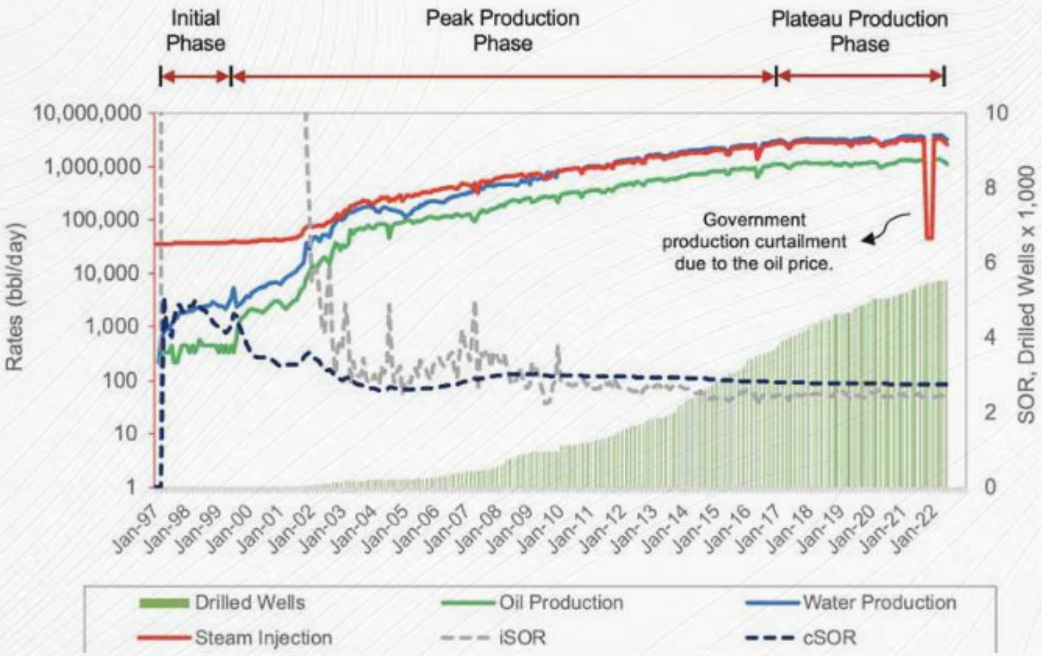
基于溶剂的稠油提高采收率模拟技术
Enabling the Future of Solvent-Based EOR

