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World Oil Resources Assessment and Potential for the 21st Century

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WORLD OIL RESOURCES ASSESSMENT AND POTENTIAL FOR THE 21ST CENTURY

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ABSTRACT

Over the last thirty there have been about two dozen estimates made for world oil resources. Few of them are really independent or new estimates. Moreover, most of them disclose neither the method of assessment which was used nor the data on which the estimates rely.

The situation is worse still for unconventional world oil resources such as heavy oil, tar sands, and oil shales. This is the reason why IIASA has launched an up-dating survey of past (and sometimes very old) estimates.

This paper summarizes the efforts of the Resources Group to better understand both world oil (conventional and unconventional) estimates and also some technological and/or economic factors affecting the future availability of liquid fuel.

World Oil Resources Assessment and Potential for the 21st Century

Oil has acquired a dominant position with respect to the world energy supply. This is not due to its long term abundance prospects. It is because of the outstanding ease of its utilization. And also, because of an exceptional low cost of production owing to exceptional geological and political conditions. In fact, these conditions, which led to the post World War II oil boom, were restricted to a small region (2% of the world's surface area) and to a mere decade (the 60's): an instant in human history.

So the reality looks like this: our civilization depends heavily on oil. Because of the difficulties and the time needed to shift to other energy sources, it is of the utmost importance to assess how long the oil era will or can last. This paper expresses a few thoughts on the subject.

Before analyzing oil resources assessments and potential for the 21st century, we would like to put forthcoming estimates in a special perspective: How much oil - or liquid fuels - will, or would we need? This is indeed not an easy question. In trying to answer it, we are confronted with a great many uncertainties. First of all, we should know how many people will be on earth in 50 or 100 years from now, and what their life-style will be like. Although the whole problem is a fascinating one, we are in fact concerned here mainly with the specific aspect mentioned above: How much oil, or liquid fuels, could be needed? Basic assumptions which we have made at IIASA in order to attempt to give a preliminary answer are:

- World population stabilized (say, at <u>less</u> than 12 billion people, 3 times the present level; possibly between 7 and 9 billion people);

- Energy needs also stabilized, or increasing very slowly (this is in contrast with some other forecasts of ever increasing energy demand);

- Oil/liquid fuels reserved for*:

    - o Transportation (there will be a limit to the number of cars and potential mileage);

    - o Petrochemicals (but other raw materials, such as coal or biomass will compete);

    - o Development phase of LDC (Less Developed Countries).

All in all, we came to a figure between 3 and 5 billion tons of oil per year**. Curiously, this figure is also an often quoted maximum for world oil production supposed to occur in the 90's (WEC, WAES, CIA, most of the oil comapnies' studies, etc.), as shown in Figure 1.

Our point of view for looking at the oil resources - and/or liquid fuels - is thus to consider how long resources could allow a plateau of oil production and consumption (Figure 1) to continue and, in view of potential resources, what should possibly be done to maintain such a level of production. In

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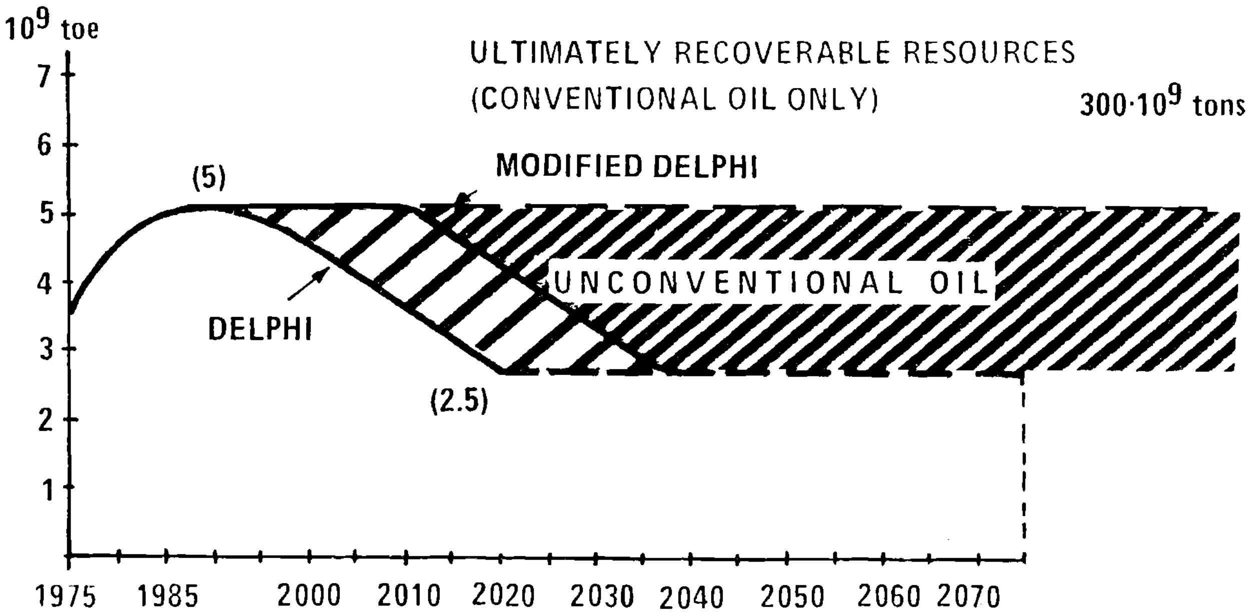
* It is often mentioned that "oil must be reserved for transportation and petrochemicals". In fact, with a progressive shift to the supply of heavier crudes, it is not clear what the maximum yield of light or intermediate products could be.

** This seems a reasonable value. However, more liquid fuel (synfuels) could be produced and consumed because of their convenience or preference for them.

Figure 1. POTENTIAL WORLD OIL PRODUCTION CURVE



other words, we challenge the bell-shaped production curve in Figure 1.

Assessments of Conventional World Oil Resources

We do not have good tools with which to tackle our problems. Unfortunately, world oil resources are very poorly known. It is important to understand why and hopefully, to aim to correct this uncomfortable situation*.

We have emphasized, as shown in Figure 2, some of the differences between reserves and resources which can help us to understand better why we know so little about resources. Generally, the interest in reserves has been very great, but there was, until recently, little or no interest in resources. The time horizon for reserves is between 10 and 30 years, and for resources long or very long term (what we, at IIASA, call the long or very long term is at least after the year 2000, say until the year 2050 or even later, clearly the 21st century).

From the economic point of view, reserves must be "profitable". This is a very important point because, in fact, we have not redefined, since the oil crisis of 1973, the meaning of the word "profitable". Is it "profitable for industry" (which was essentially the case up to now)? Is it "profitable for a country"? This question can have a big influence on the revision of reserves and/or resources. Traditionally and by "definition", resources are not profitable or unknown, and even sometimes rely on what industry calls Science Fiction Technology, i.e. technologies which have still to be developed and matured. The border line between reserves and resources is sometimes very thin: for instance, if the British Government were to change its taxation policy only slightly (and find it "profitable" to do so) so-called "marginal reserves" (the sizes of which are currently in the 50 to 100 million barrels range) would become commercial.

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* Because so many important energy policy decisions are founded on so fragile a basis.

Figure 2. **COMPARISON OF RESERVES VERSUS RESOURCES**

	RESERVES	RESOURCES
INTEREST IN . . .	GREAT	NONE IN THE PAST, NOW EMERGING
TIME HORIZON	10 – 30 YEARS	LONG, OR VERY LONG TERM
ECONOMIC ASPECT	MUST BE PROFITABLE	NON-PROFITABLE TODAY, "SCIENCE FICTION" TECHNOLOGY
ESTIMATED BY	INDUSTRY	MEMBER OF INDUSTRY, <u>OR</u> GOVERNMENTS (INSTITUTIONS)
DATA	MORE OR LESS RELIABLE, CONSERVATIVE, "PROPRIETARY", AND EXPLOITATION-ORIENTED	UNCERTAIN OR SPECULATIVE, BUT SCIENTIFICALLY ORIENTED
METHODS	INDUSTRIAL WORK (EXPENSIVE): EXPLORATION, DRILLING, AND MEASUREMENTS	PAPER OR COMPUTER WORK: "GEOLOGICAL", "HISTORICAL"

The reserves are generally estimated by industry (they are its daily bread...) and the resources have been estimated by members of the industry (most often on a hobby basis, because it is not their main occupation) or by government or scientific institutions. So that the data estimates of the reserves are more or less reliable, conservative, proprietary, and exploitation oriented. Methods of obtaining these data are expensive and include exploration and drilling. On the other hand, resource estimates are uncertain or speculative, but more scientifically oriented and based on paper - now, also computer - work.

