PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Natural Sources of Nuclear Fuel [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1974 **276**, 495-505
doi: 10.1098/rsta.1974.0034

Phil. Trans. R. Soc. Lond. A. **276**, 495–505 (1974)
Printed in Great Britain

Natural sources of nuclear fuel

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Reserves, resources, potential resources (or potential) are defined and related to price categories and it is deduced that sufficient uranium is available from reserves (866000 tonnes U) at a price of less than \$20/kg U_3O_8 to meet estimated demands to the end of the 1970s. However, this will mean rehabilitating mines that have shut down and commissioning new or regenerating old refining plant.

There is a risk of a shortage of uranium by the mid 1980s if safeguards are not taken in time to ensure that uranium can be made available from reserves and estimated additional resources (916000 t U) in the < \$20/kg U_3O_8 price category presently indicated as being in the ground. Resources in the price range \$20–30/kg U_3O_8 are over 10^6 t U and in the \$30–60/kg U_3O_8 are of the same order or more.

It is considered that prospecting on a world-wide basis should be increased appreciably and maintained at a reasonable level. Also, that new search techniques should be developed and applied mainly to the discovery of hidden ore-bodies. If this is done in good time, there is no reason to predict any absolute shortage of relatively low-cost uranium this century.

Thorium has a potential in high-temperature gas-cooled reactors. Currently known resources are of the order of 10^6 t ThO_2.

1. Introduction

The difference between reserves, resources and the abundance of uranium and thorium in the upper part of the Earth's crust is not generally appreciated. This has resulted in widely differing estimates of tonnages likely to be available as fuel for nuclear reactors. 'Ore' is defined as material that can be mined, beneficiated and sold at a profit. This implies that 'ore reserves' refers to material in known ore-bodies that is likely to be commercially viable at some time in the near future. 'Resources' refers to all material likely to be available at a realistic price, but which is unlikely to be exploited until reserves have been largely depleted.

At present there is no recognized market price for uranium, but, in order to calculate ore reserves, it is widely accepted that material available at a price of < \$20/kg U_3O_8 in concentrate form classifies as ore. Resources are categorized as material likely to be available at < \$20/kg U_3O_8, at \$20–30/kg U_3O_8, and at \$30–60/kg U_3O_8. There are no equivalent categories for thorium reserves and resources, tonnage estimates being related to material available at a price of < \$20/kg ThO_2 in concentrate form.

Ore that is deduced from geological or other evidence, but on which few if any quantitative measurements have been made, is termed 'potential ore'. There is an element of potential ore in material classified as reserves. This results because, in calculating ore reserves, geologists generally use the carefully defined categories of 'measured', 'indicated' and 'inferred' ore and in the latter category there is some overlap with potential ore. The boundaries between reserves and resources are not hard and fast and errors in calculating the amount of ore in the ground can range from a few to as much as 50 % of the actual tonnage, depending on the nature of the orebody. Relatively homogeneous deposits of uranium in flat-lying sediments are by far the easiest to assess, veins and pegmatites the most difficult. Fortunately, over 70 % of reserves of uranium are disseminated in quartz-pebble conglomerates and sandstones so that the estimates of tonnage can be accepted with a reasonable degree of confidence.

The terms 'potential resource' or simply 'potential' relate to material the location of which has not been defined but which might become available in the more distant future at a realistic price. The ultimate tonnage of uranium or thorium in the Earth's crust should neither be considered a resource nor a potential resource. Estimates such as those of Lewis (1972), who gives the figure of 10^{14} tonnes U in the Earth's crust, of which 0.25×10^{14} t is within 1.6 km of the surface, are of no value in establishing the tonnage of uranium that is likely to be utilized as nuclear fuel. Likewise, attempts to calculate ultimate uranium-ore tonnages from crustal abundance data are not helpful. What is of major importance is an understanding of the processes that resulted in uranium being concentrated in abnormal amounts in certain parts of the Earth's crust at different eras throughout the Earth's evolution.

The cut-off grade that may eventually be reached is difficult to estimate but it could easily be of the order of 50 parts/10^6 metal, which is a factor of about 10 below the lowest grade ore that could be mined at present in favourable circumstances. At this level many millions of tonnes of uranium could be made available to power breeder reactors. It is thus unnecessary, from the practical viewpoint, to attempt to estimate ultimate tonnages or to contemplate extracting uranium from rocks such as normal granites which have an average uranium content of about three times the crustal abundance of 1.6 parts/10^6.

