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Waterdrive Help

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Waterdrive

Petroleum Reservoir Waterdrive Analysis Software

by Petroleum Solutions Ltd

Waterdrive Help

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Table of Contents

	Foreword	0
Part I	Welcome to Waterdrive	7
1	Introduction	7
Part II	Dake-Welge	11
1	Single Layer Fractional Flow Model	12
	Diffuse Flow Condition	
	Segregated Flow Condition	
2	Example	
2		
	Heterogeneous with Vertical Equilibrium	
	Homogeneous with Vertical Equilibrium	
	Stiles Method	
	Dykstra-Parsons Method	
2	Example	
3	Even ale	
4	Laver Assistant	
Part III	Craig	54
1	Craig's Minimum Number of Layers	
2	Craig-Geffen-Morse Recovery Performance	
	Introduction	
	Start to Interference	
	Interference to Fillup	
	Fillup to Water Breakthrough	
	Composite Laver Performance	
	Example	
Part IV	Dykstra-Parsons	74
1	Heterogeneity Coefficients	
2	Dykstra-Parsons and Lorenz Coefficient	
3	Vertical Sweep	
4	Recovery Performance	
	Simplified Method	80
	Extended Method	
	Example	82
Part V	Log (Water Oil Ratio)	90
1	Log (WOR) Decline Forecasts	

Part VI	Water Coning	105
1	Vertical Wells	105
	Example	106
2	Horizontal Wells	111
	Exam ple	112
Part VII	General Utilities	121
1	Mobility Ratio	121
2	Displacement Efficiencies	121
3	Areal Sweep	121
4	Convert Recovery Factors	122
5	fw WOR Conversion	123
6	Trapped Gas Saturation and Residual Oil Saturation	123
7	Recovery Factors	125
8	Fit Corey Curves	125
9	Units Conversion	127
Part VIII	Application and Chart Settings	130
	Index	0

Contents

5

Waterdrive

Petroleum Reservoir Waterdrive Analysis Software



7

1 Welcome to Waterdrive

1.1 Introduction



Waterdrive is a collection of classical Waterdrive calculations and routines intended for Petroleum Reservoir Engineers to :

- Analyse the water-oil displacement processes for both homogeneous single layer and heterogeneous multi-layered systems, and permit the calculation of waterflood performance with time for oil recovery, producing watercut and water injection.
- Examine and interpret the waterdrive performance of reservoirs, or numerical simulation models, from an inspection of their production & injection history, by solving Welge's equation in reverse.
- Calculate the waterflood performance with time for a five-spot pattern, using the approach of Craig, Geffen, and Morse for relating oil recovery and producing water-oil ratio (WOR) to cumulative injected water
- Calculate Dykstra-Parsons and Lorenz Heterogeneity coefficients
- Calculate the waterflood performance with time, using two approaches based on the original work of Dykstra-Parsons, which also relates oil recovery and producing water-oil ratio (WOR) to cumulative injected water.
- For water coning in vertical and horizontal wells, determine the critical flow rate,

breakthrough time predictions and performance calculations after breakthrough.

Numerous other smaller routines, or general utilities, are provided to allow efficient calculation of mobility ratio, displacement efficiencies, areal sweep, various conversion utilities and fitting Corey curves to relative permeability data.

License.dat File

The "License.dat" file is located in the Application Startup folder (eg C:\Program Files\Petroleum Solutions\Waterdrive\)

The contents of this ASCII license file needs to contain the following license information.

[License Settings] LicensedTO = Company = ProductID = LicenseID =

If any of the above License key information is incorrect or absent, or if the License.dat file is missing then the application will fail to startup.

.NET Framework

The Profile application requires the presence or installation of Microsoft .Net Framework version 2.

.NET Framework version 2 is a component of the Microsoft Windows® operating system used to build and run Windows-based applications.

Should .NET Framework version 2 not be installed on the destination PC then a link is provided below to download this system software. The user should download and install .NET Framework version 2 before attempting to install Waterdrive.

Inttp://www.petroleumsolutions.co.uk/downloads.html

The installation of .Net Framework also requires a minimum software and hardware requirement. Details of which are shown below. Specifically, note that you cannot install the .NET Framework on a computer running the Microsoft Windows 95 operating system.

Minimum requirements

To install .NET Framework [Dotnetfx2.exe], you must have one of the following operating systems, with Microsoft Internet Explorer 5.01 or later installed on your computer:

- Microsoft® Windows® 98
- Microsoft® Windows® 98 Second Edition
- Microsoft® Windows® Millennium Edition (Windows Me)
- Microsoft® Windows NT® 4 (Workstation or Server) with Service Pack 6a
- Microsoft® Windows® 2000 (Professional, Server, or Advanced Server) with the latest Windows

service pack and critical updates available from the Microsoft Security Web site (www.microsoft. com/security).

• Microsoft® Windows® XP (Home or Professional)

Recommended hardware

CPU Recommended	RAM Recommended
Pentium 90 MHz or faster	96 MB or higher

Waterdrive

Petroleum Reservoir Waterdrive Analysis Software



2 Dake-Welge

Immiscible Displacement in Porous Media

The analysis and description of the immiscible displacement process by analytical methods are still of fundamental importance for the prediction of reservoir behaviour, despite the ready availability of numerical modelling methods.

Before any numerical simulation study an engineer should analyse, by non-numerical means, the displacement processes that are considered likely in the reservoir.

In Chapter 5 Waterdrive of Dake's "The Practice of Reservoir Engineering", he highlights the need to caution in applying core flooding experiments directly in numerical simulation studies and the dangers of conducting these simulation studies in isolation of parallel analytical calculations. An extract from chapter 5 is given below, in which he states :

"There are three levels on which the phenomenon of water-oil displacement can be viewed:

- the electron microscope scale (EMS)
- the microscopic, one-dimensional scale of a core flooding experiment
- flooding in hillsides.....which is the reality of practical reservoir engineering

.....The perennial difficulty in the description of waterdrive has always been how to relate the core flooding results, which are little affected by such complications as heterogeneity and gravity, to the hillside in which these same factors are usually dominant. The scaling-up of laboratory results for use in a meaningful fashion in field studies is one of the main topics in this and subsequent sections and particularly the sensitive matter of how the results of relative permeability experiments are input to numerical simulation models in such a way as to honour the basic laws of physics."

Reservoirs are, of course, three-dimensional.

However, reservoir thickness is almost always much smaller than the areal dimensions. Therefore, the study of displacement processes can be reduced to a two-dimensional heterogeneous (layered) problem, with the reservoir divided into vertical slices in the x-z, or y-z, plane. These routines are implemented and discussed further in the Multi Layer Fractional Flow Model section. Also, if the reservoir layer thickness is small, and is less than the capillary transition zone between oil and water, the system can further be reduced to a one dimensional homogeneous linear problem. These routines are discussed further in the Single Layer Fractional Flow Model section.

The basic assumptions made when attempting to describe the displacement processes are :

- Oil and water are the only mobile fluids in the porous medium, and move in the same direction.
- Water is displacing oil in a water wet reservoir, such that the displacement is an imbibition process, and the movement of the two fluids is described by their relative permeability curves.
- The displacement is considered as incompressible. This assumption implies that steady state conditions prevail in the reservoir with the pressure at any point remaining constant.
- The displacement is considered to be linear.

Laurie Dake's - The Practice of Reservoir Engineering

Laurie Dake's two textbooks, namely :

"Fundamentals of Reservoir Engineering", Elsevier, 1978-1985 "The Practice of Reservoir Engineering", Elsevier, 1994-2001

are probably the most referenced technical manuals within the discipline of Reservoir Engineering.

Perhaps the most fitting tribute to these books can be found on amazon.com from Malcolm Pye, of the UK's Department of Trade and Industry.

"... This book tells you all you need to know about reservoir engineering.

Chapter 5 is Laurie's masterpiece, 150 pages on waterdrive which could be published as a book in its own right. Drawing on examples from the North Sea, the biggest laboratory ever for the study of waterdrive it demolishes the misconceptions that have grown up over relative permeability curves and stresses the importance of the fractional flow equation in understanding fluid displacement. "

The techniques, presented within these two books, form the basis for the routines contained within this section.

References:

Dake, L., "Fundamentals of Reservoir Engineering", Elsevier Scientific Publishing Company, 1978.

Dake, L., "The Practice of Reservoir Engineering", Elsevier Scientific Publishing Company, 1994.

2.1 Single Layer Fractional Flow Model

Diffuse flow means that the viscous, or dynamic, forces are more dominant than the gravity forces, so that vertical variation in saturations may be neglected. Typical characteristics for this type of flow condition are low vertical permeability, combined with a high horizontal pressure gradient.

The converse to diffuse flow condition is the more common condition of segregated flow. Segregated flow is where the gravity forces are more dominant than the the viscous, or dynamic, forces, so that vertical variations in saturations are significant. Typical characteristics for this type of flow condition are high vertical permeability, combined with a low horizontal pressure gradient.

Both of the above flow conditions are implemented within this routine, and are discussed in more detail in the following sections

2.1.1 Diffuse Flow Condition

The diffuse flow condition can be encountered under two extreme physical conditions:

- a. when displacement occurs at very high injection rates so that the condition of vertical equilibrium is not satisfied and the effects of capillary and gravity forces are negligible, and
- b. for displacement at low injection rates in reservoirs for which the measured capillary transition zone greatly exceeds the reservoir thickness and the vertical equilibrium condition applies.

Diffuse flow is where the fluid saturations at any point in the linear displacement path are uniformly distributed with respect to thickness. The sole reason for making this assumption is that it permits the displacement to be described, mathematically, in one dimension and this provides the simplest possible model of the displacement process.

The following describes the method and physics governing diffuse flow displacement through a linear

homogeneous cross section of a reservoir, as outlined by Dake¹.

1. Calculate the fractional flow curve, from the following equation, allowing for gravity effects but neglecting capillary pressure.

$$f_{w} = \frac{1 - \frac{k.k_{ro}.A}{q_{t}.\mu_{o}} \cdot \frac{\Delta \rho.g.sin\theta}{1.0133x10^{6}}}{1 + \frac{\mu_{w}}{k_{rw}} \cdot \frac{k_{ro}}{\mu_{o}}}$$

2. Calculate the tangent to the fractional flow curve, from the point Sw = Swc & fw = 0. The point of tangency has the coordinates Sw=Swbt & fw=fwbt, and the extrapolation of this line to fw=1 gives the value of the average saturation behind the front at breakthrough.

The following equations can be applied to calculate the oil recovery and time at which breakthrough occurs.

$$N_{pd_{bt}} = W_{id_{bt}} = q_{id} \cdot t_{bt} = \left(\overline{S}_{w_{bt}} - S_{wc}\right) = \frac{1}{\frac{df_w}{dS_w}}\Big|_{S_{wbt}}$$

$$t_{bt} = \frac{W_{id_{bt}}}{q_{id}}$$

3. Applying the following equation to all Sw values greater than Swbt, with coordinate values of Swe & fwe, will result in the average water saturation in the reservoir block.

$$\overline{\overline{S}}_{w} = S_{we} + (1 - f_{we}) \frac{1}{\frac{df_{w}}{dS_{w}}} \Big|_{S_{we}}$$

4. For each value of Swe, the average water saturation is calculated and the subsequent oil recovery is calculated from the following equation.

$$N_{pd} = \overline{S}_w - S_{wc} = (S_{we} - S_{wc}) + (1 - f_{we})W_{id}$$

Wid, the number of pore volumes of water injected, is calculated from the reciprocal of the slope of the fractional flow curve, and is used to attach a time scale to the oil recovery from the following equation.

$$W_{id} = q_{id} t$$

References:

Dake, L., "Fundamentals of Reservoir Engineering", Elsevier Scientific Publishing Company, 1978.

2.1.2 Segregated Flow Condition

This is the most common flooding condition encountered in nature and is characterised by the following physical conditions:

- There is a high degree of pressure equilibrium across the reservoir section which encourages crossflow of fluids under the influence of gravity.
- The displacement occurs under strictly segregated conditions with a sharp interface between the water and oil.



Displacement of oil by water assuming segregated flow conditions

In a segregated flow regime we assume that ahead of the interface between the displacing fluid and the oil, oil alone is flowing, in the presence of immobile water at its irreducible saturation. Behind the interface, only displacing fluid is flowing, in the presence of immobile oil at its residual saturation.

The following describes the method of calculation for segregated flow displacement, as outlined by Dake ¹.

Calculate the endpoint mobility ratio, from the following :

$$M = \begin{pmatrix} \dot{\underline{k'_{rw}}} \\ \mu_w \end{pmatrix} \begin{pmatrix} \dot{\underline{k'_{ro}}} \\ \mu_o \end{pmatrix}$$

Calculate the dimensionless gravity number, from the following :

$$G = \frac{4.9 \times 10^{-4} k.k'_{rw}.A.\Delta\gamma.\sin\theta}{q_t.\mu_w}$$

Determine if the displacement condition will be stable or unstable; the displacement will be stable if G > M - 1, and unstable if G < M - 1.

For horizontal reservoirs with no dip and stable displacement, Widbt = 1 / M, Widmax = M and Npd can be calculated, for any value of Wid between Widbt and Widmax, from the following :

$$N_{pD} = \frac{1}{M - 1} \left(2\sqrt{W_{iD}M} - W_{iD} - 1 \right)$$

For reservoirs with dip, Widbt and Widmax can be calculated from the following :

Stable displacement

ht $W_{iD_{bt}} = 1 - \frac{h}{2L \tan \beta}$ Widmax = M / (G + 1) Widbt = 1 / (M - G) Widmax = M / (G + 1)

Unstable displacement

and Npd can be calculated, for any value of Wid between Widbt and Widmax, from the following :

Stable
displacement
Unstable
displacement
$$N_{pD} = 1 - \frac{(h - y_e)^2}{2hL \tan \beta}$$
Unstable
displacement
$$N_{pD} = \frac{1}{M - 1} \left(2\sqrt{W_{iD}M\left(1 - \frac{G}{M - 1}\right)\left(1 - \frac{W_{iD}G}{M - 1}\right)} - W_{iD}\left(1 - \frac{M + 1}{M - 1}G\right) - 1 \right)$$

where ye is the height of water at the producing well.

For completeness, the critical rate for by-passing is calculated from the following, and will be stable for dipping reservoirs at 90% of this calculated rate :

$$q_{crit} = \frac{4.9 \times 10^{-4} k.k'_{rw}.A.\Delta\gamma.\sin\theta}{\mu_w(M-1)}$$

2.1.3 Example

In Chapter 10 Immiscible Displacement of Dake's "Fundamentals of Reservoir Engineering", he provides the following example.

General Input Data	
Oil Density, gm/cc	0.81
Water Density, gm/cc	1.04
Oil viscosity [cP]	5

Water viscosity [cP]	0.5
Initial Oil FVF, Boi [rb/stb]	1.3
Current Oil FVF, Bo [rb/stb]	1.3
Water FVF, Bw [rb/stb]	1
Endpoint kro [fraction]	0.8
Endpoint krw [fraction]	0.3
Swc [fraction]	0.2
Sor [fraction]	0.2
Corey Oil Exponent	3
Corey Water Exponent	2
Porosity [fraction]	0.18
Permeability [mD]	2000
Reservoir Thickness [ft]	40
Reservoir Length [ft]	2000
Reservoir Width [ft]	625
Reservoir Dip [degrees]	0
Injection Rate [mstb/d]	1000

With regards to inputting relative permeability data, the user can choose between using Corey Exponents for Oil and Water curvature or inputting the table values directly. The example below assumes Corey Exponents are input.

Once the user has successfully input all the required data, as shown in the following screen capture, they can press the *calculate* button to calculate all stages of the performance prediction.

Diffuse Flow Results

The diffuse flow condition results are in the form of tables of Welge calculations and production profile, together with charts of Welge fractional flow and production profiles comparing both the diffuse and segregated flow conditions.

Input Data Tables Diffuse Welge Res	Charts ults Segregate	d Results Diffuse	e Profile Segrega	ited Profile			Input Data Table Diffuse Welge Re	es Charts esults Segregated	d Results Diffuse	Profile Segreg	ated Profile		
Swe	fwe	Delta Swe	Delta fwe	Wid	Avg Swe	Avg	Date	WI Rate (bbl/d)	WI Cumulative (bbl)	Oil Rate (bbl/d)	Oil Cumulative (bbl)	Recovery Factor (fraction)	Water ^
0.200000	0.000000	0.000000	0.000000	0.000000	0.000000	0.	Jan 2007	1000.0	31,000.0	769.2	23,846.2	0.024175	-
0.206061	0.000394	0.000000	0.000000	0.000000	0.000000	0.	Feb 2007	1000.0	59,000.0	769.2	45,384.6	0.046011	=
0.212121	0.001624	0.000000	0.000000	0.000000	0.000000	0 . ≡	Mar 2007	1000.0	90,000.0	769.2	69,230.8	0.070186	
0.218182	0.003762	0.000000	0.000000	0.000000	0.00000	0.	Apr 2007	1000.0	120,000.0	769.2	92,307.7	0.093581	
0.224242	0.006880	0.000000	0.000000	0.000000	0.000000	0.	May 2007	1000.0	151,000.0	769.2	116,153.8	0.117756	
0.230303	0.011051	0.000000	0.000000	0.000000	0.00000	0.	Jun 2007	1000.0	181,000.0	769.2	139,230.8	0.141151	
0.236364	0.016344	0.000000	0.000000	0.000000	0.00000	0.	Jul 2007	1000.0	212,000.0	769.2	163,076.9	0.165326	
0.242424	0.022828	0.000000	0.000000	0.000000	0.000000	0.	Aug 2007	1000.0	243,000.0	769.2	186,923.1	0.189501	
0.248485	0.030566	0.000000	0.000000	0.000000	0.000000	0.	Sep 2007	1000.0	273,000.0	769.2	210,000.0	0.212896	
0.254545	0.039616	0.000000	0.000000	0.000000	0.00000	0.	Oct 2007	1000.0	304,000.0	769.2	233,846.2	0.237071	
0.260606	0.050027	0.000000	0.000000	0.000000	0.000000	0.	Nov 2007	1000.0	334,000.0	769.2	256,923.1	0.260467	
0.266667	0.061842	0.000000	0.000000	0.000000	0.000000	0.	Dec 2007	1000.0	365,000.0	769.2	280,769.2	0.284642	
0.272727	0.075088	0.000000	0.000000	0.000000	0.00000	0.	Jan 2008	1000.0	396,000.0	769.2	304,615.4	0.308817	
0.278788	0.089785	0.000000	0.000000	0.000000	0.00000	0.	Feb 2008	1000.0	425,000.0	769.2	326,923.1	0.331432	
0.284848	0.105934	0.000000	0.000000	0.000000	0.000000	0.	Mar 2008	1000.0	456,000.0	769.2	350,769.2	0.355607	
0.290909	0.123524	0.000000	0.000000	0.000000	0.00000	0.	Apr 2008	1000.0	486,000.0	769.2	373,846.2	0.379002	
0.296970	0.142526	0.000000	0.000000	0.000000	0.00000	0.	May 2008	1000.0	517,000.0	769.2	397,692.3	0.403177	
0.303030	0.162893	0.000000	0.000000	0.000000	0.000000	0.	Jun 2008	1000.0	547,000.0	296.7	406,593.9	0.412202	
0.309091	0.184564	0.000000	0.000000	0.000000	0.00000	0.	Jul 2008	1000.0	578,000.0	170.0	411,862.8	0.417543	
0.315152	0.207456	0.000000	0.000000	0.000000	0.00000	0.	Aug 2008	1000.0	609,000.0	157.8	416,755.0	0.422503	
0.321212	0.231475	0.000000	0.000000	0.000000	0.000000	0.	Sep 2008	1000.0	639,000.0	147.8	421,188.6	0.426998	
0.327273	0.256507	0.000000	0.000000	0.000000	0.000000	0.	Oct 2008	1000.0	670,000.0	139.8	425,521.8	0.431391	
0.333333	0.282427	0.000000	0.000000	0.000000	0.000000	0.	Nov 2008	1000.0	700,000.0	133.2	429,518.1	0.435442	
0.339394	0.309099	0.000000	0.000000	0.000000	0.000000	0.	Dec 2008	1000.0	731,000.0	122.9	433,327.5	0.439304	
0 345455	0 336377	0.00000	0.00000	0.00000	0 000000	* 0 •	.lan 2009 ∢	1000.0	762 000 0	118.5	437 002 0	0 443029	*

Note that all data within the tables can be output to the clipboard by pressing CTRL+C





Segregated Flow Results

The segregated flow condition results are in the form of tables of Dake calculations and production profile, together with a production profile chart comparing both the diffuse and segregated flow conditions.