If we look at these many differences, I think that we already understand why the reserves are much better known than the resources. With this point of view, we have, at IIASA, devoted much attention to the various world oil resources assessments and tried to understand them better [1].

Some lists of world oil resources assessments during the past 25 or 30 years have been published. We have made our own list (Figure 3), most of these estimates being well-known. We have put on this list only the results we have been able to find in published papers, because sometimes reference is made to an estimate without any possibility of finding a document relating to it. On the table are the name of the estimator and his company, which is a factor often underestimated. Where applicable, we have also put the estimate for the U.S. When two values are given with a slash it is because the estimator himself has given two values: Weeks, for instance, has generally given two values, for "primary" and "secondary" recovery respectively. Values in brackets coorespond to a range of values, sometimes with a mean value. There have been about two dozen estimates since 1946.

Some experts have used similar tables to analyze potential trends of world oil resources estimates. Odell [2], for instance, has made a curve, which is well-known, the linear regression of the estimates, and has shown that the estimates generally increased with time. In addition, it is possible to see from such

Figure 3. MAJOR ESTIMATES OF WORLD OIL RESOURCES

YEAR	NAME	COMPANY	ESTIMATE x 10^9 bbl	US x 10^9 bbl	%
1946	DUCE	ARAMCO	500	100	20
1946	POGUE		615		
1948	WEEKS	JERSEY	617		
1949	LEVORSEN	STANFORD	1635		
1949	WEEKS	JERSEY	1015		
1958	WEEKS	JERSEY	1500/3000	240	16
1959	WEEKS		2000/3500	270/460	14
1965	HENDRICKS	USGS	1984/2480	320/400	16
1968	WEEKS	WEEKS	2200/3350		
1969	HUBBERT	USGS	(1350-2000)		
1970	MOODY	MOBIL	1800		
1971	WARMAN	B.P.	(1200-2000)		
1971	WEEKS	WEEKS	2290/3490		
1972	JODRY	SUN	1952	190	10
1973	ODELL	UNIV.	4000		
1974	KIRKBY, ADAMS	B.P.	(1600-2000)		
1975	MOODY	MOODY	(1705-2030-2505) 95% 5%	242	12
1976	GROSSLING	USGS	(1960-2200-3000-5600)	182-250	8
1976	KLEMME	WEEKS	1600		
1977	PARENT, LINDEN	IGT	2000		
1977	DELPHI	IFP	2200/2500		
1978	MOODY	MOODY	2030	300	15
1978	NEHRING	RAND (CIA)	(1700-2300)		

graphs, even adding most recent estimates, that the uncertainty or say, the spreading of the estimates did not decrease with time. In fact, if we take all the values listed in Figure 3, the picture appears as shown in Figure 4. Even if many values tend to increase, it is in fact difficult to draw a regression line through the estimates. At best, there appears to be a magic line or "magic figure" of 2000 billion barrels, at which many of the estimates are "knocking".

Analyzing these various estimates (through a careful reading of the documents) we can make a few comments, summarized in Figure 5:

- In 1949, 30 years ago, there was the first introduction of off-shore, which boosted the estimates.

- Ten years later, in 1959, Weeks introduced the first (broad) regional distribution.

- In 1965, Hendricks estimated "discoverable" oil in place.

- In 1969, King Hubbert introduced the first "estimate of estimates", and was the first to speak of a "consensus" around 1800-2000 billion barrels.

- In 1970 (less than 10 years ago), Moody stressed the importance of giant and supergiant fields.

- In 1975, Moody published what remains one of the best (and most influential) estimates, and introduced probability distributions [3].

- In 1977, there was the most important Delphi study [4].

- In 1978, Nehring was the first to disclose the method and the data used to perform an estimate [5].

Concerning this last point, it is worth pointing out that previous estimates were, in fact, calling mostly upon our "faith", because if the method was at best suggested, the data used to arrive at the estimates were never given (this concerns world

Figure 4. EVOLUTION OF ULTIMATE WORLD OIL RESOURCES ESTIMATES

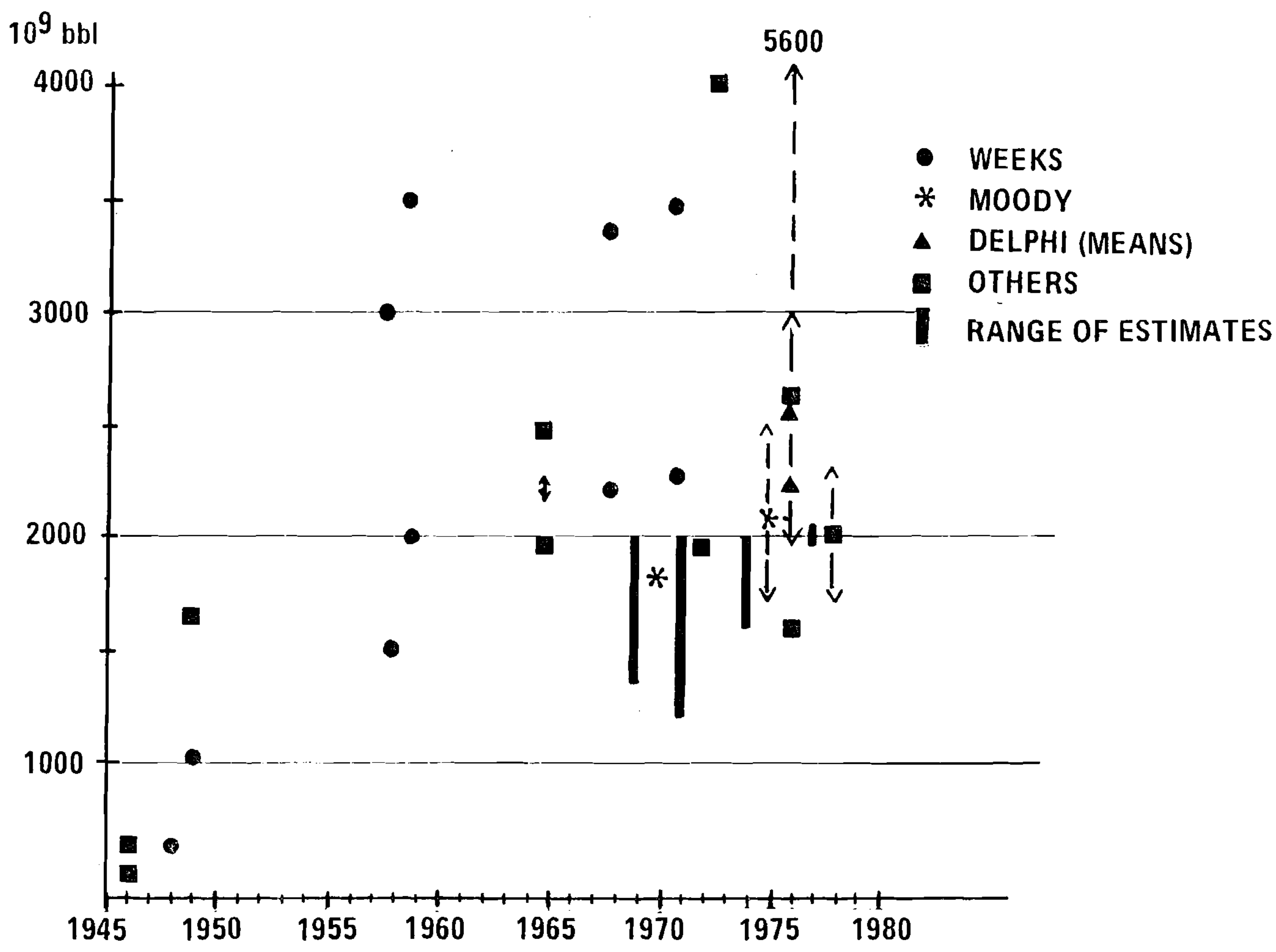


Figure 5. SOME LANDMARKS IN WORLD OIL RESOURCES ESTIMATES

1949	INTRODUCTION OF OFF-SHORE	LEVORSEN (PRATT)
1959	REGIONAL DISTRIBUTION	WEEKS
1965	OIL IN PLACE, AND DISCOVERABLE	HENDRICKS
1969	ESTIMATE OF ESTIMATES FIRST "CONSENSUS" 1800-2000 10^9 bbl	HUBBERT
1970	IMPORTANCE OF GIANT FIELDS	MOODY
1975	PROBABILITY DISTRIBUTION	MOODY
1977	D E L P H I	DESPRAIRIES
1978	DISCLOSURE OF METHOD AND DATA	NEHRING

estimates and not estimates for the U.S., for which the situation was different). This means that from the scientific point of view, it was not possible to check whether the assessment was good or not.

