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DEPARTMENT OF
MINERALS AND ENERGY

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record 1974/139

The Measurement of Mineral Resources

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Summary

Assessments of mineral resources range over a wide span, from a summation of estimated ore reserves of known deposits at one end to an estimate of the total mineral potential at the other, which would include not only known ore, but resources which are at present not economic but might become so under altered markets or technology, and resources which have not yet even been discovered.

Reserves relate to 'ore' which is defined as a mineral aggregate from which one or more metals can be economically produced. Operators of mineral deposits generally do not determine ore reserves beyond the amount that is necessary to establish the viability of their operations and the most effective planning of them for a reasonable number of years ahead. It would in many cases not be economic to attempt to determine the total ore reserve of a deposit before mining commenced. Practice and terminology in calculating reserves varies widely between different operators but the concepts most extensively used are Proved ore reserves: blocked out in three dimensions; Probable ore reserves: indicated by exposures or drilling but not sufficiently to be accurately defined; and Possible ore: which is deduced largely from a geological evaluation of possible extensions or repetitions of known ore.

In measuring resources on a regional or national scale, the terms Measured, Indicated and Inferred ore are widely used.

Similarly the petroleum industry uses terms corresponding to proved, probable and possible, whose definitions depend upon the degree of certainty with which the quantities present can be established. Generally petroleum reserves are reported in terms of recoverable quantities, which for oil is usually between 20 and 50 percent of estimated oil in place, and for gas 60-90 percent. Reserves for metallic ores and coal are calculated in situ and due allowance has to be made for amounts that cannot be extracted, commonly of the order of 50 percent for coal, but usually less than 20 percent for metallic ores.

Recognizing that what constitutes 'reserves' at any time depends upon a number of variable factors, the International Atomic Energy Agency has adopted the practice of estimating reserves of ore in terms of the amounts that would be mineable at various prices per pound of recovered uranium (U_3O_8). These are divided into Reasonably Assured Resources; recoverable within the given price range under present mining and processing technology (corresponding generally to "measured" and most of "indicated" ore) and Estimated Additional Resources, corresponding to "inferred ore".

Attempts have been made to estimate total ore potential, based either on past discoveries and production or on the percentage of many elements in the earth's crust. Obviously any particular section of the earth's crust has to be considered in relation to its known geological composition, and geological mapping in an essential prerequisite to any attempt to estimate reserves and resources of either minerals or petroleum. For petroleum similar quantitative approaches have been made, resulting in estimates of oil or equivalent gas in different sedimentary basins ranging from less than one thousand to some millions of barrels per cubic mile of sediments after making due allowance for many fundamental geological factors that affect oil occurrence. The reliance that can be placed upon such estimates is closely related to the state of knowledge of geology of the basins or the potentially metalliferous areas and of their production histories in the past.

The estimates that have been made are based largely on a summation of demonstrated and inferred reserves. Some figures are presented (Table 8) but these by no means represent the total potential resource of these commodities in Australia.

A consideration of world resources of energy-producing materials leads to the conclusion that as a long term measure the use of coal should be substituted for petroleum wherever practicable in order to conserve supplies of easily transportable liquid fuels, and that alternative sources of power generation will become available as supplies of hydrocarbons diminish, provided the necessary research is pushed forward vigorously enough.

Ore reserve terminology

Ore reserves, contrasted with mineral resources, traditionally have been divided into three classes corresponding to the three general headings in decreasing degree of certainty: proved, probable and possible. About the definitions of these three classes there is fairly wide agreement.

Proved (positive, assured) ore, is ore blocked out in three dimensions by actual underground mining operations or by drilling, but includes in addition minor extensions beyond actual openings and drill holes, where the geological factors that limit the orebody are definitely known, and where the chance of failure of the ore to reach those limits is so remote as not to be a factor in the practical planning of mine operations.

Probable (semi-proven) ore covers extensions near at hand to proved ore, where the conditions are such that ore will probably be found but where the extent and limiting conditions cannot be so precisely defined as for proved ore. Probable ore also may include ore that has been cut by drillholes too widely spaced to assure continuity.

Possible (prospective) ore is that which may reasonably be expected to exist, from an exposure in a drill hole or mine workings or for some geologic reason, but for which lack of exploration and development data precludes anything like certainty of its actual location and extent.

While there has been agreement about the definition of terms, there has been no such agreement about the usage of them. In a survey of 20 Australian mining enterprises (King, 1955), it was found that a wide variety of terms and concepts were used (Table 1) and virtually the only method of description used by more than one company was one overall category "Reserves", although it did not necessarily mean the same in one mine as in another. Terms used included broken, broken in stopes (by mines where shrinkage stoping was in use), blocked out, proved, positive, developed, partly developed, developed but unbroken, mineable, measured, indicated, prospective, probable, possible and inferred. In a recently issued pamphlet (AIMM, 1972) the Australasian Institute of Mining and Metallurgy and the Australian Mining Council recommended, inter alia, the use of the terms "Proved", "Probable" and "Possible" as defined above.

This terminology is particularly applicable to orebodies mined by underground methods.

Table 1

Categories of ore used by some Australian mining companies (from King, 1955)

Company	Descriptions of Ore Classification
Aberfoyle	"Positive", "Probable". This company also refers to ore as "Proved".
Broken Hill South Ltd	One category only. "Ore Reserve", with comment that "no ore disclosed by diamond drilling or by limited development has been included".
Boulder Perseverance	"Broken", "Proved", "Probable".
Central Norseman	One category only, "Reserves".
Dittmer	"Proven" - sub-classified as "Broken", "Developed but unbroken", "Partially developed".
Emperor	"Measured", "Indicated".
Gold Mines of Kalgoorlie	"Proved", "Probable".
Great Boulder	"Positive", "Broken", "Probable".
King Island Scheelite (1947)	"Proved". The same ore is also referred to as "Proved and payable".
Lake George	"Measured", "Indicated", "Inferred".
Lake View and Star	"Broken", "Positive", "Probable".
Mount Isa	"Developed", "Prospective".
Mount Lyell	One category only - "Reserves".
New Broken Hill Consolidated	One category only - "Ore Reserves" with comment "fully outlined and developed ready for stoping". Ore partially developed or only outlined by diamond drilling is excluded.
Norseman Gold Mines	"Proved", "Probable".
Nth Broken Hill	One category only - "Ore Reserve".
Paringa	"Broken in stopes", "Proved", "Partly Proved".
Peko	"Proven".
Raub Australian GM	
Raub Hole Section	"Broken in stopes", "Mineable", "Probable".
Malacca Section	"Probable", "Prospective".
South Kalgurli	"Blocked out", "Probable".
Zinc Corporation	One category only - "Blocked-out".

For estimation of widespread surface deposits, such as bauxite, or for reconnaissance examination of deposits, or estimates on a regional or even national scale, a classification introduced during the war specifically for such estimations by the United States Bureau of Mines and Geological Survey has been widely used. These are the terms "measured", "indicated" and "inferred", as defined below, which correspond in a general way to "proved", "probable" and "possible".

Measured ore is ore for which tonnage is computed from dimensions revealed in outcrops, trenches, workings, and drill holes and for which the grade is computed from the results of detailed sampling. The sites for inspection, sampling, and measurements are so closely spaced and the geologic character is defined so well that the size, shape and mineral content are well established. The computed tonnage and grade are judged to be accurate within limits which are stated, and no such limit is judged to differ from the computed tonnage or grade by more than 20 percent.

Indicated ore is ore for which tonnage and grade are computed partly from specific measurements, samples or production data and partly from projection for a reasonable distance on geologic evidence. The sites available for inspection, measurements, and sampling are too widely or otherwise inappropriately spaced to outline the ore completely or to establish its grade throughout.

Inferred ore is ore for which quantitative estimates are based largely on broad knowledge of the geologic character of the deposit and for which there are few, if any, samples or measurements. The estimates are based on an assumed continuity or repetition for which there is geologic evidence; this evidence may include comparisons with deposits of similar type. Bodies that are completely concealed may be included if there is specific geologic evidence of their presence. Estimates of inferred ore should include a statement of the spatial limits within which the inferred ore may lie.

This usage is also approved by the Australasian Institute of Mining and Metallurgy.

What is ore?

In the summary I have given the brief definition of ore, 'a mineral aggregate from which one or more metals can be economically produced'. The definition that is recommended by the A.I.M.M. for acceptance is somewhat more expanded - 'a solid naturally occurring aggregate from which one or more valuable constituents may be recovered, and which is of sufficient economic interest to require estimation of tonnage and grade'. It may be noted, parenthetically, that the term 'ore' is generally confined to materials containing the metallic elements, iron, gold, copper, lead, zinc, silver, etc. and is not normally used for the non-metallic elements, which are known by their specific names, e.g. salt, potash, phosphate, talc, nor for concentrations of economic minerals in alluvial gravels or in beach sands.

In the calculation of ore reserves there are five basic factors (King, 1955): length, width, depth, grade, and continuity between exposures. Also important are the complexity of the ore (or the cost of extracting the valuable components from it), and the ease with which it can be mined.

In addition, since 'ore' is an economic concept, what is 'ore' may be determined by the price of the particular metal at the time.

The mining engineer and geologist have traditionally calculated ore reserves by drawing a series of sections or plans of the orebody through those planes where most exposures and sampling data are available, or can be reasonably projected. For each such plane of intersection of the orebody, the average grade and the area are worked out, and the total tonnage is obtained by averaging between sections. In modern times the use of computers has facilitated calculation of ore reserves according to different parameters so as to present the optimum picture of the orebody according to any specified price for the product being mined. This applies particularly to those orebodies, such as the large disseminated copper orebodies, where the grade gradually diminishes outwards into unmineralized country rock, and a cut-off grade, or minimum mining grade, needs to be selected to ensure the desired average grade for the whole orebody.

Concepts of resources

Estimates of ore reserves are strictly related to the state of knowledge of the orebody at the time the estimates are made. Mine operators normally cannot afford to prove out an orebody completely particularly as it is cheaper to explore an orebody at depth by drilling from underground mine workings than from the surface. When it is first found, sufficient testing is done to determine the size, or at least a minimum figure for the size, and grade in order to establish that a mining operation is viable and the scale at which it should be designed. As ore is extracted, exploration proceeds, and it is common practice to maintain a reserve sufficient for so many years work ahead. Many mines tend to list approximately the same reserves each year, some for as much as fifty years. Ore moves from the inferred or possible category to indicated or probable, to measured or proved as further information becomes available. It follows then that a mere summation of published reserves is a very inadequate indication of a nation's resources of any particular mineral commodity. Unmeasured additions to

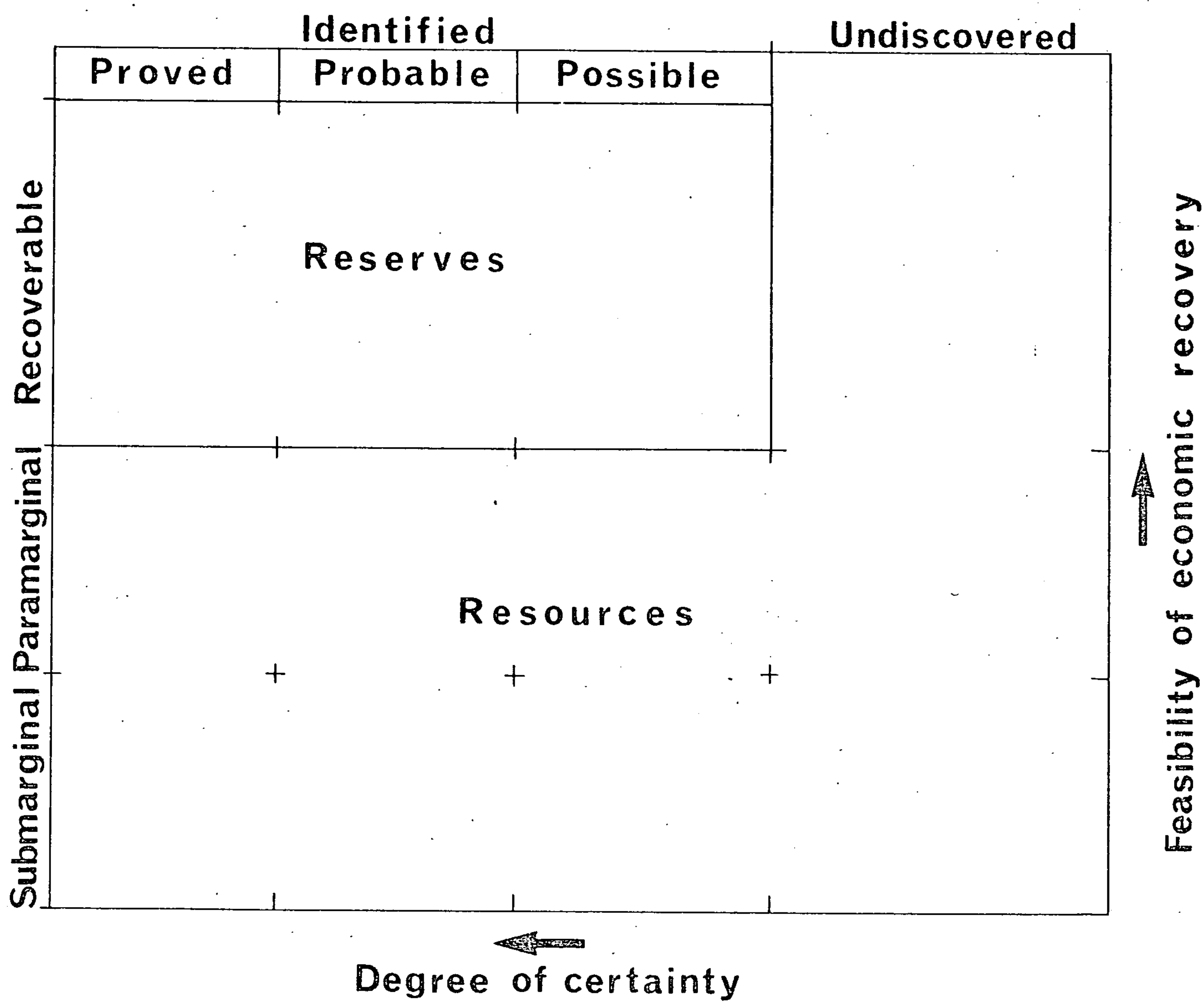


Figure 1 Classification of mineral reserves and resources. Degree of certainty increases from right to left, and feasibility of economic recovery increases from bottom to top. (McKelvey 1973)