Input Data Table	s Charts					Input Data Tab	les Charts					
Diffuse Welge Re	sults Segregate	d Results Diffus	e Profile Segrega	ated Profile		Diffuse Welge R	esults Segregate	d Results Diffuse	Profile Segre	jated Profile		
Wid [MOV]	Npd [MOV]	Wid [PV]	Npd [PV]	Days	<u>^</u>	Date	WI Rate (bbl/d)	WI Cumulative (bbl)	Oil Rate (bbl/d)	Oil Cumulative (bbl)	Recovery Factor (fraction)	Water (bbl
0.266667	0.266667	0.160000	0.160000	256.4749	=	Jan 2007	1000.0	31,000.0	769.2	23,846.2	0.024175	-
0.284171	0.283792	0.170503	0.170275	273.3101	1	Feb 2007	1000.0	59,000.0	769.2	45,384.6	0.046011	-
0.301675	0.300203	0.181005	0.180122	290.1453		Mar 2007	1000.0	90,000.0	769.2	69,230.8	0.070186	
0.319179	0.315963	0.191508	0.189578	306.9805		Apr 2007	1000.0	120,000.0	769.2	92,307.7	0.093581	
0.336683	0.331125	0.202010	0.198675	323.8157		May 2007	1000.0	151,000.0	769.2	116,153.8	0.117756	
0.354188	0.345733	0.212513	0.207440	340.6509		Jun 2007	1000.0	181,000.0	769.2	139,230.8	0.141151	
0.371692	0.359830	0.223015	0.215898	357.4861		Jul 2007	1000.0	212,000.0	769.2	163,076.9	0.165326	
0.389196	0.373450	0.233518	0.224070	374.3213		Aug 2007	1000.0	243,000.0	769.2	186,923.1	0.189501	
0.406700	0.386625	0.244020	0.231975	391.1565		Sep 2007	1000.0	273,000.0	759.7	209,714.6	0.212607	
0.424204	0.399384	0.254523	0.239631	407.9917		Oct 2007	1000.0	304,000.0	708.7	231,684.5	0.234880	
0.441709	0.411753	0.265025	0.247052	424.8269		Nov 2007	1000.0	334,000.0	660.6	251,502.8	0.254972	
0.459213	0.423754	0.275528	0.254252	441.6621		Dec 2007	1000.0	365,000.0	619.2	270,698.0	0.274431	
0.476717	0.435408	0.286030	0.261245	458.4973		Jan 2008	1000.0	396,000.0	582.0	288,739.7	0.292722	
0.494221	0.446734	0.296533	0.268041	475.3325		Feb 2008	1000.0	425,000.0	550.5	304,704.8	0.308907	
0.511725	0.457750	0.307035	0.274650	492.1677		Mar 2008	1000.0	456,000.0	520.3	320,834.5	0.325260	
0.529229	0.468471	0.317538	0.281082	509.0029		Apr 2008	1000.0	486,000.0	494.1	335,656.3	0.340286	
0.546734	0.478911	0.328040	0.287347	525.8381		May 2008	1000.0	517,000.0	470.5	350,242.1	0.355073	
0.564238	0.489085	0.338543	0.293451	542.6733		Jun 2008	1000.0	547,000.0	448.9	363,709.2	0.368726	
0.581742	0.499004	0.349045	0.299402	559.5085		Jul 2008	1000.0	578,000.0	429.0	377,006.7	0.382206	
0.599246	0.508680	0.359548	0.305208	576.3437		Aug 2008	1000.0	609,000.0	410.0	389,715.7	0.395091	
0.616750	0.518123	0.370050	0.310874	593.1788		Sep 2008	1000.0	639,000.0	392.5	401,489.3	0.407027	
0.634255	0.527343	0.380553	0.316406	610.0140		Oct 2008	1000.0	670,000.0	376.9	413,172.5	0.418871	
0.651759	0.536350	0.391055	0.321810	626.8492		Nov 2008	1000.0	700,000.0	362.2	424,039.4	0.429888	
0.669263	0.545151	0.401558	0.327091	643.6844		Dec 2008	1000.0	731,000.0	348.5	434,842.7	0.440840	
0.686767	0.553756	0.412060	0.332254	660.5196		.lan 2009	1000.0	762 000 0	335.4	445 239 5	0 451380	
0 704271	0 562171	0.422563	0 337303	677 3548	-							•

Note	that	all	data	within	the	tables	can	be	out	put	to ti	he cl	ipbo	ard	by	pressing	а СТ	RL+	С
															_				

2.2 Multi Layer Fractional Flow Model

The following text is taken directly from the Waterdrive chapter of Dake's "The Practice of Reservoir Engineering", and very appropriately describes the purpose of this section.

"The previous section described the basic theory of waterdrive on the scale of a one-dimensional core flooding experiment. The same theory of Buckley-Leverett and the practical application technique of Welge will now be extended to the description of waterflooding in macroscopic, heterogeneous reservoir sections, which is a two-dimensional problem. In this respect, the engineer must be aware that in practice, waterflooding is conducted in "hillsides", not core plugs and the efficiency of the process is governed by three physical factors, namely:

- mobility ratio (M)
- heterogeneity
- gravity"

Dake goes on to present a *recipe* for evaluating vertical sweep efficiency in heterogeneous reservoirs, which is listed below, and forms the basis for how the routines contained within this sections are structured.

"No matter what the nature of the vertical heterogeneity, the following recipe is applied to assess the sweep efficiency in edge waterdrive reservoirs.

- Divide the section in to N layers, each characterised by the following parameters: thickness, permeability, porosity, Swc, Sor, krw, kro'.
- Decide whether there is vertical pressure communication between the layers or not.
- Decide upon the flooding order of the N layers and generate pseudo-relative permeabilities to reduce the description of the macroscopic displacement to one dimension.
- Use the pseudos to generate a fractional flow relationship which is used in the Welge equation to calculate the oil recovery, Npd as a function of cumulative water influx, Wid.
- Convert the oil volume to a fractional oil recovery, Np/N, and relate this to the surface watercut, fws."

References:

Dake, L., "The Practice of Reservoir Engineering", Elsevier Scientific Publishing Company, 1994.

2.2.1 Introduction

Dake's recipe for evaluating vertical sweep efficiency in heterogeneous reservoirs is listed below.

"No matter what the nature of the vertical heterogeneity, the following recipe is applied to assess the sweep efficiency in edge waterdrive reservoirs.

- Divide the section in to N layers, each characterised by the following parameters: thickness, permeability, porosity, Swc, Sor, krw', kro'.
- Decide whether there is vertical pressure communication (Vertical Equilibrium or VE) between the layers or not.
- Decide upon the flooding order of the N layers and generate pseudo-relative permeabilities to reduce the description of the macroscopic displacement to one dimension.
- Use the pseudos to generate a fractional flow relationship which is used in the Welge equation to calculate the oil recovery, Npd as a function of cumulative water influx, Wid.
- Convert the oil volume to a fractional oil recovery, Np/N, and relate this to the surface watercut, fws."

The Vertical Equilibrium (VE) condition means that the order in which the N selected layers flood is from the base layer to the top layer of the reservoir system. VE implies the dominance of gravity, however at no stage does a vertical gravity term appear in any of the displacement equations. Instead, all that is necessary is recognition of the fact that the water density is greater than the oil density, therefore water will naturally slump to the base of the reservoir and this dictates the flooding order of the selected layers.

If the selected layers are vertically isolated from one another, so that there is a total lack of cross-flow, then the order in which the layers flood out is determined by the actual velocity of the frontal advance of water in each layer. See equation below.

$$v_i = \frac{k_i k'_{rw_i}}{\phi_i \left(1 - S_{or_i} - S_{wc_i}\right)}$$

The dependence on permeability in the above equation is obvious. However concerning the terms in the denominator, low porosity rock, having a smaller capacity, will flood faster than high capacity, and similarly the smaller the movable saturation the more rapid the advance of water. The layers will therefore flood in decreasing sequence of their calculated values of velocity.

Having determined the flooding order of the layers the next step is to generate thickness averaged or pseudo-relative permeabilities across the section for edge waterdrive.

Four methods are provided to generate a fractional flow relationship, namely Heterogeneous and Homogeneous methods where there is vertical pressure communication between layers (Vertical Equilibrium or VE), and Stiles and Dykstra-Parsons methods where there is a complete lack of pressure communication between layers.

Once the fractional flow and Welge calculations have been performed, then the user can history match the field STOOIP value from a knowledge of the fields production and injection history, and finally can predict the future performance of the field via a knowledge of the production and injection constraints. This history matching and prediction performance is highlighted in more detail in the worked example.

2.2.2 Heterogeneous with Vertical Equilibrium

The equations to calculate the thickness averaged or pseudo-relative permeabilities across the section for edge waterdrive, where the nth layer out of a total of N has flooded with water are given below :

$$\overline{S}_{w_{n}} = \frac{\sum_{i=1}^{n} h_{i} \phi_{i} (1 - S_{or_{i}}) + \sum_{i=n+1}^{N} h_{i} \phi_{i} S_{wc_{i}}}{\sum_{i=1}^{N} h_{i} \phi_{i}}$$

$$\overline{k}_{rw_{n}} = \frac{\sum_{i=1}^{n} h_{i} k_{i} k'_{rw_{i}}}{\sum_{i=1}^{N} h_{i} k_{i}} \qquad \overline{k}_{ro_{n}} = \frac{\sum_{i=n+1}^{N} h_{i} k_{i} k'_{ro_{i}}}{\sum_{i=1}^{N} h_{i} k_{i}}$$

Where for waterdrive in an inclined reservoir, if the displacement is in the more gravity stable updip direction, then the equation for the fractional flow of water is as follows :

$$f_{we_n} = \frac{1 - \frac{\bar{k}.\bar{k}_{ro}.A}{q_t.\mu_o}.\frac{\Delta \rho.g.\sin\theta}{1.0133 \times 10^6}}{1 + \frac{\mu_o}{\bar{k}_{rw_n}}.\frac{\bar{k}_{ro_n}}{\mu_w}}$$

Welge's equation, expressed in hydrocarbon pore volumes, is provided below :

$$N_{pd} = \frac{\left(\overline{S}_{we} - \overline{S}_{wc}\right) + \left(1 - \overline{f}_{we}\right)W_{id}}{\left(1 - \overline{S}_{wc}\right)}$$

where.

$$Wid = \frac{1}{\left(\frac{\Delta \bar{f}_{we}}{\Delta \bar{S}_{we}}\right)}$$

The expression to calculate surface watercut from the reservoir fractional flow value is provided below;

$$f_{ws} = \frac{1}{1 + \frac{B_w}{B_o} \left(\frac{1}{\bar{f}_{we}} - 1\right)}$$

Catering for the Presence of Edge Water in VE Waterdrive

Dake proposed the following modification of the standard Welge equation to account for edge water in a dipping reservoir undergoing vertical equilibrium displacement.

$$N'_{pd} = N_{pd} \left(1 - \frac{h}{2.L \tan \theta} \right)$$
$$W'_{id} = W_{id} - \frac{h}{2.L \tan \theta} \left(1 - S_{or} - S_{wc} \right)$$

2.2.3 Homogeneous with Vertical Equilibrium

The equations to calculate the thickness averaged or pseudo-relative permeabilities across the section for edge waterdrive, where the nth layer out of a total of N has flooded with water are given below :

$$\begin{split} \overline{S}_{w_n} &= \frac{\sum_{i=1}^{n} h_i \phi_i \left(1 - S_{or_i} \right) + \sum_{i=n+1}^{N} h_i \phi_i S_{wc_i}}{\sum_{i=1}^{N} h_i \phi_i} \\ \overline{k}_{rw_n} &= \left(\frac{\overline{S}_{w_n} - S_{wc}}{1 - S_{or} - S_{wc}} \right) k'_{rw} \ \overline{k}_{ro_n} = \left(\frac{1 - S_{or} - \overline{S}_{w_n}}{1 - S_{or} - S_{wc}} \right) k'_{ro} \end{split}$$

Where for waterdrive in an inclined reservoir, if the displacement is in the more gravity stable updip direction, then the equation for the fractional flow of water is as follows :

$$f_{we_n} = \frac{1 - \frac{\bar{k}.\bar{k}_{ro}.A}{q_t.\mu_o}}{1 + \frac{\mu_o}{\bar{k}_{rw_n}}} \cdot \frac{\Delta \rho.g.\sin\theta}{1.0133 \times 10^6}$$

Welge's equation, expressed in hydrocarbon pore volumes, is provided below :

$$N_{pd} = \frac{\left(\overline{S}_{we} - \overline{S}_{wc}\right) + \left(1 - \overline{f}_{we}\right)W_{id}}{\left(1 - \overline{S}_{wc}\right)}$$

where.

$$Wid = \frac{1}{\left(\frac{\Delta \bar{f}_{we}}{\Delta \bar{S}_{we}}\right)}$$

-

The expression to calculate surface watercut from the reservoir fractional flow value is provided below;

$$f_{ws} = \frac{1}{1 + \frac{B_w}{B_o} \left(\frac{1}{\bar{f}_{we}} - 1\right)}$$

Catering for the Presence of Edge Water in VE Waterdrive

Dake proposed the following modification of the standard Welge equation to account for edge water in a dipping reservoir undergoing vertical equilibrium displacement.

$$N'_{pd} = N_{pd} \left(1 - \frac{h}{2.L \tan \theta} \right)$$
$$W'_{id} = W_{id} - \frac{h}{2.L \tan \theta} \left(1 - S_{or} - S_{wc} \right)$$

2.2.4 Stiles Method

The Stiles method is restricted to reservoirs with no vertical pressure communication between layers and where the mobility ratio is close to a value of one. The mobility ratio assumption ensures that the velocity of frontal advance of water in each layer remains constant during the flood. That is, the velocities will be different in each layer, as dictated by the following equation, but as the flood progresses the differences between layers will remain constant: ie., there is no velocity dispersion.

$$v_i = \frac{k_i k'_{rw_i}}{\phi_i \left(1 - S_{or_i} - S_{wc_i}\right)}$$

The Stiles procedure is as follows :

- 1. Inspect the core and log data and divide the section into a total of N separate layers
- Order the N layers in the sequence in which they will successively flood-out with water, by applying the above velocity equation.
- 3. Generate pseudo-relative permeabilities by applying the following equations.

$$\overline{S}_{w_n} = \frac{\sum_{i=1}^{n} h_i \phi_i (1 - S_{or_i}) + \sum_{i=n+1}^{N} h_i \phi_i S_{wc_i}}{\sum_{i=1}^{N} h_i \phi_i}$$
$$\overline{k}_{rw_n} = \frac{\sum_{i=1}^{n} h_i k_i k'_{rw_i}}{\sum_{i=1}^{N} h_i k_i} \qquad \overline{k}_{ro_n} = \frac{\sum_{i=n+1}^{N} h_i k_i k'_{ro_i}}{\sum_{i=1}^{N} h_i k_i}$$

The only difference between Stiles and Heterogeneous VE pseudo-generation is in the flooding order in which the procedures are evaluated.

It is also apparent that, with the exception of gravity within each sand layer, gravity plays no part in the Stiles type displacement on account of the vertical separation of the layers. This results in the displacement efficiency being entirely dictated by the mobility ratio and heterogeneity. Therefore the equation for the fractional flow of water is simplified as follows :

$$f_{we_n} = \frac{1}{1 + \frac{\mu_o}{\bar{k}_{rw_n}} \cdot \frac{\bar{k}_{ro_n}}{\mu_w}}$$

Welge's equation, expressed in hydrocarbon pore volumes, is provided below :

$$N_{pd} = \frac{\left(\overline{S}_{we} - \overline{S}_{wc}\right) + \left(1 - \overline{f}_{we}\right)W_{id}}{\left(1 - \overline{S}_{wc}\right)}$$

where.

$$Wid = \frac{1}{\left(\frac{\Delta \bar{f}_{we}}{\Delta \bar{S}_{we}}\right)}$$

The expression to calculate surface watercut from the reservoir fractional flow value is provided below;

$$f_{ws} = \frac{1}{1 + \frac{B_w}{B_o} \left(\frac{1}{\bar{f}_{we}} - 1\right)}$$

2.2.5 Dykstra-Parsons Method

The Dykstra-Parsons method is the general approach to calculating vertical sweep efficiency in reservoirs with no vertical pressure communication between layers, since it is appropriate for all values of the mobility ratio. It therefore caters for velocity dispersion of the flood front between the individual layers.

The Dykstra-Parsons procedure is as follows :

- 1. Inspect the core and log data and divide the section into a total of N separate layers
- 2. Order the N layers in the sequence in which they will successively flood-out with water, by applying the following velocity equation.

$$\lambda = \frac{k.k_{rw}'}{\phi.\Delta S_w}$$

3. As each layer floods, calculate the frontal positions in all the remaining unflooded layers by solution of the following quadratic equation :

$$\frac{1}{2}Ax_j^2 + x_j = \frac{\lambda_j}{\lambda_i} \left(\frac{1}{2}A + 1\right)$$

where A is defined as :

$$A = \frac{1}{M} - 1$$

4. Calculate the fractional flow, which for a section of fixed width and individual layer thickness, h_i, may be evaluated using the following equation :

$$f_{we_n} = \frac{\sum_{i=1}^{n} \frac{\lambda_i h_i}{A+1}}{\sum_{i=1}^{N} \frac{\lambda_i h_i}{Ax_i + 1}} \approx \frac{\sum_{i=1}^{n} \frac{k_i h_i}{A+1}}{\sum_{i=1}^{N} \frac{k_i h_i}{Ax_i + 1}}$$

which is the condition pertaining after the nth layer out of a total of N has flooded. According to Dake, since the kh-product is predominant over the other parameters, the second expression is usually a perfectly acceptable approximation.

5. The corresponding thickness averaged water saturation can be calculated using the following equation :

$$\overline{S}_{w_n} = \frac{\sum\limits_{i=1}^n h_i \phi_i \left(1 - S_{or_i}\right) + \sum\limits_{i=n+1}^N h_i \phi_i S_{wc_i}}{\sum\limits_{i=1}^N h_i \phi_i}$$

Welge's equation, expressed in hydrocarbon pore volumes, is provided below :

$$N_{pd} = \frac{\left(\overline{S}_{we} - \overline{S}_{wc}\right) + \left(1 - \overline{f}_{we}\right) W_{id}}{\left(1 - \overline{S}_{wc}\right)}$$

where.

$$Wid = \frac{1}{\left(\frac{\Delta \bar{f}_{we}}{\Delta \bar{S}_{we}}\right)}$$

The expression to calculate surface watercut from the reservoir fractional flow value is provided below;

$$f_{ws} = \frac{1}{1 + \frac{B_w}{B_o} \left(\frac{1}{\bar{f}_{we}} - 1\right)}$$

2.2.6 Example

In Chapter 5 Waterdrive of Dake's "The Practice of Reservoir Engineering", he provides the following example.

General Input Data	
Oil Density, gm/cc	0.7
Water Density, gm/cc	1.02
Oil Viscosity [cP]	1.24
Water Viscosity [cP]	0.41
Oil FVF, Bo rb/stb	1.475
Water FVF, Bw rb/stb	1.03
Water FVF, Bw rb/stb	1.03
Reservoir Length [ft]	4000
Reservoir Width [ft]	1000
Reservoir Dip, degrees	10
Injection Rate [stb/d]	6000
Selected Method	Stiles
STOOIP [mmstb]	176
Use Areal Sweep Correlation ?	True
Select Pattern Method	Direct Line Drive

			Layer Inp	out Data			
Layer	Thickness	Porosity	Permeability	Swc	Sor	kro	krw
	[ft]	[fraction]	[mD]	[fraction]	[fraction]	[fraction]	[fraction]
1	8	0.259	2840	0.168	0.33	1	0.33
2	9	0.25	2000	0.165	0.33	1	0.33
3	13	0.253	1560	0.175	0.33	1	0.33
4	4	0.22	74	0.192	0.33	1	0.33
5	8	0.235	1244	0.18	0.33	1	0.33
6	6	0.228	718	0.187	0.33	1	0.33
7	11	0.227	650	0.195	0.33	1	0.33
8	14	0.215	32	0.205	0.33	1	0.33
9	14	0.22	320	0.196	0.33	1	0.33
10	7	0.213	34	0.21	0.33	1	0.33

Problem Statement

For the above data, calculate :

- 1. the reservoir fractional flow and resultant oil recovery versus watercut relationships assuming a Stiles, no vertical pressure communication between layers, method,
- 2. the likely field STOOIP value, given a knowledge of the production history.
- the future oil, water, liquid production and water injection profiles assuming the following facilities constraints; 60mbbl/d oil, 60mbbl/d water and 65mbbl/d liquid production and 65mbbl/d water injection.

Once the user has input all the necessary input data, they should press the Calculate button, as shown below. Note that the layer data can be copied and pasted into the input table by pressing the windows standard shortcut keys [CTRL+C] then [CTRL+V].

ayered Fractional Flow Mode Recent Files 👻 🔂 📮	el [Dake5_3c.lfm]	Oilfield Units	- 0									
nalytical Relative Permeability	Fractional Flow	Welge Displacement	History Match P	rediction								
Input Data]				Select Me	thod						
Oil Density 0.7	gm/cc 👻	Stiles										
Water Density 1.02	gm/cc 👻											
Oil Viscosity [cP]	1.24		Layer Properties									
Water Viscosity [cP]	0.41											
Oil EVE Borb/sth	1.475	Layer	Thickness [ff]	Porosity	Permeability [mD]	Swc	Sor [fraction]	kro [fraction]	kr ^			
Water EVE Bw rb/eth	1.03	1	8	0.259	2840	0.168	0.33	1	•			
Water FVF, DW ID/StD	1.00	2	9	0.25	2000	0.165	0.33	1				
Reservoir Length [ft]	4000	3	13	0.253	1560	0.175	0.33	1				
Reservoir Width [ft]	1000	4	4	0.22	74	0.192	0.33	1				
Reservoir Din degrees	10	5	8	0.235	1244	0.18	0.33	1				
ricoorton bip, degrees		5	5	0.228	/18	0.187	0.33	1				
Injection Rate [stb/d]	5999.9998	8	14	0.227	32	0.155	0.33	1				
Results		9	14	0.213	320	0.196	0.33	1				
		10	7	0.213	34	0.21	0.33	1				
Total Thickness [ft]	94.0000	11										
Porosity [fraction]	0.23210	12										
Permeability [mD]	934.81	13										
Swc. fraction	0.1870	14										
Sor fraction	0.6700	15										
Endering for the	1,0000	10										
Endpoint kro, fraction	0.0000	18										
Endpoint krw, fraction	0.3300	19										
Endpoint Mobility Ratio	0.9980	20							-			
Gravity Number		•			III				- F			
Sector STOOIP [mmstb]	8.5676								art CSV			
								Imp	oncov			
								Calculate Frac	tional Flow			
								ſ	Close			

The fractional flow data will be calculated and displayed in the following TAB, as shown below.

< Layered Fra	ctional Flow N	1odel [Dake5_3	3c.lfm]		
🥐 Recent File	s 🖌 🗁 🔒	🗎 💻 🔼	📧 Oilfield U	Jnits	- O
(Appledical P	Jativa Parmanh	ilit. Emotions		Diselsoon	, Match Bendiation
Analytical Re	ative Permeab	ractiona	I Flow weige	Displacem	hent filistory Match (Frediction
	Swe	kro	krw	f ^	Fractional Flow Synthetic Production Log
Layer	[fraction]	[fraction]	[fraction]	[fra	
	0.186958	1.000000	0.000000	0.	
1	0.234633	0.741442	0.085324	0.	1.00 -
2	0.286714	0.536599	0.152922	0.	
3	0.361338	0.305808	0.229083	0.	
5	0.403561	0.192553	0.266458	0.	
6	0.433847	0.143527	0.282636	0.	
7	0.488212	0.062159	0.309488	0.	0.80 -
9	0.555129	0.011175	0.326312	0.	
4	0.574409	0.007807	0.327424	0.	
10	0.605846	0.005098	0.328318	0.	
8	0.670000	0.000000	0.330000	1.	Enco
					·응 0.00
					2 0.40
					0.20 -
					0.00
					0.00 0.20 0.40 0.60 0.80 1.00
					Core Manuface1
					Swe [iracuon]
				-	kro krw fw
•	-	III		•	
,					
					Close

Since all the required data has been input to calculate synthetic production log versus various watercut values based on each layer's water breakthrough, we have provided the display and layer calculations for these synthetic production logs. See example provided below.