As a next step, it is interesting to investigate what the relative independence of these various estimates was. Levorsen, for instance, is not independent because he combined Pogue and Weeks, and added the off-shore estimate of Pratt. Weeks has made a lot of estimates but, of course, they are mere revisions and are not independent of each other. Hendricks was apparently independent. Hubbert, as we mentioned, made the first "estimate of estimates". This last process has more or less continued until the present day. To cut this long story short, Figure 6 summarizes - using the horizontal axis for independent estimates and arrows for connections - that from 1946 to 1976, a thirty-year period, we have found about six independent world oil resource estimates.

Then, in 1977, there was the very important Delphi study by Pierre Desprairies of the French Petroleum Institute for the Conservation Commission of the World Energy Conference. More than fourty experts were consulted: 27 answered the first set of questions, 22 confirmed or revised their answer in the second round. We can, however, question, by referring to the above, whether all these 22 estimates are really complete, independent estimates.

Figure 7 summarizes the main findings of the Delphi study. Ultimate world oil resources remaining to be produced (to which must be added 300 billion barrels of past cumulative production, to make these figures comparable with others given previously) would be 1900 billion barrels, excluding deep offshore and polar areas, and 2200 billion barrels if they are included, assuming the recovery rate were raised from today's average 25% to about 40% at the end of the century. (In fact, the limits imposed on the study were the year 2020 and a production cost of less than $20/bbl, in 1976 dollars). These are the values proposed by the estimator.

Figure 6. RELATIONSHIPS BETWEEN OIL RESOURCES ESTIMATES

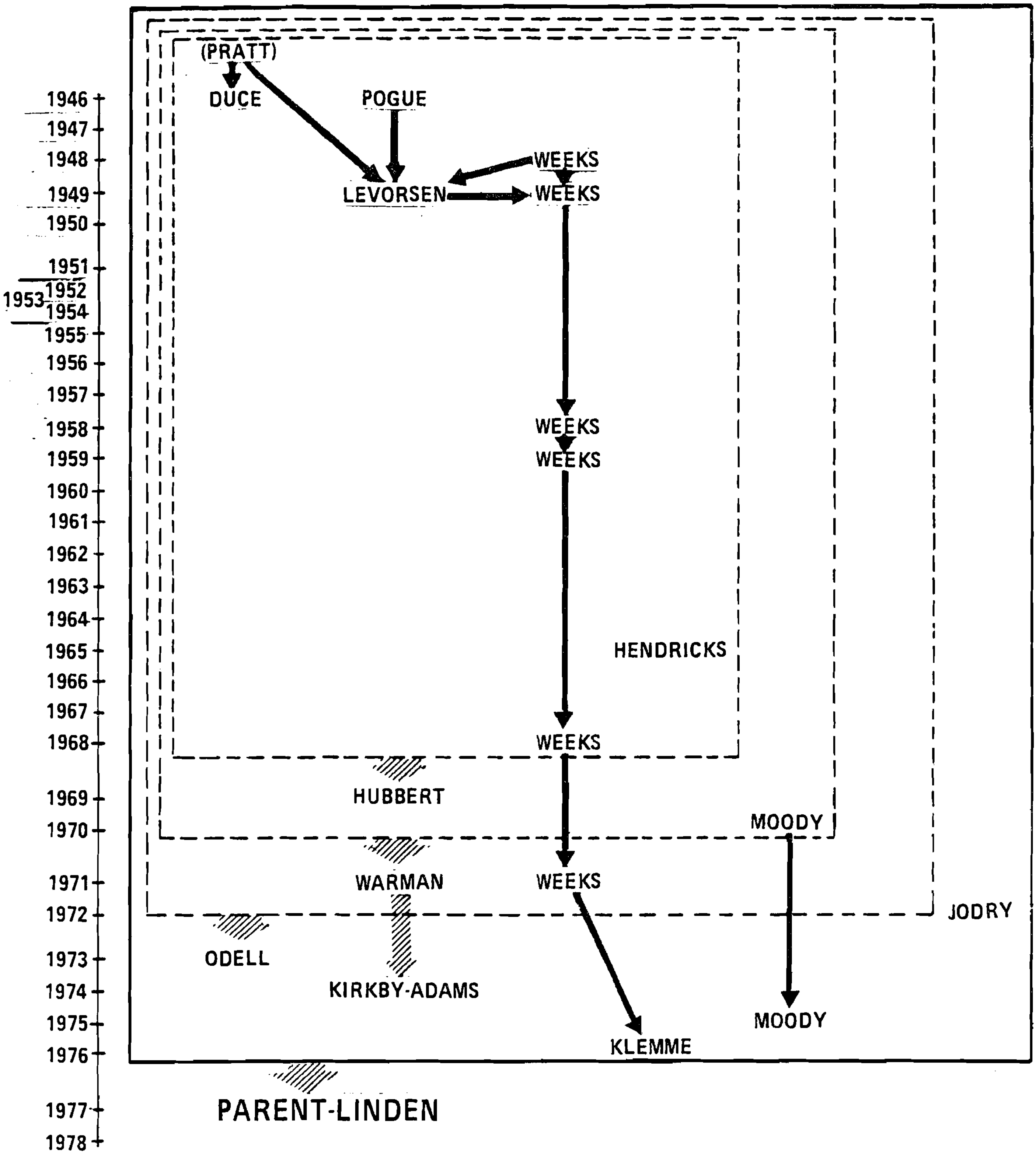


Figure 7. MAIN FINDINGS OF THE WEC-DELPHI STUDY 1977

- ULTIMATE WORLD OIL RESOURCES : 1.900 · 10^9 bbl (260 Gt)

  REMAINING TO BE PRODUCED ("CONSENSUS") : 2.200 · 10^9 bbl (300 Gt) INCLUDING DEEP-OFF-SHORE AND POLAR AREAS

- 45% OFF-SHORE

- RECOVERY INCREASING FROM PRESENT 25 % TO 40 % IN THE YEAR 2000

- INCREASING CONTRIBUTION OF ENHANCED RECOVERY : 55% OF GROSS INCREASE IN 2000

- SLOWING DOWN OF ANNUAL RATE OF GROWTH OF RESERVES : BACK TO 20 · 10^9 bbl/yr IN 2000

It is interesting to look at the degree of consensus. In the following paragraphs, we use billion metric tons of oil - instead of barrels - which were the original units of the Delphi study.) In Figure 8, the answers are plotted - their number appearing on the vertical scale and the individual estimates on the horizontal scale (value on the left without polar and offshore areas, where applicable; value on the right with polar and offshore areas). It may be seen that the answers, in fact, cover a braod range, from about 170 billion tons to 750 billion (average for 550-950 range).

In the shaded area lie the answers which the estimator, P. Desprairies, considers a consensus, 18 answers (about 2/3 of the total) between 200 and 300 billion tons, thus excluding the two lowest estimates and those higher than 300 billion tons. It is interesting to remark that, even for the group of the consensus, there is some appreciable disagreement on the potential future role of deep offshore and polar areas.

Figure 9 shows another way of presenting the same results; on the vertical scale the number of answers for the various ranges of the horizontal scale are plotted. Here again, the shaded part concerns the 18 answers of the consensus.

Finally, in relation to our IIASA studies to assess potential future world oil production, it is interesting to try to get values on regional distributions of world oil resources according to the Delphi study experts. Figure 10 shows, in a similar fashion to Figure 9, the answers for North America. We find the known phenomenon of the broad ranges of estimates (answers converted back in billion barrels). And Figure 11 shows for major regions the minimum estimates, the maximum estimates and the averages for the totality of the answers from the experts, or only for the answers of the "consensus", in the global range of 200-300 billion tons. The 1975 Moody values and the 1978 Nehring values fall into the same ranges, and more especially into the consensus ranges. However, this no longer applies to the range of estimates, generally and understandably much broader if all the answers are taken into account.

