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Global Oil Reserves – Recovery Factors Leave Vast Target for EOR Technologies.

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Since 2003 prompt and long term oil prices have been constantly climbing to levels ($70-80) that have caught everyone by surprise. The erosion of large spare capacity in the oil chain and the perception that surging demand[1] [2] will eventually outpace supplies are the two key commonly cited fundamental reasons for the escalation in prices. At the heart of the argument is that global oil resources are scarce and stretched, hence the industry will struggle to deliver incremental supplies. This consensus view is underpinned by several themes: limited access to some hydrocarbon rich regions, two decades of a sluggish worldwide exploration record, poor expectation of finding new oil provinces, increasing number of mature basins that are on production, among others.

Obviously, resources and supplies are finite but to conclude that global oil resources are stretched or that the industry is or will be unable to replace production is a myth. Consider the fact that we have consumed less than 8 percent (1 trillion barrels, Tb) of the vast volumes of oil that have been discovered so far – a resource base of 9.6 Tb of conventional and 3 Tb of non-conventional crude oil. Resource base is here defined as the original oil in place (OOIP) associated with proved reserves. Assuming a conservative average overall recovery factor of 22% for the conventional proved reserves of crude oil discovered to date (2,158 Bbo, Table 1) would establish a global resource base of 9.8 Tbo. Regarding the non conventional resources, the combined OOIP for the Canadian and Orinoco oil sands, the two largest accumulations of its kind in the world, has been reliably established at 3Tbo; proved reserves of 300 billion (Bbo) correspond to a 10 percent recovery factor obtained from current and future known field projects. More resources of this type and oil shales have been quantified elsewhere. At best they are considered contingent resources – they have not yet been proven economically recoverable.

It is physically impossible to recover and produce all of the oil in the ground, but the industry is leaving behind as much as 78% of the oil discovered in fields that have been abandoned for whatever reason or in their late stages of depletion. Looking at the future, a tenable long term goal would be to produce 70% of the resource base of conventional oils and 30% of the non-conventional extra heavy oils. And for this, EOR (enhanced oil recovery) techniques are the only alternative. What is at stake is that each percentage point improvement would unlock vast amounts of oil reserves (and production) from known reservoirs, and thus reduce the need to rely so heavily on new discoveries.

From a supply point of view, it is a fact that many of the known basins are mature [either stable or declining] whilst fewer are growing, immature or remain to be explored. There is no doubt that the incremental sources of supply will depend on the continued development of known resources, onshore Middle East and North Africa, unconventional oils, new offshore fields[3], and oil from new difficult basins.

[1] "Facing the Hard Truths about Energy", NPC Report, July 18, 2007
[2] "World Oil Outlook through 2030", OPEC Report, June 26, 2007.
[3] Moritis, Guntis, "Upstream Production Capacities to Advance in many Countries", Oil & Gas Journal, July 23, 2007.

Although EOR production accounts for only 3% of world oil production, in the near term its potential could be significant in extending the current plateau of world onshore and mature offshore production[4].

The objective of this paper is to estimate global oil resources based on a heuristic analysis of the recovery efficiency of the existing proved reserves, with a view to determine how much these reserves can be expanded by boosting their recovery factor through technology proven EOR. The reserves are sorted by oil gravity and depth which are key parameters used in the screening of oil reservoirs to establish the most viable EOR techniques. The impact of EOR on future supplies is also discussed.

EOR's Competitiveness

It is a simple fact that the economics of finding new oil in most regions of the world have been much more attractive than squeezing out the oil from aging fields. Global F&D costs[5] were $14.42 a barrel in 2006, up a whopping 29% from the previous year. Development capex for high end deepwater fields[6] with built-in pressure maintenance (gas and water injection) projects run between $4 and $6 per added barrel of reserves, with production costs in the $3-4 range. For non conventional oils, development costs for recent projects in the Canadian and Orinoco oil sands range from $4.30 to $6.25 per barrel of added reserves. Production costs for cold production are $6, and $17 with steam generation.

In contrast, capex for development of EOR projects is nearly $2 per added barrel, varying somewhat with field location, well depth, number of existing wells that can be converted for injection, source of CO_2, etc. EOR production costs – those above conventional operating costs – however, can be high depending on the cost of chemicals, of steam generation which utilizes natural gas ($10 per added barrel), and the cost of CO_2, roughly $10 per added barrel in the U.S. Incentives for CO_2 capture/sequestration could further lower the infrastructure costs associated with CO_2 delivery to the oil field, particularly those offshore.

