Just How Good is That PVT Study?

Denver SPE

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Core Laboratories

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RESERVOIR OPTIMIZATION

Overview

- **Intro to PVT. What? When? How?**
- **Good samples?**
  - **Separator**
    - **Accurate field data?**
  - **Sub-surface**
- **Compositional data representative?**
  - **GC data**
- **Oils vs. Gases**
  - **Intro to phase behavior, production trends etc**
- **PVT experiments**
  - **Material balance hold together?**
  - **Does it all make sense**

The Big Picture: Optimize Recovery?

- **Predict reservoir drive mechanism**
  - **Depletion, expansion, aquifer support**
- **Determine reservoir geophysical properties**
- **Determine rock properties**
  - **Porosity, perm/relative perms, wetting characteristics, capillary pressures**
- **Determine fluid properties**
  - **Viscosity, compressibility, gas solubility, density, shrinkage, flow assurance, chemistry, retrograde behavior**

What? Why? When? Who?

- **What is PVT analysis?**
  - **Pressure-Volume-Temperature**
  - **Physical and chemical properties**
- **Why?**
  - **Phase behavior, quality, flow assurance**
- **When?**
  - **exploration/appraisal, development, production….early and often**
- **Who?**
  - **Asset teams, reservoir engineers, facility, production engrs, flow assurance specialists, petrophysicists**

General Material Balance Equation

oil expansion + gas cap expansion + water expansion

$$N (B_t - B_{ti}) + N\,m\,B_{ti} (B_g - B_{gi})/Bgi + (N B_{ti} + N\,M\,B_{ti})\,C_w\,\Delta p\,S_w / (1-S_w)$$

+ formation expansion + H2O influx + H2O inj. + Gas inj

$$+ C_f\,\Delta p\,(N B_{ti} + N\,m\,B_{ti})/(1-S_w) + W_e + W_i B_{wi} + G_i B_{gi}$$

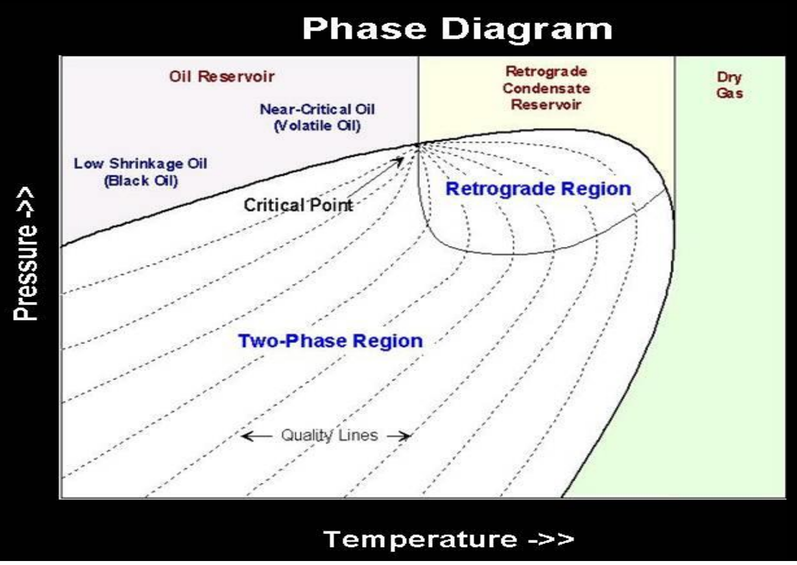
= Oil & dissolved gas production + free gas production + water production

$$= N_p B_t + N_p (R_p - R_{soi}) B_g + W_p B_w$$

Answer 3 Questions:

- **What is the fluid behavior in the range of expected operating pressures and temperatures**
- **What is the market price of the discovered hydrocarbons and how can they be accommodated in export systems, ie, sample quality**
- **Does the fluid have the potential for hydrate, wax or asphaltene precipitation, ie, flow assurance**

Reservoir Fluid Behavior



First Things First:
Let's get some samples!