Figure 8. ANALYSIS OF ANSWERS TO DELPHI

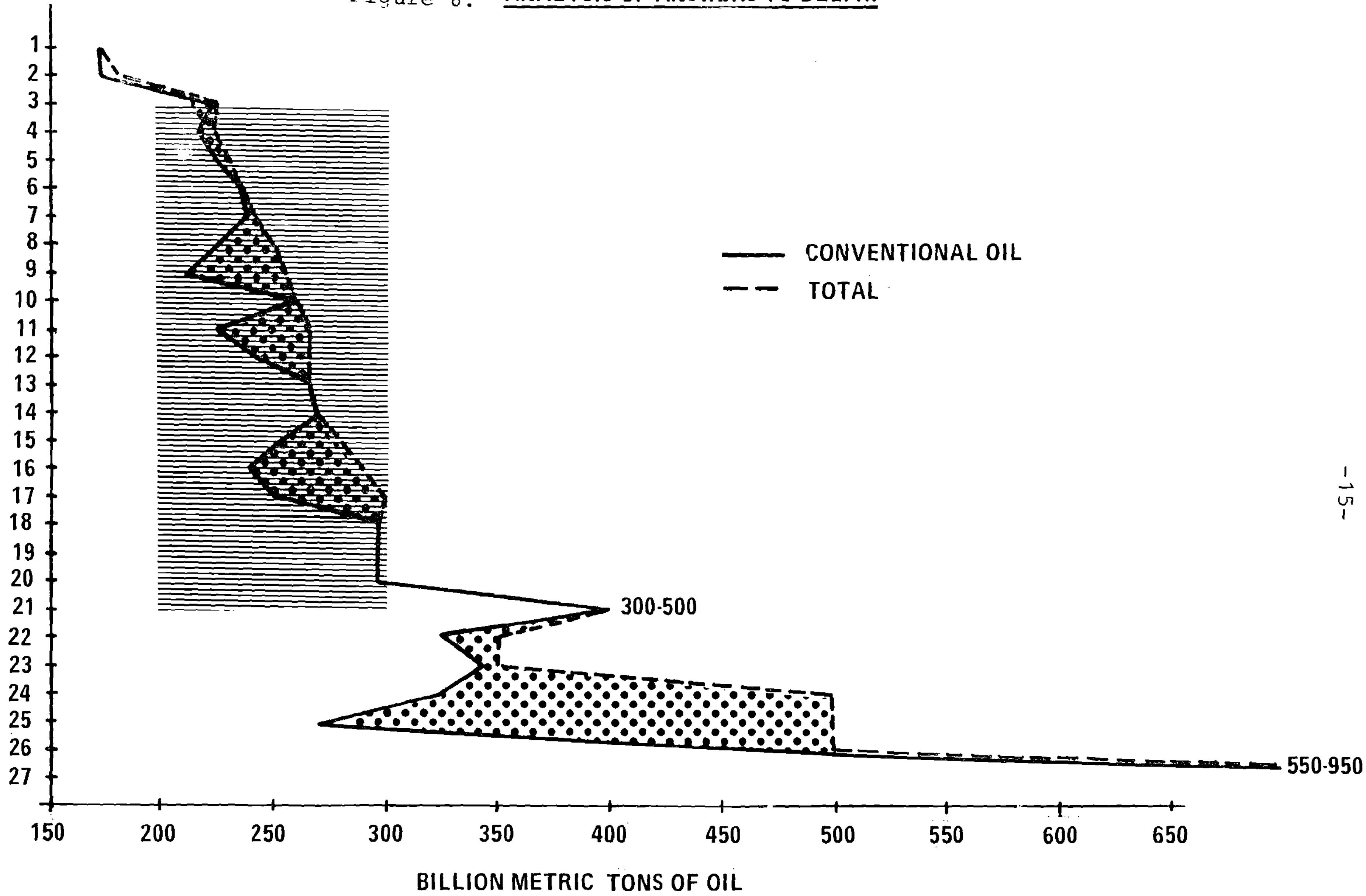


Figure 9. **WORLD OIL RESOURCES REMAINING TO BE PRODUCED (DELPHI)**

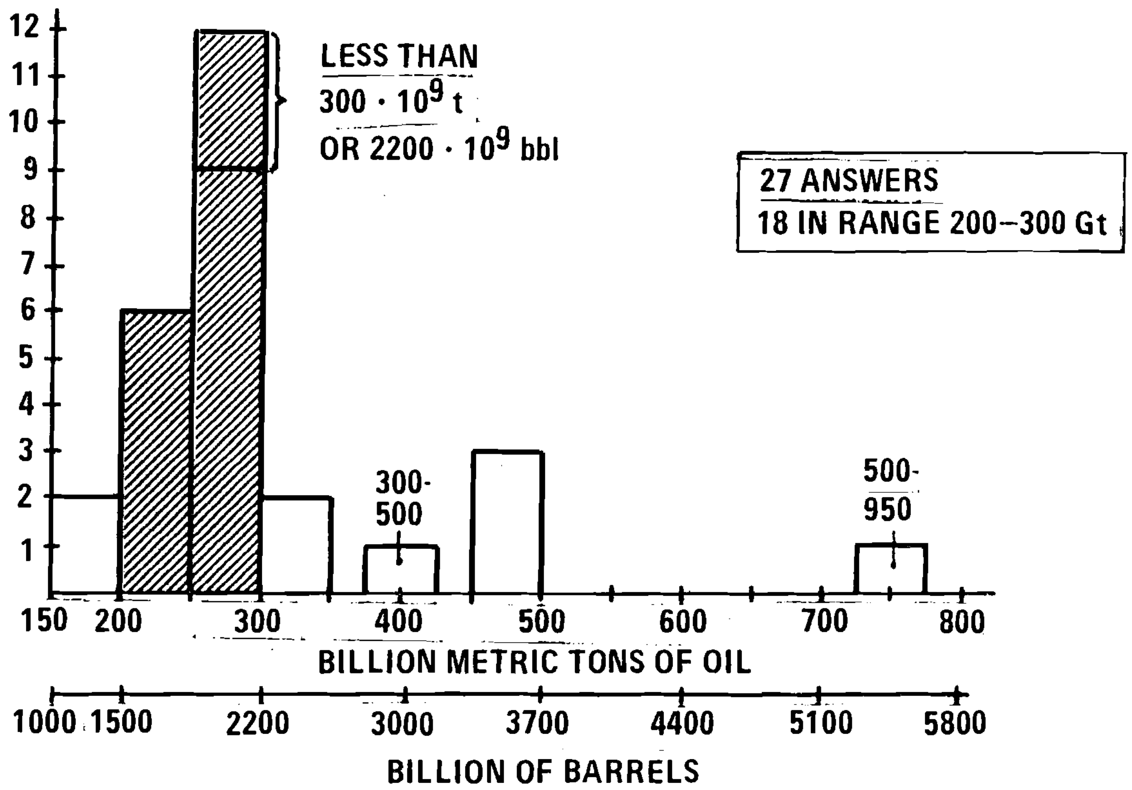


Figure 10. **ULTIMATE OIL RECOVERY IN US & CANADA (FROM DELPHI)**

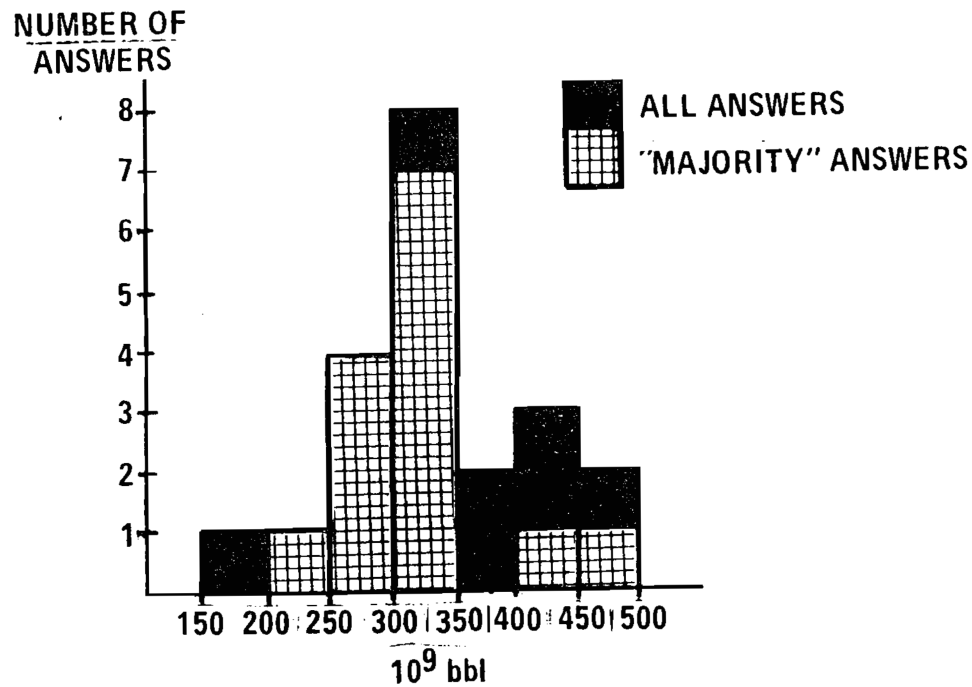


Figure 11. REGIONAL DISTRIBUTION OF DELPHI ESTIMATES
(IN Gt)

	ALL VALUES			VALUES IN RANGE 200–300 Gt*		
	MINI	MAXI	AVERAGE	MINI	MAXI	AVERAGE
SOCIALIST COUNTRIES	27.3	96.3	59.4	40.3	83	54.5
USA AND CANADA	6.2	50	28.5	15.6	45	26.1
MIDDLE EAST & NORTH AFRICA	54.8	300	109.1	76	156	101.9
AFRICA SOUTH OF SAHARA	2.7	40	11.3	4	13.4	8.8
WESTERN EUROPE	5	22	11.2	5	22	11.1
LATIN AMERICA	7.9	55	22.9	12.5	36.9	20.9
EAST AND SOUTH ASIA (INCLUDES JAPAN, AUSTRALIA & NEW ZEALAND)	5.5	30	15.1	6	25	13.6
DEEP OFFSHORE AND POLAR AREAS	0	230	38.7	0	50	21.2

*Of the 18 values in the range 200 to 300 Gt, four do not give details by regions.