The bottom line is that EOR capex is now very competitive with F&D costs and also with reserves acquisitions[7] which averaged $12.86 a barrel worldwide in 2006.

Global Oil Recovery Factor

Oil recovery factor is the percent of the in-place oil discovered that is technically recoverable. The *primary* phase of oil production from a reservoir depends on its existing natural energy source which may be one of several (see Table 2). Solution gas drive is the most widespread natural drive mechanism in the majority of the world's reservoirs and can provide a recovery of up to 20% of OOIP. This primary process is normally supplemented early in the life of the reservoir by *secondary recovery* or improved oil recovery (IOR) processes consisting of stranded gas reinjection and water flooding. Roughly one-third of the world's reservoirs have natural water drives.

When secondary recovery processes are implemented from the start of production - as is now standard practice with new oil fields - or later on during the primary phase, the process is referred to as 'pressure maintenance'. Although recovery rates of up to 70% are theoretically possible, values above 60% are very rare; they are more in the range of 45-50%.

Tertiary or EOR methods are applied at the end of the secondary phase. They can be thermal, miscible or chemical processes which attempt to sweep out as much as possible of the remaining oil. The most ubiquitous of these techniques is CO_2 flooding for medium and light oils. The 30-year history of this technology in the U.S and other countries indicates that it is possible to recover an additional 7-15% after

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[4] Sandrea, Ivan and Sandrea, Rafael, "Global Offshore Oil – Growth expected in global offshore crude oil supplies", Oil & Gas Journal, March 5 & 12, 2007.
[5] Dittrick, Paula, "Worldwide E&P spending reaches record", O&GJ, Sept. 3, 2007
[6] Goldman Sachs Global Energy Report, February 20, 2007.
[7] Editorial, Oil & Gas Financial Journal, April 2007.

water flooding. Lake et al[8] give an excellent review of the three major EOR processes, their limits in regard to oil viscosity, permeability and depth of the reservoirs.

Large scale injection of standard fluids like natural gas and water to supplement the natural energy of the reservoir was not the norm in the international arena until the 1960s. Even today, the large reservoirs are the ones generally selected. Moreover, not all IOR/EOR techniques are applicable to all reservoirs and reserves types. As a result considerable numbers of reservoirs, especially in medium and small fields which account for 50% of world production, have been left untouched by secondary recovery processes.

As a general rule, a recovery factor of 15-20%, corresponding to the solution gas drive mechanism, is usually the first estimate for a new discovery until other production mechanisms have been observed in the field. Case in point is the recent certification of the China Nanpu[9] offshore oil find; PetroChina had originally assigned a recovery factor of 40% which was subsequently downgraded to 20%.

Recovery estimates for heavy oils (< 22.3 ^{o}API) range from 10-15% for primary, 20-25% with secondary and an additional 2-6% with EOR, for a total of 30%. Extra heavy oils (≤ 10 ^{o}API) are unique. The very viscous ones may be unproducible by primary means and are subjected to steam injection from the onset as is the case of the Canadian oil sands. Their recovery factor is 10%. For the Orinoco, primary recovery by solution gas drive (referred to as cold production) is also 10%; an additional 10-15% is estimated with EOR processes still to be tested.

How can we get an estimate of the overall recovery factor associated with the existing world reserves of more than 40,000 oil fields each with multiple reservoirs? A baseline estimate is necessary so as to determine how much room there is for IOR and EOR growth. Several statistical estimates ranging from 27% to 35% have been mentioned in the literature. In a recent study of 11,242 fields, Laherrere obtained a worldwide average of 27%. Harper studied 9,000 fields and came up with a mean of 30%. The USGS estimates[10] a worldwide recovery factor of 40%.

An overall recovery factor of 22% was reported for the U.S in 1979. It had increased to 35% by 1999 and would be about 39% today if the trend continued. The overall recovery efficiency for the North Sea province is currently 46%, the highest in the world thanks to sound IOR management applied throughout the life of the fields. Examples of top oil fields include the Statfjord field with a record recovery efficiency of 66% without EOR! Prudhoe Bay is expected to reach 47% due to early gas and water injection, followed later by miscible HC gas flooding.