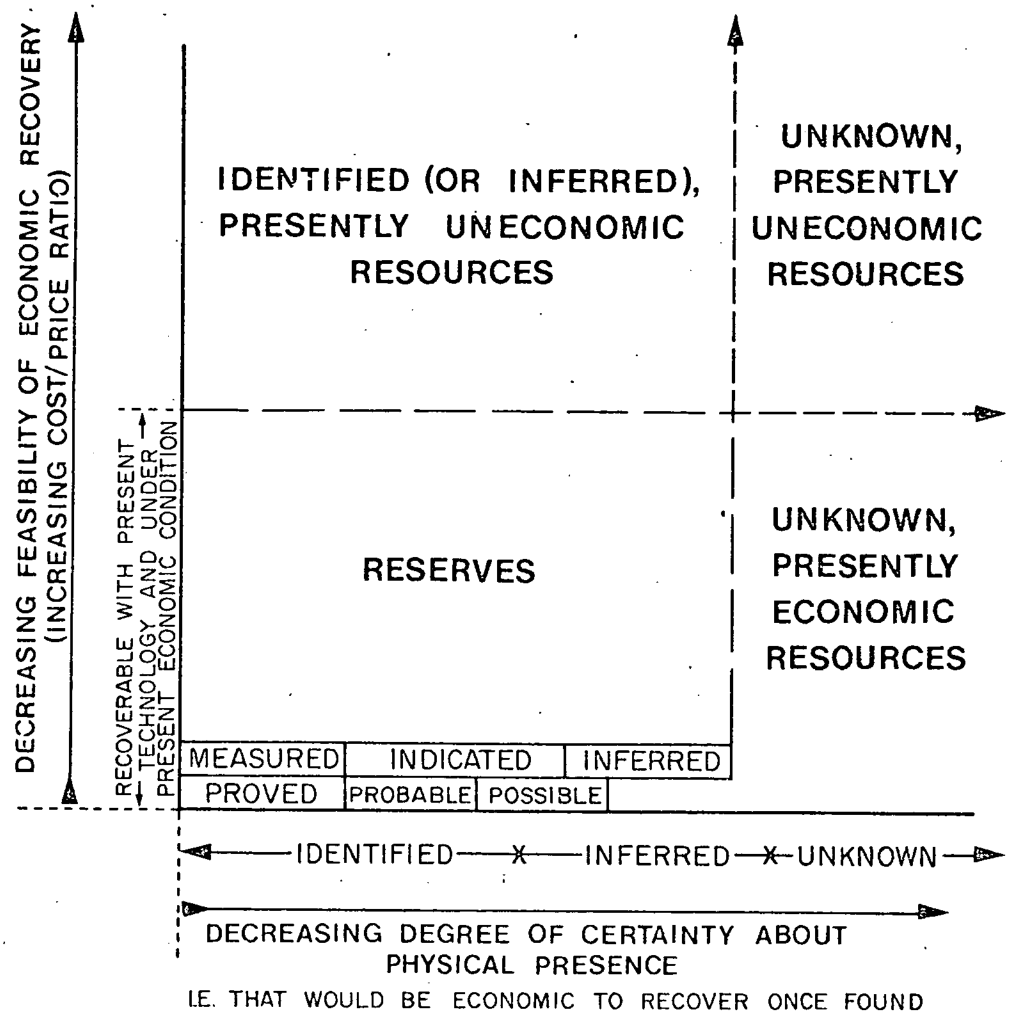


FIGURE 2 THE TWO DISTINCT DIMENSIONS OF RESOURCES.

(ZWARTENDYK 1972)

known orebodies, deposits whose existence is known or suspected but not yet measured, and possible future discoveries all have to be taken into account. Blondel and Lasky (1950) referred to resources as being reserves plus potential ones, expanding this into the 'equation'

Resources = reserves + marginal resources + submarginal resources + latent resources.

Marginal resources are those deposits which would not be economically exploitable under existing conditions, because of, for example, low grade, distance from consuming centres or transportation points, complex mineralogy, current metal price, but which could be worked if conditions were only slightly better, or in conditions of national emergency. Submarginal resources would require conditions even more favourable, but within the bounds of possibility.

McKelvey (1972) developed these concepts further in accordance with the scheme presented in figure 1, in which reserves and resources are depicted according to degree of certainty of their existence and quantity in the horizontal dimension, and feasibility of economic recovery of the metal content in the vertical dimension, subdivided into recoverable, paramarginal, and submarginal. Obviously the boundaries between these categories are movable, as paramarginal is defined as those that are recoverable at prices up to 1.5 times as much as those prevailing at present. Submarginal ores would require even greater relative price increases to make them workable, but McKelvey draws attention to the fact that for instance the cut-off grade for copper ores, by improved technology particularly for largescale open-cut mining, has been progressively reduced to a tenth of what it was at the beginning of the century.

The price received for the metal is not itself the critical factor in determining feasibility of working but the ratio of price received to cost of production. In a world where costs are continually inflating, the ratio to the prevailing metal prices tends to remain reasonably constant, though improvements in productivity per worker may allow lower and lower grade ores, of some metals at least, to be worked.

Zwartendyk (1972) developed McKelvey's scheme further (Figure 2) introducing the concepts of cost/price ratio and identified resources, and dividing unknown or undiscovered resources into those at present economic or uneconomic. He emphasized the fact that in such representation we are looking at the situation at a point in time. As time goes on, mineral deposits will tend to move in the direction of the origin of the diagram, and as they are worked out they will vanish from the picture along the left hand side of the 'reserves' block. The whole situation can be rapidly altered, of course, by a world-wide readjustment in prices, such as the recent spectacular rises in prices for petroleum, followed by phosphate and now possibly bauxite.

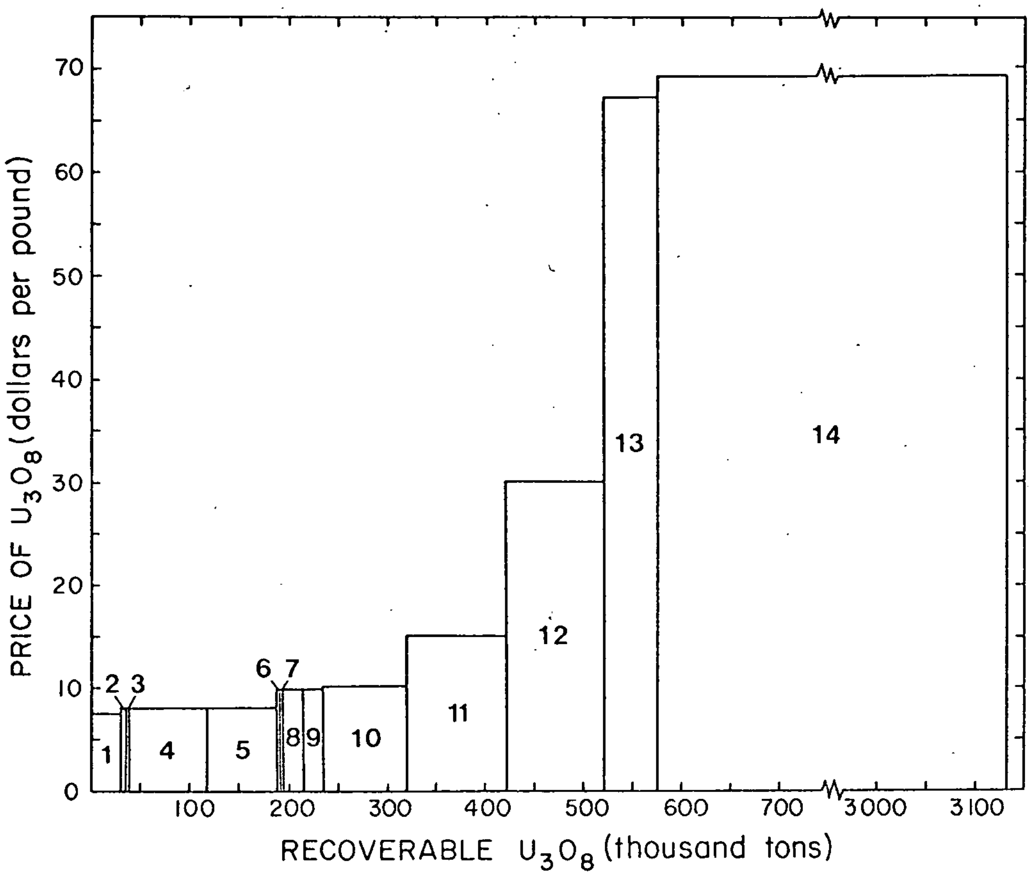


FIGURE 3 AVAILABILITY DIAGRAM FOR URANIUM IN THE UNITED STATES, (EXPRESSED AS U_3O_8)

(U.S. Bureau of Mines Information Circular 8501)

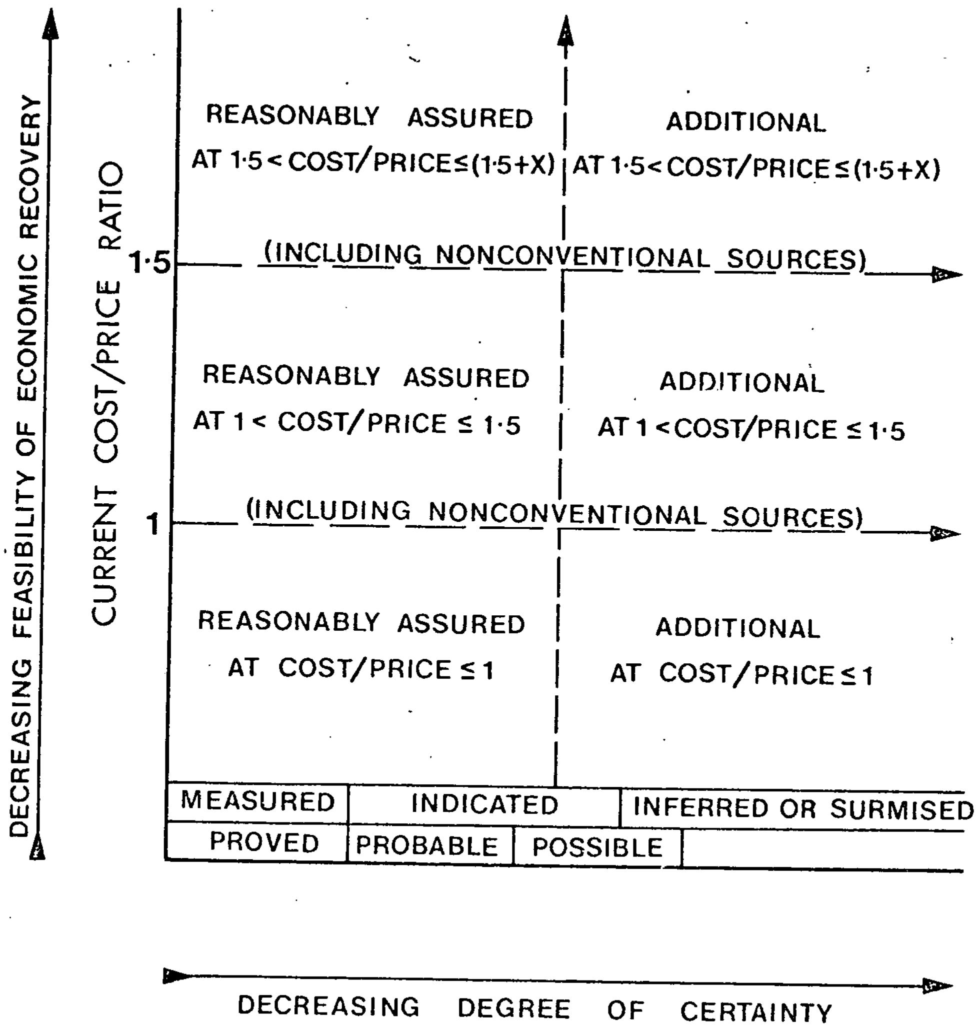
The cost/price ratio is drastically altered and vast quantities of resources formerly rated as submarginal because of low grade, difficulty of recovery, treatment, etc. suddenly became economic and move into the 'reserves' area.

One product which is subject to wide fluctuations in price because of differences in time in supply and demand is uranium, and many government agencies have adopted a usage in which resources, divided into only two classes, 'reasonably assured resources' and 'estimated additional resources', are classified according to a set of price ranges. The effects of such a classification are illustrated by Figure 3 in which the uranium resources of the United States are represented by 14 different blocks, according to the amounts that would be recoverable at different prices per lb for uranium. Details of the different categories are given in the table below.

Table 2

Additional tonnages U_3O_8 available in US at different prices per lb above $7.50 (from USBM Information Circular 8501)

Category No	Price US$ per lb U_3O_8	U_3O_8 Recoverable tons (nearest 100)	Type of deposit
1	7.52	30,000	Copper leach solutions.
2	8.00	7,100	Uranium-vanadium ore.
3	8.00	1,200	Uraniferous lignite ore.
4	8.00	78,900	Other uranium ore, mineable by open pit.
5	8.00	73,600	Other uranium ore, mineable by underground methods.
6	8.00 - 10.00	1,700	Uranium-vanadium deposits.
7	8.00 - 10.00	200	Uraniferous lignite deposits.
8	8.00 - 10.00	22,500	Other uranium deposits, mineable by open pit.
9	8.00 - 10.00	20,300	Other uranium deposits, mineable by underground methods.
10	10.00 - 18.00	85,000	Wet process phosphoric acid.
11	10.00 - 15.00	100,000	High cost conventional deposits.
12	15.00 - 30.00	100,000	High cost conventional deposits.
13	67.42	54,600	Florida phosphate rock leached zone.
14	69.32	2,557,300	Chattanooga shale.



Note: Cost/price levels are to be chosen to fit commodity, data availability, and time span considered.

FIGURE 4 PROPOSED CLASSIFICATION SCHEME FOR RESOURCES ENDOWMENT.

(ZWARTENDYK 1972)

It is considered at present that categories 13 and 14 are now academic because uranium could be recovered from sea-water at lower cost.

The terms 'reasonably assured resources' and 'estimated additional resources' have been defined by the International Atomic Energy Agency as follows (OECD, 1970) :

> The term <u>Reasonably Assured Resources</u> refers to uranium which occurs in known ore deposits of such grade, quantity and configuration that it can, within the given price range, be profitably recovered with currently proven mining and processing technology. Estimates of tonnage and grade are based on specific sample data and measurements of the deposits and on knowledge of orebody habit. Reasonably assured resources in the price category below $10 per pound are equivalent to <u>Reserves</u> in the mining sense.
>
> The term <u>Estimated Additional Resources</u> refers to uranium surmised to occur in unexplored extensions of known deposits or in undiscovered deposits in known uranium districts, and which is expected to be discoverable and economically exploitable in the given price range. The tonnage and grade of Estimated additional resources are based primarily on knowledge of the characteristics of deposits within the same districts.

Zwartendyk has built these concepts into a scheme of classification of what he calls 'Resources Endowment' which is reproduced as Figure 4.

It is to be noted that he draws the vertical line between the two categories so as to include 'measured' and most of 'indicated', in the USBM/USGS resource terminology, or 'proved' plus 'probable' and part of 'possible', in mining terms. The horizontal divisions are quite arbitrary as to both number of divisions and cost/price ratio. In a three-fold division such as that presented, the cut-off cost/price ratio in the middle and top divisions could easily be 2, rather than 1.5.

To round off this discussion of reserve and resources categories, definitions recently reviewed and recommended by the United States Geological Survey and the United States Bureau of Mines are reproduced below. These concepts, which are illustrated in Figure 5, are likely to be widely followed.

