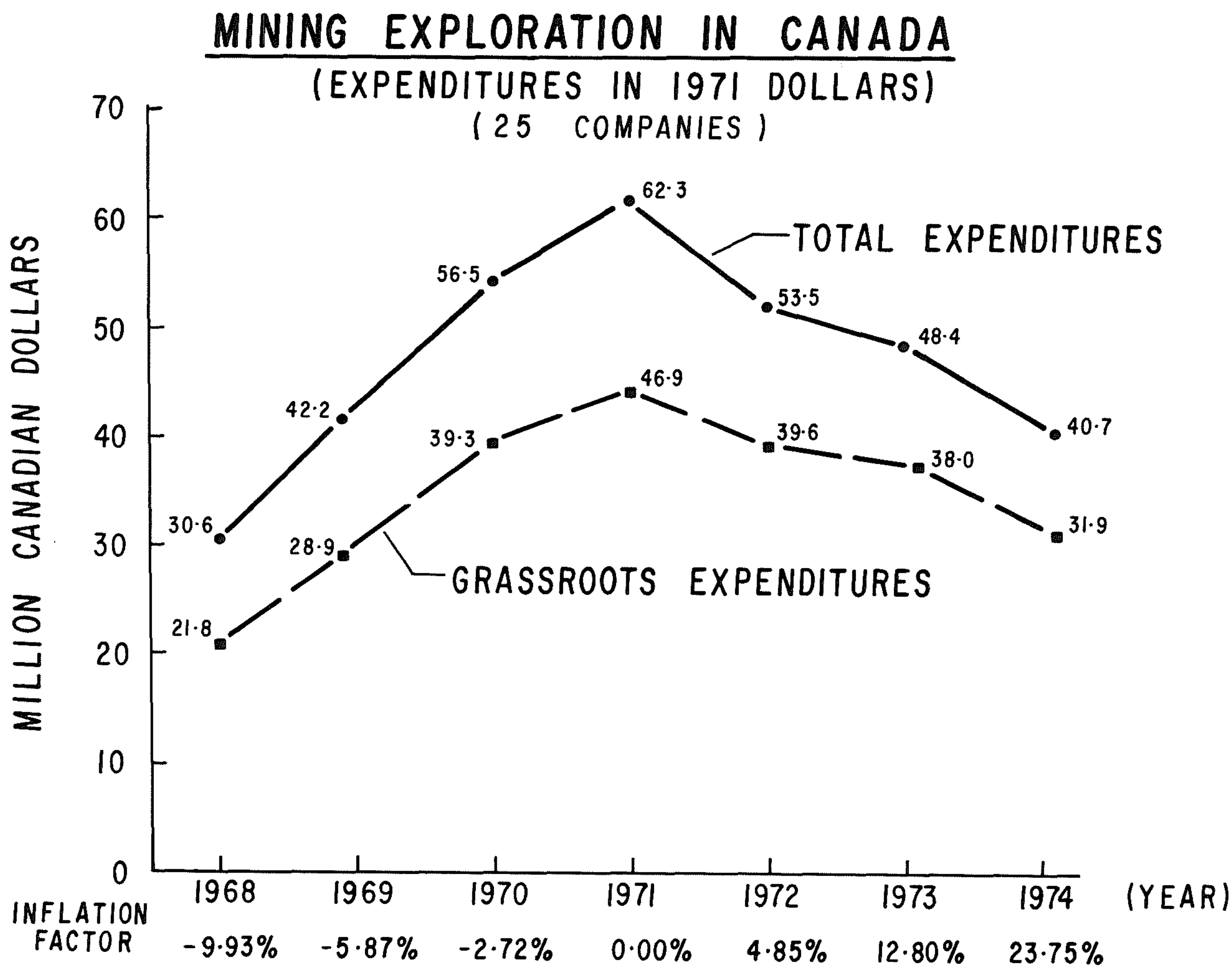

Figure 1 - Mining exploration expenditures in Canada in 1971 dollars.

In Australia, Figure 2, taken from the July 1st issue of the National Miner, (formerly the Australian Miner), but based on figures from the Australian Bureau of Mines, shows a drop of 48% between 1971 and 1973 and the drop in 1974 is almost certainly still more drastic. Exploration in the Republic of Ireland will likely decrease as a result of the recent changes in tax and royalty policies.

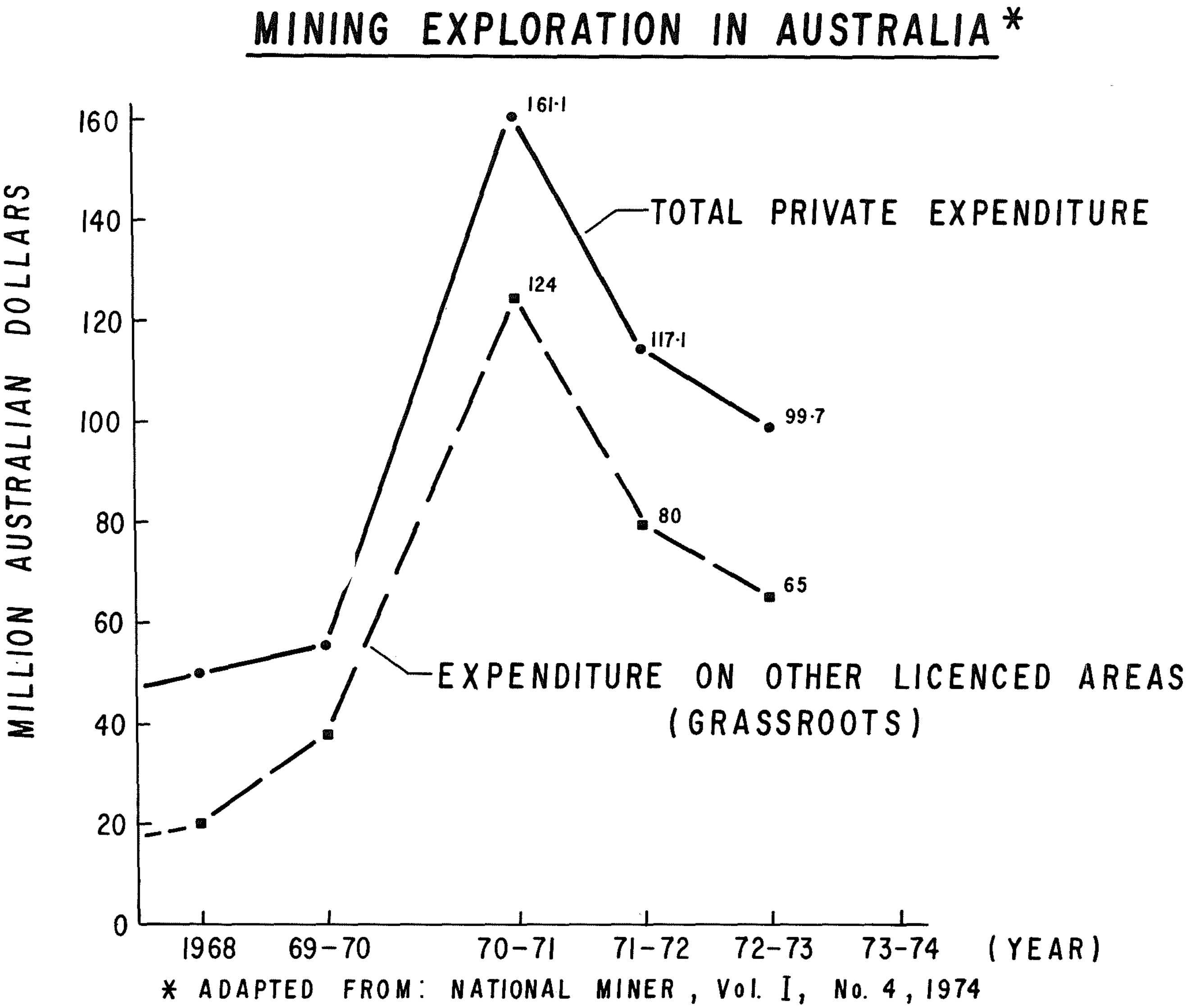

Figure 2 - Mining exploration in Australia, 1968 - 1974.

In a few countries the reverse trend is taking place, dominantly the South African Republic, Brazil and some States in the U.S.A., notably Alaska. But these exceptions are not sufficient to offset the decrease mentioned above at a time when the world requires an overall increase in terms of constant dollar exploration expenditures to provide for the growing demand for minerals and the greater cost of finding new reserves.

If industry finds it is unrewarding to spend sufficient money on exploration to continue serving most of the Commonwealth advantageously, and if we accept the premise that it is an essential industry, then we must look elsewhere for exploration funds. The only alternative source is government - federal or state provincial, i.e. taxpayers' money. This is not an impossible solution - in the Communist world this is essentially what happens and in U.S.S.R. it seems to have been successful in finding substantial new ore reserves. It would be interesting to see the pertinent figures on exploration expenditures and results but these are unlikely to be available in a way that could be fairly compared with the corresponding figures in the Western world. Sutulov[10] states that the U.S.S.R. employs about 110,000 graduates in the sciences and engineering subjects related to mineral exploration and that the budget of the Ministry of Geology for exploration activities for the last few years has been over $4 billion annually, half of this for oil and gas. These figures must be compared with the personnel employed and money spent in the Western World on all government surveys plus industry's expenditures on exploration.