A heuristic approach to estimating an overall worldwide recovery factor based on proved reserves might be useful. Proved reserves by definition encompass everything geologic and engineering that has been applied to every one of the oil fields ever discovered. Let's examine two cases, the U.S and Saudi Arabia. The U.S has a resource base[11] of 582 Bbo, and Saudi Arabia[12] 700 Bbo. Decline curve analysis[13], which is based on production from proved reserves, establishes URRs of 225 Bbo and 165 Bbo for the U.S and Saudi Arabia, respectively. The corresponding recovery factors are 39% and 23%.

It is worth noting that Saudi Arabia's recovery efficiency of 23% is at the level of the U.S average in 1979. Most of their reservoirs have been produced by primary and secondary methods; other IOR technologies

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[8] Lake, Larry W., Schmidt, Raymond L. and Venuto, Paul B., "A Niche for Enhanced Oil Recovery in the 1990s", Schlumberger Oilfield Review, January 1992.

[9] "China Nanpu Oil Find Shows Pitfalls of Estimating Reserves", Rigzone News, Aug.17, 2007.

[10] Verma, M. K., "The Significance of Field Growth and the Role of Enhanced Oil Recovery", USGS Report, 2000. www.pubs.usgs.gov.

[11] Technical Updates, DOE, March, 2006.

[12] Saleri, N.G., Oil and Gas Journal, pg 25, Oct. 4, 2004.

[13] Sandrea, R. "What About Deffeyes' Prediction that Oil will Peak in 2005?" MEES – Middle East Economic Survey, Vol. 48-No.37, Sept. 12, 2005.

are also being applied to reservoirs that are among the largest in the world. Most of their pressure maintenance programs, however, went into effect after substantial volumes of oil had been produced from the reservoirs. In the case of Ghawar, gas and water injection began more than 10 years after production start-up (1951). Experience in the North Sea indicates that reservoirs with delayed pressure maintenance programs have recoveries of up to 10 percentage points less than their counterparts that start in from day one.

Of the OPEC countries which together hold almost two-thirds of the world's reserves, Saudi Arabia's average recovery factor of 23% is in the upper echelon. Venezuela, the OPEC member with the most experience (since the 1950s) with both secondary and tertiary recovery projects, also has an overall recovery factor of 23%. Consequently, by analogy the overall recovery factor for the bulk of the world's conventional oil reserves would at best be about 20%. A simple weighted average among the major oil provinces gives an average recovery factor of 22%. This is well within the range of solution gas drive reservoirs (15-25%) with some added IOR technology effects, which are the most widespread in the world. This is the recovery value used in this paper to estimate the world's conventional oil resource base of 9.8 Tbo. The total global oil resource base would be 12.8 Tbo, including the 3 Tbo of non conventional oil. Schlumberger's[14] estimate of global oil resources is 9-13 Tbo while the AAPG's[15] is 9-11 Tbo.

Classifying the Oil Resource Base

Within a broad context, the applicability of the assortment of IOR and EOR technologies depends by and large on two factors: the API gravity of the oils and the depth of the reservoirs. In reality, the proper technical selection parameters are the oil viscosity and the reservoir pressure. These, however, are related empirically to oil gravity and reservoir depth, respectively.

World oil reserves were sorted by API gravity and depth. The gravity classifications are: light (> 35 ◦API), medium (26-35 ◦API), heavy (10^+ **-** < 26 ◦API) and extra heavy (≤ 10 ◦API). The upper tiers for heavy and medium gravity oils were changed slightly from the official definitions to better reflect limits of successful field EOR projects. The same is true for the depth classifications selected: shallow (< 3,500 feet), intermediate (3,500-10,000 feet) and deep (>10,000 feet). Tables 3 and 4 summarize the results of both sorts. These groupings provide a convenient core for classifying the coupled resource base.

Fig. 1 illustrates the gravity distribution of the world's total oil resources of 12.8 Tbo. Light and medium gravity oils make up two-thirds of the total resources while heavy and extra heavy oils make up the other third. Fig. 2 shows the depth distribution of the oil resources. Roughly one-third of the total resources are located at shallow depths which as expected matches the volumes of heavy and extra heavy oils. A similar correspondence is observed between medium gravity oils (44%) and reservoirs at intermediate depths (45%), also between light oils (22%) and deep reservoirs (21%).

Shallow reservoirs with heavy and extra heavy oils are the best disposed to steam injection processes. Intermediate and deep reservoirs with oils above 30 ◦API are the ones best adapted to miscible CO_2 injection. Other miscible processes with N_2, HC gases and flue gases require reservoirs deeper than 5,000 feet. Polymer and other chemical processes are limited mostly by temperatures, usually intermediate depth reservoirs with oils in the range of 15-30 ◦API. In situ combustion has no depth restriction, but oils below 30 ◦API are preferable.