Once the fractional flow data has been successfully calculated, proceed to the next TAB, Welge Displacement, as shown below, and press the *Calculate Welge Displacement* button.

ytical Relative Perm	eability Fractiona	Flow Welge Disp		Match Predie	ction			
			Bestfit Pre	ediction Functio	on			
Origon ?	Coefficient	1	Coefficient 2		Coefficier	nt 3	Best	Fit
Welge Calculation	Fractional Flow Cl	nart						
Swe [fraction]	fwe [fraction]	Delta Sw [fraction]	Delta fw [fraction]	Wid [PV]	Avg Sw [fraction]	Avg fw [fraction]	Npd [HCPV]	fw 🔺 [fract
0.186958	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0
0.234633	0.258184	0.047676	0.258184	0.184659	0.210795	0.129092	0.227121	0
0.286714	0.462916	0.052081	0.204732	0.254386	0.260674	0.360550	0.290739	0
0.361338	0.693777	0.074623	0.230861	0.323239	0.324026	0.578346	0.336223	0
0.403561	0.807143	0.042224	0.113367	0.372455	0.382450	0.750460	0.354759	0
0.433847	0.856233	0.030286	0.049089	0.616950	0.418704	0.831688	0.412754	0
0.488212	0.937727	0.054365	0.081495	0.667095	0.461030	0.896980	0.421621	0
0.555129	0.988803	0.066917	0.051076	1.310149	0.521670	0.963265	0.470874	0
0.574409	0.992178	0.019280	0.003375	5.712711	0.564769	0.990491	0.531505	0
0.605846	0.994892	0.031437	0.002714	11.584485	0.590127	0.993535	0.587995	0
0.670000	1.000000	0.064154	0.005108	12.558941	0.637923	0.997446	0.594117	C
•								
						[Calculate Welge D	isplacemen
							_	

The user can choose to bestfit a regression equation to better describe the Npd \lor s fws relationship, for later use in the prediction calculations, see following screen capture.



The Bestfit button returns the coefficients (C1, C2 and C3) of the following equation :

$$f_{ws} = \left(1 + C_1 \cdot \left[\frac{\left(1 - N_{pd}\right)^{C_2}}{N_{pd}^{C_2}}\right]\right)^{-1}$$

History Matching

If the oilfield under study is a producing field and the monthly values of production and injection history are known, then the User can choose to history match the total field oil originally in place, STOOIP. This is illustrated in the following screen captures. Firstly enter the monthly production and injection history, as per the format shown below, either by importing via a comma delimited ASCII file and by pressing the Import CSV button, or via copy [CTRL+C] and paste [CTRL+V] from an external application such as Microsoft Excel into the data input table below.

STOOIP Interval 1.0001	01- Jan-2001		[united]	DDIS	[DDIS]	
STOOP Interval 1.0001	01-001-2001	31	0.0000	0.0000	0.0000	
	01-Feb-2001	28	133833.3374	0.0000	197404.1726	
	01-Mar-2001	31	133833.3374	0.0000	197404.1726	
Use Areal Sweep Correlation ?	01-Apr-2001	30	133833.3255	0.0000	197404.1550	
	01-May-2001	31	133833.3494	0.0000	197404.1902	
Select Pattern Method	01-Jun-2001	30	133833.3016	0.0000	197404.1198	
lirect Line Drive	01-Jul-2001	31	133833.3494	0.0000	197404.1902	
	01-Aug-2001	31	133833.3016	0.0000	197404.1198	
	01-Sep-2001	30	133833.3972	0.0000	197404.2607	
	01-Oct-2001	31	133833.3016	0.0000	197404.1198	
	01-Nov-2001	30	133833.3016	0.0000	197404.1198	
	01-Dec-2001	31	133833.3972	0.0000	197404.2607	
	01-Jan-2002	31	133833.3016	0.0000	197404.1198	
	01-Feb-2002	28	777450.3705	2600.1699	1149417.4717	
	01-Mar-2002	31	777449.2585	5217.7789	1152111.9693	
	01-Apr-2002	30	777450.3705	7853.0340	1154827.9220	
	01-May-2002	31	777450.3705	10506.0873	1157560.5672	
	01-Jun-2002	30	777449.2585	13177.1050	1160310.0742	
	01-Jul-2002	31	777450.3705	15866.3342	1163081.6213	
	01-Aug-2002	31	711750.3395	33798.2101	1084643.9072	
	01-Sep-2002	30	711749.3212	54121.5310	1105575.4257	
	01-Oct-2002	31	711750.3395	75584.1070	1127683.3809	
	01-Nov-2002	30	711750.3395	98284.2007	1151064.4768	
	01-Dec-2002	31	711749.3212	122331.9027	1175832.1092	
	01-Jan-2003	31	711750.3395	147851.5196	1202118.8157	
	01-Feb-2003	28	558145.3007	128098.9097	955206.1962	
	01-Mar-2003	31	558146.8977	140701.4839	968189.2027	
	01-Apr-2003	30	558145.3007	153774.7259	981652.2865	
J	01-May-2003	31	558145.3007	167346.8449	995631.5694	
						Import C.C

Example formats of comma delimited ASCII file (CSV) file are shown below.

Example.csv - Notepad	1	Example.csv					
File Edit Format View Help		A	В	С	D	E	F
Month, Producing Days, Oil Volume, Water Volume, WI Volumes	1	01/01/2010	31	173405	1272	0	
01/01/2010, 31, 173405, 1272, 0	2	01/02/2010	28	174183	1272	0	
01/03/2010, 31, 178874, 2693, 0	3	01/03/2010	31	178874	2693	0	
01/04/2010, 30, 188882, 4362, 39709	4	01/04/2010	30	188882	4362	39709	
01/05/2010, 31, 205336, 6448, 288116	5	01/05/2010	31	205336	6448	288116	
01/07/2010, 31, 260691, 12881, 481735	6	01/06/2010	30	229125	9186	388027	
01/08/2010, 31, 299824, 17891, 569530	7	01/07/2010	31	260691	12881	481735	
01/09/2010,30,345516,24590,651695	8	01/08/2010	31	299824	17891	569530	
01/11/2010, 30, 448527, 44335, 800209	9	01/09/2010	30	345516	24590	651695	
01/12/2010, 31, 500359, 57738, 867074	10	01/10/2010	31	205021	33301	728600	
01/01/2011, 31, 548464, 73454, 929340							
01/03/2011, 31, 623970, 110682, 1041006							
01/04/2011, 30, 648570, 131345, 1090851							
01/05/2011,31,663992,152//0,1136988							
01/07/2011, 31, 670276, 196541, 1218934							
01/08/2011, 31, 663615, 218529, 1255126							
01/09/2011, 30, 652288, 240577, 1288371							

The user can then iterate the STOOIP value by selecting the up and down buttons adjacent to the STOOIP value, as shown below, to iterate the fractional flow history match. The user can also choose to modify the vertical layer predicted values of fws vs NpD by applying an areal sweep correlation. To enable this option simply select the Use Areal Sweep Correlation check box and then select the waterdrive pattern; namely 5 spot, direct line drive or staggered line drive.



Prediction Performance

To calculate the prediction performance, select the Prediction tab. Enter appropriate values for STOOIP, check whether to predict values from History, whether to use an areal sweep correlation in the prediction calculations, and whether to use the best fit Welge polynomial calculated in the Welge Displacement tab. Once the prediction timeframe has been entered together with the facilities constraints, the user can press the Calculate Prediction button, as shown below.

Analytical Relative Permeability Fractional Flow Welge Displacement History Match Prediction Prediction Setup Rates Chart Fractional Flow Charts Prediction Results - Table
Prediction STOOIP [mmstb] 176.1147 Predict from History ? Select Datapoint to Predict From 01-Jan-2008 Use Areal Sweep Correlation ? Select Pattern Method Direct Line Drive Use Welge Fitted Polynomial ? Prediction Timeframe Start Date Jan 2008 The Date Dec 2021 The Prediction Frequency Annually
[Facilities Constraints]
Oil Water Liquid Water Production Production Production Injection [bbls/day] [bbls/day] [bbls/day] [bbls/day]
Jan 2008 • 60000 65000 65000 Image: Second Se
Calculate Prediction
Close

Various charts and tables of prediction output are shown as examples below.








2008 2009 2010 2011 2012 2013 2014 2015 2015 2015 2016 2017 2018 2019 2020 2021	60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0	60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	11447.0 9537.6 8006.5 56812.6 55863.2 5097.7 4473.1 9 3926.3 3161.9 2819.1 2461.8 2172.5 1931.8	46714.3 49448.6 51641.2 53350.9 54710.5 55806.6 56701.1 57440.4 58058.5 588578.9 59069.7 59581.4 59950.7 60000.0	58161.3 59986.2 59647.7 60163.5 60573.7 60904.4 61174.2 61397.3 61583.7 61740.7 61888.8 62043.2 62123.2	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	0.803185 0.838309 0.865771 0.886766 0.903206 0.916299 0.936879 0.935553 0.942756 0.942756 0.942788 0.954449 0.960322	59.526 63.007 65.930 68.416 70.562 72.423 74.055 75.500 76.790 76.790 77.944 78.973 79.872
2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021	60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0	60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	9537.6 8006.5 6812.6 5863.2 5097.7 4473.1 3956.9 3525.3 3161.9 2819.1 2461.8 2172.5 1931.8	49448.6 51641.2 53350.9 54710.5 55806.6 56701.1 57440.4 58058.5 58578.9 59069.7 59581.4 59950.7 60000.0	58986.2 59647.7 60163.5 60573.7 60904.4 61174.2 61397.3 61583.7 61740.7 61888.8 62043.2 62123.2	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	0.838309 0.865771 0.886766 0.903206 0.916299 0.936553 0.942756 0.948788 0.954449 0.960322	63.007 65.930 68.416 70.562 72.423 74.055 75.500 76.790 77.944 78.973 79.872
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2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021	60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0	60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	6812.6 5863.2 5097.7 4473.1 3956.9 3525.3 3161.9 2819.1 2461.8 2172.5 1931.8	53350.9 54710.5 55806.6 56701.1 57440.4 58058.5 58578.9 59069.7 59581.4 599507. 60000.0	60163.5 60573.7 60904.4 61174.2 61397.3 61583.7 61740.7 61888.8 62043.2 62123.2	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	0.886766 0.903206 0.916299 0.926879 0.935553 0.942756 0.948788 0.954449 0.960322	68.416 70.562 72.423 74.055 75.500 76.790 77.944 78.973 79.872
2012 2013 2014 2015 2016 2017 2018 2019 2020 2021	60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0	60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	5863.2 5097.7 4473.1 3956.9 3525.3 3161.9 2819.1 2461.8 2172.5 1931.8	54710.5 55806.6 56701.1 57440.4 58058.5 58578.9 59069.7 59581.4 59950.7 60000.0	60573.7 60904.4 61174.2 61397.3 61583.7 61740.7 61888.8 62043.2 62123.2	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 64953.6	0.903206 0.916299 0.926879 0.935553 0.942756 0.948788 0.954449 0.960322	70.562 72.423 74.055 75.500 76.790 77.944 78.973 79.872
2013 2014 2015 2016 2017 2018 2019 2020 2021	60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0	60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	5097.7 4473.1 3956.9 3525.3 3161.9 2819.1 2461.8 2172.5 1931.8	55806.6 56701.1 57440.4 58058.5 58578.9 59069.7 59581.4 59950.7 60000.0	60904.4 61174.2 61397.3 61583.7 61740.7 61888.8 62043.2 62123.2	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 64953.6	0.916299 0.926879 0.935553 0.942756 0.948788 0.954449 0.960322	72.423 74.055 75.500 76.790 77.944 78.973 79.872
2014 2015 2016 2017 2018 2019 2020 2021	60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0	60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	4473.1 3956.9 3525.3 3161.9 2819.1 2461.8 2172.5 1931.8	56701.1 57440.4 58058.5 58578.9 59069.7 59581.4 59950.7 60000.0	61174.2 61397.3 61583.7 61740.7 61888.8 62043.2 62123.2	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 64953.6	0.926879 0.935553 0.942756 0.948788 0.954449 0.960322	74.055 75.500 76.790 77.944 78.973 79.872
2015 2016 2017 2018 2019 2020 2021	60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0	60000.0 60000.0 60000.0 60000.0 60000.0 60000.0 60000.0	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	3956.9 3525.3 3161.9 2819.1 2461.8 2172.5 1931.8	57440.4 58058.5 58578.9 59069.7 59581.4 59950.7 60000.0	61397.3 61583.7 61740.7 61888.8 62043.2 62123.2	65000.0 65000.0 65000.0 65000.0 65000.0 64953.6	0.935553 0.942756 0.948788 0.954449 0.960322	75.500 76.790 77.944 78.973 79.872
2016 2017 2018 2019 2020 2021	60000.0 60000.0 60000.0 60000.0 60000.0 60000.0	60000.0 60000.0 60000.0 60000.0 60000.0 60000.0	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	65000.0 65000.0 65000.0 65000.0 65000.0 65000.0	3525.3 3161.9 2819.1 2461.8 2172.5 1931.8	58058.5 58578.9 59069.7 59581.4 59950.7 60000.0	61583.7 61740.7 61888.8 62043.2 62123.2	65000.0 65000.0 65000.0 65000.0 64953.6	0.942756 0.948788 0.954449 0.960322	76.790 77.944 78.973 79.872
2017 2018 2019 2020 2021	60000.0 60000.0 60000.0 60000.0 60000.0	60000.0 60000.0 60000.0 60000.0 60000.0	65000.0 65000.0 65000.0 65000.0 65000.0	65000.0 65000.0 65000.0 65000.0 65000.0	3161.9 2819.1 2461.8 2172.5 1931.8	58578.9 59069.7 59581.4 59950.7 60000.0	61740.7 61888.8 62043.2 62123.2	65000.0 65000.0 65000.0 64953.6	0.948788 0.954449 0.960322	77.944 78.973 79.872
2018 2019 2020 2021	60000.0 60000.0 60000.0 60000.0	60000.0 60000.0 60000.0 60000.0	65000.0 65000.0 65000.0 65000.0	65000.0 65000.0 65000.0 65000.0	2819.1 2461.8 2172.5 1931.8	59069.7 59581.4 59950.7 60000.0	61888.8 62043.2 62123.2	65000.0 65000.0 64953.6	0.954449 0.960322	78.973 79.872
2019 2020 2021	60000.0 60000.0 60000.0	60000.0 60000.0 60000.0	65000.0 65000.0 65000.0	65000.0 65000.0 65000.0	2461.8 2172.5 1931.8	59581.4 59950.7 60000.0	62043.2 62123.2	65000.0 64953.6	0.960322	79.872
2020 2021	60000.0 60000.0	60000.0 60000.0	65000.0 65000.0	65000.0 65000.0	2172.5 1931.8	59950.7 60000.0	62123.2	64953.6		
2021	60000.0	60000.0	65000.0	65000.0	1931.8	60000.0			0.965029	80.667
						00000.0	61931.9	64649.5	0.968807	81.372

The user can copy any of the data to the Windows clipboard from any of the tables by either, clicking and dragging an area with their mouse and pressing CTRL+C, then pasting into an external application, or when the mouse is over a active table single right click the mouse to display the tables context menu then select the table that requires to be copied. The benefits of selecting the second approach over the first approach is that the table headers will also be be copied to the clipboard. See screen capture below.

diction Setup	Rates Chart	Fractional Flow Cha	rts Prediction R	esults - Table	
Date	Oil Capacity	Water Capacity	Liquid Capacity	WI Capacity	Oil Rat
2008	60000	.0 60000.0	65000.0	65000.0	114
2009	60000	.0 60000.0	65000.0	65000.0	9
2010	60000	.0 60000.0	65000.0	65000.0	8
2011	60000	.0 60000.0	65000.0	65000.0	6
2012		Copy Fractional F	low Calculations	5000.0	5
2013		17		5000.0	5
2014		Copy Welge Pred	iction Calculatio	ns 5000.0	4
2015		Copy PLT Calcula	tions	5000.0	3
2016		copy rer calcula	lions	5000.0	3
2017		Copy History Calo	ulations	5000.0	3
2018				5000.0	2
2019	D	Copy Prediction (Calculations	5000.0	2
2020	60000	0 000020	65000.0	65000.0	2
2021	60000	.0 Copy Pre	diction Calculatio	ons to Clipboard	1

References:

Fassihi, M., "New Correlations for Calculation of Vertical Coverage and Areal Sweep Efficiency," *SPERE*, Nov. 1986

2.3 Reverse Welge

Within the Waterdrive chapter of Dake's "The Practice of Reservoir Engineering", he presents a technique for examining and interpreting the waterdrive performance of reservoirs or numerical simulation models from inspection of their historic production/injection records. Extracts from this chapter as used to outline this technique.

"This approach to understanding the reservoir mechanics of a waterflood relies on the development of an underground fractional flow of water by solving the Welge equation in reverse. That is, for an observed set of production statistics: Np, Wi, fws, converted to their reservoir equivalents of Npd, Wid, fwe, the following equation is solved for Swe, thus establishing the fractional flow relationship: fwe versus Swe.

$$N_{pd} = (S_{we} - S_{wc}) + (1 - f_{we})W_{id}$$

In this respect the reservoir or model, no matter how complex it may be: containing numerous vertical/ horizontal wells, fractures or heterogeneity, is simply viewed as a Buckley-Leverett "black-box", in which the injection, qwi, and production, qo + qwp, are linked together by the fractional flow relationship."

The associated equations for Npd, Wid and fwe are included for completeness.

$$N_{pd} = \frac{N_p B_o}{N B_{oi}} (1 - S_{wc})$$
$$W_{id} = \frac{W_i}{N B_{oi}} (1 - S_{wc})$$
$$f_{we} = \frac{1}{1 + \frac{B_o}{B_w} \left(\frac{1}{f_{ws}} - 1\right)}$$

In solving the Welge equation for Swe, for values of Npd, Wid and fwe, it is assumed that the reservoir or simulator obeys Buckley-Leverett mechanics. Consequently, a fractional flow (fwe versus Swe) is obtained for which the extrapolation of the final points to the line fwe = 1 gives the value of Swbar, the average saturation in the "black-box", at that stage of the flood from which the oil recovery can be determined from :

$$N_{pd} = \overline{S}_w - S_{wa}$$

and the reciprocal of the tangent of this extrapolation gives the cumulative water injection required to attain the recovery as :

$$W_{id} = 1 \left(\frac{\Delta f_{we}}{\Delta S_{we}} \right)$$

Linking the above two equations with the underground material balance for waterdrive under pressure maintenance conditions, included immediately below, allows the forward calculation of production and injection profiles for a given set of facilities constraints.

$$q_{wi} = q_o B_o + q_{wp} B_w$$
$$f_{ws} = \frac{q_{wp}}{q_o + q_{wp}}$$

Integrating the above two equations, results in the following :

$$q_{wi} = q_o \left(B_o + \frac{B_w f_{ws}}{1 - f_{ws}} \right)$$

where, qwi = water injection capacity qo = oil processing capacity qo + qwp = total separation capacity qwp = water disposal capacity

The above techniques are outlined in more detail in the following example.

References:

Dake, L., "The Practice of Reservoir Engineering", Elsevier Scientific Publishing Company, 1994.

Welge, H.J., "Predicting Displacement Efficiency From Water-cut or Gas-Cut Field Data", SPE Paper 5313, 1975

Welge, H.J., "A Simplified Method for Computing Oil Recovery By Gas or Water Drive", Trans. AIME, 1952,

2.3.1 Example

Dake provides an example (Example 5.23) in his waterdrive chapter of "The Practice of Reservoir Engineering", which will be used, albeit somewhat modified, to outline this routine in more detail.

126
1.29
1.29
1
0.26
0.32

Year	Np	Wi	fws
	[mmstb]	[mmstb]	
1	3.4	4.9	0.128
2	11	18.9	0.356
3	16.9	36.6	0.631
4	21.4	55.7	0.747
5	24.9	73.7	0.794
6	28	92.6	0.828
7	30.5	111	0.859
8	32.8	130.3	0.876
9	34.8	149.2	0.891
10	36.6	168.5	0.904
11	38.1	187.5	0.919
12	39.5	206.9	0.926
13	40.7	224.3	0.93
14	41.8	242.2	0.938
15	42.7	257.9	0.942
16	43.6	274	0.943
17	44.4	290.1	0.949
18	45.2	305.4	0.947
19	45.9	321.1	0.955
20	46.6	337.6	0.957

Problem Statement

For the above production history, calculate :

- 1. the incremental oil production rate in year 21 assuming the water injection system is upgraded from is it's current level of 45,000 bwpd to 80,000 bwpd,
- 2. the remaining oil production to an abandonment watercut of 99.9%
- 3. The number of years required to reach the abandonment watercut of 99% for both the 45,000 bwpd to 80,000 bwpd levels.

