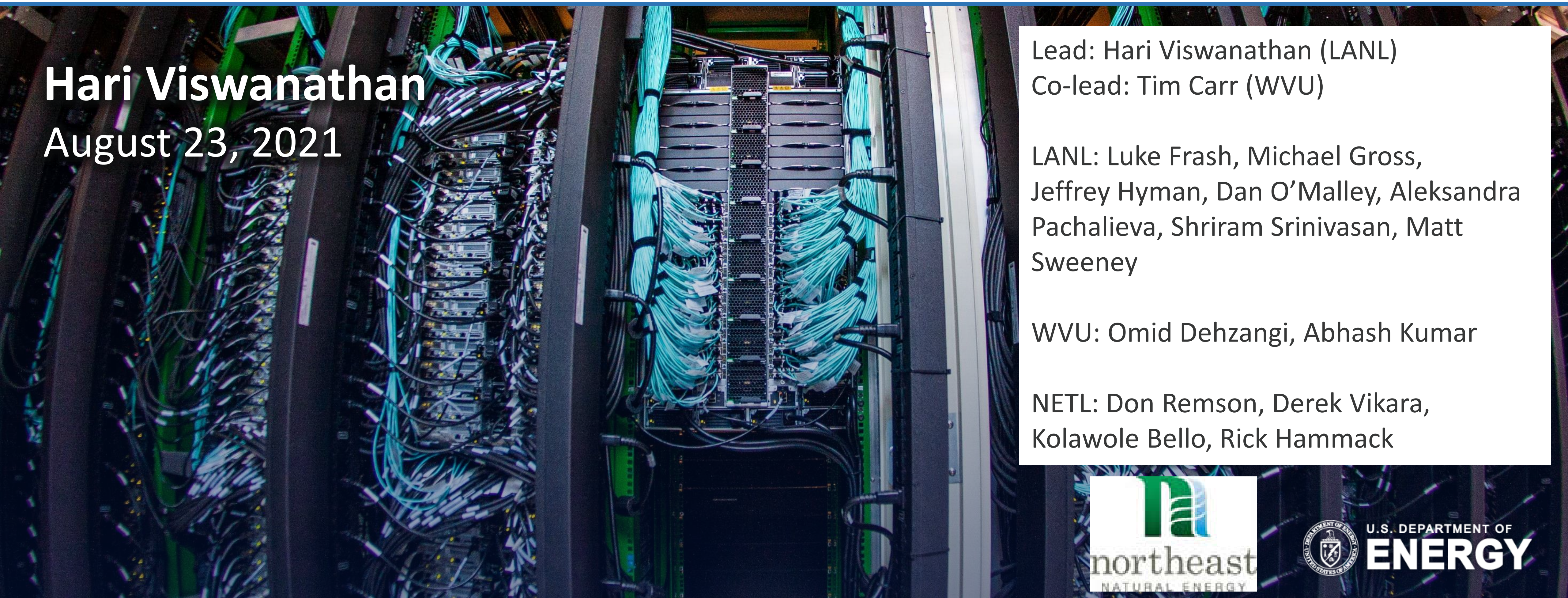
SMART Initiative

Science-informed Machine Learning to Accelerate Real Time (SMART) Decisions in Subsurface Applications



Hari Viswanathan

August 23, 2021

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Motivation: Real-Time Forecasting

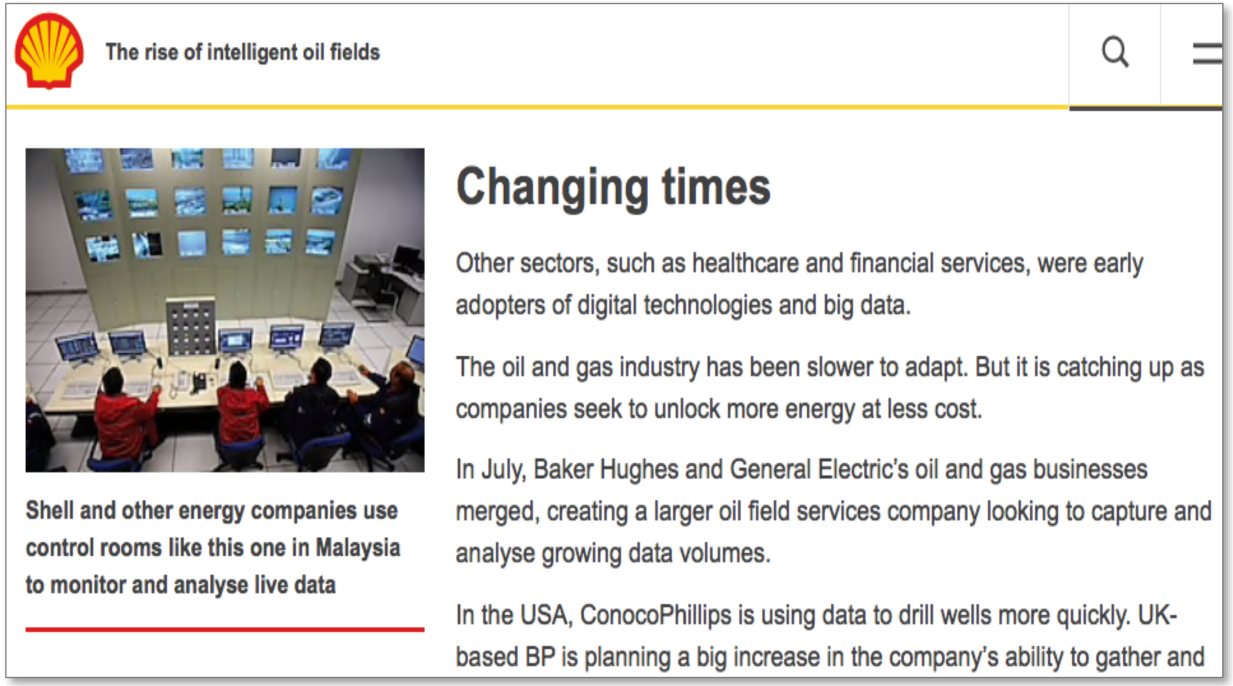
NATIONAL ENERGY TECHNOLOGY LABORATORY

Real-Time Forecasting
"Advanced Control Room"

Vision: Transform reservoir management decisions through rapid analysis of real time data to visualize forecasted behavior in an advanced control room "human-in-the-loop" format.

Real time means in seconds to minutes—rapidly enough to inform the decision.

Forecasted behavior means pressure evolution, injection/production rates, hydrocarbon recovery, storage efficiency, etc.


The rise of intelligent oil fields

Changing times

Other sectors, such as healthcare and financial services, were early adopters of digital technologies and big data.

The oil and gas industry has been slower to adapt. But it is catching up as companies seek to unlock more energy at less cost.

In July, Baker Hughes and General Electric's oil and gas businesses merged, creating a larger oil field services company looking to capture and analyse growing data volumes.

In the USA, ConocoPhillips is using data to drill wells more quickly. UK-based BP is planning a big increase in the company's ability to gather and

Shell and other energy companies use control rooms like this one in Malaysia to monitor and analyse live data

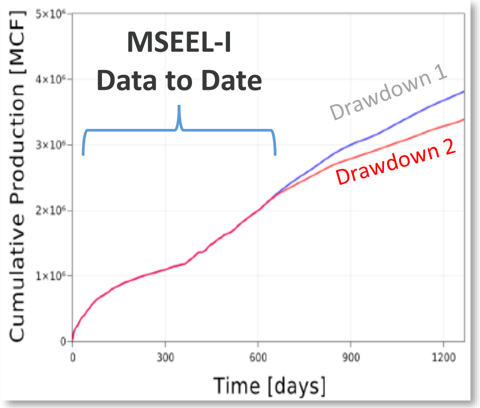
Potential Operational Decisions

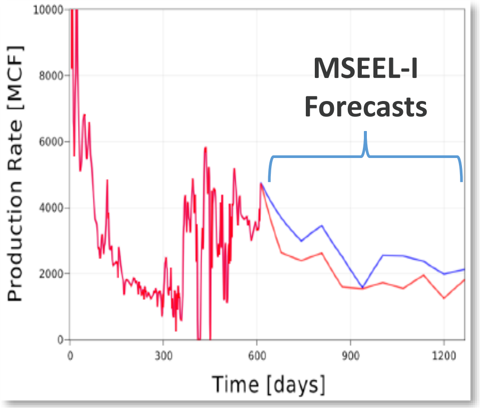
- **How to adjust production rates and pressures to maximize recovery, sweep efficiency, economics,…**
- How to adjust CO_2 injection & brine production in multiple wells to maximize storage and minimize pressure plume
- Where to place infill wells to increase total recovery
- When to inject fluids for managing reservoir pressure to increase total recovery

