Resources – Exploration and Production

Outline

- Resources vs. Reserves
- Contracts
- Drilling Process
- R/P, Success rate, Recovery factor
- Production Profile
- Oil Price

Prof. Metin Çakanyıldırım used various resources to prepare this document for teaching/training. To use this in your own course/training, please obtain permission from Prof. Çakanyıldırım. If you find any inaccuracies, please contact metin@utdallas.edu for corrections. Updated in Spring 2020.
Oil & Gas Reservoir
From Resources (Reservoirs) to Reserves

- Inaccessible: Alaska or Polar Zones.
- Unidentifiable: Unknown reserves in accessible areas
- Technically infeasible: Unextractable resources (Heavy oil) in known / accessible reserves.
- Unprofitable: Production costs more than sales price.

In the future, environmental issues can be an additional factor between Resources and Reserves.
- NY State banned fracking in 2015.
- Denton, TX banned fracking with a city ordinance in Nov 4, 2014 election. City is sued by the Texas General Land Office in Travis County Court and Oil and Gas Association in Denton County Court.
Forecasting Reserves

**Optimist:** Reserves might be increasing
- When reserves drop
- Price increases
- Unprofitable becomes profitable
- Reserves increase

Other types of energy become available
- Gas powered car substituted by electric car

**Pessimist:** Resources are decreasing
- Finite amount of hydrocarbons
- Resources are decreasing
- Price will dramatically increase
  - Barring from politically caused price increases in the 1970s, no dramatic price increases in oil price.
- Perhaps, we should be optimist in the short run but be very careful in the long run.

Estimates of oil reserves in the early 2000s:
- 1200 Giga (billion) barrels remaining
- 1000 Giga barrels (Gbbl) future discovery
- 900 Gbbl enhanced recovery
Exploration, Drilling, Completing, Production Flowchart

Reconnaissance Survey of a large area

Geophysical and Geological (G&G) Survey
  - Satellite photos
  - 3D or 4D Seismic surveys
  - Magnetic surveys

Detailed Survey of an area of interest

Detailed G & G Survey
  - Closely spaced Magnetic, Gravity & Seismic surveys

Promising? Yes

Lease

Seismic Study to Identify Drill Site

Drill and Collect Well Logs

Sufficient Oil or Gas likely?

No

Yes

Complete the Well and Produce

Plug & Abandon the Well

No

Yes
Echoes from Far Under the Ground
Map Subterranean Formations

In an apparatus called a geophone, vibrations produced by an explosion and reflected by underground formations are picked up by buried detectors, like the one at the right, and used to chart possible oil pools.
Geophysical Surveys: Seismic

- 2D Seismic Survey: Geo-(hydro) phones on a single line to survey a strip of the land. Generate seismic waves by shaking the ground with a device called vibrasizer and collect the reflected waves from the rocks.
- 3D Seismic Survey: Geo-(hydro) phones on a grid to survey with the possibility of reflecting sound wave on the same subsurface grid from different angles.
- 4D Seismic Surveys: 3D surveys of the same formations at different times.

- 4C surveys use shear waves in addition to compressional waves. Shear waves are not distorted by oil or gas in the sedimentary rock and have different speeds in different rocks (p.233-234 of Hyne).
Geophysical Surveys: Gravity & Magnetism

Geophysicists learn physics and mathematics to study the earth.

- **Gravity exploration**: \([\text{Density} \uparrow] \Rightarrow [\text{Mass} \uparrow] \Rightarrow [\text{Gravitational force} \uparrow]\).
  - Sedimentary rocks, porous rocks and salt domes are less dense than volcanic and metamorphic rocks. When a geophysicist is over low density rocks, his gravity meter detects drops in the gravitational force. He then suspects appropriate rock structures under the surface for oil formation and reservoirs.
  - Gravity meter must be on a stable platform, cannot be used on an aircraft.
  - Many salt domes in Texas are discovered by a gravity meters in the 1920s.

- **Magnetism exploration**: Iron oxides (Fe₃O₄, magnetite) create magnetic field which can be significantly stronger than earth’s magnetic field.
  - Volcanic and metamorphic rocks (basement rocks) tend to have iron oxides, whose magnetism can be detected with a magnetometer. Depth of basement rocks indicate the thickness of sedimentary rocks.
  - The device works on a mobile platform such as a walking person or on an aircraft. In the latter case, no permission necessary for a survey.

Seismic Imaging: [https://www.youtube.com/watch?v=-jJRHBsque8](https://www.youtube.com/watch?v=-jJRHBsque8)
From Surveys to Reserve Estimation

- Estimate the oil in a reservoir in terms of number of barrels
  1. Estimate volume of the reservoir
  2. Estimate the density of the oil in the reservoir
  3. Find the weight of the oil in reservoir and divide by the weight of a barrel

- Estimate can carry uncertainty information
  - Rather than a number as an estimate, use a table or a histogram:

<table>
<thead>
<tr>
<th>Reserve amount in Mbbl in one thousand barrels</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>10%</td>
</tr>
<tr>
<td>130</td>
<td>20%</td>
</tr>
<tr>
<td>135</td>
<td>40%</td>
</tr>
<tr>
<td>140</td>
<td>20%</td>
</tr>
<tr>
<td>145</td>
<td>10%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>10%</td>
</tr>
<tr>
<td>130</td>
<td>30%</td>
</tr>
<tr>
<td>135</td>
<td>70%</td>
</tr>
<tr>
<td>140</td>
<td>90%</td>
</tr>
<tr>
<td>145</td>
<td>100%</td>
</tr>
</tbody>
</table>
Cumulative Density Function for Reserve Random Variable

For the reserve random variable $X$ and its cdf $F_X(a) = P(X \leq a)$ given above, we have

- Probability of reserves less than or equal to 78 = 0.1
- Probability of reserves less than or equal to 82 = 0.3
- Probability of reserves less than or equal to 90 = 0.9

10\(^{th}\) percentile of the reserves solve $0.10 = F_X(a) = P(X \leq a)$ and it is 78 Mbbl.

90\(^{th}\) percentile of the reserves solve $0.90 = F_X(a) = P(X \leq a)$ and it is 90 Mbbl.

- 100\(^{th}\) percentile of the reserves is 64 Mbbl.
- 94\(^{th}\) percentile is 59 Mbbl.
- 90\(^{th}\) percentile is 54 Mbbl.
- 50\(^{th}\) percentile is 41 Mbbl.
- 31\(^{st}\) percentile is 34 Mbbl.
- 10\(^{th}\) percentile is 24 Mbbl.
Proven, Probable and Possible Reserves

<table>
<thead>
<tr>
<th>New names for reserve percentiles (p.102 of Hydrocarbon Reserves by Institut Francais du Petrole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10(^{th}) percentile</td>
</tr>
<tr>
<td>50(^{th}) percentile</td>
</tr>
<tr>
<td>90(^{th}) percentile</td>
</tr>
</tbody>
</table>

- Consider the example from the previous page,
  - 90\(^{th}\) percentile is 54 Mbbl.
  - 50\(^{th}\) percentile is 41 Mbbl
  - 10\(^{th}\) percentile is 24 Mbbl.