In some Commonwealth countries there is a tentative trend towards government participation in the risky and frustrating business of mining exploration. In Canada, the Province of Quebec some years ago entered with SOQUEM, followed later by Manitoba and recently the Government of Saskatchewan has taken cautious steps into some exploration joint ventures with industry. Australian Government expenditure on exploration is increasing but only partly offsetting the drop in expenditure by industry. I believe this trend, which will probably grow and will be more fully reviewed in later sessions of these meetings, is a healthy one but I doubt if the taxpayer in the more developed countries is ready to undertake the full and increasing cost of mining exploration to an extent sufficient to keep this essential industry going.

Moreover, mining exploration is a rather sensitive plant depending often on new and unconventional ideas which tend to wilt in a large and unavoidably bureaucratic organization. So although government participation in exploration is a logical and desirable movement, I believe it would not be in the public interest for government to be responsible for the dominant role in this aspect of mining.

CONCLUSIONS

To summarize what I have been trying to cover: -

1. I believe there is little chance of the exhaustion of resources of most metals within the foreseeable future. Some possible exceptions (but still probably several decades away) are tin, platinum metals and some non-metallics including coal, phosphates and potash.

2. On the other hand there are more urgent restrictions to the growth of metal consumption induced by the increased danger of pollution and the higher consumption of energy that would result from obtaining metals on an increasing scale from ever lower-grade sources.

3. Temporary "famines" in certain metals are likely in the relatively near future due to insufficient exploration and development ahead of demand. These are partly induced by government policies in various countries of the Commonwealth and urgent steps are needed to correct or circumvent the results of such actions.

There is no magic about exploration and, within the limits of efficient management, the more you spend the better are the chances of eventual success. For individual projects luck is a dominant factor and the odds are no better now than they were when poor Martin Frobisher and his friends set out from London 400 years ago. Modern scientific techniques have only counteracted the fact that most deposits that were showing on surface have already been discovered. Private enterprise will only continue in this game if the rewards at least balance the cost and risk and, as the Mining Association of Canada put it recently[12], "the cost of finding a mine is increasing while the reward of finding one is decreasing". The job could be taken over by governments but they must expect to meet just as long odds with the losses being paid for by the taxpayer who would, of course, indirectly share in the profits of successes.

I question whether such procedure would be as effective as the one under which free enterprise countries are at present operating and my own feeling is that we would be taking a dangerous risk in the provision of natural resources over the next few decades by moving too far away from our present system.

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CONSERVATION, RECYCLING, AND SUBSTITUTION OF MINERALS

BY WILLIAM A. VOGELY*

This paper discusses the operations of mineral markets in making decisions on conservation, recycling, and substitution. A modest proposal involving a multi-commodity stockpile to improve these markets will be presented.

The words of the title of this paper are loaded with value judgments. A little time discussing the concepts attached to these words will be well spent.

Conservation, as used here, refers to the demand side of the minerals equation. When mining engineers talk about conservation, they are usually considering the production process, whereby the minor constituent elements contained in an ore are captured in milling and processing. Another concept of conservation, which applies to the supply side of the equation, is that which considers the efficient extraction of an ore body through a mining plan which leaves as little ore behind as possible. The outlook of mining companies historically has been efficiency in conservation, in the sense of supply, coupled with an active expansion in the use of the minerals which they produce. Conservation in this paper refers to the efficiency in use of a mineral; that is, the minimization of mineral input per unit of product or service output, rather than the efficient production of a unit of output.

Recycling is a less ambiguous term. It refers to the reuse of minerals after they have been incorporated into a product which has been sold to consumers. This does not, of course, make the concept of recycling a simple one. The actual recycling institutions which surround the material industries are very diverse. They range from the prompt recirculation of industrial scrap

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to the very long cycles involved in the collection of obsolete scrap. Here we are talking about recycling to reduce the needs for primary mineral inputs into desired products and outputs.

Substitution is a complex concept. Substitution is occurring constantly as the economy adjusts to changing product demands and to changing supply situations. Substitution, in terms of this paper, refers to a deliberate effort to use "plentiful" minerals to replace "scarce" minerals. Both of these words "plentiful" and "scarce" are relative terms--in the real world, of course, all things are scarce in the sense that society must incur cost to obtain them. However, if one looks at the earth crust and the distribution of elements in that crust, there are elements which are plentiful in the sense they are abundant and there are elements which are scarce in the sense they occur in trace amounts. As society begins to worry about exhaustion of resources, the role of the plentiful materials is certain to grow in importance.

To present a simple thesis, it can be succinctly stated that markets for minerals are an effective mechanism for conservation, recycling, and substitution decisions. However, there are major imperfections in the operation of these markets which form the basis for society imposing conditions on them to arrive at more optimum results from the point of view of societal welfare through time.

Before we can examine this position, the obvious question arises. How do, or should, mineral markets work?

Under the market system, which applies both in my country and in the Commonwealth, decisions on mineral production and use are made as a result of individual producer and individual consumer decisions. A company decides to explore for minerals; upon making a discovery, it decides the level of investment and the amount of capacity to be installed; and then the company decides how much of that material shall be produced annually through time. On the other side of the market, a manufacturer interested in producing a product surveys the availability of materials and designs his product around a specific material input which determines his demands for that material on a per unit basis. If a material is relatively abundant in supply, that material will be relatively cheap.

In the long run, if the market is working adequately, the price of the material will approximate its marginal cost, including proper rates of return to the producers and economic rents on the intra-marginal deposits. The consumer would then be faced with a choice based on the real costs of the mineral involved and it would be used where its services, compared with possible substitutes, are worth its cost.

However, for a market to work in the way just described, there must exist several necessary conditions.

One, there must be no market power on either side of the equation. That is, there should be a sufficient number of producers and consumers such that no one can exert substantial influence on the market conditions.

Second, there must be sound information, not only concerning the current situation, but also concerning the future. The producers must know what the future costs of production of minerals will be and the consumers must know the future prices of each alternative material.

Third, political forces must not impinge on market decisions. So, the three general conditions for the market to operate effectively from a societal point of view are the lack of market power on either side of the market, the absence of political pressures, and the existence of sufficient information concerning the markets.

It is immediately obvious that the market just described does not apply to most mineral commodities. In most mineral commodities there exists a good deal of imperfect information both on the current and the future situation in material commodities. Second, many of these markets are regulated by non-market forces, such as governments, for non-economic ends. And third, there is of course, a good deal of market power in certain material markets both from the producer side and from the consumer side.

There are characteristics of mineral markets which reinforce the above mentioned failures. The supply and demand schedules for minerals tend to be extremely inelastic in the short run and quite elastic in the long run. Elasticity is a concept used by economists to measure the response of supply and demand to price changes. Inelastic means that an increase in supply will be forthcoming only with a substantial increase in price. On the demand side it means that a reduction of demand will be accomplished only with a very substantial increase in price. Markets characterized by inelastic supply and demand schedules exhibit extreme variation in price, with relatively minor variation in quantity supplied or demanded. This describes, in general, mineral markets and the existence of this extreme variation in price creates "noise" in the information system that tends to mask the underlying supply-demand situations for these materials, reinforcing the lack of perfect information.

In the long run, on the other hand, these elasticities are quite high because of the availability of ample resources in the earth to produce the materials at close to present cost and the ability of consumers to substitute for any given material. Such substitution is limited in the short run by the production function of those consumers who have designed their products around a specific material. However, in the long run, the design can be changed and very substantial substitution can take place.

Responding to this market situation, the pricing of these materials and their distribution into the economy has become subject to a number of divergent kinds of market organizations. These range from the Tin Agreement - an organization of producers and consumers - to producer pricing systems for copper, lead, zinc and aluminum. Such arrangements tend to give long-term price stability around some accepted normal price, but they also may hide changing underlying conditions of supply and demand with respect to these materials and contribute to the flow of imperfect information.

Another factor which leads to poor operation of these markets is the very long lead times involved in supply decisions and the discontinuities involved in the demand decisions. On the supply side, the period from a decision to increase mine capacity to production could be in the order of a decade, and is normally at least five years. Thus, supply decisions are made in anticipation of markets a good way down the road and they are likely to err in magnitude, if only because of the fact that several producers will be undertaking expansions at the same time without knowledge of the other's intention. On the demand side, the fact that demand is derived from the demands for the final product, through a production function, causes substitution of these materials to be discontinuous. A major producer of electrical systems will switch completely away from copper to aluminum on a 100% basis because of engineering compatibility, and such switches can therefore come with major impact on these markets.

There are then many factors relatively unique to mineral markets which reinforce those mentioned above with respect to market imperfections.

In addition to market imperfections which could form a basis for society's decision to interfere in the operation of these markets, there are two other considerations which also could form the basis for such interference. First, the market will operate to provide for the optimum use of material through time only if the rate of discount applied to future values is the same for the private market decision maker as for society as a whole. Let us suppose that a private decision maker values future income discounted at a 20% rate whereas society values future income at a 10% rate. In this case, the private market will use a material faster than would be the case for society as a whole. Economic theory indicates that a producer will produce a material as long as its current price is greater than the future price he expects, discounted by his discount rate. If this is not true, it would pay him to hold the material to sell at the later date. Thus a producer, who has a high rate of discount, will require a higher price in the future to withhold production than would be the case were his rate of discount lower. If the producer has a higher rate of discount than that for society, he will tend to produce now rather than hold the material and thus reduce the supplies available for future generations.

Secondly, there are costs to society which now are not counted in private costs. The economists call these costs "externalities". If for example, the production of coal involves the destruction of land for other uses and involves in the utilization of coal, substantial pollution damages, there are costs in the production and use of coal which are not internalized in the market prices. Thus, the cost of the material to consumers is understated, and once again the private market will decide to use the material faster than would be dictated were the entire cost of society considered in the market decision.

