A New Approach to MPFM Performance Assessment in Heavy Oil

by

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Overview

- **MPFM performance is assessed with a model using:**
  - physical characteristics of the sensors
  - fluid properties
  - operating conditions
  - published information in the public domain
- **High Viscosity Heavy Oil application**
  - Fiscal MPFM measurement required due to project economics
  - Tight emulsion, high viscosity100 to 4,000 cP with entrained gas
  - 0% to 60% WLR, 0% to 60% GVF, 3kbpd to 25kbpd liquid
  - Dual Gamma Venturi MPFM
  - Venturi with low RN $< 2,000$ that required a Cd correction
- **Benefits of using performance model:**
  - evaluate MPFM requirements early in project development
  - assess feasibility before main funding commitments are made
  - avoids costly, time consuming tests and wasteful duplication of tests
  - independent and transparent means of verification of vendors claims

I did not have…….

Don't believe everything you are told ☺

The Application

- A process facility nearby had the capability to process Heavy Oil fluids and export through to a common pipeline with an existing LACT unit
- Cost of process plant for measurement of Heavy Oil with a LACT unit was prohibitive and wasteful
- Parties exposed due to different ownership
- Existing facility production is fifteen times greater than the Heavy Oil so relative exposure is lower
- Fiscal Heavy Oil MPFM measurement was acceptable with the appropriate tariffs to the Pipeline Entrants, Royalty Owners and the Regulatory Authorities

Fluid Properties & Conditions

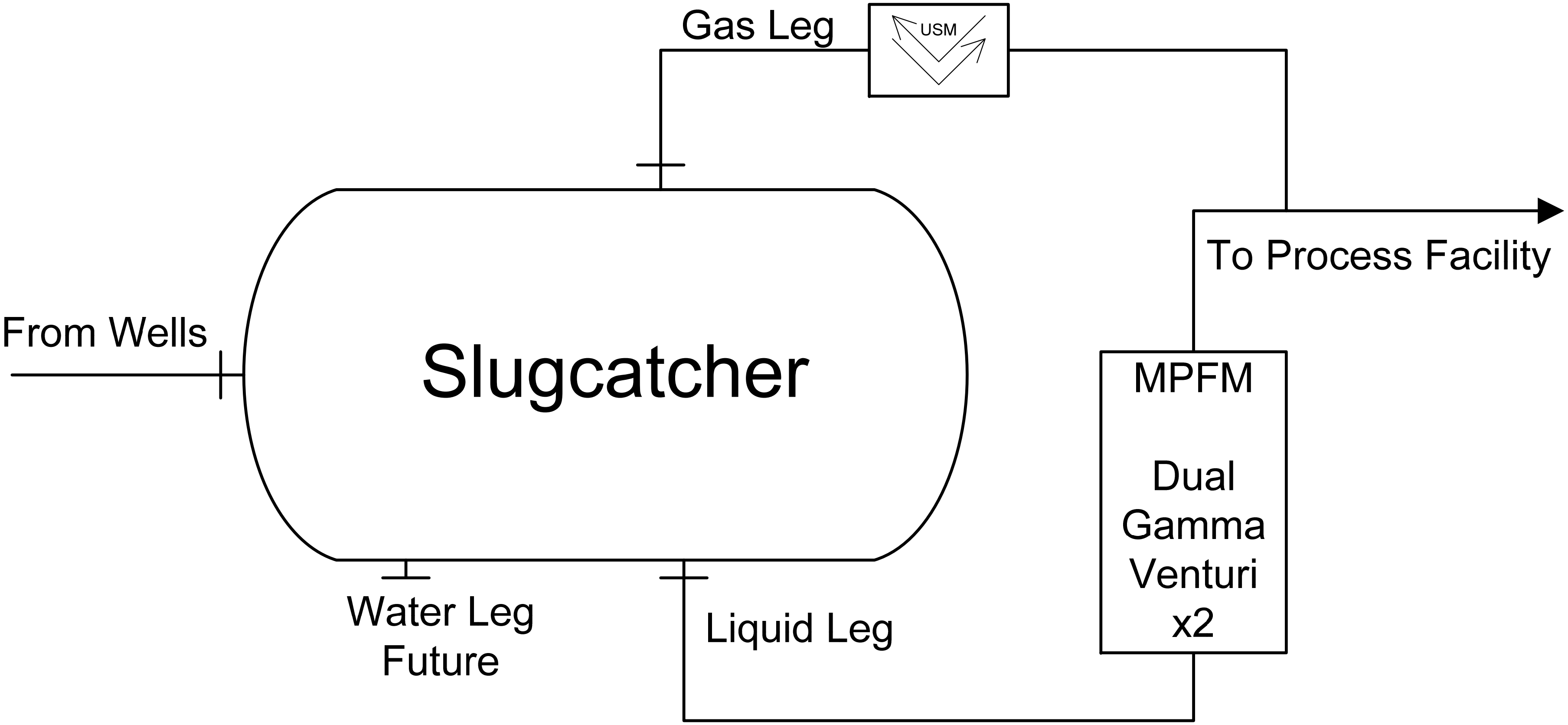
<u>Fluid Properties</u>

• GVF	0% to 60% No phase slip	
• WLR	0% to 60% No phase slip	
• Flow regime	slugging	
• Liquid regime	tight emulsion (due to ESP's)	
• Gas regime	entrained (bubbles in emulsion	
• Oil gravity	19 to 21 API°	(925 to 940 kg/m^3)
• Prod. Water	63.5 to 65.0 lb/cf	(1010 to 1040 kg/m^3)
• Gas SG	0.67 to 0.69	(0.83 to 0.86 kg/m^3)
• Viscosity	50 to 10,000 cP (due to emulsion)	
• Reynolds No.	100 to 20,000 (dependant on Venturi)	