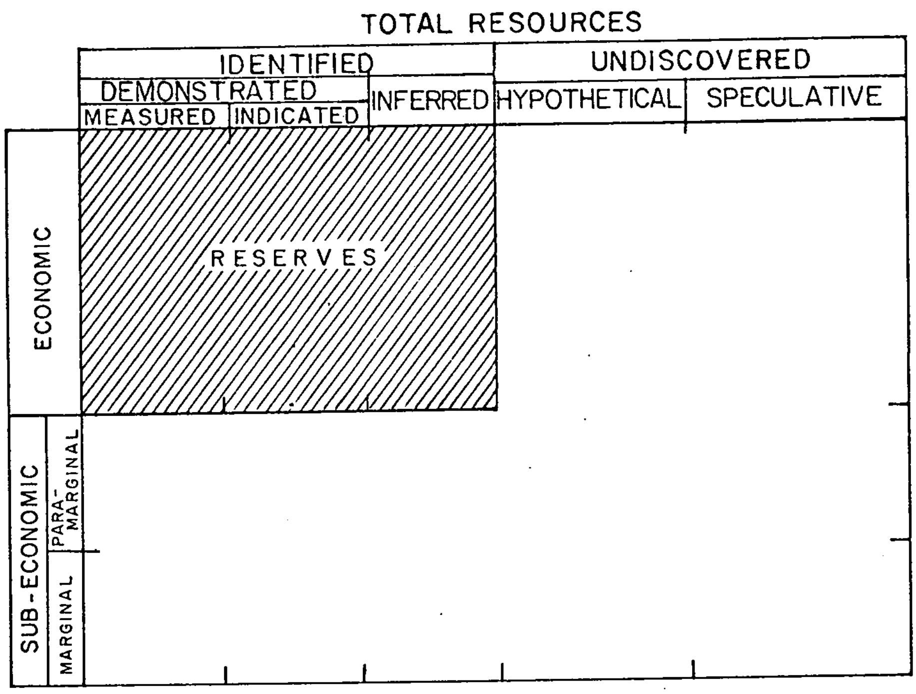


Figure 5 Proposed new classification of mineral resources and reserves USGS/USBM, (Mining Magazine 1974)

Recommended definitions -

Resource: A concentration of naturally occurring solid, liquid, or gaseous materials in or on the earth's crust in such form that economic extraction of a commodity is currently or potentially feasible.

Identified resources: Specific bodies of mineral-bearing material whose location, quality and quantity are known from geologic evidence supported by engineering measurements with respect to the demonstrated category.

Undiscovered resources: Unspecified bodies of mineral-bearing material surmised to exist on the basis of broad geologic knowledge and theory.

Reserve: That portion of the identified resource from which a usable mineral and energy commodity can be economically and legally extracted at the time of determination. The term ore is used for reserves of some minerals.

The following definitions for measured, indicated, and inferred are applicable to both the Reserve and Identified-Subeconomic resource components.

Measured (proved): Material for which estimates of the quality and quantity have been computed, within a margin of error of less than 20 per cent, from sample analyses and measurements from closely spaced and geologically well-known sample sites.

Indicated (probable): Material for which estimates of the quality and quantity have been computed partly from sample analyses and measurements and partly from reasonable geologic projections.

Demonstrated: A collective term for the sum of materials in both measured and indicated resources. (This form was introduced and recommended by Blondel and Lasky in 1956.)

<u>Inferred (possible)</u>: Material in unexplored extensions of Demonstrated resources for which estimates of the quality and size are based on geologic evidence and projection.

<u>Identified-Subeconomic resources</u>: Materials that are not Reserves, but may become so as a result of changes in economic and legal conditions.

<u>Paramarginal</u>: The portion of Subeconomic Resources that (a) borders on being capable of production economically or (b) is not commercially available solely because of legal or political circumstances.

<u>Submarginal</u>: The portion of Subeconomic Resources which would require a substantially higher price (more than 1.5 times the price at the time of determination) or a major cost-reducing advance in technology.

<u>Hypothetical resources</u>: Undiscovered materials that may reasonably be expected to exist in a known mining district under known geologic conditions. Exploration that confirms their existence and reveals quantity and quality will permit their reclassification as a Reserve or Identified-Subeconomic resource.

<u>Speculative resources</u>: Undiscovered materials that may occur either in known types of deposits in a favourable geologic setting where no discoveries have been made, or in as yet unknown types of deposits that remain to be recognised. Exploration that confirms their existence and reveals quantity and quality will permit their reclassification as Reserves or Identified-Subeconomic resources.

Units of measurement

Australia is 'going metric' and there is an increasing tendency throughout the world for countries not already using the metric system to convert to it. With regard to quantities of metallic ores this causes little confusion, because metric tons (tonnes) are very close to the long tons of the imperial system - 2205 lb compared to 2240 lb, and the order of quantity is not significantly altered. In American practice, however, and fairly widely in the uranium industry, the unit short ton (2000 lb) has commonly been used because of the convenience in converting from pounds to tons. With increasing metrification, this term like long tons will gradually disappear.

In terms of grade, most metallic ores are measured in percentages, which are universal. Ores in which the amount of valuable mineral is very low, however, may be measured in pounds (or ounces etc.) per ton. In particular, uranium has been widely assessed in pounds per short ton, which is easily converted to percentages: 1 percent = 20 lb per short ton
1 lb per short ton = 0.05 percent.
Some of the other units in common use, however, are not so easily convertible. Ores of gold (and silver) have usually been quoted in ounces (troy), pennyweights and grains per ton; one pennyweight per ton equals 1.53 grams per metric ton (or parts per million).

Alluvials gravels containing valuable detrital minerals such as gold or tin are measured generally in units of weight - pennyweights (troy weight) or grains for precious metals, pounds or ounces (avoirdupois), for example tin, per cubic yard, which is 0.765 of a cubic metre. Coal is normally assessed on its calorific value in BTU per lb, which is numerically 1.8 times calories per gram.

The situation with regard to petroleum units is even more confusing because both liquids and gases are involved and the commonest unit of everyday measurement of liquids, the gallon, is different in the US and imperial terminologies. However, the unit of measurement most used in estimating reserves is the US barrel, which is 35 imperial or 42 US gallons. There are 6.29 US barrels to a cubic metre and 7 to 7.6 US barrels to a metric ton of crude petroleum, depending of course on the gravity of the petroleum.

Gas in the British system is measured in cubic feet, of which there are 35.3 to the cubic metre.

Table 3 lists a number of equivalents in metric and imperial systems that are used in measurements of ores and petroleum.

Table 3

Metric equivalents of some units used in resources measurements.

Conversion factors

To convert	into	multiply by	reciprocal
Long tons (2240 lb)	metric tons	1.016	0.9842
Short tons (2000 lb)	" "	0.907	1.1023
Pounds (lb) (Avoirdupois)	grams	453.6	0.0022
lb per long ton	gm per metric ton	446.4	0.00224
lb per short ton	" " " "	500	0.002
Ounces (oz) (Avoirdupois)	grams	28.350	0.0353
Ounces (oz) (Troy) (20 dwt)	grams	31.103	0.0322
Ounces (Troy) per long ton	gm per metric ton	30.612	0.0327
Ounces (Troy) per short ton	" " " "	34.285	0.0292
Pennyweight (dwt) per long ton	" " " "	1.5306	0.6533
Cubic yards (27 cub. feet)	cubic metres	0.7646	1.308
Cubic feet	cubic metres	0.0283	35.3147
lb per cubic yard	kg per cubic metre	0.593	1.6863
Oz (Avoirdupois) per cubic yard	kg " " "	0.0296	33.7838
Grains per cubic yard	grams per cubic metre	0.085	11.7647
Barrels (42 US, 35 imp. gallons)	cubic metres	0.159	6.29
Barrels (32.5 API gravity oil)	Metric tons	0.137	7.3
BTU per lb	calories per gram	0.5556	1.8

Petroleum reserves

The measurement of petroleum reserves, while following the same general principles as those of mineral ores, poses a number of different problems. Petroleum is liquid or gaseous, ores are solid, petroleum is mobile, ore static, ores are extracted directly, petroleum remotely. Mineral ore reserves are generally quoted as ore in situ; due allowance has to be made for mining dilution on one hand, and ore remaining in pillars or otherwise unextractable. For coal this is commonly of the order of 50 per cent, for metallic ores usually less than 20 per cent. Petroleum reserves on the other hand are generally quoted as "recoverable", taking into account such parameters as are known about reservoir conditions and likely recovery rate. This is commonly between 20 and 50 percent of estimated oil in place, but under exceptional reservoir conditions may be boosted by secondary recovery methods to as high as 70 percent or even more. Gas recoveries are normally higher than for oil and usually fall in the 60-90 percent range.

Generally the terms proved, probable and possible are in wide use, although the American Petroleum Institute has avoided the use of "probable" and "possible" in its recommended reserve terminology and has preferred the use of 'proved developed', 'proved undeveloped', and 'indicated additional'.

A comparison of three methods of hydrocarbon reserve classification is set out in Table 4 (Magee Pers. comm.). The cross-hatched areas in the table indicate possible areas of deficiency in each method of classification. These definitions are used and accepted widely in the petroleum industry by major oil companies, governmental agencies and authorities, and financial interests, and there is general understanding and concurrence with respect to their application and interpretation.

In the Soviet Union, the classification used for reserves of petroleum (ECAFE, 1965) is based on the general classification introduced in 1933 for all types of minerals; this classification, as in the case of the "proved-probable-possible" type generally used elsewhere, is based on a descending degree of availability and reliability of data upon which the estimates of reserves can be made. Definitions of these categories (Alexin, 1964) are as follows :

"Category A - Reserves computed for each area delineated by wells providing industrial flows of oil or gas. Detailed studies made of: conditions of the deposit, nature of changes in reservoir properties, oil or gas saturation, chemical composition and layout of the deposits, productivity of wells, pressure, temperature and other data necessary for computing the reserves and deciding on the conditions for rational exploitation.

TABLE 4

COMPARISON OF HYDROCARBON RESERVES CLASSIFICATIONS

UNCERTAINTY OR RISK		API*	BMR	WAPET
DEGREE	REASON FOR UNCERTAINTY			
SMALL		PROVED DEVELOPED. Drilled and defined by gas/oil or oil/water contacts if any and economically recoverable through existing wells.	PROVED* reserves are the quantities of crude oil (and/or gas) which the geological and engineering data demonstrate with reasonable certainty to be recoverable in the future from known reservoirs under existing economic conditions. They represent strictly technical judgments, neither conservative nor optimistic.	PROVED. Recoverable from reserves with reasonable certainty considering subsurface control, producing mechanisms and existing economic conditions.
SMALL	Economic doubt as to feasibility of drilling additonal wells for enhanced recovery or of establishing suitable market outlets etc.	PROVED UNDEVELOPED. Adjoin drilled areas of proved reserves and are considered proved by analysis of current well information.		POTENTIAL I. As for PROVEN except that these reserves cannot be produced under existing economic conditions. Normally associated with potential reserves too small to justify a market outlet.
FAIR	Insufficient production testing or evaluation of an improved recovery technique such as fluid injection.	INDICATED ADDITIONAL. Reserves potentially available from improved recovery techniques such as fluid injection where application of the technique remains unproven.		POTENTIAL II. As for PROVEN but these reserves have not been proved by sufficient production history. Often relates to assisted recovery operations or zones with limited production history.
FAIR	Lack of geological control. Note similarity to API "PROVED UNDEVELOPED" but implied uncertainty is greater.		PROBABLE. Susceptible of being proved and are defined by less direct well control but are based on evidence of producible hydrocarbons within limits of a structure or reservoir.	POTENTIAL III. Cannot be estimated with reasonable certainty due to lack of subsurface control. These reserves are estimated from available data with a high probability of major revisions occurring as additional data become available.
GREAT	Lack of geological control. Note that WAPET would not normally consider log evaluation alone sufficient to warrant a reserves allocation. Flow testing usually required to establish type of hydrocarbon & producibility.		POSSIBLE. Less well-defined by structural control; Based largely on electrical log and widespread evidence of hydrocarbon saturation. Includes extensions of PROVED or PROBABLE areas where so indicated by geophysical or geological studies.	

* API, 1965

"Category B - Reserves on a field, the industrial oil or gas productivity of which is proved by the presence on it of wells with favourable results from well logging and coring, and with the field yielding an industrial flow of oil or gas from not less than two wells revealing a productive deposit at various hypsometric points. Approximate studies made of the deposit conditions, properties, oil and gas saturation and other parameters."

Category A would clearly correspond to "proved" reserves and category B partly to "proved" and partly to "probable" reserves, depending on the amount of data available, and the varying limits applied to "probable" reserves.

"Category C_1 - Reserves of oil fields for which the conditions of the oil or gas deposits have been ascertained from data on geological-exploratory or geophysical operations, properties of productive horizons and where computing parameters have been established for individual wells or obtained by analogy with adjacent prospected fields. The field must have one well producing an industrial flow of oil or gas.

"Category C_2 - Reserves of new structures in oil or gas producing regions, from strata whose productivity has been established on other fields and also reserves of oil or gas from deeply bedded strata, inside fields already known, which are presumed to be oil or gas producing on the basis of general geological data."

Category C_1 clearly corresponds to "probable" reserves as used elsewhere (see Table 4), while Category C_2 would correspond to "probable" reserves according to some definitions, and more generally to "possible" reserves. Recently, an additional category D, with two groups D_1 and D_2, has been introduced (Avrov, et al, 1965) to include broad evaluation of additional potential in sedimentary basins as yet incompletely studied; category D ("prognostic reserves") would include some "possible" or "inferred" reserves, but would generally correspond to "resources", used on a regional scale.

Category D_1 includes oil and gas contained in sedimentary basins within areas both proved and prospective which need to be regionally explored to enable a judgment to be made about the distribution of reservoirs and impervious beds in the geological section and of formations suitable for oil and gas generation and accumulation.

Category D_2 includes oil and gas contained in sedimentary basins within areas from which little geological information has been obtained and which are known only by small-scale studies; also included in this category is possible petroleum in sections below depths penetrated by deep drilling.

Calculations of reserves of oil (and gas) in any given structure depend upon 1) general knowledge of the geology of the area, 2) geophysical, mainly seismic, surveys, and 3) information obtained by drilling. In the earlier stages of exploration, perforations will be relatively few. Calculations have to take into account: the size and shape of the reservoir, existence of faults, etc., determined largely from interpretation of seismic surveys; thickness, porosity and permeability of producing beds and variations in these parameters; water saturation; gas dissolved in oil; and the positions of oil-water and gas-oil contacts, determined by drilling; and allowance made for petroleum that is not recoverable. Initial estimates generally do not take into account possible secondary recovery methods which may increase recoverable reserves by up to 50 percent or in exceptional cases up to 100 percent. As more wells are put down, and possibly more detailed seismic work carried out or more sophisticated interpretation techniques applied, estimates of reserves become more accurate and tend to pass from the "probable" to the "proved" category.