- **Surface Separator:**
  - **Large volumes of reservoir fluid are produced**
  - **Flow rate stability can be monitored, no sense of 'urgency'**
  - **Multiple sample sets can be collected**
  - **GOR key**
- **Surface Wellhead**
  - **Likely multi-phase**
- **Subsurface (Standard Downhole Samples):**
  - **Ideal when GOR not available or not accurate**
  - **Recommended for solids analyses**
- **Formation Test Tools**

Quality Check on Samples

- Surface separator samples
  - ‘mini reservoir’
  - Opening pressures, bubble points
  - Separator GOR is KEY!!
  - Equilibrium ratio comparisons
- Subsurface samples
  - Formation Test Tool
    - Comparisons vs depth, consistencies
    - Mud contamination
    - Restoration effort
  - Standard wireline samples
    - Consistencies between samples
    - Onsite Psat

Black Oil Behavior

- Heavy oil – lean gas
- Composition: heavy and light components
- Uniform shrinkage and gas liberation
- Production trends
  - Consistent until Psat is reached
- Heavy Oil:
  - Density, viscosity increase
  - Mobility decreases
- Lean Gas:
  - Large viscosity/density discrepancy between gas/oil
  - ‘preferential’ flow
  - Negligible liquid contribution, ie condensate

Reservoir Fluid Compositions

Flash Summary (18,000 psia and 170 °F to 15.025 psia and 80 °F)						
Gas-Oil Ratio	1935	scf/stb	apor Gravity	0.771	(Air = 1.00)	
FVF	1.969	Vsat/Vstd	API Gravity	31.3	°API @ 60°F (Water Free)	

Component (Symbol)	(Name)	Atm. Vapor (mole%)	Atm. Liquid (mole %)	Atm. Liquid (wt %)	Mole Weight	Specific Gravity (Water = 1.0	Reservoir Fluid (mole %)	Reservoir Fluid (wt %)
N_2	Nitrogen	0.238	0.000	0.000	28.01	0.809	0.191	0.083
CO_2	Carbon D	0.241	0.000	0.000	44.01	0.818	0.193	0.132
H_2S	Hydrogen	0.000	0.000	0.000	34.08	0.801	0.000	0.000
C1	Methane	82.346	0.114	0.008	16.04	0.300	65.981	16.390
C2	Ethane	5.603	0.086	0.011	30.07	0.356	4.505	2.098
C3	Propane	4.445	0.312	0.059	44.10	0.507	3.623	2.473
iC4	i-Butane	0.818	0.163	0.040	58.12	0.563	0.688	0.619
nC4	n-Butane	2.263	0.730	0.181	58.12	0.584	1.958	1.762
iC5	i-Pentane	0.806	0.735	0.226	72.15	0.624	0.792	0.885
nC5	n-Pentane	1.040	1.310	0.402	72.15	0.631	1.094	1.222
iC6	Hexanes	0.537	1.718	0.630	86.18	0.664	0.772	1.030
nC6	Hexanes	0.398	1.780	0.653	86.18	0.664	0.673	0.898
ylcyclopei	Methylcyc	0.192	1.189	0.426	84.16	0.754	0.390	0.509
Benzene	Benzene	0.033	0.217	0.072	78.11	0.884	0.070	0.084
yclohexar	Cyclohexa	0.095	0.847	0.303	84.16	0.783	0.245	0.319
C7	Heptanes	0.377	4.862	2.073	100.20	0.688	1.270	1.970
ylcyclohe	Methylcyc	0.128	2.045	0.854	98.19	0.775	0.509	0.775
Toluene	Toluene	0.040	0.876	0.343	92.14	0.874	0.206	0.294
iC8	Iso-Octan	0.045	0.000	0.000	114.23	0.696	0.036	0.064
C8	Octane	0.184	6.602	3.209	114.23	0.707	1.461	2.584
hyl Benze	Ethyl Ben:	0.012	0.521	0.236	106.17	0.874	0.113	0.186
n&p-Xylen	m&p-Xyle	0.025	0.971	0.439	106.17	0.868	0.213	0.351
o-Xylene	o-Xylene	0.008	1.012	0.457	106.17	0.885	0.208	0.342