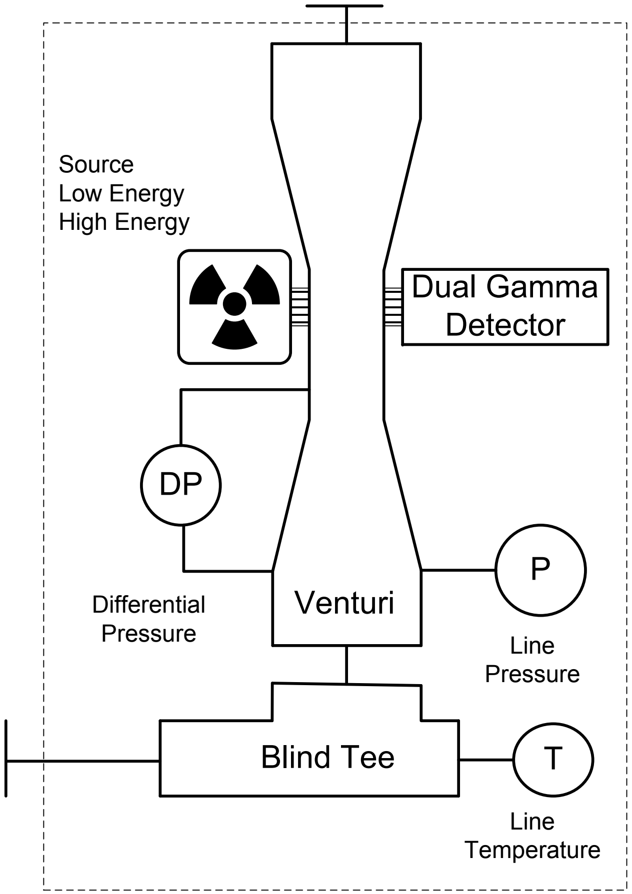
<u>Operating Conditions</u>

• Temperature	59 to 121 °F	(15 to 50 °C)
• Pressure	150 to 300 psig	(10 to 20 barg)

Heavy Oil Measurement



MPFM Model



Multi Phase Flow Meter

- **Dual Gamma**
  - High Energy
  - Low Energy
  - GVF
  - WLR
  - Mixture Density
- **Venturi Mass Flow Rate**
  - Measures Mass Flow Rate
  - Differential Pressure
  - Static Pressure
  - Temperature
  - Blind Tee mixer
- **Oil Standard Volume**

MPFM Module Uncertainty

1. **Instrument Uncertainty** - DP, P, T by RSS
2. **Line and Standard Conditions** – API thermal and compressibility and AGA8 gas compressibility and water density from salinity all by MCS
3. **Dual Gamma** – GVF, WLR and mixture density from oil, gas and produced water actual density and mass attenuation from Low and High Energy EPR and measurement count by MCS
4. **Venturi** – Mass flow from mixture density and ISO5167-4 by RSS and MCS
5. **Cd Correction** – Venturi RN used to find Cd from table with uncertainty from curve fit deviation

Knowing and Unknowing

1. There are known known's - there are things we know that we know.
2. There are known unknowns - that is to say that there are things we now know we don't know.
3. But there are also unknown unknowns - the things we do not know we don't know.

Known’s and Unknown's

1. **Sensor Measurement Uncertainty** - generally well understood by the equipment vendors and quantifiable. Known’s
2. **Fluid Property Uncertainty** – fluid properties, flow regime and flow rate are changeable and difficult to quantity in real time which can be mitigated by regular sampling. Somewhat Unknown.
3. **Empirical Relationship Uncertainty** –found in calculation methods such as the Venturi Coefficient of Discharge Cd at low Reynolds Number and are often overlooked. Unknown's
4. **Calculation Method Uncertainty**– uncertainty can be magnified or diminished when measurements, fluid variables and constants are combined by calculation and there may be uncertainty in some calculation methods. These can be quantified by sensitivity analysis and with MCS. Known’s

Dual Gamma Module (1)

The detector has a low energy and high energy detection level which is expressed as:

$$N_{le} = N_{le0} \cdot e^{-x \cdot \left(\mu_{leo} \cdot \rho_o \cdot \alpha_o + \mu_{lew} \cdot \rho_w \cdot \alpha_w + \mu_{leg} \cdot \rho_g \cdot \alpha_g \right)}$$ Low energy

$$N_{he} = N_{he0} \cdot e^{-x \cdot \left(\mu_{heo} \cdot \rho_o \cdot \alpha_o + \mu_{hew} \cdot \rho_w \cdot \alpha_w + \mu_{heg} \cdot \rho_g \cdot \alpha_g \right)}$$ High energy

The equations can be represented in terms of linear attenuation constants for each energy:

$$K_{le} = \frac{\ln\left(\frac{N_{le}}{N_{le0}} \right)}{-x} = \mu_{leo} \cdot \rho_o \cdot \alpha_o + \mu_{lew} \cdot \rho_w \cdot \alpha_w + \mu_{leg} \cdot \rho_g \cdot \alpha_g$$

$$K_{he} = \frac{\ln\left(\frac{N_{he}}{N_{he0}} \right)}{-x} = \mu_{heo} \cdot \rho_o \cdot \alpha_o + \mu_{hew} \cdot \rho_w \cdot \alpha_w + \mu_{heg} \cdot \rho_g \cdot \alpha_g$$

The sum of the phase fractions is unity:

$$\alpha_o + \alpha_w + \alpha_g = 1$$

Dual Gamma Module (2)

- With the sum of the phase fractions (unity), Kle and Khe, each phase fraction can be found
- Kle and Khe can be found by calibration for each phase and the EPR for each energy level.
- Kle and Khe can be found from linear attenuation constants for each compound for each phase. NIST data was used here with reservoir data in the absence of samples and a MPFM.
- GVF, WLR and Mixture Density are found from each phase fraction and density at line conditions.
- Line conditions are found in a separate module.

Dual Gamma Module (3)