CMG

Current Status of SAGD in Canada

Comprises 25% of the Canadian oil production – 1.44 million bbl/day



30 years of SAGD performance

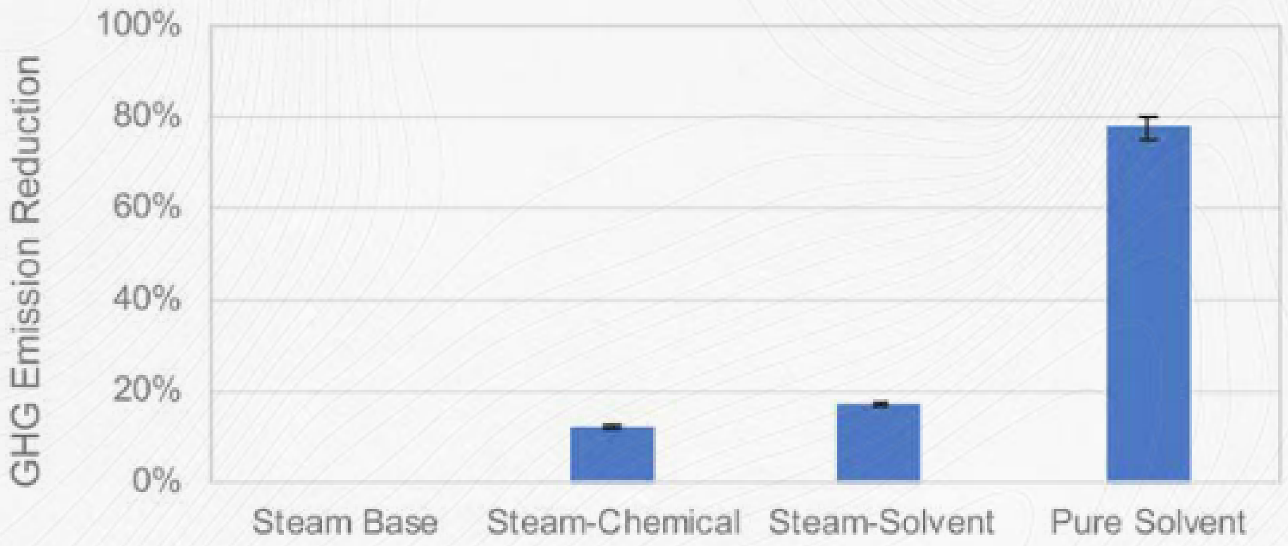
22 SAGD projects

300 pads and 2,700 well pairs

Active SAGD projects distribution*

*Modified from SPE-212970-MS and DOI:10.5194/acp-15-3893-2015

Great Potential for Thermal Technologies



SAGD/post-SAGD improvements in reducing GHG emissions (adopted from Canadian Energy Research Institute 2020)

Steam - Chemical:

- Alkalis
- Surfactants
- Ionic liquids
- Solvents
  - dimethyl ether
  - diethyl ether
  - additives
- Nanoparticles
- Chelating agents
- Deep eutectic solvents
- Biodiesel
- Switchable-hydrophilicity solvent

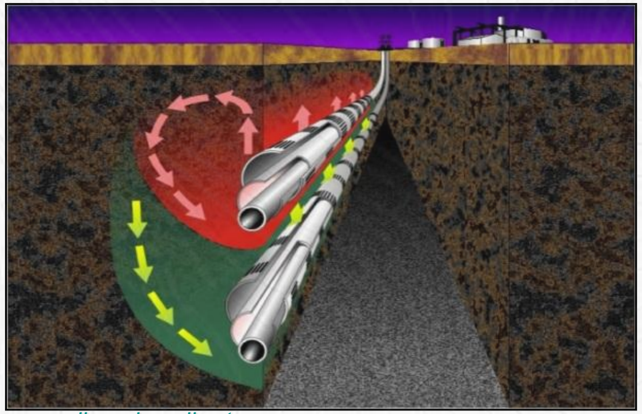
Solvents

- NCG (methane)
- CG (propane)
- Liquid (C5+)

Steam Processes

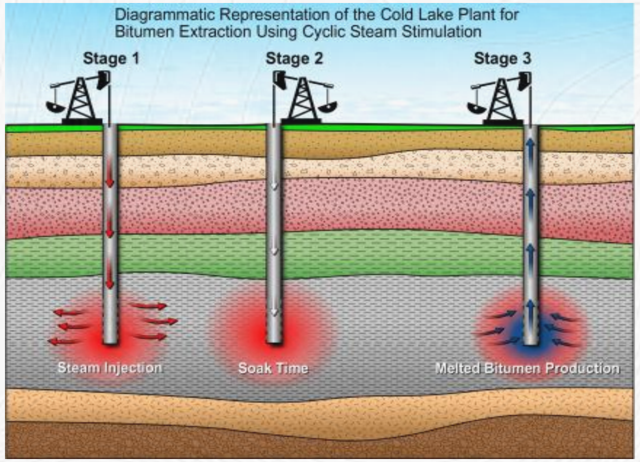
- High temperature steam
- Heavy oil viscosity reduction by temperature
- Heat loss to the surrounding formations
- Up to 70% recovery
- High operating cost

Steam Assisted Gravity Drainage (SAGD)