In this example, the yearly production data has been spline curve fitted to allow the data to be input as monthly data, and formatted into the correct input units. See input screen below.

put Data Charts Tables Welge Prediction					
STOOIP [mmstb] 126	Historical Data	Prediction Data			
Initial Oil FVF, Boi [rb/stb] 1.29	Month	Producing Days	Oil Volume [bbls]	Water Volume [bbls]	1.
Current Oil FVF, Bo [rb/stb] 1.29	01-Jan-2010	31	173405.0000	1272.0000	
Water EVE Bw [rb/stb]	01-Feb-2010	28	174183.0000	1272.0000	
	01-Mar-2010	31	178874.0000	2693.0000	
Swc fraction 0.26	01-Apr-2010	30	188882.0000	4362.0000	
	01-May-2010	31	205336.0000	6448.0000	
Sor, fraction 0.32	01-Jun-2010	30	229125.0000	9186.0000	1
	01-Jul-2010	31	260691.0000	12881.0000	
	01-Aug-2010	31	299824.0000	17891.0000	1
	01-Sep-2010	30	345516.0000	24590.0000	1
	01-Oct-2010	31	395931.0000	33321.0000	
	01-Nov-2010	30	448527.0000	44335.0000	1 C C
	01-Dec-2010	31	500359.0000	57738.0000	1 - C
	01-Jan-2011	31	548464.0000	73454.0000	1.00
	01-Feb-2011	28	590281.0000	91232.0000	1.00
	01-Mar-2011	31	623970.0000	110682.0000	1
	01-Apr-2011	30	648570.0000	131345.0000	1
	01-May-2011	31	663992.0000	152770.0000	1
	01-Jun-2011	30	670856.0000	174586.0000	1
	01-Jul-2011	31	670276.0000	196541.0000	1. 🔻
	∢ [- P-
				Import CS	SV
				Calc	ulate

Note that the monthly production and injection history, as per the format shown above, can be input either by importing via a comma delimited ASCII file and by pressing the Import CSV button, or be copied and pasted into the input table by pressing the windows standard shortcut keys [CTRL+C] then [CTRL+V].

Example formats of comma delimited ASCII file (CSV) file are shown below.

Example.csv - Notepad	-	Example.csv						
File Edit Format View Help		А	В	С	D	E	F	
Month, Producing Days, Oil Volume, Water Volume, WI Volumes	1	01/01/2010	31	173405	1272	0		
01/01/2010, 31, 1/3405, 12/2, 0 01/02/2010, 28, 174183, 1272, 0	2	01/02/2010	28	174183	1272	0		
01/03/2010, 31, 178874, 2693, 0	3	01/03/2010	31	178874	2693	0		
01/04/2010, 30, 188882, 4362, 39709	4	01/04/2010	30	188882	4362	39709		
01/05/2010, 31, 205336, 6448, 288116 01/06/2010, 30, 229125, 9186, 388027	5	01/05/2010	31	205336	6448	288116		
01/07/2010, 31, 260691, 12881, 481735	6	01/06/2010	30	229125	9186	388027		
01/08/2010, 31, 299824, 17891, 569530	7	01/07/2010	31	260691	12881	481735		
01/10/2010, 31, 395931, 33321, 728500	8	01/08/2010	31	299824	17891	569530		
01/11/2010, 30, 448527, 44335, 800209	9	01/09/2010	30	345516	24590	651695		
01/12/2010, 31, 500359, 57738, 867074	10	01/10/2010	21	202031	22201	728500		
01/02/2011.28.590281.91232.987242								
01/03/2011, 31, 623970, 110682, 1041006								
01/04/2011, 30, 648570, 131345, 1090851								
01/06/2011, 30, 670856, 174586, 1179617								
01/07/2011, 31, 670276, 196541, 1218934								
01/08/2011, 31, 663615, 218529, 1255126								
01/09/2011,50,052200,2405/7,12005/1								

Once the user is happy with the input data they should press the Calculate button, and the following

charts and tables should be displayed.



The following chart is the production and injection history data converted to a Welge fractional flow.



The user can zoom into the late time data to better digitize extrapolation points. To zoom click and drag the left mouse button for the required zoom area. To unzoom press the small icons located in the top of the y-axis scrollbar or at the left edge of the x-axis scrollbar.



To select extrapolation to digitize, highlight the chart's context menu list by pressing the right mouse button whilst anywhere within the chart area. Then select the "Add Extrapolation Points" & "Select Points", as shown below. Then simply left mouse click where you want to add digitized points. Once the user is happy with the number and location of digitized points, select an area within the margins of the chart (ie,. not in the data display area), and again pressing the right mouse button, select "Add Extrapolation Points" & "End Selection", as shown below.



The following should be displayed. Although some automatic re-zooming may take place, which may require manually unzooming and re-zooming into the area of interest with the chart.



Once the user is happy with the fractional flow extrapolation that have been digitized and curve fitted, they should select the "Welge Prediction" TAB, as shown below.

Within this TAB the user can input a prediction timeframe, facilities constraints and a bestfit prediction function.

The Bestfit Prediction Function returns the coefficients (C1, C2 and C3) of the following equation :

$$f_{we} = \left(1 + C_1 \cdot \left[\frac{(1 - E_D)^{C_2}}{E_D^{C_2}}\right]\right)^{-1}$$

where Ed is the microscopic displacement efficiency, given by the following formula :

$$E_D = \frac{Sw - Sw_c}{1 - Sw_c - So_r}$$

ediction Se	tup Pre	ediction Results	- Table Predictio	n Results - Chart			
		Bestfit Predicti	on Function			Prediction Timeframe	
	Coeffic	ient 1 0.22321			:	Start Date Jan 2030	× v
	Coeffic	ient 2 2.84778	B	est Fit		End Date Dec 2050	÷ •
	Coeffic	ient 3 0.40067			R	Reporting Frequency Monthly	~
				Facilities C	onstraints		
Date		Oil Production [bbls/day]	Water Production [bbls/day]	Liquid Production [bbls/day]	Water Injection [bbls/day]		
Jan 2030	•	50000.0000	50000.0000	50000.0000	50000.0000		
							•
							Celeviete

Once the user presses the *Calculate* button, as shown above, the Welge prediction is performed, for the selected timeframe, using the curve fitted fractional flow extrapolation and the facilities constraints. In this example, for the 45,000 bwpd injection case, the following two screen captures show the predicted water injection and oil production profiles.



From the above, the prediction is constrained throughout the prediction period by water injection, and the oil production profile appears to merge with history and extrapolate well.

The calculated initial oil rate in year 21 is approximately 2200 bopd, and the ultimate recovery predicted at abandonment watercut is 50.5 mmstb. A remaining reserve figure of 3.9 mmstb,

To quantify the incremental oil production rate for upgrading the water injection capacity to 80,000 bwpd is shown in the following screen captures. The user simplys input the 80,000 bpd for water injection (and water and liquid production, since this will be the next constraint to be met in the prediction calculations) and again presses the *Calculate* button.

Prediction Points Bestfit a Prediction Polynomial Select Datapoint to Predict From 01-Dec-2029 Swe five Ifractioni Ifractioni 0.25940768 0.09933288 0.25940768 0.09933288 0.25940768 0.09933288 0.25940768 0.09933288 0.25940768 0.09933288 0.25940768 0.09933288 0.26362883 0.32417613 0.29176983 0.60584789 0.32976018 0.77880424 0.37619283 0.87269482 0.42262548 0.92705253 0.49157093 0.96905622 0.53800358 0.99376427 Value Facilities Constraints Date Production Ibbls/day] Ibbls/day] Ibbls/day] Ibbls/day] Jan 2030 50000.0000 80000.0000 80000.0000 80000.0000 0.9376427 Image: Constraints	ut Data Charts (Ta	ables Welge	Predict	tion e Prediction Resu	llts - Chart				
	Select Datapoint 01-Dec-2029 Swe [fraction] 0.25940768 0.26362883 0.29176983 0.32976018 0.37519283 0.4262548 0.49157093 0.53800358	five [fraction] 0.09933288 0.32417613 0.60584789 0.77880424 0.92705253 0.96905622 0.99376427	m •	Number of po fwe = a+ b -107.550(13 Start Date Date Jan 2030	Best lynomial terms p.Sw+ c.Sw ² + 31.013 -6510.06(Jan 2030 Oil Production [bbls/day] 50000.0000	fit a Prediction Po 6 d.Sw^3+ e.Sw^4 15819.69 -19067. Prediction Timefr e Rep Facilities Constra Water Production [bbls/day] 50000.0000	ynomial + f.Sw^5 4(9112.755) ame Ind Date Dec 205 orting Frequency ints Liquid Production [bbls/day] 80000.0000	Best Fit	

The results for the 80,000 bwpd case are shown below. From these calculations, the oil rate predicted initially in year 21 is approximately 2300 bopd, an incremental oil rate of 600 bopd over the 45,000 bwpd injection case. The 80,000 bwpd injection case also reaches 50.5 mmstb ultimate recovery, but 5 years earlier.

Obviously the additional capital expenditure required to upgrade injection capacity may be more than offset by the acceleration of oil production and the saving of 5 years field operating expenditure.



2.4 Layer Assistant

A simple Log Value Layering tool is provided to quickly sub divide either Gamma ray, Porosity, Permeability or Water saturation logs into a discrete series of layers for use in the Multi Layer Fractional Flow Model or Craig-Geffen-Morse Layer model.

-pu	Layering	Tables (Resulta			
	🔲 Gamma	Ray ? 🛛 🗷 I	Porosity ?	Permeabili	ity ? 🛛 🗷 Water Saturation ?
	Depth [ft]	Porosity [fraction]	Permeability [mD]	Swc [fraction]	
	6324.6799	0.1264	67.203	0.9877	
	6324.7791	0.2246	669.9681	0.6393	
	6324.8783	0.3143	2570.6768	0.408	
	6324.9776	0.3461	3781.8635	0.4091	
	6325.0768	0.344	3690.1106	0.3707	
	6325.1760	0.3495	3931.448	0.3586	
	6325.2752	0.3447	3718.9041	0.4565	
	6325.3744	0.35	3954.3132	0.3013	
	6325.4737	0.35	3954.3132	0.4134	
	6325.5729	0.35	3954.3132	0.387	
	6325.6721	0.35	3954.3132	0.366	
	6325.7713	0.2979	2076.0085	0.599	
	6325.8706	0.0242	0.0897	1	
	6325.9698	0.0464	1.2258	1	
	6326.0690	0.0645	4.548	1	
	6326.1682	0.0904	17.6049	1	
	6326.2674	0.1253	64.9246	1	
	6326.3667	0.1514	138.4365	1	
	6326.4659	0.161	177.1293	1	
	6326.5651	0.1594	170.1202	0.9502	-
	6326.4659 6326.5651	0.161 0.1594	177.1293	1 0.9502	-

Either copy and paste the log data directly into the input data grid shown above, or use the Import CSV button to import an ASCII comma delimited file into this data grid. It is important to note that the structure of the CSV file must contain 5 columns of data even if the 5 columns are not used (column 1 = depth, column 2 = GR, column 3 = Porosity, column 4 = Permeability, column 5 = Swc). In the instance where the log data is not used simply enter 0 values for the entire column of values.

For the example shown above the top line of the CSV would look like ; 6324.6799, 0, 0.1264, 67.203, 0.9877.

Then select the "Layering Tables" tab, as shown below, input the required Variance Lag points [default value is set to 10], then select the log in which to calculate the numbers of layers, and press the Calculate button. Once the Calculation has been performed the log and layer values should be shown in the Layering Chart and Summary Table. The user can quickly change the character of the layering by iterating with both the Layer Tolerance slider bar and the Variance Lag points.

Once the user is happy with the layering calculations, they can choose to display other logs and layer averages in the final tab "Resultant Layer Charts", as shown in the right hand image below.



Waterdrive

Petroleum Reservoir Waterdrive Analysis Software



3 Craig

Forest Craig's SPE Monograph "*The Reservoir Engineering Aspects of Waterflooding*", first published in 1971, is referenced in practically all text books and technical papers associated with waterdrive and water flooding literature.

His techniques, presented within this textbook, form the basis for the routines contained within this section.

3.1 Craig's Minimum Number of Layers

Craig outlined guidelines for selecting the minimum number of layers needed to predict the performance of a reservoir under waterflooding operation. The author simulated the performance of a waterflood five-spot pattern that is composed of 100 layers with permeability variations ranging from 0.4 to 0.8. The minimum number of layers required to match results of the 100-layer model was determined as a function of mobility ratio and permeability variation.

His guidelines are the basis for this routine.

To calculate the minimum number of layers from Craig's data, simply enter the Dykstra-Parsons Permeability Variation, the Mobility Ratio and the WOR limit to be modelled, as shown below.

Minimum Number of Layers	- • •
Dykstra-Parsons Permeability Variation 0.	3
Mobility Ratio 1	
Input Watercut or WOR	
Watercut, fraction 0.9090	91
Water Oil Ratio 10	
Required Minimum Number of Layers 50	
Calculate	Close

References:

Craig, Jr., F., "The Reservoir Engineering Aspects of Waterflooding", Society of Petroleum Engineers, 1971

3.2 Craig-Geffen-Morse Recovery Performance

3.2.1 Introduction

To obtain waterflood performance with time for a five-spot pattern the approach of Craig, Geffen, and Morse for relating oil recovery and producing WOR to cumulative injected water is coupled with the correlation of Caudle and Witte for calculating five-spot water injection rates.

This method of predicting five-spot water injection performance is valid either with or without free gas present, provided that there is no trapped gas behind the flood front. The calculations, however, are not

valid for floods in which there is bottom water present.

These calculations assume a vertical sweep efficiency of 100 percent in each layer, ie., the fluids are not segregated by gravity.

For stratified reservoirs with layers of different water-oil relative permeability characteristics, the performance of each layer must be calculated individually.

The performance of a waterflood can be divided into four stages.

- 1. Start to Interference The period of radial flow out from the injectors from the start of injection until the oil banks, formed around adjacent injectors, meet. The meeting of adjacent oil banks is termed "interference".
- 2. Interference The period from interference until fillup of the pre-existing gas space. Fillup is the start of oil production response.
- 3. Fillup to Water The period from fillup to water breakthrough at the producing wells. Breakthrough marks the beginning of Breakthrough water production.
- 4. Post Water The period from water breakthrough to floodout. Breakthrough

For a multi layered system, Craig proposed performing the calculations for one selected layer, identified as the **base layer**. The performance of each of the remaining layers is obtained by "sliding the timescale", and summing the individual layer performance variables to calculate the composite multi layer performance. See Composite Layer Performance.

References:

Craig, Jr., F., "The Reservoir Engineering Aspects of Waterflooding", Society of Petroleum Engineers, 1971

Craig, F., Geffen, T., and Morse, R., "Oil Recovery Performance of Pattern Gas or Water Injection Operations from Model Tests" JPT, Jan. 1955

Caudle, B., and Witte, M., "Production Potential Changes During Sweep-out in a Five-Spot System" AIME, 1959, Vol. 216

Ahmed, T., "Reservoir Engineering Handbook", Elsevier, 2006

3.2.2 Start to Interference

This is a period of radial flow out from the injectors from the start of injection until the oil banks, formed around adjacent injectors, meet. The meeting of these adjacent oil banks is termed "interference".

The performance calculations, for this stage, are given by the two following steps:

1. Calculate the cumulative water injected to interference from the following equation :

$$W_{ii} = \frac{\pi.h.\phi.S_{gi}.r_{ei}^2}{5.615}$$

where,

Wii = cumulative water injected to interference

```
Sgi = initial gas saturation
```

 $\phi = \text{porosity}$

rei = half the distance between adjacent injectors

2. Assume successive values of cumulative water injected, ranging between 0 and Wii, and calculate the water-injection

rate from the following equation :

$$i_{w} = \frac{0.00707.k.h.\Delta P}{\left(\frac{\mu_{w}}{k_{rw}}.ln\left(\frac{r}{r_{w}}\right) + \frac{\mu_{o}}{k_{ro}}.ln\left(\frac{r_{o}}{r}\right)\right)}$$

where,

iw = water injection rate ΔP = pressure difference between injector and producer k = absolute permeability, md kro = relative permeability of oil at Swi krw = relative permeability of water at SwBT ro = outer radius of the oil bank r = outer radius of the water bank rw = wellbore radius

The outer radii of the oil and water banks are calculated from the following equations :

$$r_{o} = \sqrt{\frac{5.615.W_{inj}}{\pi.h.\phi.S_{gi}}} \qquad r = r_{o}\sqrt{\frac{S_{gi}}{\overline{S}_{wBT} - S_{wi}}}$$

3.2.3 Interference to Fillup

This is the period from interference until fill up of the pre-existing gas space.

Fill-up is marked by the following four events :

- 1. No free gas remaining in the flood pattern
- 2. Arrival of the oil-bank front to the production well
- 3. Flood pattern response to the waterflooding
- 4. Oil flow rate equal to the water injection rate

The performance calculations, for this stage, are given by the following steps:

1. Calculate the cumulative water injected at fill-up by applying the following equation :

$$W_{if} = PV.S_{gi}$$

where, Wif = cumulative water injected at fill-up PV = total flood pattern pore volume Sgi = initial gas saturation

2. Calculate the areal sweep efficiency at fill-up by using the following equation :

$$E_{A} = \frac{W_{inj}}{PV.(\overline{S}_{wBT} - S_{wi})}$$

3. Using the mobility ratio and the areal sweep efficiency at fill-up, determine the conductance ratio from the following equation :

$$\gamma = a_1 + (a_2 + a_3.E_A).M^{(a_4 + a_5.E_A)} + a_6 \cdot \left(\frac{M}{E_A}\right)^2 + a_7.M$$

where,

a1 to a7 are coefficients based on mobility ratio. also, for an areal sweep efficiency of 100%, the conductance ratio equals the mobility ratio.

4. For a constant pressure difference, the initial (base) water injection rate is given by the following equation :

$$i_{base} = \frac{0.003541.h.k.k_{ro}\Delta P}{\mu_o \left[\ln \left(\frac{d}{r_w} \right) - 0.619 \right]}$$

5. Calculate the water injection at fill-up from the following equation :

$$i_{wf} = \gamma . i_{base}$$

6. Calculate the incremental time occurring from interference to fill-up from the following equation :

$$\Delta t = \frac{W_{if} - W_{ii}}{\left(\binom{i_{wi} + i_{wf}}{2}\right)}$$

3.2.4 Fillup to Water Breakthrough

This is the period from fillup to water breakthrough at the producing wells.

During this stage, the oil production rate is essentially equal to the injection due to the fact that no free gas exists in the swept flood area. With continuous water injection, the leading edge of the water bank eventually reaches the production well, and marks the time to water breakthrough.

The performance calculations, for this stage, are given by the following steps:

1. Calculate cumulative water injected at breakthrough by using the following equation :

$$W_{iBT} = PV.(\overline{S}_{wBT} - S_{wi})E_{ABT}$$

2. Assume several values of cumulative water injected between Wif and WiBT and calculate the areal sweep efficiency at each value, using the following equation :

$$E_{A} = \frac{W_{inj}}{PV.(\overline{S}_{wBT} - S_{wi})}$$

3. Calculate the conductance ratio γ for each assumed value of Winj, again from the following equation :

$$\gamma = a_1 + (a_2 + a_3.E_A).M^{(a_4 + a_5.E_A)} + a_6 \cdot \left(\frac{M}{E_A}\right)^2 + a_7.M$$

where,

a1 to a7 are coefficients based on mobility ratio. also, for an areal sweep efficiency of 100%, the conductance ratio equals the mobility ratio.

4. Calculate the water injection rate at each Winj step, from the following :

$$i_{\rm w} = \gamma . i_{\rm base}$$

5. Calculate the oil flow rate during this stage from :

$$q_o = \frac{i_w}{B_o}$$

6. And finally, calculate the cumulative oil production from the following :

$$N_p = \frac{W_{inj} - W_{if}}{B_o}$$

3.2.5 Post Water Breakthrough

This is the period from water breakthrough to floodout.

After breakthrough, the water-oil ratio increases with a subsequent decline in the oil flow rate. The swept area will continue to increase as additional water is injected. The incrementally swept area will contribute additional oil production, while the previously swept area will continue to produce both oil and water.

The performance calculations, for this stage, are given by the following steps:

1. Assume several values for the ratio Winj/WiBT and calculate the cumulative water injected for each ratio from the following

$$\mathbf{W}_{inj} = \left(\frac{\mathbf{W}_{inj}}{\mathbf{W}_{iBT}}\right) \cdot \mathbf{W}_{iBT}$$

2. Calculate the areal sweep efficiency at each assumed ratio from the following equation :

$$E_{A} = E_{ABT} + 0.633.log \left(\frac{W_{inj}}{W_{iBT}}\right)$$

3. Calculate the ratio Qi/QiBT that corresponds to each value of Winj/WiBT using the following equation :

$$\frac{Q_i}{Q_{iBT}} = 1 + a_1 \cdot e^{-a_1} [Ei(a_2) - Ei(a_1)]$$

where,

$$a_1 = 3.65.E_{ABT}$$
 $a_2 = a_1 + ln \left(\frac{W_{inj}}{W_{iBT}} \right)$

and Ei is the exponential integral function.

4. Determine the total pore volumes of water injected from the following :

$$\mathbf{Q}_{i} = \left(\frac{\mathbf{Q}_{i}}{\mathbf{Q}_{iBT}}\right) \cdot \mathbf{Q}_{iBT}$$

5. Calculate the slope dfw/dSw for each value of Qi from the following :

$$\left(\frac{df_w}{dS_w}\right)_{Sw2} = \frac{1}{Q_i}$$

6. Calculate the value of Sw2, the water saturation at the producing well, that corresponds to each value

of dfw/dSw.