2. Uranium distribution

Uranium is widely distributed in the Earth's crust in minerals of varying degree of chemical complexity especially in association with acid igneous rocks. The element appears to have been concentrated, along with other volatile elements, in upper crustal rocks in early Precambrian times. Thus, some 90% of presently known ore reserves occur in well-defined provinces in Precambrian cratonic masses such as the Shield areas of Australia, Canada and South Africa or in sediments immediately overlying Precambrian rocks as in the case of the Colorado–Wyoming uranium province.

Recent geochronological studies have shown that the processes of introduction or remobilization of uranium minerals generally extended over a long interval of time. For example, in the Blind River–Elliot Lake province of Ontario discrete uranium- or thorium-bearing mineral species are from 2500 to 600 million years (Ma) old. The same, though less extensive, time interval between early and late introduction of uranium applies in the case of phanerozoic rocks. For example, in the Colorado Plateau uranium was introduced into sediments during at least two periods – one 210 Ma and the other 110 Ma ago (Miller & Kulp 1963).

Information of this type is invaluable as a guide to exploration geologists in the search for additional reserves and resources, since once a uranium province has been recognized, detailed attention can be given to the physico-chemical controls that resulted in the element being concentrated to an economic tenor. An outstanding example of the value of geochronology to the discovery of major additions to the reserves of the Colorado–Wyoming uranium province is provided by the work of Stieff, Stern & Milkey (1953), who showed that fresh uraninite from the Happy Jack Mine, White Canyon District, Utah, is 65 Ma old. Before 1953, it was widely accepted that uranium in the sandstones and mudstones was syngenetic and essentially confined to the Morrison and Entrada formations of Jurassic age ($\approx$ 150 Ma old). The revelation that at least some uranium in the province was much younger than the host rocks led to the widening of the search to rocks of all ages in the region. The result was the discovery of major new deposits in sediments ranging in age from Triassic to Miocene ($\approx$ 220 to 20 Ma old).

(*a*) *Economic uranium minerals*

Although uranium is an important constituent of about 100 minerals, significant production of uranium concentrate has been from only six primary and five secondary species. The primary minerals are uraninite UO_2, and the less-well crystallized variant pitchblende; coffinite $U(SiO_4)_{1-x}(OH)_x$; brannerite $(U, Y, Ca, Fe, Th)_3Ti_5O_{16}$; davidite $(Fe, Ce, U)(Ti, Fe)_3(O, OH)_7$; uranothorite $(Th, U)SiO_4$; and uranothorianite $(Th, U)O_2$. Secondary species are carnotite $K_2(UO_2)_2(VO_4)_2 . nH_2O$; tyuyamunite $Ca(UO_2)_2(VO_4)_2 . 9H_2O$; torbernite $Cu(UO_2)_2(PO_4)_2 . 12H_2O$; uranophane $Ca(UO_2)_2Si_2O_7 . 6H_2O$; and autunite $Ca(UO_2)_2(PO_4)_2 . 12H_2O$.

(*b*) *Uranium reserves*

It has already been emphasized that reserves are not known with a high degree of accuracy. To illustrate this, reference can be made to the official estimates of reserves for the non-communist countries at the end of the years 1958 and 1961. The 1958 figures were 820000 t U but by 1961 the estimate had been reduced to 525 900 t, though only 82015 t U had been recovered during the interval. At the end of 1972 revisions of estimates together with new discoveries resulted in reserve figures being increased to 866000 t U (table 1), which is a net gain of only 46000 t over 14 years. During the period 1959–72, however, 278665 t U were produced.

TABLE 1. ESTIMATED WORLD RESERVES OF URANIUM (NON-COMMUNIST COUNTRIES); PRICE RANGE < \$20/kg U_3O_8†

country	reserves 10³ t U	estimated additional resources/10³ t U
Australia	71	78.5
Canada	185	190
France	36.6	24.3
Gabon	20	5
Niger	40	20
South Africa	202	8
U.S.A.	259	538
others	53	52
totals	866	916

From O.E.C.D. N.E.A./I.A.E.A. Report 1973.
† Relates to present-day prices.