To review briefly then, there are five bases for society's deciding to interfere in the operation of mineral markets. They are imperfect information, the existence of political influences on portions of the market, market power on both the producing and consuming sides, differential rates of time discount for private markets and society, and finally, the externalities involved in the use of materials which are not reflected in market prices.

It is impossible to generalize on the kind of societal interference which would be justified in materials markets. However, we can develop a general description of the options and alternatives available for increasing the level of conservation (i.e., minimizing the use of material), for fostering recycling and for forcing substitutions. The major tools available are (1) the taxing power of sovereign governments, (2) the imposition of standards in construction and manufacture, which is a legitimate exercise of governmental power, (3) providing better information, (4) the fostering of specific research and development aimed at reducing the price of the relatively abundant materials, and (5) insuring the lack of market power by producers and consumers through legal means.

The use of taxes results in higher prices of materials to consumers above the cost of the mineral, to reflect the externalities involved in the production of that material and to offset the time discount problem. Such a tax, currently under consideration in the United States, is the proposal for a heavy excise tax on the use of gasoline. By making gasoline more expensive, the market will operate to conserve it and use it more efficiently. Producers will be faced with a reduced market, so will lower current production and reduce levels of investment, thus leaving more petroleum for future generations.

Standards of construction and manufacture could be applied in several ways. As an example, one could require the automobile manufacturers to design a car for ease of disassembly to separate its ferrous and non-ferrous scrap components. Secondly, one could impose prohibitions on the use of materials in certain areas, as for example, forbidding burning of natural gas under boilers to generate electricity. Third, building codes can be used to affect material consumption. Standards of construction and manufacture have associated problems rising largely from their inflexibility. The underlying conditions of material markets may change very rapidly and standards have a habit of becoming ingrained into the framework and are not subject to rapid change. Nevertheless, this is obviously a tool which is available and is likely to be used by governments throughout the world.

Information has been a traditional function of governments in western societies. The United States, through its Bureau of Mines and the Department of Commerce, provides much of the basic information for business decisions by United States concerns. The same, I'm sure, is true elsewhere. However, the information systems provided by governments have been deficient in that they have not normally covered financial aspects of these markets. Improved information systems, making reliable data available while preserving the confidentiality of individual company operations, can make a major contribution to improving the operations of materials markets. In the United States there is substantial pressure from Congress and the Administration to improve the flow of information about energy in response to the recent energy crisis, and the President's Material Policy Commission called for a vastly improved data system for all minerals. I believe we are going to see steps taken in the United States to improve the flow of information and, hopefully, thereby to improve the market's ability to make decisions.

The research and development tool has been used in the United States and, I'm sure by other governments, to foster substitutions. Because of the inability of private concerns to recover the cost of research investments, it may well be that the level of investments in research and development of substitute materials is below the societal optimum. In such cases, society should finance such research and development and make the results freely available for the private sector to use in production decisions. Once again, my example comes from the energy field. The 10 billion dollar effort currently under way in the United States is directly addressed to the development of alternate abundant sources of energy which would replace the current use of fossil fuels.

The last point raises sensitive issues in a meeting such as this Congress. Nevertheless, it is incumbent upon governments to ensure that no producer or consumer group exerts inordinate power in the marketplace. The cartelization of basic materials is a real problem for the world. One need only point to the impact of the current prices of oil on world-wide inflation and financial structures to illustrate the point. If cartels are international in character, then it will take some kind of international force to handle the problem. The anti-trust laws in the United States and similar laws in other countries can be applied in domestic markets, but they lose their effectiveness in face of country-sponsored cartel actions.

An indirect tool should be considered to improve the operation of mineral markets. This is the stockpiling of basic materials by an international organization, under strict buy-and-sell rules, on a multi-commodity basis. The idea of multi-commodity stockpiles is not new. It was developed and actively considered during the "Great Depression" as a means of placing a floor upon raw material prices. The basic idea is to acquire a basket of materials in fixed physical proportions, and to sell the same basket at a higher price. The transactions could be financed by using the materials themselves as a basis for a stockpile currency, which would have a rate of exchange with all the currencies of the world. Such a system would dampen the very wide swings in prices, while not interfering with the relative prices of these materials, and thus, distorting market decisions.

This is not the place to fully develop this idea, but I believe I have said enough to perhaps start some thinking on the subject.

It is my hypothesis that, in fact, markets can work and are working to conserve, recycle, and substitute materials for each other. However, as we approach the problem of continued economic growth for a world which faces, in some ultimate sense, finite resources, it may well be that we should impose on these markets institutional arrangements to arrive at more optimum results from the point of view of society's welfare over time. Before we interfere with these markets, however, we must assure ourselves that our interference is in a form to use the market mechanism itself and not to impose a rigid set of rules upon the economy. Such a set of rules would be counter-productive in that it would create shortages, it would create dislocations--it would create the very situation we seek to avoid. The proposal for an international multi-commodity stock-pile meets this criteria. It is my hope that discussion of this plan can begin, and that appropriate action can be taken in due time.

TRENDS IN GOVERNMENT-INDUSTRY RELATIONS

BY H. RONALD FRASER*

I find that introducing the subject of "Trends in Government-Industry Relations" is an awesome task because I believe that over recent months everything that can be said on the subject has been said - often.

Indeed the political economic nexus has always been the crux of social development and the resource industries as the foundation of any economic structure have always been most sharply viewed in the political focus.

Throughout the centuries agriculture and mining have been drastically affected for good or ill by state intervention. In England the Enclosures Acts switched the thrust of the economy from mixed farming to sheep grazing; created the environment for the industrial revolution by making England the world centre of the textile industry within which most of the seminal inventions of the industrial revolution occurred and at the same time released an unemployed labour force of unprecedented size to man the new industries.

Over a thousand years earlier an almost identical series of edicts from the Roman Emperors created the great latifundia which sapped the social and economic vitality of the Empire and brought it to ruin.

Repeatedly, the cycle of stimulus and protection on the one hand and restraint and control on the other, has created a love-hate relationship between industry and government. Patents of Monopoly gave impetus to new ventures; Factories Acts restrained manufacturers from exploitation of labour. This cycle of co-operation and conflict is still with us.

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The years following the first world war were marked by quite happy relationships between government and mining. The need for post-war reconstruction, the short ages of the Korean War and the forecasts of the monumental Paley Report all tended to convince governments of the absolute necessity for a healthy mining industry and greater national self-sufficiency in mineral products. As a result, soft loans, fast write-offs, tax holidays and guaranteed price contracts became part of the common currency of industry-government negotiations.

Canada is a prime example of the effects of this happy relationship. With no great mineralized zones like the African Copperbelt, the Andean Cordillera or the porphyries of the South Western United States of America, Canada nevertheless grew in stature as a copper producer. Prospectors swarmed over the Precambrian Shield and up and down the Rockies. While I can find no statistics on the subject, it would not surprise me if more small orebodies were found and brought to production in Canada over the last quarter of a century than in all the rest of the world. This effort was, of course, not limited to copper. Lead, zinc, asbestos, tungsten, nickel, uranium, iron ore, to mention but a few, were among the metals where Canadian production featured high in the world tables. Other by-products were substantial too. Highly skilled cadres of management were built up. Canada assumed a leading place in the provision of services to mining such as engineering, design and the development of prospecting techniques and equipment.

This spectacular Canadian success was of course not unique. The States of Arizona, Utah and New Mexico witnessed an enormous growth in mineral production as did Chile, Peru, Zambia, the Congo and Australia. New names like Bougainville, Marinduque and Ertsberg began appearing on the maps.

All this led not unnaturally to a state of euphoria in the mining industry which makes it all the harder to understand the sudden reversal of attitudes which we now face. What has happened? Why are we suddenly so unloved? We are in this position now of trying to understand what has happened to us.

Chronologically, the first issue was nationalism or, in some cases perhaps, more specifically a resentment of exploitation by foreigners. These attitudes were first manifested in Africa and South America. In the latter a steadily increasing yoke of heavy taxation gave way first to partial and then total nationalization. In Africa, with its greater dependence on expatriate expertise the foreign investor fared better. First, in the Congo nationalization was followed by a not unacceptable management contract. In Zambia government acquisition of a controlling interest was effected on terms that were mutually agreed and was offset by management and sales contracts. Government involvement has since increased but always through negotiations and with compensation. These territories and others in Africa have welcomed foreign participation in new ventures on terms set out in conventions negotiated between the parties.

These events seemed relatively remote to mining industries in the established industrial countries. The first onslaught which they were to face came from a different quarter. A minor branch of botany - the study of the manner in which a species establishes a colony in a new habitat - provided the catchword for the young, the concerned and those anxious to use this concern to sell a lapel badge or buy a vote - ecology was the word. Threats to the ecology were identified in all directions and the mining industry became a prime target: desecration of the landscape by strip mining or tailings disposal, smelter smoke, mercuric contamination and so forth were laid at its door and government was called upon to intervene.

