PS Hydraulic Fracture Modeling and the Road to Prediction - A Finite Element Approach*

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Search and Discovery Article #41777 (2016)**
Posted March 21, 2016

*Adapted from poster presentation given at AAPG-SPE Joint Forum Reality-Based Reservoir Development: New Teams, Techniques, Technologies September 23, 2015, Oklahoma City, Oklahoma

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Abstract

In unconventional play development programs the concept of a resource or statistical play is used to define production success or failure for a field rather than individual well performance. A complex challenge in is the predictability of any single well in the program, with statistical variation of production being an accepted facet in the development program. A potential solution to the problem is to use a combination of a first principles approach in combination with a data driven model. A calibrated model representing all relevant anisotropic reservoir conditions (deformation, stress, strength) and the hydraulic stimulation mechanism is used to test changes to the design of the well and the completion in the virtual environment. This approach attempts to integrate many discrete datasets to eliminate uncertainty. The methodology used, data requirements, pitfalls and successes of this solution are discussed and examples of the predictability of this approach that have recently been published, with the impact on EUR, are examined.

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Jason Pitcher, Cameron, Johannes Will, Dynardo GmbH

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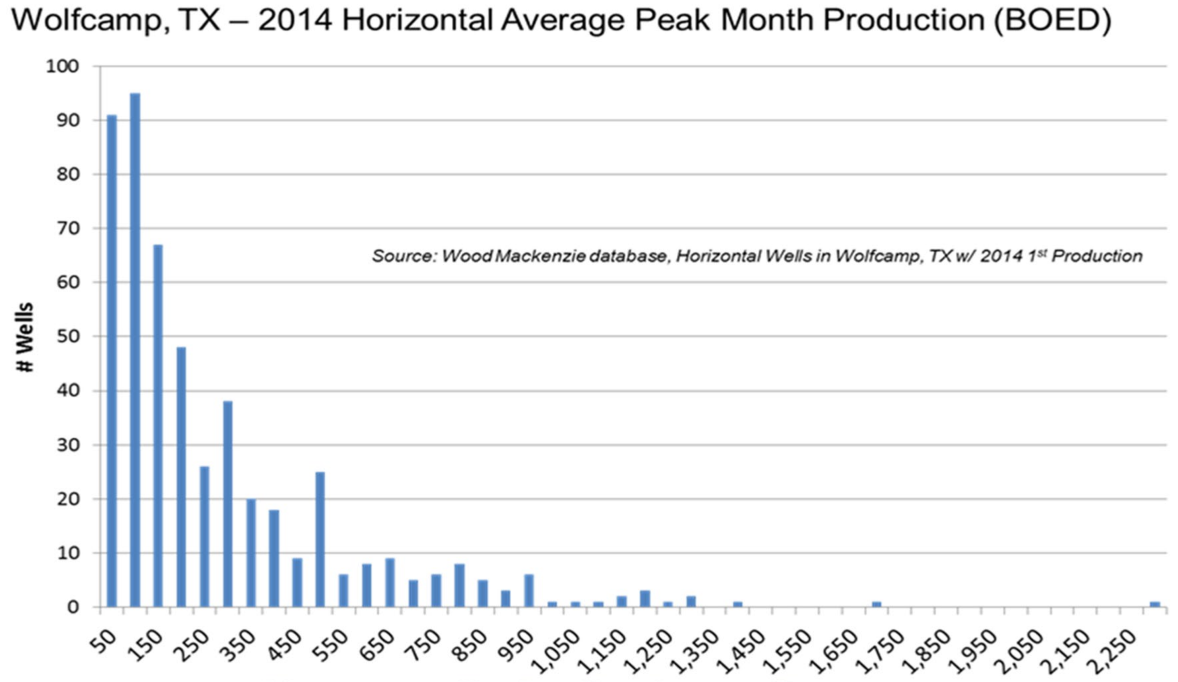
In unconventional play development programs the concept of a resource or statistical play is used to define production success or failure for a field rather than individual well performance. A complex challenge in is the predictability of any single well in the program, with statistical variation of production being an accepted facet in the development program.
A potential solution to the problem is to use a combination of a first principles approach in combination with a data driven model. A calibrated model representing all relevant anisotropic reservoir conditions (deformation, stress, strength) and the hydraulic stimulation mechanism is used to test changes to the design of the well and the completion in the virtual environment. This approach attempts to integrate many discrete datasets to eliminate uncertainty.
The methodology used, data requirements, pitfalls and successes of this solution are discussed and examples of the predictability of this approach that have recently been published, with the impact on EUR, are examined.