Conversion factors commonly used in uranium and thorium resource assessment

1 tonne (t) = 0.9842 long ton (or U.K. ton)
= 1.1023 short ton
1 tonne U = 1.300 short ton U_3O_8
1 tonne U = 1.179 tonne U_3O_8
1 % U_3O_8 = 20 lb U_3O_8/short ton
= 10 kg U_3O_8/tonne

(i) *Canada*

The bulk of the reserves of Canada occur in peneconcordant deposits in quartz-pebble conglomerates near the base of the Huronian Supergroup in the Elliot Lake–Blind River region. The ore-bodies are elongate or tabular and vary greatly in size. On average the economic horizons are about 3 m thick but they range from 2 to 12 m and contain an average of about 0.1 % U_3O_8 in currently mineable areas. The main radioactive minerals are uraninite and brannerite, but minerals such as monazite and uranothorite are present and variations in the relative proportions of all these minerals result in changes in the uranium:thorium ratio of ore from 4:1 to 1:4 between different mines. The thorium-rich ores tend to be more refractory and therefore more costly to up-grade. Reserves are relatively easy to assess by drilling, although some are deep-seated, and are estimated to be about 150 000 t U.

The remaining 35000 t of Canada's reserves are divided between vein-type desposits in the Beaverlodge area of Saskatchewan, British Columbia, Northwest Territories and Newfoundland. Limited reserves – probably of the order of 2000 t U – also occur in the granite pegmatites of the Bancroft area of Ontario. The most significant discoveries of uranium in Canada in recent years have been of vein and replacement orebodies in the Carlswell–Wollaston Lake area of northern Saskatchewan.

(ii) *United States of America*

The uranium province of the Colorado Plateau, the Middle Rocky Mountains and the Great Plains is the most important in the U.S.A. The deposits occur essentially in fluviatile quartzoze sandstones and mudstones and vary in size from small pockets to masses several hundred metres in lateral dimensions and up to 30 m in thickness. The larger deposits are commonly about 3 m thick and contain more than 10^6 t of ore at a grade of 0.2 % U_3O_8. The bulk of the reserves is contained in deposits less than 100 m deep and nearly half of the reserves could be mined by open-pit methods. Similar though much smaller deposits occur in the Gulf Coastal Plain of Texas. Reserves total 250000 t U.

The main uranium minerals are uraninite and coffinite though many secondary minerals occur near the surface, particularly carnotite. Ore is readily amenable to treatment and chemical concentrate can therefore be produced relatively cheaply.

Deposits in the form of veins, stockworks and mineralized breccias occur at several locations, the major ones being in the Colorado Mountain area, the Basin and Range Province and the Northern Rockies. The reserves together amount to approximately 9000 t U.

(iii) *Republic of South Africa*

The uranium deposits of the Witwatersrand basin are the most important in the African continent. They are peneconcordant and essentially confined to quartz-pebble conglomerates somewhat similar to those of the Elliot Lake–Blind River field. They differ mineralogically, however, in that the only important uranium mineral is a low-thorium uraninite with a Th:U ratio of $\approx$ 1:33. The host sediments are about 8000 m thick in the central part of the basin and contain five main uranium-bearing horizons. The grade of the ore averages 0.025–0.03 % U_3O_8 and at a selling price of < \$20/kg U_3O_8 is available only as a by-product of gold extraction. Reserves are about 114000 t U.

Uranium also occurs in alaskitic pegmatites at Rössing near Swakopmund in southwest Africa. The main ore mineral is uraninite but a number of secondary minerals are present near the surface. Official figures of reserves and grade have not been released but they are quoted as being 77000 t at an average grade of 0.035 % U_3O_8.

A relatively small tonnage of uranium occurs in uranothorianite, which is present as an accessary mineral in the carbonatite complex of Palabora in North East Transvaal. Reserves are 11000 t though the grade (0.005 % U_3O_8) is such that uranium can only be recovered as a by-product.

(iv) *Australia*

In 1970 uranium reserves in Australia were estimated to be 16700 t U contained mainly in the pyrometasomatic deposit of Mary Kathleen in Queensland and in smaller vein-type deposits in Northern Territory. Since then, however, active prospecting in favourable geological environments has resulted in a succession of discoveries in four main provinces: Rum Jungle–Alligator Rivers; Mary Kathleen–Westmoreland; Mount Painter–Radium Hill; and Kalgoorlie–Wiluna.