But even in the consensus range, and although agreement on the global value is plus minus 20%, there is no clear convergence of estimates at the regional level. The ratios between higher and lower values vary from 3 (Socialist countries, which do not publish statistics! And for the Middle East, this factor of 2 representing a very big difference of 80 billion tons, roughly equivalent to present known world reserves) to 4 (but with less significance for the total). The highest disagreement of opinion among the experts is related to deep offshore and polar areas. It is fair to say that the Delphi study in fact occurred about at the turning point: concerning deep offshore, the original optimism of the mid-70's has now been succeeded by an (exaggerated?) pessimism.

This is where we stand with regional estimates for world oil resources and the material with which we are working. It seems appropriate to say that, from the scientific point of view, our knowledge is very, very poor.

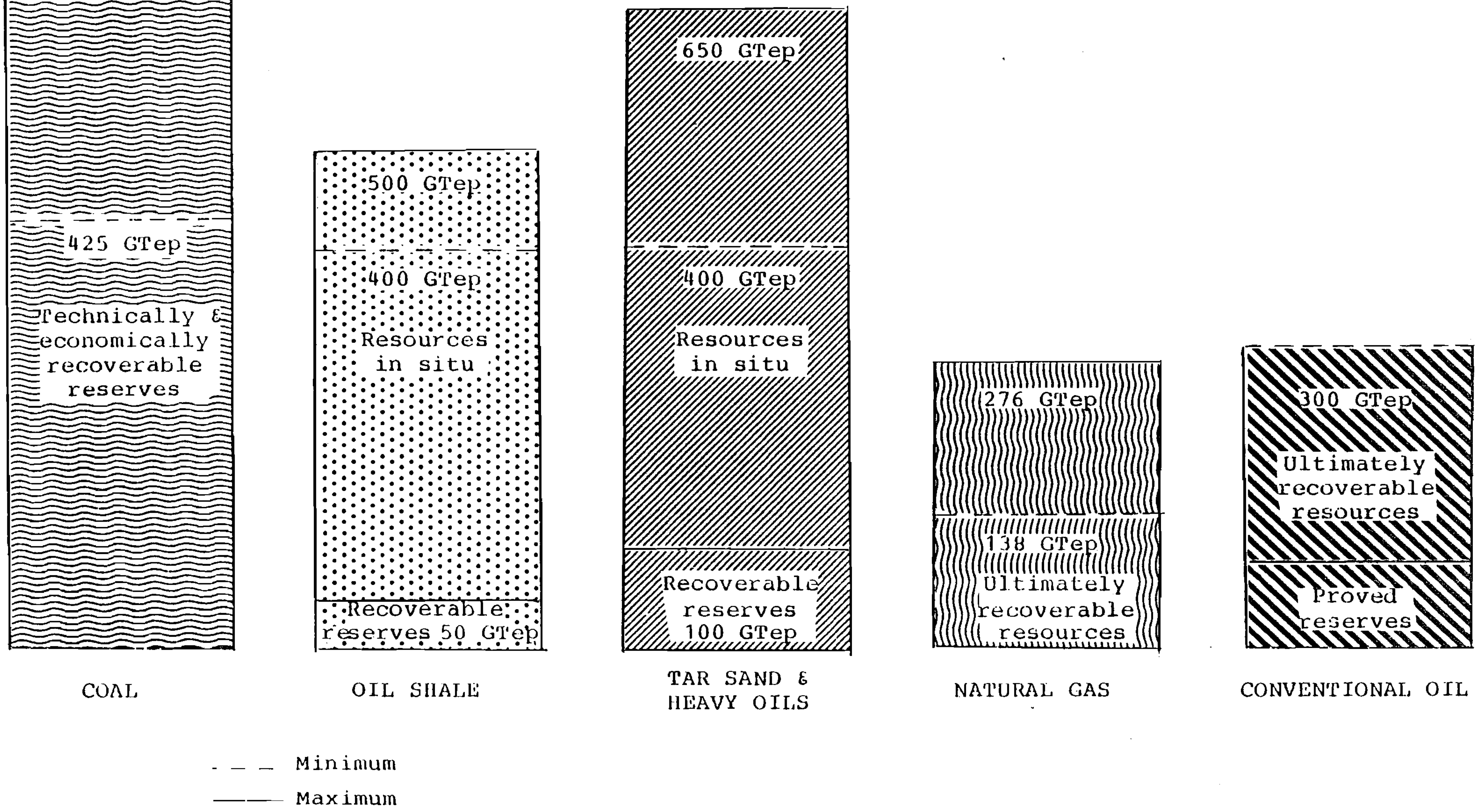
Assessments of World Unconventional Oil Resources

We can assess the situation of world unconventional oil resources by saying that it is still much worse than for conventional oil resources.

True, there are some very large deposits, more or less well known - and curiously, located on the "oil ring" described by Nehring (Athabasca Tar Sands, Colorado Oil Shales, Orinoco Heavy Crudes). The aggregate resources in the ground of these very large deposits are considerable, at least 800 billion tonnes, of which about 150 billion tonnes are presently considered to be recoverable (Figure 12), which has to be compared to the 900 billion tonnes of conventional oil originally in place*. But the question of main interest to us is to know what may possibly exist beyond these huge deposits at a global level, i.e. what the potential regional distribution of these unconventional oil resources is. Because of a lack of economic interest (let us recall: reserves must be profitable), very little effort has been made to assess these resources in most of the countries.

* Accepting the Delphi values.

Figure 12. FOSSIL FUEL RESERVES AND RESOURCES



As was shown during our 1976 IIASA-UNITAR Conference on the "Future Supply of Nature-Made Petroleum and Gas" [6], sources of global data are generally very few, and very old. Contrary to what was expected, the first UNITAR Conference on Heavy Crudes and Tar Sands [7] did not really improve the situation. Most improvements were related to Canada and, to a lesser extent, to the U.S. and Venezuela. Many of us, in the energy community, had expected that a serious effort would get started after the 1973-74 oil crisis. Apparently (we will come back to this later) and unfortunately, this did not happen. Except in the three above-mentioned countries plus, possibly, a very few exceptions.

This is why IIASA has launched its own survey of unconventional oil resources, through questionnaires and direct contacts. Our study is about mid-way so that it is premature to present final results and/or conclusions. However, some of our progress will be reported by way of example to comment on global resources tables presented hereafter.

Heavy crudes and tar sands

At the Edmonton meeting, R. Meyer from the U.S.G.S., presented a global estimate of resources and possibly recoverable reserves of heavy crudes and tar sands (Figure 13). Recovery rates for tar sands were generally very conservatively estimated at 10% or less [8].

We, at IIASA, consider these figures somewhat misleading in asmuch as they aggregate rather good data - for Canada, the U.S.A. and Central America (essentially Venezuela) - with poor to very poor data for the other regions.

It is interesting to point out that, in known areas - and the ones, in fact, where knowledge has increased further - there has generally been an increase in the estimates:

- Athabasca tar sands. 627 billion barrels in 1976 (Alberta Energy Resources Conservation Board) [9], 869 billion barrels in 1979 (Alberta Research Council [10] referring to a study by Outtrim and Evans [11]).

Figure 13. **ESTIMATE OF HEAVY CRUDE AND TAR SAND RESERVES**

(10^6 BARRILS)

	MEDIUM CRUDE OILS $20 \leqslant {}^{o}API \leqslant 25$	HEAVY CRUDE OILS ${}^{o}API < 20^{o}$	DEPOSITS(*)	TOTAL
CANADA	119	69	333010	333198
USA	2271	2254	2512	7037
MIDDLE AMERICA	108	331		439
SOUTH AMERICA	8376	5654	100012	114033
EUROPE	154	734		6
AFRICA	4197	89	175	4461
MIDDLE EAST	32759	3528		36287
URSS/ASIA	660	97	16	773
	48644	12747	435731	497122

(*)In this table Meyer uses the word deposits to refer to crude oil which do not occur in conventional reservoirs.

FROM R. MEYER, USGS

- Lloydminster heavy crudes. Evolution of two probabilistic estimates for 1976 (A.E.R.C.B. [9]) and 1979 (Geological Survey of Canada [12]) are shown in Figure 14.