Uncertain Outcomes

- Oil prices have fallen by ~50%
- Significant number of wells drilled but unprofitable
- Optimal completion uncertainty
- Delineating acreage – where is the sweet spot?

Wolfcamp, TX – 2014 Horizontal Average Peak Month Production (BOED)

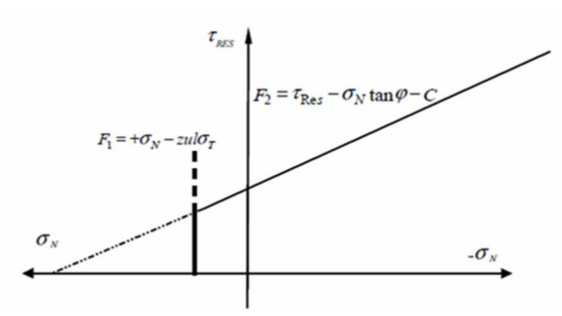


Wolfcamp Well Distribution - All Operators

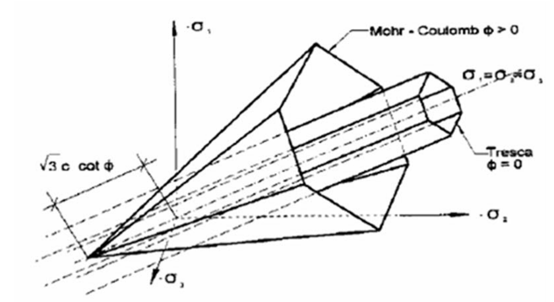
- Low confidence in prediction of outcome
- High number of variables
- Shale is a jointed rock
- Due to bedding plane and natural fracture system anisotropic strength behavior dominate fracture growth
- 3D modeling including all strength anisotropies is mandatory
  - Isotropic mechanical material models will fail
  - 2D or pseudo 3D (2.5D) models will fail
  - Porous flow approach is inadequate

3D Finite Element Approach

- Two component system
  - Mechanical Model
  - Hydraulic Flow Model
- Rocks exhibit anisotropic strength behavior
- Intact rock model incorporate:
  - Layering
  - Natural Joint Systems
- Lateral Homogeneity
  - Assumption that bulk rock description can be modelled.
- Vertical Heterogeneity
  - Discrete layers described where properties are vertically consistent.
- Variables included in model:
  - In situ stress
  - rock strength
  - natural fractures
- The nature of a jointed rock system is a key element to a functional materials model, as this is an important control of the anisotropic strength behavior of the system.