The deposits of the Rum Jungle–Alligator Rivers province occur in faulted and folded metasediments of Lower Proterozoic-Carpentarian age. They are of medium tonnage and relatively high grade ($\approx$ 0.25 % U_3O_8). Reserves have not yet been established but indications are that together they are likely to contain in excess of 100000 t U. Deposits in the Westmoreland area are essentially of pitchblende in sheared sediments and each have only a few thousand tonnes U.

In South Australia uranium occurs at Lake Frome and Yrramba in sandstone deposits similar to those of the Colorado plateau. The ore mineral is finely divided pitchblende and grades are of the order of 0.2 % U_3O_8. Reserves are not yet firmly established but are estimated to be more than 20000 t U.

The recent discovery of a type of uranium deposit new to Australia at Yeelirrie 80 km southwest of Wiluna, Western Australia, considerably enhances Australia's role as a potential supplier of uranium. The company reports reserves of 40000 t U at an average grade of 0.15 % U_3O_8.

(v) *France*

The main uranium deposits of France are vein-type with pitchblende the main uranium mineral. Reserves are officially given as 36600 t U, 75 % of which are in the districts of Limousin, Forez and Vandée. The remaining 25 % occur as peneconcordant deposits of Permian age in the Hérault basin.

(vi) *Gabon*

The peneconcordant deposits of Mounana and Oklo occur in feldspathic sandstones intercalated with conglomerates but are strongly controlled by faulting. Uranium is present as pitchblende and several secondary uranium minerals. Reserves are 20000 t U.

(vii) *Niger*

Uranium in Niger occurs as peneconcordant deposits in Carboniferous and Cretaceous sediments of the Agadès basin, bordered to the east and north by Precambrian crystalline rocks of the Aïr massif and to the northwest by the Hoggar massif. Ore grade material at Arlit averages 0.25 % U_3O_8 and the disposition of the orebodies are such that mining of much of the ore can by by open-pit methods. Reserves are estimated to be 40000 t U.

(viii) *Other countries*

Other countries with reserves of more than 1000 t U include Argentina, Central African Republic, Greenland, Italy, Japan, Mexico, Portugal, Spain, Turkey, Yugoslavia and Zaïre. Reserves in all of these countries together total 52 700 t U.

3. Availability of reserves

Attention was first drawn to the problem of availability of reserves at the Third International Conference on the Peaceful Uses of Atomic Energy (Mabile & Gangloff 1965; Bowie 1965). The most obvious restriction to output results when uranium is mined as a by-product. However, there can also be physical difficulties due to the geometry of the ore deposit or to the environmental effect of mining low-grade ore in a developed country.

Approximately half of the reserves (75000 t U) of the Elliot Lake–Blind River province are in the property of Denison Mines Limited. Mill capacity was initially 5500 t/day, but this is being extended to 6800 t/day. It could no doubt be increased further to 9000 t/day; but it seems doubtful if this would result in production exceeding 4000 t U/year. Canada's planned capacity is for an output of 6500 t U/year, and to extend this beyond 11000 t U/year would mean the development of additional reserves.

Table 2. World uranium production (tonnes U)

country	1959 (peak year)	1972
Argentina	—	26
Australia	860	—
Canada	12243	4003
Congo (Zaïre)	1786	—
France	897	1380
Gabon	—	210
Japan	—	15
Niger	—	870
Portugal	115	81
South Africa	4966	3076
Spain	—	60
Sweden	—	7
U.S.A.	13398	9900
totals	34265	19628

Partly based on O.E.C.D. N.E.A./I.A.E.A. Report 1973.

There are no major problems of uranium availability in the U.S.A. because of the nature of the deposits, though recovery will become more difficult as underground mining increases. But in the case of the Republic of South Africa it seems unlikely that more than 5000 t U could be produced annually as a by-product of gold from the Witwatersrand. Production from open-cut mining at Rössing will help boost South African output even though the grade is low.