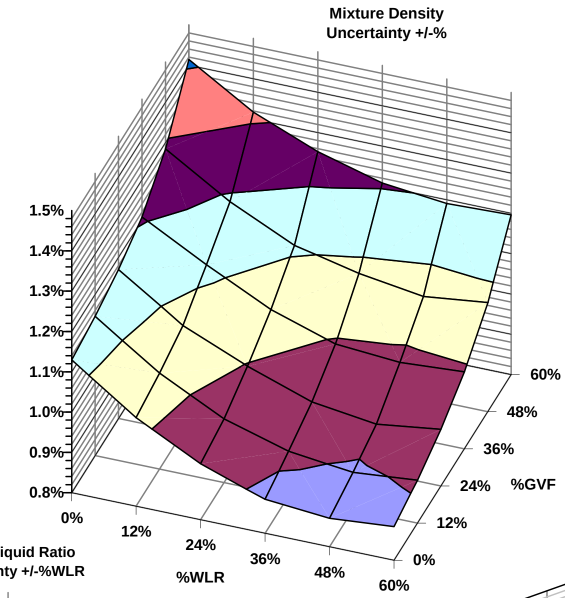
Dual Energy Gamma Densitometer - MCS Uncertainty					
Constants and Uncertainties					
Mixture	Name	Units	Minimum	Maximum	
Gas Volume Fraction	GVF	%gas/mix	0.0%	60.0%	
Water Liquid Ratio	WLR	%wtr/liq	0.0%	60.0%	
Density	Name	Units	Value	Uncertainty	Bias
Gas density	Rhog	kg/m^3	14.98	4.41%	0.00
Oil density	Rhoo	kg/m^3	923.7	1.00%	30.00
Water density	Rhow	kg/m^3	1027.3	1.00%	30.00
Gamma Detector	Name	Units	Value	Uncertainty	Bias
Path length	x	m	0.052	0.010%	0.00000
Low Energy	Name	Units	Value	Uncertainty	Bias
EPR Count Rate	Nle0	Hz	24,109.7	1.46	0.00
EPR Ave. Period	tle0	Sec	43,200		
EPR Samples	Sle0		1		
Measurement Count	mtle	Hz			0.00
Measured Ave. Period	tle	Sec	40		
Measured Samples	Sle		1		
Gas attenuation	Muleg	m^2/kg	0.025830400	0.50%	0.0000000
Oil attenuation	Muleo	m^2/kg	0.024967800	0.50%	0.0000000
Water attenuation	Mulew	m^2/kg	0.037914000	0.50%	0.0000000
High Energy	Name	Units	Value	Uncertainty	Bias
EPR Count Rate	Nhe0	Hz	12,541.4	1.06	0.00
EPR Ave. Period	the0	Sec	43,200		
EPR Samples	She0		1		
Measurement Count	mthe	Hz			0.00
Measured Ave. Period	the	Sec	40		
Measured Samples	Sle		1		
Gas attenuation	Muheg	m^2/kg	0.018003700	0.50%	0.0000000
Oil attenuation	Muheo	m^2/kg	0.017045900	0.50%	0.0000000
Water attenuation	Muhew	m^2/kg	0.017131700	0.50%	0.0000000

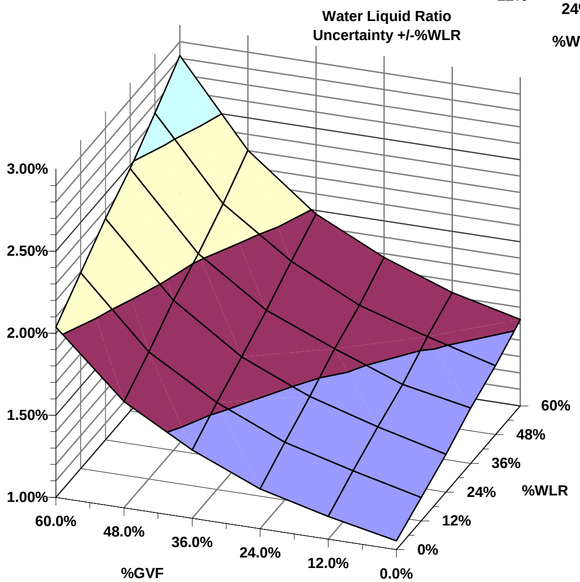
Input to the MCS includes bias

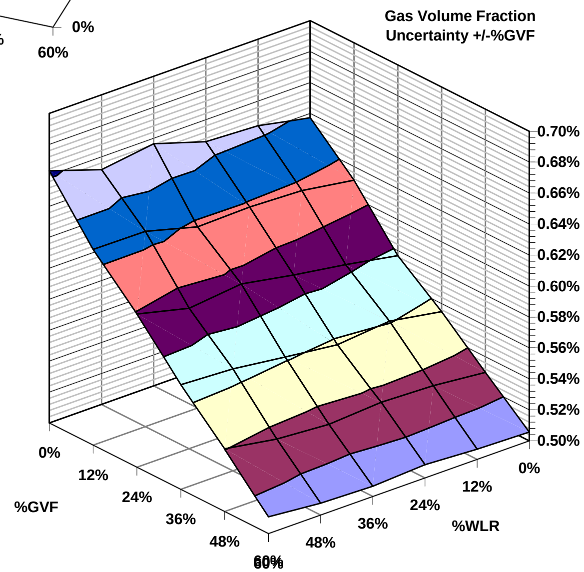
Bias in the results is found from the difference between the MCS result mean, with, and without, bias

Uncertainty is found from the distribution of the MCS results

Dual Gamma Module (4)







Fluid	Quantity	Name	Unit	Value	Uncertainty	
Conditions	Temperature	Tmix	°F	78.0		
			°C	25.56	0.45	
	Pressure	Pmix	psig	250.00		
			barg	17.042	0.76	
Oil	Gravity	APIoil	°API	20.6		
	Standard Density	ρsoil	kg/m^3	929.39		
	Vapour Pressure	Pvap	psig	10.00		
			barg	0.68		
	Thermal Correction	Ctloil	factor	0.992877		
	Pressure correction	Cploil	factor	1.001022		
	volume correct.	VCFoil	factor	0.993891		
	actual density	ρaoil	kg/m^3	923.71		
	standard volume correction factor			0.993891	0.10%	0.99399971
Water	standard density	ρswtr	kg/m^3	1,030.030		
	salinity		kg/kg	0.0429196		
	actual density	ρawtr	kg/m^3	1,027.319		
	standard volume correction factor			0.997368	0.10%	0.997866191
Gas	standard density	ρsgas	kg/m^3	0.83107		
	actual density	ρagas	kg/m^3	14.985		
	dyn. viscosity	μgas	cP @60°F	0.015		
	kin. viscosity	νgas	cSt	1.00102		
AGA8 Gas Density						
Line Conditions	**Measurement**	**Uncertainty**				**Trial Values**
Temperature deg C	25.56	0.450				25.43
Pressure bara	18.05	0.755				18.40
Gas Composition	**Compostion mol%**	**Normalised mol%**	**Component Uncertainty %**	**Uncertainty mol%**	**Trials**	**Normalised Trials**
Nitrogen mol%	0.720	0.720	1.00%	0.0072	0.7185	0.7174
Carbon Dioxide mol%	1.360	1.360	1.00%	0.0136	1.3676	1.3655
Methane mol%	85.330	85.330	2.00%	1.7066	85.4663	85.3403
Ethane mol%	6.150	6.150	1.00%	0.0615	6.1468	6.1377
Propane mol%	3.810	3.810	1.00%	0.0381	3.8206	3.8150
n-Butane mol%	2.020	2.020	1.00%	0.0202	2.0175	2.0145
i-Butane mol%	0.000	0.000	1.00%	0.0000	0.0000	0.0000
n-Pentane mol%	0.580	0.580	1.00%	0.0058	0.5807	0.5799
i-Pentane mol%	0.000	0.000	1.00%	0.0000	0.0000	0.0000
n-Hexane mol%	0.030	0.030	1.00%	0.0003	0.0297	0.0297
n-Heptane mol%	0.000	0.000	1.00%	0.0000	0.0000	0.0000
n-Octane mol%	0.000	0.000	0.00%	0.0000	0.0000	0.0000
n-Nonane mol%	0.000	0.000	0.00%	0.0000	0.0000	0.0000
n-Decane mol%	0.000	0.000	0.00%	0.0000	0.0000	0.0000
Total mol%	100.000	100.00			100.15	100.00
Normalised	**True Result**	**Method Uncertainty**	**MCS Mean**	**MCS Uncertainty**	**Trials with Method**	**Trials**
Line Density Kg/m3 (AGA8)	14.98	0.10%	14.98	4.41%	15.29	15.29
Standard Density Kg/m3 (AGA8)	0.8311	0.10%	0.83	0.34%	0.8310	0.8310
Line/Standard	18.03		18.02	4.40%	18.40	18.40