**What are proven, probable and possible reserves?**
- Proven reserves=24 Mbbl. Probable reserves=41-24 Mbbl. Possible reserves=54-41 Mbbl.

- Sometimes the 5\(^{th}\) percentile is called *proven* reserve and the 95\(^{th}\) percentile is *proven + probable + possible* reserves.
- Unfortunately, Hydrocarbon Reserves book does not connect these to percentiles and offers additional notation that you do not need to know for this course:
  - 1P = P10 = 90\(^{th}\) percentile = Proven reserves + Probable reserves + Possible reserves
  - 2P = P50 = 50\(^{th}\) percentile = Proven reserves + Probable reserves
  - 3P = P90 = 10\(^{th}\) percentile = Proven reserves
  - Then Pxy satisfies Probability(Reserves ≥ Pxy)=0.xy; for more see one slide after summary.

- If X and Y are random reserves at two locations, what is the sum? It is X+Y given by a convolution.
Towards a Lease: Mineral Rights (MR) in the USA

- In the USA, ownership of surface of a land can be separate from the mineral rights. Often, the landowner is actually only the surface owner. Ownership of both surface and mineral rights is called a fee interest.

- Property code (law) in the USA is set and enforced by individual states such as Texas (TX).

  - Texas Property Code, Sec. 75.001: Mineral means oil, gas, uranium, sulfur, lignite, coal, and any other substance that is ordinarily and naturally considered a mineral (?) in this state, regardless of the depth (!) at which the oil, gas, uranium, sulfur, lignite, coal, or other substance is found. Texas constitution and statutes are at www.statutes.legis.state.tx.us/Download.aspx.

    - Surface rights owner has the rights to Non-Minerals:
      » Sand, gravel, limestone, water regardless of location/depth.
      » Substances recovered by the destruction of the surface (any reasonable surficial method of recovery, strip-mining of coal)

        - If strip mining [is] … a reasonable method of recovery …, then the surface owner … reasonably expect that method to be used …; and he would not intend to convey it as a "mineral" to the mineral owner. Therefore, … the surface owner need only show that a reasonable method of extraction would have entailed the destruction of the surface. Upon such a showing, the substance would be deemed not to be a “mineral”.


    - To prove that substance is not mineral, you must prove that the extraction of this substance through reasonable methods will cause destruction of the surface.

    - This 1977 ruling evolved and tied to the depth of the substance
      » Minerals: Substances such as lignite, coal or iron is a mineral deep in the ground (>200 feet deep ≈ 60 m).
      » Non-minerals: Same substances close to the surface, i.e., within 60 metres. See http://recenter.tamu.edu/pdf/840.pdf.

- Mineral Estate is Dominant in TX: If a conflict builds up when the mineral rights owner wants drilling but the surface rights owner does not, it is resolved in favor of Mineral Right Owner despite the objections of Surface Estate Owner.
Lease: Royalty Interest (RI) vs. Working Interest (WI)

- Owner of mineral rights can **lease** the property to obtain royalty interest.
  - **Royalty Interest (RI, nonworking interest):** portion (often 1/8 or 3/16) of the revenue received by the Mineral Rights Owner (MRO)
    - MSO owner after the lease becomes the Royalty Interest Owner (RIO)
    - RIO does not pay for Exploration & Production (E&P) costs.
  - **Working (operating) Interest (WI),** remaining revenue portion for the E&P company, the Working Interest Owner (WIO)
    - WIO performs operations & pays for costs.
  - Post-production costs (transportation, purification) can be shared between RIO and WIO.

- A lease transfers
  - 100% of WI and \((1 - x)\)% of RI → WIO (the E&P company)
  - in return for keeping the \(x\)% of the revenue with RIO.

<table>
<thead>
<tr>
<th>Revenue=0</th>
<th>Revenue&gt;0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WI</td>
</tr>
<tr>
<td>Landowner</td>
<td>100%</td>
</tr>
<tr>
<td>E&amp;P Company</td>
<td>0%</td>
</tr>
</tbody>
</table>
Lease: Variations in Interests

- **Undivided WI**: Devon can jointly explore with Chesapeake in the undivided land (Plano and Richardson) by sharing both the cost and the revenue. They may operate as 50% MR owner of the undivided land. They have joint WI.
  - Joint exploration minimizes risk of each company.
  - Divided WI: Devon can sell MR of Plano to Chesapeake. Devon and Chesapeake each respectively owns MR in Richardson and Plano. Each operates as 100% MR owner in the own land.

- **Overriding Royalty Interest (ORI)**: WI can be sold to another company and it works like a RI.
  - Devon can sell MR of Richardson to Apache and keep a percentage (often 1/8) of future revenue in an ORI.

- **Production Payment Interest (PPI)**: WI can be sold to another company and it works like an ORI except that payments are limited to a pre-determined amount of oil/gas/money or the PPI expires at a pre-determined date.
  - Devon can sell MR of Richardson to Apache for at most $20 Million of PPI. If Apache finds oil and earns more than $20 million, it pays only $20 Million. If no oil is found, Apache pays nothing.

- **Net Profits Interest (NPI)**: MR is bought by offering a percentage of net profit (not revenue)
  - Foreign governments
  - Offshore interests owned by states or the federal government

- **Pooled or Unitized Working Interest**: Obtained by combining small / irregular lands to meet spacing regulations (at most one oil well in 40 acres = 400*400 m\(^2\)) or to increase efficiency.
  - Texas Natural Resources Code, Sec. 71.052. INSERTING POOLING PROVISIONS IN LEASES: A city, town, or political subdivision may insert in an oil and gas lease or in an oil, gas, and mineral lease executed by it a provision authorizing the lessee [WIO, the E&P company] to pool the lease, the land or minerals included in the lease, or any part of these with any other land, leases, mineral estates, or parts of any of these to form a drilling or spacing unit for the exploration, development, and production of oil or gas and authorizing the lessee to form the units and accomplish the pooling by written designations filed in the county in which the land is located.
Contract Terms

Lease between Lessee (E&P Company) and Lessor (Mineral Owner)

- **Lease Bonus:** Sign-in bonus, a lump sum per acre, paid by lessee to lessor. $25-25,000/acre.
- **Royalty Provision:** Percent of revenue or profit paid to lessor. 1/8, 3/16, 1/5.
- **Primary Term:** Length of the lease contract. The contract expires if the lessee does not start drilling/production within this term. 1-5 years.
- **Delay Rental Payment:** Payments per acre and per year made to lessor to extend the (primary) term of the contract.
- **Shut-in Payment:** Paid to lessor to compensate his loss from a producing well that is closed because of inaccessible pipeline or too low oil/gas price.
- **Right to Assign Interest:** This is lessee’s right to carve out ORI/PPI without the consent of the lessor.
- **Right to Free Use of Resources:** This is lessee’s right to use portion of produced oil and gas locally to carry out production operations.
- **Option Payment:** This is payment made to MR owner so that the owner does not lease the land to another company for a while. Paying this, the potential lessee takes the land out of the market.
- **Offset Clause:** If another working interest owner drills a well that is too close to access the same reservoir, the right of lessee to drill an offset well to the reservoir without lessor’s consent.
- **Forced (compulsory) pooling provisions:** Your neighbor leases his small lot which is not sufficient for efficient drilling and production. E&P company wants to lease your lot for efficiency but you do not want to lease. E&P company can obtain a “forced pooling order” from appropriate agencies in your state to drill your land. The order provides you with $x$% of the RI.
- **Minimum royalty, timing of royalty, etc.**

If the land does not produce by the end of the lease term and is not extended, lease contract expires.