Typical Differential Liberation

Pressure (psia)		Oil Density (g/cm^3)	Oil Compress. (V/V/psi) x 10^6	Oil Viscosity (cP)	Liberated GOR, R_l (scf/bbl)	Solution GOR, R_{sd} (scf/bbl)	Oil FVF, B_{od} vol/resid. vol	Solution GOR, R_s (scf/bbl)	Sep. Adj. FVF, B_o (vol/ST vol)
18,000		0.690	8.09	0.474	0	2087	1.848	1707	1.608
17,000		0.684	8.27	0.455	0	2087	1.863	1707	1.621
15,683	**Reservoir**	**0.674**	**8.57**	**0.433**	**0**	**2087**	**1.884**	**1707**	**1.639**
14,000		0.666	9.02	0.398	0	2087	1.914	1707	1.665
13,000		0.660	9.40	0.381	0	2087	1.932	1707	1.681
12,000		0.653	9.89	0.362	0	2087	1.951	1707	1.697
11,000		0.647	10.50	0.348	0	2087	1.972	1707	1.715
10,000		0.639	11.56	0.327	0	2087	1.995	1707	1.735
9000		0.631	12.74	0.328	0	2087	2.020	1707	1.758
8000		0.622	14.08	0.329	0	2087	2.049	1707	1.783
7500		0.617	15.32	0.377	0	2087	2.065	1707	1.797
6824	**Saturation**	**0.610**	**18.18**	**0.337**	**0**	**2087**	**2.091**	**1707**	**1.819**
5500		0.663	11.02	0.418	762	1325	1.699	1084	1.532
3750		0.708	9.46	0.577	1262	825	1.471	675	1.365
2250		0.745	8.36	0.811	1577	510	1.334	417	1.265
750		0.781	7.28	1.211	1862	225	1.212	184	1.176
150		0.801	6.80	1.518	1988	99	1.151	81	1.130
15		0.822		1.590	2087	0	1.075	0	1.075
15	@ 60°F	0.876	**API = 29.94**				1.000		

Gas Properties

Pressure	Gas Density	Gas Z Factor	Incr. Gas Gravity	Cum. Gas Gravity	Gas FVF, B_g	Total FVF, B_t	Calc. Gas Viscosity
(psia)	(g/cm^3)	(vol/vol@std)	(Air = 1.00)	(Air = 1.00)	es bbl /mmsc	(vol/resid. vol)	(cP)
5500	0.297	1.026	0.862	0.862	646	2.191	0.038
3750	0.202	0.912	0.764	0.823	842	2.533	0.025
2250	0.113	0.893	0.697	0.798	1375	3.502	0.018
750	0.038	0.923	0.722	0.786	4262	9.147	0.014
150	0.009	0.957	0.935	0.796	22097	45.085	0.012
15.025	0.002	1.000	1.778	0.842	230973	483.161	0.010

Fundamental Assumptions

- **PVT cell = mini reservoir**
- **Lab check: mass in = mass out**
- **QA check: assume recovery of 1 STB**
  - **2.1 FVF, 2087 SCF/B GOR**

Ok…But first does it make sense? Flash Comparison

Experimental Procedure	GOR (SCF/stb)	FVF (Psat bbl/stb)	Gas Gravity	API at 60 °F
Reservoir Oil Single-Stage Flash	1935	1.969	0.771	31.3
Differential Liberation @ Res. Temperature	2087	2.091	0.842	29.9
Multi-Stage Separator Test	1707	1.819	0.690	33.8

Conversion Factors

- **1 cu.ft. = 28317 cc = 7.48 gallons**
- **1 bbl = 5.61 cu.ft. = 42 gallon = 158984cc**
- **1 lb = 453.6 gms**
- **Gms/cc = lb/ft3 * 350.5**
- **Gas MWT, lbs/lb-ml = gas spec.grav. * 28.96 lbs/lb-ml (MWT of air)**
- **Molar volume of inert gas = 371.2 cu.ft/lb-ml**
- **Gms/cc = 141.5/(API+131.5)**
- **Lbs gas = cu.ft/ molar volume * gas MWT**
- **Lbs oil = density * volume**

Typical Differential Liberation

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13,000		0.660	9.40	0.381	0	2087	1.932	1707	1.681
12,000		0.653	9.89	0.362	0	2087	1.951	1707	1.697
11,000		0.647	10.50	0.348	0	2087	1.972	1707	1.715
10,000		0.639	11.56	0.327	0	2087	1.995	1707	1.735
9000		0.631	12.74	0.328	0	2087	2.020	1707	1.758
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2250		0.745	8.36	0.811	1577	510	1.334	417	1.265
750		0.781	7.28	1.211	1862	225	1.212	184	1.176
150		0.801	6.80	1.518	1988	99	1.151	81	1.130
15		0.822		1.590	2087	0	1.075	0	1.075
15	@ 60°F	0.876	**API = 29.94**				1.000		

Material Balance

6824 psia: 0.610 g/cc, 2087 GOR, 2.091 FVF, 28.9°API, 0.842 cumm gas gravity

Assume recovery of 1 STB:
By definition, initial volume = 2.091 Bbl and 2087 SCF liberated gas.

