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TECHNOLOGY AND PETROLEUM EXHAUSTION: EVIDENCE FROM TWO MEGA-OLDFIELDS

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ABSTRACT. In this paper we use results from the Hotelling model of non-renewable resources to examine the mainstream view among economists that improvements in recovery technology can offset declines in petroleum reserves. We present empirical evidence from two well-documented mega-oilfields: the Forties in the North Sea and the Yates in West Texas. Patterns of depletion in these two fields suggest that technology temporarily increases the rates of production at the expense of more pronounced rates of depletion in later years - in line with Hotelling's predictions. Insofar as our results are generalizable, they call into question the view of most economists that technology can mitigate absolute resource scarcity. This raises concerns about the capacity of current mega-fields to meet future oil demand.

Key Words: Non-renewable resource scarcity, technological change, oil depletion.

1. The economic view of resource scarcity

A recurring theme in resource economics textbooks is that absolute resource scarcity is not a major concern for economic policy. The standard view is that the price system, by encouraging substitution, exploration, and technological advances, in effect creates more resources as prices increase. In this view, scarcity is properly seen as an economic not a physical concept [1]. The view expressed in a recent text by Hanley, Shogren, and White [2] is typical:

> As a resource gets scarcer, its price will, other things being equal, tend to rise. This will reduce consumption (by substitution, for example), and increase production…What is more, as prices rise producers will be encouraged to engage in more exploration, which will increase the resource base if finds are made.

On the face of it, this argument is quite reasonable. However, it is one thing to accept the general statement that as a resource becomes scarce its price will rise and suppliers can profitably search for more of it and invest in technologies that boost production, but quite another to argue that the increasing scarcity of an essential resource like petroleum can be easily accommodated. The later position has been the basic message of resource economists for several decades now. The standard economic position is that scarcity is a relative, not absolute, concept and that there is nothing unique about any particular productive input, including petroleum.

Recent theoretical developments and empirical evidence suggests that economists may have been too quick to dismiss absolute scarcity. First of all it has become clear that the Walrasian general equilibrium model, upon which standard resource economics is based, depends on some strong assumptions that do not accurately describe real-world consumer or producer behavior [3], [4], [5], [6]. Theoretical economic models that address the issue of resource scarcity assume rational and fully informed agents, efficient allocation through time, and that present and future resource stocks are known. Secondly, the use of prices as indicators of absolute scarcity has been shown to be seriously misleading. Much of the empirical literature using historical prices to show that resources are not becoming scarce does not adhere to the same premises as the theoretical literature [7], [8]. Thirdly, the *ceteris paribus* assumption never holds so that we have to worry about a number complicating factors always present when dealing with non-renewable resources. These include the Jevons effect that efficiency leads to lower prices and more consumption [9], the presence of historical lock-in of built infrastructure, and the political power of vested interests dependent upon continued exploitation of a particular resource [10], just to name a few. Finally, economists tend to see technology as a free good that depends only on human ingenuity, not physical constraints [11], [12], [13]. This technological optimism has been met with a great deal of criticism during the past few years. A number of physical scientists, as well as a growing minority of economists, argue that this view overlooks the uniqueness and finiteness of oil resources.

In this paper we use a result of Hotelling [14] to examine the hypothesis that technology will mitigate the finiteness of petroleum reserves. Hotelling presented a formal analysis of non-renewable resources and derived some basic implications as to how technological investment in a finite resource affects the resource price, the extraction path, and the time until depletion.[1] Although the assumptions Hotelling used may have

[1] Reserves are classified as proven, probable or possible. To be classified as "proven" the degree of certainty must be 90% [15].

been unrealistic he was able to isolate the effect of each variable if the others are held constant. We use his basic model to analyze the production patterns of two mega oil fields: the Forties in the North Sea and the Yates field in Texas—fields that have applied advanced enhanced oil recovery (EOR) extraction technology—and examine the relationship between exhaustion rates and technological change. We find that the pattern of depletion in the Forties and Yates fields generally follows Hotelling's predictions. Our results question the traditional economic view that technology can easily overcome oil scarcity and they raise concerns about the capacity of current mega-fields to meet future oil demand.

The next section presents the basic theoretical structure of the Hotelling model of non-renewable resources. The Forties and Yates oilfield case-study results are reported in the third section. A fourth section expands on one result of the Hotelling model: the case of an increase in demand. Finally, the last section presents the conclusions of our work.