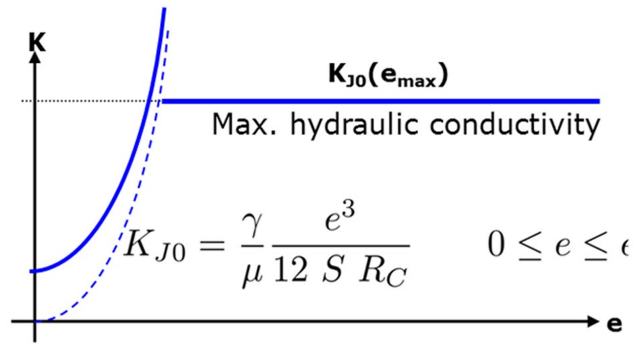


anisotropic Mohr-Coulomb tension cut-off yield surfaces for joints



isotropic Mohr-Coulomb yield surface for intact rock

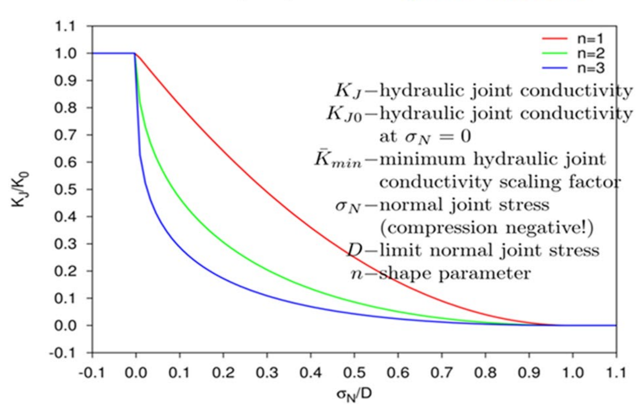
- Stress-independent hydraulic joint conductivity K_{J0} covers joint opening based on plastic strain



$$K_{J0} = \frac{\gamma}{\mu}\frac{e^3}{12\ S\ R_C} \qquad 0 \le e \le e_{max}$$

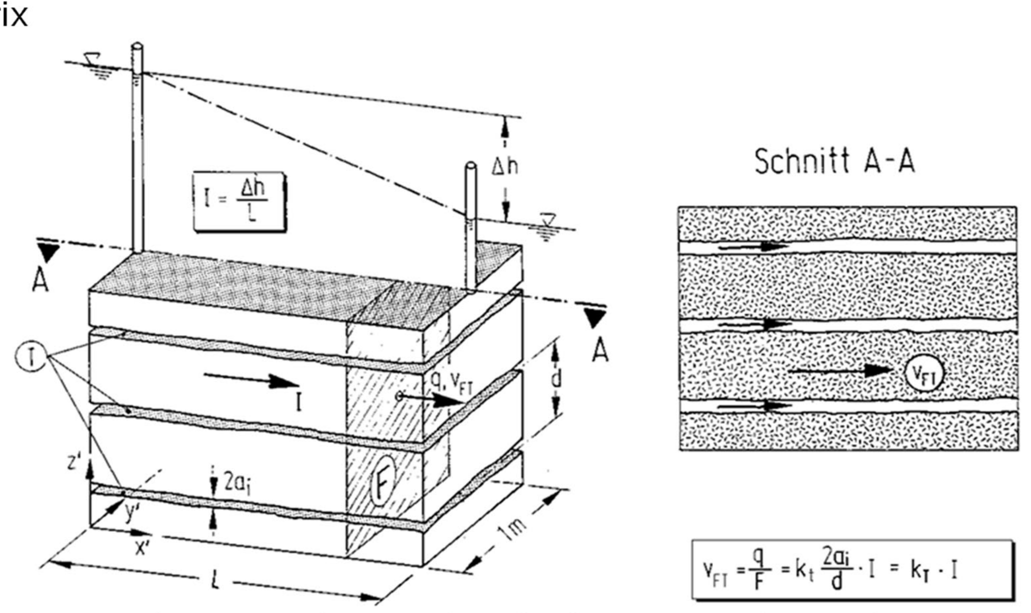
K_{J0} – stress independent hydraulic joint conductivity
γ – specific weight of fluid (water: 62.43lbf/ft^3)
μ – dynamic viscosity of fluid (water: $2.094 \cdot 10^{-5}$psf s)
e – effective hydraulic joint opening
e_{max} – maximum effective hydraulic joint opening
S – joint distance ($S \le l_{eq}$)
R_c – joint roughness cofficient

- Stress-dependent hydraulic joint conductivity K_J covers joint closure



$$K_J = K_{J0}\begin{cases}1 & \sigma_N > 0\\ [1-\bar{K}_{min}]\left[1-\left(\frac{\sigma_N}{D}\right)^{\frac{1}{n}}\right]^2 + \bar{K}_{min} & D \le \sigma_N \le 0\\ \bar{K}_{min} & \sigma_N < D\end{cases}$$