2.091 bbls * 0.610g/cc * 350.5lbs/bbl = 447.0 lbs
1 STB (28.9°API) = 141.5/(131.5+28.94) * 350.5 = 307.1 lbs

2087 SCF / 371.2 SCF/lb-ml * 0.842 * 28.96lbs/lb-ml = 137.7 lbs

447.0 lbs in, 307.1 + 137.7 = **444.8 lbs out**
6.895 lb-ml in, 1.307 lb-ml + 5.622 lb-ml = 6.929 lb-ml out

Diff Lib Compositional Balance

- **Residual Oil**
- **Incremental liberated gas**
- **Associated compositions**

Componen	Liberated Gas 10000 psia (mole %)	9000 psia (mole %)	8000 psia (mole %)	7500 psia (mole %)	6824 psia (mole %)	15.025 psia (mole %)	Residual Liquid (mole %)	Calc. Res. Fluid (mole %)
Nitrogen	0.263	0.279	0.221	0.130	0.040	0.001	0.000	0.176
Carbon Diox	0.210	0.225	0.223	0.285	0.338	0.141	0.000	0.187
Hydrogen Su	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Methane	82.229	85.673	88.253	84.185	66.078	26.114	0.021	65.498
Ethane	4.447	4.448	4.415	6.577	11.390	8.344	0.103	4.358
Propane	3.269	2.957	2.737	4.222	10.511	16.340	0.550	3.600
Iso-Butane	0.613	0.522	0.443	0.635	1.613	3.711	0.262	0.680
N-Butane	1.658	1.375	1.127	1.586	4.290	13.643	1.104	2.018
Iso-Pentane	0.659	0.508	0.367	0.455	1.249	5.186	0.864	0.813
N-Pentane	0.888	0.674	0.463	0.553	1.521	7.093	1.729	1.185
Hexanes	1.065	0.789	0.495	0.488	1.267	7.506	3.228	1.541
Heptanes	1.395	0.946	0.543	0.432	0.986	6.881	5.858	2.123
Octanes	1.220	0.634	0.305	0.186	0.501	3.794	7.947	2.203
Nonanes	0.913	0.452	0.197	0.157	0.151	1.125	6.928	1.749
Decanes	1.170	0.517	0.211	0.108	0.066	0.122	7.035	1.811
Undecanes							5.320	0.997
Dodecanes							4.648	0.871
Tridecanes							4.632	0.868
Tetradecanes							4.140	0.775
Pentadecanes							3.657	0.685

Comp Comparison

	Diff Lib.	Flash Test
Nitrogen	*(mole %)*	(mole %)
Carbon Dioxide	0.176	0.191
Hydrogen Sulfide	0.187	0.193
Methane	0.000	0.000
Ethane	65.498	65.981
Propane	4.358	4.505
i-Butane	3.600	3.623
n-Butane	0.680	0.688
i-Pentane	2.018	1.958
n-Pentane	0.813	0.792
Hexanes	1.185	1.094
Hexanes	1.541	0.772
Methylcyclopentane	2.123	0.673
Benzene	2.203	0.390
Cyclohexane	1.749	0.070
Heptanes	1.811	0.245
Methylcyclohexane	0.997	1.270
Toluene	0.871	0.509
Iso-Octane	0.868	0.206
Octane	0.775	0.036
Ethyl Benzene	0.685	1.461
m&p-Xylene	0.872	0.113
o-Xylene	0.548	0.213
Nonanes	0.653	0.208

In summary….

- Do compositions look reasonable?
  - Methane content? MWTs?
- Do property values follow expected trends
  - Psat vs. other pressures?
- Is material balance rigorous?
  - mass, molar, compositional
- Does the flash comparison make sense?
  - Thermodynamically sound?