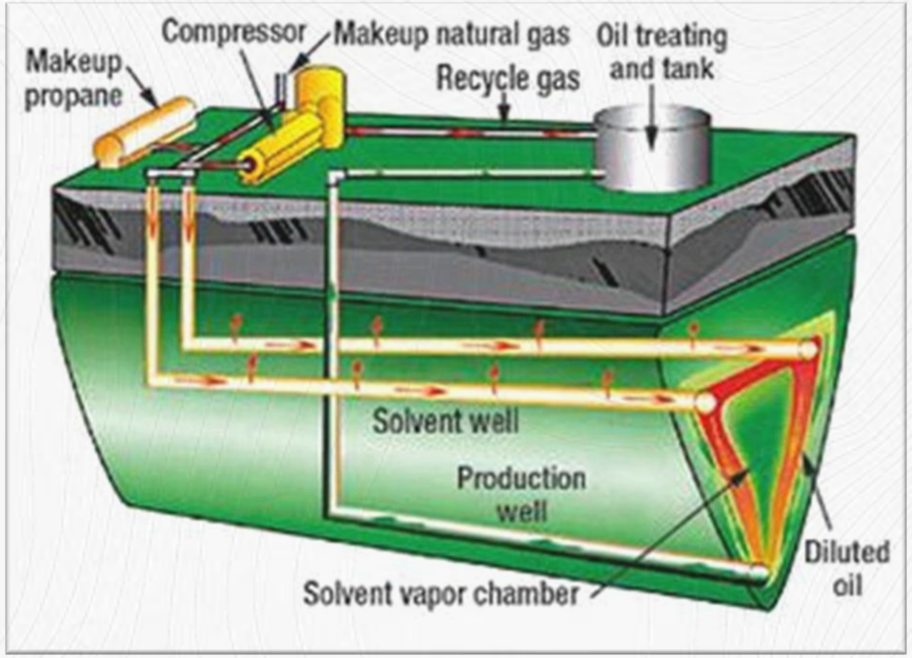
www.oilsands.ualberta.ca

Cyclic Steam Stimulation CSS



Solvent Processes

- Solvent dissolution reduces oil viscosity
- Solvents in vapor phase decrease trapping
- Solvents mostly stay with the oil
- Diffusion and dispersion of solvent control the dilution and mixing process
- Mass-transfer is often slower than heat transfer