- California tar sands. Estimates have increased from 270-323 million barrels in 1965 (Ball Associates [13]) to 966 million barrels in 1979 (F.O. Hallmark [14]) through the addition of new deposits, not including two large but conjectural deposits.

- Utah tar sands. Estimates have grown from 2.0 - 4.3 billion barrels in 1965 (Ball Associates [13]) to 22.4 - 29.2 billion barrels (Ritzma) in 1979 [15].

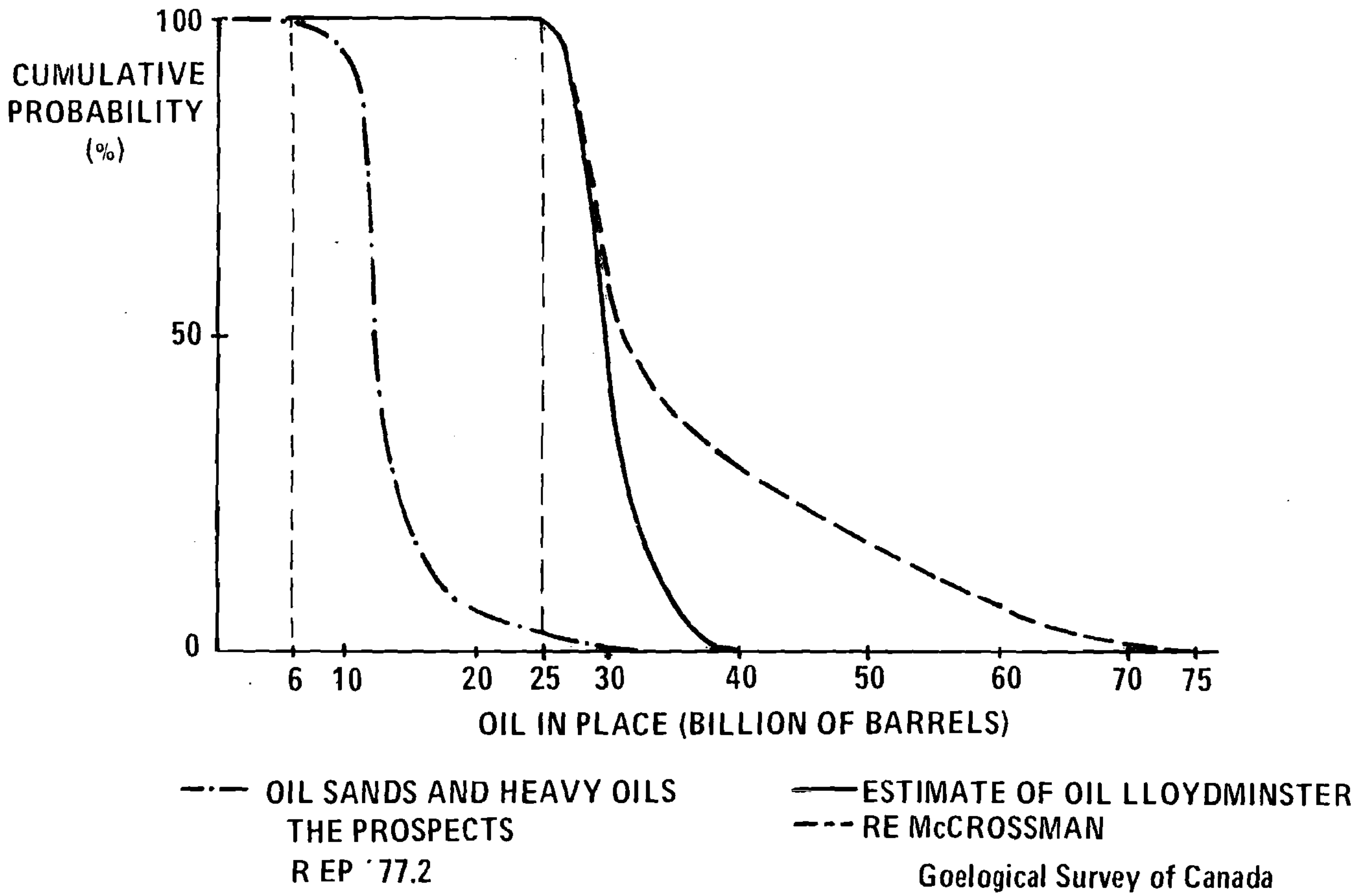
An important question is, of course: Could this be expected to be a general phenomenon, i.e. that deposits were very conservatively estimated in the past (sometimes, a long time ago, as much as a few decades) and that more recent and better assessments will upgrade them? It is premature, and unfortunately not possible, to give a definite answer to this question. However, three examples outside North America - among the few we have at hand - give some preliminary information.

- In Madagascar, a 1954 BP study (used in Meyer's assessment) [16] estimated tar sand resources at 1.79 billion barrels. A 1962 survey performed by the Malagasy Oil Company [17] arrived at a possible estimate of 22 billion barrels (3 billion toe).

- In Italy, Meyer's estimate referred to 50 million tons (about 360 million bbl) of recoverable heavy oil. The most recent AGIP assessment [18] mentions 350 million tonnes of heavy oil originally in place in developed fields and 1200 million tons of heavy OOIP in discovered but not yet developed fields. Assuming a low recovery factor of 10% (because of technical difficulties), this represents about 155 million tonnes of recoverable oil (1100 billion barrels).

- In Peru, based on previous estimates, Meyer gave 60 million barrels of recoverable reserves. At Edmonton, A.A. Pardo (Petroleos del Peru) [19] mentioned that in place reserves heavy crudes for the Maranon Basin are estimated at 1500

Figure 14. LLOYDMINSTER–AREA HEAVY OILS



million bbl. A low 10% recovery rate would lead to 150 million barrels.

These few examples illustrate, if at all necessary, the difficulties, but also the potential evolution, of such reserves and resources estimates of heavy crudes and tar sands.

Oil shales

World oil shale resources were given by Donnell at the IIASA-UNITAR Conference [20], as shown in Figures 15 and 16. In fact, most of the data originate from the excellent 1965 U.S.G.S. Circular 523 by Duncan and Swanson [21], itself a collection of old to very old data. These tables (Meyer, Duncan & Swanson, Donnell, etc.) are, in fact, first tentative answers on the global existence and/or availability of unconventional oil

Our IIASA survey permits an additional perspective; continuing again with a few examples:

- In France, 440 million barrels of oil (shale) resources according to Donnell. A three-year study (1974-1978) [22] including 35 core drillings over a broad area east of Paris plus 10 core drillings in a selected area within the broad area, has identified about seven billion barrels and more than 400 million barrels respectively, with contents of between 40 and 100 liters of oil per ton of rock (restricted to an overburden ratio of about 2).

- In Morocco, there was no estimate by Duncan and Swanson but in 1974, Matveyev [23] gave about 600 million barrels today, known resources are estimated at 1.6 billion barrels and total resources can possibly reach 5 billion barrels [24].

In contrast to these two important upward revisions, our survey has also revealed downward revisions, such as for Italy (final figure not yet known, but foreseen to be lower than the previous figure of 35 billion barrels) [25], for the United Kingdom [26],

Figure 15. KNOWN SHALE OIL RESOURCES OF THE WORLD LAND AREAS
(10^9 barrels)
(Modified from Duncan and Swanson)

Continents	Recoverable under present conditions	Marginal and submarginal
Africa	10	90
Asia	24	84
Australia and New Zealand		1
Europe	30	46
North America	80	2,120
South America	50	750
	190	3,091

Figure 16. SHALE OIL RESOURCES BY COUNTRY

	Small resources	
	10^6 m^3	10^6 barrels
Chile	3	18.9
Israel	3	18.9
Jordan	7	44.0
Tasmania	3	18.9
Turkey	3	18.9
	10^6 tons	10^6 barrels
Austria	1	8
Malagasy	4	32
Poland	6	48
	Medium resources	
	10^6 m^3	10^6 barrels
South Africa	20	125.8
Argentina	60	377.4
Australia	40	251.6
Bulgaria	20	125.8
Spain	40	251.6
France	70	440.3
Luxembourg	110	691.9
New Zealand	40	251.6
Thailand	130	817.7
Yugoslavia	30	188.7
	10^6 tons	10^6 barrels
Morocco	74	592
	Large resources	
	10^6 m^3	10^6 barrels
West Germany	320	2,012.8
Burma	320	2,012.8
Brazil	127,320	800,842.8
Canada	7,000	44,030.0
Peoples Republic of China	4,430	27,864.7
Zaire Kinshasa	16,000	100,640.0
USA	250,000	2,000,220.0
Great Britain	160	1,006.4
Italy (Sicily)	5,600	35,224.0
Sweden	400	2,516.0
USSR	17,900	112,591.0

(where data are most uncertain, but interest is very low), and for New Zealand (no available figure, but a statement - based on 20 core drillings - that resources are smaller than previously estimated and of no economic importance) [27].