It is too early yet to comment on possible production difficulties in Australia but there would appear to be no serious problems. It will be necessary to control radon build-up at properties where the average grade is high, such as at Nabarlek, by making sure that adequate ventilation facilities are installed.

Production in France could not be raised to more than 2000 t U/year unless significant new finds are made. In the Gabon, production is likely to be limited to 1200 t U/year. Output from Niger will probably be of the same order, being restricted by high transportation costs and the mining of additional ore underground. Present production is compared with the peak producing year of 1959 in table 2. Estimates of the uranium that could be available from the seven main and other potential producing countries listed above are given in table 3. This estimate equates with the medium-range forecast and would indicate the possibility of demands being satisfied to the beginning of the 1980s. It is of major importance, however, to note that the predicted demand – allowing for the introduction of fast breeder reactors – is likely to more than double from 1980 to 1990 (figure 1).

Table 3. Estimated capability of uranium production by 1980

country	annual production capacity/tonnes U
Australia	10000
Canada	11000
France	2000
Gabon	1200
Niger	1500
South Africa	7500
U.S.A.	25000
others	2000
totals	60200

Based on O.E.C.D. N.E.A./I.A.E.A. Report 1973.

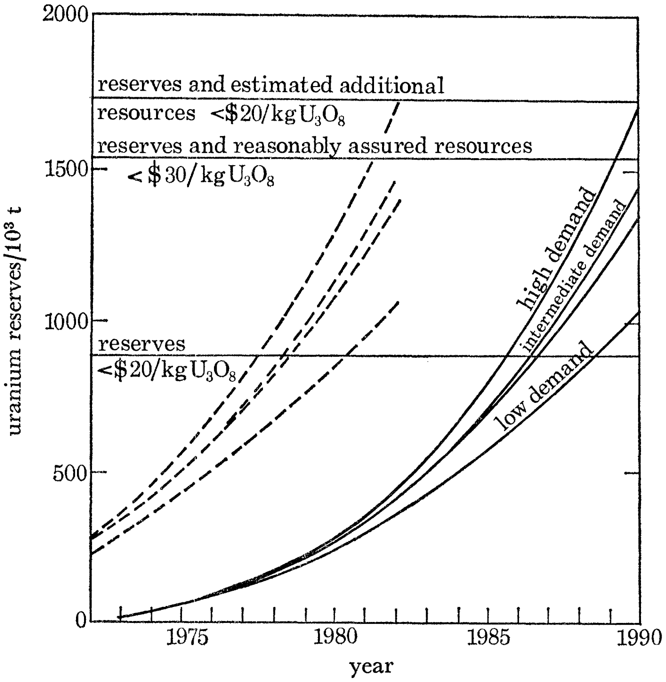

Figure 1. Relationship between uranium reserves, resources and estimated cumulative requirements. The dashed curves allow for an 8-year forward reserve. (Based on O.E.C.D. N.E.A./I.A.E.A. Report 1973.)

4. Estimated additional resources at < \$20/kg U_3O_8

The estimated additional resources possibly available but not yet known with any certainty in the seven main producing countries total 864000 t U with 52000 estimated as being present in other countries (table 1). These resources have in many instances to be delineated, upgraded to reserves and made available at the required rate. To sustain an output of 150000 t U/year, reserves would require to be approximately three times those currently estimated. The obvious question is where are they to be found?

No doubt new reserves will be discovered in known producing areas and in new uranium provinces. However, the task of doing so is not going to prove as easy as it was during the 1950s when most of the main uranium provinces presently known were recognized.

5. Reasonably assured and estimated additional resources at \$20–30/kg U_3O_8

Reasonably assured and estimated additional resources in the non-communist countries total 1312000 t U (table 4), with by far the largest proportion in Canada, Sweden, the U.S.A. and South Africa. The low grade of these deposits makes the problems of availability more acute than in the case of conventional ore deposits. For example, the extensive occurrences in the Västergotland and Närke districts of Sweden contain about 10^6 t U_3O_8, but because of mining and treatment losses the resources are estimated at 310000 t U – which is a realistic figure – but for environmental reasons it is not considered that output is likely to exceed 2000 t/year.