http://bittooth.blogspot.ca

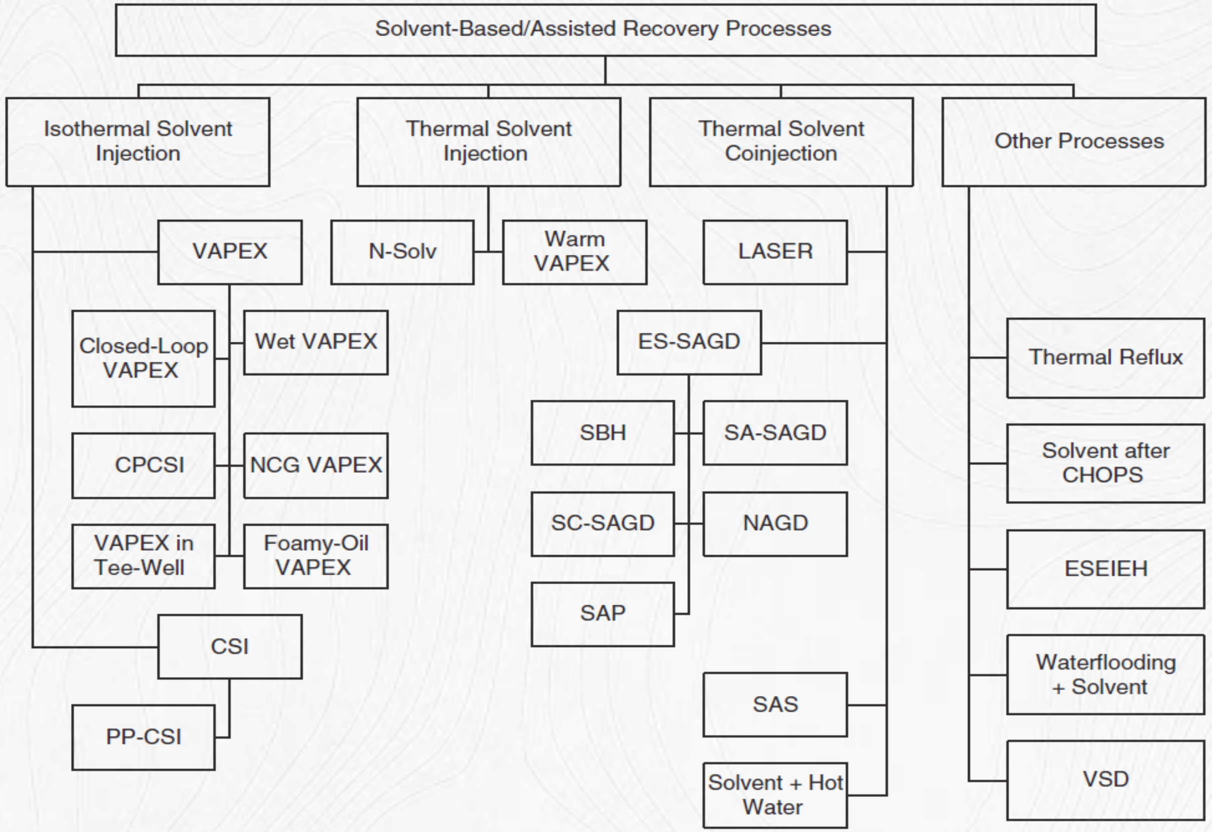
Solvent-Based Recovery Processes

Hybrid Processes

- Addition of heat to VAPEX
- Addition of solvent to SAGD/CSS/Steamflood

Examples

- Heated solvent injection (N-Solv)
  - Solvent is injected at the dew point of the reservoir condition
- Expanding solvent SAGD (ES-SAGD)
- Solvent aided SAGD (SA-SAGD)
- Steam and gas push (SAGP)
- VAPEX initiated by SAGD (SAVEX)
- Steam alternating solvent (SAS)
- Liquid addition to steam for ER (LASER)



Key Development Areas

Solvent Process Wizard
- For Quicker Model Setups
- Boundary leak-off considerations

Post-Processing Workflows
- For arriving to insights sooner

Advanced Process Dynamics
- Viscosity Mixing
- Rate-Dependent Dissolution/Exsolution
- Asphaltene Deposition
