Interaction between reactivity and flow in the in-situ production of oil from oil shale

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Outline

- Problem description
- Description of solution approach
- Flow and reaction parameters
- Results
- Observations

In-situ Oil Shale Processing

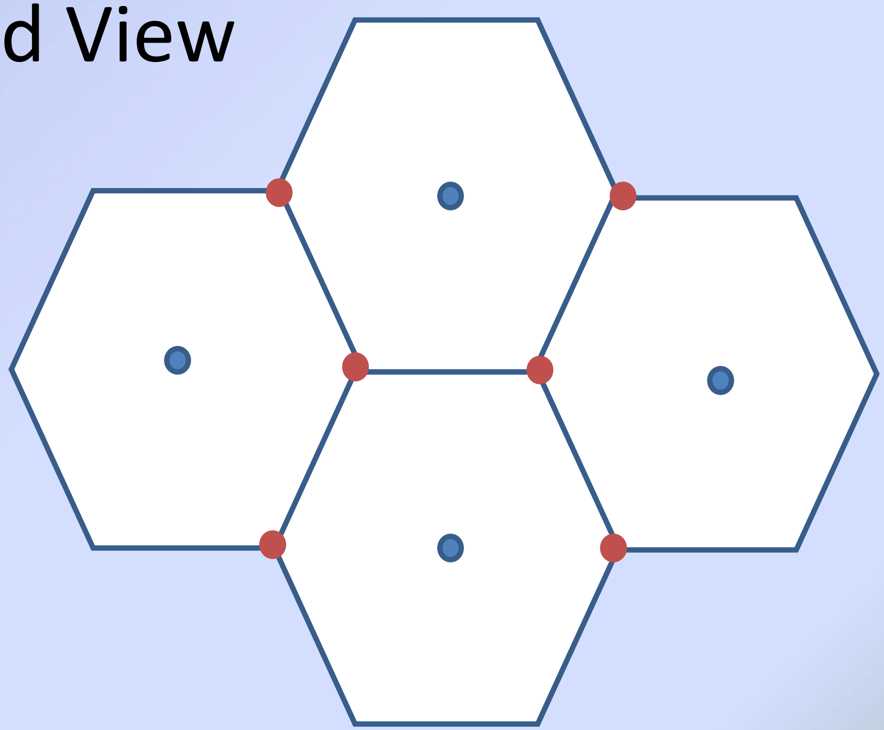
- Underground resources are heated by some means to convert insoluble/impermeable kerogen into oil and gas products.
- The interlinked processes of heat transfer, kerogen conversion and flow are complex.
- This paper is an attempt to understand these linkages.