Production data provide an even better basis for more accurate estimation of reserves. Early estimates tend to be conservative, and further work indicates additional reserves as illustrated by the following table for American oil fields, from Lovejoy and Homan (1965).

Table 5

Comparison of present estimates of discoveries with initial American Petroleum Institute estimates for new fields and new pools.

Fields discovered during period	Initial API estimate of discoveries millions of barrels	Present (1964) estimate millions of barrels	Ratio present to initial estimate
1939-1943	1600	9686	6.1
1944-1948	2017	9888	4.9
1949-1953	2933	9525	3.2
1954-1958	2261	5859	2.6

This table seems to indicate that the accuracy of methods of estimating reserves has increased over the years, but it probably reflects also the average size of the new fields discovered, and the state of knowledge about the geological conditions prevailing in these new fields.

Resource estimates

Referring to Figure 5, it is possible in most developed countries to obtain a reasonably accurate figure at any point in time for demonstrated ores, by simply summing the reported proved and probable reserves of known orebodies. Most mining operators also have a fair idea of the ultimate potential size of their deposit and from this a figure for inferred ores can be obtained. Figures for paramarginal and submarginal can be obtained in the same way from national inventories and reports of individual enterprises. As pointed out earlier, the dividing lines between these categories may move up and down according to the relative levels of commodity prices and costs of production at any given time.

It is the undiscovered resources that are so difficult to quantify, particularly because large areas that would be favourable for the occurrence of minerals of various kinds are covered by later sediments, surface alluvium, glacial drift, volcanic rocks, or lie offshore around the continental margins. The two principal approaches that have been made to this problem are 1) to make projections from past performances of discovery and production, and 2) to relate the possible existence of undiscovered deposits to the abundance of the elements in the earth's crust and in various geological environments. These methods are particularly applicable to large areas of the earth's crust, for example, United States, Canada, Australia, China, particularly where the geology is well enough known to apply suitable corrections according to the area that is exposed of rocks suitable for the occurrence of particular types of deposits.

A statistical approach of this type has been presented by De Geoffroy and Wu with respect to areas of the Canadian Shield. In one such study (1970) they analyse the metal content as shown by past production, proved and projected reserves of a 'control' area, highly productive and well-known, of 130,000 sq. km. of the greenstone belt of the Canadian Shield, and used this to calculate the mineral potential of the remainder of the greenstone belts, a total of 743,000 sq. km. The result obtained was 1478 ore deposits worth 84,683 million dollars, on the basis of 1968 metal prices. However, this was reduced to what the authors considered a more realistic estimate by dividing the area into four zones based largely on the estimated costs of working due to difficulty of access, etc. This reduced estimate was 493 orebodies worth 53,047 million dollars on the same basis, or a resource potential of approximately $70,000 per square kilometre. In this study, as in many others of mineral deposits and of petroleum fields, the size distribution has been found to be log normal, which means that out of a large number of deposits a few contain most of the ore; similarly most of the world's petroleum is found in the 'giant' fields.

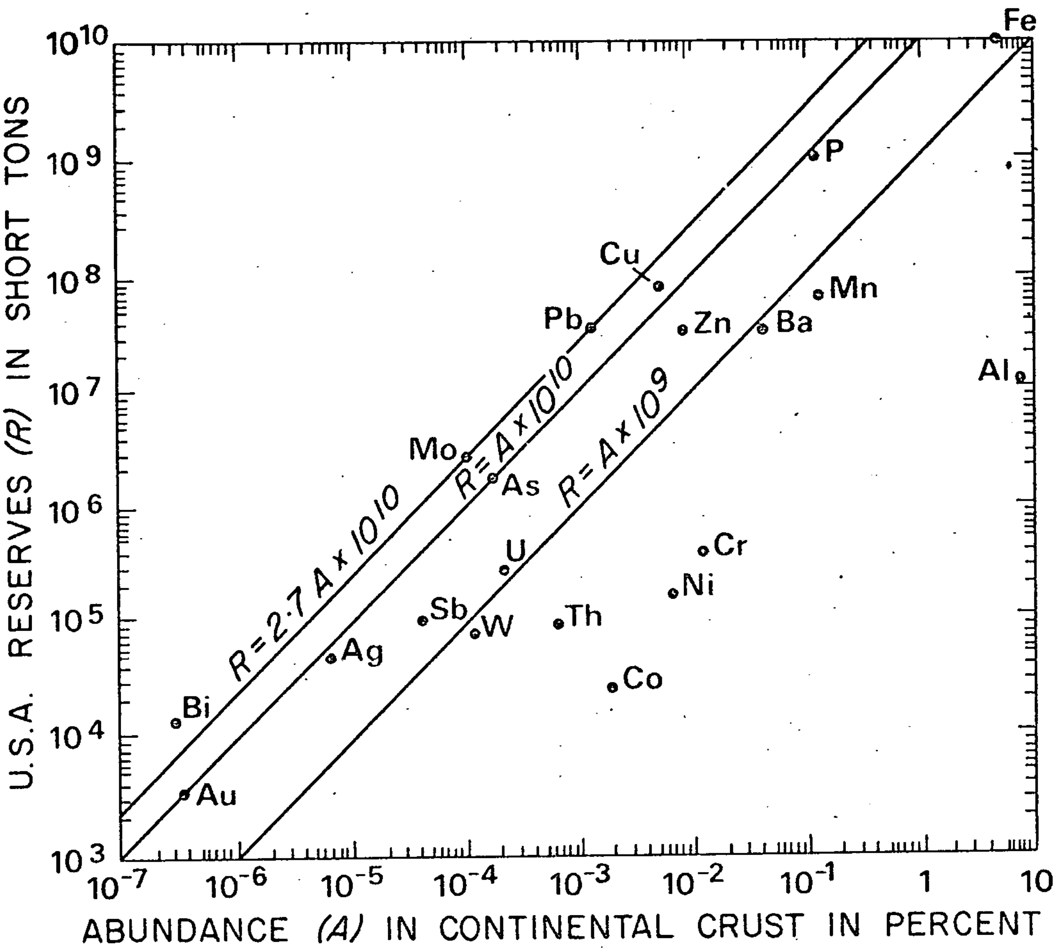


FIGURE 6 U.S.A. reserves of elements compared to their abundance in the earth's crust. Modified from McKelvey (1960)

TABLE 6.—*Abundance, mass, reserves, and resources of some metals in the earth's crust and in the United States crust*

[Abundance in grams/metric ton (g/mt); mass and reserves in metric tons (mt) Calculations = mass (metric tons) × abundance (decimalized) = total content of element]

Element	Total earth's crust				Oceanic crust		Continental crust		Continental crust segments: Shield areas		Continental crust segments—Con.: Folded belts		United States crust		United States crust to 1-km depth	United States: Reserve [1]	United States: Recoverable resource potential [2]	United States: Ratio of potential to reserve	World: Reserve [3]	World: Recoverable resource potential [4]	World: Ratio of potential to reserve	Grade [5]
	Goldschmidt [6] (g/mt)	Vinogradov [7] (g/mt)	Lee and Yao [8] (g/mt)	Mt×10[12]	[8] G/mt	Mt×10[12]	[8] G/mt	Mt×10[12]	[8] G/mt	Mt×10[12]	[8]G/mt	Mt×10[12]	[8]G/mt	Mt×10[12]	Mt×10[9]	Mt×10[6]	Mt×10[6]		Mt×10[6]	Mt×10[6]		
Antimony	1	0.5	0 62	14.9	0.91	8.1	0.45	6.8	0.46	4.9	0.43	1.9	0.45	0.41	11.2	0.10	1.1	11	3.6	19	5	Unknown.
Beryllium	6	3.8	1.3	31.2	.83	7.4	1.5	23.8	1.5	16.7	1.6	7.1	1.5	1.4	38	.073	3.7	50	.016	64	4,000	
Bismuth	.2	.009	.0043	.1	.0066	.059	.0029	.041	.003	.029	.0025	.012	.0029	.0025	.07	.013	.007	.5	.081	.12	1.5	
Cobalt	40	18	25.	600	37	330	18	270	19	190	16	80	18	16	440	.025	44	1,760	2.14	763	360	
Copper	70	47	63	1,510	85	760	50	760	52	550	46	210	50	45	1,230	77.8	122	1.6	200	2,120	10	0.86 percent.
Gold	.001	.0043	.0035	.084	.0035	.032	.0035	.052	.0034	.035	.0038	.017	.0035	.003	.085	.002	.0086	4.1	.011	.15	14	
Lead	16	16	12	290	10	90	13	200	13	.140	13	60	13	12	330	31.8	31.8	1	.54	550	1,000	3 percent.
Lithium	65	32	21	500	20	180	22	320	21	220	23	100	22	20	550	4.7	54	12	.78	933	1,200	
Mercury	.5	.083	.089	2.1	.11	.9	.08	1.2	.078	.81	.086	.39	.08	.072	2.0	.013–.028	.20	15–6.8	.11	3.4	30	
Molybdenum	2.3	1.1	1.3	31.2	1.5	14.6	1.1	16.6	1.1	11.6	1	5	1.1	1	27	2.83	2.7	1	2	46.6	23	Unknown.
Nickel	100	58	89	2.130	140	1,200	61	920	64	.680	53	.240	61	55	1,500	.18	149	830	68	2,590	38	1.5 percent.
Niobium	20	21	19	460	18	160	20	300	20	210	19	90	20	20	550	Unknown	49	Unknown	Unknown	848	Unknown	
Platinum	.005	--------	.046	1.1	.075	.67	.028	.43	.031	.30	.022	.13	.028	.026	.71	.00012	.07	560	.009	1.2	133	
Selenium	.09	.05	.075	1.8	.1	.89	.059	.91	.054	.64	.071	.27	.059	.055	1.5	.025	.14	6	.695	2.5	36	
Silver	.02	.07	.075	1.8	.091	.82	.065	.98	.067	.70	.062	.28	.065	.059	1.6	.05	.16	3.2	.16	2.75	18	
Tantalum	2.1	2.5	1.6	38.4	.43	3.8	2.3	34.7	2.3	24.3	2.4	10.4	23	2.1	57.5	.0015	5.6	4,000	.274	97	354	
Tellurium	.0018	.001	.00055	.013	.00088	.0078	.00036	.005	.00038	.0036	.00031	.0016	.00036	.00031	.0085	.0077	.0009	.11	.054	.015	.3	
Thorium	11.5	13	5.8	140	4.2	37	6.8	.100	6.6	68	7.1	32	6.8	6	.160	.54	16.7	31	1	288	288	Unknown.
Tin	40	2.5	1.7	40.8	1.9	16.8	1.6	24	1.5	16.3	1.7	7.7	1.6	1.4	38	------	3.9	[9] ?	5.8	68	12	0.6 percent.
Tungsten	1	1.3	1.1	26.4	.94	8.3	1.2	18.1	1.2	12.7	1.2	5.4	1.2	1.1	30	.079	2.9	37	1.2	51	42	
Uranium	4	2.5	1.7	40.8	1	7.8	2.2	33	2.1	22.6	2.3	10.4	2.2	2	55	.27	5.4	20	.83	93	112	
Zinc	80	83	94	2,250	120	1.030	81	1,220	83	870	77	350	81	73	2,000	31.6	198	6.3	81	3,400	42	4 percent.
	G/mt	G/mt	G/mt	Mt×10[15]	G/mt	Mt×10[15]	G/mt	Mt×10[15]	G/mt	Mt×10[15]	G/mt	Mt×10[15]	G/mt	Mt×10[15]	Mt×10[12]	Mt×10[6]	Mt×10[6]	Ratio of potential to reserve	Mt×10[6]	Mt×10[9]	Ratio of potential to reserve	
Aluminum	81,300	80,500	83,000	1,990	84,000	747	83,000	1,242	84,000	869	82,000	373	83,000	74.5	2,000	8.1	203,000	24,000	1,160	3,519	3,000	
Barium	430	650	390	9.4	370	3.3	400	6.1	400	4.3	390	1.8	400	.37	10	30.6	980	32	76.4	17	223	
Chromium	200	83	110	2.6	160	1.4	77	1.2	81	.84	68	.36	77	.070	1.92	1.8	189	387	696	3.26	47	
Fluorine	800	660	450	10.8	420	3.74	470	7.1	470	5	480	2.1	470	4.30	11.8	4.9	1,151	235	35	20	600	
Iron	50,000	46,500	58,000	1,392	75,000	667	48,000	725	49,000	508	4,000	217	48,000	43.5	1,200	1,800	118,000	65	87,000	2,035	23	
Manganese	1,000	1,100	1,300	31.2	1,800	16	1,000	15.2	1,100	10.6	930	4.6	1,000	.9	24.9	1	2,450	2,450	630	42	67	
Phosphorus	1,200	930	1,200	28.8	1,400	12.5	1,200	16.3	1,200	11.4	1,100	4.9	1,200	.98	26.8	931	2,940	3	15,000	51	34	
Titanium	4,400	4,500	6,400	153.6	8,100	72.1	5,300	81.5	5,500	57.1	5,000	24.4	5,300	4.9	1.30	25	13,000	516	117	225	2,000	
Vanadium	150	91	140	3.36	170	1.51	120	1.85	120	1.3	110	.55	120	.11	3	.115	294	2,560	10	5.1	500	

[1] U.S. Bureau Mines (1970); 1 short ton =0.91 mt.
[2] Recoverable resource potential = 2.45 $A \times 10^6$ (abundance A expressed in g/mt).
[3] U.S. Bureau Mines (1970); 1 short ton =0.91 mt; does not include United States reserve.
[4] Recoverable resource potential =2.45 $A \times 17.3 \times 10^6$ (abundance A expressed in g/mt; land area of world is 17.3 times United States land area).
[5] U.S. Bureau Mines (1970); data on world basis.
[6] Goldschmidt (1954, p. 74-75).
[7] Vinogradov (1962, p. 649-650).
[8] Lee and Yao (1970, p. 778-786). All calculations are based on this work.
[9] Very high.

Calculation of mass of crustal segments

Total earth's crust	24×10^{18} mt.
Oceanic crust	8.9×10^{18} mt (37 percent of total crust).
Continental crust	15.1×10^{18} mt (63 percent of total crust).
Shield areas	10.6×10^{18} mt (30 percent of continental crust or 43.8 percent of total crust).
Folded belts	4.54×10^{18} mt (30 percent of continental crust or 19.1 percent of total crust).
United States crust	0.90×10^{18} mt (based upon United States as 1/17 of land area of world's continental crust).
United States crust to 1-km depth	24.6×10^{15} mt (based upon average thickness continental crust =36.5 km; therefore 1 km is 2.74 percent of United States crust).

McKelvey (1972) and Erickson (1972) present methods of calculating potential resources of any mineral for the United States, based on crustal abundances of the elements. One simple method is based on the assumption that the potential recoverable resource should approach 0.01 per cent of total amount of each element in the earth's crust down to 1 km depth. Data on which such calculations are based are presented in Table 6, compiled by Erickson.