- Comp-Dependent Rel Perms

Advanced Well Dynamics
- Extensibility of well controls
- Coupling to a strong wellbore model

Modelling More than 3-Phases
- Multiple oleic phases

> Workstream Development Plans

> Current Status of Developments

> What is Coming Next

Solvent Process Wizard

Creation of a comprehensive guided task for providing step-by-step input support for solvent studies. Intended to include the key physics of consideration and intelligent default values

2024 Q4

- Initial concepts and workflow

2025 Q1

- Develop key requirements and flow

2025 Q2

- **Storyboarding and Mockups - validation with Operators and Research Consortiums**

2025 Q3/Q4

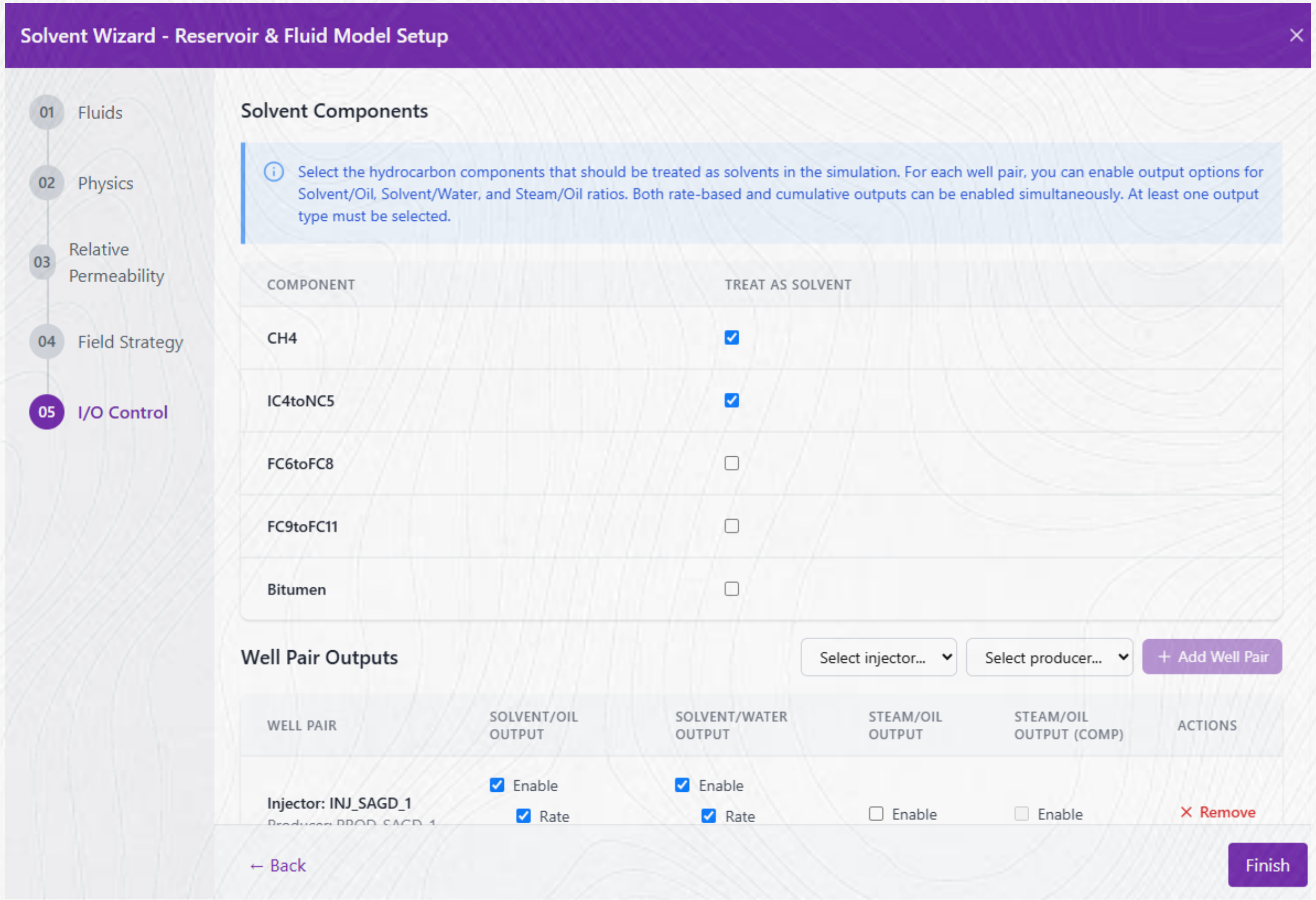
- Iterative development and validation for process-wizard within Builder platform