If the land does produce, operating company prepares a **division order** (listing interest owners and percentages) and sends this order to all owners. Division order executed (signed) by mineral owner to receive royalty checks. For more details, see J. Fambrough. 2009. *Minerals, Surface Rights and Royalty Payments*. TAMU Real Estate Center, Working paper #840. Available at [http://recenter.tamu.edu/pdf/840.pdf](http://recenter.tamu.edu/pdf/840.pdf).
Signing a Lease
Landman as an Agent

- Lessor = Landowner; Lessee = E&P Company; Landman = Agent

- Landman’s responsibilities:
  - negotiating for the acquisition or divestiture of mineral rights;
  - negotiating business agreements for exploration and production
  - determining ownership in minerals through the research of public and private records, reviewing the status of title, curing title defects and otherwise reducing title risk
    » Deaths, foreclosures, state or private land, Indian reservations, environmentally restricted land
  - managing rights and/or obligations derived from ownership of interests in minerals;
  - unitizing or pooling of interests in minerals.

- Some lands may have unknown owners or unknown MR owners, the landman searches for MR owners through county clerk records which are often not online.

- If no MR owners can be found, the landman can file for an establishment of an escrow account with state authorities. States can act as a lessor and keep the RI in an escrow account until the owner shows up.


- Example: Your state forces you to pool your 16 acre land with 24 acres of your neighbor. The pooled land is leased to an E&P company which offers 3/16 of royalty interest. The E&P offers $500 per acre as a sign in bonus. What percent of production revenue obtained from 40 acres will be yours? FYI, 1 acre = 1/640 square mile = 4046 square metre = Football field.
  - Answer: \((\frac{16}{40})*(\frac{3}{16})=\frac{3}{40}=7.5\%\).

More information: American Association of Professional Landmen (AAPL) [www.landmen.org](http://www.landmen.org)

Listing of lands for lease for mineral rights: [http://mineralownermart.com](http://mineralownermart.com)
Mineral Rights in US Federal Land, Canadian Crown Land, Other Countries

- US has federal lands especially in the Western states. Canada’s federal land is called Crown land. Mineral rights in these places are owned by the federal government.

- Most countries, other than US/Canada, own the mineral rights of their entire territory, regardless of whether the land is private or not.

- E&P companies sign contracts with governments to operate in federal lands in North America or in other countries.

- Basic premise of these contracts is revenue/cost sharing.
  - Concession Agreement: E&P company pays for cost of exploration, drilling, development and production. E&P company also pays taxes, bonuses and royalties (shared revenue) to the government. E&P maintains the remaining revenue.
  - Concession Agreement with Government Cost Sharing: Governments may agree to pay for some portion of development or production cost if they can increase the shared revenue.
  - Production Sharing Agreement: E&P pays for cost of exploration and drilling.
    » If no oil or gas, agreement expires at the end of its term.
    » If oil or gas found, estimate the total value of the reserve.
    » A portion of this value, cost oil, is kept by the E&P company.
    » Cost-oil is designed to cover costs of exploration, drilling, development and production.
    » Profit-oil (=Total value-cost oil) is split between the E&P company and the government.

![Mineral Rights Table](image)

<table>
<thead>
<tr>
<th></th>
<th>Cost oil</th>
<th>E&amp;P company</th>
<th>Government</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Profit oil</strong></td>
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<tr>
<td><strong>Total Reserve Value</strong></td>
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<tr>
<td><strong>Total Reserve Value</strong></td>
<td></td>
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</tbody>
</table>

**Table of Mineral Rights in Various Locations**

- **Historical Trend**
  - High E&P Company Risk and Revenue
  - High Government Risk and Revenue

<table>
<thead>
<tr>
<th></th>
<th>Concession Agreement</th>
<th>Concession Agreement with Government Cost Sharing</th>
<th>Production Sharing Agreement</th>
</tr>
</thead>
</table>

- **Concession Agreement**
- **Concession Agreement with Government Cost Sharing**
- **Production Sharing Agreement**
Governments Recruit Bidders for Fields: Ecuador, Ronda Suroriente Field

- SHE (Secretaría de Hidrocarburos, Ministerio de Recursos Naturales No Renovables)
- SHE runs road-shows to attract investors in Houston, Paris, Singapore, Beijing in 2012-13. Program for the Paris road show is below:

08:30 - 09:00  Registration and Coffee
09:00 - 09:10  Introduction to Event and Speakers Tim Zoba Jr, Managing Director, Global Business Development, IHS Global Inc.
09:10 - 09:20  Welcome by Ambassador
09:20 - 09:40  Ecuador and its Petroleum Industry Wilson Pastor, Minister of Non-Renewable Resources
09:40 - 10:00  Legal Aspects of the Round Andres Fabara, SHE
10:00 - 10:40  Economic Aspects and Bid Selection Wilson Pastor Minister / Patricio Machado SHE
10:40 - 11:00  Social and Environmental Aspects and Round Schedule Andres Fabara, SHE
11:00 - 11:30  Coffee Break
11:30 - 12:30  Technical and Geological Aspects Alfonso Jimenez, SHE
12:30 - 13:00  Q&A SHE Team [=Andres (legal), Alfonso (technical), Patricio (financial)]
13:00 - 14:00  Lunch
14:00 - Private Meetings by Appointment

- See Ronda Suroriente under Cases on Merit webpage and www.rondasuroriente.gob.ec
- Under cases you can find contract description document as well as road show slides covering technical, legal and financial aspects.
Governments sign leases with companies
Transparency and Accountability

Governments sell the extraction rights to international companies in return for taxes – basically the revenues shared with governments. (Secretary of Hydrocarbons, Department of Energy, etc.)

Resource Curse:
- Benefits of oil, gas and mining are not realized by the host country or its people.
- Unfortunately, resource industries seemed to make other industries less competitive by drawing attention and focus away from them and hence keeping resource-rich countries underdeveloped.
- These countries are associated with increased poverty, conflict and corruption.