The growth of hostility to the mining industry is itself a fascinating ecological study. Having obtained a foothold in the environmental area, it underwent a subtle mutation. Mining not only disfigured or disturbed the environment, it actually consumed natural resources and so a conservation movement developed to urge control of the spoliation of the all too finite resources of nature. As the flowering of this movement coincided with the upturn in the economic cycle it appeared that the mining industry was not only doing terrible things but that it was also doing them profitably. This became a new indictment for the charge sheet and because these profits were much higher than the industry had enjoyed in the immediate past - do you remember 1972 - the opprobrious epithet of windfall profits was added and it became clearly the duty of government to take them away from the industry. In some countries such as Australia and Canada, where local capital had shown perhaps a percipient reluctance to invest in mining, a considerable proportion of mining investment was foreign controlled - which added another hideous trait to the face of the mining ogre. The ecological invasion was complete and in Canada it required only a few flourishes from that gifted demagogue, Mr. David Lewis, leader of the National Democratic Party, with his talk of corporate welfare bums and ripoffs, to complete the picture of the mining industry as insensitive, destructive and greedy.

All this also set the directions for increasing government intervention in the mining industry: tighter controls in the areas of pollution and use of land, attempts to limit mining development in the interests of conserving natural resources, whether by fiscal means or direct control, the discriminatory taxation of the resource industries by way of royalties or excess profits taxes, the control of foreign ownership and the growing acceptance of the theory that mineral resources belong to the people - and if you think this means that each Canadian is to be given a share of Inco, Noranda and Imperial Oil then you don't understand what politicians mean by "the people". The question of government equity participation in mining is the subject of a separate presentation so I will refer to this only incidentally.

I would like briefly to review each of these trends.

The environmentalist issue, which as I have remarked was probably the start of the industry's difficulties, has now become of minor importance. The pressure groups have largely moved on to newer fields and the media have sensed a public apathy to the issue not unrelated to the realization that the tab for this sort of thing ultimately has to be paid - in fact the media are now happily castigating the automobile manufacturers over the cost of pollution control devices.

The conservationist issue is still with us in various forms. The general thesis is that reserves of many mineral products are severely limited and if steps are not taken to ration their exploitation our immediate posterity is going to be left destitute of many essentials and we shall stand convicted as criminal exploiters before the tribunal of history. The argument advanced is that development might have to be discouraged by actual control or penal taxation and that this will not only stretch out reserves but result in much higher prices being realized for the ore that is left in the ground as a result of this policy. The government of British Columbia leans heavily towards such theories.

Perhaps this is a case where we should heed the Biblical injunction "Be not anxious about tomorrow rather let tomorrow be anxious about itself". The whole history of the mining industry underlines the argument that the technology of the moment should be exploited to the full. The problems of tomorrow will be resolved by tomorrow's technology and even if they are not the sort of withholding that the advocates of this theory are talking about has little significance on a long-term basis. If there are only ten years supply of metal X, a cutback to 50% of current consumption might mean that metal X supplies, allowing for population growth, will see the world through for 15 years. That sort of deferment has no real meaning and it would probably be far better that the producers of metal X devote the high profits which will undoubtedly be generated by the progressive shortage of the metal to evolving a satisfactory substitute or finding or expanding reserves by new technology.

If one applies the perfect vision of hindsight to this problem it is obvious that no generation has ever had the knowledge to pontificate about and plan for the needs of succeeding generations.

A hundred years ago with increasing costs reducing the cut-off grades of copper ores, potentially vast new demands for copper as a conductor of electricity and the working out of known reserves there were indeed grounds for pessimism and a metal-minded Malthus might have pleaded with the Cornish miners to cut back production for the sake of generations yet unborn. For a start such a prophet would have grossly underestimated the true demand for the metal. He would also have underestimated the new ore discoveries yet to be made, the effects of new metallurgical processes on the cut-off grades of ore, of open-cast mining in the production cost of the low grade porphyries, of the supplemental role of aluminum as a conductor of electricity and many other factors of which you are all aware. So today the mineral economists will calculate in frighteningly low numbers the reserves of copper and other metals, accurately enough in terms of current technology, and these figures will be used with cries of doom by the more sensational journalists and be believed and acted upon by the more naive politicians. But none of us can penetrate the veil of the future and salvation may be at hand in any number of areas. In exploration we have advanced very little beyond being able to discover what actually sticks up out of the ground. New geophysical techniques enable us to grope a few hundred feet below the surface but the depths remain unplumbed. Vast areas of forest and desert are effectively unexplored. We are only beginning to be conscious of the ocean bed as a field of exploration. Metallurgically we will undoubtedly be presented with a greatly changed picture. Sea water alone could provide us with most of our mineral needs for the foreseeable future if we could extract them economically. The role of substitutes has hardly been explored. It is within all our memories when copper producers were endeavouring to hold prices under £300 per ton for fear that virtually their entire market might be lost to aluminum. Sodium, one of the commonest metals in the earth's crust could do a far better job of electricity conduction than either copper or aluminum and in spite of initial problems retains an enormous potential. Think of the effects on the metal industry if electricity could be beamed to the consumer instead of being carried along conductors. I am not attempting to crystal gaze but merely to illustrate that even within the limits of our imagination which is certainly going to fall ludicrously short of what will be achieved it is possible to envisage all sorts of eventualities which will give the lie to the conservationists.

Apart from being unsupported by historical experience the conservationist philosophy can be positively pernicious. Mineral deposits may appear to be less transient than rosebuds but the poet Herrick's advice to "Gather ye rosebuds while ye may" is probably valid for the mining industry. It is incontrovertible that many, if not most of what were once the richest mineral treasures would today be marginal or uneconomic because technology has passed them by. The mines of Laurium, whose silver made Athens the mistress of the Mediterranean, limp along as a minor producer of lead rather than silver, thanks to modern techniques of froth flotation. The tin and copper mines of

Cornwall, which drew the Phoenicians across the oceans and in the last century determined the location of the Royal School of Mines, are now mining museums not because the ore is exhausted but because new techniques have made them uneconomic. How many deposits in this country, in Australia and elsewhere may suffer the same fate because those who exercise political control over the industry do not have a feel for or understanding of its realities, is hard to say. What is certain is that the greatest erosion of mineral reserves in Canada and, no doubt, elsewhere is attributable to politicians who use, without knowledge or discrimination, the powerful and dangerous weapon of taxation. Anyone receiving a report of an orebody containing 100,000,000 tons of ore with copper at 1.4% and zinc at 8.5% knows that this is a type of shorthand which recognizes that the mineral comes in a whole gamut of grades maybe from 15% to 0.1% but that in determining the reserves a cut-off grade representing the lower limit of economic recovery of say 0.25%, has been selected and that the figures reported represent an average of the economic ore. It seems impossible to get across to politicians and their advisers that if they are going to impose royalties or other cost elements on the project that same orebody may have to be reported as containing 60,000,000 tons of 2.0% copper and 12% zinc so that the legislative pen can consume more ore in 10 seconds than a miner's pick in as many years.

An oddity that is worth mentioning is that the conservationists appear to direct their energies to prevent minerals being mined and thereby ignore several very obvious facts, notably: that everything produced today is almost certainly going to be produced more cheaply than at any future date, that most metals are relatively indestructible and that they therefore go into society's stock of goods where they continue to be available. (Their use can be changed in the course of normal recycling or to meet emergencies). There is, therefore, very little waste as a result of mining. Where waste is conspicuous is in the way materials are used and disposed of after use and yet this has received comparatively little attention from conservationists apart from some token collection of old newspapers and bottles to make people feel that something is being done.

One of the most obvious factors necessitating higher profits at the moment is inflation. It may well be that the stock exchanges are recognizing this by marking down stocks in the face of ever increasing profits. Corporate profits represent the major source of new investment and the belief that we are enjoying unduly high profits may well prove illusory. The rate of return on mining investment in Canada is currently running only about 20-25% higher than the average of the last five years and is, in fact, lower than it was four or five years ago. Costs of new projects have increased anything up to three or fourfold over the same period and even without the effects of loss of incentives, not to mention the depredations of the various taxing authorities, it must be very doubtful whether funds will be available to maintain the growth of production which the world will require.

There are two elements affecting the profits of the mining industry which are not well understood and lead to misunderstanding of the industry by press, public and politicians. The first of these is the price cycle which affects most metals. This cycle generally runs on a three or four year basis and has a quite remarkable range - copper prices for example ranged between £407 and £1,400 over a two year period between June 1972 and April 1974. This is obviously reflected in profits and in this country the rate of return on capital employed in the metal mining was three times as high last year as in 1972 but still not as high as the 1970 rate and the average rate over the last five years is in line with other but less risk-prone industries.

The other element which affects large sectors of the mining industry is the range between high grade and marginal deposits and also the effect of size on costs of production. This can result in the lowest cost producer operating at only a quarter or a fifth of the cost of the marginal producer. This, of course, is not always evident in corporate financial statements since most large companies operate deposits of varying quality. What is evident, however, is that a tax regime which would be tolerable for a rich mine would be disastrous for marginal mines. Conversely, of course, the favourable tax treatment which mining formerly enjoyed in Canada and which was designed to permit the development of marginal deposits simply represented more icing on the cake for the rich operators. This has obviously contributed in part to the reaction against mining in some quarters. The Ontario Government's solution has been to impose a steeply progressive tax on profits. This again shows a lack of comprehension by confusing the size of a company with the value of individual deposits. What the Ontario legislation has done, in effect, is to ensure that with marginal rates in excess of 70% Inco or Ecstall Mines will never develop a marginal orebody although it is precisely to companies such as these with financial strength and high generation of cash that the industry looks for the maintenance of its tempo of development.

In other parts of the world this problem has been to some extent resolved. In South Africa precious metals and diamonds are the property of the state and exploitation contracts are granted against a tax formula developed for each mine. In many developing countries each mine is the subject of a convention between the state and the operator which obviously recognizes what the traffic will bear in the way of taxation with regard to the particular orebody.