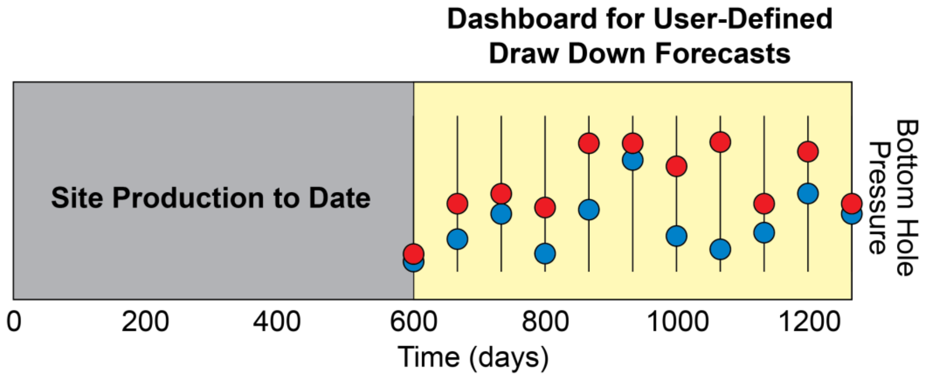
Vision: Accurate Real-time Forecasting of Fractured Reservoirs

MSEEL DOE Field Site

Real-time Pressure Management Dashboard







Prototype for Real-time Forecasting of Pressure Management Scenarios for MSEEL-I

Phase 1 Goals: Enable real-time forecasting at MSEEL to predict the pressure dependent behavior relative to recovery efficiency

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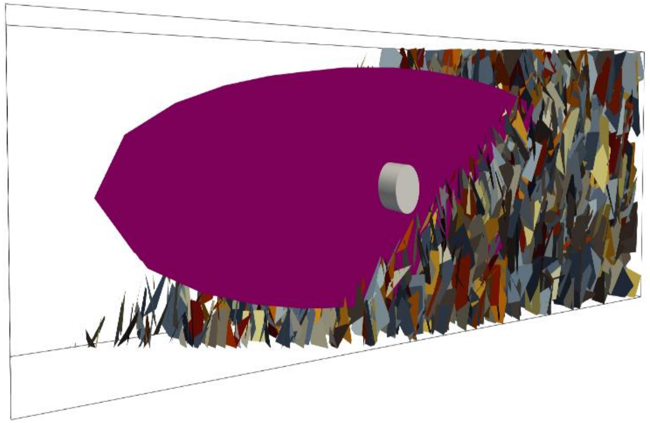
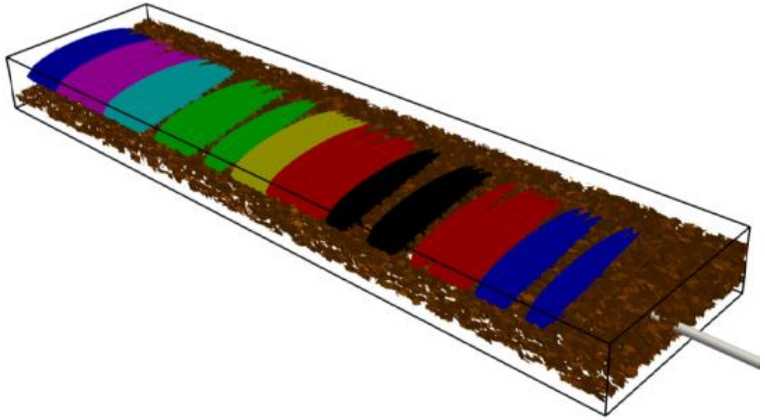
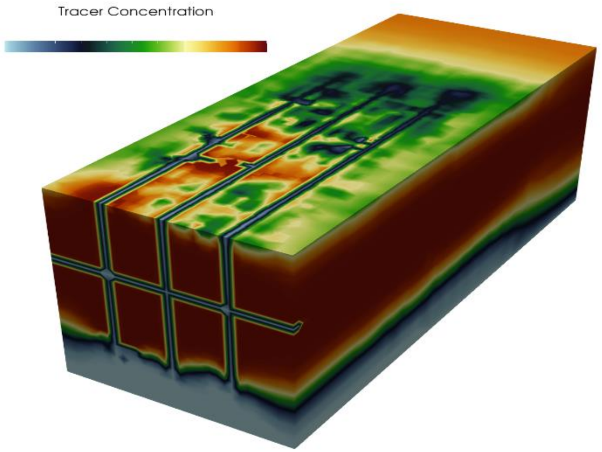


Natural fractures around a single stage in MIP-3H

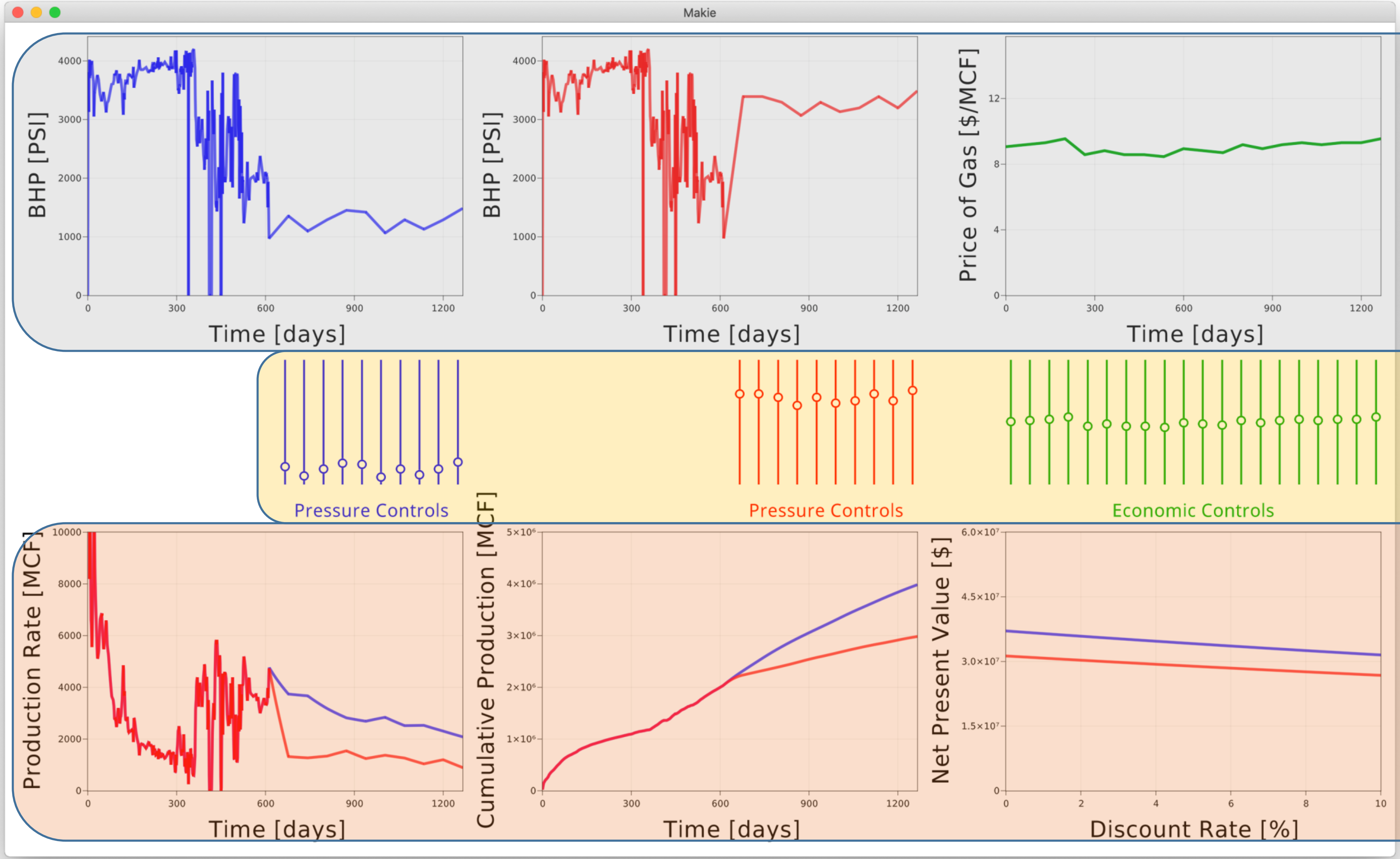


Fracture network along entirety of MIP-3H



Initial simulation of drainage along fracture network.