Model Description

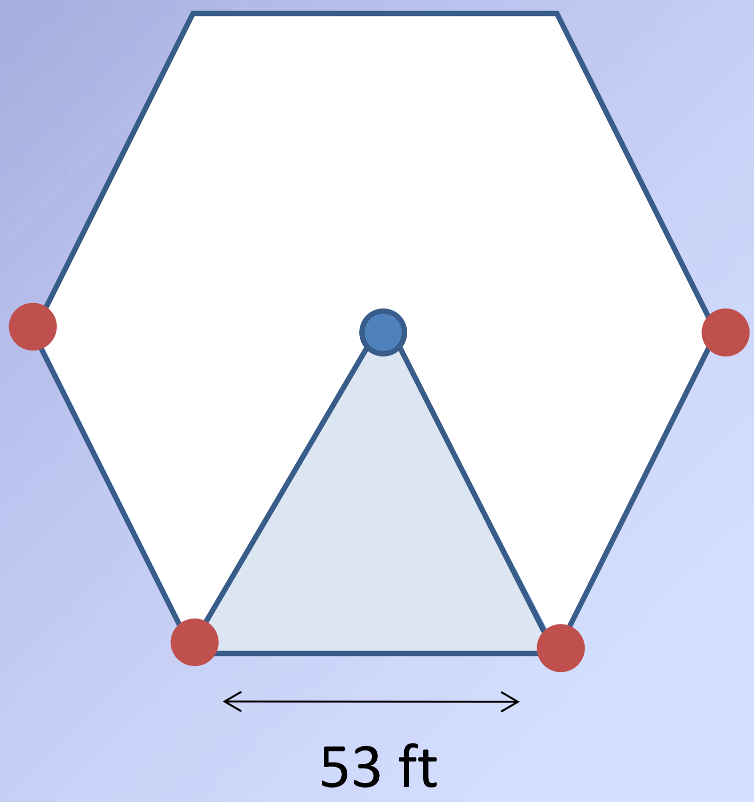
Aerial Field View

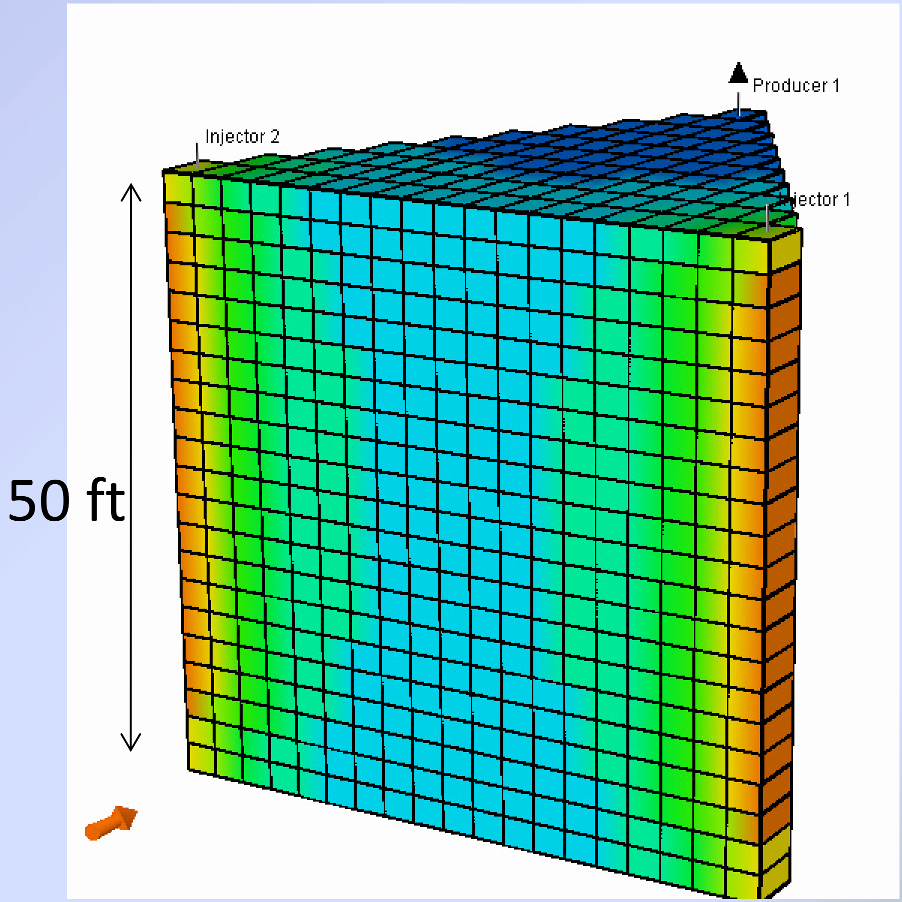
- Producer

- Heater

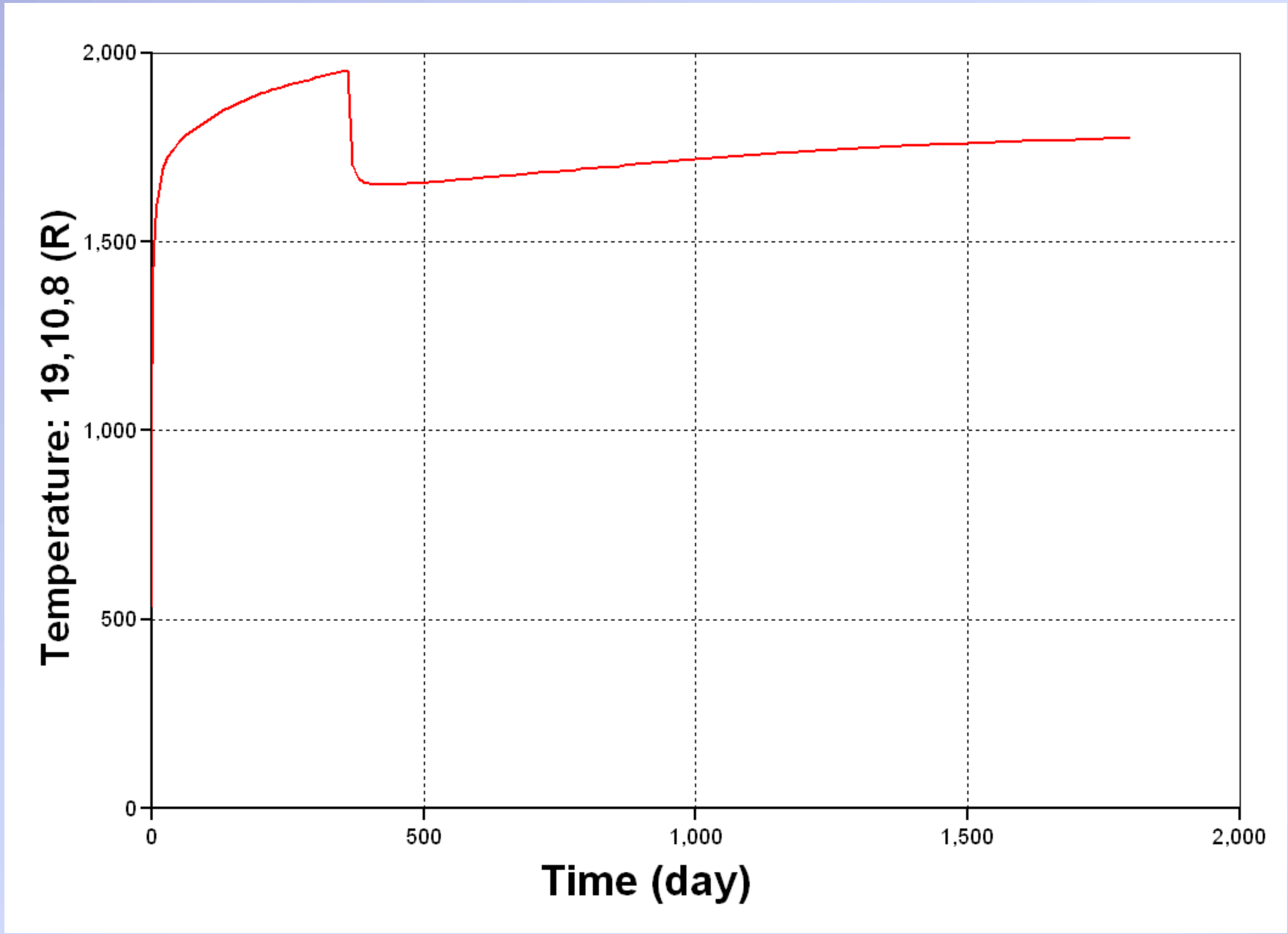


Model Description

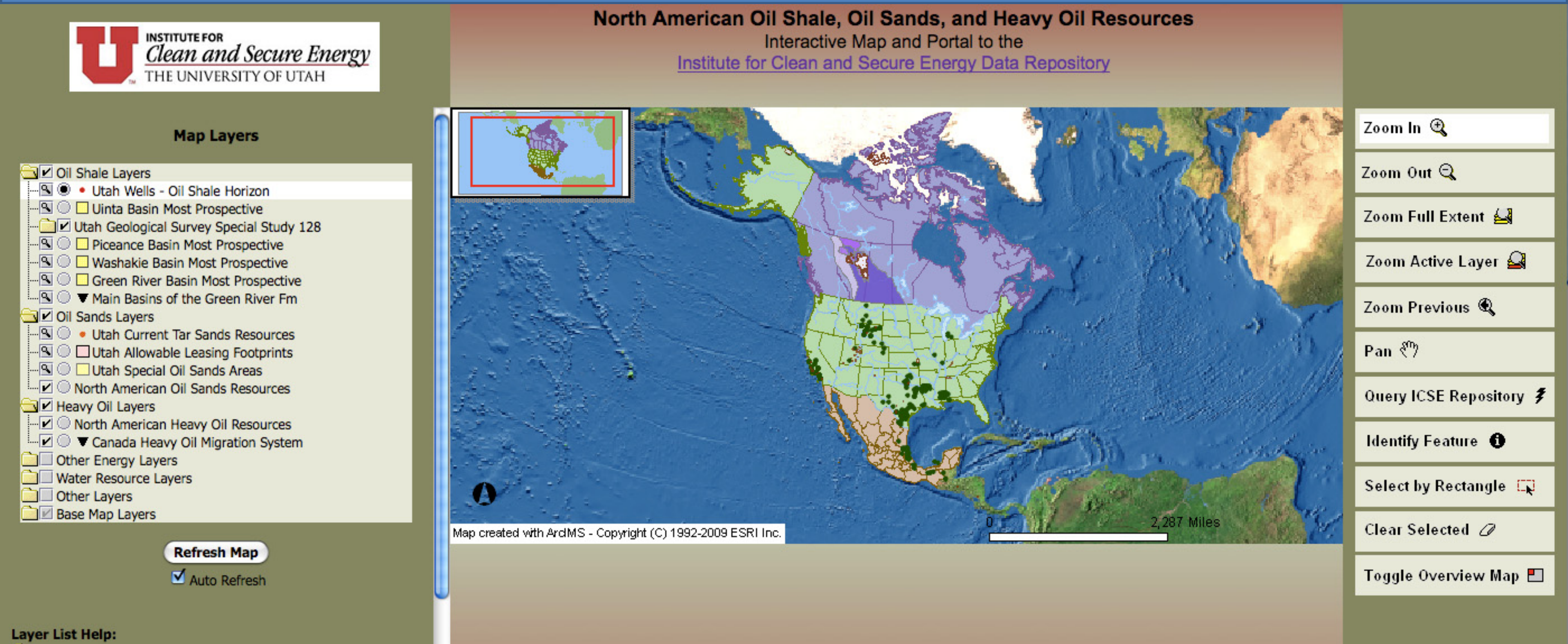




Heat Input: Temperature Near Heating Well

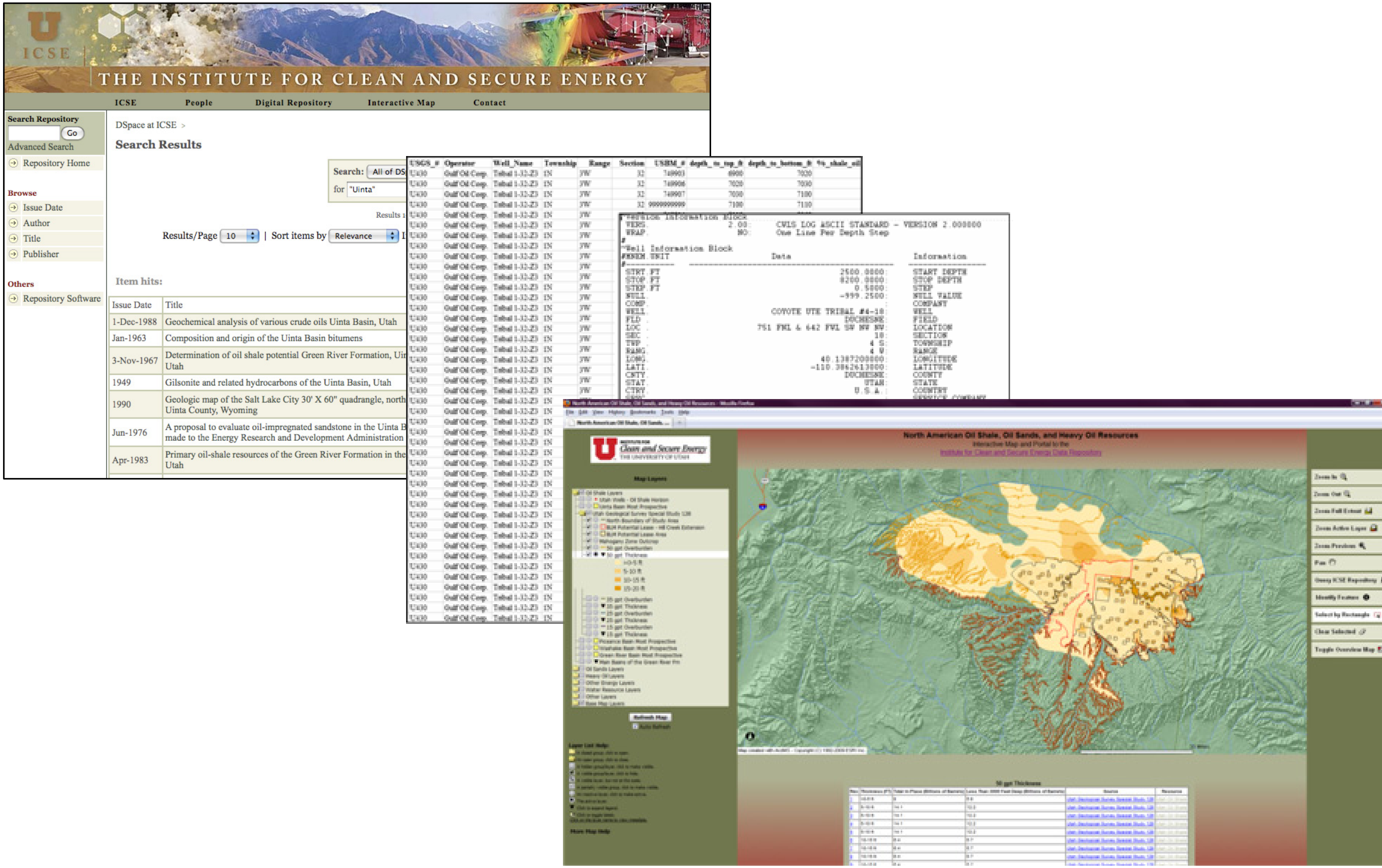


Institute for Clean and Secure Energy Interactive Map

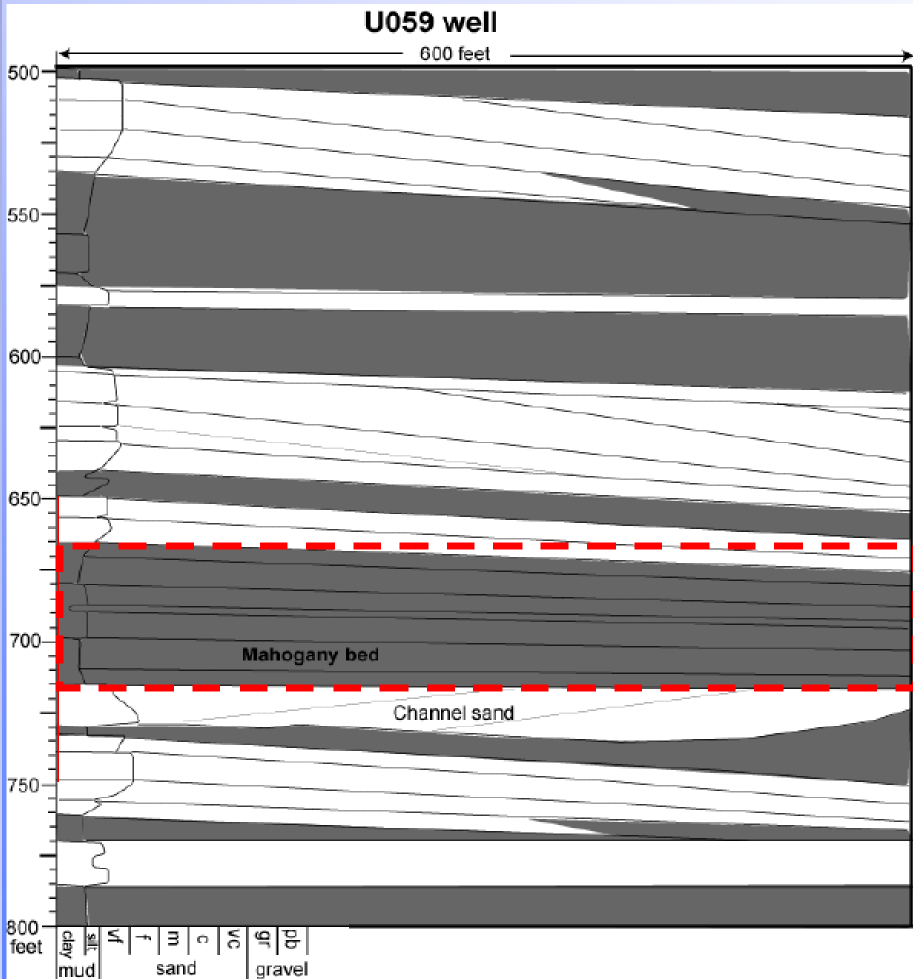


- ✓ Connect to data & documents related to North American oil shale, oil sands, & heavy oil resources with geospatial interface
- ✓ Access well attributes (formation tops, etc.), Fischer assays, & unpublished digitized wells logs for several hundred Uinta Basin wells
- ✓ View maps of oil shale resources with additional layers such as land ownership, wilderness areas, & co-located resources
- ✓ Link to interactive map can be found at www.icse.utah.edu

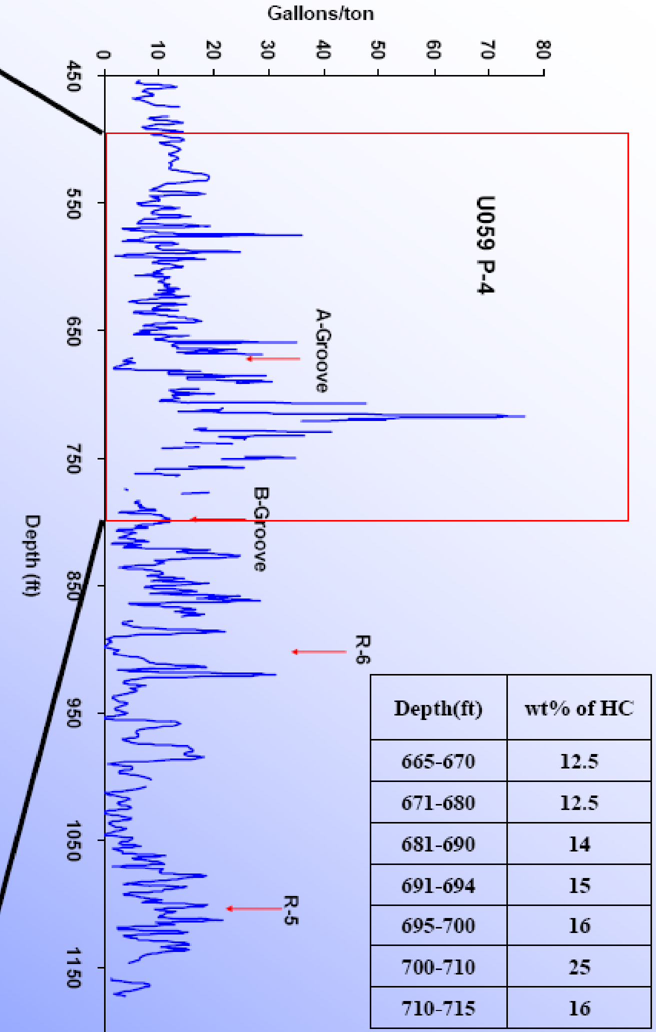
Institute for Clean and Secure Energy Interactive Map Examples



Geology



Sedimentology and bedding architecture of U059 well from gamma log (white: sandstone, gray: mudstone).



Depth(ft)	wt% of HC
665-670	12.5
671-680	12.5
681-690	14
691-694	15
695-700	16
700-710	25
710-715	16

Oil-yield derived from density log

Reservoir Model

- Conservation of mass