Another method is based on McKelvey's observation that the tonnage of mineable reserves of the well-explored elements in the United States is roughly equal to their crustal abundance in percent times one or ten billion (Fig. 6). Erickson took lead in the US, which is well measured, as a yardstick and derived the formula Reserves equal 2.45×10^6 as a measure of estimating currently recoverable resources. This was based on crustal abundance of lead of 0.0013 percent and calculated US reserves of lead of 31.8×10^6 metric tons, but account should also be taken of 32×10^6 tons of lead that has already been mined, indicating that the index should be doubled.

Table 7 from Erickson, showing the ratio of potential resources to known reserves for the United States (based on his formula for lead of $R = 2.45 \times 10^6$ metric tons) and for the world, illustrates the fact that many land areas of the world have not been so intensely explored as the United States and therefore the potential for discovering additional resources is higher.

Table 7

Ratio of potential resources to known reserves

United States		World	
Pb	1	Sb	5
Mo	1	Cu	10
Cu	1.6	Pb	10
Ag	3.2	Sn	12
Au	4.1	Au	14
Zn	6.3	Ag	18
Sb	11	Mo	23
Hg	15	Hg	30
U	20	Ni	38
Th	31	Zn	42
W	37	W	42
Ni	830	U	112
Sn	Very high	Th	288

PROVED RESERVES OF CRUDE OIL IN THE UNITED STATES, 1945-1972

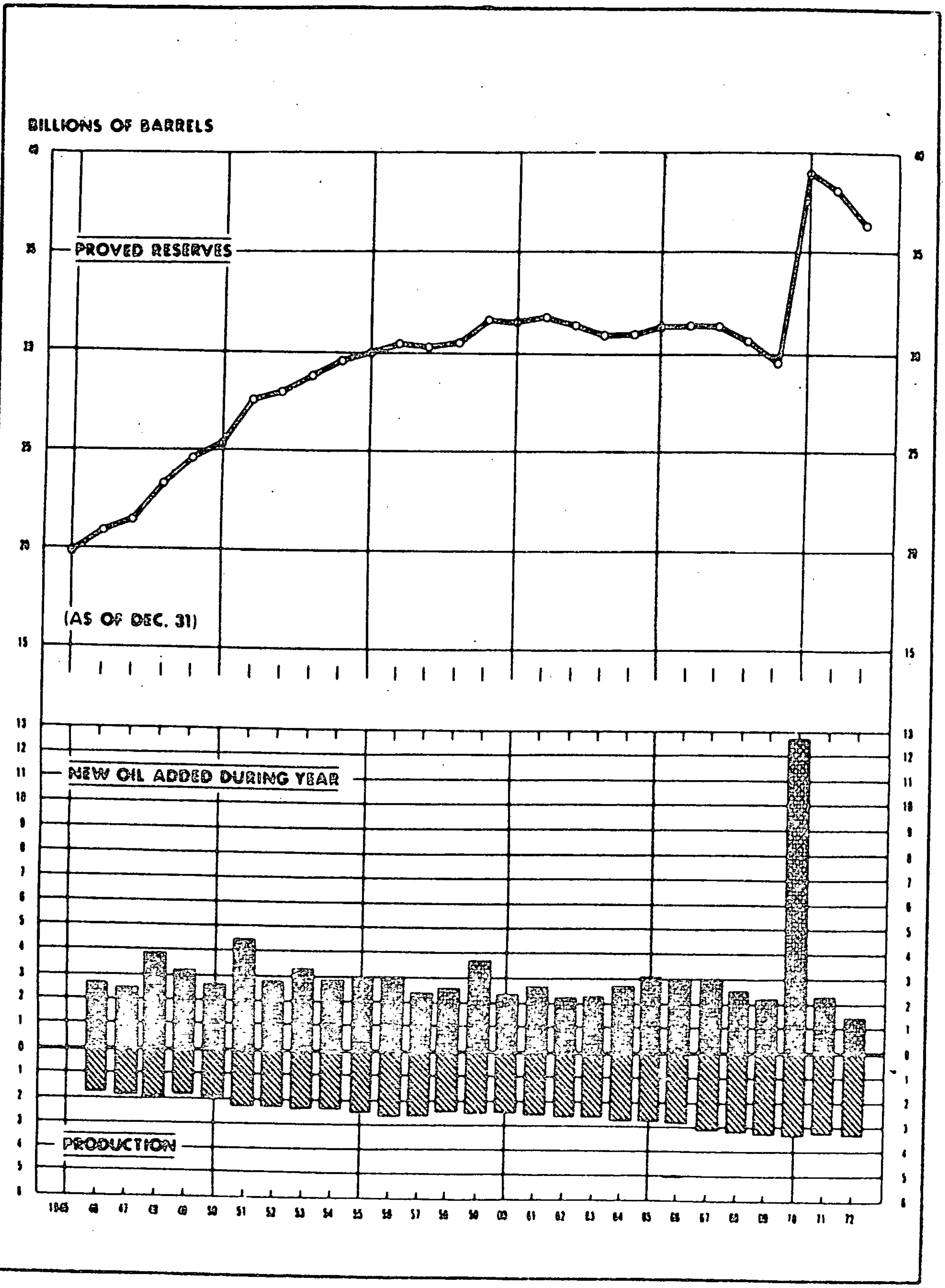


FIGURE 7 RESERVES AND PRODUCTION OF CRUDE OIL IN THE UNITED STATES (THE ENERGY INDEX P. 20).

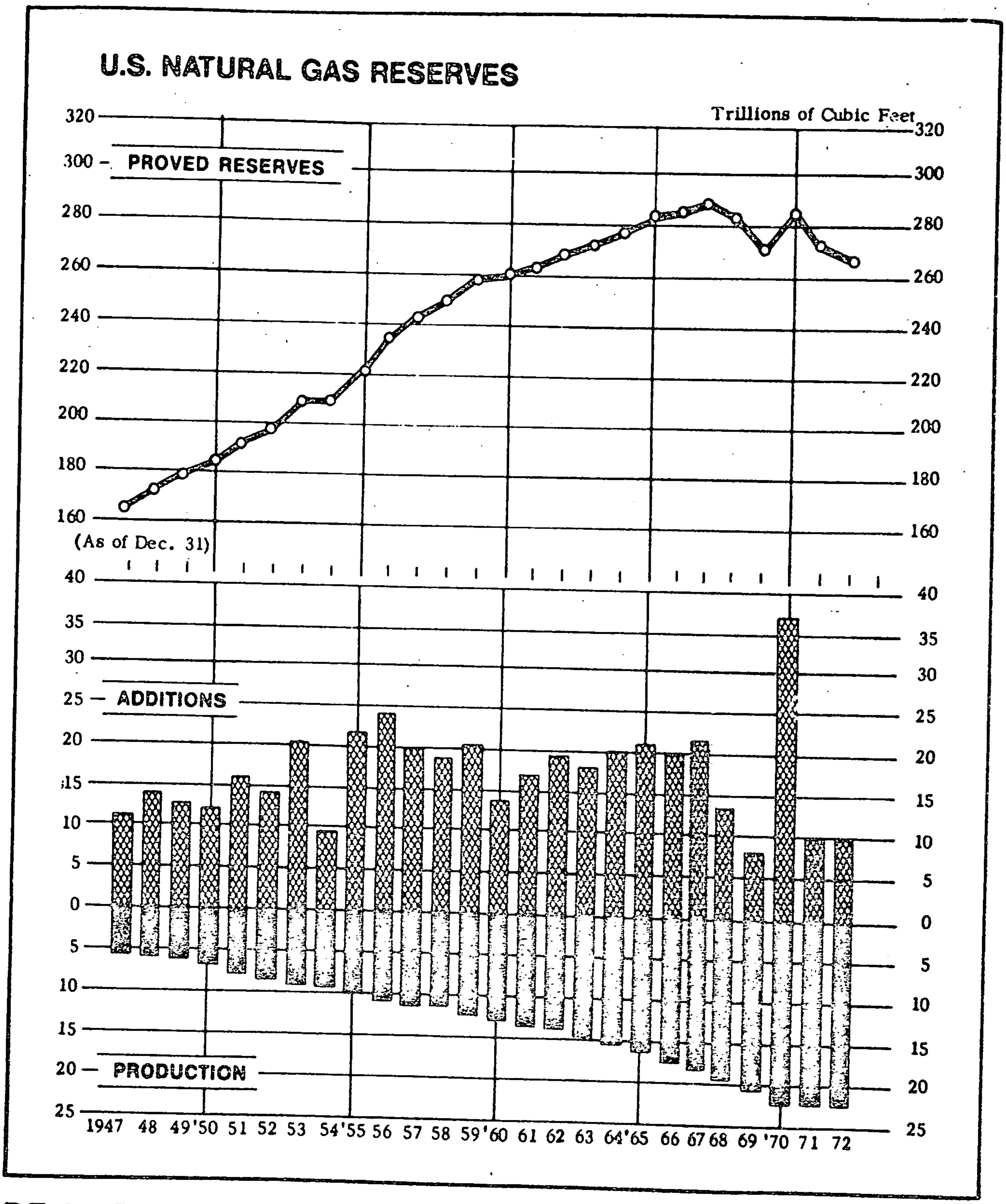


FIGURE 8 RESERVES AND PRODUCTION OF NATURAL GAS IN THE UNITED STATES (THE ENERGY INDEX P. 30).

Petroleum resources

Calculations of potential petroleum resources are fraught with less uncertainties than minerals and are likely to be more accurate. Many projections have been made based on the growth of production, increases in reserves, and discovery per unit of exploration effort. Figures 7 and 8 illustrate such an approach for United States (note the jump in discoveries and reserves in 1970 due to the Alaskan oil finds).

The other principal approach to the estimation of petroleum potential is to measure either the volume or the area of sediments in sedimentary basins, derive a formula for the amount of oil per unit volume or per unit area, making allowances for the distribution of different lithologies in the sedimentary section and its geological history, and calculate from this the potential oil resources. Gas is commonly estimated as a ratio of gas to oil, averaged over a sufficiently large area.

Lewis G. Weeks has been one of the most prominent writers in this field. He uses methods based on areas of basins, the percentage which it is estimated will prove oil-bearing, the estimated yield per acre, or barrels of oil per cubic mile or cubic kilometre of total sediments or of effective reservoir beds, combined with worldwide studies of and experience with all classes and conditions of sedimentary basins.

To make an estimate of world offshore petroleum resources (Weeks, 1965), he divides offshore areas into -

Class A - contains or is in continuity with, an excellent producing area and has like geology.

Class B - contains or is in continuity with a fair producing area, or has geology similarly favourable.

Class C - prospects are submarginal or not commercially attractive on the basis of present information but some can not be ruled out of a higher classification.

Class D - no prospects.

For Class A, he allows a recoverable oil content of 35,000 barrels per acre for 4 percent of the area - 481,000 square km - and for Class B, 20,000 barrels per acre for $2\frac{1}{2}$ percent of the area - 4,242,000 square km, giving a total of approximately 700,000,000 barrels.

Similar calculations for onshore petroleum resources have given estimates generally of the order of 2×10^{12} barrels of oil and 7×10^{15} cub. ft of gas.

The Australian position

With respect to minerals, Australia has not yet been sufficiently explored for any reasonable calculations of mineral potential to be based on the knowledge of reserves of any given area. Approximately 55.5 percent of Australia's 7,687,000 sq km is hidden under Mesozoic or other sedimentary cover that is non-prospective for metallic ores. The area of the Archaean Shield is about 750,000 sq km and prospectivity of this may be assumed to be somewhat similar to that of areas of like geology in the Canadian Shield, referred to earlier.

The only real estimates that it has been practicable to make so far are those obtained by a summation of demonstrated reserves, obtained mainly from companies' estimates, together with inferred ore, based on all available information. Coal and bauxite for instance are extrapolated over wide areas. Density of borings may range from several kilometres apart for reconnaissance assessment of total extent of area of deposits to boring on a close grid of as little as 10 metres in order to maintain close grade control in mining in order to meet contract specifications.

The Bureau of Mineral Resources has a continuing program of resource assessment designed in which first assessments of black coal, mineral sands and tin have been completed and in which assessments of copper, lead and zinc are under way. Assessments are designed to cover both reserves and resources, including experimental assessments of potential resources, and are linked with investigation of mining and treatment costs by which the potential of marginal resources can be better understood.

Available estimates for Australia are given in Table 8.

Table 8

Estimates of Australian resources of some minerals

Mineral or Metal	Reserves '000 metric tons	
Black Coal	200 000 000	Recoverable 100,000 metric tons ±; more than half coking coal.
Brown Coal	97 000 000	Mostly mineable by open cut.
Iron ore	30 000 000	Additional large low-grade deposits exist.
Bauxite	4 500 000	Limited extensions probable.
Nickel *	4 500	Mainly indicated by drilling good chances for extensions.
Lead *	27 000	(Mainly operating mines and (drilled orebodies;
Zinc *	37 000	(conservative resource estimates.
Copper *	6 000	Conservative resource estimate.
Manganese	200 000	Mainly in one area.
Zircon	11 300	(Associated in mineral sand deposits.
Rutile	8 000	(
Ilmenite	50 000	Mainly in mineral sand deposits.
Tin *	321	Recoverable tin metal.
Phosphate rock	2 700 000	Low grade 20 ±% P_2O_5

Crude Oil	369×10^6 cubic metres	(proved + probable reserves.
Natural gas liquids	220×10^6 cubic metres	(
Natural Gas	0.8×10^{12} cubic metres	(

* Expressed as contained metal in ore.

For geological reasons, very large additions to petroleum reserves are not expected to be made onshore on the Australian mainland. A speculative attempt (Konecki, 1972) at estimating Australia's potential reserves offshore resulted in a figure of 120×10^9 barrels of crude oil equivalent (including gas and natural gas liquids) on the continental shelf out to the 200 metre bathymetric line, and this might be increased to perhaps 200×10^9 barrels, by including the outer margin down to the edge of the continental rise.

However, for a variety of reasons, including great water depths, large distances from shore, hostile weather conditions, difficult and expensive drilling and production technology, these figures must be regarded as highly speculative, representing orders of magnitude rather than specific quantities, and would have to be drastically reduced when it came to exploitation. Only very large fields beyond the continental shelf could be considered for commercial development.

World Energy Crisis

Discussion of measurement of reserves and resources inevitably leads to a consideration of one of the world's most pressing current problems - the future sources of materials from which energy is derived. Table 9 presents an estimate of resources according to present knowledge, compiled from available published sources. The figures are reasonably conservative. They make some allowance for petroleum yet to be found, nothing for improved secondary recovery, which, as pointed out earlier, can increase resources substantially. Figures for uranium are very conservative (see Figure 3). Much more uranium would certainly be found if the price rose above \$15 US per lb, and such a price rise would not proportionately increase the cost of power from uranium (refer to Figure 9). Long before the price of the raw material became a prohibitive or even a major factor in the production of nuclear power, uranium would be extractable from sea-water.