2. Hotelling revisited

It is only a small exaggeration to say that most contemporary resource economics is a footnote to Hotelling's paper "The Economics of Exhaustible Resources." [14]. Following Krautkraemer [16], the basic Hotelling equation can be written as:

$$\text{Maximize} \int e^{-\delta t}[B(q(t),S(t)) - C(q(t), S(t))]dt \qquad (1)$$

subject to:

$$\dot{S}(t) = -q(t),\ S(t) \geq 0,\ q(t) \geq 0,\ S(0) = S_0 \qquad (2)$$

where B[q(t), S(t)] represents gross benefits, C[q(t),S(t)] are the extraction costs; S is the remaining stock, δ is the rate of discount, and q(t) is the time path for resource extraction that maximizes the present value of the stream of net benefits from extraction. Notice that this key equation for resource policy only contains discounted monetary units. All information about the physical resource base comes through the price system.

It can be seen from equation (1) that any new technology that lowers extraction costs, other things being equal, will increase the net present benefits of extraction. The effect of this on the resource price and the time path of extraction are shown in Figure 1. A technological improvement that reduces extraction costs (from C to C') results in a lower resource price (the decline from P to P') at the beginning of the time path of exhaustion and a steeper rise in price at the end, and it decreases the time left until exhaustion. We argue below that Figure 1 approximates what is actually happening in the representative oil fields we examined.

If Figure 1 is an accurate description of an exhaustible resource, then its exhaustion path will show a pattern depicted in Figure 2 below. Technological change increases production for a while but then the path to exhaustion becomes steeper.
To the extent that technological advance increases present output at the expense of future output this implies that prices may be misleading indicators of future resource scarcity. Today's lower prices may be the result of extracting more of the future's resource supply. This is essentially the claim currently being made by a number of prominent energy researchers [17], [18], as well as popular writers on the subject of "peak oil" [19]. They argue that the approaching peak of world oil production is being masked by great improvements in extraction technology since the 1990s and that these technological

improvements will make the decline steeper and the price rise more rapid in the years to come. This view is summarized by Zittel [20] in the conclusion to a study of North Sea oil production:

> This analysis shows how false it is to base our confidence on oil reserves being sufficient to maintain, let alone increase current production levels. Once the peak production of large fields is passed, the situation may switch very fast. According to our experience, individual oil companies are tempted to keep a high production rate as long as possible, instead of planning to smooth the future decline. Therefore, it might be feared that future decline will be the steeper, the longer the world's oil companies try to hold high production levels.

This is essentially the same point Hotelling made in his classic paper. Is there compelling empirical evidence supporting this point of view?

3. Is Extraction Technology Masking Scarcity? Evidence from the North Sea and West Texas

In this section we present the production paths that followed in the North Sea Forties and the West Texas Yates mega oilfields using historical production data reported by the United Kingdom Department of Trade and Industry and the Railroad Commission of Texas, respectively. We purposely focus on these two well-surveyed and well-documented individual fields—rather than more aggregate examples—so as to acknowledge the strict scarcity of the resource, as assumed in Hotelling's framework.

The Forties and the Yates have been subject during their productive years to the application of enhanced oil recovery (EOR) technologies. EOR measures (also called secondary and tertiary measures) are often cited as a means of significantly increasing future recoverable reserves of oil by mobilizing resources and enhancing the recovery of oil and gas in place. EOR techniques include boosting extraction rates by better drainage of the oil in place: when the pressure in the oil field has decreased to a level where the viscosity of oil dominates the production profile leading to lower extraction rates, pressure can be raised artificially by water or gas injection, or by reducing the viscosity with the injection of steam or a chemical surfactant [21]. EOR technologies are widely used and do have the potential to enhance oil production. However, we present evidence that these measures increase the production rates only temporarily; apparently EOR reassures make it possible to extract the oil faster for a few years, but partially at least at the cost of steeper subsequent decline rates [22].

3.1. The North Sea Forties oilfield

The Forties oilfield (named Forties after the sea area in which it lies) is the first and largest oilfield in the UK North Sea; it was discovered in 1970 and rapidly became the symbol of Britain's North Sea oil boom. The time path of production in mega-fields such as this one shows a characteristic shape, slightly different from the classic bell-shaped curve shown in Figure 2. Oil companies usually try to recover high initial investments as fast as possible by initially producing the fields at high rate. Production is normally capped at the maximum flow rate that can be kept given the pipeline system's capacity and the technology in place, generating a plateau for a while. Eventually a decline in production occurs, driven by the decrease of pressure in the field and rising water levels.