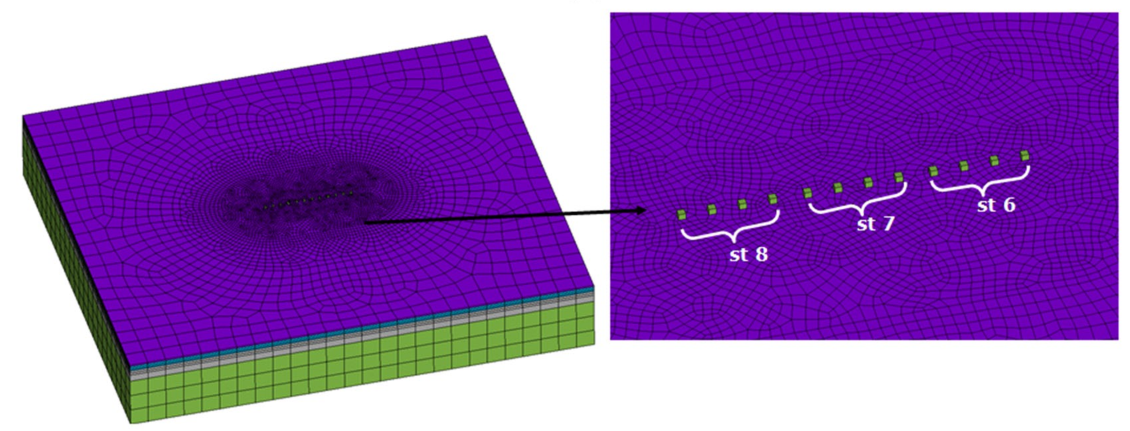
- Superposition of fluid flow in initial jointed rock mass and fluid flow in up to 4+2 joint sets results in anisotropic hydraulic conductivity matrix



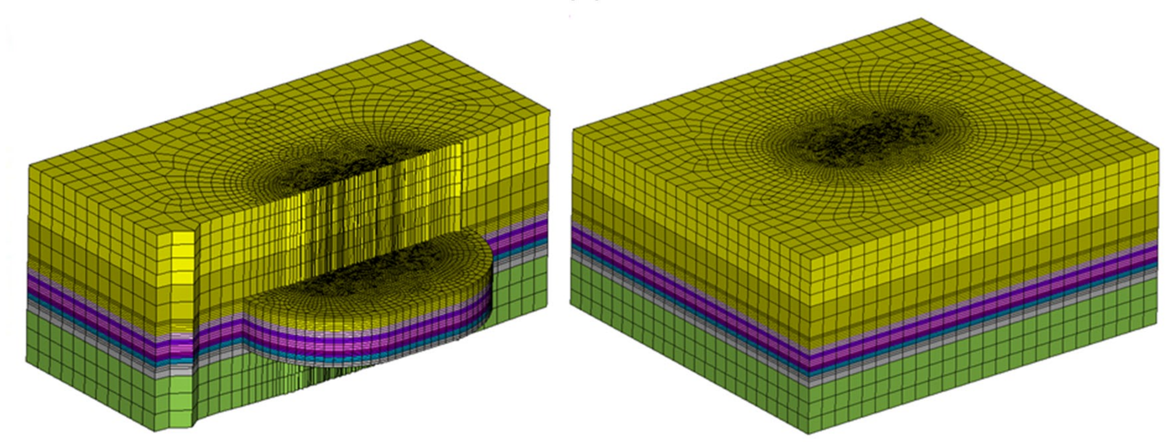
(Source: Wittke, W.: Felsmechanik; Springer-Verlag 1984)

- Hydraulic model is based on assumption of laminar flow (Darcy flow) in multiple (parallel) joints
- Incorporates anisotropic hydraulic element
- Hydraulic model mesh 8x finer than mechanical model – captures pressure gradients.
- Superposition of fluid flow in initial jointed rock mass and fluid flow in up to 4+2 joint sets results in anisotropic hydraulic conductivity matrix
- Only brick elements used in model
- Analysis is non-linear based on multi-surface plasticity material approach
- Domains of fine-mesh and coarse-mesh are defined in the parametric model to balance accuracy and computational efficiency

(a)