Environmental, social and political concerns
- Government accountability and transparency issues
  » Angola’s opaque management of its resources
- US Foreign Corrupt Practices Act: US companies cannot bribe foreign officials to win favors/contracts
  » Baker-Hughes accepted wrong-doing and bribing in Russia, Uzbekistan, Angola, Nigeria
  - 2001-3: Bribing to win an oil-services contract in the north of Caspian Sea, Karachaganak, Kazakhstan

Transparency in the management of resources
- Revenues earned from the resources: Publish What You Pay (PWYP) campaign by society; see http://www.publishwhatyoupay.org
  » Publication of revenues paid to governments can cause conflicts with governments if the revenues are not going to public funds
- Distribution of revenues to initiatives -- to support other social initiatives and other industries

Extractive Industries Transparency Initiative (EITI) requires member governments to publish the revenues and how they are used; see https://eiti.org/countries/reports

Transparency is necessary but not sufficient for Accountability
Exploration, Drilling, Completing, Production Flowchart

Geophysical and Geological (G&G) Survey

Detailed G & G Survey

Promising?

Yes

Lease

Drill and Collect Well Logs

Seismic Study to Identify Drill Site

Cost and Economic Analysis

No

Sufficient Oil or Gas likely?

Yes

Complete the Well and Produce

No

Plug & Abandon the Well
Onshore Drilling

Lessee (WI owner) signs a drilling contract with a drilling contractor. Drilling company handles the rest: **Identify Drill Site**

- **Prepare Site:** Level Site, Build Roads, Reserve Pits and Waste Pits.
- **Secure Water Supply:** Necessary for mud and hydraulic fracking.
- **Drill 20-100 feet with truck-mounted rig,** a truck cannot support the weight (200 tons) of a long drillpipe (>1000 meters)

- **Rigging up**
- **Mud** is circulated to lubricate drilling bit, raise rock cuttings to surface (for sampling) and keeps the formation fluids from entering the wellbore.
- **Mousehole Connection:** Adding 30 feet long pieces to drill pipe as the wellbore becomes deeper.
- **Tripping in/out:** Replacing worn out drill bit.
- **Casing:** Cementing a steel pipe into the wellbore. Drill bit moves inside the casing.

Casing confines the production to the wellbore, limits interaction with the soil, waterbed. It also helps to control the pressure.

Oil Drilling: [https://www.youtube.com/watch?v=Su3Rf5pFQyM](https://www.youtube.com/watch?v=Su3Rf5pFQyM)
Five Major Drilling Systems

- **Engines** to power hoisting, rotating, circulating system

- **Hoisting system**: Derrick, hook, cables
  - Hoisting system (cable extending from the derrick) is connected to the rotating system (Kelly) with a swivel. Bearings in the swivel allow the cables to stand still while Kelly rotates.

- **Rotating system**: Kelly, Turntable, Drillpipe, Drill collar, Drill bit
  - Engines power the Rotary (Turn) table to turn clockwise
  - Turntable turns the Kelly going through it
  - Kelly is screwed to the drillstring (made up of 30 feet long drillpipes). Drill string can bend and extend for kilometers.
  - Drillstring at the bottom is connected to the drillcollar. Drillcollar is heavier and stronger than drillpipes. The weight of the drillcollar pushes the drillstring deeper.
  - Drillcollar is connected to the drillbit:
    - PDC (Polycrystalline diamond cutter) bit scratches at high frequency
    - Roller cone bit has 3 rotating bits cutting at low frequency
    - Rotate at high frequency facing soft rock with a small bit
  
  Bits as well as the turntable are the main rotating pieces.

- **Circulating system**: Mud hoghs (pumps), drilling mud, mud storage tanks, mud purification tanks for mud returning from subsurface.
  - Drilling mud has the weight and applies pressure to formation liquids
  - If the mud is not heavy enough, formation liquids flow into the wellbore and deform it.
  - Sometimes flow is so strong that pressure rises up in the wellbore and blowout preventer may blowout.

- **Information system**: Sensors (behind drill bit), information screens on site and off site (for remote control).

Oil Drilling: https://www.youtube.com/watch?v=SfazJ6P_g7w. Drilling (hammer; rotary: oil, mining; laser) https://www.youtube.com/watch?v=eYptR2nXLlA
Costs of Drilling Wells in the Leased Land

- Estimate the costs and put them into Authority for Expenditure (AFE).
- Project Drilling Time as it affects many costs (e.g., hired roughnecks, rented equipment, food, lighting, heating costs)
  - Depends on completed well vs. dry hole.
  - Hard to estimate.
  - Average time to drill a 3000-metre well in Permian Basin (west Texas) is 21 days. Renting a rig costs $12,000 - $16,000/day and drops with the oil price.
- AFE costs include tangible and intangible components, often finer classification
- AFE is the exploration-to-production budget and is shared with interest owners responsible for paying for exploration and completion expenses. Creditors (e.g., banks) of the E&P companies ask for AFE to evaluate financial viability.
- AFE can include 15% contingency allowance.
  - AFE of Macondo was $96 M; actual turned out to be $154 M.

<table>
<thead>
<tr>
<th>Operator:</th>
<th>Date:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lease: Field:</td>
<td></td>
</tr>
<tr>
<td>Sec. T R County: State:</td>
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</table>

Authority for EXPENDITURE

<table>
<thead>
<tr>
<th>Intangible Costs</th>
<th>Dry Hole (24.5 Days)</th>
<th>Completed (32.5 Days)</th>
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<tbody>
<tr>
<td>Location Preparation</td>
<td>$30,000.00</td>
<td>$65,000.00</td>
</tr>
<tr>
<td>Drilling Rig and Tools</td>
<td>$298,165.75</td>
<td>$366,612.94</td>
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<tr>
<td>Drilling Fluids</td>
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<tr>
<td>Rental Equipment</td>
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<tr>
<td>Cementing</td>
<td>$49,534.68</td>
<td>$54,368.73</td>
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<tr>
<td>Support Services</td>
<td>$152,285.44</td>
<td>$275,647.59</td>
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<tr>
<td>Transportation</td>
<td>$70,200.00</td>
<td>$83,400.00</td>
</tr>
<tr>
<td>Supervision and Administration</td>
<td>$23,282.00</td>
<td>$30,790.50</td>
</tr>
<tr>
<td>Subtotal</td>
<td>$814,927.94</td>
<td>$1,126,581.00</td>
</tr>
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<table>
<thead>
<tr>
<th>Tangible Costs</th>
<th>Dry Hole (24.5 Days)</th>
<th>Completed (32.5 Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tubular Equipment</td>
<td>$406,100.87</td>
<td>$846,529.44</td>
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<tr>
<td>Wellhead Equipment</td>
<td>$16,864.00</td>
<td>$156,201.00</td>
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<tr>
<td>Completion Equipment</td>
<td>$0.00</td>
<td>$15,717.00</td>
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<tr>
<td>Subtotal</td>
<td>$422,964.87</td>
<td>$1,016,447.44</td>
</tr>
</tbody>
</table>

Subtotal | $1,237,893.00 | $2,145,028.00 |

Contingency (15%) | $185,683.94 | $321,754.25 |

Total | $1,423 M | $2,467 M |
Drilling Contracts

Drilling (contractor) company is paid on the basis of

- Footage rate (depth), common on land
- Day rate (duration), common offshore, different rates for idleness (standby, testing)
- Turnkey rate (Lump sum for drilling to a certain depth and completing.)