In general there is cause for grave concern where government seeks to tax the mining industry at rates in excess of those applicable to industry generally. Such discrimination can be defended in terms of non-economic or social considerations. This is the justification for discriminatory taxes on alcohol and tobacco which are deemed injurious to health or on luxury items such as jewellery and furs on the theory that luxuries should contribute more heavily to the fiscal kitty than necessities. Why a basic industry which is the foundation of a broad spectrum of other industries should be so treated is beyond understanding and seems to point to some lemming urge to self-destruction in our stress-ridden society. Part of this is undoubtedly due to our methods of financial reporting: comparing one year or one quarter's results with the immediately preceding period which certainly has no relevance in an industry subject to cyclical price fluctuations and which is given undue prominence in the financial pages of the press; the tendency to view profit figures in a vacuum without reference to resources invested to earn them (that a Canadian politician should be allowed to refer to profits of a million dollars a day by Imperial Oil as being obscene without reference to the investment involved and be quoted without comment and even with the approval by the respectable press of this country is an indication either of dishonesty or naivety on the part of those responsible for the formation of public opinion); the method of reporting in North America whereby the difference between the accounts reflecting current prudent accounting practice and the accounts prepared in accordance with the prescriptions of current tax legislation is described as "deferred taxation" is a misnomer which provokes hostility, because of the implication that the company concerned has been getting away with something and finally the reporting of investments on the basis of historical dollars and income in current dollars inflates the apparent profitability of a business.

The ultimate point at issue is that profit is the major source of investment funds. It may be argued to what extent funds generated by an undertaking should be left with management for reinvestment and to what extent they should be returned to the proprietors for their own reinvestment decisions. Traditionally, managements have been able to count on 50% or more of net earnings for reinvestment. Present tax policies emerging in Canada, Ireland and elsewhere will deprive the industry of the greater part of the funds it counted on for new projects and will render mining extremely unattractive for new investment. In a politico-economic sense it should be a matter of very great concern that large amounts of investment capital are being removed from the corporate area where management is being held increasingly accountable for its decisions to that of government where public accountability for investment decisions is easily evaded and where investments are governed by all sorts of non-economic motivations whose values are impossible to assess.

This brings us to another trend in government interventions which is very disturbing and that is the intrusion into the actual functions of management. In modern times government has quite properly assumed certain rights of control, particularly in areas affecting the health and well-being of employees and the public at large and of investors and it is clearly right that management should be obliged to adhere to acceptable standards in these areas. What is new is the tendency for government to abrogate selectively certain economic management responsibilities such as the right to determine production grade or rate of production and the competitive involvement of government in marketing. Here in Canada we have had provincial administrations determining minimum prices and production quotas. We are faced with demands for payment of royalties in kind, with the produce being sold by state marketing boards which will have access to all the information accumulated by the mining company's own sales organizations. This type of intrusion is making it increasingly difficult for management to function in an integral co-ordinated manner especially when there is not even any clarity with regard to government's long-term intention and the ground rules necessary for long-term planning are admittedly going to be changed arbitrarily by administrative decision. In this country at any rate, mining policy is currently a prescription for chaos.

The last area on which I wish to touch is the xenophobic syndrome. Many of us belong to a generation which believed that from the crucibles of war a new spirit of international co-operation and freedom of movement of men, money and materials would be born. Instead, we have seen the rebirth of a narrow political and economic nationalism. In many of the developing countries this can be understood even if it is still to be deprecated. What is quite incomprehensible is that countries like Australia and Canada and even some European countries with well developed economies should be putting up the shutters to international co-operation. This is especially felt in the mining industry which has long been the most international of industries. Mining skills, mining money and mining men have migrated freely across the continents to wherever the opportunities and needs for their services existed. With relatively few exceptions mining investment has not been associated with attempts at political domination and the mining industry has accepted the political and social structures of the host countries. This, of course, is not surprising since anybody who opens a mine gives a hostage to the country in whose jurisdiction it operates and the host nation has complete and unquestioned power to enforce its policies.

I have explored a number of trends of which the mining industry is critical or which it finds disturbing. It is all too human a quality to dwell critically on what is disliked or unpleasant and to take for granted all that is good and pleasing so, after this long jeremiad, I would like to pay tribute to the many people in government service in this country and elsewhere in bureaux of mines, departments of mines, geological surveys and various research organizations who by their high professional standards, enthusiasm and devotion to the well being of the mining industry have provided the essential foundations for prospecting and mining development.

Most of what I have said today has been rehashed hundreds of times wherever mining men meet. We are all clear as to our problems but it is difficult to find any consensus in solutions.

The search for a solution must surely start with an understanding of the motives of governments in developing these new trends. These, however, are mostly as varied as the circumstances of the governments concerned. They may, however, be grouped in broad categories.

The first, usually confined to developing nations, is encountered where the industry makes a preponderant contribution to one or more areas of the national economy such as gross national product, employment or foreign exchange. The mono-economies of Zambia and Chile and other heavily mining oriented economies such as Zaire and Peru are examples. In these cases a feeling that government must have an immediate and direct control on the levers that operate the economy or merely a feeling of national pride may be the driving force for government involvement. In such cases, and especially where the country in question does not have a strong indigenous private sector and, where the mining industry therefore tends to be foreign controlled, many significant divergences of interest between government and the mining industry are likely to develop.

Undertakings will seek to maintain reasonable dividends to their shareholders; the state will wish to maximize reinvestment. Undertakings will seek to restrain taxation; the state to maximize it. Undertakings will seek to maximize productivity, the state will regard the creation of jobs as more important. Undertakings will wish to purchase supplies and services on the most economic basis, the state will wish to support local industry. Undertakings will wish to evolve their marketing and distribution to give a satisfactory geographical spread to maximize returns and to develop into growth markets, the state will tend to associate this function with its foreign policy.

In the case of established operations this conflict of interest has led to partial or complete nationalization and to the extent that the original operators have remained they are more or less disgruntled and frustrated.

In the case of new projects the approach tends to be by way of a convention which endeavours to prescribe the rights of both parties and the course of action to be followed in specific circumstances. No convention, however, can provide for all contingencies and the tendency has been for a more or less contentious dialogue to develop between the state and the operator with the latter, tied in by his investment, always on the defensive.

Some mining companies are tending in the direction of becoming service companies rather than investors and this obviously avoids many of the risks which we have been discussing. On the other hand, the pickings are likely to be very much smaller and while a conventional mining company might make a sideline of service operations as some already do, partly to keep their teams together during problem periods, it is doubtful whether, if the trend were to grow, the rewards from this type of service would be sufficient to permit mining companies to keep staff of the size and quality to supply a consistently high-class service. Mercenaries have played an important role in military history but have usually lacked the motivation to handle prolonged difficult situations.

The second category of countries which are most actively pursuing the trend towards involvement are those committed to a doctrinaire socialism. The reaction of mining companies operating under a free enterprise philosophy has generally been to salvage what they can and get out once they are convinced that a country is firmly committed to such a system.

There remains quite a broad group of countries, including this one, where motivation is much more confused. There appear to be all sorts of elements in the situation: socialists avowedly committed to state ownership and control, a variety of pressure groups with environmentalist, conservationist and fiscal theories.

Above all, government itself is feeling the pressure of inflation and is looking for sources of funds that can be tapped without too much political risk. There are also random factors. Here, in Canada, the mining industry has been caught in the cross fire of a constitutional and fiscal battle between the federal government and the provinces. If visitors to Canada are not familiar with this conflict they certainly will be before they leave.

What can be done in these circumstances? The classical alternatives are to run away, to fight, or to reach an understanding. There has already been a certain amount of running away but in a world where trends we have been talking about tend to be pretty well universal and vary in intensity rather than in character, there are not too many places to run.

Fighting is happening to some extent and suggestions have not been lacking that industry and, particularly the mining industry, should take off the gloves and get into the political fight. Prominent members of the major political parties in this country have been saying privately that the political parties cannot afford to buck radical opinion and the support it enjoys from the media and that it behooves industry and, particularly the mining industry, to use its resources to form public opinion. Others have suggested that industry ought to use its clout to back a political leader who will give them a fair deal. I find all this very disquieting indeed. This is the sort of thinking and talking that gave the world Hitler and Mussolini.

I believe this sort of approach to be wrong. We may have fallen down in putting our case to the public and it is up to us to set this right. I do not believe, however, that it is our function or that we have the right to build up a political machine as the instrument of achieving specific economic conditions just as I do not believe that political leadership of any party has the right to abdicate its responsibility for leading public opinion to support the creation of an economic environment conducive to the nation's future prosperity. I think the hostility and breakdown in relations between government and industry and, particularly the resource industries, has gone too far and that it is high time that government and industry took the time to explain and understand each other's needs and objectives. We need this here in Canada, in Australia, in Ireland and wherever mutual lack of comprehension is leading to waste, to delays, to frustration and to the break up of industries which have served their countries well. If Canada today is freer of shortages, less pressed by inflation and more fundamentally prosperous than almost any country in the world, it is due primarily to the achievements of its resource industries under the sympathetic support which they received from government in the fifties and early sixties.

This lesson has to be heeded if we are to confront successfully the problems of the coming years which I fear will be greater than any we have known in the last thirty years.

FOREIGN INVESTMENT AND THE MINING SECTOR IN THE DEVELOPING COUNTRIES

BY A. BROCHES*

The broad topic of this session is "National Trends in Mineral Resource Development" and this presentation deals with "Foreign Investment and the Mining Sector in the Developing Countries". Let me start out by indicating the context within which I propose to discuss these matters.