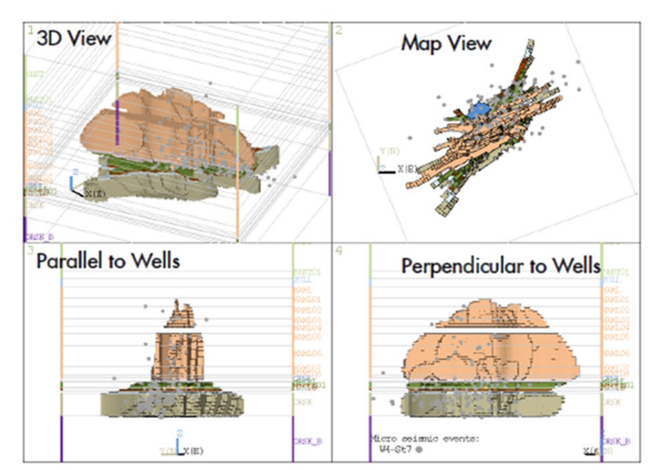


(b)

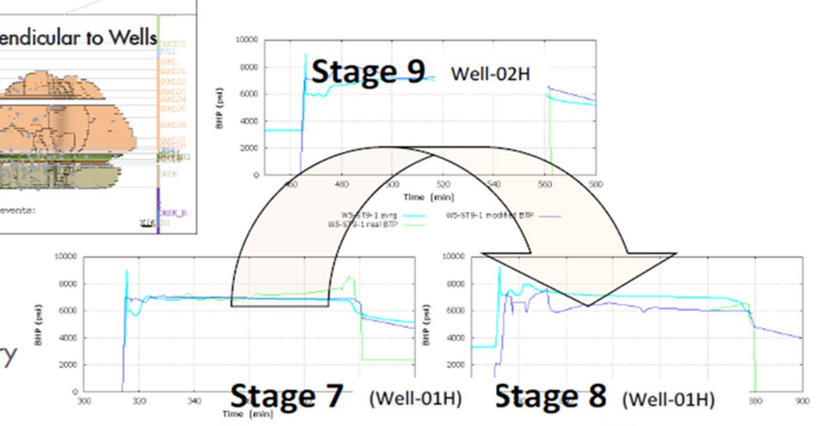


Calibration

- Calib 1: Model calibration with MS data

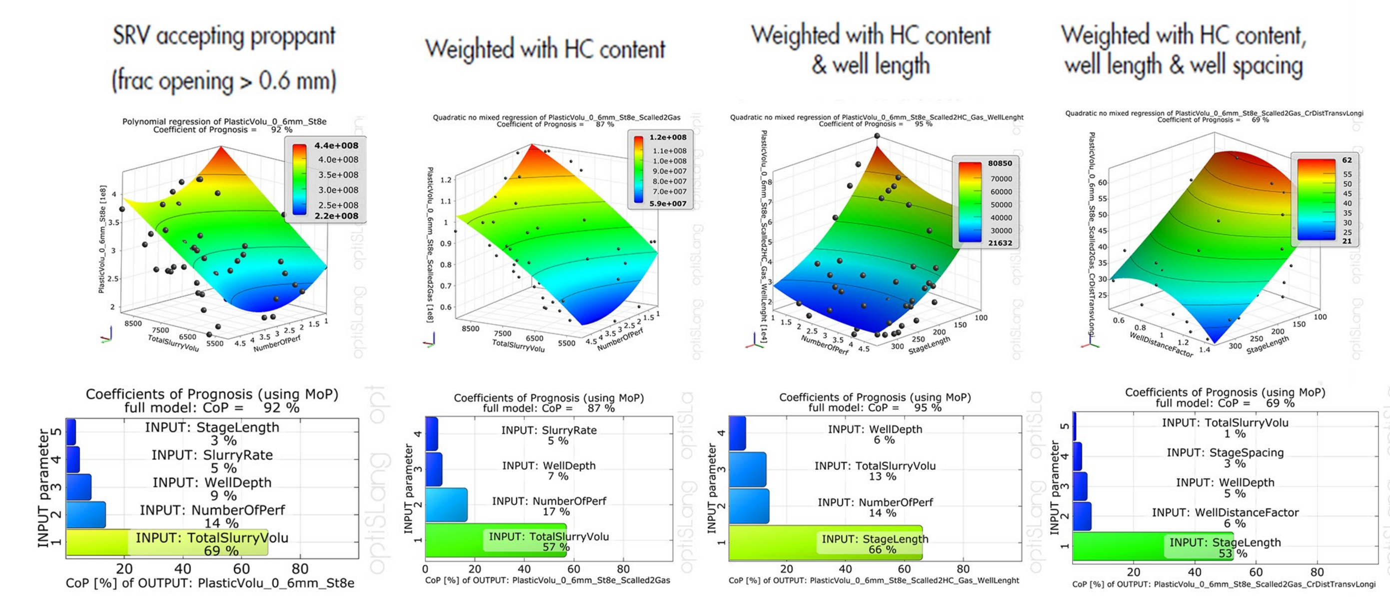


- Calib 2: Model calibration by matching pumping rate using calculated BHP as input
- Calib 3: Model calibration by matching calculated BHP using pumping rate as input
- Calib 4: Model calibration by matching pumped total fluid-slurry volume with frac volume