Fluid Conditions Module

Venturi Overview

- **Mixture Actual Volume Flow** rate uses Mixture Density from the Dual Gamma Module and ISO5167-4 for the Venturi. Uncertainty is found by RSS and MCS
- **Venturi** Coefficient of Discharge Cd at low Reynolds Number is found from a look-up table.
- **Oil Actual Volume Flow** is found from

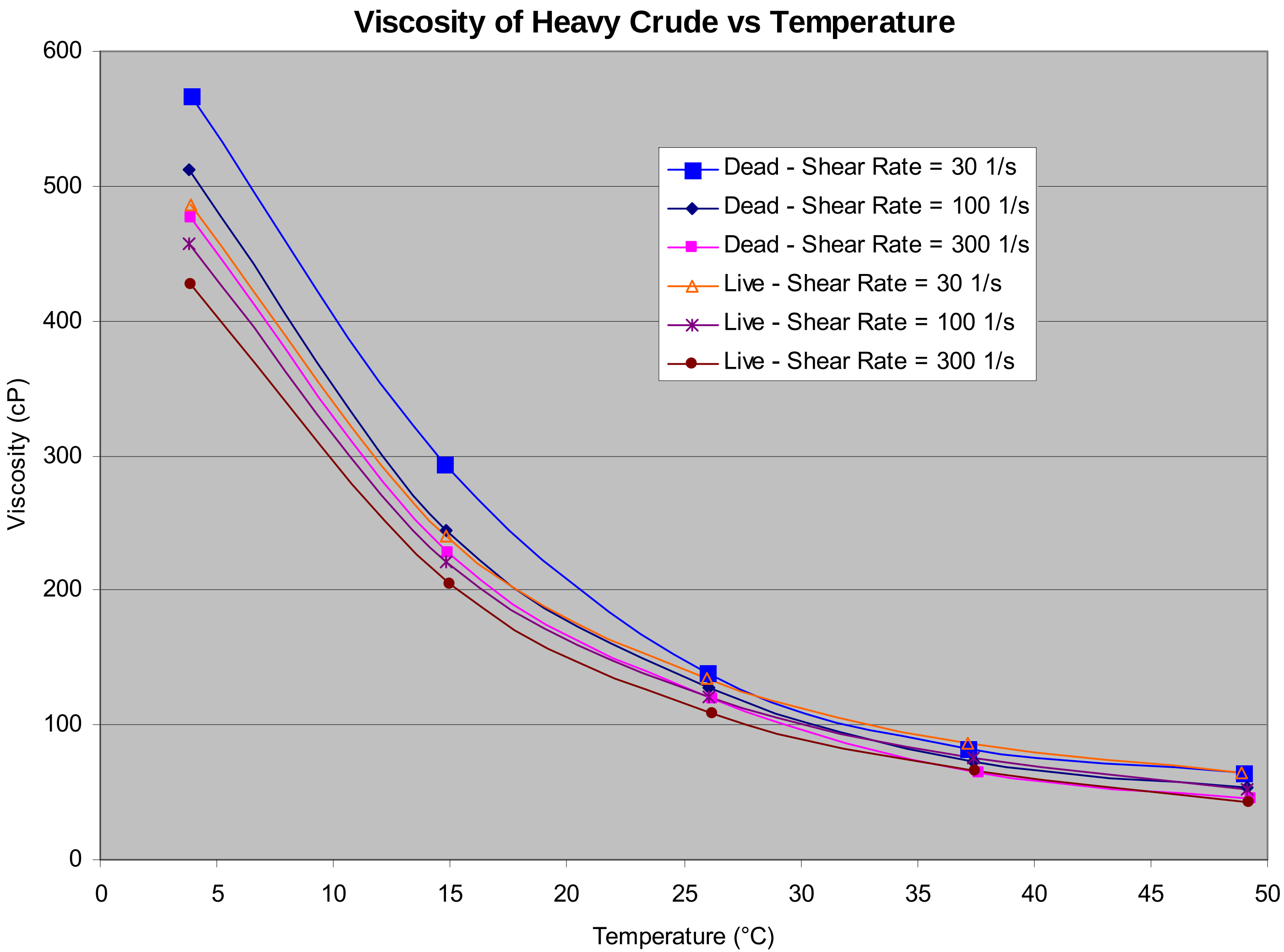
  Qvoil = Qvmix x (1-GVF) x (1-WLR)
- **Oil Standard Volume Flow** rate is found from the API thermal and compressibility corrections