7. Calculate the reservoir water cut at the producing well for each value of Sw2, from the following equation :

$$f_{w2} = \frac{1}{1 + \frac{\mu_w}{\mu_o} \cdot \frac{k_{ro}}{k_{rw}}}$$

8. Determine the average water saturation in the swept area, from the following :

$$\overline{S}_{w2} = S_{w2} + \frac{1 \text{-} f_{w2}}{\left(\frac{df_w}{dS_w}\right)_{S_{w2}}}$$

9. Calculate the surface water-oil ratio that corresponds to each value of fw2, from the following :

$$WOR_{s} = \frac{f_{w2} \left[1 - \Delta N_{p_newly}\right]}{1 - f_{w2} \left[1 - \Delta N_{p_newly}\right]} \left(\frac{B_{o}}{B_{w}}\right)$$

10.Calculate cumulative oil production incorporating for the oil lost to the unswept area of the flood pattern, from the following :

$$N_{p} = N_{S}.E_{D}.E_{A} - \frac{PV.(1 - E_{A}).S_{gi}}{B_{o}}$$

where,

 ${\rm E}_{\rm D}$ is the displacement efficiency, and is calculated from the following :

$$E_{D} = \frac{\overline{S}_{w} - S_{wi} - S_{gi}}{1 - S_{wi} - S_{gi}}$$

11.Calculate cumulative water production from the following :

$$W_p = \frac{W_{inj} - N_p.B_o - PV.S_{gi}}{B_w}$$

12.Calculate krw at Sw2 and determine the mobility ratio M after breakthrough from the following :

$$\mathbf{M} = \frac{\mathbf{k}_{\mathrm{rw}} @ \overline{\mathbf{S}}_{\mathrm{w2}}}{\mathbf{k}_{\mathrm{ro}} @ \mathbf{S}_{\mathrm{wi}}} \cdot \left(\frac{\boldsymbol{\mu}_{\mathrm{o}}}{\boldsymbol{\mu}_{\mathrm{w}}} \right)$$

13. Calculate the conductance ratio γ .

$$\gamma = a_1 + (a_2 + a_3.E_A).M^{(a_4 + a_5.E_A)} + a_6 \left(\frac{M}{E_A}\right)^2 + a_7.M$$

14. Calculate the water injection rate, from the following :

$$i_{\rm w} = \gamma . i_{\rm base}$$

15. And finally, calculate the oil and water production rates, from the following :

$$q_o = \frac{i_w}{B_o + B_w . WOR_s} \qquad q_w = q_o . WOR_s$$

3.2.6 Composite Layer Performance

To calculate the performance of all the other layers, in a multi layer reservoir that may differ in thickness, porosity, and permeability, the following calculation steps are applied.

- 1. Divide the reservoir into the required number of layers.
- 2. Calculate the performance of the base layer (layer n) from Start to Interference to Fillup to Water Breakthrough to End.
- 3. Obtain values of cumulative liquid volumes (NP, WP, Winj) and liquid rates (qo, qw, qwi) as a function of time t for the base layer (layer n).
- 4. For each layer, including the base layer n, calculate the follow ing : (k/f), (f.h) and (k.h)
- 5. For each reporting timestep, the follow ing is calculated for each layer i . Where, n = base layer, i = layer i, NP*, WP*, Winj* = volumes at t*, qo*, qw *, and qw i* =rates at t*

$$\mathbf{t}_{i}^{*} = \mathbf{t} \frac{\begin{pmatrix} \mathbf{k} \\ \boldsymbol{\phi} \end{pmatrix}_{i}}{\begin{pmatrix} \mathbf{k} \\ \boldsymbol{\phi} \end{pmatrix}_{n}} \ \mathbf{N}_{p} = \mathbf{N}_{p}^{*} \frac{\langle \boldsymbol{\phi} \cdot \mathbf{h} \rangle_{i}}{\langle \boldsymbol{\phi} \cdot \mathbf{h} \rangle_{n}} \ \mathbf{W}_{p} = \mathbf{W}_{p}^{*} \frac{\langle \boldsymbol{\phi} \cdot \mathbf{h} \rangle_{i}}{\langle \boldsymbol{\phi} \cdot \mathbf{h} \rangle_{n}} \ \mathbf{W}_{inj} = \mathbf{W}_{inj}^{*} \frac{\langle \boldsymbol{\phi} \cdot \mathbf{h} \rangle_{i}}{\langle \boldsymbol{\phi} \cdot \mathbf{h} \rangle_{n}} \ \mathbf{q}_{o} = \mathbf{q}_{o}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{n}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{n}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{n}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{n}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{n}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{n}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{n}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{n}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{n}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}} \ \mathbf{q}_{wi} = \mathbf{q}_{wi}^{*} \frac{\langle \mathbf{k} \cdot \mathbf{h} \rangle_{i}}$$

6. The composite multi layer performance at each reporting timestep t is obtained by the summation of all the individual layer values.

The above calculation is only valid for reservoirs having equal initial gas saturation in each layer and insignificant producing rate prior to fillup.

3.2.7 Example

In Appendix E4 of Craig's "*The Reservoir Engineering Aspects of Waterflooding*", he presents the following example for calculating the Composite WOR Recovery Performance

General Input Data	
Oil viscosity [cP]	1
Water viscosity [cP]	0.5
Oil FVF, Bo [rb/stb]	1.2
Water FVF, Bw [rb/stb]	1
Residual Oil Saturation, Sor [fraction]	0.3
Initial Water Saturation, Swc [fraction]	0.1
Initial Gas Saturation, Sgi [fraction]	0.15

Injector wellbore radius [ft]	1
Pressure difference injector-producer [psi]	3000
Half distance between injectors [ft]	660
Distance injector to producer [ft]	932
Pattern Area, Acres	40
Base Layer Reservoir Thickness [ft]	5
Base Layer Permeability [mD]	31.5
Base Layer Porosity [fraction]	0.2

Relative Permeability Data

<u>Sw</u>	<u>kro</u>	<u>krw</u>
0.1	1	0
0.3	0.373	0.07
0.4	0.21	0.169
0.45	0.148	0.226
0.5	0.1	0.3
0.55	0.061	0.376
0.6	0.033	0.476
0.65	0.012	0.6
0.7	0	0.74

Lay	/er Properties	
<u>Thickness [ft]</u>	Permeability [mD]	Porosity [fraction]
5	31.5	0.2
5	20.5	0.2
5	16	0.2
5	13.1	0.2
5	10.9	0.2
5	8.2	0.2
5	7.7	0.2
5	6.3	0.2
5	4.9	0.2
5	3.2	0.2
	Lay <u>Thickness [ft]</u> 5 5 5 5 5 5 5 5 5 5 5 5 5	Layer Properties Thickness [ft] Permeability [mD] 5 31.5 5 20.5 5 16 5 13.1 5 10.9 5 8.2 5 7.7 5 6.3 5 4.9 5 3.2

Once the user has successfully input all the required data, as shown in the following two screen captures, they can press the *calculate* button to calculate all stages of the performance prediction.

The user can choose to enter Relative Permeability table values, as shown below, or choose to enter Corey coefficients for Oil and Water curvature, since all the other endpoint parameters are required for other calculation steps [kro, krw, Sor, Swc].

Craig 63

Input Data Calculation Results						
General Data Layer Data and Prediction Setup						
Endpoint kro, fraction	1	В	Base L Jase Layer Reserv	ayer Properties roir Thickness [ft] 5	
Endpoint krw, fraction	0.74		Base Laver P	ermeability [mD	31.5	
Oil viscosity [cP]	1		D 1 1		0.0	
Water viscosity [cP]	0.5		base Layer I	-orosity (fraction	0.2	
Oil FVF, Bo [rb/stb]	1.2	Input Relative Per	meability Chart			
Water FVF, Bw [rb/stb]	1		orev Coefficients	Input]	able Values	
Residual Oil Saturation, Sor [fraction]	0.3	Input Table Valuer		() input	abie values	
Initial Water Saturation, Swc [fraction]	0.1					
Initial Gas Saturation, Sgi [fraction]	0.15	Sw [fraction]	kro [fraction]	krw [fraction]		Â
		0.100000	1.000000	0.000000		
		0.300000	0.373000	0.070000		
Injector wellbore radius [ft]	1	0.400000	0.210000	0.169000		
Pressure difference injector-producer [psi]	3000	0.450000	0.148000	0.226000		
Unit distance between inicators (6)	660	0.50000	0.100000	0.300000		
Hall distance between injectors [it]	000	0.00000	0.061000	0.3/6000		
Distance injector to producer [ft]	932	0.650000	0.033000	0.476000		
Pattern Area Acres 🗸	40	0.700000	0.000000	0.740000		
						-

Craig–Geffen–Mors	e Recovery Per	formance Metho	d [CraigExample	.cgm]			
Recent Files 👻 🕻	> 🛃 🗎 5	P 人 🗟 Oilfi	eld Units 🖃	0			
Input Data Calculati	ion Results						
General Data Laye	r Data and Pred	iction Setup					
	Require	ed Number of Laye	rs 10	•	Predictio	n Setup	
Layer Number	Thickness [ft]	Permeability [mD]	Porosity [fraction]		Start Date	Jun 2007	÷-
Base Layer = 1	5	31.5	0.2		End Date	Jan 2050	T
2	5	20.5	0.2		Reporting Frequency	Monthly	-
3	5	16	0.2				
4	5	13.1	0.2				
5	5	10.9	0.2				
7	5	0.2	0.2				
8	5	6.3	0.2				
9	5	4.9	0.2				
10	5	3.2	0.2				
						Calculate	Close

Stage 1 : Start to Interference

The Stage 1 - Start to Interference is calculated if the user input an initial gas saturation value > 0.

Layer Out	put Composite	Layers Results					
lpoint Mobi	lity Ratio 1.48	0000 Brea	akthrough Swba	r Mobility Ratio 0.8	10407	Breakthrough	Swbar [fraction] 0.564602
	1.1.1		te Meleter Dece		Development		
to interiere		ice to Fillup (Fillup	o to vvater brea	kthrough (Fost wate	r breaktnrou	gn Combined	
	10			Start to Interference	e]		
	-		70 70				422.00
	1	ime to interference	[days] /3.70	Wate	r injection ra	te at interference [i	501/d] 423.35
Winj	Oil bank radius	Water bank radius	Injection rate	Avg.injection rate	Delta Time	Cumulative	
obisj	[ft]	[ft]	[bbl/d]	[bbl/d]	[days]	[days]	
1,828.02	147.58	83.86	553.94	0.00	3.30	3.30	
3,656.04	208.71	118.59	517.26	535.60	3.41	6.71	
5,484.07	255.62	145.24	497.97	507.62	3.60	10.31	
7,312.09	295.16	167.71	485.14	491.55	3.72	14.03	
9,140.11	330.00	187.51	475.63	480.38	3.81	17.84	
0,968.13	361.50	205.40	468.13	471.88	3.87	21.71	
2,796.15	390.46	221.86	461.97	465.05	3.93	25.64	
4,624.18	417.42	237.18	456.77	459.37	3.98	29.62	
6,452.20	442.74	251.57	452.27	454.52	4.02	33.64	
8,280.22	466.69	265.18	448.33	450.30	4.06	37.70	
0,108.24	489.47	278.12	444.82	446.57	4.09	41.80	
1,936.27	511.23	290.49	441.66	443.24	4.12	45.92	
3,764.29	532.11	302.35	438.80	440.23	4.15	50.07	
5,592.31	552.20	313.76	436.18	437.49	4.18	54.25	
7,420.33	571.58	324.77	433.76	434.97	4.20	58.46	
9 248 35	590.32	335.42	431.53	432.65	4.23	62.68	

Stage 2 : Interference to Fillup

The Stage 2 - Interference to Fillup is also calculated if the user input an initial gas saturation value > 0.

	yers Results				
Endpoint Mobility Ratio 1.48000	0 Breakthrough S	wbar Mobility Ratio 0.	810407 E	Breakthrough Swbar [fractio	n] 0.564602
art to Interference Interference	to Fillup Fillup to Water F	Breakthrough Post Wat	er Breakthrough	Combined	
10	\$	Interference to Fill	up		
	Time to fillun (days) 1	09.14	Water injection	n rate at fillun (bbl/d) 256.6	3
	- 100 to 100 p [00/0]		Trator Injouror	Conductance ratio 0.953	B

Stage 3 : Fillup to Water Breakthrough

The Stage 3 - Fillup to Water Breakthrough calculation panel is shown below :

se Layer Outp	ut Composite Laye	ers Results						
indpoint Mobili	ty Ratio 1.480000	Breakthroug	gh Swbar Mobil	ty Ratio 0.810407	Bre	akthrough Swbar	[fraction] 0.564	602
rt to Interferen	ce Interference to	Fillup Fillup to Wat	er Breakthroug	Post Water Break	through Co	mbined		
		A.	or broardinoug		unougn (or			
		- 0	Interfe	rence to Fillup				
	Time to wate	r breaktbrough [days]	336.93	Water inje	ction rate bre	akthrough [bbl/d]	237 79	
	Time to wate	i breaktinough [days]				akanoogn [bond]	207.70	1
	Areal sweep effici	ency at breakthrough	0./135		Dil rate at bre	akthrough [bbl/d]	198.16	
				Cumula	ative oil at bre	eakthrough [bbls]	46930.59	
								-
Winj [bbls]	Areal sweep efficiency	Conductance ratio	Injection rate [bbl/d]	Avg.injection rate [bbl/d]	Delta Time [days]	Cumulative Time [days]	Oil Rate [bbl/d]	Cumu O [bb
46,550.20	0.3229	0.9538	256.63	0.00	0.00	109.14	213.86	
49,514.24	0.3434	0.9503	255.70	256.16	11.57	120.71	213.08	
52,478.28	0.3640	0.9468	254.75	255.22	11.61	132.32	212.29	
55,442.31	0.3845	0.9432	253.79	254.27	11.66	143.98	211.49	
58,406.35	0.4051	0.9396	252.82	253.31	11.70	155.68	210.69	
61,370.39	0.4256	0.9360	251.85	252.34	11.75	167.42	209.88	12
64,334.43	0.4462	0.9324	250.87	251.36	11.79	179.22	209.06	14
67,298.46	0.4668	0.9287	249.89	250.38	11.84	191.05	208.24	1
70,262.50	0.4873	0.9251	248.90	249.40	11.88	202.94	207.42	1
73,226.54	0.5079	0.9214	247.91	248.41	11.93	214.87	206.59	2
76,190.57	0.5284	0.9177	246.92	247.41	11.98	226.85	205.76	2
79,154.61	0.5490	0.9140	245.92	246.42	12.03	238.88	204.93	2
00 110 05	0 5005	0.0100	244.01	DAE 41	10.00	250.00	204.00	2

Stage 4 : Post Water Breakthrough

The Stage 4 - Post Water Breakthrough calculation output panel is shown below :

Endpoint Mobility	Ratio 1.480000) Breakthro	ough Swbar Mobi	ility Ratio 0.810407	Breakt	nrough Swbar (fr	action] 0.5646	02
art to Interference	Interference to	Fillup Fillup to Wa	ater Breakthroug	h Post Water Brea	kthrough Combi	ined		
Winj / WiBT ratio	Winj [bbls]	Areal sweep efficiency	Qi / QiBT ratio	Pore volumes injected [Qi]	dfw / dSw	Sw2 [fraction]	fw2 [fraction]	Swept S
1.00	102,866.91	0.7135	1.0000	0.4646	2.1524	0.4676	0.7899	
1.20	123,440.29	0.7636	1.1935	0.5545	1.8034	0.4893	0.8348	
1.40	144,013.67	0.8059	1.3776	0.6400	1.5624	0.5060	0.8653	
1.60	164,587.06	0.8427	1.5553	0.7226	1.3839	0.5221	0.8872	
1.80	185,160.44	0.8750	1.7283	0.8030	1.2454	0.5320	0.9006	
2.00	205,733.82	0.9040	1.8978	0.8817	1.1341	0.5405	0.9121	
2.20	226,307.20	0.9302	2.0645	0.9592	1.0426	0.5488	0.9233	
2.40	246,880.58	0.9541	2.2289	1.0355	0.9657	0.5570	0.9307	
2.60	267,453.96	0.9761	2.3913	1.1110	0.9001	0.5650	0.9375	
2.80	288,027.35	0.9965	2.5520	1.1857	0.8434	0.5730	0.9441	
3.00	308,600.73	1.0000	2.7075	1.2579	0.7950	0.5779	0.9482	
3.20	329,174.11	1.0000	2.8602	1.3289	0.7525	0.5818	0.9514	
3.40	349,747.49	1.0000	3.0109	1.3989	0.7149	0.5857	0.9546	
3.60	370,320.87	1.0000	3.1598	1.4681	0.6812	0.5894	0.9577	
3.80	390,894.26	1.0000	3.3071	1.5365	0.6508	0.5932	0.9608	
4.00	411,467.64	1.0000	3.4528	1.6042	0.6234	0.5969	0.9639	
4.20	432,041.02	1.0000	3.5970	1.6712	0.5984	0.6005	0.9668	
4.40	452,614.40	1.0000	3.7399	1.7376	0.5755	0.6042	0.9685	
4.60	473,187.78	1.0000	3.8815	1.8034	0.5545	0.6078	0.9702	
4 80	493.761.17	1.0000	4.0220	1.8686	0.5352	0.6113	0.9718	

Stage 5 : Combined Base Layer Profile Prediction

The combined base layer performance output panel and charts are shown below :

ndpoint Mobility	Ratio 1.48000	0 Brea	kthrough Swbar M	lobility Ratio 0.81040)7 Breakthroug	h Swbar [fraction] 0.564	602
rt to Interference	Interference t	o Fillup Fillup	to Water Breakthr	ough (Post Water Bre	akthrough Combined		
sults Table Cha	art Rates v's Tir	me Chart WOF	R v's Recovery Fac	ctor	2		
Cumulative Time [days]	Injection rate [bbl/d]	Oil Rate [bbl/d]	Water Rate [bbl/d]	Cumulative oil production [bbl]	Cumulative water production [bbl]	Cumulative water injection [bbl]	Recove Facto [fractio
3.30	553.94	0.00	0.00	0.00	0.00	1,828.02	0.0
6.71	517.26	0.00	0.00	0.00	0.00	3,656.04	0.0
10.31	497.97	0.00	0.00	0.00	0.00	5,484.07	0.0
14.03	485.14	0.00	0.00	0.00	0.00	7,312.09	0.0
17.84	475.63	0.00	0.00	0.00	0.00	9,140.11	0.0
21.71	468.13	0.00	0.00	0.00	0.00	10,968.13	0.0
25.64	461.97	0.00	0.00	0.00	0.00	12,796.15	0.0
29.62	456.77	0.00	0.00	0.00	0.00	14,624.18	0.0
33.64	452.27	0.00	0.00	0.00	0.00	16,452.20	0.0
37.70	448.33	0.00	0.00	0.00	0.00	18,280.22	0.0
41.80	444.82	0.00	0.00	0.00	0.00	20,108.24	0.0
45.92	441.66	0.00	0.00	0.00	0.00	21,936.27	0.0
50.07	438.80	0.00	0.00	0.00	0.00	23,764.29	0.0
54.25	436.18	0.00	0.00	0.00	0.00	25,592.31	0.0
58.46	433.76	0.00	0.00	0.00	0.00	27,420.33	0.0
62.68	431.53	0.00	0.00	0.00	0.00	29,248.35	0.0
66.93	429.46	0.00	0.00	0.00	0.00	31,076.38	0.0
71.19	427.52	0.00	0.00	0.00	0.00	32,904.40	0.0
75.40	405 70	0.00	0.00	0.00	0.00	24 722 42	0.0





To switch between a Linear Y Axis and a Logarithmic Y Axis on the above WOR vs Er plot, select the chart's context menu by a single right mouse click within the chart area.

Stage 6 : Combined All Layers Profile Prediction

The combined all layers performance output panel and charts are shown below.

Base Layer Ou	tput Composite	e Layers Results					
	STO	OIP [mmstb] 1.9390	6				
Results Table	Chart Rates v's	Time Chart WOR v	's Recovery Fa	ctor			
Date	WI Rate (bbl/d)	WI Cumulative (bbl)	Oil Rate (bbl/d)	Oil Cumulative (bbl)	Water Rate (bbl/d)	Water Cumulative (bbl)	Recovery Fac (fraction)
Jun 2007	1888.8	60,531.3	0.0	0.0	0.0	0.0	0.00
Jul 2007	1781.7	117,074.8	0.0	0.0	0.0	0.0	0.00
Aug 2007	1660.1	170,383.9	89.0	0.0	0.0	0.0	0.00
Sep 2007	1533.3	218,241.6	213.0	2,745.2	0.0	0.0	0.00
Oct 2007	1440.1	263,798.7	304.7	9,314.8	0.0	0.0	0.00
Nov 2007	1352.6	305,422.9	396.3	17,735.8	0.0	0.0	0.00
Dec 2007	1274.0	346,269.7	479.4	28,462.6	0.0	0.0	0.0*
Jan 2008	1222.9	384,786.8	529.1	42,359.2	0.0	0.0	0.02
Feb 2008	1178.2	419,695.4	572.9	56,376.3	0.0	0.0	0.02
Mar 2008	1149.0	456,113.1	596.0	72,898.8	0.0	0.0	0.03
Apr 2008	1121.2	489,771.1	618.9	90,220.8	0.0	0.0	0.04
May 2008	1097.8	523,722.0	605.1	106,218.8	51.7	3,254.4	0.05
Jun 2008	1075.7	556,474.6	589.2	121,471.0	105.0	6,612.4	0.0€
Jul 2008	1049.9	589,618.7	584.0	137,518.5	151.8	10,223.5	0.07
Aug 2008	1035.6	622,083.7	596.3	154,991.0	158.0	14,531.4	0.07
Sep 2008	1028.1	653,016.4	600.0	172,816.1	164.0	18,700.3	0.08
Oct 2008	1020.1	684,927.1	604.6	191,045.6	171.0	23,278.4	0.05
Nov 2008	1012.8	715,573.2	596.6	207,052.9	199.4	29,982.4	0.10
Dec 2008	1011.4	746,717.1	580.2	224,725.1	228.7	36,909.9	0.11
Jan 2009	1009.6	778,026.3	564.0	242,037.8	257.2	44,440.3	0.12
Feb 2009	1007.9	806,277.5	549.5	257,600.8	282.9	51,307.9	0.13
•			III				•





The user can choose to display the Y axis of the WOR versus recovery factor as a logarithmic scale, in line with common industry practice. To switch between a Linear Y Axis and a Logarithmic Y Axis on the above plot, select the chart's context menu by a single right mouse click within the chart area.

References:

Craig, Jr., F., "The Reservoir Engineering Aspects of Waterflooding", Society of Petroleum Engineers, 1971
Waterdrive

Petroleum Reservoir Waterdrive Analysis Software



4 Dykstra-Parsons

4.1 Heterogeneity Coefficients

Dykstra and Parsons introduced the concept of the permeability variation V, which is designed to describe the degree of heterogeneity within the reservoir. Values for this coefficient range between zero for a completely homogeneous system and one for a completely heterogeneous system.

To obtain the value of permeability variation V, the permeability dataset is sorted from minimum to maximum and displayed on a chart of log probability scale, as shown below.



The equation for permeability variation V is included below.

$$V = \frac{stdev(Log(k))}{avg(Log(k))} = \frac{Log(k)_{P50} - Log(k)_{P84.1}}{Log(k)_{P50}}$$

Both of the above equations have been implemented into this routine. The significance of the Log(k) at a probability value of 84.1% is that it is the equivalent of one standard deviation away from the 50% probability value assuming a log normal distribution (which permeability distributions often displays this characteristic).