2025 Q4+

- Release of Wizard and further workflow validations

Solvent Process Wizard

- **Streamlined Workflow**
  - Structured, step-by-step process
- **Reduced Complexity**
  - Automates key setup tasks
- **Improved Consistency & Accuracy**
  - Standardization in model setup
- **Friendly Design**
  - Guided inputs, tooltips, and error handling to support both expert and new users



Post-Processing Workflows

Ability to 'Tag' Solvent components and auto-output key metrics for analysis

2024 Q4

- **Released** solvent-based automatic outputs
- **Released** SR3 output file optimization for enhanced interactivity support in Results

2025 Q1

- **Released** Optimization for plotting FlexWell results and metrics

2025 Q2+

- Follow-up developments on solvent-based inputs/outputs
- Investigation into CMOST + Solvent workflows
- **Released (2025.20)** - Results Template for Solvent Processes (pre-defined plots/dashboards)

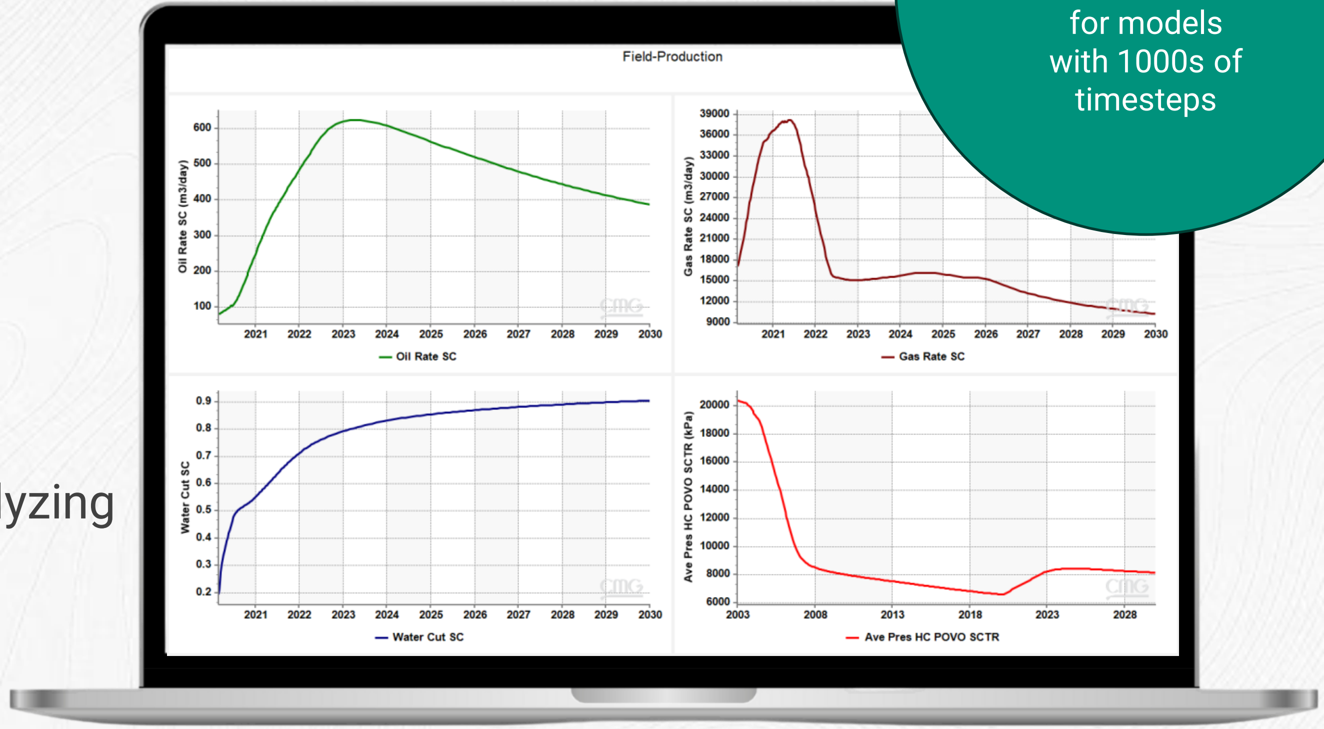
CMG

Performance Enhancements via SR3 Optimization

SR3 Optimized for Results performance:

- Optimize SR3 files in CMG Launcher
- Load simulation result files (SR3) significantly faster in RESULTS
- Plot timeseries instantaneously
- Profile plotting speed drastically improved
  - **Under 3s**
- Works with all three simulators IMEX, GEM and STARS
- Spend less time waiting and more time analyzing

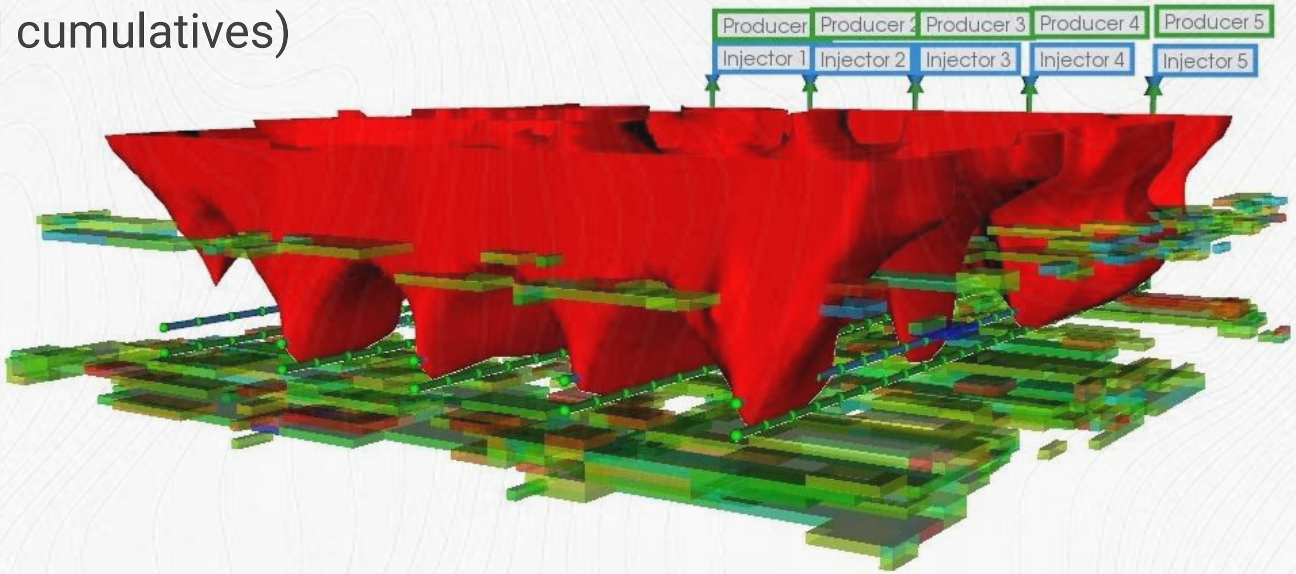
Up to **60x faster**
for models with 1000s of timesteps