Real-time forecasting demo

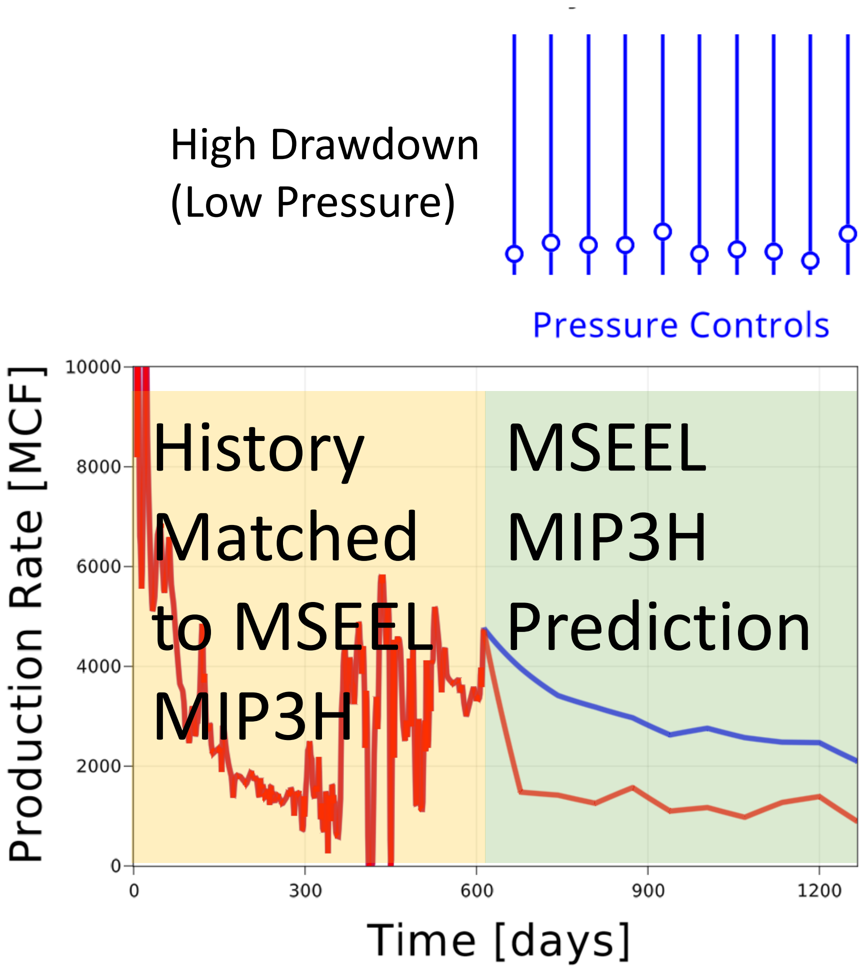


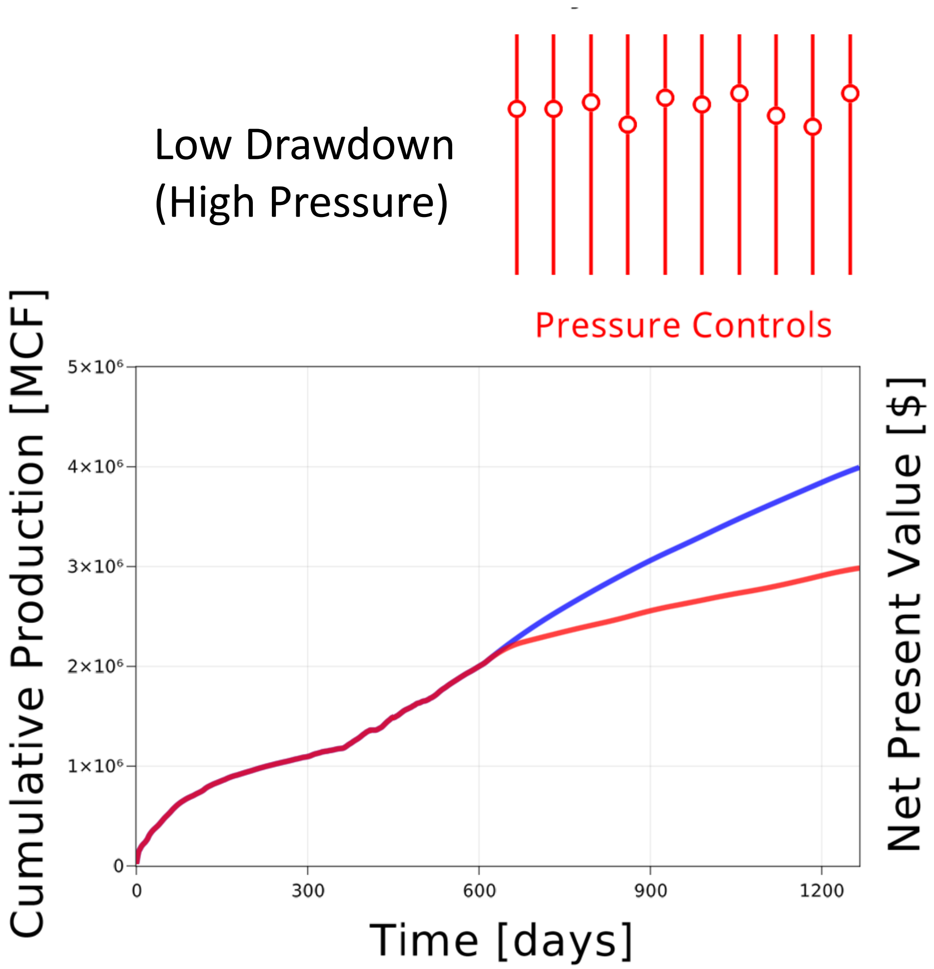
What is being controlled

Controls

Real-time predictions

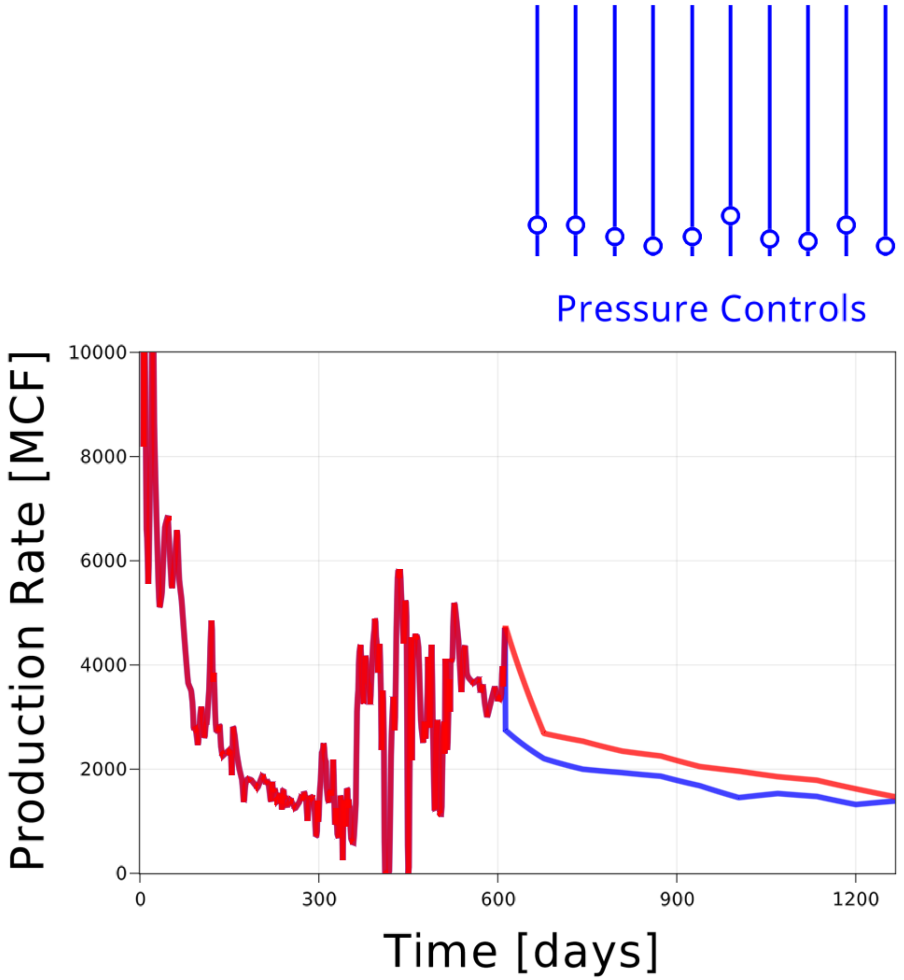
High drawdown (blue) vs low drawdown (red) with no fracture closure