EOR and Future Oil Production

According to the Oil & Gas Journal's Worldwide EOR Surveys, the volume of oil produced by EOR methods doubled from 1982 to 1990 (1.2 mb/d), and doubled again to 2.5 million barrels a day (mb/d) in 2006. U.S EOR production is 649,000 b/d, roughly 14% of total U.S. production. Worldwide, Oil & Gas

[14] "Highlighting Heavy Oil", Schlumberger Oilfield Review, Summer, 2006.
[15] "AAPG Hedberg Conference", Nov. 12-17, 2006, Colorado, USA

Journal found 303 active EOR projects[16], and the single largest – steam injection in the Duri field of Indonesia – produces 220,000 b/d. Four countries – USA (153), Canada (45), Venezuela (41), and China (39) – account for 92% of the total number of projects. Table 5 gives an overview of the general characteristics of these field projects: number of projects by type, minimum and maximum EOR production rates, depth and API gravity ranges. Twenty-nine new projects (CO_2, 16; Steam, 6; Polymer, 4; and Combustion, 4) were planned for 2006-07.

A one percent increase of global recovery efficiency would bring forth 88 Bbo of expanded conventional oil reserves, sufficient to replace *three* years of world production at current rates of 27 Bbo a year. The contribution of unconventional resources is not included because these are new – so far less than 7 Bbo (~0.2%) have been produced. Large-scale application of conventional EOR will impact the production profile of the world very much in the same way it has been until now – adding more production and by easing the decline of mature fields. It would throw in roughly 1 mb/d for every 10 Bbo of added reserves. The EOR capex required to develop 88 Bbo of added reserves is estimated to be about $190 billion, roughly 80% of the global E&P capex for 2006. A well-timed disposition to make outlays of this magnitude will eventually determine the impact of EOR on future global supplies. The oil potential is there.

Final Remarks

- Now that oil prices are soaring and have a long-term perspective of staying much higher than historical levels, cash flow is at a high which is good for EOR. EOR can unlock already discovered, remaining buried resources in existing fields which are estimated at 11.8 Tbo worldwide. All resource holders should consider the benefits of this new and growing opportunity.
- The recovery factor for the bulk of the world's conventional reserves is around 22% so there is plenty of room for growth. For non conventional extra heavy oils, the current recovery factor is 10%; an additional 10-15% is possible for both the Canadian and Orinoco sands. Cumulative production to date is still insignificant, barely 2% of reserves.
- The North Sea fields have the best overall record of recovery, averaging 46%. The U.S follows with 39%. Oil fields with top recovery factors are Statfjord (North Sea) and Prudhoe Bay (U.S) with 66% and 47%, respectively.
- Worldwide, a one percent increase in the global recovery factor represents 88 Bbo of added conventional reserves, equivalent to the replacement of *three* years of global production. The estimated capex required to develop these reserves is roughly $190 billion (bn), corresponding to 80% of the global E&P capex outlays ($236 bn) in 2006. The impact of EOR on future global oil supplies depends on the disposition to make significant investments over the long term.
- Successful IOR/EOR projects are long-lived, manpower intensive, may need long lead times to do the R&D vital to the tailoring of the processes, and require constant sophisticated engineering monitoring. Two-thirds of the world's resource base is located in countries which have strong NOCs and/or policies with restrictive access to IOCs which have some of the best EOR technologies.
- Offshore, with a resource base of 2.7 Tbo, has its own complexities that make difficult the application of EOR techniques. Reservoirs can be deep (up to 40,000 feet), drilling infill wells are costly and wells per platform are usually fixed. In other words, EOR should be incorporated in the master plan of the field for maximum results.

EOR's role is primarily one of extracting the last technically extractable drop of oil from the reservoir while extending the economic life of the abundant mature oil fields. Its contribution will be crucial for the continued expansion of world oil production. EOR is quite a challenge, both technologically and economically, but it is worth pursuing.

[16] "Worldwide EOR Survey", Oil & Gas Journal, April 17, 2006.