To begin with, I want to stress that my concern with foreign investment will be limited to investment in the Third World.

Second, while dealing with the issue of current national trends as they affect foreign investment, I do not propose to discuss in detail the different ways in which these trends manifest themselves.

Third, the mining sector is of crucial importance to producing and consuming nations alike, and foreign investment has played a central role in Third World mining development.

Fourth, over the past decade foreign investment has become an increasingly controversial matter in its political as well as its economic aspects.

Fifth, the aura of tension and conflict surrounding foreign investment inhibits the development of the mining sector in the less developed countries (LDC's) and threatens to inflict unacceptable penalties on international political and economic relations.

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Finally, this situation calls for thoughtful and concerted efforts to move away from confrontation and to work towards rational solutions to the benefit of all parties in interest. It is in this area I believe that international agencies can make a contribution and I shall discuss some specific instances of efforts in this direction.

When we look at the mining sector, we find some intriguing statistic: although the land area of the less developed countries is twice as large as that of the developed countries, their share in the world's estimated non-fuel mineral reserves by value is not significantly higher than that of the rich countries.

It surely is not fanciful to suggest that this measure of disproportion is likely to be the result of man's work as an explorer. Estimates of reserves are the result of exploration. It is a fact that the search for non-fuel minerals has been less intensive in the developing countries for at least two reasons: first, large investors have preferred to operate under stable governments and laws, with assured terms of access to land, transport, communication and geological surveys; second, the economically developed countries tend to be located in temperate zones where rock formations are well exposed, and it is only in the past forty to fifty years that prospecting techniques have advanced from surface probing to coping with the dimension of depth.

If we turn from exploration to exploitation, we find an even greater imbalance. It has been estimated that the developed countries' share of mineral production was about 41% of the value of world production in 1970. In the same year, the less developed countries' share was only 33%. When we take one further step, from production to processing, it is estimated that only 30% of the minerals produced in the less developed countries is processed there.

The economic importance of mining projects to the developing countries is obvious. They are typically export-oriented and, apart from employment and other possible beneficial effects, provide the country with essential foreign exchange. In some of the poorer countries, one large mining project can make a substantial impact on the country's economy. It was estimated that in 1970, the share of the non-fuel mineral sector in Zambia's Gross Domestic Product was over 40%. In Bolivia, Gabon, Liberia, Mauritania and Surinam, the sector's share of GDP was between 25 and 30%. Mines are often located in remote areas and the infrastructure facilities required for their exploitation may serve in some cases to support other developmental activities.

By and large the countries of the Third World lack both the technical and commercial capability and the financial means required to develop the potential of their mining sector. They must therefore look to external sources for either technical or financial assistance, and in most cases for both. Until now, foreign investment - private foreign investment - has been the almost exclusive source of external financial as well as human resources.

A realistic assessment of the possibilities for the future can, it seems to me, lead to only one conclusion, namely that regardless of considerations of policy and ideology, private capital will inevitably continue for a considerable time to play an essential role if development is to go forward. This is so far the simple reason that the flow of funds from official sources is now, and will almost certainly continue to be, insufficient to meet the investment needs of the mining sector, especially in the poorer countries. Technical and commercial capability will also have to be provided from abroad, although on a gradually decreasing scale.

We all know that the present situation is one of tension and conflict. This is evidenced by pronouncements and policy declarations by individual governments, and collectively in UNCTAD and the UN General Assembly, as well as in controversies between host governments and the foreign investor. I need not mention examples of such controversies which have led to expropriation and other unilateral actions on the part of the host governments concerned.

I think it is possible to distinguish two separate aspects of the divergence of interests between host countries and investors. The first is the level of the financial arrangements (such as royalties, taxation, equity and/or profit participation), in other words in the area of sharing the immediate benefits of the operation. With respect to older projects, the host governments feel they should not remain bound to contractual arrangements arrived at in what were, or are perceived by them to have been, conditions of inequality. In many cases renegotiation has taken place, in many others the conflict has not been amicably resolved. In regard to new projects, host governments are now demanding a larger share of the benefits through various techniques and devices. The nub of the problem here is to find a situation of equilibrium which will give adequate incentives to the foreign investor while satisfying the legitimate and reasonable demands of the host countries.

The other area of conflict concerns the level of minerals policy. Decisions on matters such as the rate of exploration and exploitation, marketing policy, transfer pricing (where applicable) and local processing, were traditionally taken by the foreign investor in the light of his own best interests. These may or may not coincide with the long-term interests of the host country as perceived by it, and host countries now demand far-reaching control of these matters, including also conservation, restoration and environmental impact.

The reconciliation of these conflicting interests is complicated by a past history of political and economic inferiority of the LDC's and a deep-seated suspicion on their part that in dealing with foreign investors they will not be getting a fair deal. It is these feelings which in combination account for the extremely far-reaching elaborations of the concept of permanent sovereignty over natural resources put forward at recent international gatherings, including the special session of the UN General Assembly in the spring of 1974. Some of them appear to raise almost unsurmountable barriers to continue foreign investment. One should not overlook, however, that notwithstanding these pronouncements, a number of developing countries which supported the principle underlying them have almost contemporaneously taken action to attract foreign investment, and in that connection have voluntarily limited the absolute and discretionary power they have claimed for themselves by concluding agreements with investors and with governments of capital exporting countries, and by adhering to multilateral treaties such as the ICSID Convention about which something will be stated later on.

I submit that in this situation which is not only characterized by conflicting interests but also by inherent complexities and a great deal of confusion, there are constructive actions and policies that can be pursued by the international community in the interest of poorer and richer countries alike. It is to these actions and policies that I shall now turn.

Some of them are directed at strengthening the bargaining position of the LDC's by providing them with knowledge of their mineral potential. The United Nations have been doing extremely valuable work in this field through the United Nations Development Program. The UNDP, established in 1958 and financed by yearly voluntary contributions on the UN membership, makes grant monies available for pre-investment studies, leaving follow-up investments to the international lending agencies, such as the World Bank Group or the regional development banks, to bilateral assistance sources as well as to the private sector. In this connection it is interesting to note that when UNDP starts a mining pre-investment project, the recipient country usually has or is expected to adopt a mining code which encourages large investments.

From 1959 to 1972, the UNDP has financed some 90 pre-investment projects in the mining and ground-water exploration fields. Most of these projects and especially the more recent ones have combined physical investigations of large areas of the country involved with technical assistance for strengthening the government departments involved in geology and mineral resources, and the training of their staff.

During this period, the total amount granted by UNDP for mineral and ground-water resources development has been more than $130 million. Although the amount is small compared with what has been invested by the industry as a whole, the results are by no means negligible. Projects financed by UNDP have resulted in the indication of major ore bodies in Iran, Mexico, Panama and the Philippines, for instance. Exploitation of some of these deposits has already begun.

The UNDP has also provided assistance for the training of government officers in mining matters generally, and more specifically, in the development of the necessary skills to draft and administer mining laws and regulations, and to deal with current and potential investors.

It is beyond dispute that a well-trained and experienced group of economists, lawyers and technicians is an essential asset for a country wishing to develop its mining potential. Unfortunately these skills are still lacking to a considerable degree and the resulting need for heavy reliance on outside experts, who frequently must be found among those who normally advise the investing community, is a matter of concern to the LDC's. A number of ideas have been advanced and put into practice, some of them by way of experiment, to remedy this situation. As regards legal experts, I can mention training courses and workshops at universities, the United Nations Mining Advisory Service, and a project for the establishment of a group of experienced legal and financial consultants which would serve only the developing countries.

In an effort to increase the sums available for mineral research, a United Nations Revolving Fund for Mineral Resources Exploration was recently established. Although the fund will initially be financed by voluntary contributions, it is hoped that the replenishment contributions which recipient governments will have to repay from successful exploration projects will be a major source of future funds. Nevertheless, the ability of the fund to become self-sustaining will depend largely on a number of basic decisions yet to be made and on the success of its exploration efforts.

The fund was established by General Assembly resolution on December 17, 1973. In it, the General Assembly invited the World Bank to co-operate with the fund and initially to participate in the preparation of procedural arrangements for its operation which the bank willingly did.

Such endeavors as UNDP or Revolving Fund financing of exploration projects may, in the long run, have a profound effect on the structure of investments for exploitation of the resources so found. It is obvious that the bargaining position of a host country is stronger once initial exploration has taken place and the parties have a better idea of the risk involved in the proposed investment. The agreements they reach in these circumstances will tend to be more stable, more viable, than would otherwise be the case.

Mention should also be made of World Bank financing in support of mining projects. In Bolivia the bank's soft loan affiliate, the international development association, is financing a feasibility study for the establishment of a national exploration fund. This is part of a larger project which includes financing of technical assistance for training and a study of Bolivia's taxation in the mining sector, as well as investments in mineral production. In addition, and more importantly it has undertaken a number of financing operations which have served the purpose of facilitating the investment of foreign private capital in projects which make a significant contribution to the economy of the developing country involved.

The World Bank may become involved in mining projects in two ways. In the first place, it may be asked to make financing available for a project located in a developing country and to be carried out and operated by foreign investors. A loan for such a project, which would be made to the foreign investors, would need to be guaranteed by the host country according to the World Bank's charter. This was the situation, for example, with respect to the Falconbridge nickel project in the Dominican Republic. Secondly, the bank may be asked by the government of a developing country to finance an infrastructure project, a road, railway or power plant, which is required for a mining project. Recent examples are loans to Guinea in connection with the Boké bauxite project and to Botswana to support the BCL copper and nickel project.