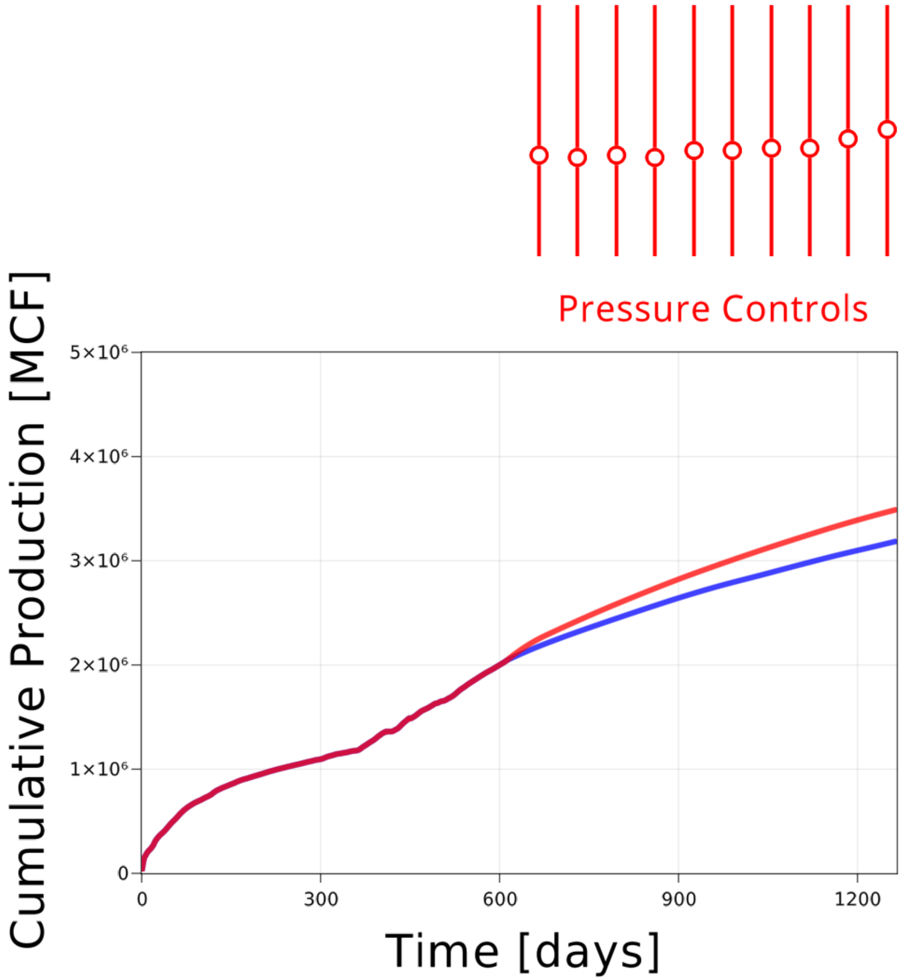




High drawdown produces 25% more gas than Low drawdown if fracture closure due to draw down is not considered, **But…**

High drawdown (blue) vs low drawdown (red) with fracture closure



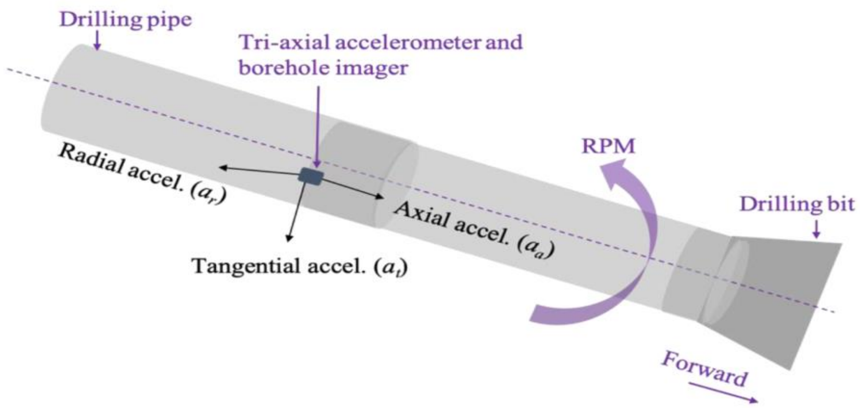


Lower drawdown can produce more with more complex physics of fracture closure considered

Key Tools Developed in Phase 1 for Phase 2 CO_2 Injection Case

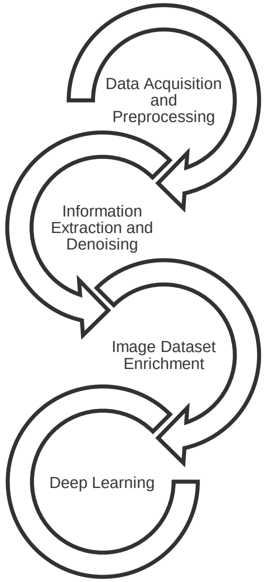
- Cost-efficient machine learning approaches to reservoir imaging and design
- Transfer Learning and Multi-Fidelity Methods
- Site Behavior Libraries
- Graph-based machine learning emulators for fractured systems
- Methods to combine reservoir forecasting and economics frecasting

WVU Characterization ML Tools

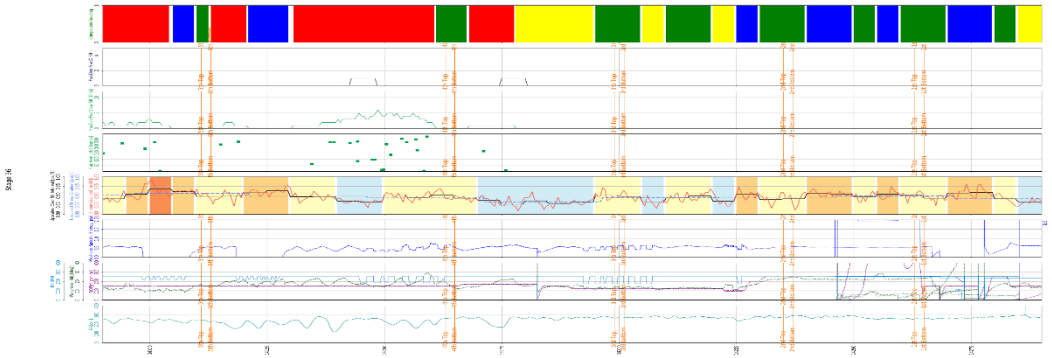


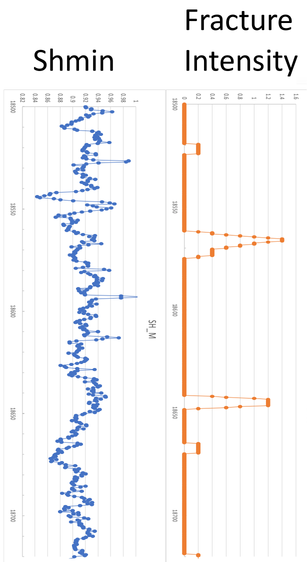
Drill string borehole imager and vibration sensor.