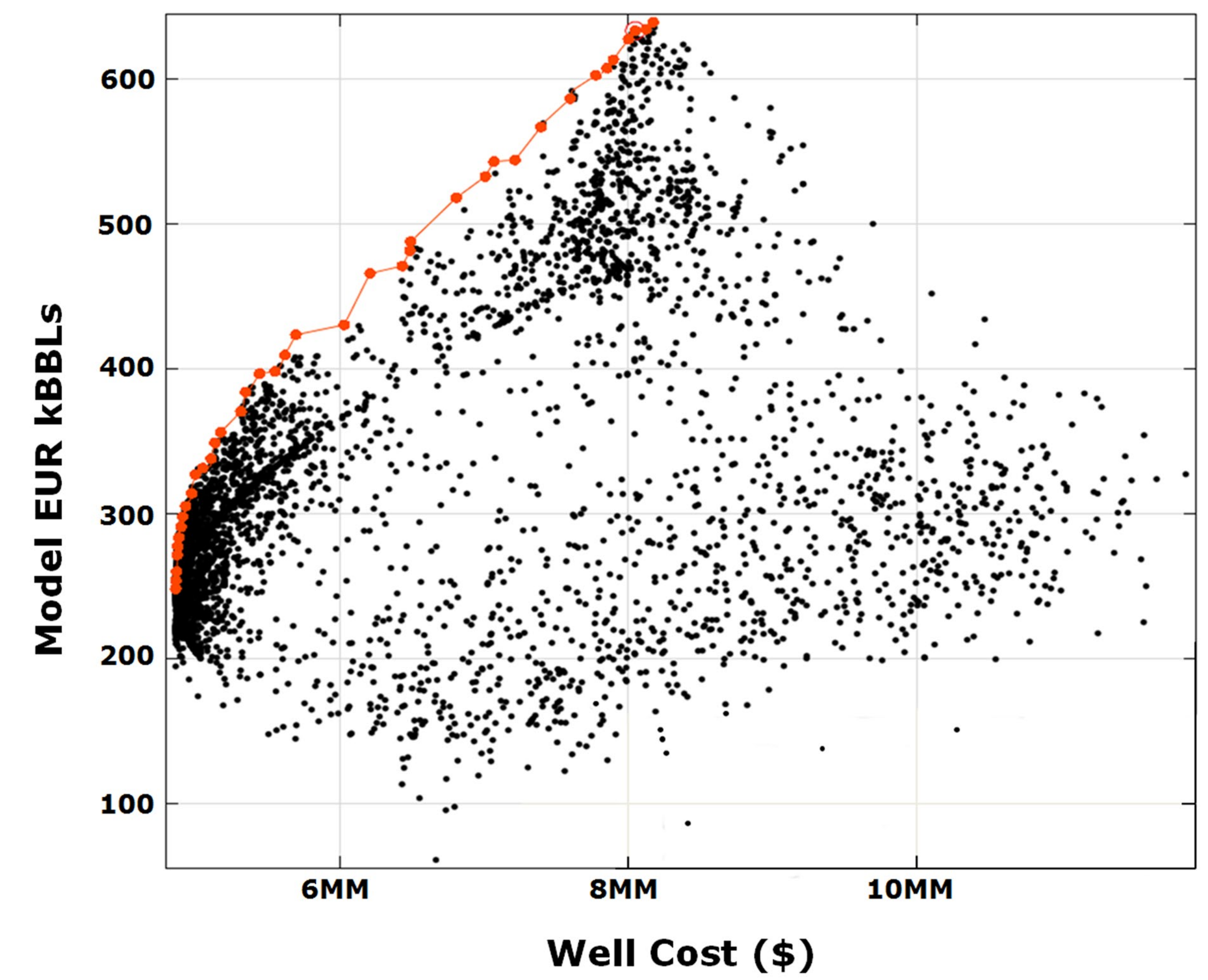


- Output from the Fracture Model is a volume of proppant accepting fractured rock.
  - Calibrated to MS, Pump Rate, Pressure, Fluid Volume
- Verification.....
  - Incorporate reservoir model data
  - Hydrocarbon quantity
  - Recovery Factor (RF)
- Verification of forecast quality of EUR estimation of the calibrated reservoir model at neighboring wells
- Used to verify model well output
- Additional verification via blind test