Frequently, such projects are located in poor countries and this has typically been the case of those with which the World Bank has been concerned. They are often referred to as enclave projects since they lie outside the mainstream of economic activity of the host country. They have other common distinguishing characteristics. For instance, they typically involve investments of a size far beyond the capacity of the host country to provide. Their production is destined for export. The project is frequently a captive one, in the sense that it relies on the foreign shareholders of their associates for the marketing of the production. Finally, the mineral resources being exploited in such projects may be the country's principal, if not only, natural resources to support its economic development. One characteristic deserving special mention is that if the project is successful, it should be more than self-liquidating in terms of foreign exchange. This means that if the financial viability of the project can be assured, the World Bank can lend in support of the operation, notwithstanding limitations on the general credit-worthiness of the host country which, as I noted, may be very poor.

Mining projects sponsored by foreign investors present the World Bank with a threshold question: why lend at all? While the World Bank is to promote private foreign investment, it is a lender of last resort. We supplement private capital but don't substitute for it. It is a fact that whether our financing is required for the production part of the project or for related infrastructure facilities, the foreign sponsors would in many cases be able to provide all the required funds. They nevertheless seek World Bank financing. In most of these cases the main motivation is the political umbrella constituted by a World Bank presence in the project. What is interesting is that the host country, too, welcomes the World Bank presence and for broadly the same reasons. Each side tends to look upon the World Bank as an impartial participant in the venture. Honorable and gratifying as this role may be, it is not one that can be discharged without difficulty.

It would go far beyond the scope of my subject to embark on a detailed discussion of the World Bank's financing operations in the mining sector. I believe nevertheless that I should indicate in a very summary way how we view, and deal with, two aspects of mining projects.

The first is the financial soundness to which I referred earlier. This matter obviously receives close attention to eliminate risk for the World Bank as well as the host country. Frequently the project is a captive one and typically it is under-capitalized. This leads the World Bank to seek assurances from credit-worthy foreign sponsors which may take the simple form of unconditional financial guarantees or more complicated forms including, singly or in combination, take or pay contracts for the product or for the power or transport facilities; over-run and provision of working capital commitments by shareholders; subordination of shareholders' advances; dividend restrictions and the like. Where the construction of the infrastructure project by the government has to precede the construction of the mining project, special safeguards, including voting trusts, may be demanded. The effect of these assurances is to eliminate the financial risk for the lender, i.e. the

World Bank or the host government which acts either as the borrower or the guarantor. But, although assuming the full financial and commercial risk of the operation, in normal circumstances foreign investors do not want these assurances to apply in the case of such political risks as expropriation or interference in the operations of the project. In principle we are prepared to accept that position. One can even say that the existence of a political risk is a major justification for our involvement. However, I need hardly say that working out the details of what constitutes "political risk" "force majeure" which will suspend or release the foreign sponsors' obligations is a troublesome affair requiring lengthy negotiations.

I now turn to the second aspect which is directly related to the fact that the World Bank is not just a bank, but a development institution. We therefore have no business, to put it bluntly, to finance a project, regardless of its financial return, unless it produces a significant and, in the circumstances, fair and reasonable return to the host country.

This obviously may place the bank in a delicate position, in which both sides may solicit its support on points of difference in their mutual relations.

We may safely assume that the foreign investors have equipped themselves with all the expertise required for the negotiations. This is of course only very seldom true of the host country. We therefore urge the host country to retain the necessary outside experts, assist it in finding such experts, and in some instances where the government wrongly, in our opinion, felt either that it could handle the negotiations with the foreign sponsors without outside help, or that it could look to the World Bank for the protection of its interests, we have made the engagement of qualified experts a cunditio sine qua non for our participation in the financing.

That is of course not to say that the Bank does not get involved in the substance of the agreement between the investors and the host government. We will of course always see to it that these agreements are such as to protect our own investment. Secondly, we want to satisfy ourselves that the conditions are fair to both sides and that they are perceived to be so. We will not participate in operations that from the start bear the seeds of conflict. Inequitable agreements are strictly non-viable. Beyond that it is difficult to be precise.

All I can say is that without becoming outright advocates for the point of view of either party, we try to make sure that all relevant considerations are fully taken into account by both parties. If this should in fact be of greater assistance to the host country than to the investor in the negotiations, I submit that it is in the equal long-term interest of both.

Investment agreements in the mining sector are typically intended for the long-term. In such long-term contracts, the chances that a conflict will arise during the life of the contract are of course much greater than in contracts of shorter duration: changes in the circumstances that affect the benefits the parties expected to reap from the project may lead the party which feels it is "losing" to try to renegotiate the terms of the contract. The other party, on the other hand, may feel that it has good reasons to refuse renegotiation. This may lead to conflicts in the execution of the agreements, frequently although by no means exclusively at the instance of the host government.

This leads me to another activity sponsored by the World Bank Group, namely settlement of investment disputes.

In the middle 1960's the World Bank sponsored an international convention providing for international procedures for the settlement of investment disputes between host states and foreign investors. The Convention created the International Centre for Settlement of Investment Disputes, or ICSID for short. Sixty-five states, of whom more than two-thirds are developing countries, have already become parties. The agreement provides for conciliation or arbitration of investment disputes which the parties voluntarily submit to the Centre. The Centre will not take jurisdiction unless the parties have given their consent, but -- and this is extremely important -- consent once given is irrevocable. In other words, both parties have the assurance that a conciliation or arbitration undertaking accepted at the beginning of a long-term relationship will retain its effectiveness throughout that relationship.

This assurance is based on a treaty. Another important and innovative provision of the Convention is that as a counterpart of the willingness of a host country to submit to international settlement proceedings with a foreign investor, the investor's home state is barred from exercising diplomatic protection or making an international claim.

The Convention effects a number of constructive possibilities. First, it seeks to depoliticize investment disputes, to avoid political confrontation between the host state and the home state. Second, by offering investors and host states an assured forum which, incidentally, will apply the law which the parties have agreed will be applicable, it seeks to improve the investment climate by creating an atmosphere of confidence. There may not be many instances in which the availability of recourse to the International Centre for Settlement of Investment Disputes will be the decisive element in an investment decision. On the other hand, I do think, and I have seen it proved in practice, that the availability of an international dispute settlement mechanism substantially improves the host country's bargaining power and is likely to lead to a better quality investment from the host country's point of view. The reason is obvious. In every investment decision in the Third World the investor has to assess the political risk. The degree to which an investor is willing to become involved in the host country's economy, and to make the maximum contribution to that economy consistent with his overall investment aims, must be related to his expectations of a long-lasting relationship with potential for growth, undisturbed by unilateral action on the part of the host country.

GOVERNMENT PARTICIPATION IN MINERAL DEVELOPMENT AND EXPLORATION

BY DR. I. A. LITVAK* AND DR. C. J. MAULE*

Two quotations will serve as introduction:

1. Within ten years all the multinational resource companies will be nationalized - (Senator Church, U. S. Senate).
2. The world in which the economically younger countries must grow up is one that is shaped very largely by the requirements and initiatives of the more advanced countries, which account for four-fifths of all international trade and seven-eights of all production - (U. N. Report).

These two quotes highlight the three main actors in our discussion of government participation in mineral resource development - namely, multinational corporations (MNC's), the governments of developed countries (DC's) and the governments of less developed countries (LDC's).

The purpose of this paper is to examine the implications of government participation in those circumstances where LDC's are mineral producing countries selling, via multinational corporations, to DC's which are largely mineral consuming countries.

To discuss the implications of government participation in mineral resource development as outlined, it is useful to note certain aspects of the three actors with respect to mineral production, consumption and trading.

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First consider the LDC's and assume a situation where one mineral has an enormous impact on the economy:

1. There is a general perception on the part of these mineral producing countries that they have received a raw deal in connection with the development of their raw materials. In many instances this is because their minerals have been exploited by foreign investors whose impact has been not only on their country's economic development but also on its political development. Present circumstances are thus wrapped up with the developing countries' antipathy towards both multinational corporations and colonial linkages.

In the economic sphere, the LDC's arguments for government participation are advanced on a number of familiar grounds: that economic development has been thwarted by the failure of foreign companies to expand mineral production or to create backward and forward linkages with the rest of the economy; that the minerals are exported to the capital exporting country in a relatively unprocessed state; that there is underutilization of local personnel in senior management positions; and that an insufficient share of the rent from mineral development is collected by the developing country. Underlying these complaints are two important concerns - first, that the economy of the country is tremendously dependent on one industry, such as Zambia and Zaire on copper, and Guyana and Jamaica on bauxite, and second, that the type of jobs available to the local population, because of the stage of mineral production undertaken means that the country is condemned to specialize in unskilled labour tasks which will hinder future development.

2. Politically, governments of LDC's view their increasing participation in mineral development as an act of decolonization. Although in most instances, formal political independence has already been achieved, the presence of foreign investors in mining is viewed as economic colonialism which has to be modified or terminated if real political independence is to be enjoyed.

3. Arguments that the actions of governments of LDC's are illegal or contrary to existing concession agreements often made many years earlier, has little force in the developing country. It is pointed out that original concession agreements were made in the pre-independence period by individuals who did not

represent the country, who were perhaps under duress, and at a time when the economic significance of the concessions was not known. Moreover, developing countries are not willing to subject their investment disputes to international arbitration on the grounds that it is insulting to infer that their own courts would not handle a dispute fairly. It is also felt that any action proposed by the International Centre for the Settlement of Investment Disputes, would detract from the sovereignty which they should exercise over their natural resources.