  Qsvoil = Qvoil x Ctloil x Cploil

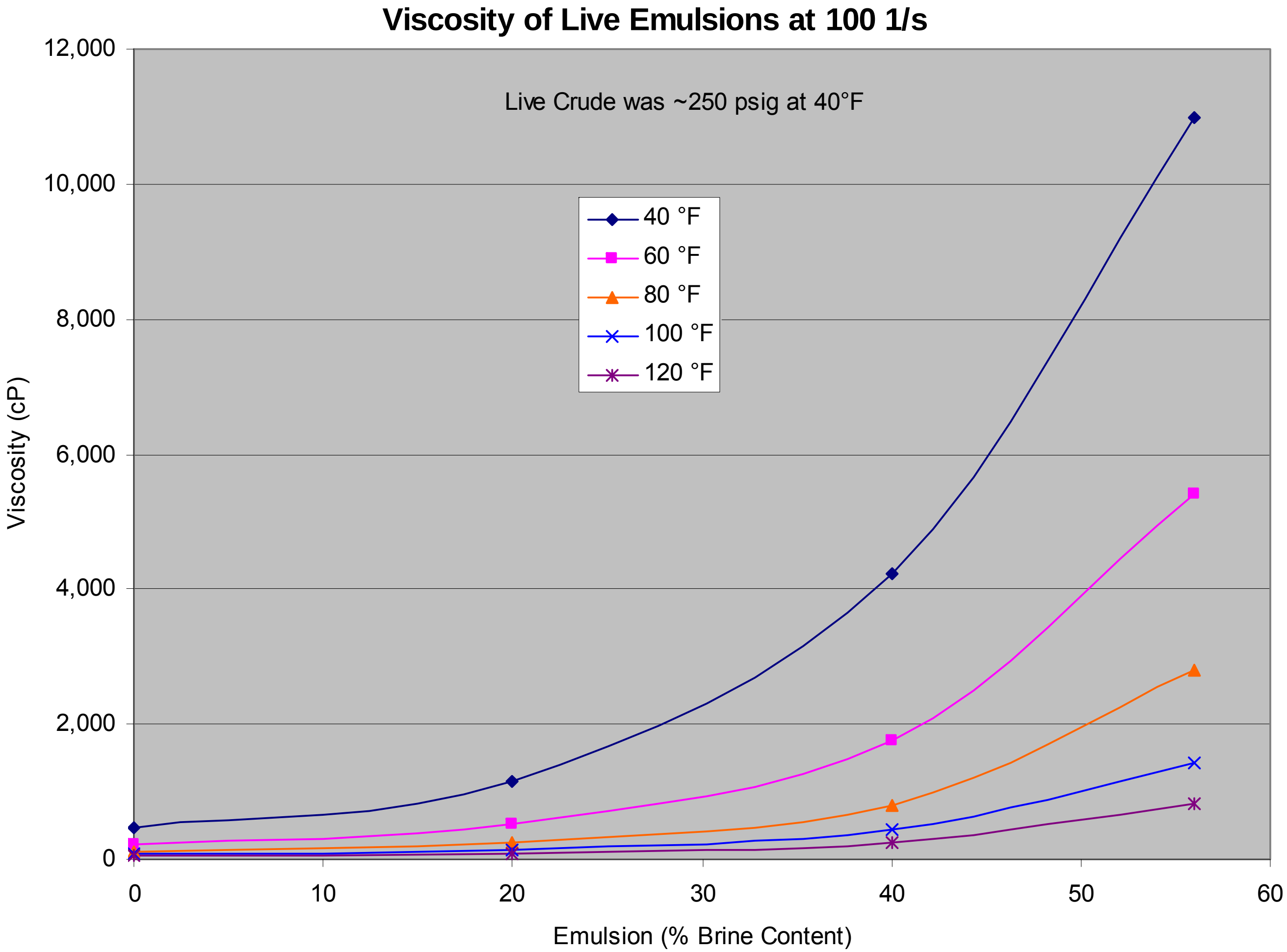
Viscosity

- **Emulsion Viscosity** was found from a laboratory study reservoir fluids by shearing the fluids in a mixture at various rates to simulate the action of the ESP's to find the viscosity over the expected temperature range
- The following slides show variation in the viscosity dead crude with temperature and the variation of an emulsion of live crude with WLR and temperature