Figure 3 illustrates the historical production pattern of the Forties, and Table 1 shows the change in annual production rates (extraction rates) for selected years. The field began production in 1975, and within three years, it reached a plateau at 500,000 barrels per day. This plateau lasted for about three more years before the decline started in 1981. During the period 1981-1986 yearly production declined at an average rate of 6.4 %

In an attempt to boost production and recover production rates, in 1986 an additional (fifth) oil platform[2] was built, and EOR measures were implemented in 1987 by injecting gas (CO_2) into the reservoir. EOR measures and the additional platform did reduce the decline in production to about half of the previous average (from 6.4 to 3.5 %). However, during the two following years, annual production dropped sharply, to an average rate of decline of 19.32 %. From then on, yearly production in the Forties declined at an average rate of 10.44 % (see Table 1). Technology arrested the decline in production for a year, from 1987 to 1988, but then the decline resumed at a rate steeper than before the additional investments in technology took place.

Our analysis is constrained by the fact that there is no control case available to compare what the rates of depletion might have been without the application of EOR technology. Hence, it is impossible to determine precisely the contribution of EOR measures to the ultimate recovery of the field. However, for offshore mega-fields like the Forties, plotting annual production versus cumulative production shows a characteristic

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[2] An oil platform is a large structure used to house workers and machinery needed to drill and then produce oil and natural gas in the ocean. Depending on the circumstances, the platform may be attached to the ocean floor, consist of an artificial island, or be floating.

behavior: as soon as the plateau has passed, the production decline is almost linear. Hence, the extrapolation of that decline line to the x-axis permits a good estimate of the field's ultimate recovery [23]. Figure 4 shows annual production in the Forties' field as a function of cumulative production, with a straight decline trend after the plateau.
This pattern implies that the additional platform and gas injection temporarily increased production without greatly affecting the field's ultimate total recovery. The figure suggests that once the field reached its peak production level, EOR technology only slightly altered the path of depletion and the level of ultimate recovery, contradicting the widely promoted view that technology has the potential of increasing recoverable oil reserves enough to mitigate absolute scarcity.[3]

3.2. The West Texas Yates oilfield

Another example of the effect of EOR measures occurred in the Yates oilfield – US 7th largest oilfield – located in Pecos County, West Texas. The historical pattern of production of the Yates is quite different from the pattern observed in the Forties' (see Figure 5).

The Yates field was discovered in 1926, and by 1927 reached a daily average production of 9,099 barrels of oil. The field showed an early production peak in 1929, with a production level of 41 million barrels of oil. Rates started to decline in 1930, and by 1941 had dropped to under six million barrels. Temporary measures such as observance of special rules with regards to water production in the fields allowed rates to increase again - reaching a new lower peak of 18 million barrels in 1948. After this year

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[3] A very similar pattern of production and depletion is found in another well-surveyed offshore mega-field: Prudhoe Bay, located in Alaska, United States.

however, the field experienced a continuous decline and the Railroad Commission of Texas allowed the injection of salt water and gas into producing formations. These early measures maintained pressure and retarded water encroachment, thus exposing a greater area of the reservoir to gravity drainage. By the year 1979, production in the Yates had more than doubled.

In 1984, however, the field started to show signs of decline again, and rates of production decreased continuously during the following eight years. New EOR measures were implemented at that time in an attempt to recover, once again, extraction rates: reported is the application of water flooding, polymer injection and carbon dioxide flooding in 1993. These last attempts were successful for about 4 years, but in 1997 production not only started to fall again, but it did so at rates much higher than the ones averaged in the period 1985-1993 [21].

Figure 6 shows the production of the Yates field during the period 1984-2002, and Table 2 shows the average rates of depletion that the Yates field showed before and after the EOR technology was applied. By 2002 production rates were well below the ones reported prior to the implementation of the EOR measures. Again, investment in technology temporarily recovered production rates, but it did so at the expense of a steeper rate of decline in later years.

4. Demand, royalties, and geopolitics: Hotelling once again

We have argued that the evidence indicates that technological change increases production for a while but then the path to exhaustion becomes steeper than it would have been without the new technology. *Ceteris paribus*, technological change increases resource supply and decreases the resource price for a while but results in sharply higher prices in later periods because the resource is exhausted faster than it would have been without the new technology. This implies that current prices are misleading indicators of future resource scarcity: today's lower prices are the result of extracting more of the future's resource supply. Furthermore, increasing demand for petroleum, as shown below, may complicate the worldwide situation.