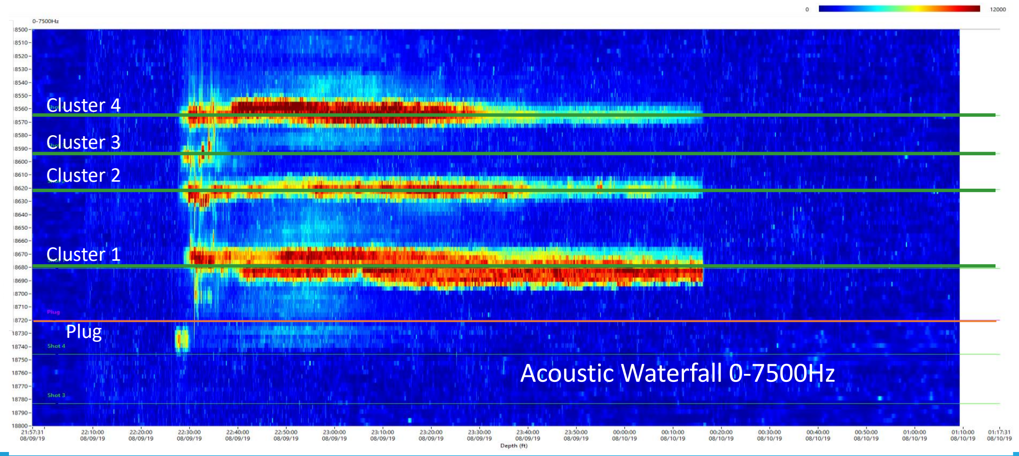
Drill String Acceleration Data Analysis



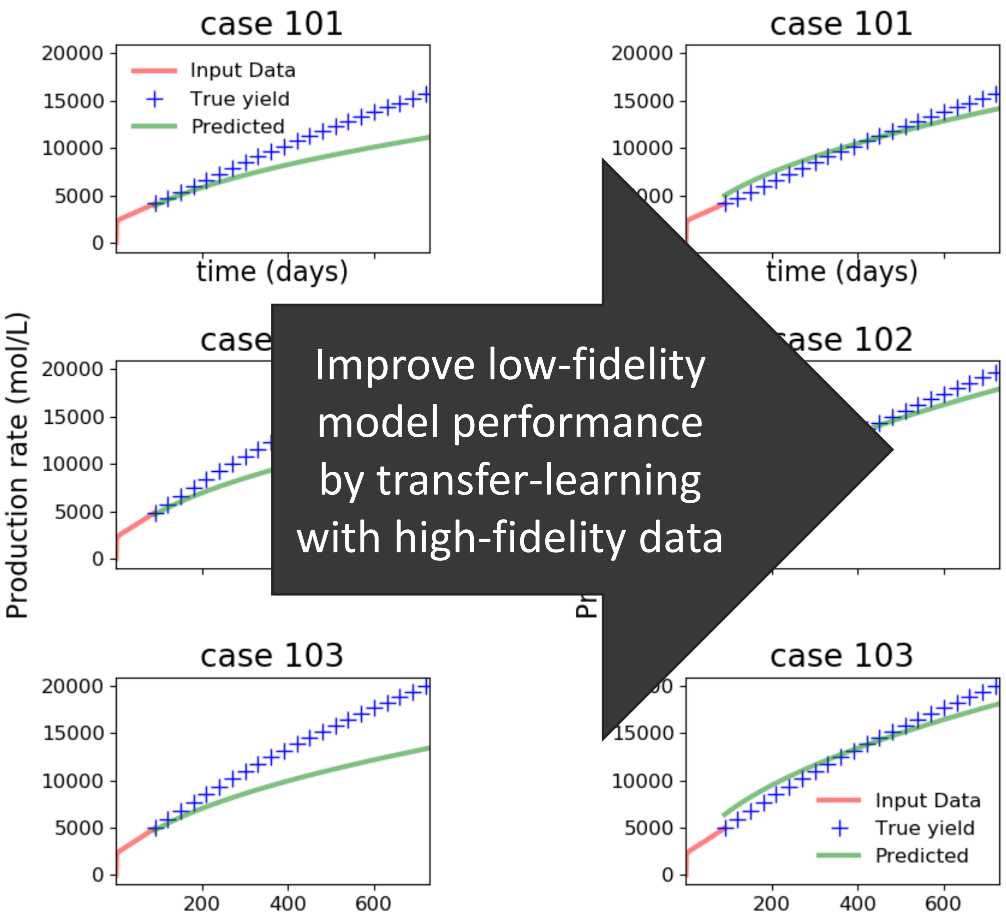
Low Fidelity Approaches Integrated with High Fidelity Approaches to make Smart Decisions

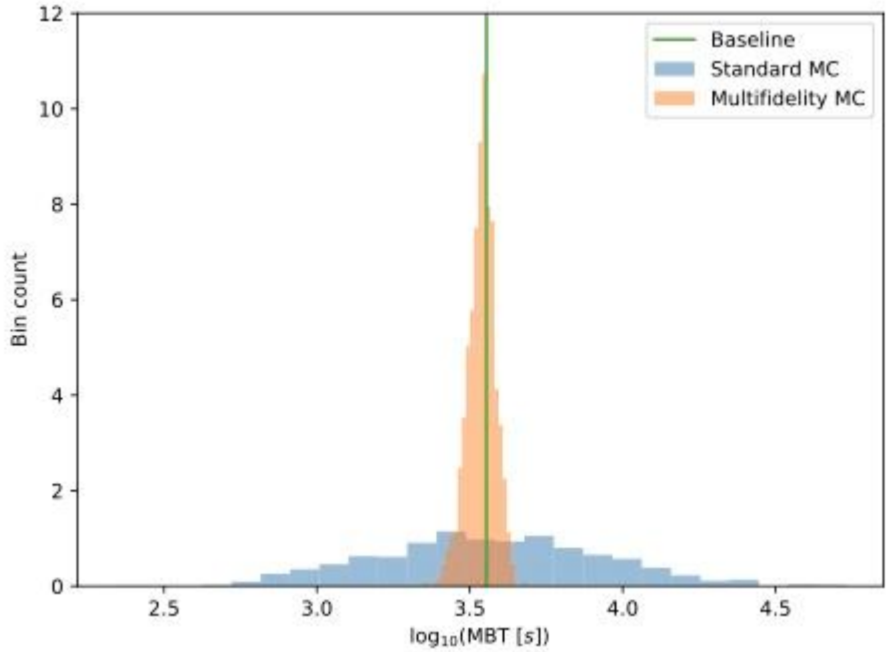






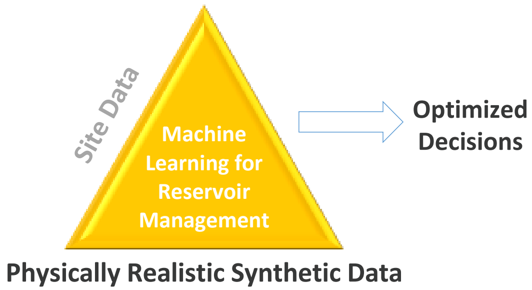
Transfer Learning and Multi-Fidelity Methods