Combination: Footage rate until a depth, day rate afterwards.

◆ Contract includes
  - Location
  - Spud date, starting day. Start of drilling is called spudding in.
  - Vertical/Horizontal
  - Drilling depth/displacement, drill hole diameters
  - Formations to be drilled
  - Drilling mud composition, tests to be done, casing diameter and depth, cementing type

◆ A contractor can own its own rigs or can rent from another company.
  - Helmerich & Payne Inc., Patterson-UTI Energy Inc., Nabors Industries, etc. own and rent rigs. Some (FlexRig 5 of HP) is better suited for horizontal drilling. HP has about 300 rigs, about 295 utilized in late 2014. Rig contracts are being cancelled or not signed due to low oil price, which reduces rig utilization.
Offshore Drilling

Lessee (WI owner) signs a drilling contract with drilling contractor. RI is owned by the government. Offshore drilling is much more costly.

- **Test well**: In some offshore fields, very little is known so companies come together to pay for the cost of drilling test wells before signing any contracts. Governments permit this.

- **Cost data from Rystad energy**
  - Offshore shelf cost ~$40/bbl
  - Deepwater cost ~$53/bbl
  - Ultra deepwater cost ~$60/bbl

Ultra Deepwater >1500 meters

Subsea Completions
Drilling Problems

- **Fishing**: A piece of drillstring breaks and drops into the wellbore.
- **Stuck pipe**: Tight curves in the wellbore can cause portions of drill string to be stuck.
- **Sloughing shale**: Wellbore walls absorb water and become soft, and possibly fall to the bottom of well.
- **Lost circulation**: Drilling mud moves into the formations if formations are too porous and too permeable.
- **Formation damage**: Drilling mud sticks to the walls of wellbore and blocks the oil flow into the wellbore.

- Movement of the drilling mud can be used to rotate the drill bits.
- **Mud motor failures**
  - Motor failure in the Bakken costs approximately **$150,000 per incident**.
  - When reviewed by subject matter experts during post mortems, drilling dysfunctions are identifiable but are not always recognized by the crews drilling the well.
  - One form of dysfunction can be rectified easily, if identified –
    - Specifically dysfunctions induced by an improperly configured auto driller, which can lead to:
      - Reduced drilling efficiency by 2-15% per stand.
      - Motor failure (chunking).
  - A solution that allows **identification of this form of dysfunction in real time** enables mitigation.
  - Compute **MSE (Mechanical Specific Energy)**, proportional to total mud flow rate, differential pressure and inversely proportional to bit area and rate of penetration. Monitor total mud flow rate, differential pressure, bit area and rate of penetration.
Mud Motor Failure: Excessive Chunking

Successful Results - Case 12 Hours Prior to Incident

From Webinar on 28 Jan 2014 titled “Preventing Mud Motor Failure in the Bakken” by M. Isbell, Hess Corp. and M. Johnson., Verdande Tech.

Inspection of Motor after the fact revealed significant chunking
Exploration, Drilling, Completing, Production Flowchart

- **Geophysical and Geological (G&G) Survey**
  - **Promising?**
    - Yes: **Lease**
    - No: **Seismic Study to Identify Drill Site**
  - **Sufficient Oil or Gas likely?**
    - Yes: **Complete the Well**
      - Produce
    - No: **Cost and Economic Analysis**
      - **Drill and Collect Well Logs**
      - **Seismic Study to Identify Drill Site**
      - **Promising?**
        - Yes: **Complete the Well**
          - Produce
        - No: **Plug & Abandon the Well**
Rising from the Mud

Source: Photo taken by Ryan Campagnola in July 2015.
Completion of a Well

   - Casing string limits interaction of the oil with the substances around the wellbore
     » Avoids contamination of the surrounding water by hydrocarbons
     » Avoids dilution of hydrocarbons by liquids surrounding the wellbore
   - Casing string also stabilizes the well: Avoids break down of the sides of the well and caving into the well.
   - Casing strings are in various diameters (10-90 cm). The thicker casing is closer to the surface.
   - Each casing is in various length (5-13 m) and is screwed into another to make casing string.
   - After casing string is inserted in the wellbore, it is cemented to the sides of the wellbore.

◆ 2. Tubing String: Series of pipes inserted into casing from the surface all the way to reservoir. Tubing carries the oil to the surface. Tubing is not cemented, so it can be removed for repairs.

◆ 3. Bottom-Hole Completion. This is the completion in the reservoir.
   - Open-hole completion: Nothing in the reservoir.
   - Gravel pack completion: A gravel pack (coarse sand) is inserted around the wellbore in the reservoir.
   - Set-through completion: A casing pipe or a liner is inserted into the reservoir and cemented, later on holes are opened in this pipe using a perforation gun.

◆ 4. Wellhead: Large steel fitting on the surface that is welded to the casing. Wellhead equipment includes casing head, tubing head and controls for production (sometimes called Christmas tree).

◆ 5. Pumps: To suck the oil from the reservoir.
Exploration, Drilling, Completing, Production
Flowchart

Geophysical and Geological (G&G) Survey

Yes

No

Promising?

Seismic Study to Identify Drill Site

Drill and Collect Well Logs

Cost and Economic Analysis

Sufficient Oil or Gas likely?

Yes

No

Complete the Well

Plug & Abandon the Well

Lease

Yes

No

Produce
Production Profile of Oilfields

**Production profile** is the annual production of a field, region, country over its lifetime.

- Steep increase towards peak
- Flatter drop after the peak

It is not for a single well. Production levels at wells are not smooth.

Over this region, production has a plateau.

“Plateau production region”.

At least 0.85*Peak production

[Jakobsson et al. 2014]
**Additional vs. Accelerated Reserve Recovery**

Creation of additional reserves due to technology

Accelerated extraction e.g., thicker tube

"Granite Wash… straddles the Texas-Oklahoma border. Apache has been drilling in the area for 35 years, but new methods of recovering oil and natural gas, including horizontal drilling and hydraulic fracturing, or fracking, have transformed its potential.”

WSJ: “Apache Reaches Oil Deal on Home Turf” by D. Gilbert on Jan 23, 2012

1. **Primary recovery**: Using pressure in the reservoir or a pump to bring oil & gas to the surface.
2. **Secondary recovery**: Flooding with water to increase reservoir pressure.
3. **Tertiary recovery**: Introducing chemicals, gas or heat to decrease viscosity to facilitate the flow.

Previously dry-wells started production in Permian Basin by using new technology.
Success Rate, Recovery Factor and Reserves/Production

- **Success rate:** Ratio of number of non-dry wells to total number of wells drilled
  - Success rate increases with improved surveying technologies.
  - The number of wells do not convey the reserve information.