Gas-Condensate Behavior

- Very light system
- Life is great…..above the dew point
- Depletion below dew point:
  - Condensation begins
  - Liquid production drops, yields drop
  - Near-wellbore condensate ‘banking’
  - Perm barriers

Depletion Studies

Vapor Properties

Pressure (psia)	Gas Density (g/cm^3)	Z Factor (Gas Phase)	Z Factor (2 Phase)	Gas Mole Weight	Gas Viscosity (cP)	Gas FVF (B_g) (bbl gas @ P,T per MMscf)
15,833	**0.531**	**2.546**	**2.546**	**40.63**		**587**
8157	**0.480**	**1.453**	**1.453**	**40.63**		**650**
6500	0.389	1.227	1.239	34.15	0.058	690
5500	0.328	1.021	1.125	28.30	0.044	678
4000	0.236	0.906	0.982	24.81	0.029	827
3000	0.169	0.892	0.895	23.43	0.022	1086
2000	0.106	0.912	0.810	22.52	0.018	1666

Displaced Volumetrics and Liquid Properties

Pressure	Moles Displaced	Reservoir Fluid Displaced	Relative Liquid Volume		Absolute Liquid Volume
(psia)	(gmole)	(% of initial moles)	(% of V_{res})	(% of V_{sat})	(% of V_p)
15833					
8157	**0.000**	**0.00**	**0.00**	**0.00**	**0.00**
6500	0.059	5.79	12.15	10.98	10.28
5500	0.066	12.20	34.42	31.08	28.96
4000	0.150	26.80	39.74	35.89	30.20
3000	0.133	39.79	38.95	35.17	28.86
2000	0.162	55.62	36.44	32.91	23.49

‘Produced’ Compositions

Constant Volume Depletion Fluid Compositions

Component	Saturation Pressure (mole %)	6500 psia (mole %)	5500 psia (mole %)	4000 psia (mole %)	3000 psia (mole %)	2000 psia (mole %)	Liquid at 2000 psia (mole %)
Nitrogen	0.299	0.326	0.341	0.353	0.362	0.354	0.066
Carbon Dioxide	0.498	0.499	0.508	0.518	0.526	0.543	0.304
Hydrogen Sulfide	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Methane	70.334	73.101	76.002	78.814	80.170	80.940	30.633
Ethane	7.782	7.963	7.946	7.946	7.892	8.149	6.864
Propane	4.155	4.140	3.981	3.860	3.801	3.842	5.127
Iso-Butane	0.962	0.933	0.898	0.850	0.814	0.793	1.298
N-Butane	1.869	1.782	1.701	1.570	1.501	1.452	2.793
Iso-Pentane	0.885	0.812	0.759	0.679	0.634	0.583	1.508
N-Pentane	0.964	0.854	0.793	0.694	0.624	0.559	1.945
Hexanes	1.340	1.164	1.035	0.856	0.734	0.610	3.033
Heptanes	1.652	1.524	1.411	1.225	1.104	0.875	3.973
Octanes	1.731	1.607	1.463	1.174	0.964	0.730	5.557
Nonanes	1.126	1.087	0.971	0.768	0.616	0.470	4.350
Decanes Plus	6.403	4.210	2.191	0.692	0.260	0.100	32.549

Calculated Recoveries

Experimental and Equation of State Predictions								
			Pressure (psia)					
		Initial in place	Sat 8157	6500	5500	4000	3000	2000
Moles in PVT Cell	(gmole)	1.136	1.026	0.966	0.900	0.751	0.617	0.455
Moles Vapor Liberated / Step	(gmole)		0.110	0.059	0.066	0.150	0.133	0.162
EOS Predicted Liquid Fractions								
1st Stage: 1800 psia and 130 °F	(mole fraction)		0.279	0.236	0.189	0.128	0.089	0.048
2nd Stage: 650 psia and 130 °F	(mole fraction)		0.686	0.668	0.640	0.590	0.552	0.518
3rd Stage: 200 psia and 110 °F	(mole fraction)		0.842	0.835	0.825	0.808	0.796	0.785
4th Stage: 15 psia and 60 °F	(mole fraction)		0.806	0.795	0.779	0.754	0.736	0.716
Predicted Liquid Molar Volume	(cc/gmole)		206.0	190.5	175.5	161.0	155.1	151.8
Calculated Surface Recoveries								
Initial Reservoir Fluid in Place	mscf	1000	903.1					
Vapor Produced / Step	mscf		96.9	52.3	57.9	131.9	117.3	143.0
Cumulative Vapor Produced	mscf		96.9	149.2	207.1	338.9	456.3	599.2
Predicted Surface Liquids	stb	201.9	19.6	7.9	5.9	7.4	3.9	2.3
Cumulative Surface Liquids	stb	0	19.6	27.4	33.4	40.7	44.7	47.0
Predicted Surface Vapour	mscf	869.9	84.3	46.8	53.4	125.8	114.0	140.9
Cumulative Surface Gas	mscf	0	84.3	131.1	184.5	310.3	424.3	565.2
Instantaneous Yield	stb/mmscf	232.1	232.1	167.9	111.4	58.6	34.4	16.2
Average Yield	stb/mmscf	232.1	232.1	209.2	180.9	131.3	105.3	83.1
Instantaneous GOR	scf/stb	4308	4308	5957	8979	17073	29045	61544
Average GOR	scf/stb	4308	4308	4781	5529	7617	9499	12038
Gas Recovery Factor	%	0.0	8.4	13.1	18.4	31.0	42.4	56.5
Liquid Recovery Factor	%	0.0	9.7	13.6	16.5	20.2	22.1	23.3