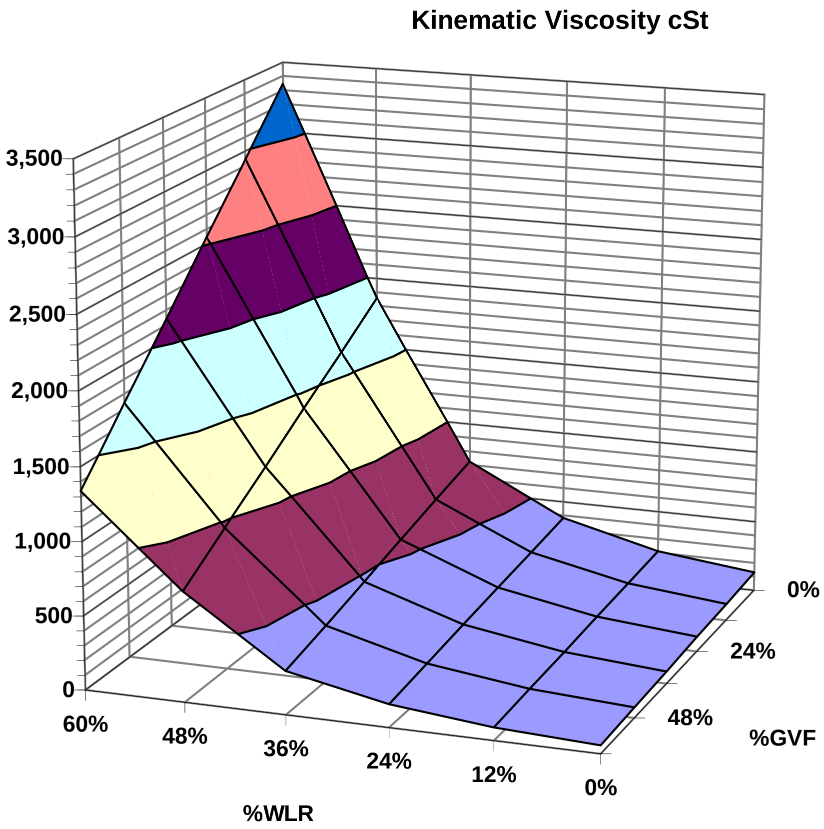
Heavy Crude Viscosity



Emulsion Viscosity



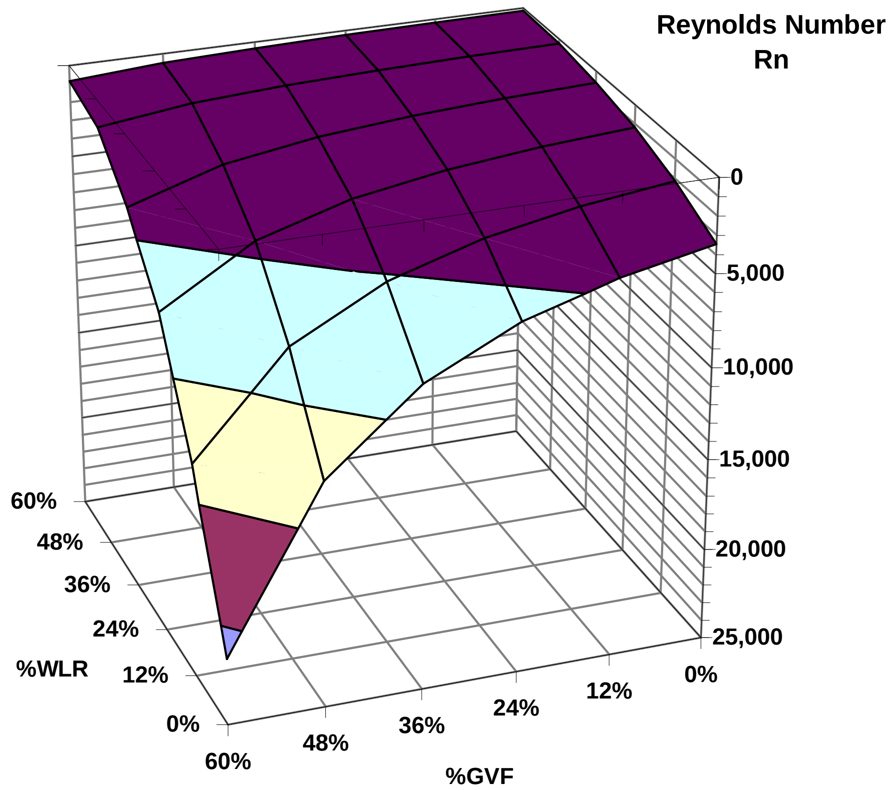
Kinematic Viscosity



- **Kinematic Viscosity** increases with increasing WLR due to the emulsion and with GVF due to density decrease

Reynolds Number

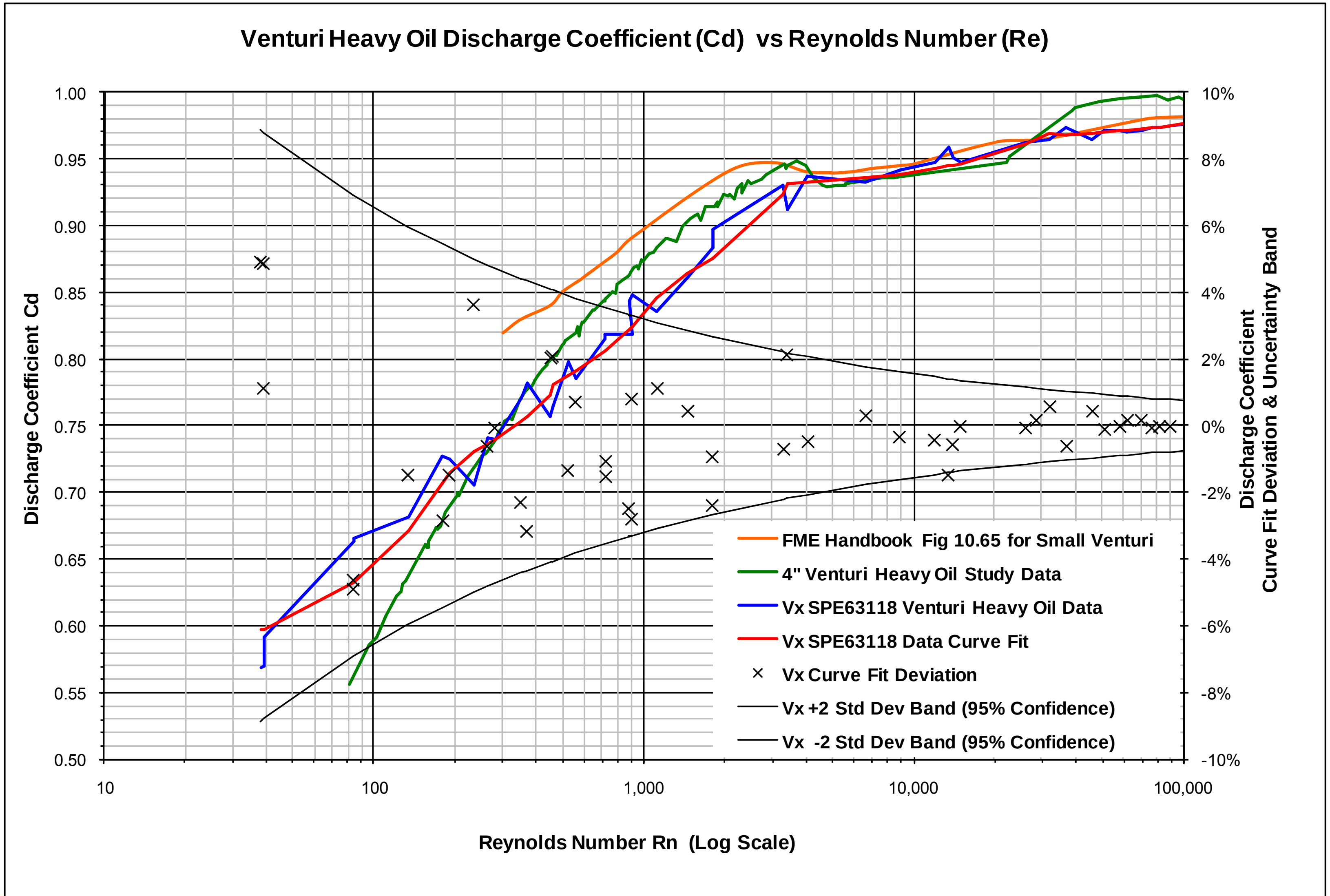
- **Reynolds Number** decreases with kinematic viscosity