$$R_{C_i} = \frac{\partial}{\partial t}\left(\left[\sum_{p=1}^{Np}(\phi S_p \rho_p x_{p,i})\right]\right) - \nabla \cdot \left((\sum_{p=1}^{Nf} x_{p,i}\rho_p \vec{v}_p)\right) - \left(\sum_{r=1}^{Nr} s_{r,i}\mathcal{R}_r + Qm_i\right)$$

- Conservation of energy

$$R_E = \frac{\partial}{\partial t}\left(\left[\sum_{p=1}^{Np}(\phi S_p \rho_p \hat{U}_p) + U_{rock}\right]\right) - \nabla \cdot \left((\sum_{p=1}^{Nf} \hat{H}_p \rho_p \vec{v}_p)\right) - \left(\sum_{r=1}^{Nr} \Delta H_r \mathcal{R}_r + Qe\right)$$

- Constraints

$$R_{\sum S} = \sum_{p=1}^{Np} S_p - 1$$

$$R_{\sum x_p} = \sum_{i=1}^{Nc} x_{p,i} - 1$$

$$R_{K_k} = K_{p1-p2,i}\, x_{p2,i} - x_{p1,i}$$

Modeled using STARS
Thermal Reservoir Simulator
From Computer Modeling Group (CMG)

Reaction Mechanism (Five Reactions)

- Kerogen → Heavy Oil + Light Oil + Gas + CH_4 + Char
- Heavy Oil → Light Oil + Gas + CH_4 +Char
- Light Oil → Gas + CH_4 + Char
- Gas → CH_4 + Char
- Char → CH_4 + Gas + coke

- Species are lumped into representative components with representative properties.
- Reaction scheme adapted from various sources.

Kinetics

- What is the rate different products are formed?
- How precise must kinetic data be to appropriately model kerogen pyrolysis at field scales?

Flow

- How do changes in fluid composition affect overall production?
- In this complex system, how important is accurate estimation of relative permeabilities?
- What impact does fluid composition have on heat transfer in a reservoir?