In 1950, Schmalz and Rahme proposed a single term for characterizing the permeability distribution within a pay section. Referring to the chart below, they defined the Lorenz coefficient of heterogeneity as the (area between the green curve and the red curve) / (area between the red curve and the X axis).

The value of the Lorenz coefficient ranges from 0 to 1, a uniform permeability reservoir having a Lorenz coefficient of zero.

This calculation and display has also been included within this routine.



The following example is taken from data presented in Craig's SPE Monograph "*The Reservoir Engineering Aspects of Waterflooding*", to better explain the various aspects of this routine.

Once the routine is launched the following input screen is displayed.

< н	eterogeneity (Coefficients		1		
•	Recent Files	· 🗁 🛃 🗎	🖵 🛃 🔟	Metric Units 💽 🥑)	
Inp	ut Data Statist	tics		1	Input Data Lorenz Dykstra / Parsons	
	Depth [m]	Thickness [m]	Porosity [fraction]	Permeability [mD]		
				Import CSV		
				13	Calculate	Close

The user can input data either by using the Import CSV button to load a comma delimited ASCII file, or

simply copy and paste or drag and drop data from an external application, such as Microsoft Excel.

Once the data has been input, the user should press the calculate button to display the charts of porosity and permeability versus depth, together with the Lorenz and Dykstra-Parsons charts and calculated coefficients. At this point the following should be displayed.



Selecting the Lorenz TAB display the Lorenz chart and calculated coefficient. Likewise, selecting the Dykstra-Parsons TAB display the Dykstra-Parsons chart and calculated coefficients. Both examples are provided below. The first coefficient in the Dykstra-Parsons TAB is calculated from the Average and Standard Deviation, whereas the second coefficient is calculated from interpolated values of P50 and P84.1.



Exporting Charts to Clipboard or File

The user can quickly copy and paste the chart to the Windows clipboard or save the chart as a graphic image file by selecting the context menu (right-muse click) while the mouse is within the chart area. The following should be displayed.



Also the user can also choose to display the permeability versus depth chart as a logarithmic scale for permeability, is required. This is also shown below.



References:

Dykstra, H., Parsons, R., "*The Prediction of Oil Recovery by Water Flood*", Secondary Recovery of Oil in the United States, 2nd ed. American Petroleum Institute, 1950

Schmalz, J. P. and Rahme, H. D., "*The Variation of Waterflood Performance With Variation in Permeability Profile*", Prod. Monthly, 1950.

Craig, Jr., F., "The Reservoir Engineering Aspects of Waterflooding", Society of Petroleum Engineers, 1971

4.2 Dykstra-Parsons and Lorenz Coefficient

A simple routine has been included to convert between Dykstra-Parsons and Lorenz coefficients. The input screen is included for completeness below.

Convert between Dykstra-Parsons and Lorenz Coefficient	- • 🔀
Dykstra-Parsons Permeability Variation, V 0.6 Lorenz Coefficient, L 0.510513	Input one to calculate other

Simply enter a number into a blank cell, then TAB out of the cell or mouse click the other blank cell, to calculate the required coefficient.

References:

Warren, J. E. and Price, H. S., "Flow in Heterogeneous Porous Media," SPE Paper 1579-G, 1961

4.3 Vertical Sweep

Dykstra and Parsons correlated vertical sweep efficiency with the following parameters:

- Permeability variation, V
- Mobility ratio, M
- Water-oil ratio

The authors presented their correlation in a graphical form for water-oil ratios of 0.1, 0.2, 0.5, 1, 2, 5, 10, 25, 50, and 100 bbl/bbl.

Using a regression analysis model, de Souza and Brigham grouped the vertical sweep efficiency curves for 0 = M = 10 and 0.3 = V

= 0.8 into one curve and developed a regression equation that has been implemented into this routine.

Simply enter the required input data, then press the *Calculate* button, as shown below.

Oykstra–Parsons Vertical Sweep Efficiency	
Mobility Ratio	Watercut or WOR
Oil viscosity, cP 5	Watercut, fraction 0.95
Water viscosity, cP 0.5	Water Oil Ratio 19.00
Endpoint kro, fraction	Dykstra-Parsons Permeability Variation 0.6
Endpoint krw, fraction 0.35	bykata raisonar erindability variation
or, Input Mobility Ratio 3.500000	
	Vertical Sweep Efficiency, fraction 0.820211
	Calculate

References:

Dykstra, H., Parsons, R., "*The Prediction of Oil Recovery by Water Flood*", Secondary Recovery of Oil in the United States, 2nd ed. American Petroleum Institute, 1950

de Souza, A., Brigham, W., "A Study on Dykstra-Parsons Curves", Stanford University Petroleum Research Institute, 1981

4.4 Recovery Performance

When predicting reservoir performance to include the effects of reservoir vertical heterogeneity, the reservoir is represented by a series of layers with no vertical communication (no cross-flow between layers).

Two Dykstra–Parsons methods are discussed in more detail in this section. Both of these methods use the Dykstra–Parsons heterogeneity index to describe the vertical permeability variation, as opposed to describing each layer's value of thickness, permeability, and porosity, as presented in the Dake-Welge and Craig-Geffen-Morse methods implemented in previous sections.

References:

Ahmed, T., "Reservoir Engineering Handbook", Elsevier, 2006

4.4.1 Simplified Method

Dykstra and Parsons presented a correlation for predicting waterflood oil recovery that uses the mobility ratio, permeability variation, and producing water–oil ratio as correlating parameters.

Johnson developed a simplified graphical approach for the Dykstra and Parsons method that is based on predicting the overall oil recovery at water-oil ratios (WOR) of 1, 5, 25, and 100 bbl/bbl.

The technique of calculating the simplified Dykstra and Parsons method is presented below :

- 1. Calculate the permeability variation and mobility ratio.
- 2. The overall oil recovery factor is calculated from four WOR values of 1, 5, 25, 100 bbl/bbl. The original curves of Johnson have been digitised and input into this routine to permit interpolation between permeability variation and mobility ratio. The oil recovery factor at water breakthrough is calculated by extrapolating back to a WOR of zero.
- 3. Calculate the cumulative oil production at each of the four WOR values, and the cumulative oil production at water breakthrough for a WOR = 0, from the following :

$$N_p = N_S R$$

- 4. For a constant injection rate, adding the fill-up volume Wif to the cumulative oil produced at breakthrough and dividing by the injection rate will estimate the time to breakthrough.
- 5. The equation to link water injection to oil and water production and fillup volume is presented below. This equation is used together with the relationship of WOR vs overall oil recovery factor to derive the oil and water production rates versus time.

$$W_{inj} = N_p B_o + W_p B_w + W_{if}$$

References:

Dykstra, H., Parsons, R., "*The Prediction of Oil Recovery by Water Flood*", Secondary Recovery of Oil in the United States, 2nd ed. American Petroleum Institute, 1950

Johnson, C., "Prediction of Oil Recovery by Waterflood - A Simplified Graphical Treatment of the Dykstra-Parsons Method" AIME, 1956

Ahmed, T., "Reservoir Engineering Handbook", Elsevier, 2006

4.4.2 Extended Method

This technique of calculating the extended Dykstra and Parsons method is presented below :

1. From the relative permeability data and oil and water viscosities, calculate the fractional flow relationship from the following

$$f_{w2} = \frac{1}{1 + \frac{\mu_w}{\mu_o} \cdot \frac{k_{ro}}{k_{rw}}}$$

2. Calculate the slope of dfw/dSw and determine the average water saturation at breakthrough.

3. Calculate the displacement efficiency at breakthrough, from :

$$E_{D} = \frac{\overline{S}_{w} - S_{wi} - S_{gi}}{1 - S_{wi} - S_{gi}}$$

4. Calculate the areal sweep efficiency at breakthrough, from :

$$E_A = \frac{1}{1+A}$$

where.

$$A = (a_1.ln(M + a_2) + a_3).f_w + a_4.ln(M + a_5) + a_6$$

Where coefficients a_1 to a_6 in the above equation depend on the waterdrive mechanism; i.e., Five Spot, Direct Line Drive or Staggered Line Drive.

- 5. Calculate the vertical sweep efficiency at assumed reservoir water-oil ratios (WOR) of 1, 2, 5, 10, 15, 20, 25, 50, and 100 bbl/bbl, using the technique of de Souza and Brigham. The vertical sweep efficiency at water breakthrough is calculated by extrapolating back to a WOR of zero.
- 6. Calculate the fractional flow values, and surface WOR from the above assumed reservoir WOR, from the following :

$$f_{w2} = \frac{WOR_s}{WOR_r - 1}$$
 $WOR_s = WOR_r \left(\frac{B_o}{B_w}\right)$

7. Calculate cumulative water injected at breakthrough using the following equation :

$$W_{iBT} = PV.(\overline{S}_{wBT} - S_{wi})E_{ABT}.E_{VBT}$$

8. Calculate cumulative oil produced at breakthrough, from the following :

$$N_{pBT} = \frac{W_{iBT} - W_{if} \cdot E_{VBT}}{B_o}$$

9. Calculate the time to breakthrough, from the following :

$$t_{BT} = \frac{W_{iBT}}{q_{wi}}$$

10. Interpolate values of Sw, and calculate values of Swbar, from calculated values of fractional flow fw2, calculated previously in step 5 above.

$$\overline{S}_{w2} = S_{w2} + \frac{1 \text{-} f_{w2}}{\left(\frac{df_w}{dS_w}\right)_{S_{w2}}}$$

- 11.Calculate the areal sweep efficiency for each value of fw2, calculated previously in step 5 above, using equations listed in step 4 above.
- 12. Calculate the displacement efficiency, for each value of Swbar calculated in step 10 above, using equations listed in step 3 above.
- 13. Calculate cumulative oil production for each assumed WOR from the following :

$$N_{p} = N_{S}.E_{D}.E_{A}.E_{V} - \frac{PV.S_{gi}.(1 - E_{A}.E_{V})}{B_{o}}$$

14. The equation to link water injection to oil and water production and fillup volume is presented below. This equation is used together with the relationship of WOR vs overall oil recovery factor to derive the oil and water production rates versus time.

$$W_{inj} = N_{pWOR} .B_o + W_{pWOR} .B_w + PV.S_{gi}.E_{vWOR}$$

References:

Dykstra, H., Parsons, R., "*The Prediction of Oil Recovery by Water Flood*", Secondary Recovery of Oil in the United States, 2nd ed. American Petroleum Institute, 1950

Buckley, S., and Leverett, M., "Mechanism of Fluid Displacement in Sands" AIME, 1942

Felsenthal, M., Cobb, T., and Heur, G, "A Comparison of Waterflooding Evaluation Methods" SPE Paper 332, 1962.

de Souza, A., Brigham, W., "A Study on Dykstra–Parsons Curves", Stanford University Petroleum Research Institute, 1981

Ahmed, T., "Reservoir Engineering Handbook", Elsevier, 2006

4.4.3 Example

In Chapter 14 Principles of Waterflooding of Ahmed's "*Reservoir Engineering Handbook*", he provides the following example.

General Input Data	
Oil viscosity, cP	2
Water viscosity, cP	0.5
Endpoint kro, fraction	0.4
Endpoint krw, fraction	0.3
Mobility Ratio	3
Dykstra-Parsons Permeability Variation	0.8
Porosity [fraction]	0.15
Residual Oil Saturation, Sor [fraction]	0.35
Initial Water Saturation, Swc [fraction]	0.25
Initial Gas Saturation, Sg [fraction]	0
Corey Oil Exponent	2
Corey Water Exponent	2
Oil FVF, Bo [rb/stb]	1.3
Water FVF, Bw [rb/stb]	1.05
STOOIP [mmstb]	0.716123
Injection Rate [mstb/d]	0.8
Method	Five Spot

Once the user has successfully input all the required data, as shown in the following two screen captures, they can press the *calculate* button to calculate all stages of the performance prediction.

Dykstra-Parsons Recovery Performance Methods [ExtendedFullCase.dpr]	×
🥐 Recent Files 👻 📴 🛃 📄 🖵 🖉 Oilfield Units 🔽 🮯	
Mobility Ratio Oil viscosity, cP 9.23 Water viscosity, cP 0.346 Endpoint kro, fraction 0.8 Endpoint krw, fraction 0.3 Mobility Ratio 10.003613	
Dykstra-Parsons Permeability Variation 0.15 Porosity [fraction] 0.35 Residual Oil Saturation, Sor [fraction] 0.2 Initial Water Saturation, Swc [fraction] 0.2 Initial Gas Saturation, Sg [fraction] 0 Oil FVF, Bo [rb/stb] 1.35 Water FVF, Bw [rb/stb] 1.01 STOOIP [mmstb] 12 Injection Rate [mstb/d] 5 Method Five Spot	
Prediction Setup Start Date Jan 2007 End Date Dec 2020 Reporting Frequency Monthly Calculate Close	

With regards to inputting relative permeability data, the user can choose between using Corey Exponents for Oil and Water curvature or inputting the table values directly. The example below assumes Corey Exponents are input.

Simple Method Results

The simple method results are in the form of a WOR √s oil recovery factory chart and table, together with a oil and water production profile and table.





Extended Method Results

The Extended method results are also in the form of a WOR vs oil recovery factory chart and table, together with a oil and water production profile and table.





Note that all data within the tables can be output to

The user can also choose to display the Y axis of either the Simple or Extended WOR versus recovery

factor charts as a logarithmic scale, in line with common industry practice. Simply press the right mouse button within a chart area, to display the chart's context menu list, and toggle between linear and logarithmic scales.



Waterdrive

Petroleum Reservoir Waterdrive Analysis Software



5 Log (Water Oil Ratio)

5.1 Log (WOR) Decline Forecasts

In terms of Waterdrive decline analysis, the Log(Water Oil Ratio) vs Cumulative Oil Production (or Np) to predict oil recoveries for water oil ratios (WOR) greater than 1 or watercut greater than 50% is commonplace.

Therefore we have developed a simple routine to permit low, mid and high trend decline analysis of Log (WOR) vs Np relationships. The user can also convert to an oil production rate vs time series, by either assuming a starting oil rate or by a constant liquid production rate, which for steady state waterdrive fields is also a commonplace assumption.

The following series of screen captures describe how to use this workflow :

The user can copy and paste (via CTRL+C and CTRL+V) production data into the Input Data Table - just select the top left data cell as highlighted below, or choose to import data via the Import CSV button also shown below. The user can also choose to optionally input the Stock Tank Oil Originally in Place (STOOIP) and the application will automatically calculate recovery efficiencies versus time.

The historical data frequency used can be defined by the User, but <u>we advise to input monthly</u> <u>production figures</u>, as all of the prediction calculations are done with a monthly prediction frequency.

Month Producing Days Di I Volume [bbis] Water Volume [bbis] 01-Jul-1989 31 521280.6000 0.0000 01-Jug-1989 31 1155853.3000 0.0000 01-Sep-1989 30 1333754.3000 0.0000 01-Oct-1989 31 1218097.3000 0.0000 01-Nov-1989 30 132229.1000 0.0000 01-Jun-1990 31 1236752.8000 0.0000 01-Mar-1990 28 76184.7000 0.0000 01-Mar-1990 30 132275.2000 0.0000 01-Jun-1990 30 1324275.6000 0.0000 01-Jun-1990 30 1087816.4000 0.0000 01-Jun-1990 30 1324275.6000 0.0000 01-Jul-1990 31 128069.6000 0.0000 01-Jul-1990 30 147702.900 0.0000 01-Nov-1990 31 127059.300 31.4000 01-Nov-1991 31 14700.9700 257.9000 01-Mar-1991 31 141000	ST	OOIP [mmstb]	43		
Month Producing Days Volume (bbls) Water Volume (bbls) 01-Jul-1989 31 521280 600 0.0000 01-Aug-1989 31 1155853.300 0.0000 01-Sep-1989 30 1333754.300 0.0000 01-Oct-1989 31 1218097.3000 0.0000 01-Nov-1989 30 122209.1000 0.0000 01-Nov-1990 31 12816.000 0.0000 01-Jan-1990 31 128752.8000 0.0000 01-Mar-1990 31 1324756.000 0.0000 01-Jul-1990 31 1324756.000 0.0000 01-Jul-1990 31 1280752.8000 0.0000 01-Jul-1990 31 12816.4000 0.0000 01-Jul-1990 31 12816.5000 0.0000 01-Jul-1990 31 12816.25000 0.0000 01-Jul-1990 31 1270359.300 31.4000 01-Sep-1990 31 1270359.300 31.4000 01-Mar-1991 31 141093.7000					
01-Jul-1989 31 521280.6000 0.0000 01-Aug-1989 31 1155853.3000 0.0000 01-Sep-1989 30 1333754.3000 0.0000 01-Oct-1989 31 1218097.3000 0.0000 01-Nov-1989 30 1122209.1000 0.0000 01-Nov-1990 31 1438724.9000 0.0000 01-Jan-1990 31 1438724.9000 0.0000 01-Agr-1990 31 1236752.8000 0.0000 01-Agr-1990 31 302311.5000 0.0000 01-Jur-1990 31 326752.8000 0.0000 01-Jur-1990 31 326125.0000 0.0000 01-Jur-1990 31 226125.0000 0.0000 01-Jur-1990 31 226125.0000 0.0000 01-Sep-1990 31 1321225 0.0000 01-Sep-1990 31 1321225 0.0000 01-Sep-1990 31 1321225 0.0000 01-Jul-1991 31 1270359.3000 31.4000 01-Feb-1991 28 1145091.4000 195.0000	Month	Producing Days	Oil Volume [bbls]	Water Volume [bbls]	
01-Aug-1989 31 1155853.3000 0.0000 01-Sep-1989 30 1333754.3000 0.0000 01-Oct-1989 31 1218097.3000 0.0000 01-Nov-1989 30 1122209.1000 0.0000 01-Jun-1990 31 1438724.9000 0.0000 01-Jan-1990 31 1438724.9000 0.0000 01-Agn-1990 31 1302311.5000 0.0000 01-Agn-1990 31 1324275.6000 0.0000 01-Jun-1990 31 1226125.0000 0.0000 01-Jun-1990 31 1226125.0000 0.0000 01-Jun-1990 31 1221225.0000 0.0000 01-Sep-1990 31 1321225.0000 0.0000 01-Sep-1990 30 1477702.9000 0.0000 01-Jun-1990 30 1477702.9000 0.0000 01-Jun-1991 31 121093.000 31.4000 01-Sep-1990 31 141093.7000 257.9000 01-Agn-1991 31 141093.7000 257.9000 01-Agn-1991 30 134346.3000 188.)1-Jul-1989	31	521280.6000	0.0000	
D1-Sep-1989 30 1333754.3000 0.0000 D1-Oct-1989 31 1218097.3000 0.0000 D1-Nov-1989 30 122209.1000 0.0000 D1-Dec-1989 31 1138116.0000 0.0000 D1-Jan-1990 31 1438724.9000 0.0000 D1-Apr-1990 31 1236752.8000 0.0000 D1-Mar-1990 31 1324375.6000 0.0000 D1-Mar-1990 30 1302311.5000 0.0000 D1-May-1990 30 1324275.6000 0.0000 D1-Jul-1990 30 1087816.4000 0.0000 D1-Jul-1990 31 128089.6000 0.0000 D1-Sep-1990 30 774722.2000 0.0000 D1-Sep-1990 31 1321225.0000 0.0000 D1-Sep-1990 31 137702.9000 0.0000 D1-Jul-1991 31 14702.9000 0.0000 D1-Jul-1991 31 14402.0000 0.0000 D1-Jul-1991 31 144346.3000 188.7000 D1-May-1991 30 324346.3000 188.7000 <td>1-Aug-1989</td> <td>31</td> <td>1155853.3000</td> <td>0.0000</td> <td></td>	1-Aug-1989	31	1155853.3000	0.0000	
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D1-Sep-1990 30 774722.2000 0.0000 D1-Oct.1990 31 1321225.0000 0.0000 D1-Nov-1990 30 1477702.9000 0.0000 D1-Dec-1990 31 1174402.0000 0.0000 D1-Jan-1991 31 1270359.3000 31.4000 D1-Feb-1991 28 1145091.4000 195.0000 D1-Mar-1991 31 1410093.7000 257.9000 D1-Mar-1991 30 1344346.3000 188.7000 D1-May-1991 30 1344346.3000 62.9000 D1-Jun-1991 30 272870.8000 0.0000 D1-Jul-1991 31 98850.3000 0.0000	1-Aug-1990	31	1280869.6000	0.0000	
D1-Oct-1990 31 1321225.0000 0.0000 D1-Nov-1990 30 1477702.9000 0.0000 D1-Dec-1990 31 1174402.0000 0.0000 D1-Jan-1991 31 1270359.3000 31.4000 D1-Feb-1991 28 1145091.4000 195.0000 D1-Mar-1991 31 1410093.7000 257.9000 D1-Mar-1991 30 1344346.3000 188.7000 D1-May-1991 31 1151274.3000 62.9000 D1-Jun-1991 30 272870.8000 0.0000	1-Sep-1990	30	774722.2000	0.0000	
D1-Nov-1990 30 1477702.9000 0.0000 D1-Dec-1990 31 1174402.0000 0.0000 D1-Jan-1991 31 1270359.3000 31.4000 D1-Feb-1991 28 1145091.4000 195.0000 D1-Mar-1991 31 1410093.7000 257.9000 D1-Mar-1991 30 1344346.3000 188.7000 D1-May-1991 30 272870.8000 0.0000 D1-Jul-1991 30 272870.8000 0.0000	1-Oct-1990	31	1321225.0000	0.0000	
D1-Dec-1990 31 1174402.0000 0.0000 D1-Jan-1991 31 1270359.3000 31.4000 D1-Feb-1991 28 1145091.4000 195.0000 D1-Mar-1991 31 1410093.7000 257.9000 D1-Mar-1991 30 1344346.3000 188.7000 D1-May-1991 31 1151274.3000 62.9000 D1-Jun-1991 30 272870.8000 0.0000 D1-Jul-1991 31 988500.3000 0.0000	1-Nov-1990	30	1477702.9000	0.0000	
D1-Jan-1991 31 1270359.3000 31.4000 D1-Feb-1991 28 1145091.4000 195.0000 D1-Mar-1991 31 1410093.7000 257.9000 D1-Mar-1991 30 1344346.3000 188.7000 D1-May-1991 31 1151274.3000 62.9000 D1-Jun-1991 30 272870.8000 0.0000 D1-Jul-1991 31 988500.3000 0.0000	1-Dec-1990	31	1174402.0000	0.0000	
D1-Feb-1991 28 1145091.4000 195.0000 D1-Mar-1991 31 1410093.7000 257.9000 D1-Mar-1991 30 1344346.3000 188.7000 D1-May-1991 31 1151274.3000 62.9000 D1-Jun-1991 30 272870.8000 0.0000 D1-Jul-1991 31 988500.3000 0.0000	1-Jan-1991	31	1270359.3000	31.4000	
01-Mar-1991 31 1410093.7000 257.9000 01-Apr-1991 30 1344346.3000 188.7000 01-May-1991 31 1151274.3000 62.9000 01-Jun-1991 30 272870.8000 0.0000 01-Jul-1991 31 988500.3000 0.0000	1-Feb-1991	28	1145091.4000	195.0000	
D1-Apr-1991 30 1344346.3000 188.7000 D1-May-1991 31 1151274.3000 62.9000 D1-Jun-1991 30 272870.8000 0.0000 D1-Jul-1991 31 988500.3000 0.0000	1-Mar-1991	31	1410093.7000	257.9000	
D1-May-1991 31 1151274.3000 62.9000 D1-Jun-1991 30 272870.8000 0.0000 D1-Jul-1991 31 988500.3000 0.0000	1-Apr-1991	30	1344346.3000	188.7000	
01-Jun-1991 30 272870.8000 0.0000 01-Jul-1991 31 988500.3000 0.0000	1-May-1991	31	1151274.3000	62.9000	
01-Jul-1991 31 988500,3000 0.0000	1-Jun-1991	30	272870.8000	0.0000	
)1-Jul-1991	31	988500.3000	0.0000	

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Once the production data has been successfully input, the user should press the Calculate Button, as shown above, to populate the calculation Table and Chart.