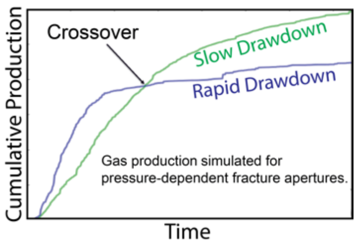


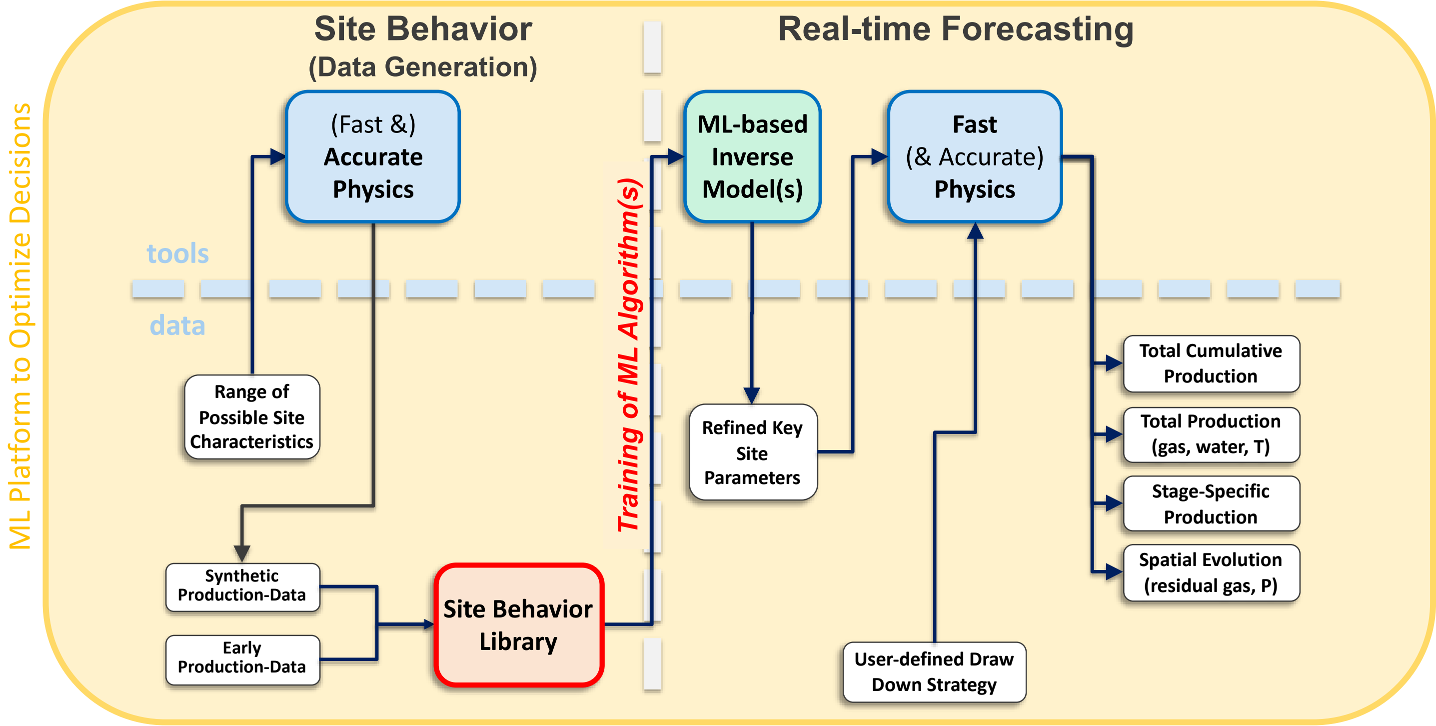
Reduce uncertainty by combining high-fidelity and lower-fidelity models for improved UQ performance

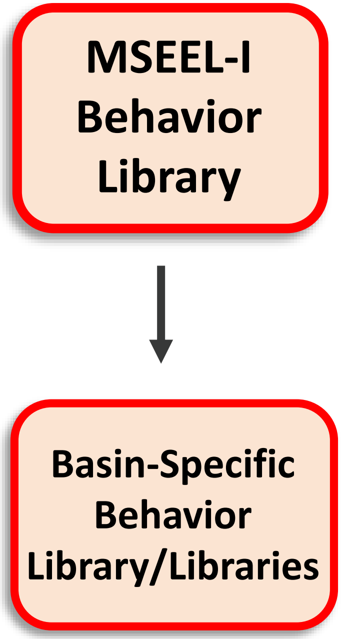
“Behavior Library” that allows operators to tailor pressure drawdown for optimum recovery.



Decision: Drawdown slowly or rapidly?



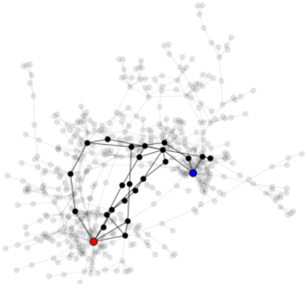




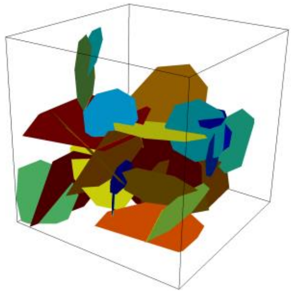
Workflow for Fractured Systems using Machine Learning and Graphs to Accelerate Physics-Based Reservoir Models

Fractured Rock at Field Site

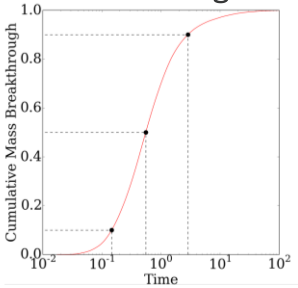
Pruned Graph



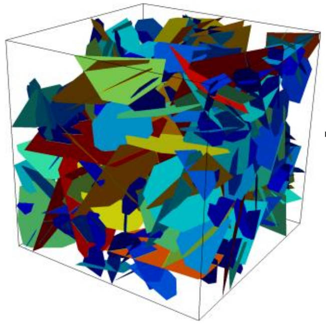
Pruned DFN



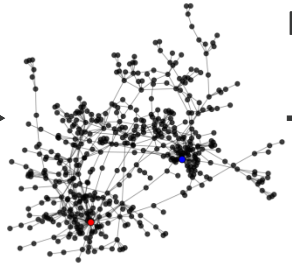
QOI - Breakthrough



Machine Learning / Physics Informed Pruning

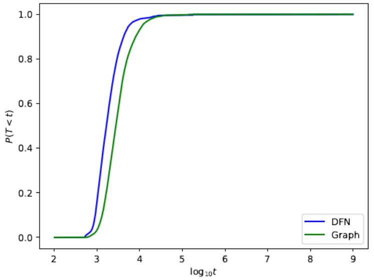


High Fidelity DFN



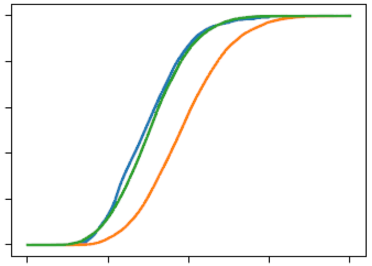
Graph Representation

Physics on Graph



QOI - Breakthrough

UQ / Bias Correction



Corrected Breakthrough

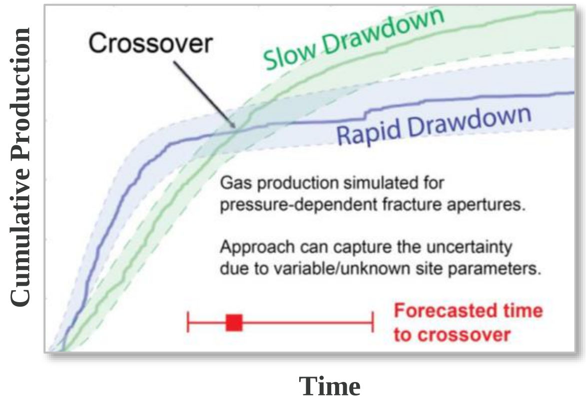
Role of Technoeconomic Analysis (TEA) in Evaluating Pressure Drawdown Strategies

- **Traditional production of unconventional oil and gas wells is aimed at acquiring high initial production via rapid pressure draw down**
  - Rapid drawdown allows the operator to realize returns on investments quickly