- What is the relationship between flow and kinetic parameters?

Experimental Design Matrices

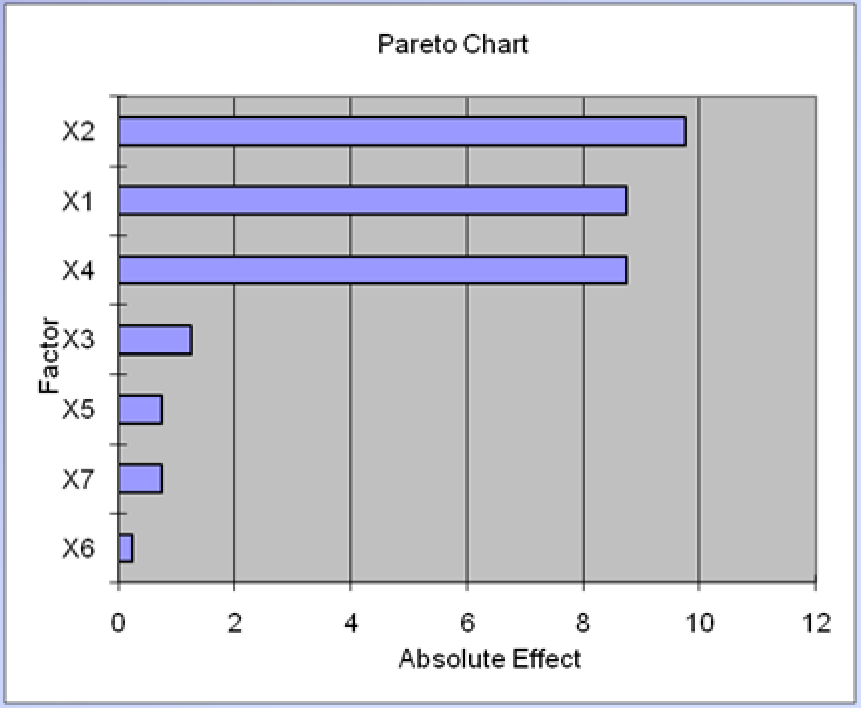
Eight Run Fractional Factorial
Design For Five To Seven Factors

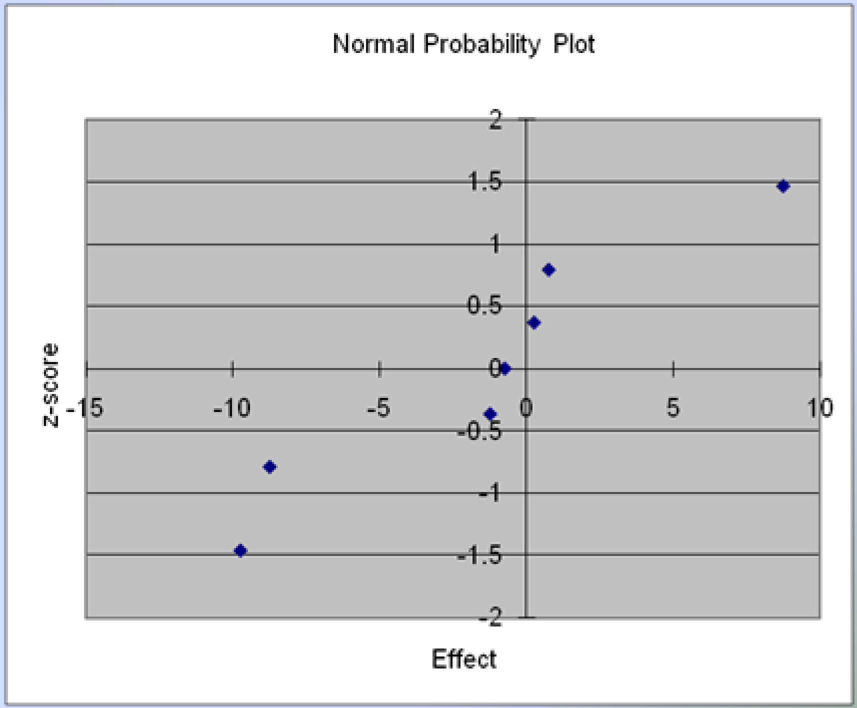
Run	X1	X2	X3	X4	X5	X6	X7
1	-	-	-	+	+	+	-
2	+	-	-	-	-	+	+
3	-	+	-	-	+	-	+
4	+	+	-	+	-	-	-
5	-	-	+	+	-	-	+
6	+	-	+	-	+	-	-
7	-	+	+	-	-	+	-
8	+	+	+	+	+	+	+

X1-X7 represent variable parameters
(-) represents a low value
(+) represents a high value

Pareto Charts and Normal Probability Plots

These tools can help you quickly estimate the importance and impact individual parameters have on some response.





Parameters

- Molecular weight. Stoichiometry. Initial kerogen concentration.
- Activation energies for reactions 1-4.
- Distribution of activation energy for kerogen conversion.
- Relative permeability representation.
- Reaction Enthalpy

Molecular Weight

	Kerogen	Heavy Oil	Light Oil	Gas	Methane	Char	coke
MW (+)	20000.55	424.49	152.03	52.01	16.04	12.60	14.55
MW (-)	2974.84	424.61	151.99	51.95	16.04	12.55	14.55
Form (+)	$C_{1479}H_{2220}$	$C_{31.75}H_{42.82}$	$C_{11.19}H_{17.51}$	$C_{3.35}H_{11.63}$	CH_4	$CH_{0.55}$	$C_{1.19}H_{0.32}$
Form (-)	$C_{220}H_{330}$	$C_{31.76}H_{42.81}$	$C_{11.19}H_{17.50}$	$C_{3.35}H_{11.62}$	CH_4	$CH_{0.53}$	$C_{1.19}H_{0.32}$
Stoic rxn 1 (+)	-1	37.29	13.86	25.03	17.06	38.71	0
Stoic rxn 1 (-)	-1	5.55	2.06	3.72	2.54	5.80	0
Stoic rxn 2 (+)		-1	2.18	0.06	0.03	7.13	0
Stoic rxn 2 (-)		-1	2.18	0.06	0.03	7.13	0

Mass balance is essential, and depends on MW of representative components and stoichiometry in each reaction.
Note that the values listed here show two decimal places for convenience.