- **Recovery factor:** Ratio of Reserves to Resources
  - 30-40% for oil, increases with well stimulation
    - e.g., Reserves = 80 Mbbl = 80,000 bbl and Resources = 200 Mbbl, so recovery factor = 80/200.
  - 80% for gas

- Reserves can be determined by estimating the size of the field.
  - Start with the reservoir volume
  - Estimate area and depth by using test wells
  - Reserve is proportional to the Volume, Porosity, Recovery factor

- **R/P:** Reserves in Mbbl and Production in Mbbl per year
  - R = 80 Mbbl; P = 2 Mbbl per year
  - R/P = 40 years, an estimate of lifetime of remaining reserves

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<th></th>
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</thead>
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<td>Oil</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Gas</td>
<td>50</td>
<td>55</td>
<td>60</td>
<td>63</td>
</tr>
</tbody>
</table>

Evolution of Estimates (yrs) for depleting Oil and Gas
Estimation of Production

- **Bottom-up Production Profile**: Start with a small production unit (well/field) and find its production quantity separately and sum up over all units.
  - More data required but details are visible.
  - Understanding of reservoirs, production, supply chain
- **Top-down Production Profile**: Extrapolate the previous production quantities (for region or the entire industry) by often regressing against macroeconomic and technological factors.
  - Less data but less understanding. For more, see Hubert models after summary.
Double Rainbow: A sign of good fortunes

Source: Photo taken by Mike Cooper and Quinn Holtby in Canada in July 2015.
Recording and Reporting of Activities
Accounting for E&P Companies

Recording of produced oil and gas:
– Produced oil is treated, separated and stored in tanks. When it is transferred from the tanks (drill site), it is recorded in a run ticket.
– Produced gas is transferred through pipelines that extend all the way to the wellbore. The amount of gas shipped is recorded in a gas settlement statement.

Accounting is challenging for E&P companies
– High uncertainty in finding resources and size of reserves
– High cost of initial investment
– Limited connection between investment and return: Large investment may return nothing (dry hole)
– Long time horizon from exploration (cost) to selling (revenue). When to expense for tax purposes?

In 1977, FASB (Financial Accounting and Standards Board, fasb.org) released SFAS No.19: Financial Accounting and Reporting by Oil and gas Producing Companies (Google fas19.pdf).
– SFAS No. 19 advocated for successful efforts method and eliminated full cost method.

<table>
<thead>
<tr>
<th>Full Cost (FC)</th>
<th>Type of costs</th>
<th>Successful Efforts (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capitalized (deferred)</td>
<td>Geological &amp; Geophysical costs</td>
<td>Expensed now</td>
</tr>
<tr>
<td>Capitalized (deferred)</td>
<td>Exploratory cost of a dry hole</td>
<td>Expensed now</td>
</tr>
<tr>
<td>Country (credit transfer)</td>
<td>Amortization cost center</td>
<td>Field or reservoir</td>
</tr>
</tbody>
</table>

In 1978, SEC (Securities Exchange Commission, sec.org, federal government) released ASR 253
– SEC’s ASR 253 reverses FASB’s SFAS No.19. ASR 253 permits

<table>
<thead>
<tr>
<th>Full Cost (FC)</th>
<th>Successful Efforts (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASR 258</td>
<td>ASR 257=SFAS No.19</td>
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</tbody>
</table>
Recording and Reporting of Activities  
Accounting for E&P Companies

- Back and forth
  - In 1979, coming inline with SEC, FASB released *SFAS No. 25: Suspension of Certain Accounting Requirements for Oil and Gas Producing Companies*.
  - SEC was not satisfied with ASR 257 or 258 for their failure to account for reserves. *Reserve Recognition Accounting* (RRA) was introduced to include reserve valuation in income statements.
  - In 1982, SEC was not satisfied with RRA and asked FASB for help. FASB released SFAS No. 69 ([www.fasb.org/pdf/fas69.pdf](http://www.fasb.org/pdf/fas69.pdf)): Disclosures about Oil and Gas Producing Activities.

  - Choose between SE & FC methods: Apache FE until 2016 & SE afterwards
  - If SE is chosen, use SFAS No. 19 = ASR 257 as amended; else use Reg. S-X 4.10 guidelines where most costs are capitalized.
  - Report SFAS No. 69 as supplemental financial information.
    - SFAS No. 69 requires the disclosure of historical and value based information:
      - Proved reserve (10th percentile) quantity information
        - LaRoche Petroleum Consultants (located 2 miles east of UTDallas) ([www.larocheltd.com/services.htm](http://www.larocheltd.com/services.htm))
      - Costs incurred for property acquisition, lease, exploration and development activities
      - Capitalized costs related to production activities
      - Results of operations for production activities
    - A standardized measure of discounted future cash flows from proved reserves

Reconciliation of Reserves

- Last year’s reserves < This year’s reserves + This year’s production (depletion rate)

For more, see *Fundamentals of Oil and Gas Accounting* by Wright & Gallun.
Promising?

Geophysical and Geological (G&G) Survey

Yes

Detailed G & G Survey

No

Lease

Seismic Study to Identify Drill Site

Drill and Collect Well Logs

Cost & Economic Analysis

Sufficient Oil or Gas likely?

Yes

Complete the Well

Produce

Accounting

No

Plug & Abandon the Well

• State commissions permit, monitor, record and check for compliance of oil and gas wells
  • Texas Railroad Commission (RRC) [http://www.rrc.state.tx.us/](http://www.rrc.state.tx.us/)
    • To see wells (dry/producing/plugged) and pipelines (gas/liquid) on an interactive map, check on these on the “Visibility” button at the top of the page [http://wwwgisp.rrc.state.tx.us/GISViewer2/](http://wwwgisp.rrc.state.tx.us/GISViewer2/)
    • If you click "identify" button on the top bar and select “wells”, you can then click on a well on the map and view more information such as operator and well logs. Thanks to Allen (Merit’15) for this info.
  • Oklahoma Corporation Commission (OCC) [http://www.occeweb.com/og/oghome.htm](http://www.occeweb.com/og/oghome.htm)
• This information can be useful for your course project
Surprising amount of production activity under the DFW airport tarmac.

- Horizontal wellbores
- Wellheads at the northern end of North Employee Parking lot.
- They are connected to a gas gathering pipeline that goes northwards.
Resting Rigs

- Picture of idle rigs from West Texas (WT) in February 2015 when the WT Intermediate oil price is about $45/bbl.
- Picture is from Helmeric and Payne (www.hpinc.com) Permian basin yard on I-20 between Midland and Odessa.
- There are about 20 rigs in the picture representing $300 million of idle investment.
Oil Price History and Present

Historical Crude Oil prices, 1861 to Present

Data Source: Chartsbin.com

Price over $80 happened 4 times in history but not over long durations.
Oil Price Models: Adelman

- Prices did not rise from the 1880s to the 1970s, despite the depletion.