The hydrocarbon reserves however are finite, especially those of oil and gas, although they are still increasing. Figures 7 and 8 indicate a downturn for the United States and that the peak of reserve growth has passed but even this is likely to be altered by the effects of increased exploration caused by the recent rise in petroleum prices. Figure 10 shows the annual production and the remaining reserves, both of which are increasing, and also the reserves to production ratio which is sharply declining.

TABLE 9

NON RENEWABLE ENERGY RESOURCES OF THE WORLD

(Sources: World Oil, World Petroleum, Petroleum Times, World Energy Conference 1974, International Petroleum Encyclopaedia, US Bureau of Mines World Summary of Oil Shale, International Atomic Energy Agency)

	World		Australia		
Energy Source	Reserves	Resources	Reserves	Resources	Thermal Energy Equivalents
rude Oil - bbl recoverable)	$691,120 \times 10^6$	$1,313,822^* \times 10^6$	$2,672 \times 10^6$	-	1 bl = 0.63×10^{10} Joules 1 tonne = 4.32×10^{10} 1 mil. tonnes= 4.32×10^{16}
atural Gas - cu.ft. recoverable)	$1,896 \times 10^{12}$	$4,914 \times 10^{12}$	29.0×10^{12}	-	1 cu.ft. = 1.05×10^6 Joules = 1000 BTU
lack Coal - tonnes 50% recoverable)	$1,996,657 \times 10^6$	$4,914,843 \times 10^6$	$23,000 \times 10^6$	$177,000 \times 10^6$	1 tonne = 2.9×10^{10} Joules 1 mil. tonnes= 2.9×10^{16}
rown Coal - tonnes 80% recoverable)	$268,962 \times 10^6$	$1,797,262 \times 10^{12}$	$55,000 \times 10^6$	$44,000 \times 10^6$	1 tonne = 0.8×10^{10} Joules
hale Oil (crude Oil ontent bbl)	$190,150 \times 10^6$	$5,320,000 \times 10^6$	150×10^6	$1,000 \times 10^6$	See crude oil
ranium - tonnes U_3O_8					
10 per lb	1,174,000	1,137,000	188,000		1 tonne Uranium =
10 - $15 per lb	929,000	826,000	126,000		2.0×10^{15} Joules

* Includes oil content of tar sands.

TABLE 10

PRIMARY ENERGY RESOURCES OF THE WORLD - IN 10^{21}[1] JOULES

FIGURES PRINCIPALLY 1973

	World		Australia	
	Reserves	Additional Resources	Reserves	Additional Resources
(1) Non-renewable				
Crude Oil	4.4	8.3	0.017	
Natural Gas	2.0	5.2	0.03	
Black Coal	29.0	71.3	0.33	2.56
Brown Coal	1.7	11.5	0.35	0.28
Shale Oil	1.2	33.5	0.0009	0.006
Total Fossil Fuels	38.3	129.8	0.73	2.85
Uranium (thermal fission)				
Recoverable at US$10 per lb	2.0	1.9	0.32	
Recoverable US$10-15 per lb	1.6	1.84	0.21	
Total non-renewable	41.9	133.1	1.26	2.85
Potential				
Uranium Fission (fast breeder)	102		16	
(2) Renewable - Potential				
Fusion				
Solar				

(1) 10^{21} Joules = 9.5×10^{12} therms - 9.5×10^{17} BUT = 2.8×10^{14} KWH - 22500 million tons oil = 34500 million tons coal

(2) Hydro-electric and geothermal sources omitted

(3) Solar energy reaching earth's surface is 2.34×10^{24} Joules or 6.5×10^{17} KWH.

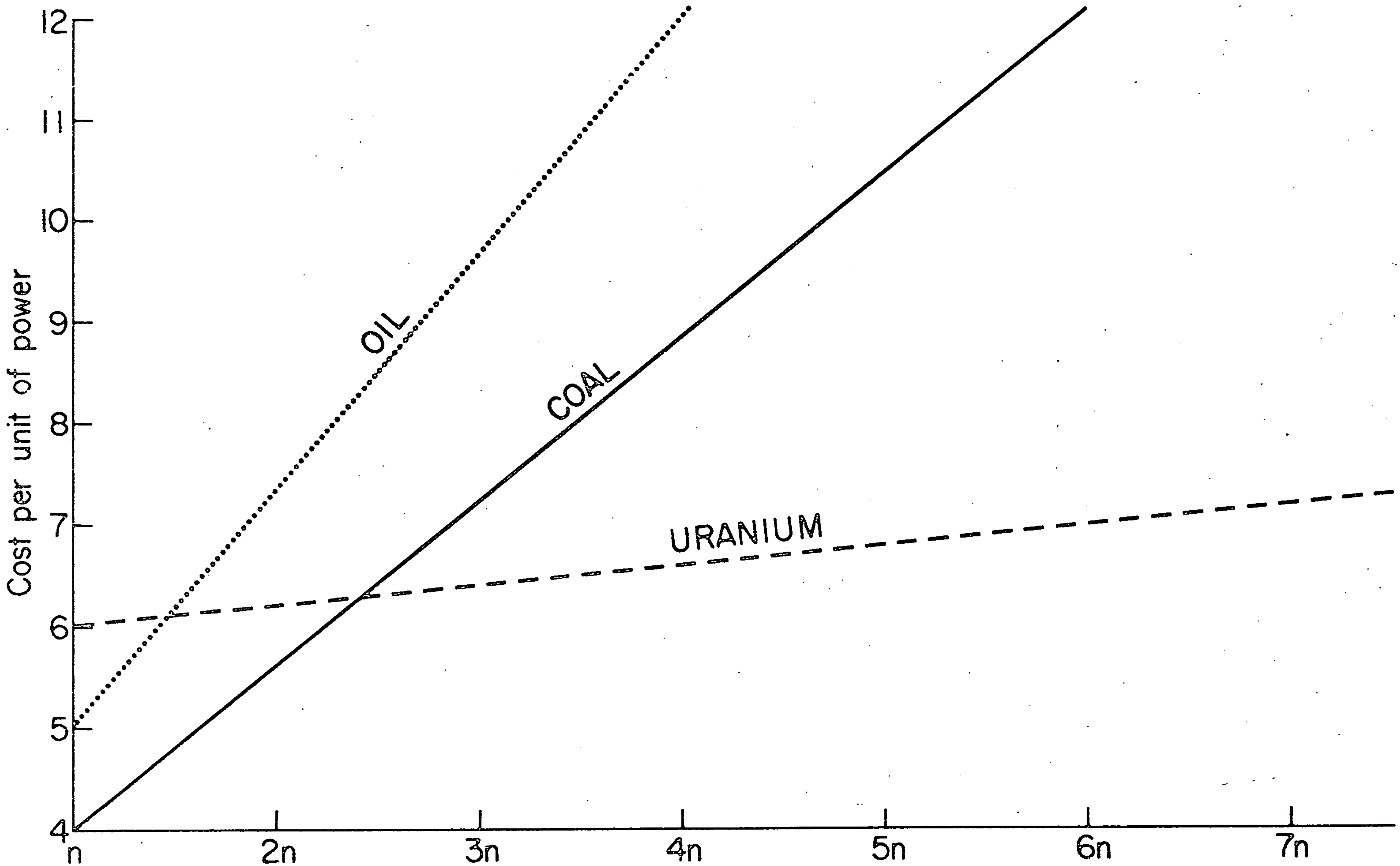


FIGURE 9 RELATIVE COSTS OF POWER PRODUCTION PER UNIT OF RAW MATERIAL

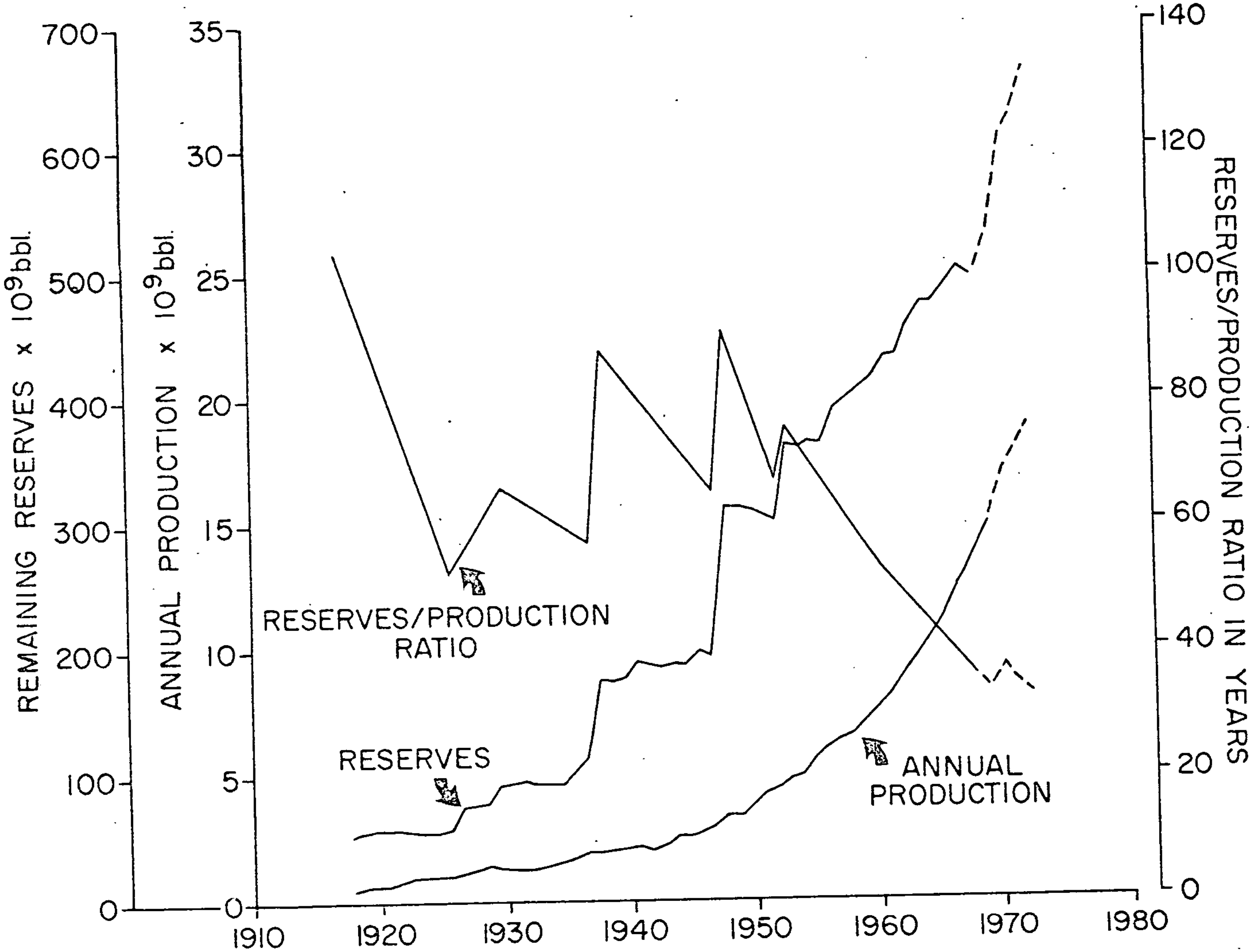


FIGURE 10 WORLD PRODUCTION, RESERVES AND RESERVES/PRODUCTION RATIO.
(AFTER WARMAN 1971)

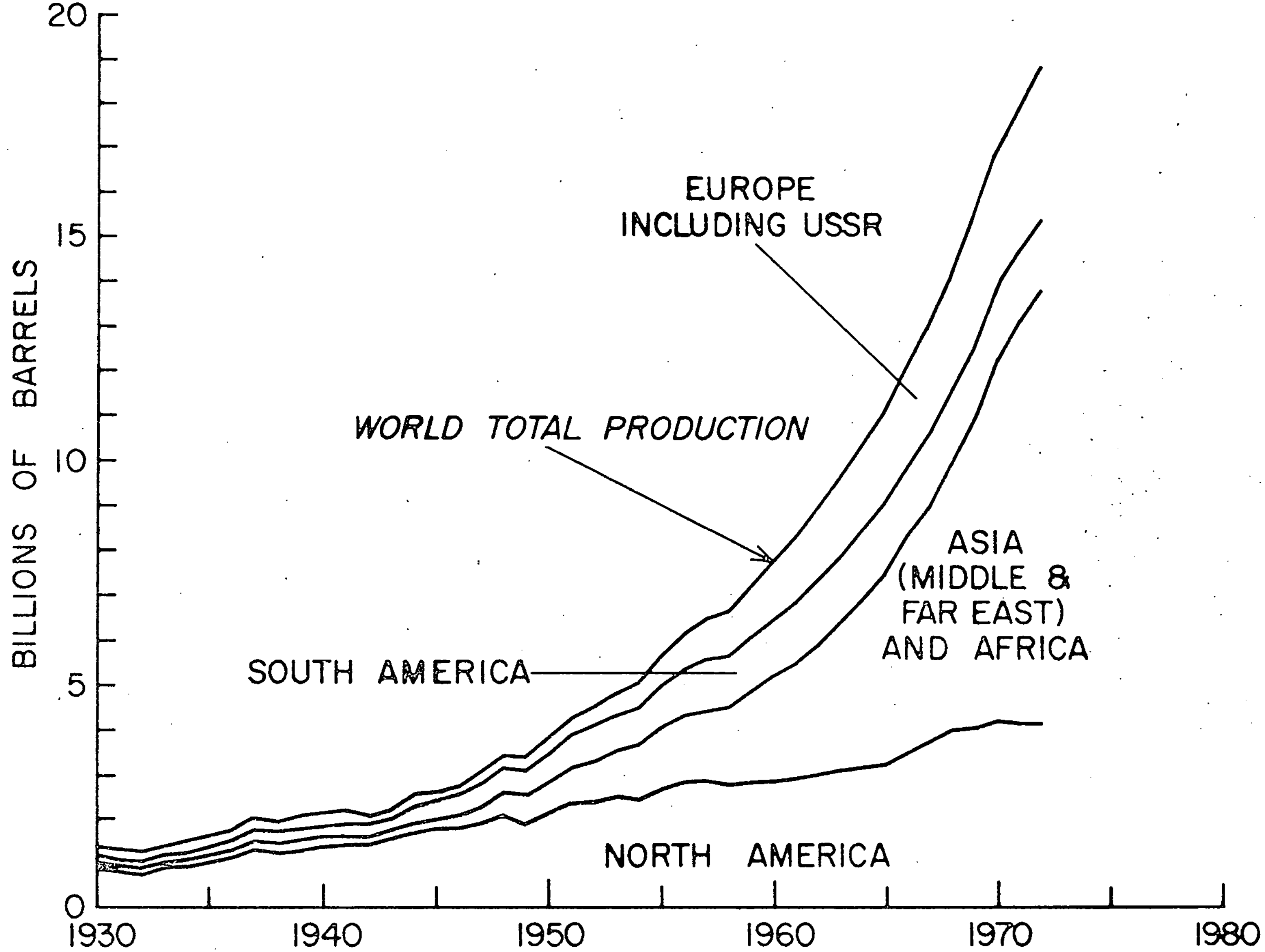


FIGURE 11 WORLD CRUDE OIL PRODUCTION (WORLD OIL IN FIGURES, 1974).