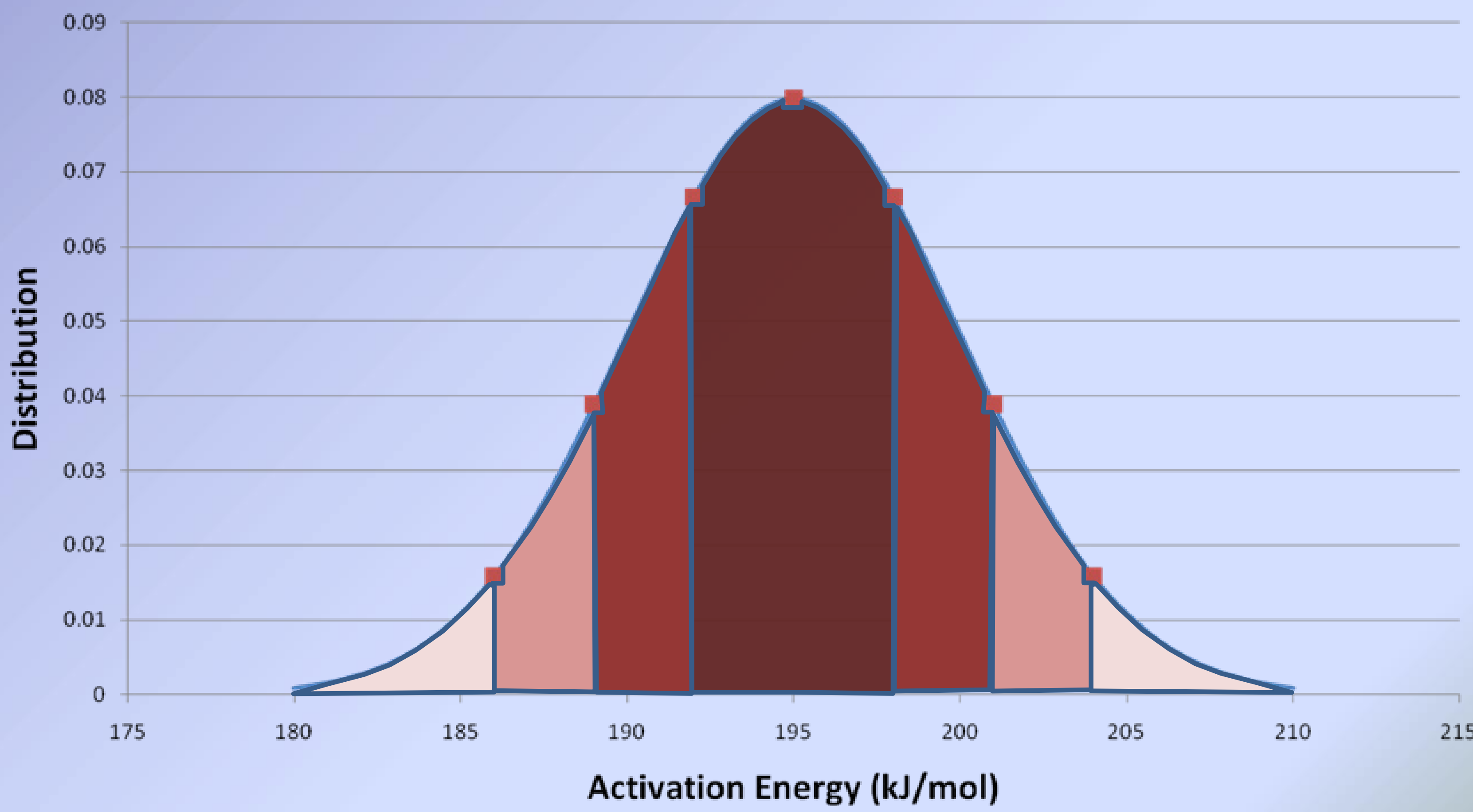
Activation Energies

Ranges for activation energies reported in literature.

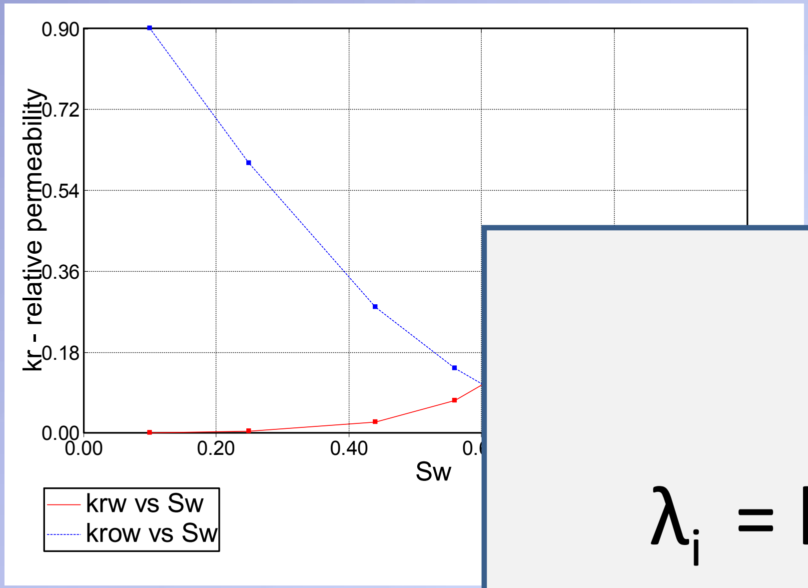
Reaction	Low Activation Energy (kJ/mol)	High Activation Energy (kJ/mol)
Kerogen Cracking	195	225
Heavy Oil Cracking	208	260
Light Oil Cracking	208	260/233
Gas Cracking	235	270

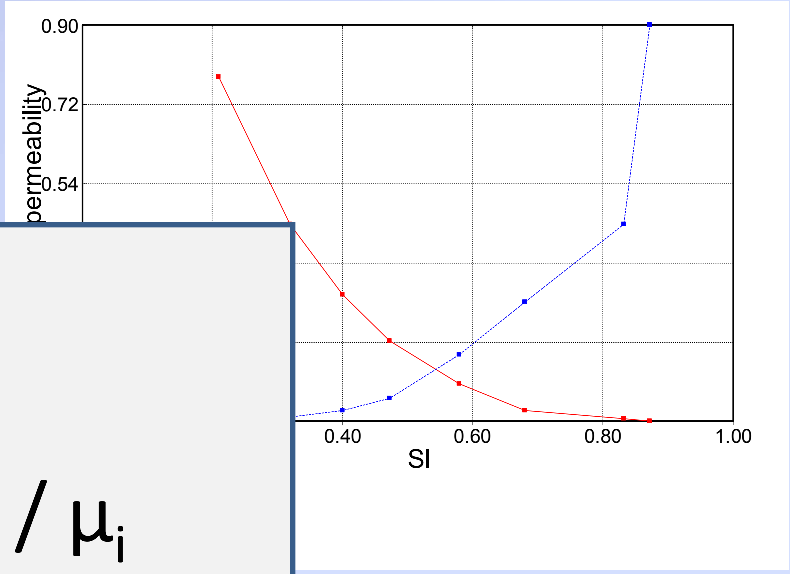
The impact of these activation energies to outputs may not be trivial due to complexities in the problem (i.e. convective vs. conductive heat transfer)