- Adelman provides a critique of Hotelling model:
  “The assumption dropped [from Hotelling 1931] is that there exists "an exhaustible natural resource ... a fixed stock of oil to divide between two [or more] periods“. There is no such thing. The total mineral in the earth [a in Hotelling 1931] is an irrelevant non-binding constraint.
  “the larger deposits would be found earlier even by chance. Once found, the better mineral would be developed first. Thus marginal [production] costs and prices would rise, even if ultimate depletion were infinitely distant.”

  “If expected finding-development costs exceed the expected net revenues, investment dries up, and the industry disappears. … Depletion has a built-in brake, rising cost at the margin.”

Depletion $\Rightarrow$ Price $\uparrow$ $\Rightarrow$ Reserves $\uparrow$

Abundance $\Rightarrow$ Price $\downarrow$ $\Rightarrow$ Reserves $\downarrow$
Oil Transactions, Benchmarks and Prices

- **Spot transaction**: Transact now for exchanging physicals **now** with no expectation of a repeat.
- **Futures transaction**: Transact now for exchanging physicals **later** with no expectation of a repeat.
- **Term transaction**: Transact now for exchanging over a period.
  - Refineries like term transactions to avoid switching back and forth between different types of oil.
  - Refineries posted prices for crude oil accounting for API gravity differential.
    - API gravity differential: Price difference between light and heavy oil.

- **Benchmarks**:
  - NYMEX’s basis for futures contracts:
    - West Texas Intermediate (WTI) delivered at Cushing, OK.
    - Brent crude oil from North Sea.

- **OPEC (Organization of Petroleum Exporting Countries) plays a role in pricing**.
  - Is OPEC keeping the price low to clear the playing field from mid-size/small producers?
    - Yes, OPEC is not cutting its production.
    - No, OPEC’s production is little with respect to the production in the rest of the world and negligible in view of the fact that we are experiencing oil abundance with limited global economic growth.
Summary – Oil

Geophysical and Geological (G&G) Survey → Detailed G & G Survey → Lease, Contracts → Seismic Study to Identify Drill Site → Drill & Collect Well Logs → Economic Analysis

No → Oil / Gas likely?

Yes → Complete the Well

No → Continue to Produce?

Yes → Price, Sell

No → Produce

Yes → Account

Plug & Abandon the Well for Now

Caption
   Engineering
   Management
Resources

Based on
- Petroleum and Reserves. Chapter 11 of Basic Petroleum Geology by P. Link.
- Hydrocarbon Reserves. Chapter 3 of Oil, Gas Exploration and Production by Institut Francais du Petrole.
- Upstream Oil and Gas Operations. Chapter 1 of Fundamentals of Oil and Gas Accounting by C. J. Wright and R.A. Galun.
- Introduction to Oil and Gas Accounting. Chapter 2 of Fundamentals of Oil and Gas Accounting by C. J. Wright and R.A. Galun.
Richard Lau Lectures
YouTube https://www.youtube.com/watch?v=

- Ch1: How Earth was Formed
  https://www.youtube.com/watch?v=IdcC5v4JQRw&list=PLVJDTaS7rj9MbsQh8BhLzUHpUDLZLYve
- Ch2: Petroleum Origins
  https://www.youtube.com/watch?v=OWysYg_0I-M&list=PLVJDTaS7rj9OlZ1AdXSFUI-BhOX-apIA0
- Ch3: Petroleum Exploration
  https://www.youtube.com/watch?v=HLxltgUixYs&list=PLVJDTaS7rj9NsxPhqw31WZXr_8rY3sqHL
- Ch4: Contracts & Regulations
  https://www.youtube.com/watch?v=uJe6Rw8sJmw&list=PLVJDTaS7rj9MRzpfcnxQRXq5QRpVJXnOq
- Ch5: Reservoir Performance
  https://www.youtube.com/watch?v=pe71rV92GY8&list=PLVJDTaS7rj9OgTcMpBbwzYtcQDrdLpjI1
- Ch6: Drilling
  https://www.youtube.com/watch?v=Vlzau_N-aMg&list=PLVJDTaS7rj9PHYcRB0kzQOZ4MjiilrJY5
- Ch7: Formation Evaluation
  https://www.youtube.com/watch?v=cICNHNd2EjI&list=PLVJDTaS7rj9PxfOW1DJWqcd76hePuqUpT
- Ch8: Well Completion
  https://www.youtube.com/watch?v=jBty_TqyXcQ&list=PLVJDTaS7rj9NMsyNVb-6oZg2-emI7cc84
- Ch9: Field Appraisal and Development
  https://www.youtube.com/watch?v=sNzZIGt1ba4&list=PLVJDTaS7rj9Mzt_Gip-QjupTSxQ6nkqvG

Metin’s Disclaimer: I have not watched all of these videos. The few that I watched were nice. If you find the content of any of these offensive or useless, let me know.
<table>
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<th>Acronym</th>
<th>Full Form</th>
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</tr>
<tr>
<td>BPM</td>
<td>Barrel Per Minute</td>
</tr>
<tr>
<td>Cap</td>
<td>Capacity</td>
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<tr>
<td>CSG</td>
<td>Casing</td>
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<td>Drill Collar</td>
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<td>Displacement</td>
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<td>Drill Pipe</td>
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<tr>
<td>DS</td>
<td>Drill String</td>
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<tr>
<td>ECD</td>
<td>Equal Circulating Density</td>
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<td>EFF</td>
<td>Efficiency</td>
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<td>EMW</td>
<td>Equivalent Mud Weight</td>
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<td>End Of Build</td>
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<td>IMDPP</td>
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<tr>
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<td>Kick Off Point</td>
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<tr>
<td>NU/ND</td>
<td>Nipple Up, Nipple Down for BOP</td>
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<tr>
<td>RDMO</td>
<td>Rig Down, Move Out</td>
</tr>
<tr>
<td>MIRU</td>
<td>Move In, Rig Up</td>
</tr>
<tr>
<td>RIH</td>
<td>Run In Hole</td>
</tr>
<tr>
<td>TOOH</td>
<td>Trip Out Of Hole</td>
</tr>
<tr>
<td>PU</td>
<td>Pick Up (referring to tools to run in)</td>
</tr>
<tr>
<td>WOB</td>
<td>Weight On Bit</td>
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<tr>
<td>TRQ</td>
<td>Torque</td>
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<td>Weight Or Sinker Bars In Rod String</td>
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<td>LBS</td>
<td>Pounds (Used In Mud Weight Or Tubular Weight)</td>
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<td>TRRC</td>
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<td>TBG</td>
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<td>Well Bore Diagram</td>
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<td>Bottom Hole Assembly</td>
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<td>Cross Over</td>
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<td>Perforated Sub (Tubing)</td>
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<td>Shut In Drill Pipe Pressure</td>
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<tr>
<td>SPM</td>
<td>Strokes Per Minute</td>
</tr>
<tr>
<td>SPP</td>
<td>Slow Pump Pressure</td>
</tr>
<tr>
<td>TVD</td>
<td>True Vertical Depth</td>
</tr>
<tr>
<td>PSA</td>
<td>Pound of Sand Additive per gallon of fluid</td>
</tr>
<tr>
<td>PPA</td>
<td>Pound of Proppant Additive per gallon of fluid</td>
</tr>
<tr>
<td>ECD</td>
<td>Equivalent Circulating Density</td>
</tr>
<tr>
<td>OBM</td>
<td>Oil Base Mud</td>
</tr>
<tr>
<td>WBM</td>
<td>Water Base Mud</td>
</tr>
<tr>
<td>FIT</td>
<td>Formation Integrity Test</td>
</tr>
<tr>
<td>LOT</td>
<td>Leak Off Test</td>
</tr>
<tr>
<td>RU/RD</td>
<td>Rig Up/Rig Down</td>
</tr>
<tr>
<td>More??</td>
<td>More??</td>
</tr>
</tbody>
</table>
Liquid Supply Outlook