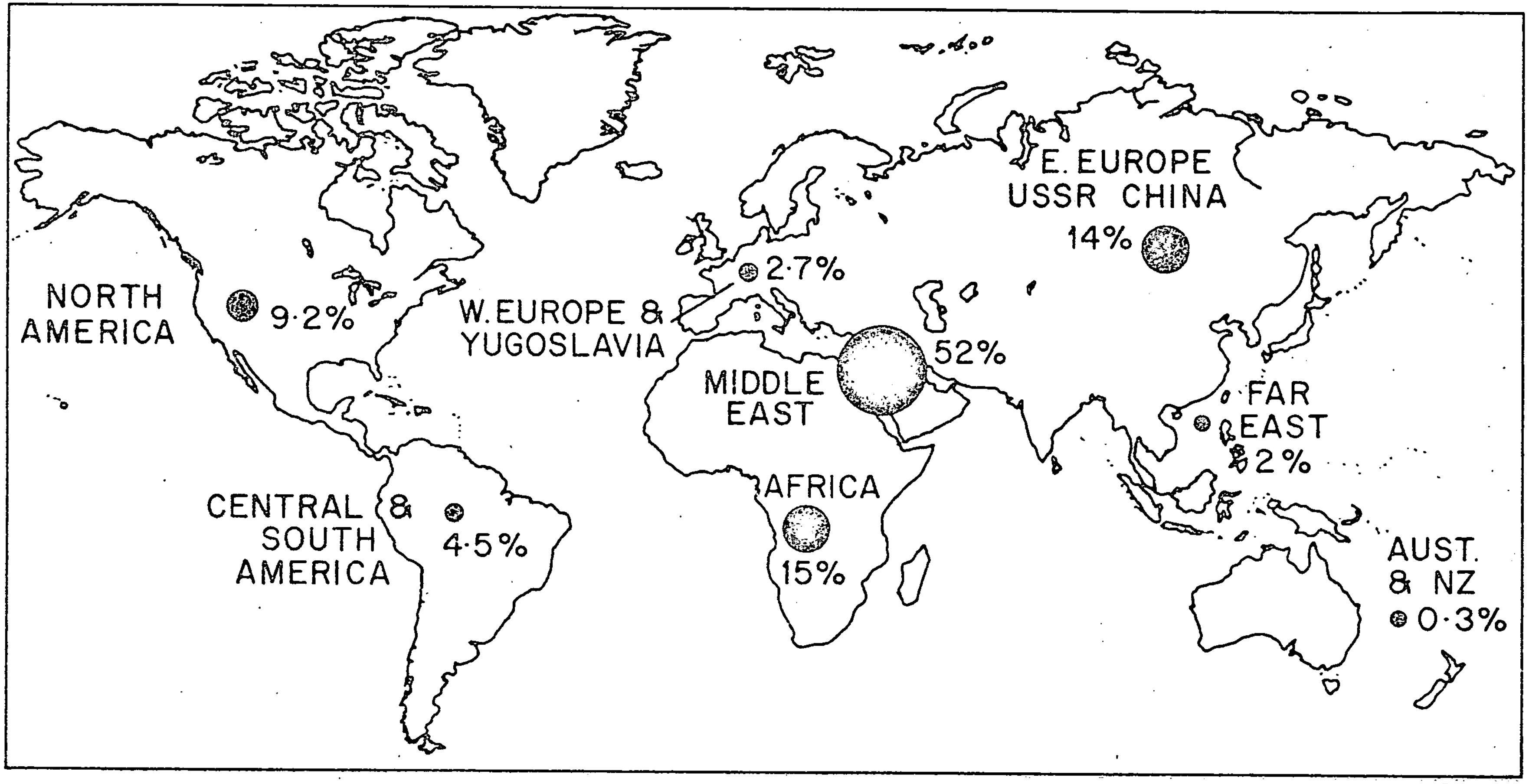


FIGURE 12 WORLD RESOURCES OF CRUDE OIL (INCLUDING OIL CONTENT OF TAR SANDS) - 2 MILLION MILLION BARRELS, RECOVERABLE.

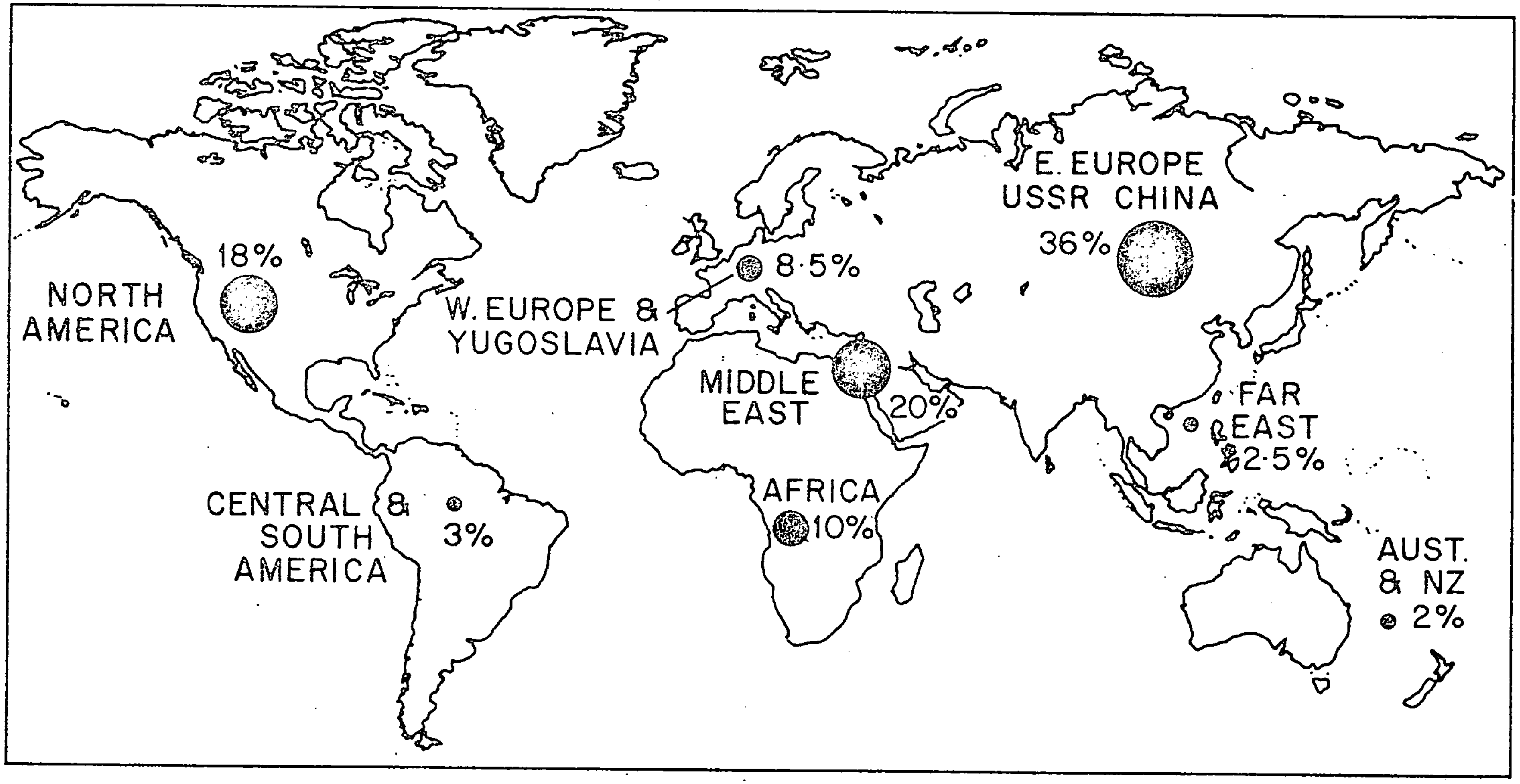


FIGURE 13 WORLD RESOURCES OF NATURAL GAS - 6·8 THOUSAND MILLION MILLION CUBIC FEET, RECOVERABLE.

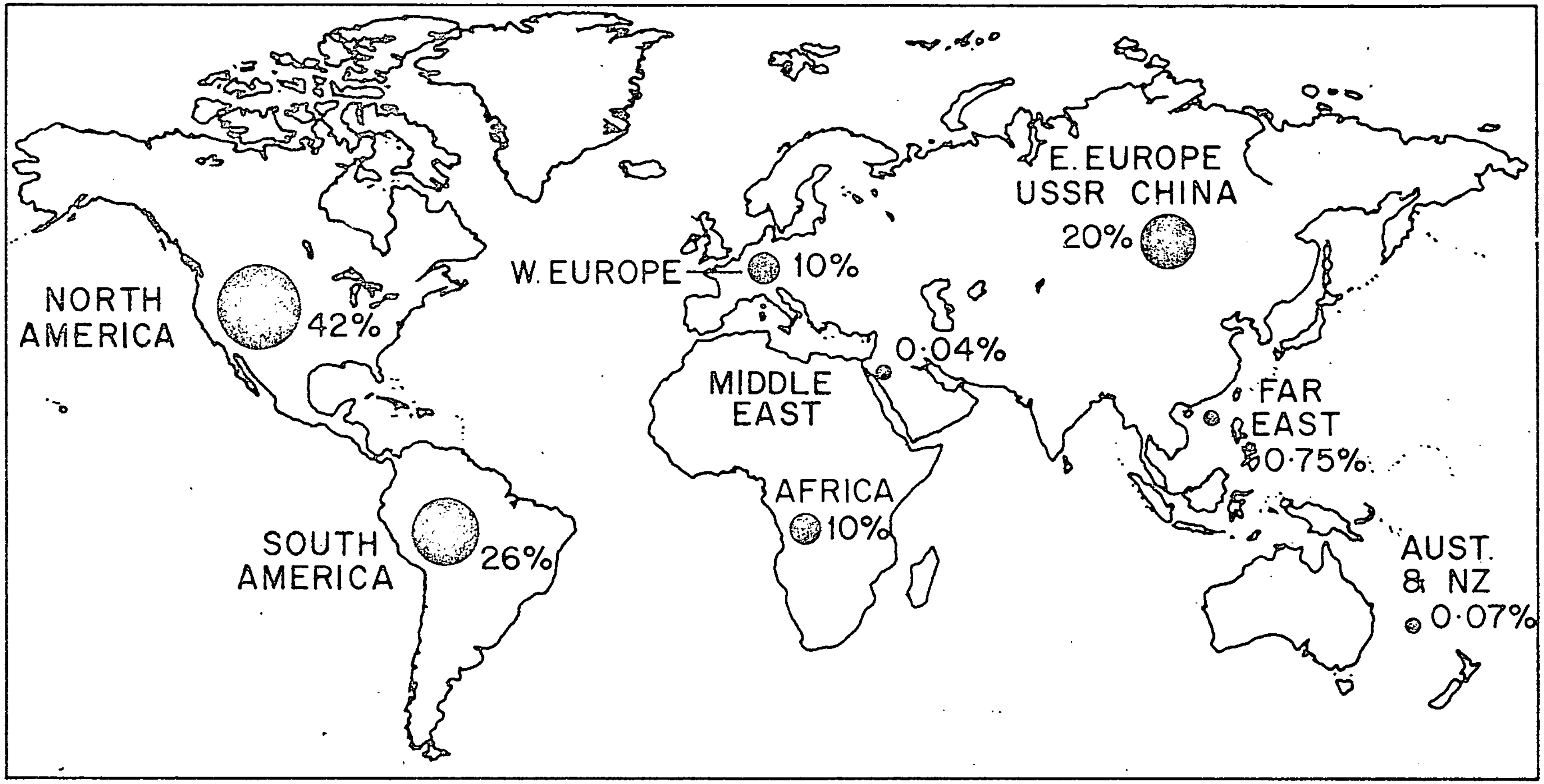


FIGURE 14 WORLD RESOURCES OF CRUDE OIL CONTENT OF OIL SHALE- 5·5 MILLION MILLION BARRELS.

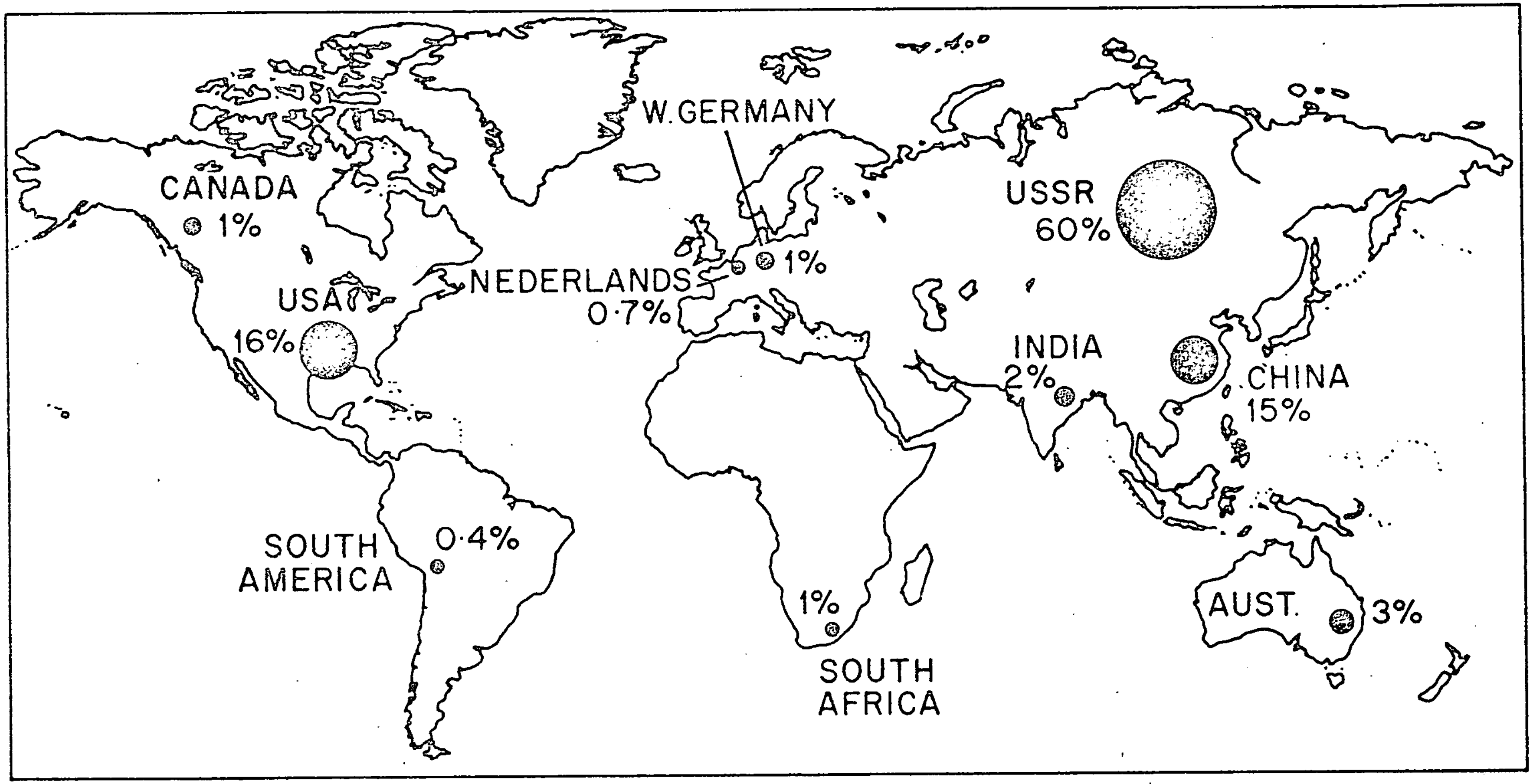


FIGURE 15 WORLD RESOURCES OF BLACK COAL - 3·5 MILLION MILLION TONNES.