Material Balance

- **Assume 100 moles of initial fluid in place**
- **Calculate 'reservoir volume' V=ZN(100)R(10.73)T/P**
- **'% produced' equals moles removed**
- **Calculate individual moles removed using composition and % produced**
- **Assume gas removed and gas remaining have same comp**
- **Calculate liquid moles vs gas moles remaining using vol % liquid measurement**
- **Calculate retrograde liquid comp using summation of liquid moles remaining.**

Material Balance

Reservoir Volume: V=ZNRT/P =
(1.453)(100)(10.73)(250+460)/8157 = 135.70 cu.ft.

	Psat	6500	5500	4000	3000	2000	2000 psi liquid
C1	70.33	73.10	76.00	78.81	80.17	80.94	
% Prod	0	5.79	12.20	26.80	39.79	55.62	
Vol % liquid							32.91

70.33 moles of C1 initially:
.0579*73.10+.0641*76.00+.1460*78.81+.1299*80.17+.1583*80.94
= 43.84 moles of methane removed
=26.49 moles of methane remain in cell, ie reservoir
..vapor-liquid ratio?

Material Balance (continued)

Reservor volume * (1 – vol fraction liquid) = volume of 2000psi gas
135.7 cu.ft * (1-.3291) = 91.04 cu.ft. gas

N=PV/ZRT = (2000)(91.04)/(0.912)(10.73)(710) = 26.21 mls of gas
26.21 mls gas = 26.21*.8094 moles methane = 21.21 mls methane in gas
26.49 total methane in cell – 21.21 methane in gas = 5.28 methane in liquid @ 2000 psi

100 moles initial – 55.62 moles removed = 44.37 total moles remaining
44.37-26.21 = 18.17 mls of liquid remaining in cell

7.48 mls methane/ 18.17 mls liquid = 29.06% methane in 2000# liquid
29.06% vs 30.63% measured

In summary….

- **Do compositions look reasonable?**
- **Do comps and calculated yields follow expected trends**
  - **Instantaneous vs. cumulative**
  - **% ‘produced’, ie removed**
- **Is material balance rigorous?**
  - **do compositions balance**

Wrapping it up..

- **Samples, surface data need to be good**
- **Material balances need to be tight**
- **But it needs to “make sense” also**
- **Starts with representative reservoir fluid**
- **Measurements are all tied together with chromatographic analyses**
- **Black Oils: flash comparison is very useful tool**

PVT lab

New Expansion

Pressurized Fluid Imaging (PFI) System

Blueprint for Fluids Program

- Proper sampling
- Chemistry
- Physical properties
  - fluid flow assurance, viscosity etc, dead oil analyses
- Reservoir depletion simulation
  - CME, Diff Lib, CVD
- Surface recovery simulation
  - separator tests
- Mathematics

How’s it used?

- Reserves - Bo, Rs
  - oil and gas, fluid energy, recovery efficiency
- Project Revenue - crude oil prices
- Facilities - maximum output
  - Design of separator trains, tubular valves, pipelines etc.
- Development well counts - viscosity
- Subsea Completions
  - flowline distances, diameters
  - need for solids inhibition
- Secondary Recovery
  - need for waterflood, gas injection
- Facility upgrades
- Allocation – who gets what?
- More fluids analysis=more information=more ammunition=better models=MORE EFFICIENT USE OF ASSETS=OPTIMAL $$$ SPENT=LOWER F&D COSTS

Thanks for not falling asleep!
Questions?

Core Lab
RESERVOIR OPTIMIZATION