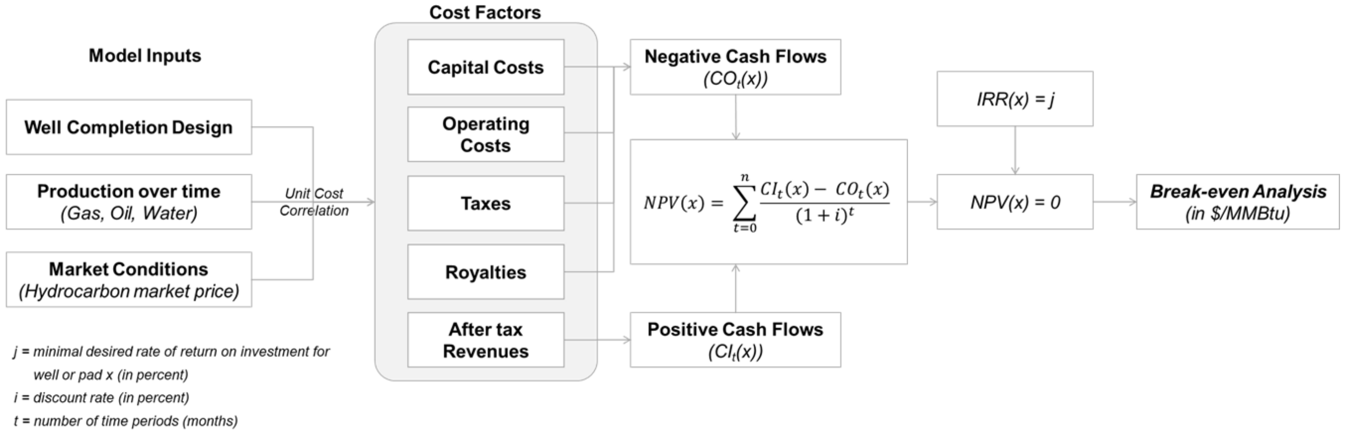
- **Preliminary modeling has shown that increasing flowing bottom hole pressure by reducing the choke setting at the wellhead can result in a greater of production over time**

- **Analysis is needed to cross-check the economic viability of the pressure management strategies resulting from the model predictions**
  - Facilitates development of optimization schemes that balance
    1. Improving recovery efficiencies of unconventional reservoirs
    2. Attaining desired economic rates of return

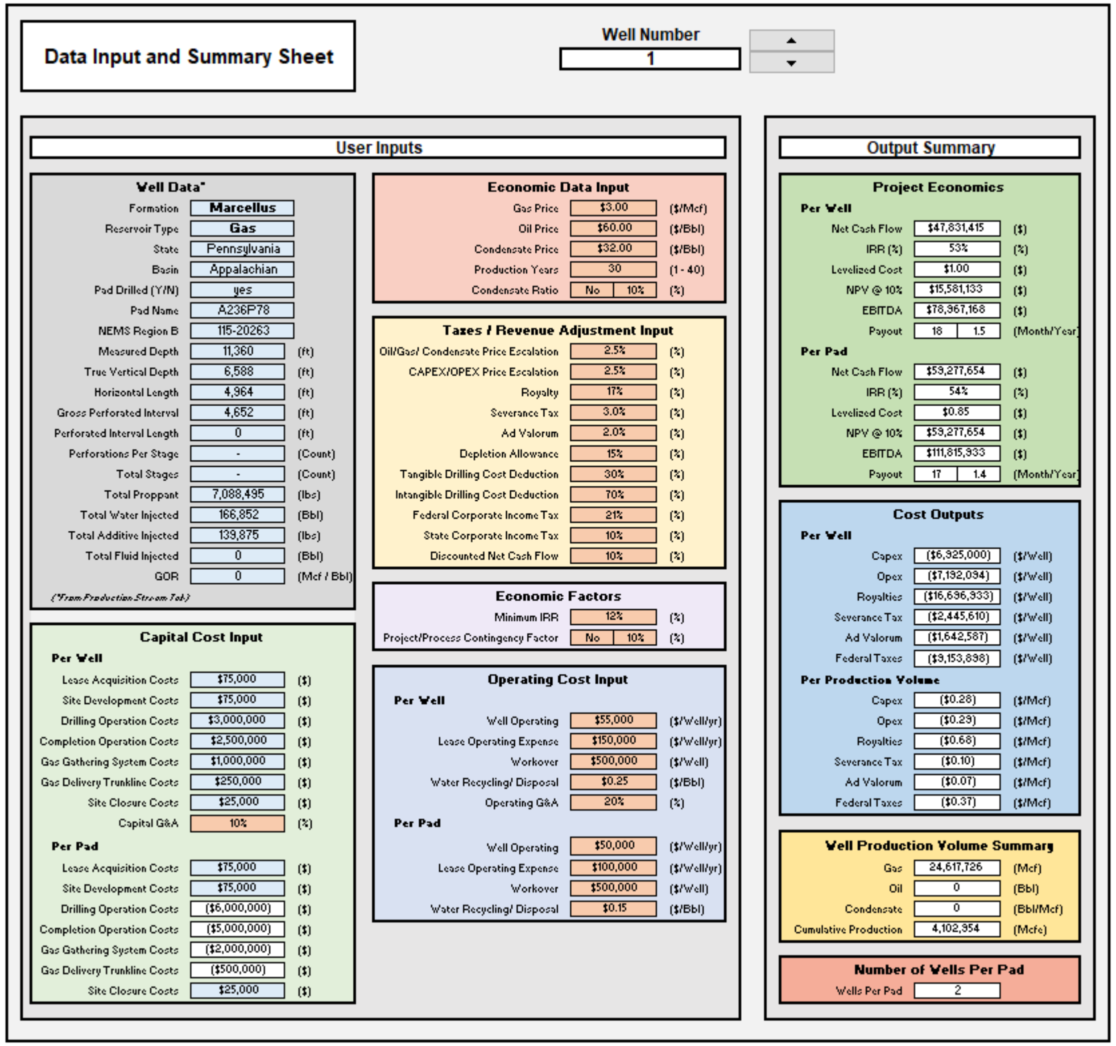
Cumulative gas production curves under large and small drawdown cases



Modeling process of technical–economic boundary of FECM/NETL Unconventional Shale Well Economic Model



NETL Economic Tools – Unconventional Shale Well Economic Model



Data Input and Summary Sheet

Well Number: 1

User Inputs

Well Data*		
Formation	Marcellus	
Reservoir Type	Gas	
State	Pennsylvania	
Basin	Appalachian	
Pad Drilled (Y/N)	yes	
Pad Name	A236P78	
NEMS Region B	115-20263	
Measured Depth	11,360	(ft)
True Vertical Depth	6,588	(ft)
Horizontal Length	4,964	(ft)
Gross Perforated Interval	4,652	(ft)
Perforated Interval Length	0	(ft)
Perforations Per Stage	-	(Count)
Total Stages	-	(Count)
Total Proppant	7,088,495	(lbs)
Total Water Injected	166,852	(Bbl)
Total Additive Injected	139,875	(lbs)
Total Fluid Injected	0	(Bbl)
GOR	0	(Mcf / Bbl)

(*From Production Stream Tab)

Capital Cost Input		
Per Well		
Lease Acquisition Costs	$75,000	($)
Site Development Costs	$75,000	($)
Drilling Operation Costs	$3,000,000	($)
Completion Operation Costs	$2,500,000	($)
Gas Gathering System Costs	$1,000,000	($)
Gas Delivery Trunkline Costs	$250,000	($)
Site Closure Costs	$25,000	($)
Capital G&A	10%	(%)
Per Pad		
Lease Acquisition Costs	$75,000	($)
Site Development Costs	$75,000	($)
Drilling Operation Costs	($6,000,000)	($)
Completion Operation Costs	($5,000,000)	($)
Gas Gathering System Costs	($2,000,000)	($)
Gas Delivery Trunkline Costs	($500,000)	($)
Site Closure Costs	$25,000	($)

Economic Data Input		
Gas Price	$3.00	($/Mcf)
Oil Price	$60.00	($/Bbl)
Condensate Price	$32.00	($/Bbl)
Production Years	30	(1 - 40)
Condensate Ratio	No / 10%	(%)

Taxes / Revenue Adjustment Input		
Oil/Gas/ Condensate Price Escalation	2.5%	(%)
CAPEX/OPEX Price Escalation	2.5%	(%)
Royalty	17%	(%)
Severance Tax	3.0%	(%)
Ad Valorum	2.0%	(%)
Depletion Allowance	15%	(%)
Tangible Drilling Cost Deduction	30%	(%)
Intangible Drilling Cost Deduction	70%	(%)
Federal Corporate Income Tax	21%	(%)
State Corporate Income Tax	10%	(%)
Discounted Net Cash Flow	10%	(%)

Economic Factors		
Minimum IRR	12%	(%)
Project/Process Contingency Factor	No / 10%	(%)