4. The governments of LDC's tend to have short time horizons regarding mineral resource development. This may be due to the known short run preoccupations of politicians often enhanced by political instability. It may be due to the demonstration effect from other LDC's and the pressure from domestic political elements pressing for nationalization. It may also be influenced by fear that the resource will lose its value as alternative supplies or substitutes are found.

5. There is a scarcity of managerial ability to run nationalized companies in LDC's. Dr. Banks, an observer of events in the copper industry in Zambia, Zaire and Peru throws doubt on this capability in one industry sector, noting that both Zambia and Zaire retained management contracts with the nationalized companies. With respect to Peru, he notes:

> "As I see it, the large European and American corporations are able to abuse their position in underdeveloped countries, because they happen to be able to solve the technical and administrative problems involved in exploiting the resources of these countries, while the indigenous population, particularly their so-called educated class, either cannot or will not."

Turning now to the DC's, their position is as follows:

1. The parents of MNC's reside within their borders - their nationals own the shares and when nationalization or other forms of government participation involve wealth deprivation of their nationals, they are pressured to intervene.

2. The DC's argue for adherence to procedures of international law to arbitrate international investment disputes.

3. The DC's perceive restrictions on mineral exports from LDC's as a form of economic blackmail with repercussions for their highly interdependent economies having effects on employment, inflation, growth and the balance of payments.

4. The DC's react to artificial shortages by diversifying sources of mineral supplies.

5. In the case of expropriation, domestic political groups in DC's pressure for retaliatory sanctions such as the reduction of aid and trade concessions.

As for the MNC's which link the developing and developed countries, their position involves the following:

1. MNC's react to government participation by both LDC's and DC's so as to protect their earnings by risk-reducing measures.

2. MNC's have an enormous capability and flexibility which they use to restructure their contractual relations to protect earnings. Every change of government policy not only creates a problem but also presents them to benefit from these opportunities.

3. MNC's can influence the governments of DC's and LDC's in policy changes, but if this fails and earnings are threatened, they can often pass on cost increases in one country as price increases in another as was recently done by the international oil companies.

4. MNC's will be viewed as a negative force in the LDC by a large element if not all of the host country.

The foregoing represent some of the aspects of LDC's, DC's and MNC's which influence their reaction to each other. We would now like to discuss the implications of government participation in mineral resource development in two areas - producer cartels and government ownership.

(a) Producer cartels

The impact of producer cartels has received increasing attention as a result of OPEC's activities in recent months. It is argued on the one hand that producer cartels will be formed and will be equally effective in such other industries as copper and bauxite. It is argued on the other hand that OPEC's success is only short run because of forces that have been set loose in consuming countries. There is little doubt that the economic and political conditions surrounding the supply of copper and bauxite are markedly different and less favourable to cartels than the conditions surrounding the supply of oil.

The evasive actions taken by the governments of consuming countries can already be seen. For example, the U. S. Bureau of Mines is financing research into the extraction of aluminum from aluminum bearing clays in the U. S.; support is being given to research undertaken on methods of recycling metals such as copper and aluminum and on developing substitute materials; and exploration is being promoted in less politically risky areas. In the field of energy, the U. S. has announced its intention of being self-sufficient by 1980. Its ability to achieve self-sufficiency in other minerals is probably much greater, because, unlike oil, these minerals tend to be recoverable as scrap. The supply of secondary copper already represents a substantial contribution to total supply, and the price elasticity of supply is sufficiently large to expect increased recovery rates as the price of copper increases.

Evasive action may not be as easy to implement for Japan and the countries of Western Europe as it is for the U. S. because of the latter's relative self-sufficiency in many minerals. While Japan and W. Europe will move in the same direction as the U. S., they may also attempt to negotiate special arrangements with individual mineral producing countries. A forerunner of this was the dealing by individual countries during the "oil crisis" of 1973. In a sense, this strengthens the possibility for producer cartels and weakens the chances for the formation of consumer cartels. However, once negotiated, such agreements will at the same time tend to divide both the consuming countries from each other and the producing countries from each other. The result could be a form of economic warfare as individual countries attempt to corner particular sources of supply or markets for themselves. In this scenario, the role of the multinational resource companies will be influential.

There have been examples of co-operative action, which falls short of a cartel, on the part of resource consuming nations. Again the example of oil comes to mind. The actual formation by governments of consumer cartels is difficult to envisage for many minerals because of the wide disparity of interests on the part of consuming countries. It would certainly involve a high degree of liaison between governments and companies in the consuming countries, something that could be more readily achieved in some countries than in others.

What is more likely to occur is the formation of cartels on the part of multinational resource companies, which may receive the tacit approval of the governments of consuming countries. For example, the international oil companies received a formal U. S. antitrust exemption to bargain collectively with the oil producing countries. The North American aluminum countries are bargaining collectively with the Jamaican government with no formal antitrust exemption, but with the knowledge of the U. S. and Canadian governments. These same companies, together with European aluminum companies, are also involved in a "Gentleman's Agreement" to protect the price of aluminum in the west from aluminum imported from socialist countries. Collective agreements are also engaged in by iron ore producing companies.

While the companies will be forced to change their bargaining strategy, their flexibility will allow them to adjust and probably benefit from changing government policy. Their strategy may well be to protest measures of economic nationalism in developing countries to appease shareholders and avoid being prosecuted for failure to protect their shareholders' interests. However, if they feel they can pass on tax increases or losses due to expropriation, and perhaps increase their profits, they may in fact give in to the demands of the mineral producing governments.

(b) Government ownership

State intervention through whole or partial ownership of mineral producing companies is one definite action being taken by producing countries. In a sense these are following the example of many industrialized countries including Canada, which have been ready to nationalize some of their domestic companies, to initiate government corporations and to raise corporate taxes.

The extent of state ownership of mineral resources is considerable in the case of copper. As noted by Sir Ronald Prain, in 1960, government participation in copper production amounted to $2\frac{1}{2}$% of free world capacity; by 1971, the figure was 43%, mainly due to government participation and nationalization of copper companies in Zaire, Chile and Zambia.

Nationalization presents considerable problems for governments and for the countries involved. The case of Kennecott in Chile is illustrative of the problems faced by the Allende government in its attempt in 1970 to nationalize Kennecott without compensation. The company, anticipating this possibility a number of years earlier, had established a web of contractual relationships which meant that the governments of the U. S., Japan and a number of Western European countries would be affected. Kennecott had loans from U. S. institutions, insurance coverage from the U. S. government, and had sold the collection rights for long term contracts for copper to a number of Asian and European financial institutions. In the end, Allende had to reimburse Kennecott.

The governments of capital exporting countries (DC's) have particular concerns at the time of the foreign nationalization of their firms' assets. Their nationals are the owners of the assets, and are likely to be subject to wealth deprivation unless "prompt, adequate and effective compensation" is paid. Claims against government investment insurance schemes, as already mentioned, may have to be paid, and tax revenue may be lost both as a result of income and capital losses. Special circumstances may affect individual countries. For example, Canada has no bauxite deposits but a large aluminum smelting capacity.

Foreign investment insurance schemes have been used by a number of governments to permit their corporations to protect investments, and in this sense to participate in the corporations' activities. The future of such government-subsidized schemes must be questioned. In the event that a country nationalizes an insured company, without fair compensation, that country is likely to be struck off the list of countries to which insurance schemes apply. Assured continuity of government insurance schemes would thus require no claims ever being made. Another problem with investment insurance is that its presence may encourage countries to expropriate assets and companies to be expropriated if they want to withdraw from a country.

New foreign investment in mineral resource development in developing countries will undoubtedly be on different terms than in the past, and the governments of capital exporting countries will have to associate themselves with their firms' (the investors) actions, because they are inevitably drawn into disputes that tend to arise at a later date. A number of trends are likely to occur. First, concession agreements will be signed for a much shorter period than previously. Second, planned divestment as a technique of withdrawal by companies will be used increasingly. This will be associated in many instances with the companies retaining a management contract with the original company, a technique used by Zambia and Zaire with its nationalized copper mines. A third trend will see increasing use of consortia of companies to develop mineral resources. These consortia will include private companies from different countries and the governments of mineral producing countries through their state enterprises. A fourth trend arises out of problems associated with the taxation of vertically integrated companies which are located in different countries.

There is a tendency for governments of producing and consuming countries to view tax collection from a company which is partly in their jurisdiction as a zero-sum game. For example, one reason for the increase in oil taxation in producing countries is the readiness with which governments in consuming countries have been ready to raise taxes on gasoline consumption. This kind of outright conflict may be resolved through increasing governmental agreement on the overall profitability of the operation and the share that is due to each government. Obviously this proposal becomes less practical the more governments are involved with any given company. However, the development of tax treaty arrangements may be used both to levy taxes and to control multinational corporations. Such agreements may also be useful in ensuring that a concession agreement signed by a company is adhered to by the company and the producing country.

The governments of LDC's, in their quest for greater benefits from their mineral resources must recognize that demand for minerals is much more inelastic with respect to price in the short run than in the long run. Whatever benefits accrue to them in the short run are likely to initiate forces which will undermine future benefits. This may well be a desirable strategy for these governments which need capital now for immediate development and which discount very greatly future returns, but it carries certain implications. The main one is the extent to which sufficient earnings will be made to permit diversification in an economy highly dependent on one resource. A second concerns the extent to which the country has the will and capability to implement the diversification.