The case of increased demand and enhanced recovery (resulting in a fall in production costs) can also be analyzed using Hotelling's framework (see Figure 7). An improvement in recovery technology shifts the Hotelling price path downward and rotates it to the left. An increase in demand shifts the price path up and to the left. The combined effect on price is that EOR offsets the price effect of increased demand (partially or completely) but both effects reduce the time until resource exhaustion. In figure 6, EOR reduces the time to exhaustion from T to T' and increased demand from T' to T". The implication of a possible sharp increase in demand for petroleum is that, even with the best technologies in place, we may face global oil exhaustion much sooner than what it is customarily anticipated.

Because of the rapidly growing international demand for petroleum - much of it coming from the United States and Europe, but a rapidly increasing share from China, India, and other developing nations - the world's requirement for petroleum is projected to increase considerably. If Hotelling's predictions follow, then the world may experience a much steeper rise in prices and the time of exhaustion may come sooner than expected. The case makes compelling the need for policies to encourage alternative sources of energy and conservation, and certainly the need of reconstructing a world economy whose political institutions and physical infrastructures are now based on the availability of cheap oil [24].

5. Discussion and Conclusion

Petroleum resources are not infinite on our planet and in the coming decades increasing pressure will be placed on the ability of oil to supply energy for the world's growing economies. Technological progress has been posed as the major contributor in the coming years to the mobilization of new reserves and increasing the lifetime of present reserves. In this paper we examined this hypothesis and showed evidence from two well documented mega-oilfields - the Forties in the North Sea and the Yates in West Texas - that support the counter-argument that technology, rather than substantially increasing the lifetime of present reserves, may only mask increasing absolute scarcity, in accordance with Hotelling's theoretical predictions. Technology does have the effect of increasing extraction initially and makes it possible to extract more of the petroleum in a given field, but it does so at the cost of increasing the rate of depletion – and decreasing the lifetime of the resource. Contrary to standard economic assumptions, temporary low prices may be misleading indicators of the ability of the economy to adjust to resource exhaustion. The Classical economists were aware of this but contemporary welfare economics has all but abandoned concern with real, physical production processes in favor of abstract models of exchange in an idealized purely mathematical framework.

If our results are generalizable they have serious implications for future world oil supply. If the pattern of depletion in the Forties and the Yates oilfields holds for the mega-fields in the Middle East this does not bode well for future petroleum supply and prices. Saudi Arabia - the world's leading oil producer – will soon face the peaking of its already mature giant fields. The case is made explicit by Simmons [15]: most of Saudi Arabia's oil output is generated by a few giant fields, of which Ghawar - the world's largest - is the most prolific. While the Yates and Forties fields at their peaks produced about 30 million barrels of oil a year, the Ghawar field has produced at at rate of 10 million barrels *per day.* The giant Saudi fields are aging (they were first developed 40 to 50 years ago), and are already subject to EOR measures (water injection and other secondary measures) to maintain high levels of production and compensate for the drop in natural field pressure. If the pattern of exhaustion of these fields follows the ones shown in the Forties and Yates, then we can expect accelerated rates of depletion some time in the near future. In addition, as time goes on, the ratio of water to oil in these underground fields will rise to the point where further oil extraction will become difficult, if not impossible. According to Simmons [15] there is little reason to assume that future Saudi exploration will result in the discovery of new fields large enough to replace those now in decline.

We have gathered and analyzed data for two of the three regions in the world that do actually publicly report historical production for individual fields - namely the United Kingdom, the United States and Norway. Individual oilfield estimates are confidential in most other countries, and are available only at great expense from commercial databases of variable quality [25]. Although results from two fields alone do not make by themselves a solid case that technology accelerates depletion, they should lead the way to a larger analysis. It is impossible to predict with any degree of reliability what the future rates of oil production are likely to be without first understanding field-by-field depletion rates [26]. It becomes critical then to develop and release reserve estimates, particularly for the mega-fields in Saudi Arabia, if we are to evaluate where the future of oil production, upon which the world's economies now depend.