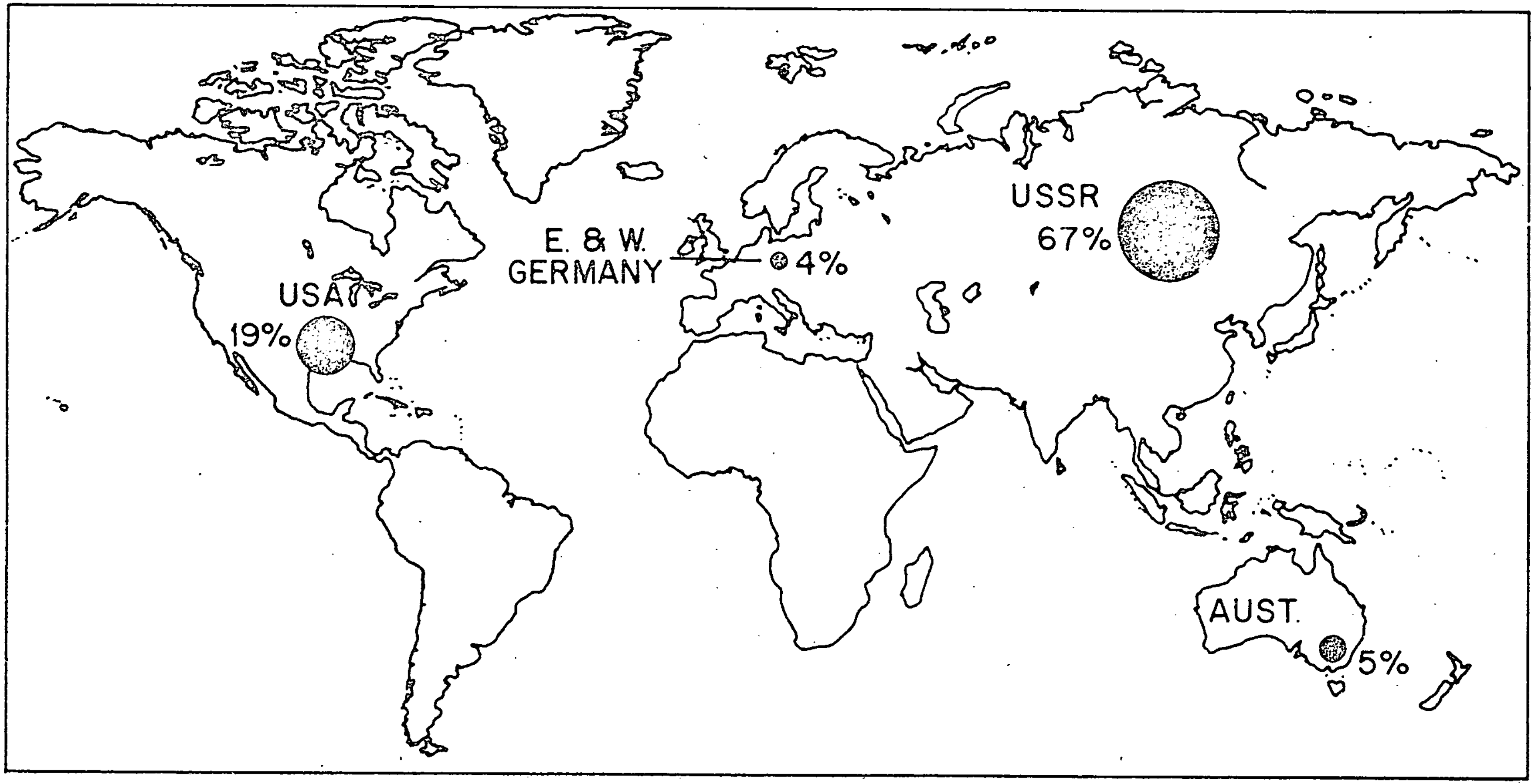


FIGURE 16 WORLD RESOURCES OF BROWN COAL - 1·6 MILLION MILLION TONNES.

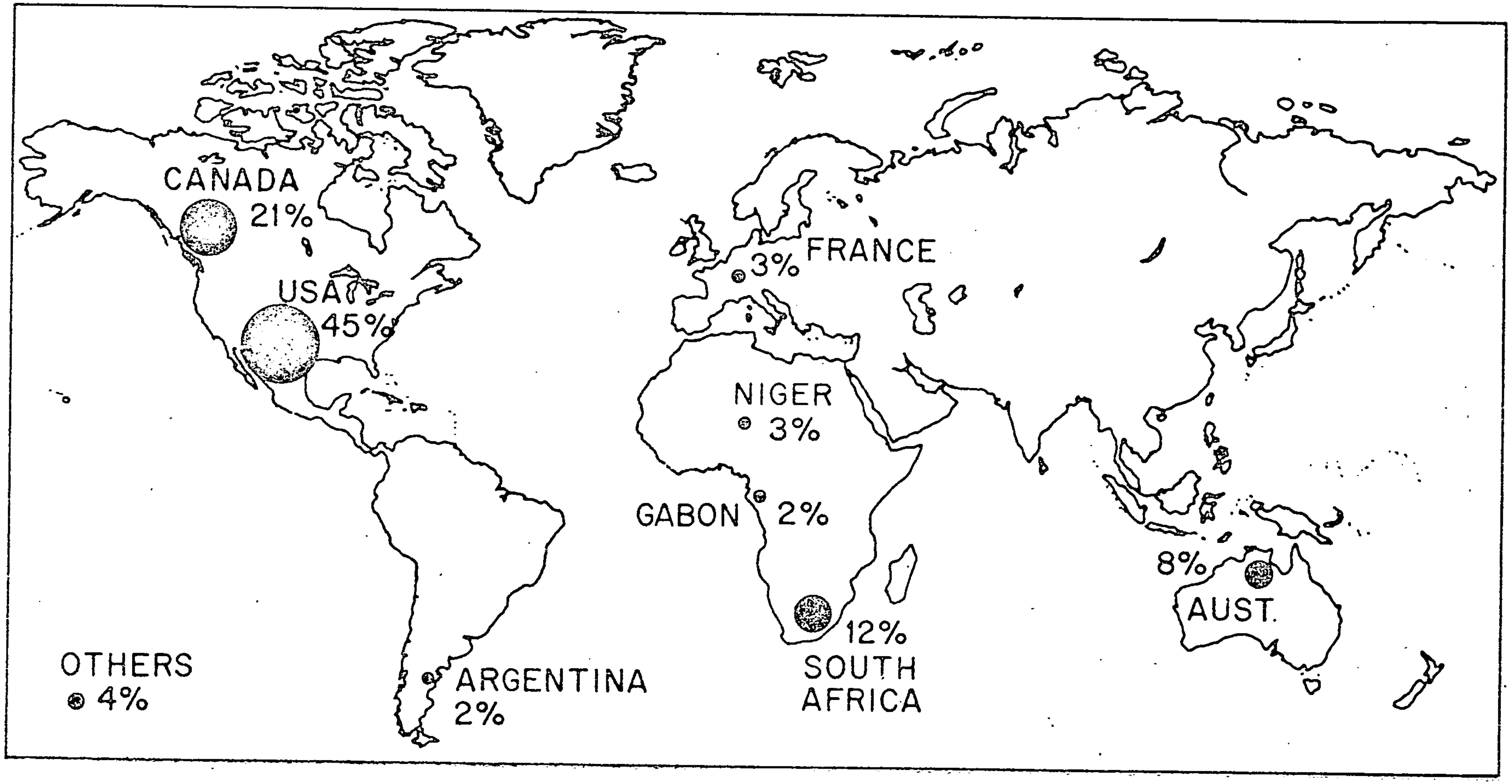


FIGURE 17 WORLD RESOURCES (EXCLUDING USSR, CHINA & E. EUROPE) OF URANIUM < \$US10 PER LB, 2·3 MILLION TONNES, RECOVERABLE AND \$US10-15 PER LB, 1·8 MILLION TONNES, RECOVERABLE.

Figure 11 demonstrates the importance of the Middle East contribution to oil production since 1960. Figures 12 to 17 represent in a generalized way the world distribution of the main mineral sources of energy - crude oil, natural gas, oil shale, black and brown coal, and uranium. Table 10 represents the primary energy resources of the world converted from the units shown in Table 9 into the units of energy commonly used for such presentations - joules x 10^{21}, which is equivalent to about 22,500 million tonnes of oil.

The current energy crisis is mainly one of petroleum, precipitated by political action by petroleum producing countries but apparent in the USA before that, influenced by the following factors :

(i) lag in extensions to refinery capacity in eastern and central USA due to:

- (a) environmental problems;
- (b) uncertainty of sources of crude oil supplied for design of new refinery plant;
- (c) limitations of east port facilities.

(ii) balance of payment problems in 1973 inherent in the rising costs of imported oil.

(iii) delay in the construction of the Alaskan pipeline due to environmental problems.

(iv) shortage of natural gas supplies in western USA partly due to depressed price.

(v) wasteful usage of petroleum in USA.

(vi) higher petroleum consumption due to methods of reducing exhaust pollution (recently introduced, but more recently relaxed).

Shortages and price rises of petroleum have had many beneficial effects. They have :

(i) drawn attention to problems of future supplies of energy producing materials.

(ii) put preservation of the environment, in some areas at least, into a more rational perspective. This has resulted, for instance, in approval for the Alaskan pipeline to go ahead, which in two or three years' time can replace most of US petroleum imports, at least for a few years.

(iii) led to increased exploration activity, particularly offshore.

(iv) by drastically altering the economics of petroleum production, renewed interest in fields that were previously considered unattractive and promoted the use of secondary recovery methods.

(v) encouraged research into and development of oil shale, tar sands, geothermal, solar and tidal energy, gasification of coal, etc., not to mention nuclear energy.

(vi) instituted measures in some countries at least to conserve petroleum and electric power. (US total imports in February 1974 were down 1.6 million barrels per day (24.6%) compared with February 1973. (This decrease is just three times the total Australian consumption.))

(vii) drawn attention to the plight of developing countries with no petroleum production and the need for aid to meet the increased prices.

Some analyses of the world energy situation

Production of electrical energy by nuclear fission is already established and is increasing, although some pollution problems have yet to be solved. Contributions by fast breeder can confidently be expected by the end of the century, technology promises the harnessing of nuclear fusion and probably solar energy in due course, and much more uranium would become available as prices rose. Two models of projected future world consumption of energy in relation to known resources of energy-producing materials are presented in Table 11. These analyses suggest that:

(i) There need be no basic shortage of energy in the world in the future; but changes must occur in the pattern and we will have to pay more for it. Problems may arise from misuse of non-renewable resources or from lagging technology.

(ii) World use of non-renewable energy resources is currently out of balance in that about 64 percent of world energy (about 50 percent of Australian energy) comes from petroleum, including oil and gas, whereas about 65 percent of known sources of non-renewable energy is provided by coal.

TABLE 11

FUTURE WORLD ENERGY USE

UNIT OF ENERGY CONSUMPTION - 10^{21} JOULES

		World	Australia	
Usage	1970	0.3	0.002	
Estimated,	year 2000	1.0	0.007	(Av. annual increase 4.1%)

Possible models of major future World Energy Uses (assuming overall increase in energy demands of 4.1%[1] per annum and disregarding hydro, Geothermal etc)

MODEL 1	1971 I (world usage) %	1985 %	1985 Cumulative (from 1970) Energy (10^{21} Joules)	2000 %	2000 Cumulative Energy (10^{21} Joules)	2020 %	2020 Cumulative Energy (10^{21} Joules)	2050 %	2050 Cumulative Energy (10^{21} Joules)	Total Known Resources
US MODEL										
Petroleum	64	60	3.5	50	9.6	45	24	40	80	54.6*
Coal	33.7	26	1.7	15	3.6	15	8	10	24	113.4
						Fast Breeder, Fusion, Solar				
Nuclear	0.3	10	0.2	35	1.9	40	14	50	75	6.0 +

MODEL 2	1971 %			2000 %	2000 Cumulative (from 1970) Energy (10^{21} Joules)	2020 %	2020 Cumulative Energy (10^{21} Joules)	2050 %	2050 Cumulative Energy (10^{21} Joules)	
Petroleum	64			30	7.2	25	15	20	44	54.6*
Coal	33.7			35	6.0	35	17	30	60	113.4
						Fast Breeder, Fusion, Solar				
Nuclear	0.3			35	1.9	40	14	50	75	6.0 +

(1) Average Annual Increase in world energy use: 1929-1971 3.4% 1961-1971 5.5% 1969-1971 5.0%

* including shale oil

I omitting hydro etc.

(iii) In an attempt to correct the imbalance petroleum should be reserved for usage in which it has obvious advantages against other known sources of energy - particularly for flexible, low-tonnage transport on land, sea and in the air.

Steps that can be taken to conserve petroleum for optimum use include :

(a) higher price for crude oil to producers (especially for new production) and refined products in order to encourage:

(i) exploration for petroleum.

(ii) conservation of resources.

(iii) development of offshore potential, tar sands and shale oil reserves.

(iv) use of coal rather than petroleum as feedstock for petrochemicals.

(v) development of alternative transport systems - electric cars in cities, etc.

(b) avoid using petroleum in power stations.

(c) rail transport by electricity as far as possible and beyond this by coal rather than by oil.

(iv) Used wisely, world non-renewable energy resources should provide adequate lead time for the development of renewable resources such as the nuclear fast breeder and fusion techniques. In the light of technical progress in the last 20 years, it would seem unduly pessimistic to suggest that technology in the next 30 years should not provide acceptable solutions to the following problems, but it must be recognized that major research efforts will be required:

(a) waste disposal from nuclear fission

(b) the possible hazards of fast breeders

(c) problems of the harnessing of solar energy

(d) development of fusion reactors.

In particular, research is needed on -

1. More efficient use and conservation of energy.
2. Increased usage of coal and oil from shale and solution of the associated environmental problems.
3. Possible development of geothermal energy.
4. Improvement of solar energy technology.
5. Use of hydrogen as a fuel.
6. Battery driven vehicles.

Bureau of Mineral Resources
Canberra

June 30, 1974.

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