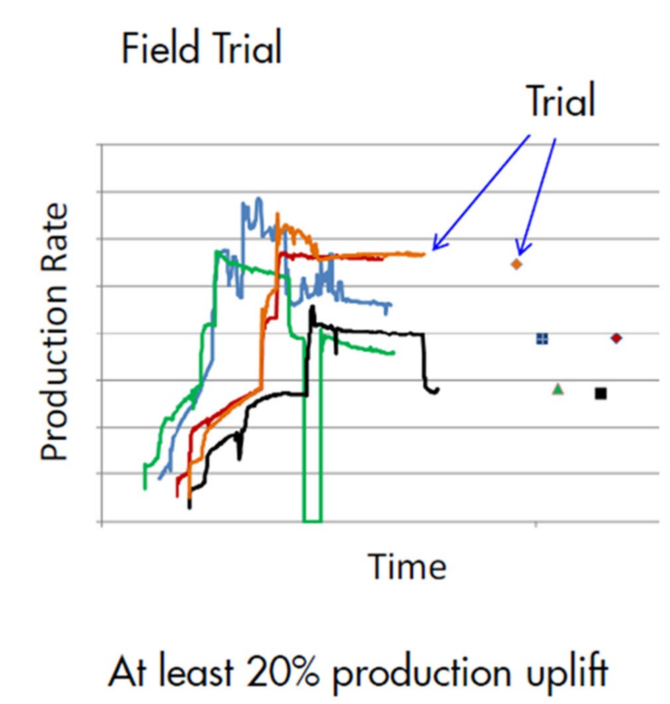
Optimizing the System

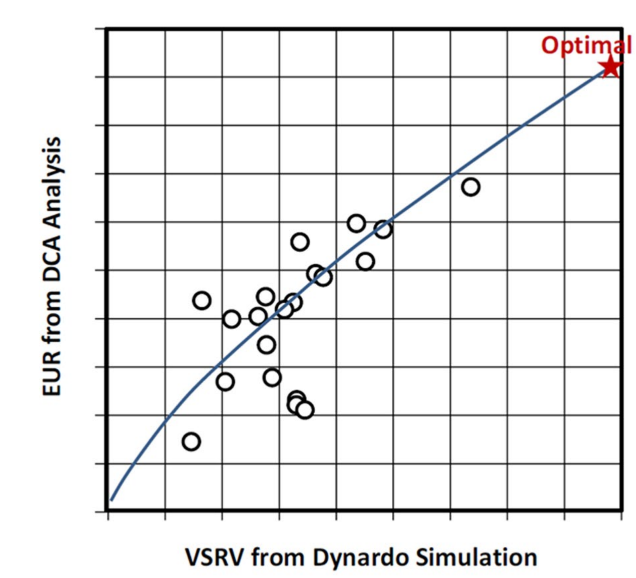


- Optimization results depend on the defined objective functions
  - Output is a Pareto plot showing the efficient frontier.
  - Incorporating cost functions allows for efficient optimization in economic space



- Goals for optimization are optimal fracture design, well landing, fluid volume, fluid rate as well as optimal well spacing.





Hydraulic Fracturing Simulator – Field Results