Most answers indicate that, presently, resources offer little or no interest. In fact, it is clear that most, if not all of the deposits, are relatively smaller and of a smaller oil content than the Colorado oil shale deposits, and that no effort will probably be made elsewhere before the U.S. really begin to exploit their huge oil shale reserves (apart maybe from the special case of Brazil).

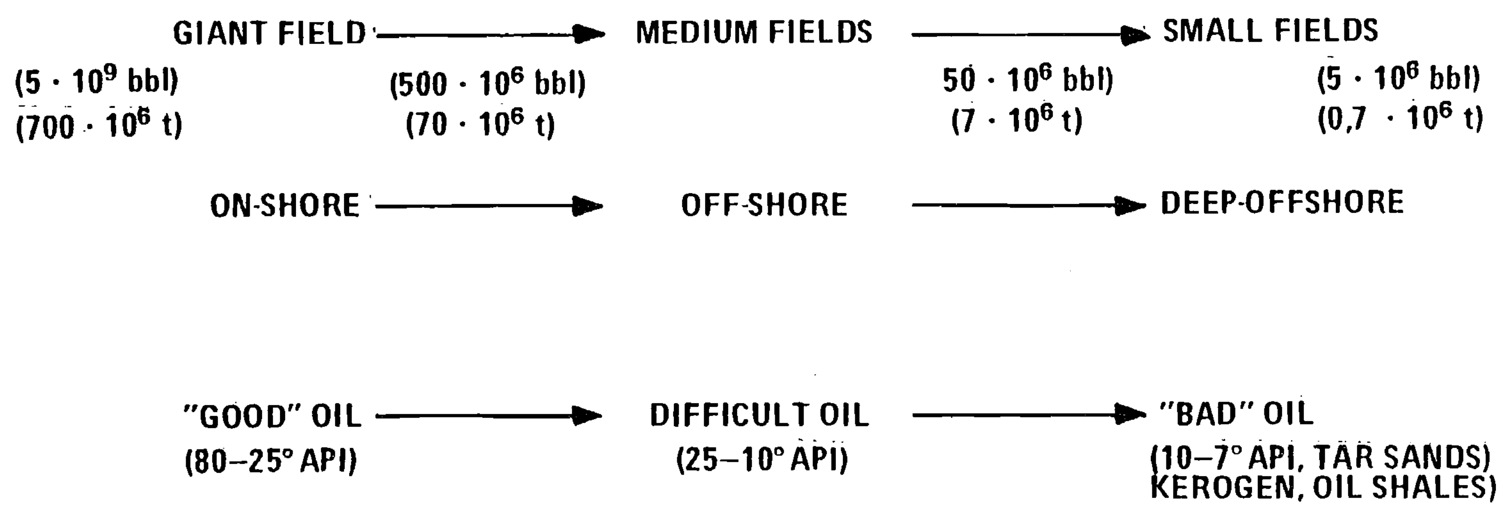
The Three Paths to Costly Oil

There is no doubt that the cost of oil - we are not speaking here of its price! - shows a rising trend, regardless of the line of development followed. We have summarized this in Figure 17.

The first path is the historical one: the oil industry, especially on-shore, shifts progressively from supergiants (larger than 700 million tons or 5 billion barrels) eagerly searched for all over the world and giant oil fields (larger than 70 million tons or 500 million barrels), which were both the most profitable - and still account for more than 70% of world oil production - to medium-size fields and finally, to small fields. Small fields already account for 15% of U.S. production. It is sometimes argued that this could happen in the U.S. because of the special situation where the wealth underground belongs to the owner of the surface: thousands and thousands of farmers have taken the risk; a few became millionaires. This only means that in other countries - if the same result is to be achieved - other or new types of incentives will have to be found. We are confident that, since it will take a long time before finding a substitute for oil, these incentives will indeed be found. National oil companies will probably be the first to benefit from them.

Looking at past world history, it is clear that there is an enormous gap in the drilling effort, as brilliantly shown by Grossling in his "Window on Oil" [28]. Regarding the prospects,

Figure 17. **THE THREE PATHS TO COSTLY OIL**



we, at IIASA, agree qualitatively with Grossling, but not "quantitatively" in the sense that we find him somewhat optimistic. But we are convinced that there is still a lot of oil to be found.

Curiously, it is interesting - but somewhat disappointing - to see how the western world has reacted to the 1973-74 crisis. This is illustrated by Figure 18 for rig activity and Figure 19 for exploratory drilling. Two conclusions can be drawn: 1) There is a continuous - and even increasing - difference between the U.S. and Canada, on the one hand and the other parts of the western world, on the other; 2) Only the U.S. and Canada have dramatically increased their search for oil and gas since the oil crisis.

From the Delphi study, a tentative supply curve for the 300 billion tons of oil remaining to be produced can be drawn (Figure 20). Incidentally, a similar curve was mentioned by Shell representatives a few months ago [29]. This means that a good part, about $^{2}/3$ of these 300 billion tons of oil, were considered to be producible at less than $12/bbl (1976 dollars)* (with corresponding investments of less than $10,000 per barrel per day capacity).

For these reasons, we think that, on a global basis, this path will remain the preferred one in coming decades, and will probably extend reasonably into the XXIst Century. It can provide sufficient time -taking into account that world consumption and/or production of oil will increase much slower than previously forecasted - for a timely penetration of unconventional oil, provided a few countries pave the way (the U.S. with the Synfuel program and Canada with tar sands).

The second path, the off-shore line, began with a technological extension of on-shore exploration and production, and was further encouraged for political reasons. Especially,

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* Let us recall that the greater part of oil today is still produced at costs probably not higher than $2/bbl.

Figure 18. WORLD RIG ACTIVITY (EXCLUDING SOCIALIST AREAS, AT 1978)

BY COUNTRIES

USA	2219
CANADA	241
MEXICO	174
ALGERIA	101
ARGENTINA	73
INDONESIA	61
BRAZIL	54
IRAN	53

VENEZUELA	41
INDIA	40
UNITED KINGDOM	34
IRAQ	29
LIBYA	28
GERMANY	25
SOUDI ARABIA	24
YUGOSLAVIA	22
BURMA	20

ABU DHABI	19
PERU	19
TRINIDAD	19
NIGERIA	18
NETHERLANDS	17
SYRIA	17
EGYPT	15
JAPAN	14
MALAYSIA	13
TURKEY	13
ITALY	12
AUSTRIA	11
AUSTRALIA	10
COLUMBIA	10
PAKISTAN	10

+ 30 COUNTRIES BETWEEN 1 AND 9 RIGS (TOTAL 120 RIGS)

BY REGIONS

SIZE OF PROSPECTIVE AREAS (SQUARE MILES)

		GROSSLING	IVANHOE
NORTH AMERICA (US + CANADA)	2460	4.421.400	
LATIN AMERICA	402	4.804.600	1.819.300
EUROPE	142	1.394.000	
MIDDLE EAST	193	1.344.800	
AFRICA	182	5.034.590	2.691.200
ASIA	186		
SOUTH PACIFIC	13		