Distribution of Activation Energy

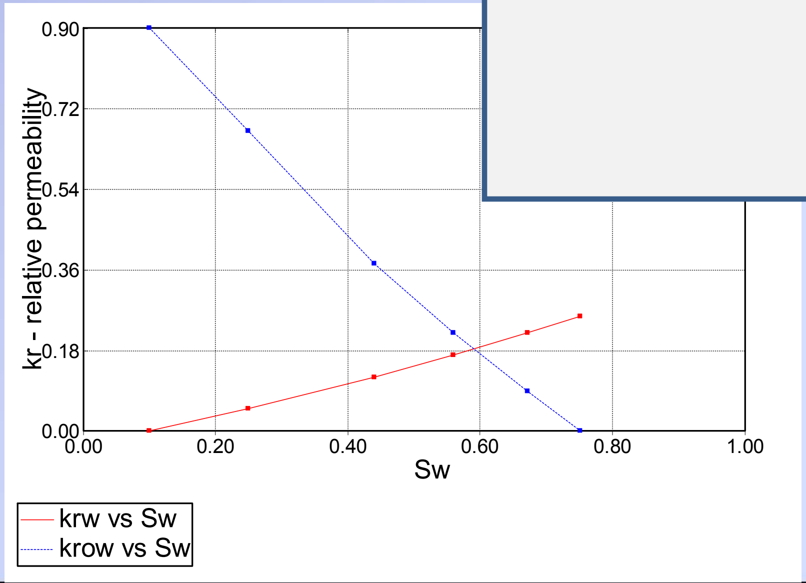


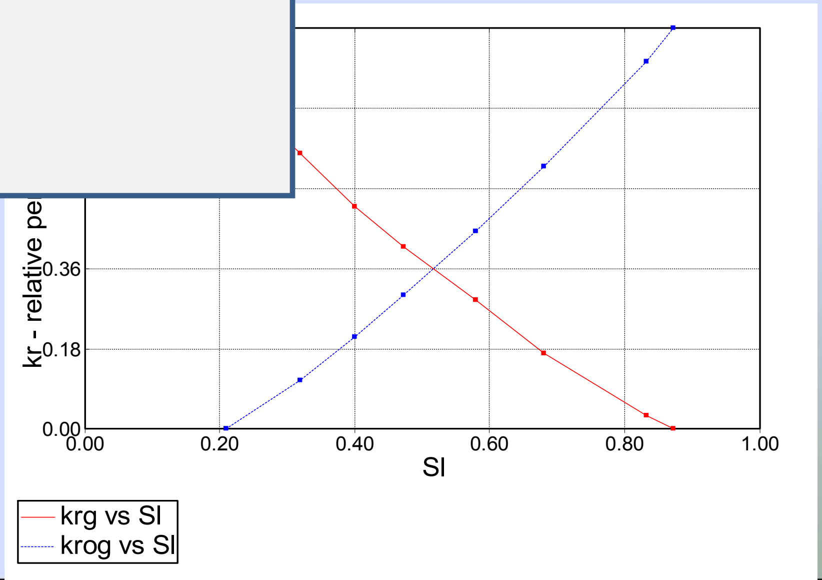
Relative Permeability





$$\lambda_i = k\, k_{ri} \;/\; \mu_i$$

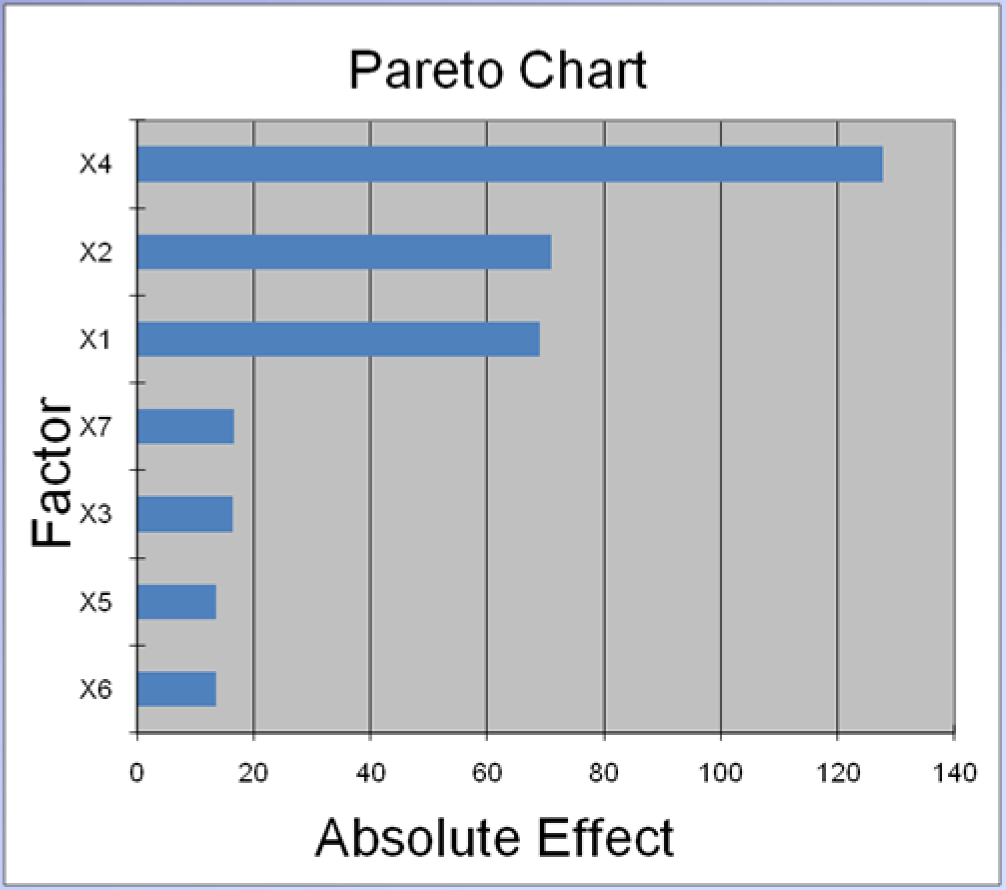




Enthalpy of Reaction

- Initial estimates of 46.5 kJ/gmol were used for all cracking reactions.
- Some sources in literature use a value of 0 kJ/gmol for these reactions.

Improving Stability

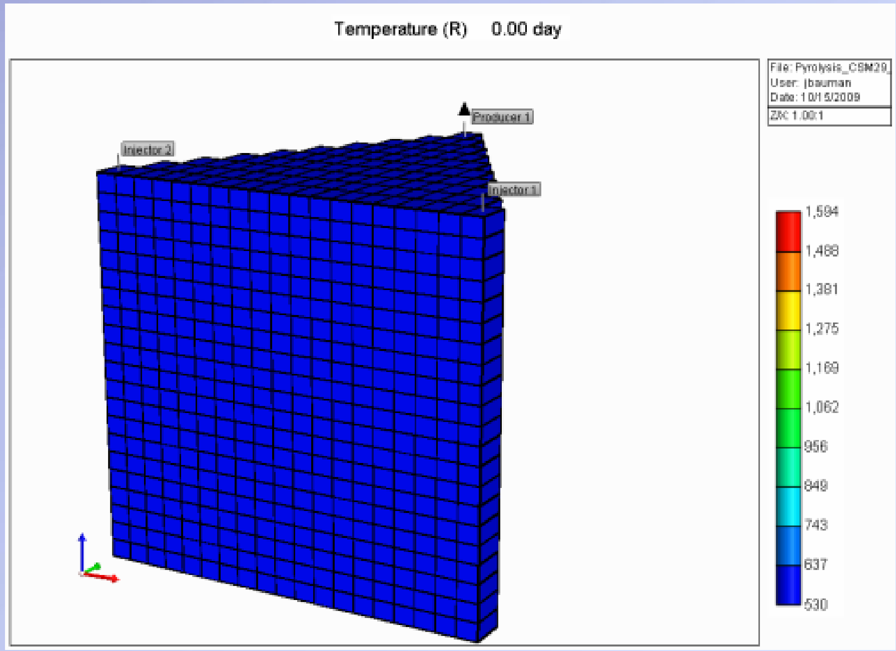


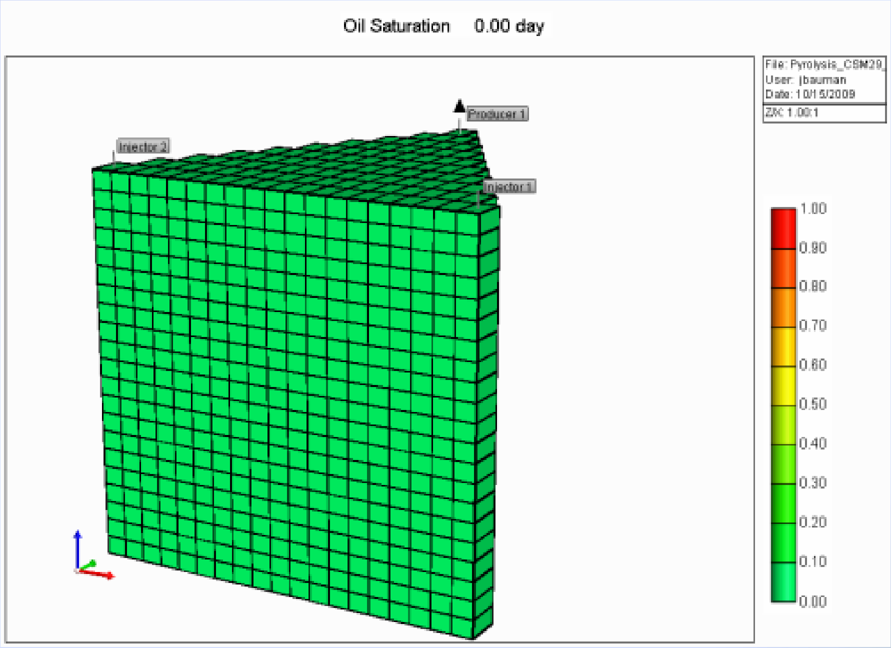
		-1	1
X1	MW/stoic/conc.	3000	20000
X2	E1	8.383E+04	9.673E+04
X3	E2	8.942E+04	1.118E+05
X4	E3	8.942E+04	1.118E+05
X5	E4	1.010E+05	1.161E+05
X6	E distribution	without	with
X7	rel perm	linear	curved

Output	Simulation Time

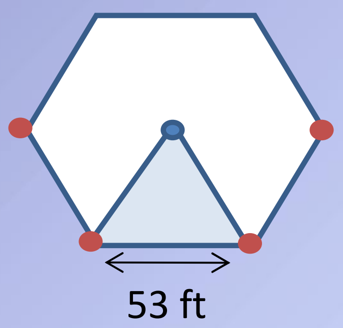
If the oil cracking activation energy is larger than the gas cracking activation energy, the runs were unstable, possibly because gas immediately reacts and immediately flows, causing very small time steps.