On the Charts Tab the following Log(WOR) vs Cumulative Oil Production chart is displayed. The user can choose to zoom into the display to better digitize points for curve fitting a linear relationship. This functionality is shown below and is enabled by left mouse clicking and dragging a highlighted box. Once happy with the selected area, unrelease the mouse button and the chart area will zoom in.



To select points to be fitted, select the Select Points button as shown below for the Fit Mid Trend. The process can be repeated for the Low and High trend analysis.



Once the Select Points button has been selected and highlighted, the user can select points directly in the chart area, by a series of single right mouse clicks, as shown below.



Once all of the required points have been selected, select the End Selection button, to fit a straight line through the selected points, as shown below.





Once a straight line has been fitted through through the selected points, the User can see the Gradient and Intercept values associated with the straight line in the Prediction Tab, as shown below.

Cog WOR [Test_NorthSea2.wor]	Oilfiald Unite			
Input Data Charts Tables Prediction				
Prediction Setup Prediction Results - Table F	Prediction Results - Chart			
	Log(WOR) Prediction Settings		
	Calculate Low Trend ?	Calculate Mid Trend ?	Calculate High Trend ?	
	Low Trend Values	Mid Trend Values	High Trend Values	
Log(WOR) v's Np Gradient		0.057751		
Log(WOR) v's Np Intercept		-5.013703		
Set Initial Value from	Use decline trend 🔹	Use decline trend	Use decline trend	
Abandonment WOR Value				
Convert to Time Options	Constant Liquid Rate 👻	Constant Liquid Rate 👻	Constant Liquid Rate	
Input Prediction Liquid Rate				
Illtimate Recovery Immath and %1			[]	
Remaining Recovery [mmstb]				Quick Calculate
			Prediction Timeframe	
			Start Date Jan 2009	÷.
			End Date Jan 2012	
			Reporting Frequency Monthly	_
				Calculate
				Close

To convert to time or quickly calculate Ultimate and remaining recovery, the user should input Abandonment assumptions for Water Oil ratio and select how to convert to time, as shown below. The Quick Calculate button only uses the fitted linear relationship and intersects this with the Abandonment WOR value.

Log WOR [Test_NorthSea2.wor]				
🥐 Recent Files 👻 🔂 📓 📮 🛴 📓	Oilfield Units 👻 🙆			
Input Data Charts Tables Prediction				
Prediction Setup Prediction Results - Table	Prediction Results - Chart			
	Log(WOR) Prediction Settings		
	Calculate Low Trend ?	Calculate Mid Trend ?	Calculate High Trend ?	
	Low Trend Values	Mid Trend Values	High Trend Values	
Log(WOR) v's Np Gradient		0.057751		
Log(WOR) v's Np Intercept		-5.013703		
Set Initial Value from	Use decline trend 🔹	Use last value 🔍	Use decline trend 🔹	
Abandonment WOR Value		30		
Convert to Time Options	Constant Liquid Rate	Constant Liquid Rate	Constant Liquid Rate 🕞	
Input Prediction Liquid Rate		17500		
Ultimate Recovery [mmstb and %]		111.2971, 77.83 %		Quick Calculate
Remaining Recovery [mmstb]		1.8952		2
			Deadiation Timeforms	
			Start Date Jan 2009	* v
			End Date Jan 2012	
			Reporting Frequency Monthly	
				Calculate
				Class
				Close

To convert the prediction to time, the user also needs to enter the start date, end date and reporting frequency. All internal calculations are done monthly, however the user can choose to report either monthly, semi annually or annually. This is shown for illustration purposes below :

put Data Charts Tables Prediction				
rediction Setup Prediction Results - Table	Prediction Results - Chart			
	Log(WOR) Prediction Settings		,
	Calculate Low Trend ?	Calculate Mid Trend ?	Calculate High Trend ?	
	Low Trend Values	Mid Trend Values	High Trend Values	
Log(WOR) v's Np Gradient		0.057751		
Log(WOR) v's Np Intercept		-5.013703		
Set Initial Value from	Use decline trend 💌	Use last value 🔽	Use decline trend 💌	
Abandonment WOR Value		30		
Convert to Time Options	Constant Liquid Rate	Constant Liquid Rate 🕞	Constant Liquid Rate 🕞	
Input Prediction Liquid Rate		17500		
Ultimate Recovery [mmstb and %]		111.2971, 77.83 %		
Remaining Recovery (mmstb)		1.8952		Quick Calculate
			Prediction Timeframe	
			Start Date Jan 2009	* v
			End Date Jan 2012	
			Reporting Frequency Monthly	
				Calculate

Once the user enters the prediction input correctly and presses the Calculate button, as shown above, the Prediction tables and Charts are populated. The User can copy the Table data from the application by a single right mouse click, to select the table Context menus. as shown below :

aput Data Charts Tables Prediction									
Prediction Setup Prediction Results - Table Prediction Results - Chart									
Mid Prediction Low Prediction High Prediction									
Date	Oil Rate [bbls/d]	Water Rate [bbls/d]	Liquid Rate [bbls/d]	Watercut [fraction]	Water Oil Ratio	Cumulative Oil [MMbbls]	Cumulative Water [MMbbls]	Cumulative Liquid [MMbbls]	
Jan 2009	717.62	16782.38	17500.00	0.958993	23.3861	109.4242	145.1422	254.5664	
Feb 2009	715.79	16784.21	17500.00	0.959098	23.4485	109.4442	145.6122	255.0564	
Mar 2009	713.77	16786.23	17500.00	0.959213	23.5176	109.4664	146.1325	255.5989	
Apr 2009	711.83	16788 17	17500.00	0 959324	23.5845	109.4877	146.6362	256.1239	
May 2009	709.84	Copy Histo	orical Calculation	ns Table	23.6536	109.5097	147.1567	256.6664	
Jun 2009	707.91	Conv Mid	Prediction Calcu	lations Table	23.7205	109.5310	147.6604	257.1914	
Jul 2009	705.94		Prediction calcu	autoris rable	23.7896	109.5528	148.1811	257.7339	
Aug 2009	703.98	Copy Low	Prediction Calcu	Ilations Table	22.0500	100 F177	18.7017	258.2764	-
Sep 2009	702.09	🛅 Copy High	Prediction Calc	ulations rapic	rediction Calcula	tions Table to Cli	9.2057	258.8014	=
Oct 2009	700.14	16799.86	17500.00	0.959992	23.9948	109.6174	149.7265	259.3439	
Nov 2009	698.27	16801.73	17500.00	0.960099	24.0618	109.6384	150.2305	259.8689	
Dec 2009	696.35	16803.65	17500.00	0.960208	24.1310	109.6600	150.7514	260.4114	
Jan 2010	694.44	16805.56	17500.00	0.960318	24.2001	109.6815	151.2724	260.9539	
Feb 2010	692.72	16807.28	17500.00	0.960416	24.2626	109.7009	151.7430	261.4439	
Mar 2010	690.83	16809.17	17500.00	0.960524	24.3318	109.7223	152.2641	261.9864	
Apr 2010	689.01	16810.99	17500.00	0.960628	24.3988	109.7430	152.7684	262.5114	
May 2010	687.14	16812.86	17500.00	0.960735	24.4680	109.7643	153.2896	263.0539	
Jun 2010	685.33	16814.67	17500.00	0.960838	24.5350	109.7848	153.7941	263.5789	
Jul 2010	683.48	16816.52	17500.00	0.960944	24.6042	109.8060	154.3154	264.1214	
Aug 2010	681.64	16818.36	17500.00	0.961049	24.6734	109.8272	154.8367	264.6639	
Sep 2010	679.86	16820.14	17500.00	0.961151	24.7404	109.8476	155.3413	265.1889	
Oct 2010	678.04	16821.96	17500.00	0.961255	24.8097	109.8686	155.8628	265.7314	
Nov 2010	676.28	16823.72	17500.00	0.961355	24.8768	109.8889	156.3675	266.2564	
Dec 2010	674.48	16825.52	17500.00	0.961458	24.9460	109.9098	156.8891	266.7989	
Jan 2011	672.68	16827.32	17500.00	0.961561	25.0153	109.9306	157.4108	267.3414	
Feb 2011	671.07	16828.93	17500.00	0.961653	25.0778	109.9494	157.8820	267.8314	-
LL 0011	000.00	10000 71	17000.00	0.004700	00.4474	100.0700	100 4007	000.0700	-

Various display elements of the prediction chart can be changed for both historical production, prediction phase (either Oil, Water or Total Liquids) and Y Axis type, see below :





Once happy with the prediction sensitivities, the user can create either Adobe PDF or Microsoft Excel reports, as depicted below :

Log WOR [Test_NorthSea2.wor] Recent Files Image: Control of the second	
Input Data Charts Tables Prediction Prediction Results - Table Prediction Results - Table Prediction Results - Chart	
- 24 months 👻 Oil Production 👻 🖍 🗃 🛃 Set Chart Y Axis Type 💌	
$\begin{bmatrix} 2500 \\ 2000 \\ \hline $	
0 01/01/2008 01/01/2010 (Oil Rate History Mid Oil Rate	01/01/2012
	Close



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11	Low Trend Values					
12	Log(WOR) v/s Np Gradient :	0.149837				
13	Log(WOR) v's Np Intercept :	-14.433366				
14	Set Initial Value from :	Use last value				
15	Abandonment WOR Value :	28				
16	Convert to Time Options :	Constant Liquid Rate				=
17	Input Prediction Liquid Rate :	15000				
18	Ultimate Recovery [mmstb and %] :	109.9324, 76.88 %				
19	Remaining Recovery [mmstb] :	0.5305				
20						
21	Mid Irend Values	0.050704				
22	Log(WOR) VS Np Gradient	0.059704				
23	Set Initial Value from :	-0.2020				
25	Abandonment WOR Value	30				
26	Convert to Time Options	Constant Liquid Rate				
27	Input Prediction Liquid Rate :	17500				
28	Ultimate Recovery [mmstb and %] :	111.2327, 77.79 %				
29	Remaining Recovery [mmstb] :	1.8307				
30						
31						
32						
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Waterdrive

Petroleum Reservoir Waterdrive Analysis Software



6 Water Coning

Production from an oil well creates a pressure gradient that tends to elevate the oil-water contact in the immediate vicinity of the well. Balancing this flowing gradient is the tendency of oil and water to maintain gravity equilibrium, owing to the density difference between the two fluids.

When the dynamic viscous forces at the well exceed gravitational forces, a water cone ultimate breaks through into the well perforations.

Critical rate is defined as the maximum allowable oil flow rate to avoid a water cone breaking through.

The coning problem for both vertical and horizontal wells typically involves the following calculations:

- Determination of the critical flow rate
- Breakthrough time predictions
- Well performance calculations after breakthrough

6.1 Vertical Wells

Several vertical well critical rate correlations are available in the literature, most of which are included within these routines.



In all of vertical well coning calculations the assumption is made that the perforations are always located at the top of the oil zone, thereby maximising the distance between the perforations and the oil-water contact.

It is important to note that these correlations are valid for a continuous oil pay zone with oil-water contact or gas-oil contact or both. These correlations show that the critical rate depends upon effective oil permeability, oil viscosity, density difference between oil and water or oil and gas, well penetration ratio, and vertical permeability. The use of this routine is highlighted with the following example.

References:

Bournazel, C., and Jeanson, B., "Fast Water Coning Evaluation", SPE Paper 3628, 1971

Sobocinski, D. P., and Cornelius, A. J., "A Correlation for Predicting Water Coning Time", JPT, May 1965.

Kuo, C. T., and Desbrisay, C. L., "A Simplified Method for Water Coning Predictions", SPE Paper 12067, 1983

Hoyland, L. A., Papatzacos, P., and Skjaeveland, S. M., "*Critical Rate for Water Coning: Correlation and Analytical Solution*", SPE Paper 15855, 1989

Chierici, G. L., "Principles of Petroleum Reservoir Engineering Volume 2", Springer-Verlag 1994

Joshi, S., "Horizontal Well Technology", Pennwell, 1991

Chaperon, I., "Theoretical Study of Coning Toward Horizontal and Vertical Wells in Anisotrophic Formations: Subcritical and Critical Rates", SPE Paper 15377, 1986.

Schols, R. S., "An Empirical Formula for the Critical Oil Production Rate", Erdoel Erdgas, January 1972

Meyer, H. I., and Garder, A. O., "Mechanics of Two Immiscible Fluids in Porous Media", J. Applied Physics, November 1954

6.1.1 Example

Chierici provides the following example in Chapter 12 of his textbook "Principles of Petroleum Reservoir Engineering Volume 2".

Input Data	
Perforated Interval, m	6
Thickness of Oil Zone, m	30
Total Thickness, m	50
Wellbore Radius, m	0.1052
Drainage Boundary Radius, m	321
Porosity, fraction	0.25
Radial Permeability, mD	500
Vertical Permeability, mD	500
kv/kh ratio	1
Endpoint kro, fraction	0.9
Endpoint krw, fraction	0.4
Oil Density, gm/cc	0.78
Water Density, gm/cc	1.03
Oil FVF, Bo rm³/sm³	1.25
Water FVF, Bo rm ³ /sm ³	1
Oil Viscosity, cP	2
Water Viscosity, cP	0.6
Oil Flow Rate, m ³ /d	100

Once the user has successfully input all the required data, as shown in the following two screen
captures, they can press the <i>calculate</i> button to perform the coning calculations.

put Data Results						Input Data Results				
	Calc	ulate ?					Calc	culate ?		
 Critical Rate 		Production above	ve Critical Rat	e		Oritical Rate		Production abo	ve Critical Rate	
Perforated Interval, ft	19.685	Oil Density	0.78	gm/cc	•	Perforated Interval, ft	19.685	Oil Density	0.78	gm/cc
Thickness of Oil Zone, ft	98.4252	Water Density	1.03	gm/cc	•	Thickness of Oil Zone, ft	98.4252	Water Density	1.03	gm/cc
Total Thickness, ft	164.042	Oil	FVF, Bo rb/st	tb 1.25		Total Thickness, ft	164.042	Oi	il FVF, Borb/stb	1.25
Wellbore Radius, ft	0.345	Water	FVF, Borb/st	b 1		Wellbore Radius, ft	0.345	Water	r FVF, Borb/stb	1
Drainage Boundary Radius, ft	1053.1496	C)il Viscosity, c	₽ 2		Drainage Boundary Radius, ft	1053.1496	(Dil Viscosity, cP	2
Porosity, fraction	0.25	Wate	er Viscosity, c	P 0.6		Porosity, fraction	0.25	Wat	er Viscosity, cP	0.6
Radial Permeability, mD	500	Oil F	low Rate, bbl/	/d 628.98		Radial Permeability, mD	500	Oil	Flow Rate, bbl/d	628.98
Vertical Permeability, mD	500	Criti	cal Flow Rate	, bbl/d		Vertical Permeability, mD	500	Crit	ical Flow Rate, b	b/ld
Endpoint kro, fraction	0.9	Meyer	and Garder			Endpoint kro, fraction	0.9	Meyer	and Garder 80	0.10
Endpoint krw, fraction	0.4		Chierici			Endpoint krw, fraction	0.4		Chierici 18	32.37
		н	oyland et al		_			H	loyland et al	56.11
			Chaperon		_				Chaperon 1	38.30
			Schols [Schols 12	20.90
Re	esults for Producti	on above Critical Ra	ite			Re	sults for Product	ion above Critical R	ate	
		Critical Flo bbl/d	w Rate Brea	akthrough T days	ime			Critical Flo bbl/o	ow Rate Break	through Tim days
So	obocinski and Cor	nelius				So	bocinski and Co	melius 340.23	345.0	5
	Bournazel and Je	anson					Bournazel and Je	anson 276.93	143.10	6

Recent Fil	les 🕶 🗁 🚂 📄 🖵 🖻	→ Oilfield Units	۵
put Data	lesults		
able Chart	Match		
t/t(bt)	Sobocinski and Cornelius Time (days)	Bournazel and Jeanson Time (days)	Kuo and DesBrisay fw (fraction)
0.5600	193.2	80.2	0.0000
0.5914	204.1	84.7	0.0141
0.6229	214.9	89.2	0.0258
0.6543	225.8	93.7	0.0369
0.6857	236.6	98.2	0.0475
0.7171	247.4	102.7	0.0576
0.7486	258.3	107.2	0.0673
0.7800	269.1	111.7	0.0766
0.8114	280.0	116.2	0.0855
0.8429	290.8	120.7	0.0940
0.8743	301.7	125.2	0.1023
0.9057	312.5	129.7	0.1103
0.9371	323.4	134.2	0.1180
0.9686	334.2	138.7	0.1254
1.0000	345.0	143.2	0.1326
1.1880	409.9	170.1	0.1715
1.3760	474.8	197.0	0.2046
1.5640	539.7	223.9	0.2335
1.7520	604.5	250.8	0.2591
1.9400	669.4	277.7	0.2821
2.1280	734.3	304.6	0.3029
2.3160	799.1	331.5	0.3220
2.5040	864.0	358.5	0.3396
2.6920	928.9	385.4	0.3560
2.8800	993.7	412.3	0.3712
3.0680	1058.6	439.2	0.3854
3.2560	1123.5	466.1	0.3989


🔍 Ve 🌔 F	Vertical Well Water Coning Calculations [Chierici Example.cng] Image: Chierici Example.cng Image: Chierici Example.cng <td< th=""></td<>								
Inpu Tab	Input Data Results Table Chart Match								
	Produ	uction History			Breakthrough Time				
	Time (Days)	fw (fraction)	Â	Sobocinski and Cornelius	60.67				
	0.078333333	0		Bournazel and Jeanson	31.32				
	0.887083333	0		Dournazor and obligon	47.0				
	1.887083333	0		Actual	17.8				
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	10.425	0							
	10.50833333	0							
	11.43125	0							
	12.43125	0							
	13.43125	0							
	14.43125	0.004926108							
	15.43125	0.005291005	Ŧ						
		Import CS	V						
				Calculate	Close				

With the above input panel, and a knowledge of production history (time in days and watercut), the user can iterate the vertical permeability to achieve an acceptable match. See example provided below.



6.2 Horizontal Wells

The use of horizontal well technology in developing hydrocarbon reservoirs have been widely applied during the 1990's, and subsequent years.

The advantages of using a horizontal well over a conventional vertical well are their larger capacity to produce oil for the same drawdown, together with a longer breakthrough time at a given production rate.

Several horizontal well critical rate correlations are available in the literature, most of which are included within these routines. The method of Kuo and Desbrisay has been used within this routine, for horizontal wells, to predict the performance after water breakthrough.

The list of routines available are :

- · critical rate calculations for gas and water coning,
- · breakthrough time calculation for both gas and water, and
- production performance above critical rate for water.

Accessing these routines is via a dropdown list box located towards the top of the application, as shown below.

Horizontal Well Coning Calculations					
🌾 Recent Files 👻 🗁 🛃 📄 🖵 📈 📧 🕅	etric Units 🔄 🧿				
Input Data Results					
Calculate Critical Rate - Water Coning	Gas Density				
This Critical Rate - Water Coning	Oil Density				
Thickr Water Breakthough Time	Water Density				
Gas Breakthough Time Heig Gas & Water Breakthough Time	Oil FVF, B				
Heigh Production above Critical Water Rate	Water FVF,				
Well Length [L], m	Oil Vis				
Well Radius, m	Water Viso				
Major Length [ve] m	Swe				

References:

Chaperon, I., "Theoretical Study of Coning Toward Horizontal and Vertical Wells in Anisotrophic Formations: Subcritical and Critical Rates," *SPE Paper 15377*, 1986.

Efros, D. A., "Study of Multiphase Flows in Porous Media", Gastoptexizdat, Leningrad, 1963.

Karcher, B., Giger, F., and Combe, J., "Some Practical Formulas to Predict Horizontal Well Behavior," *SPE Paper 15430*, 1986

Joshi, S., "Horizontal Well Technology", Pennwell, 1991.

Ozkan, E., and Raghavan, R., "Performance of Horizontal Wells Subject to Bottom Water Drive," SPE Paper 18545, 1988.

Papatzacos, P., Herring, T. U., Martinsen, R., and Skjaeveland, S. M., "Cone Breakthrough Time for Horizontal Wells," *SPE Paper 19822*, 1989.