Operating Cost Input		
Per Well		
Well Operating	$55,000	($/Well/yr)
Lease Operating Expense	$150,000	($/Well/yr)
Workover	$500,000	($/Well)
Water Recycling/ Disposal	$0.25	($/Bbl)
Operating G&A	20%	(%)
Per Pad		
Well Operating	$50,000	($/Well/yr)
Lease Operating Expense	$100,000	($/Well/yr)
Workover	$500,000	($/Well)
Water Recycling/ Disposal	$0.15	($/Bbl)

Output Summary

Project Economics		
Per Well		
Net Cash Flow	$47,831,415	($)
IRR (%)	53%	(%)
Levelized Cost	$1.00	($)
NPV @ 10%	$15,581,133	($)
EBITDA	$78,967,168	($)
Payout	18 / 1.5	(Month/Year)
Per Pad		
Net Cash Flow	$59,277,654	($)
IRR (%)	54%	(%)
Levelized Cost	$0.85	($)
NPV @ 10%	$59,277,654	($)
EBITDA	$111,815,933	($)
Payout	17 / 1.4	(Month/Year)

Cost Outputs		
Per Well		
Capex	($6,925,000)	($/Well)
Opex	($7,192,094)	($/Well)
Royalties	($16,696,933)	($/Well)
Severance Tax	($2,445,610)	($/Well)
Ad Valorum	($1,642,587)	($/Well)
Federal Taxes	($9,153,898)	($/Well)
Per Production Volume		
Capex	($0.28)	($/Mcf)
Opex	($0.29)	($/Mcf)
Royalties	($0.68)	($/Mcf)
Severance Tax	($0.10)	($/Mcf)
Ad Valorum	($0.07)	($/Mcf)
Federal Taxes	($0.37)	($/Mcf)

Well Production Volume Summary		
Gas	24,617,726	(Mcf)
Oil	0	(Bbl)
Condensate	0	(Bbl/Mcf)
Cumulative Production	4,102,954	(Mcfe)

Number of Wells Per Pad	
Wells Per Pad	2

Model evaluates economics of unconventional shale wells on a per well and per pad level

The model allows for direct comparison of alternative technologies through multiple profitability indicators

Model Input

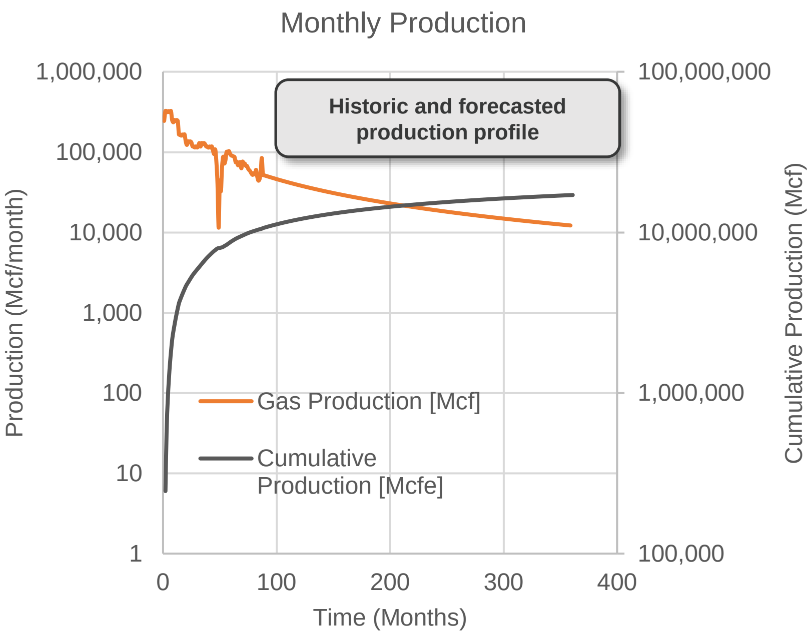
- Production data for the life of the well
- Can compare the economics of 700 wells in a single model run

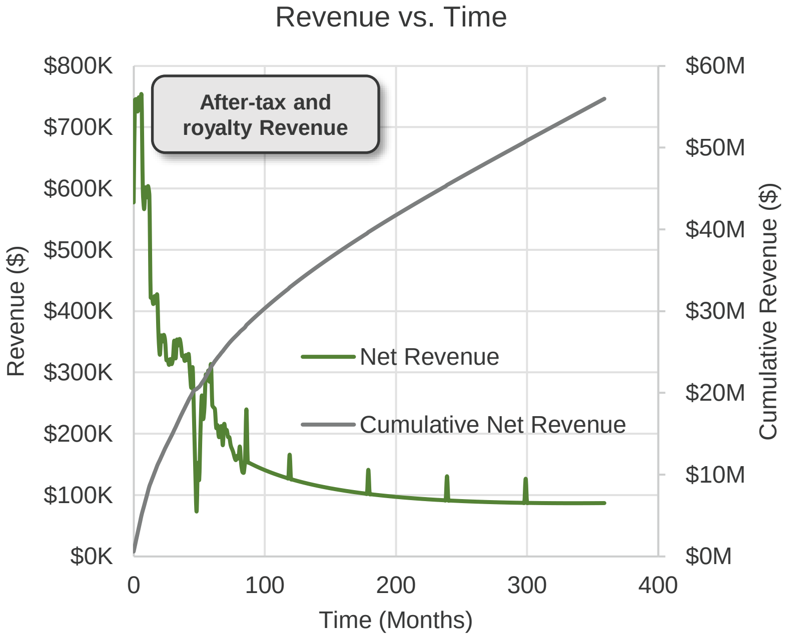
Model Outputs (month or pad basis)

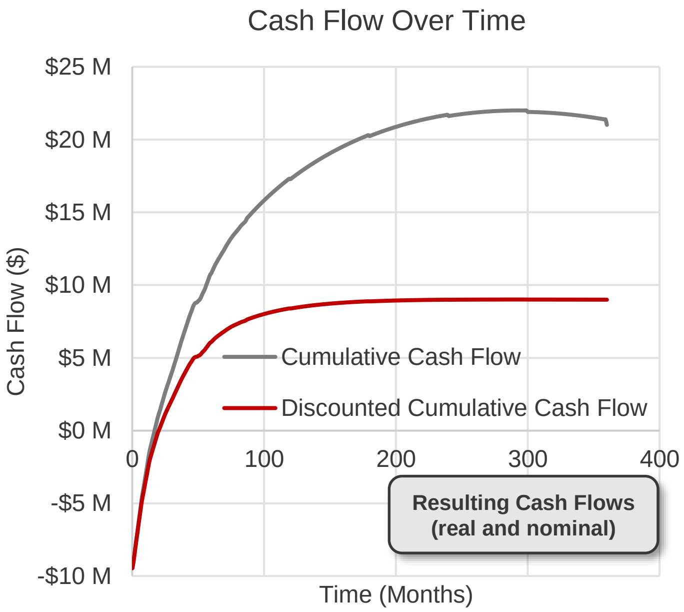
- Net cash flow, NPV, IRR, EBITDA, breakeven price, payout month, and payout year

NETL Economic Tools – Unconventional Shale Well Economic Model

NETL is augmenting the existing Task 7 Phase I efforts by leveraging the Unconventional Shale Well Economic within the LANL/WVU workflow to enable a robust TEA analytical capability







Research Approach:
1) Infuse time-series production data generated from LANL that explore various drawdown strategies
2) Evaluate and analyze modeling results
3) Perform sensitivity analyses on economic parameters to assess impact on result outcomes

Phase 2 Planning: CO_2 sequestration in saline aquifer

- Pressure management is equally important for injecting fluid and CO_2 sequestration
  - Optimize CO2 without setting off felt seismic events
  - Optimize most gas in without harming reservoir (inverse of O&G)
- How do we transition oil sector to storage sector?
  - Big companies not really doing it (optimize storage but going after product)
  - Will be small independents but they don't have R&D
- Integrate task 7 tools with tasks 1-6
  - MSEEL WVU tools: 1) leaks we can characterize, 2) seismic hazard characterization, 3) ML to characterize data
  - Transfer learning and multi-fidelity machine learning tools
  - Scenario libraries
  - Graph-based machine learning emulators for fractured systems
  - Economic tools integrated with machine learning workflows is unique

Questions?

Thank you!

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