Our study shows that details are important. It is not enough to say that technology will call forth substitutes as oil is exhausted. The critical question is how rapidly supplies are depleted and how rapidly quality substitutes can be made available at reasonable prices. EOR methods may just accelerate depletion of existing reserves OR they may accelerate depletion and capture significant additional reserves. In this paper we make a tentative case that, for two large fields at least, the first possibility was the case. What happens in other fields and for the industry as a whole depends critically on the physical characteristics of the fields and the nature of new technology. Can new technology improve the recovery rate significantly beyond the current 35% average? To our knowledge there is no technology now on the horizon that would do that. As we move down the depletion curve the energy return on energy invested (EROI) [27] will decrease. This is important since on the way up the peak EROI acts as a push and on the way down acts as a pull on the economic feasibility of recovery. With its low extraction costs and flexibility petroleum is a unique source of energy far superior to any suggested alternatives. The "peak oil" debate has become polarized between those who say "there is nothing to worry about, technology will solve everything" and "we're about to run out of oil and world's economies will collapse." Either one of these statements may be true and the realistic answer may not be in the middle. But the first step in gauging the implications of peak oil is to critically examine what has happened in the past and try to extrapolate the results to the future.

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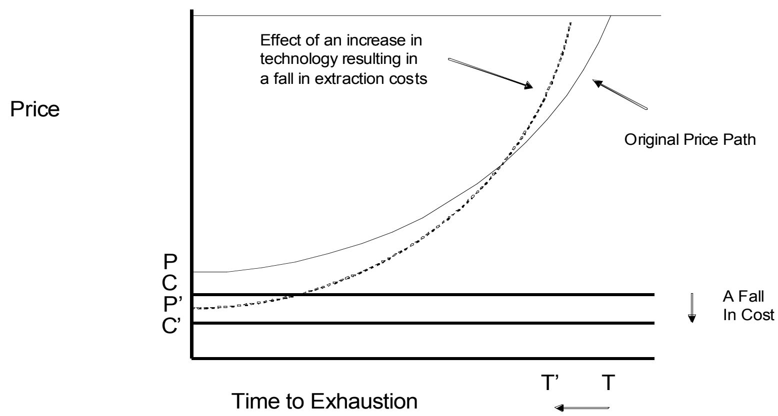

Fig. 1. Hotelling on technological change that lowers cost
Adapted from Pearce and Turner [28].