Kuo, C. T., and Desbrisay, C. L., "A Simplified Method for Water Coning Predictions", SPE Paper 12067, 1983

6.2.1 Example

Joshi provides several examples in Chapter 8 of his textbook "Horizontal Well Technology" that will be used to highlight various aspects of the calculations within these routines.

Critical Rate for Gas Coning

From Joshi's Example 8.7, the following data is provided and the Engineer is asked to calculate the critical rate for gas coning.

Input Data				
Thickness of Oil Zone, ft	80			
Height - GOC and Well, ft	72			
Well Length [L], ft	1640			
Well Radius, ft	0.328			

Major Length [xe], ft	2640
Minor Length [ye], ft	2640
Radial Permeability, mD	70
Vertical Permeability, mD	70
Gas Density, gm/cc	0.21
Oil Density, gm/cc	0.69
Water Density, gm/cc	1.01
Oil FVF, Bo rb/stb	1.1
Oil Viscosity, cP	0.42

Once the user has successfully input all the required data, as shown in the following two screen captures, they can press the *calculate* button to perform the coning calculations.

Horizontal Well Coning Calculations [Joshi Examp	ble87.cnh]	×	< Horizontal Well Coning Calculations [Joshi Example87.cnh]			
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Input Data Results			Input Data Results			
Calculate Critical Rate - Water Coning	Gas Density 0.21 gm/cc 💌		Calculate Critical Rate - Water Coning	Gas Density 0.21 gm/cc 🔹		
Thickness of Oil Zone, ft 80	Oil Density 0.69 gm/cc 🔍		Thickness of Oil Zone, ft 80	Oil Density 0.69 gm/cc -		
Thickness of Water Zone, ft	Water Density 1.01 gm/cc 🗸		Thickness of Water Zone, ft	Water Density 1.01 gm/cc -		
Height - GOC and Well, ft 72	Oil FVF, Bo rb/stb 1.1		Height - GOC and Well, ft 72	Oil FVF, Bo rb/stb 1.1		
Height - OWC and Well, ft	Water FVF, Bw rb/stb		Height - OWC and Well, ft 72	Water FVF, Bw rb/stb		
Well Length [L], ft 1640	Oil Viscosity, cP 0.42		Well Length [L], ft 1640	Oil Viscosity, cP 0.42		
Well Radius, ft 0.328	Water Viscosity, cP		Well Radius, ft 0.328	Water Viscosity, cP		
Major Length [xe], ft 2640	Swc, fraction		Major Length [xe], ft 2640	Swc, fraction		
Minor Length [ye], ft 2640	Sor, fraction		Minor Length [ye], ft 2640	Sor, fraction		
Porosity, fraction	Endpoint kro, fraction		Porosity, fraction	Endpoint kro, fraction		
Radial Permeability, mD 70	Endpoint krw, fraction		Radial Permeability, mD 70	Endpoint krw, fraction		
Vertical Permeability, mD 70	Oil Flow Rate, bbl/d		Vertical Permeability, mD 70	Oil Flow Rate, bbl/d		
Show Well Schematic	Breakthrough time, days		Show Well Schematic	Breakthrough time, days		
Critical Flow Rate, bbl/d	Ozkan-Raghavan		Critical Flow Rate, bbl/d	Ozkan-Raghavan		
Joshi	Papatzacos		Joshi 308.773	Papatzacos		
Giger and Karcher	Ontinum wall alreament shows the Ola/C #		Giger and Karcher 76.311	Ontinum well placement shows the OWC #		
Chaperon	Opumum wen pracement above the Ovic, it		Chaperon 751.489	Optimum weir placement above the Ovic, it		
Efros	Papatzacos		Efros 76.297	Papatzacos		
·	Calculate Close		Close			

Water Breakthrough Time

From Joshi's Example 8.8, the following data is provided, and the Engineer is asked to calculate the water breakthrough time for a bottom waterdrive oil reservoir.

Input Data	
Thickness of Oil Zone, ft	160
Well Length [L], ft	2000
Well Radius, ft	0.328
Porosity, fraction	0.2
Radial Permeability, mD	200
Vertical Permeability, mD	20
Oil Density, gm/cc	0.76
Water Density, gm/cc	1.01
Oil FVF, Bo rb/stb	1.1
Oil Viscosity, cP	1.3
Swc, fraction	0.27
Sor, fraction	0.25
Oil Flow Rate, bbl/d	5000

Horizontal Well Coning Calculations [Joshi Example88.cnh]							
Input Data Results							
Calculate Water Breakthough T	me 🔽	Gas Density	0.091906667	psi/ft 👻			
Thickness of Oil Zone, ft	160	Oil Density	0.76	gm/cc 🚽			
Thickness of Water Zone, ft	80	Water Density	1.01	gm/cc 👻			
Height - GOC and Well, ft	72	Oi	I FVF, Bo rb/stb	1.1			
Height - OWC and Well, ft	80	Water	FVF, Bw rb/stb	1			
Well Length [L], ft	2000	C	Dil Viscosity, cP	1.3			
Well Radius, ft	0.328	Water Viscosity, cP		0.4			
Major Length [xe], ft	2640	Swc, fraction		0.27			
Minor Length [ye], ft	2640	Sor, fraction		0.25			
Porosity, fraction	0.2	Endpoint kro, fraction		1			
Radial Permeability, mD	200	Endpoint krw, fraction		0.35			
Vertical Permeability, mD	20	Oil Flow Rate, bbl/d		5000			
Show Well Schem	atic	B	reakthrough time	e, days			
Critical Flow Rate	, bbl/d	Oz	kan-Raghavan	267.791			
Joshi Joshi Giger and Karcher			Papatzacos	1545.224			
		Optimum w	ell placement ab	ove the OWC, ft			
Efros		Papatzacos					
L			Calculate	Close			

Gas and Water Breakthrough Time and Optimal Well Placement

From Joshi's Example 8.11, the following data is provided, and the Engineer is asked to calculate the breakthrough time and optimum well placement for simultaneous gas and oil breakthrough for a bottom water oil reservoir with a gas cap.

Input Data	
Thickness of Oil Zone, ft	92
Well Length [L], ft	1500
Well Radius, ft	0.328
Porosity, fraction	0.31
Radial Permeability, mD	5580
Vertical Permeability, mD	1.8
Gas Density, gm/cc	0.13
Oil Density, gm/cc	0.79
Water Density, gm/cc	1.01
Oil FVF, Bo rb/stb	1.178
Oil Viscosity, cP	1.6
Oil Flow Rate, bbl/d	8000

Horizontal Well Coning Calculations [Joshi Example811.cnh]							
🥐 Recent Files 👻 📴 🔄 📮 👗 📓 Oilfield Units 💽 🥥							
Input Data Results							
Calculate Gas & Water Breakthe	Calculate Gas & Water Breakthough Time Gas Density 299.86544499						
Thickness of Oil Zone, ft	92	Oil Density	790	kg/m ³ 🗸			
Thickness of Water Zone, ft	80	Water Density	1010	kg/m³ 👻			
Height - GOC and Well, ft	72	Oi	I FVF, Bo rb/stb	1.178			
Height - OWC and Well, ft	80	Water	FVF, Bw rb/stb	1			
Well Length [L], ft	1500	c	Dil Viscosity, cP	1.6			
Well Radius, ft	0.328	Wat	Water Viscosity, cP				
Major Length [xe], ft	2640	Swc, fraction		0.27			
Minor Length [ye], ft	Minor Length [ye], ft 2640		Sor, fraction 0.2				
Porosity, fraction 0.31		Endpo	oint kro, fraction	1			
Radial Permeability, mD	Radial Permeability, mD 5580		int krw, fraction	0.35			
Vertical Permeability, mD	1.8	Oil f	Flow Rate, bbl/d	8000			
Show Well Schem	atic	B	reakthrough time	e, days			
Critical Flow Rate	, bbl/d	Oz	kan-Raghavan				
Joshi Joshi Giger and Karcher Chaperon		Papatzacos 1340.661					
		Optimum w	ell placement ab	ove the OWC, ft			
Efros			Papatzacos	47.126			
			Calculate	Close			

Production above Critical Water rate

Extending Joshi's Example 8.8, the Engineer is asked to calculate the post water breakthrough performance for a bottom water oil reservoir, using the technique of Kuo and Desbrisay.

The following screenshots highlight the data input and resultant calculations

Horizontal Well Coning Calculations [Joshi Example88.cnh]								
🥐 Recent Files 👻 📴 📄 🖵 🛃 🔟 Oilfield Units 🔽 🚳								
Input Data Results								
Calculate Production above Crit	ical Water Ra 👻	Gas Density	0.091906667	psi/ft 🖵				
Thickness of Oil Zone, ft	160	Oil Density	0.76	gm/cc 🚽				
Thickness of Water Zone, ft	80	Water Density	1.01	gm/cc 🚽				
Height - GOC and Well, ft	72	Oi	I FVF, Bo rb/stb	1.1				
Height - OWC and Well, ft	80	Water	FVF, Bw rb/stb	1				
Well Length [L], ft	2000	(Dil Viscosity, cP	1.3				
Well Radius, ft	0.328	Wat	er Viscosity, cP	0.4				
Major Length [xe], ft	2640	Swc, fraction		0.27				
Minor Length [ye], ft	2640	Sor, fraction		0.25				
Porosity, fraction	0.2	Endpo	oint kro, fraction	1				
Radial Permeability, mD	200	Endpo	int krw, fraction	0.35				
Vertical Permeability, mD	Vertical Permeability, mD 20		Flow Rate, bbl/d	5000				
Show Well Schem	atic	B	reakthrough time	, days				
Critical Flow Rate	, bbl/d	Oz	kan-Raghavan	135.811				
Joshi	Joshi		Papatzacos	1098.284				
Giger and Karcher		Optimum w	ell placement ab	ove the OWC, ft				
Efros			Papatzacos					
Calculate								



Similar to the vertical well calculations, with the following input panel, and a knowledge of production history (time in days and watercut), the user can iterate vertical permeability to achieve an acceptable match.

 Horizontal Well Coning Calculations [Joshi Example88.cnh] 							
🥐 Recent Files 👻 📴 🖳 📃 🖳 🔟 Oilfield Units 💽 🎯							
Input Data Results Table Chart Match							
Production History	Breakthrough Time days Ozkan-Raghavan 135.811 Papatzacos 1098.284 Actual Calculate Actual Tune Match to kv/kh kh, mD 20 kv/ mD 20 ÷ kv/kh ratio 0.10000						
	Calculate Close						

To toggle on and off individual series within the chart, just toggle the chart context menu item, as shown below.



Waterdrive

Petroleum Reservoir Waterdrive Analysis Software



7 General Utilities

7.1 Mobility Ratio

A simple utility is provided to quickly calculate the waterdrive Mobility Ratio, and an example is included below.

< Mobility Ratio	
Oil viscosity, cP Water viscosity, cP Endpoint kro, fraction	1 0.3 1
Endpoint krw, fraction Mobility Ratio	0.35
Calculate	Close

7.2 Displacement Efficiencies

The overall recovery efficiency of any fluid displacement process is given by the product of the macroscopic efficiency (or volumetric efficiency Ev x Ea - reservoir scale) and the microscopic displacement efficiency, Ed (pore scale).

A simple utility is provided to quickly iterate between initial connate water saturation (Swc), remaining or residual oil saturation (Sor) and vertical and areal sweep efficiencies to calculate ultimate recovery factor from the following.

Ultimate Recovery Factor = Ed * Ev * Ea, where Ed = (1-Sor-Swc) / (1-Swc).

An example is shown below.

< Displacement Efficiencies and Recovery factor 🛛 📼 💌
Microscopic Displacement Efficiency
Swc, fraction D.1500
Sor, fraction 0.2000
Ed, fraction 0.764706
Vertical Sweep Efficiency Ev, fraction 0.8000
Areal Sweep Efficiency Ea, fraction 0.8000
Ultimate Recovery Factor, fraction 0.489412
Close

7.3 Areal Sweep

Dyes et al. correlated the increase in areal sweep efficiency after breakthrough with the ratio of water

volume injected at any time after breakthrough, W_{inj}, to water volume injected at breakthrough, W_{iBT}, as given by the following equation.

$$E_{A} = E_{ABT} + 0.633 .log \left(\frac{W_{inj}}{W_{BT}}\right)$$

Dyes et al. also presented a graphical relationship that relates areal sweep efficiency with reservoir water cut fw and the reciprocal of mobility ratio 1/M.

Fassihi used a nonlinear regression model to reproduce these graphical relationships, by using the following expressions.

$$E_{A} = \frac{1}{1+A} \qquad \text{ where, } \qquad A = (a_{1} \cdot \ln(M + a_{2}) + a_{3}) \cdot f_{w} + a_{4} \cdot \ln(M + a_{5}) + a_{6}$$

Where coefficients a_1 to a_6 in the above equation depend on the waterdrive mechanism; ie., Five Spot, Direct Line Drive or Staggered Line Drive.

An example calculation is shown below.

Mobility Ra	tio	
Oil viscosity, cP	1	Watercut, fraction 0.95
Water viscosity, cP	0.3	Method Five Spot
Endpoint kro, fraction	1	
Endpoint krw, fraction	0.35	Ea, fraction 0.986558
or, Input Mobility Ratio	1.166667	Calculate

References:

Dyes, A., Caudle, B., and Erickson, R., "Oil Production After Breakthrough as Influenced by Mobility Ratio," *JPT*, April 1954

Fassihi, M., "New Correlations for Calculation of Vertical Coverage and Areal Sweep Efficiency," *SPERE*, Nov. 1986

7.4 Convert Recovery Factors

A routine is provided to allow the user to quickly convert between commonly used variables for Recovery factor, namely recovery factor as a fraction, and as a barrel per acre-ft or for gas MMscf per acre-ft. The user can solve between any of the unknowns by simply leaving the required input cell empty.

An example calculation is shown below.

Convert between Recovery Factors		< Convert between Recovery Factors
Oil Gas Porosity, fraction 0.3 Water Saturation, fraction 0.25 Oil FVF, rb/stb 1.35 Recovery Factor, fraction 0.45 Recovery Factor, bbls/ac-tt	Enter known variables to solve for the remaining unknown variable	Oil Gas Porosity, fraction 0.3 Water Saturation, fraction 0.25 Oil FVF, rb/stb 1.35 to solve for the remaining unknown variables Recovery Factor, fraction 0.45 Recovery Factor, bbls/ac-ft
Calculate	Close	Calculate Close

7.5 fw WOR Conversion

A simple utility is provided to quickly convert between Watercut and Water-Oil Ratio.

An example is shown below.

Convert between Watercut and Water Oil Ratio	_ • •
Watercut, fraction 0.96 Water Oil Ratio 24.00	Input one to calculate other Close

7.6 Trapped Gas Saturation and Residual Oil Saturation

Craig published two correlations to account for the reduction in residual oil saturation as a result of the presence of initial gas saturation.

The first correlation linked initial gas saturation, Sgi, to trapped gas saturation, Sgt.

The second correlation linked trapped gas saturation, Sgt, to the reduction in residual oil saturation, Δ Sor. These correlations are included within the first datatab and an example calculation is shown below :

Initial Gas Saturation and Residual Oil Saturation	
Sgi, Sgt and Delta Sor Optimum Gas Saturation	
Initial Gas Saturation, Sgi [fraction]	0.03
Trapped Gas Saturation, Sgt [fraction]	0.031518
Reduction in Residual Oil Saturation, DSor [fraction]	0.030429
	Close

Khelil suggests that waterflood recovery can possibly be improved if a so-called "optimum gas saturation" is present at the start of the flood. This correlation is included within the second datatab and an example calculation is shown below :

Initial Gas Saturation and Residual Oil Saturation	n 🗆 🗖 💌
Sgi, Sgt and Delta Sor Optimum Gas Saturation	
Permeability [mD]	350
Porosity [fraction]	0.23
Initial Water Saturation, Swc [fraction]	0.2
Oil viscosity [cP]	0.6
Water viscosity [cP]	0.4
Oil FVF, Bo [rb/stb]	1.35
Optimum Gas Saturation, Sg [fraction]	0.0032
	Calculate
	Close

References:

Cole, F., "Reservoir Engineering Manual", Gulf Publishing Company, 1969

Craig, Jr., F., "The Reservoir Engineering Aspects of Waterflooding", Society of Petroleum Engineers, 1971

Khelil, C., "A Correlation of Optimum Free Gas Saturation With Rock and Fluid Properties", SPE Paper 1983, 1967

Ahmed, T., "Reservoir Engineering Handbook", Elsevier, 2006

7.7 Recovery Factors

The API Subcommittee on Recovery Efficiency presented a statistical study of recovery efficiency in 1967. From a statistical analysis of data from 312 reservoirs, they developed correlations for water drive recovery from sandstone reservoirs, and for solution gas drive recoveries from sandstone and carbonate reservoirs.

Their correlations have been implemented within this utility and an example calculation is shown below :

< API Recovery Factor Estimates		
🔄 Oilfield Units 🔽 🚳		
Permeability [mD]	350	Oil FVF Bo [rb/stb] 1.3
Porosity [fraction]	0.23	Oil FVF Bob at Pb [rb/stb] 1.35
Sw [fraction]	0.25	Oil Viscosity [cP] 0.6
Initial Pressure [psi]	4500	Oil Viscosity at Pb [cP] 0.5
Bubblepoint Pressure [psi]	3750	Water Viscosity [cP] 0.4
Abandonment Pressure [psi]	2600	
Primary Depletion Est	imate	Waterdrive Estimate
Recovery Factor [bbl/ac-ft]	359.5228	Recovery Factor [bbl/ac-ft] 558.0868
Recovery Factor [%]	36.268%	Recovery Factor [%] 54.213%
		Calculate Close

References:

Arps., J. J., Brons, F., van Everdingen, A. F., Buchwald, R. W. and Smith, A. E.: "A Statistical Study of Recovery Efficiency" Bulletin 140, API, 1967

7.8 Fit Corey Curves

An often used approximation of relative permeability is the Corey correlation which is a power law relationship with respect to water saturation.

These equations are highlighted for completeness below.

$$k_{ro} = k_{roep} \times \left[\frac{1 - S_w - S_{or}}{1 - S_{wc} - S_{or}}\right]^{N_o}$$
$$k_{rw} = k_{rwep} \times \left[\frac{S_w - S_{wc}}{1 - S_{wc} - S_{or}}\right]^{N_w}$$

A simple utility to curve fit Corey type curves for a relative permeability dataset.

Simply type the relative permeability numbers (or more conveniently copy [CTRL+C] and paste [CTRL+V], or drag and drop) into the **Input Relative Permeability** datatab, choose to input user endpoints or use the table values, then press the **Best Fit** button, as shown below.

The bestfit exponents of the Corey Relative Permeability equations will then be calculated.

< Fit C	Fit Corey Relative Permeability Curves [ExampleCoreyFit.cor] Recent Files				
Inp	ut Relative Perm	eabilities Chart	and Corey Outpu	t	
	Sw [fraction]	kro [fraction]	krw [fraction]	-	Input Endpoints
	0.1	1	0		Use Table Values
	0.3	0.373	0.07		Input Values below
	0.4	0.21	0.169		
	0.45	0.148	0.226		Swc 0.100000
	0.5	0.1	0.3		Sor 0.300000
	0.55	0.061	0.376		301 0.00000
	0.6	0.033	0.476		kroep 1.000000
	0.65	0.012	0.6		krwep 0.740000
	0.7	0	0.74		
					Bestfit Corey Numbers
					2.250407
					No 2.238487
					Nw 2.250687
					Best Fit
				•	
					Close

The user can view the relative permeability data and fit in the chart provided, and can also choose to copy and paste the calculated Corey Relative Permeability data for use within other routines in this or other applications. To copy data from the datatab shown below, simply highlight and drag your selection within the table and press CTRL+C to copy to the clipboard.



References:

Corey, A.T. "The Interrelation Between Gas and Oil Relative Permeabilities". Production Monthly, Nov 1954

7.9 Units Conversion

Most commonly used oil industry conversion factors have been implemented into this general purpose units conversion application.

Just type a number in the **Convert From** input box, select a unit, then double click on the **Convert To** unit, and the result will appear in the highlighted Convert To result box.

An example is shown below.



Waterdrive

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8 Application and Chart Settings

To change aspects of the application or chart settings, select the Application Settings toolbar located at the bottom right of the main application window, as shown below.

Craig	
Dykstra-Parsons	
Water Coning	
General Utilities	
Applications	
Application Settings	
Change Chart Settings	

Once this toolbar is selected the contents of the toolbar area should change to a editable property grid and allow the User to change most aspects of the application and chart preferences.

Application Setur	igs	
Application Options		1
Visual Style	Blue	
Result Boxes	Glass VS	
Report Font	Silver	l
4 Production and Inje	Curri Jana Jaunga	Ч
Oil Rate Series	192, 255, 192	
Water Rate Series	DodgerBlue	
Liquid Rate Series	Violet	1
Water Injection Rate	192, 255, 255	
Facilities Capacity S	Black	
Historical Rates Seri	Green	
Oil Cumulative	Green	
Water Cumulative	Blue	
Liquid Cumulative	Violet	L
Water Injection Cum	Cyan	
Watercut	Cyan	
Water Oil Ratio	128, 255, 255	
Oil Rate Marker	4 point star	
Water Rate Marker	4 point star	
Liquid Rate Marker	4 point star	
Water Injection Mar	4 point star	
Facilities Capacity	Square	
Historical Rates Mar	4 point star	
Oil Cumulative	4 point star	
Water Cumulative	4 point star	
Liquid Cumulative	4 point star	
Water Injection Cum	4 point star	
Watercut	4 point star	
Water Oil Ratio	4 point star	
4 Fractional Flow Set	inas	
Kro Series	Green	
Krw Series	Blue	
fw Series	Blue	
Welge Straight Line	Red	
Kro Series Marker	4 point star	
Krw Series Marker	4 point star	
fw Series Marker	4 point star	
Welge Straight Line	4 point star	
4 Single Laver Fraction	nal Flow Settings	
Diffuse Rate		•
√ ····		
Select Application Visu	al Style	
Applications		
Application Setti	ngs	
		-

The User can scroll up and down within this property grid and modify the application and chart settings to suit their requirements.