Figure 19. FREE WORLD TOTAL EXPLORATORY WELL COMPLETION

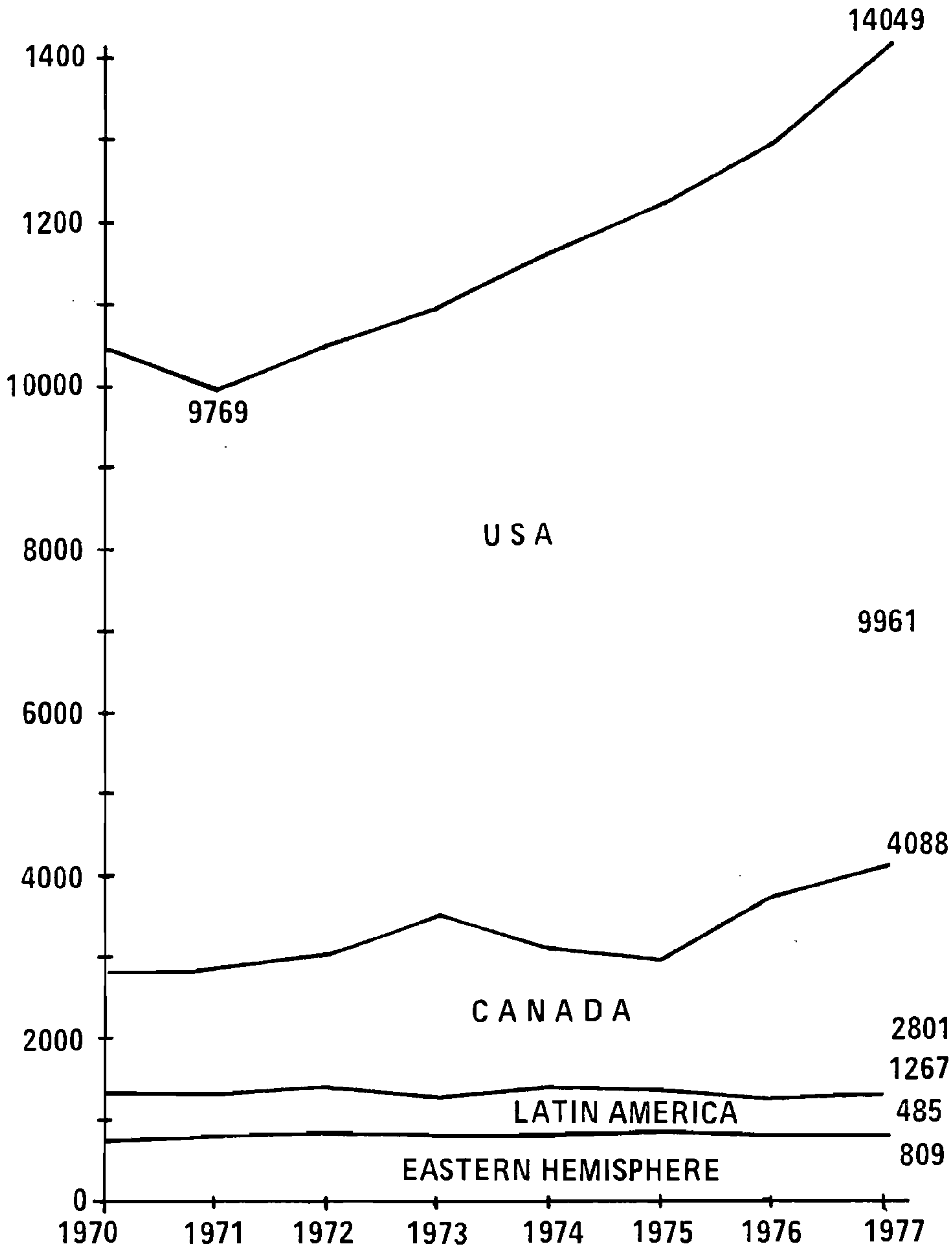
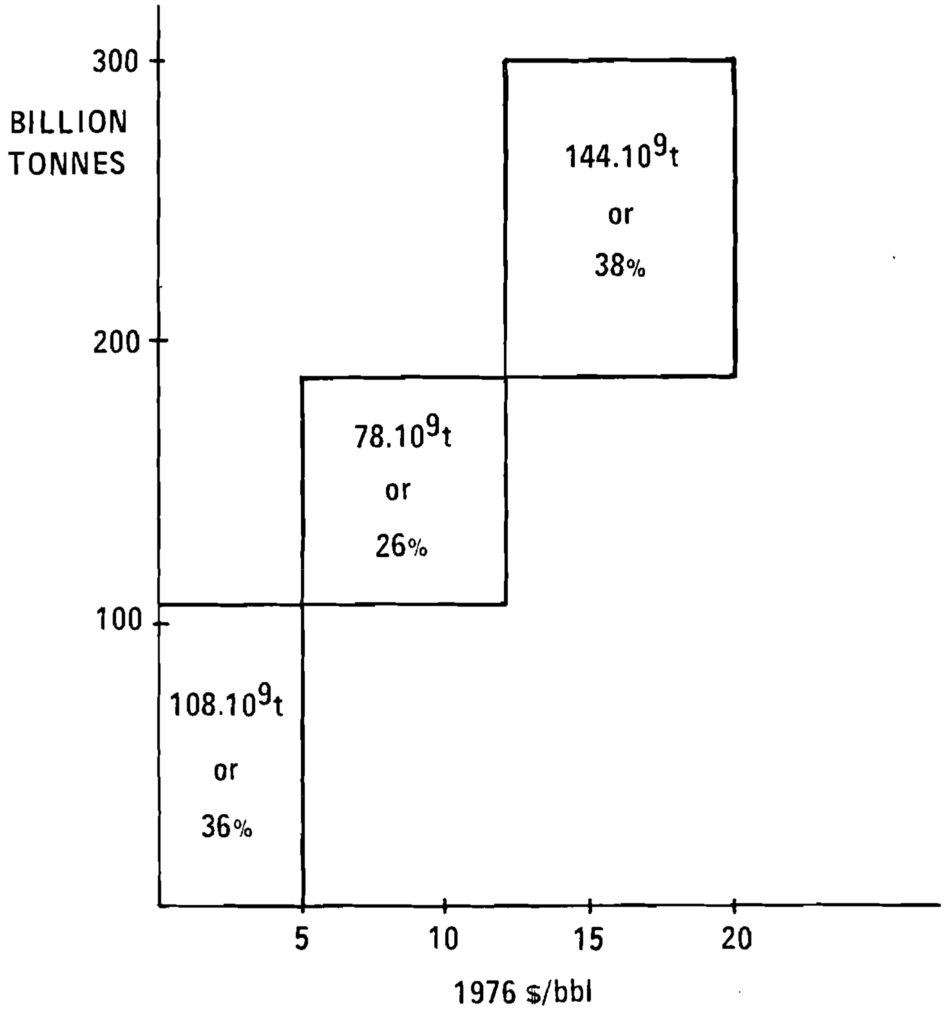


Figure 20. WORLD OIL SUPPLY CURVE, ACCORDING TO DELPHI (1977)



for instance, in the North Sea (highly appealing political stability) where the most impressive technological progress has been achieved, unfortunately accompnied by parallel and dramatic cost increases ($10,000 - 12,000/bbl per day capacity). In U.S. Atlantic off-shore, there is some disappointment, for instance with regard to Baltimore Canyon. This, together with discouraging results up to now in deep offshore, has somewhat slowed down the race to deeper and deeper water, and has led some experts to revise their previous hopes for deep offshore potential downward. Higher and higher costs are obvious, but the resources - if any - are elusive. Curiously, this path goes the opposite way to the first: going deeper and deeper unfortunately , because of increasing costs, obliges oil operators to concentrate only on the biggest deposits: giants in normal offshore (as mentioned above for North Sea "marginal" fields) and probably super-giants in deep-offsh re, unless new methods of production are developed.

The third path goes from "good oil" to "bad oil" (oil shales) passing through "difficult oil" (heavy crudes and tar sands). Such an evolution is highly technology dependent and will really occur - if it occurs - as a result of a political will and first, only in a few countries. These few countries - presumably Canada and the U.S.A. - have the double incentive of high oil consumption <u>and</u> imports and of owning the largest deposits presently known; they also have the advantage of highest technological levels. A point which is not clear, but the answer to which could be highly important at the world level, is to understand whether path three will resemble path one or path two as far as sizes of deposits are concerned. Because of the immature state of development of the technology, it is hard to anticipate whether only large to very large deposits will be producible or whether small deposits will also be producible, possibly through different methods. With our present knowledge, investments for the third path are the highest among the various steps of our three paths: $25,000 to $30,000 per barrel per day capacity for new tar sand projects in Alberta.

These very high costs (tar sands, deep offshore, oil shales, etc.) and the huge size of deposits and/or production facilities point to a necessary and permanent role of major oil companies, with the hope that the necessary steps will be taken to encourage them, or simply to keep them alive....

CONCLUSION

We are hopeful that the necessary amounts of liquid fuels can be produced, according to our curve proposed in Figure 1, with a progressive - and well-planned - penetration of unconventional oil*.

Two final comments are proposed by way of conclusion:

1. The three paths to costly oil lead, in fact, to a new dimension in oil history. Not only because of the dramatic increases in costs in monetary value, but also in costs of natural (and human) resources. Impacts on, and requirements for other natural (and human) resources will become greater and greater for producing these new sources of energy. So much so that, in fact, energy resources can no longer be considered isolated from other resources such as Water, Land, Materials and Manpower, these same resources being discussed during this U.S.G.S. Centennial Symposium. To understand these systems aspects better, we have developed the WELMM approach (Water, Energy, Land, Materials and Manpower) at IIASA and summarized our opinion in the slogan: Man does not consume energy, but WELMMITE.... A lot remains to be done to achieve a better understanding in this direction.

2. Much will depend on what will happen in the next decade in North America. If successful, these efforts will open

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* We do not underestimate the possible role of liquids from coal, but this question is somewhat outside the scope of this paper.

the way to new resources, not only for North America, but all over the world. It is with some melancholy that I must confess that, apparently, the region depending the most on oil and, unfortunately, imported oil, Western Europe, has restricted itself to a wait-and-see position....

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