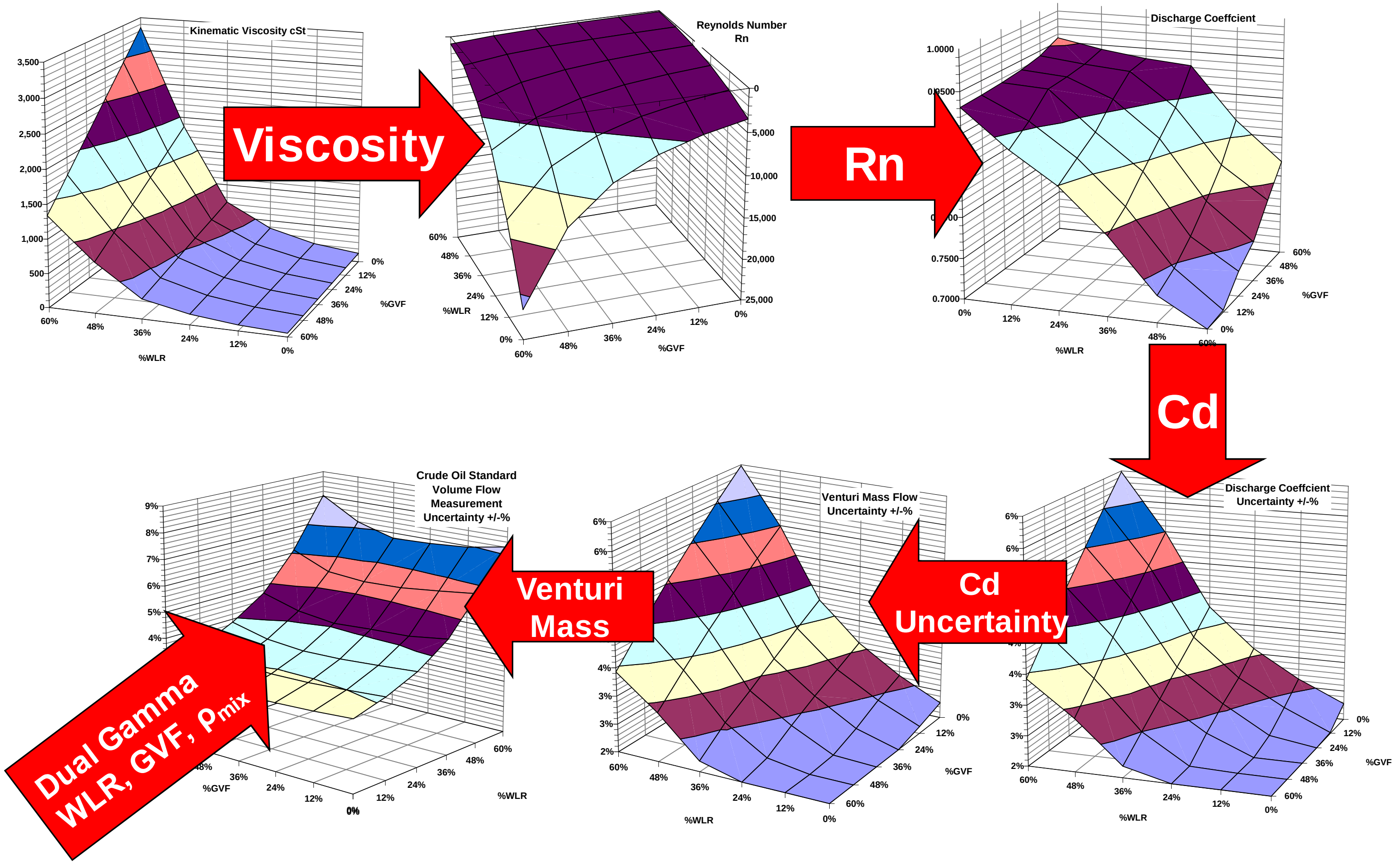
Cd Correction (1)

- Cd is found from a curve fit of Reynolds Number to Cd from Heavy Oil paper SPE63118
- Curve Fit of SPE63118 agrees well with a recent Heavy Oil Venturi study and is similar to the FME Handbook with the hip in the same place
- Uncertainty of SPE63118 was found from the standard deviation of the curve fit deviation with the original data. May not be representative but the in the absence of other information this has to suffice

Cd Correction (2)



Oil Standard Volume Uncertainty



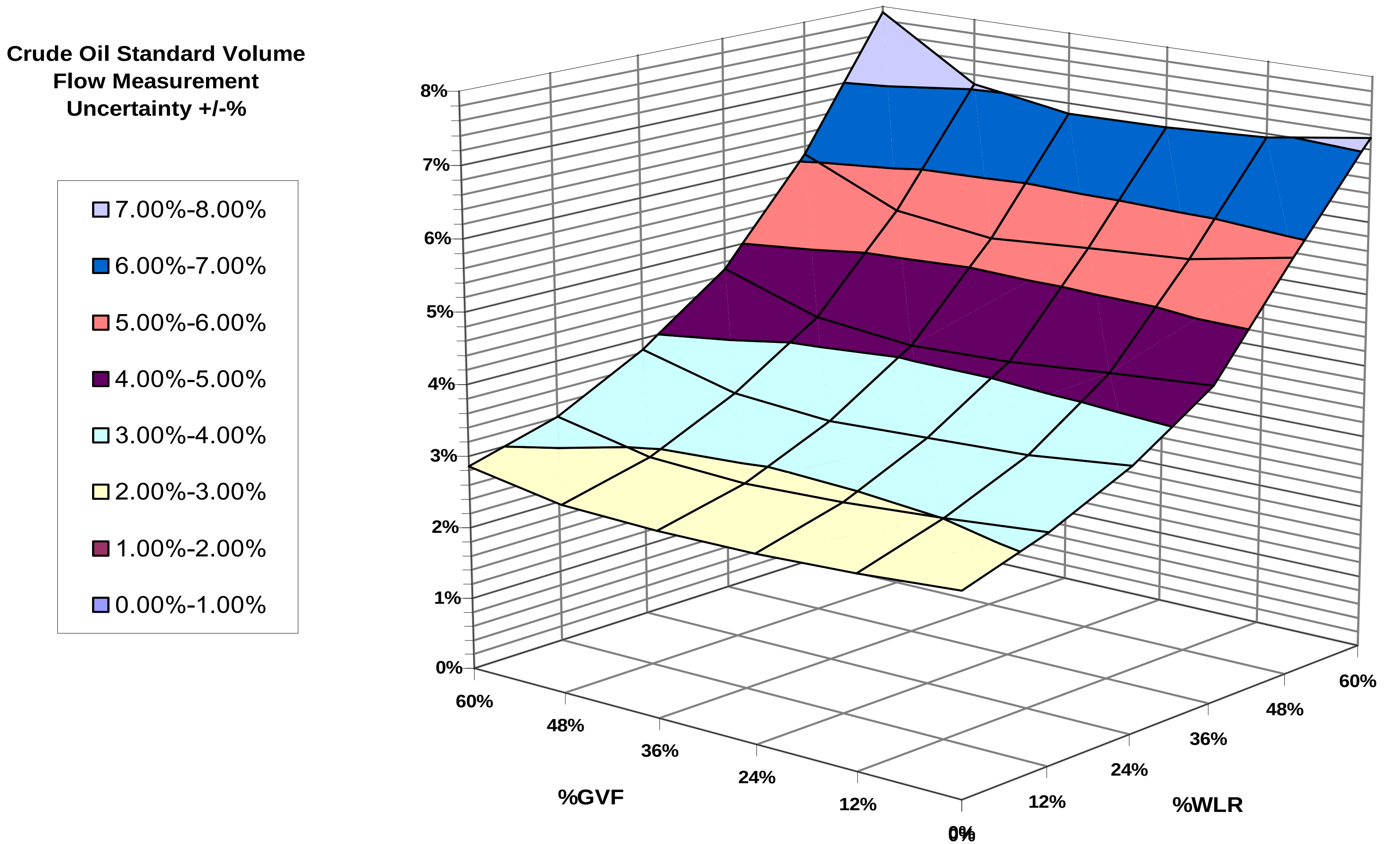
Case	1			
Description	Units	Measurement	Uncertainty	Bias
Meter	Type	52mm		
Gamma Count Sample Rate	Seconds	40		
Liquid Line Flow Rate	bpd	20,000		
Gas Standard Density	SG	0.68	0.0023 lb/cf	0 lb/cf
Oil Standard Density	API°	20.6	0.58 lb/cf	1.87 lb/cf
Water Standard Density	lb/cf	64.30	0.32 lb/cf	1.87 lb/cf
Temperature	°F	78	0.45	
Pressure	psig	250.00	0.76	
Emulsion Viscosity	%WLR	cP		
	0%	121.00		
	12%	198.00		
	24%	361.00		
	36%	698.00		
	48%	1,806.00		
	60%	3,299.00		