Table 4. Estimated world resources of uranium (non-communist countries); price range \$20–30/kg U_3O_8†

country	reasonably assured resources/10^3 t U	estimated additional resources/10^3 t U
Australia	29.5	29
Canada	122	219
France	20	25
Niger	10	10
South Africa	62	26
Sweden	270	40
U.S.A.	141	231
others	26	52
totals (rounded)	680	632

From O.E.C.D. N.E.A./I.A.E.A. Report 1973.

† Relates to present-day prices.

6. Future outlook

Currently known reserves are adequate to supply the predicted requirements to 1980 if adequate steps are taken in time to regenerate or rebuild plant that has become obsolete during the period of hiatus in production that is now showing signs of having ended. In order that continuity of supply can be assured, however, adequate forward reserves must also be established. This lead time is normally accepted as being a minimum of eight years. For < \$20/kg U_3O_8 reserves, this means that more than twice the reserves established since the early 1950s must be found in approximately half the period of time that was then available. This is such a formidable task that it is predicted that uranium could well have to be recovered from resources in the \$20–30/kg U_3O_8 range during the latter part of the 1980s.

7. THORIUM RESERVES AND RESOURCES

Information available on thorium reserves and resources are less reliable than for uranium as there has been no significant requirement of thorium for nuclear reactors. High-temperature gas-cooled reactors have been constructed that operate on a thorium fuel cycle and if early promise is upheld, thorium could become an important nuclear fuel of the future. Reserves and estimated additional resources at < \$20/kg ThO_2 are given in table 5. Important ore minerals are monazite (Ce, La, Nd, Th) PO_4, thorite $ThSiO_4$, uranothorite (U, Th)SiO_4 and brannerite.

TABLE 5. WORLD RESERVES AND RESOURCES OF THORIUM (NON-COMMUNIST COUNTRIES); PRICE RANGE < \$20/kg ThO_2

country	reserves 10^3 t Th	estimated additional resources/10^3 t Th
Brazil	1.2	31.8
Canada	80	80
Arab Republic of Egypt	14.7	280
India	—	300
South Africa	20	—
U.S.A.	52	265
others†	8	—
totals (rounded)	176	957

Based on O.E.C.D. N.E.A./I.A.E.A. Report 1973.

† Mainly in Australia, Korea, Malagasy Republic, Malaysia, Malawi, Nigeria, Sierra Leone.

Production in the past has been mainly from placer and vein deposits, but in recent years the element has been recovered as a by-product of uranium from the Elliot Lake–Blind River uranium deposits. Canadian reserves and resources in the < \$20/kg ThO_2 price range are estimated to be 160000 t Th. Even larger reserves and resources occur as beach deposits in India, where there are 300000 t Th. Large reserves (14700 t Th) with resources estimated at 280000 t Th also occur in beach deposits in the Arab Republic of Egypt. Similar deposits occur in Brazil, where reserves and resources total 33000 t Th. South Africa has large reserves and resources in detrital monazite in Karoo sediments and in vein deposits in Cape Province – which in the mid 1950s produced over 8000 t monazite/year. In the U.S.A. thorium occurs in the minerals thorite and monazite in vein deposits in Colorado, Idaho and Montana. These contain reserves of approximately 37000 t Th and much of the estimated additional resources of 265000 t Th of the U.S.A. The remaining 15000 t Th reserves are in placer deposits in Idaho, Montana and North and South Carolina.

8. CONCLUSIONS

Presently known reserves in the price category of < \$20/kg U_3O_8 amount to 886000 t U. To this can be added about 100000 t U, which will almost certainly be established as reserves in Australia in the near future. There is therefore adequate uranium defined to ensure that there should be no shortages in the 1970s. By 1980 it is estimated that uranium available from known sources could reach 60000 t U/year, which is the same as the medium-range forecast figure for that year's requirement (table 6). There is likely to be little spare production capacity unless immediate steps are taken to ensure that output can be substantially increased by that time.

It is estimated that demand will be nearly double the 1980 figure by 1985 and continue to increase to around 160000 t/year by 1990. To ensure that production keeps pace with demand, and that an 8-year forward reserve is maintained, is a task that will tax the abilities of geologists, mining engineers and metallurgists alike over the coming years.

Accumulative requirements are forecast as being about 1400000 t U to 1990. and with an 8-year forward reserve this will mean the discovery of more than twice presently known reserves by 1982. How can this be done?