Table 1: Regional Distribution of Global Oil Reserves

	Remaining Reserves (1P) - 2006			
	Conventional		**Non-Conventional**	
	Bbo	**%**	**Bbo**	**%**
Middle East	734	64		
FSU	78	7		
South America	62	5	128[1]	44
North Africa	60	5		
West Africa	46	4		
North America	41	4	165[2]	56
North Sea	14	1		
Others	112	10		
World Rem. Reserves	**1147**	**100**	**293**	**100**
Cum. Production	**1011**		**7**	
World URR	**2158**		**300**	
Est. OOIP[3]	**9800**		**3000**	

Notes: [1] Orinoco oil belt; [2] Canadian oil sands; [3] *Est. OOIP* = URR/RF; RF is Recovery Factor assumed 22% for conventional and 10% for non conventional oils.
Sources: O&GJ, ENI, OPEC.

Table 2: Expected Oil Recovery Efficiencies, % OOIP

Primary Methods		
Liquid and rock expansion	up to	5%
Solution gas drive		20
Gas cap expansion		30
Gravity drainage		40
Water influx		60
Secondary Methods	up to	70
Gas re-injection		
Water flooding		
Tertiary Methods	up to	80
Thermal (Steam, Combustion, Hot water)		
Miscible (CO_2, HC gases, N_2, Flue gas)		
Chemical (Polymers, Surfactants)		

Table 3: Distribution of Global Oil Reserves by API Gravity

	Remaining Reserves (1P) - 2006			
	Conventional		Non-Conventional	
	Bbo	%	Bbo	%
Light (>35 API)	332	29	-	-
Medium (26 – 35 API)	653	57	-	-
Heavy (<26 API)	162	14		
XHeavy (≤10 API)			293*	100
World	**1147**	**100**	**293**	**100**

Notes: * Canadian (165Bbo; 8-14 ◦API; 4.8 %S) and Orinoco oil sands (128 Bbo; 8.5-9.3 ◦API; 2.5-4.0 %S).
Sources: IHS, ENI, RepsolYPF, Credit Suisse.

Table 4: Distribution of Global Oil Reserves by Depth

	Remaining Reserves (1P) - 2006			
	Conventional		Non-Conventional	
	Bbo	%	Bbo	%
Shallow < 3,500 feet	163	14	293	100
Intermediate 3,500 – 10,000 feet	663	58		
Deep >10,000 feet	321	28		
World	**1147**	**100**	**293**	**100**

Sources: IHS, Credit Suisse.

Table 5: Characteristics of Active EOR Projects

Type	No of Projects	Production, b/d	Depth, ft	API
Steam	119	76 – 220,000	350 – 5,740	8 - 26
CO_2	94	100 – 35,000	1,900 – 10,900	19 - 43
HC gases	38	10 – 80,000	4,040 – 14,500	15 - 45
Combustion	21	100 – 8,100	1,640 – 9,500	18 - 38
Polymer	20	53 – 4,900	1,063 – 4,626	21 - 34
Nitrogen	5	1,000 – 500,000*	4,600 – 15,400	16 - 51

* Estimated for the Cantarell project.
Source: O&GJ Worldwide EOR Survey, 2006

Figure 1: World Oil Resources by API Gravity, trillion barrels 2006

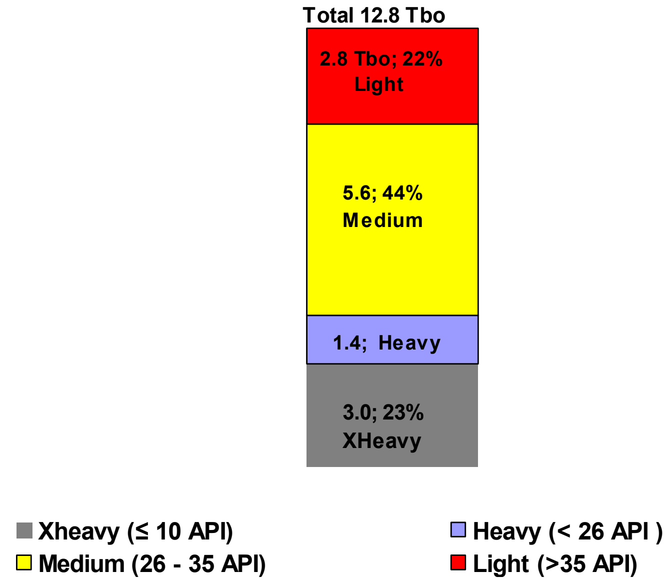

Figure 2: World Oil Resources by Depth, trillion barrels 2006