Results	Units	GVF=0%, WLR = 0%	GVF=60%, WLR=0%	GVF=0%, WLR=60%	GVF=60%, WLR=60%
Oil Standard Volume Observed	stbpd	20,011	20,022	8,032	7,918
Oil Standard Volume Uncertainty	%	2.7%	2.8%	7.1%	7.6%
Oil Standard Volume Bias	%	-0.1%	-0.1%	-0.4%	-0.4%
GVF Observed	%GVF	-3.3%	58.7%	-3.1%	58.8%
GVF Uncertainty	%GVF	0.6%	0.5%	0.7%	0.5%
GVF Bias	%GVF	3.3%	1.3%	3.1%	1.2%
WLR Observed	%WLR	0.0%	0.0%	59.9%	59.9%
WLR Uncertiancy	%WLR	1.0%	2.0%	1.5%	2.7%
WLR Bias	%WLR	0.0%	0.0%	0.1%	0.1%
Mixture Density Observed	kg/m^3	953.52	390.40	1,015.81	415.30
Mixture Density Uncertainty	%	1.1%	1.4%	0.9%	1.2%
Mixture Density Bias	%	-3.1%	-3.1%	-2.9%	-2.9%
Mixture Mass Flow Observed	kg/s	34.19	35.02	36.49	37.32
DP Observed	mbar	1515	3690	3108	5356
Viscosity Observed	cSt	131	53	3346	1339
Reynolds Number Observed		3459	21374	135	846
Discharge Coefficient Observed		0.932	0.955	0.672	0.819
Discharge Coefficient Uncertainty	%	2.164%	1.242%	5.960%	3.367%

Results

DP	1.5 to 5.5 bar
Qm	34 to 37 kg/s
Visc	53 to 3,346 cSt
Rn	135 to 21,374
Cd	0.67 to 0.93
UCd	1.2 to 6% OMV
Qsv	7.9 to 20 kstbpd
UQsv	2.7 to 7.6% OMV

Oil Standard Volume Uncertainty



Conclusions (1)

- **Oil Standard Volume Uncertainty**
  - ±3%OMV within ± 0.5%OMV agreement between analysis and the stated uncertainty for 0 to 12%WLR and 0 to 60%GVF
  - The stated uncertainty did not allow for low Cd. Once this was included the worst case difference dropped from ±5.5%OMV to ±3%OMV
  - Confirmed analysis as a means of verification
  - Uncertainty at >12%WLR increased due to high viscosity so temperature will be kept as high as possible by plant operation

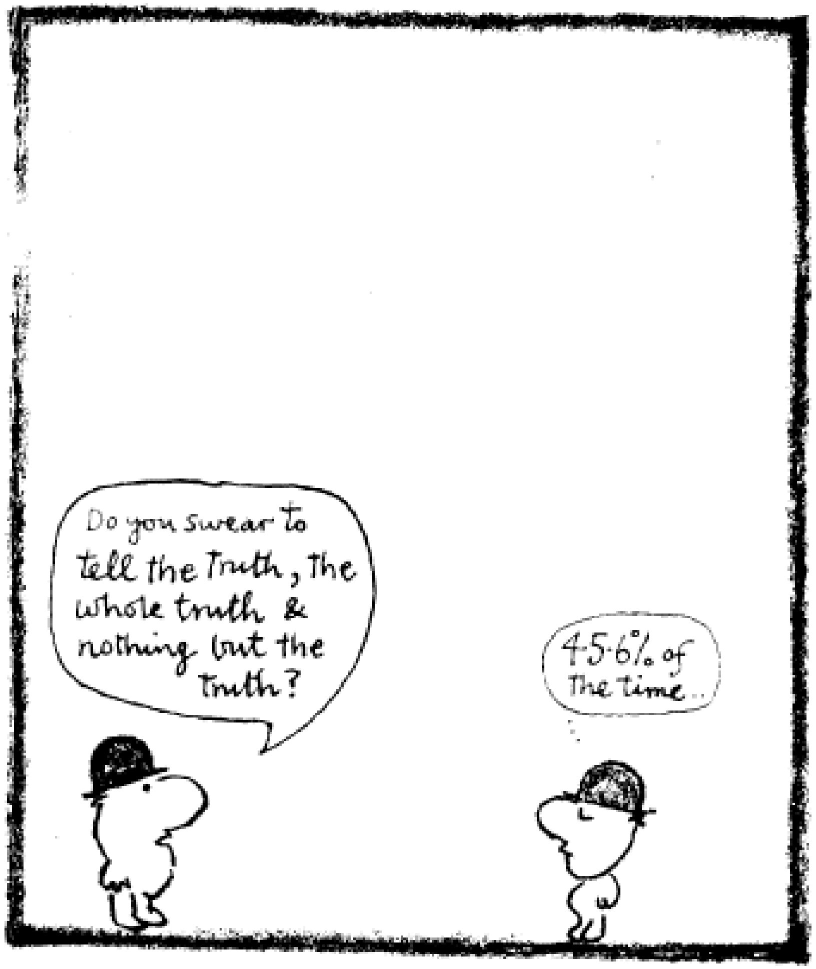
Conclusions (2)

- **Benefits of Analytical Performance**
  - Use early in a project before committing funds
  - Independent verification with physical properties
  - Lower cost and shorter timescale than testing
  - Transparency improves confidence in MPFM's
  - A greater range of scenarios can be examined
  - Model may be used throughout field life
- **Future Developments**
  - Use all available RN vs Cd characterisation data
  - Add a slip model, not required for Heavy Oil
  - Link mass attenuation to automatically calculate

Thanks to…

- Co-authors Gordon Stobie & Chip Letton
- Andrew Hall for his assistance with mass attenuation factors

Questions?


Do you swear to tell the truth, the whole truth & nothing but the truth?
45.6% of the time..