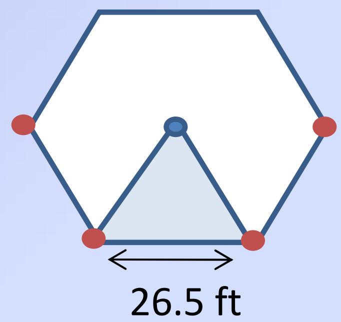
No oil produced with given parameters

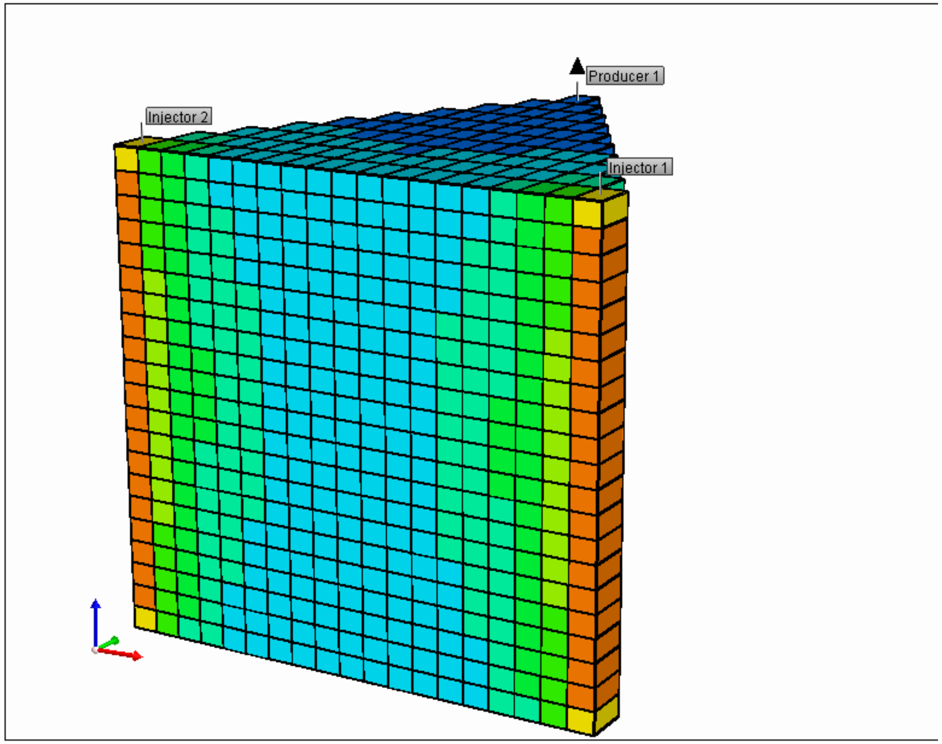


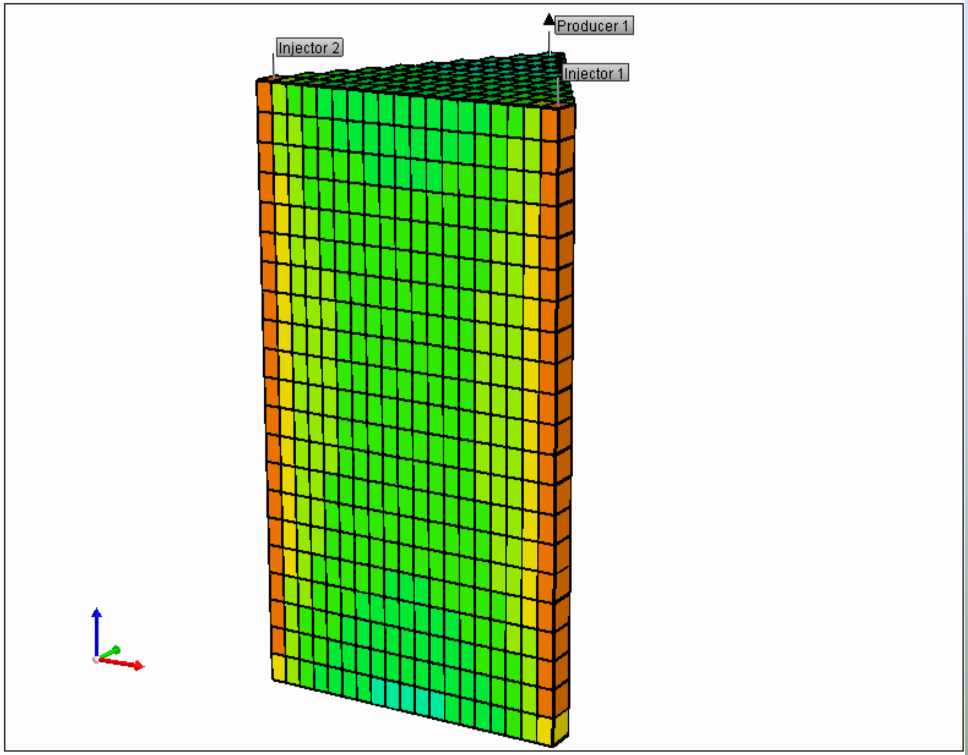


Shorten the distance between wells





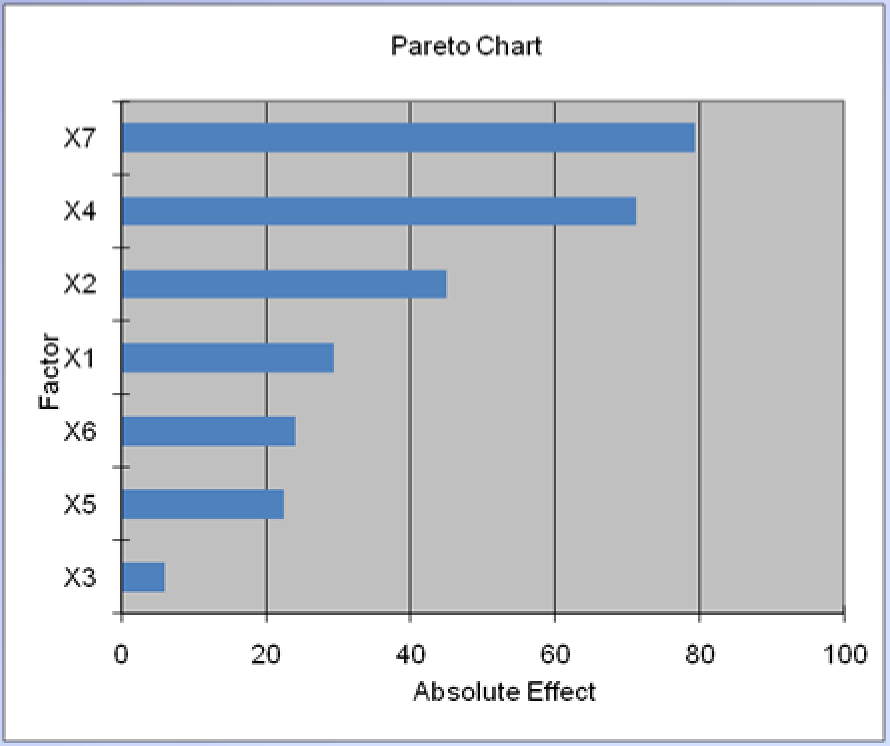


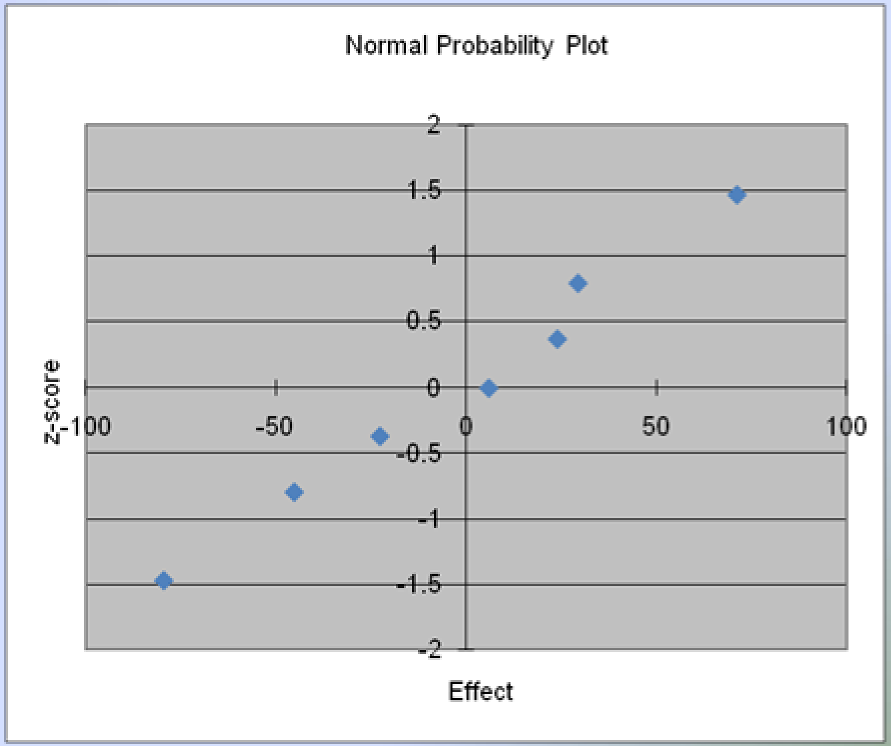


Screening Runs, Smaller Field

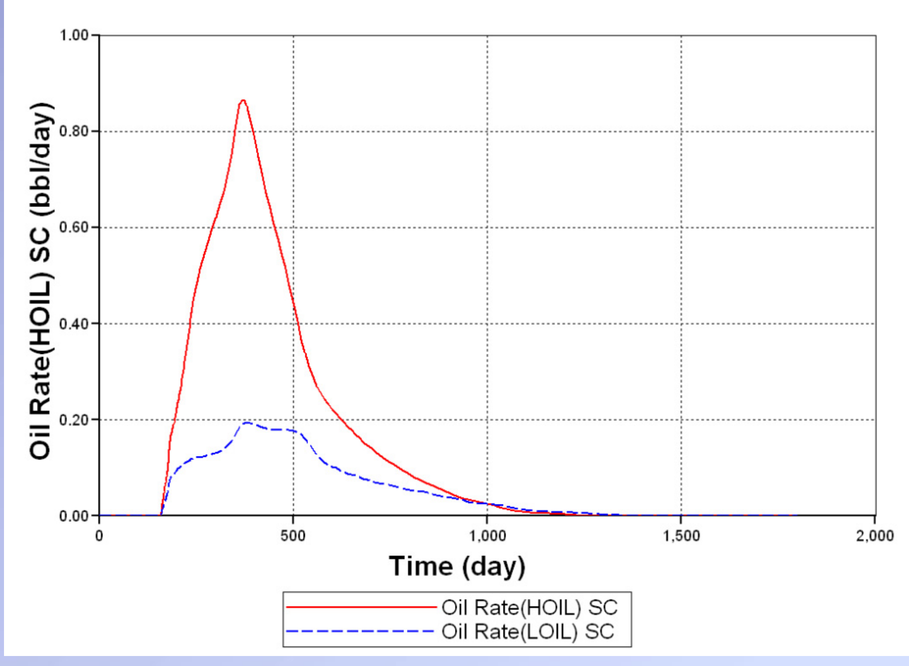
		-1	1
X1	MW/stoic/conc.	3000	20000
X2	E1	8.383E+04	9.673E+04
X3	E2	8.942E+04	1.118E+05
X4	E3	8.942E+04	1.000E+05
X5	E4	1.010E+05	1.161E+05
X6	E distribution	without	with
X7	rel perm	linear	curved

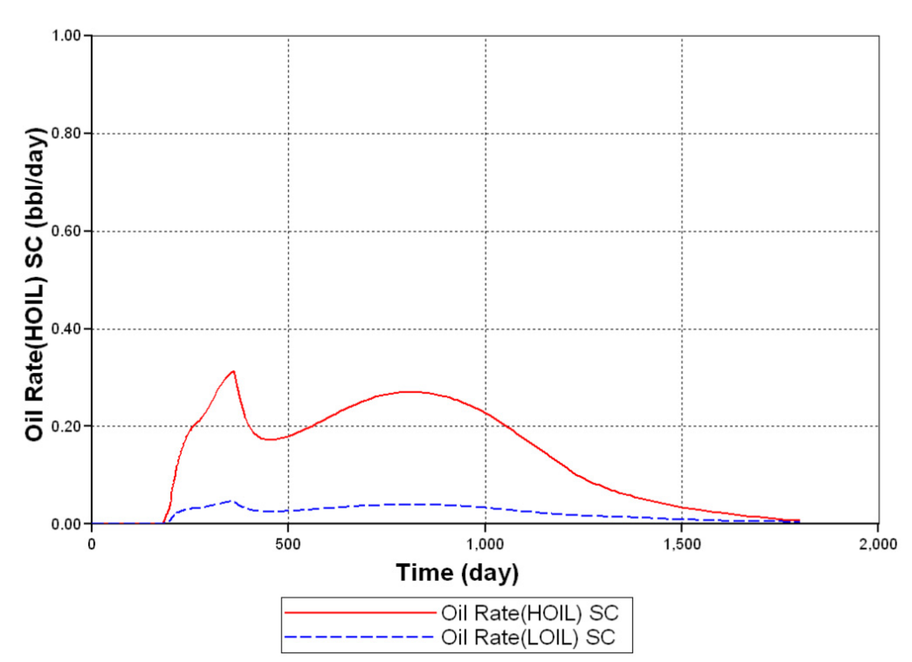
Output:	Oil Produced in 1800 days





Oil production changes are significant



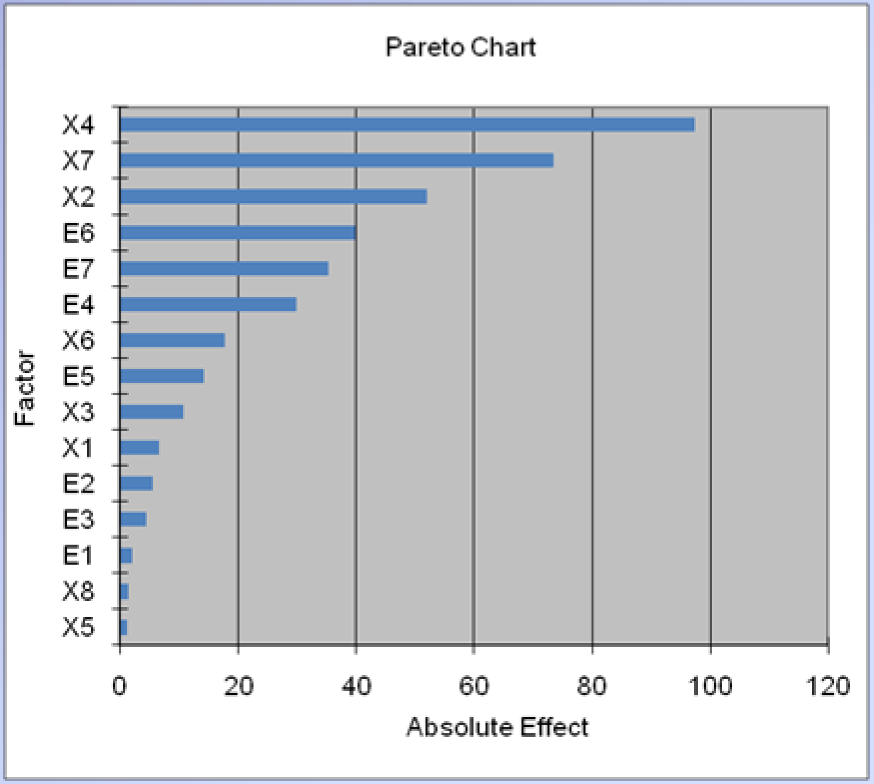


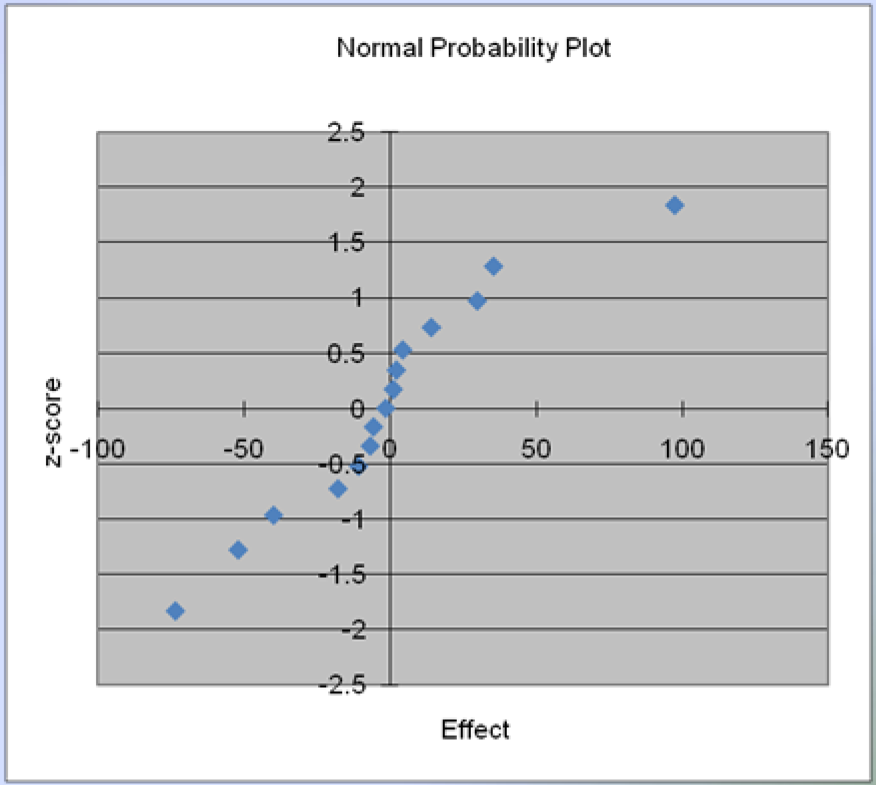
This example showing oil production rates of heavy and light oil for two different runs shows there can be significantly different outcomes when manipulating parameters. It would be valuable to understand how these parameters are affecting these results.

Screening Runs, single factors clear of interactions

Added X8: Enthalpy of Reaction.

Note: 'E' factors represent possible pair interactions of parameters.





Observations

- Factorial experiment design methods can be useful for judging the impact of input parameters and their interactions in simulation.
- Mobility of oil may be low due to insufficient heat transfer in a reservoir.
- Values within typical ranges for kinetic and mobility parameters, especially their interactions, may all be significant for predicting oil production.
- The flow and kinetic parameters, and their interactions may be crucial for accurate modeling of in-situ processing.

Acknowledgements

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