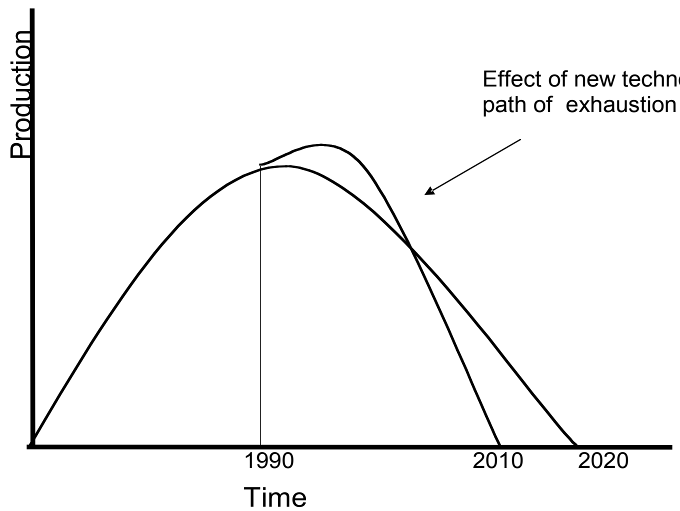

Fig. 2. Technological advance masks impending production declines

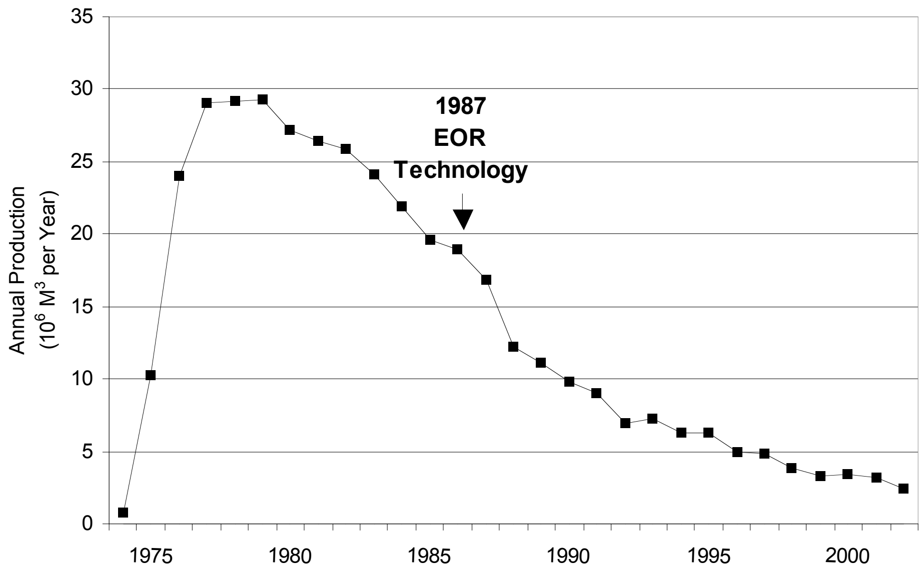

Fig. 3. Historical pattern of production in the Forties oilfield (UK)
Data Source: UK Department of Trade and Industry

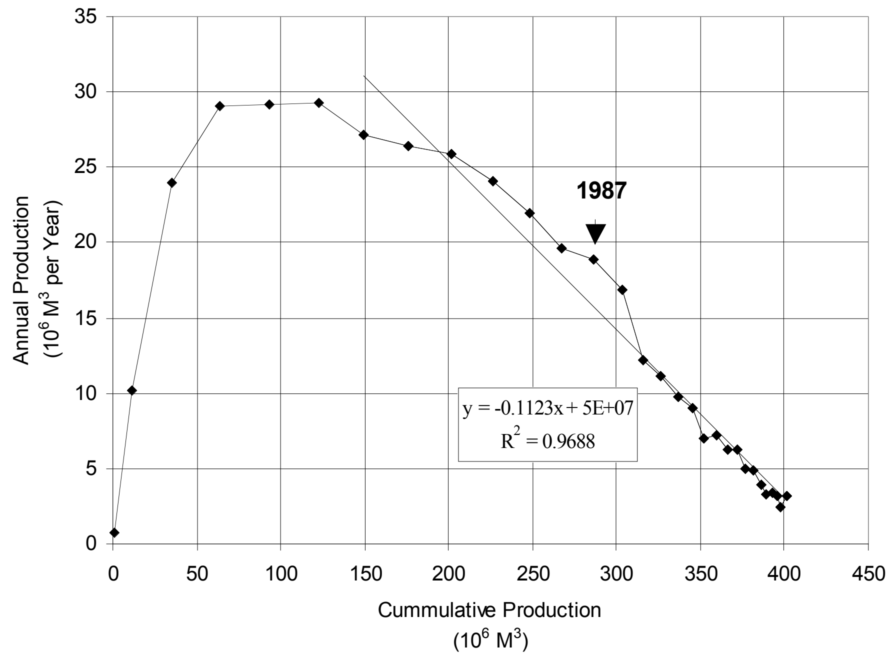

Fig. 4. Pattern of cumulative production of the Forties oilfield (UK)
Data Source: UK Department of Trade and Industry

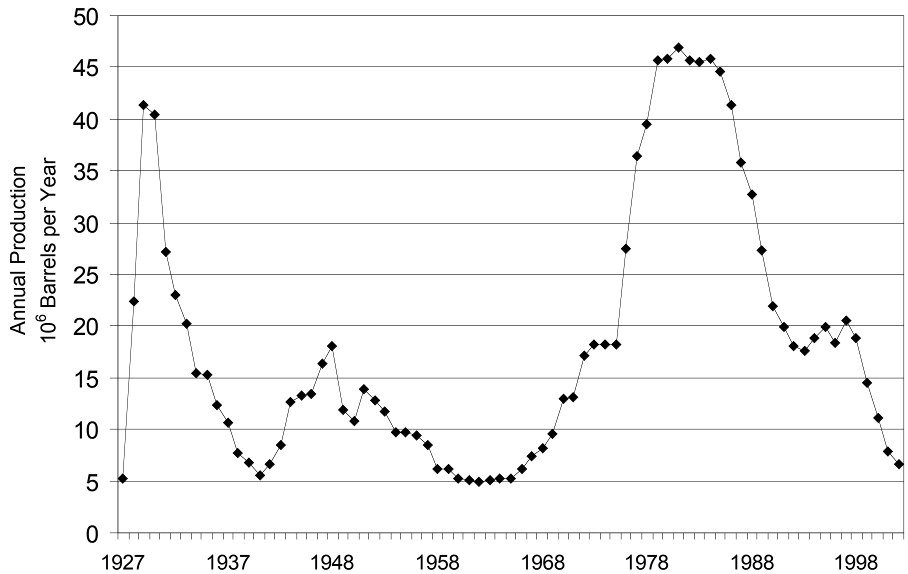

Fig. 5. Historical Pattern of Production of the Yates Oilfield
Data Source: Railroad Commission of Texas