Global Liquids

Liquids Supply
Million Barrels Daily Oil Equivalent

Average Growth / Yr.
2005 – 2030
0.8%

2030
OPEC
Non-OPEC

2005

OPEC Crude
NGL, OPEC Condensate, Other
Canadian Oil Sands
Non-OPEC Crude & Condensate
Biofuels

Source: D. Fu Presentation on April 21, 2011:
The Outlook for Energy: A View to 2030
P10, P50, P90 for Proven, Probable and Possible Reserves

- 1P = P90 or P95 = Proven reserves
- 2P = P50 = Proven reserves + Probable reserves
- 3P = P10 or P05 = Proven reserves + Probable reserves + Possible reserves

Complementary cumulative density is
1 – Cumulative density

Probability(Reserves ≥ P95) = 0.95
Probability(Reserves ≥ P05) = 0.05
Probability(Reserves ≥ Pxy) = 0.xy
P50 is median
Pxy is the (1-xy)th percentile.

General convention

- As a percentile
  - 10th or 5th
  - 50th
  - 90th or 95th
Oil Price Models: Hotelling for Monopolist

- The revenue of selling \( q \) units at price \( p(q) \) is \( q \ p(q) \). When obtained in the future time \( t \), it is discounted by \( \exp(-\gamma t) \) to obtain the present value \( q(t) \ p(q(t)) \exp(-\gamma t) \). Over a horizon of \([0,T]\), the total discounted revenue is sum of \( q(t) \ p(q(t)) \exp(-\gamma t) \).
- Total consumption over \([0,T]\) is sum of \( q(t) \) which should be equal to total reserves \( a \).

Revenue maximization problem is

\[
\max_{q(t)} \int_{0}^{T} q(t)p(q(t)) \exp(-\gamma t) dt \quad \text{Subject to} \quad \int_{0}^{T} q(t) dt = a.
\]

Lagrangean is objective minus lambda times the constraint and maximized by setting

\[
\exp(-\gamma t) \frac{d}{dq(t)}(q(t)p(q(t))) - \lambda = 0
\]

Equivalently,

\[
\frac{d}{dq(t)}(q(t)p(q(t))) = \lambda \exp(\gamma t)
\]
Hotelling Example for Monopolist

Consider a specific price $p$, as a function of quantity sold $q$: $p=(1-\exp(-Kq))/q$. Price is zero if quantity is a lot. It is $K$ if quantity is zero.

Hence, $q(t)p(q(t)) = (1-\exp(-Kq(t)))$ whose derivative is $K\exp(-Kq(t))$ which should be equal to $\lambda \exp(-\gamma t)$ for optimality. Solving for $q(t)$, we obtain

$$q(t) = \frac{\log(K/\lambda) - \lambda t}{K}$$

Setting $q(T)=0$, we can find the Lagrangean multiplier lambda

$$\log(K/\lambda) = \gamma T$$

Since total production is $a$,

$$a = \int_0^T \frac{\log(K/\lambda) - \gamma t}{K} dt = \frac{\gamma}{K} \int_0^T (T-t) dt = \frac{\gamma}{K} \frac{T^2}{2}$$

Finally, optimal duration and production are

$$T = \sqrt{2Ka/\gamma} \quad \text{and} \quad q(t) = \frac{\gamma}{K} \left(\sqrt{2Ka/\gamma} - t\right) \text{ for } 0 \leq t \leq T.$$
Consider a specific price $p$, as a function of quantity sold $q$: $p = (1 - \exp(-200q))/q$. $\gamma = 1/9$ which corresponds to annual interest rate of 11.1%.

- $a = 4100 \times 10^9$ barrels of oil.

Finally, optimal duration and production are

$$T = \frac{\sqrt{2Ka}}{\gamma} = \sqrt{\frac{2 \times 200 \times 4000 \times 10^9}{1/9}} = 400 \times 400 \times 3 \times 10^5 = 4.8 \times 10^8$$

$$q(t) = \frac{1}{9 \times 4000 \times 10^9} \left(4.8 \times 10^8 - t\right) \text{ for } 0 \leq t \leq 4.8 \times 10^8.$$  

Consume little to consume forever!
Oil Price Models: Hotelling for Competitors

- H. Hotelling (1931) also proposes that price of the oil today can be deduced from the price of an alternative fuel (backstop technology) discounted to today’s net present value. Competitors who are not subject to reserve limits think in these terms.
- Suppose oil will finish in 2140 and we will then be using electricity instead of oil. Further suppose that cost of electricity that is equivalent to 1 barrel of oil will be $3000.

What should the oil price be in 2040 if annual interest rate is 10%?
- Hotelling says: $3000 \times e^{-0.10 \times 100} = 3000/e^{10} = 3000/22026 = $0.14.

What should the oil price be in 2040 if annual interest rate is 1%?
- Hotelling says: $3000 \times e^{-0.01 \times 100} = 3000/e = 3000/2.718 = $1100.37.

Two problems:
- The result depends too much on the interest rate. Price increases by 10,000 times when the interest rate drops by 10 times. What is the correct interest rate in the next 100 years?
- How do we estimate the price of the alternative resource in 2140?
- Do we run out of oil in 2140, earlier or later?

What to remember from Hotelling:
There is a strategic value of the oil in the ground that is based on not just today’s but also the future uses of oil.
Hubbert Theory of Decline for Total Production

Sum of production profiles appear to be symmetric and bell curve, even if each profile is quite different. It is observed by King Hubbert in the 1950s.

It appears to be a consequence of central limit theorem. But it is not: x-axis is time, not observations from the same population.
Quantity Model: Hubbert Theory

- Hubbert Theory: Sum up the oilfield production profiles. The result will look like a bell-curve: increasing production, a peak and then decreasing production:

- Lower production is a sign that the reserves may not be exhausted and refutes the Hotelling Model.

- There can be smaller (larger) peaks after the one in the 1970s. Especially, new production technologies can increase US production significantly.