Table 6. 'Best' estimate of annual uranium requirements (non-communist countries)

	10^3 tonnes U			10^3 tonnes U	
year	annual	cumulative	year	annual	cumulative
1973	17	17	1982	77	417
1974	20	37	1983	85	502
1975	25	62	1984	95	597
1976	30	92	1985	105	702
1977	35	127	1986	116	818
1978	40	167	1987	128	946
1979	45	212	1988	140	1086
1980	60	272	1989	151	1237
1981	68	340	1990	164	1401

Based on O.E.C.D. N.E.A./I.A.E.A. Report 1973.

Nearly all of the known uranium provinces of the world were discovered during (or had been recognized before) the era of intensive search for uranium between 1945 and 1958. This applies even in the case of Australia, although the reserves in that country were not considered to be as large as is now anticipated. The fall of discovery rate of new uranium deposits during the 1960s resulted from two main reasons: lack of demand and the fact that a high percentage of deposits with surface manifestations had already been discovered in readily accessible parts of the world. The present erosional surface of the Earth is fortuitous so far as uranium deposits are concerned and it is to be expected that many more deposits than have been discovered are too deeply buried to be detected by γ-ray measurements. To ensure that such deposits are discovered will mean increasing basic research relating to the geology, mineralogy and chemistry of known uranium occurrences; improving our understanding of regional and local controls of ore deposition; and developing geophysical and geochemical methods of detecting orebodies tens to hundreds of metres below surface.

In the field of extractive metallurgy, continued and intensified research is also necessary into new methods of beneficiation. For example, it has recently been shown (Davis *et al.* 1972) that mechanical sorting of ore, bacterial leaching, and new methods of chemical leaching can assist appreciably in reducing the costs of extracting uranium from marginal grade ore. Much more can be done on other extractive techniques including leaching of ore *in situ*.

Presently negotiated prices for uranium concentrate (\$12–16/kg U_3O_8) are too low to ensure that known orebodies are not high-graded leaving the remainder in the ground and thus reducing reserves. Furthermore, the cost of prospecting for uranium, which is estimated to have averaged about \$2/kg U_3O_8, will increase as discovery becomes more difficult. With no real short-term economic incentive to prospect, which is a situation pertaining in almost every country with the exception of Australia, the risk of a shortage of uranium in the 1980s is increased. For this reason, the sooner the market recovers from the present position of over-supply, the greater is the chance of adequate uranium being found in time to meet future demands

In the event of all precautions being taken and a shortage of uranium still appearing a probability, recourse can be made to the recovery of uranium from submarginal raw material from which well over 10^6 t U could be recovered. Should this still prove inadequate, there are further resources in the price category of $30–60/kg U_3O_8 that could be made available from conventional type deposits of low grade in Australia, Brazil, Canada, South Africa and Spain. In addition, uranium could be obtained from the phosphate-leached zone of the Florida phosphate deposits, as well as in limited quantities from sea water and as a by-product in the manufacture of triple super-phosphate from phosphate rock.

Existing uranium stockpiles – not all officially disclosed but probably amounting to 80000 t U – could act as a buffer against any unpredicted shortage, but this is certainly not a time for complacency so far as future supplies are concerned. The lesson of diminishing additions to ore reserves per metre drilled in the U.S.A. in 1972 (U.S.A.E.C. Report, 1973) should make it clear that new uranium provinces must be located. The aim should be to encourage an immediate and major increase in prospecting in geologically favourable areas and to develop new techniques of discovering hidden sources of present-day ore grades. If adequate steps are taken, and in time, a sufficiency of uranium should be available to supply the needs of the 1980s and well beyond. The possible utilization of thorium and the introduction of breeder reactors should prevent any shortage developing this century, but only if adequate foresight is exercised throughout the many branches of the uranium industry.

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Discussion

Dr W. C. Marshall (*A.E.R.E. Harwell, Didcot, Berkshire*)

During the discussion, Dr Bowie was asked the question: 'What is the cost of producing uranium from sea water?' Dr Bowie said that it was about $60/kg U but that someone from Harwell should answer that question. Dr Marshall confirmed that the work by Norman Keen and his colleagues at Harwell, up-dated to present-day values of money, suggests that uranium could be obtained from sea water at the figure Dr Bowie gave.