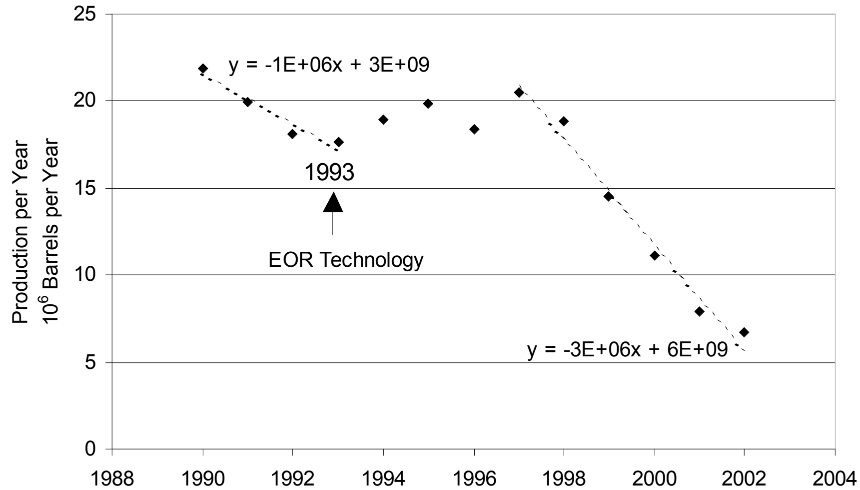

Fig. 6. Pattern of Production of the Yates Oilfield during the period 1998-2002

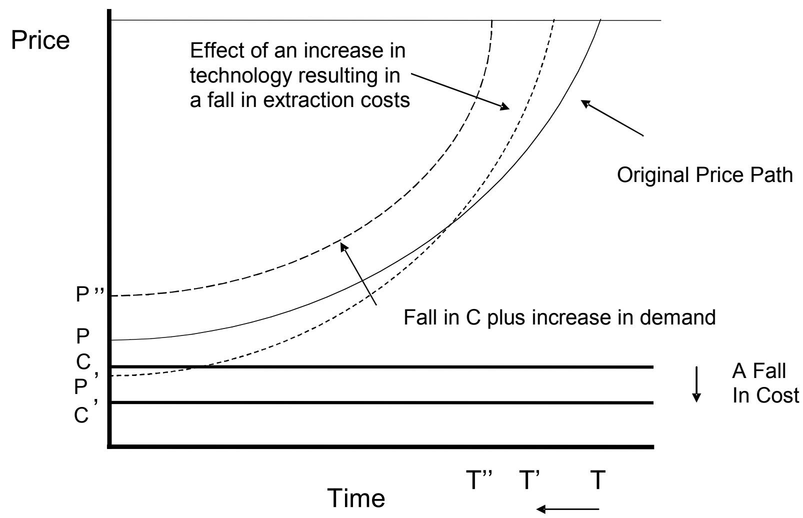

Fig. 7: The effects of EOR technology and increasing demand

Table 1
Evolution of extraction rates in the Forties (UK) in selected years

Selected Years	**Average Change in Extraction per Year**	
	10^6 M^3	%
1975-1978	9.45	473.25
1979-1980	0.84	0.29
1981-1986	-1.60	-6.40
1987	-0.69	-3.54
1988-1989	-3.37	-19.32
1990-2003	-0.70	-10.44

Table 2
Evolution of extraction rates in the Yates (Texas, USA) in selected years

Selected Years	**Change in Extraction per Year**	
	10^6 Barrels per Year	%
1991	-1.86	-8.49
1992	-1.90	-9.51
1993	-0.47	-2.60
1994	1.27	7.21
1995	0.96	5.07
1996	0.24	1.20
1997	0.42	2.11
1998	-1.70	-8.29
1999	-1.86	-22.95
2000	-3.38	-23.30
2001	-1.86	-29.20
2002	-1.17	-14.84