Greatly reduce the time spent in Results dashboards and formula setups

Tag Components as ‘Solvents’ for output purposes – auto-outputs:

- Solvent split from oil (i.e. non-solvent oil rates and cumulatives)
- Solvent inj and prod, rates and cumulatives
- Solvent-Oil Ratio, inst. and cumulative
- Solvent-Water Ratio, inst. and cumulative
- Solvent Recovery

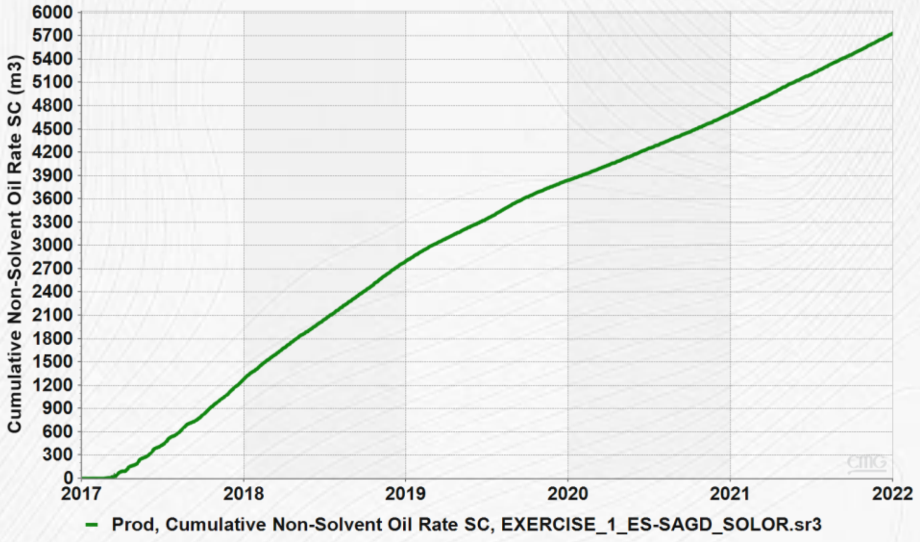


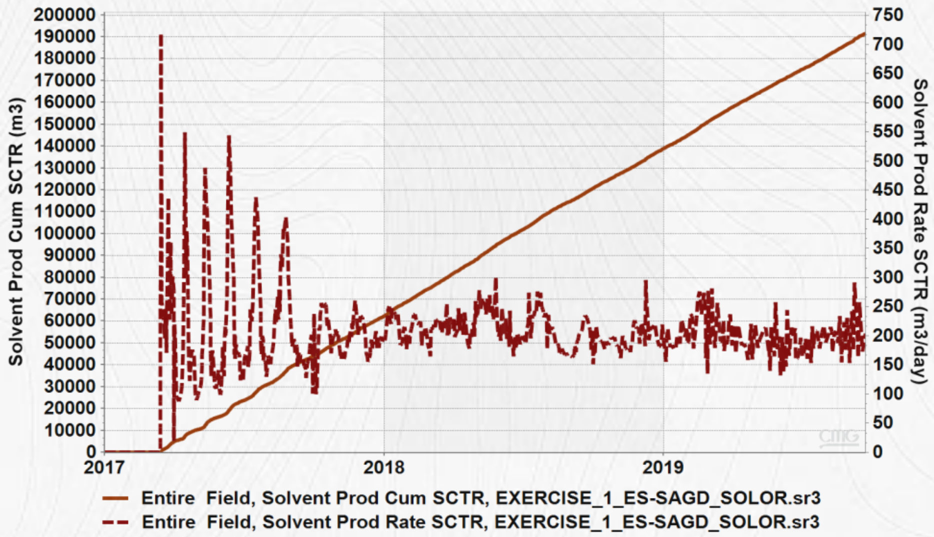
Outputs available per-sector and well pair

Reduce challenges in defining uncertainty & optimization workflows in **CMOST**.

Greatly reduce the time spent in Results dashboard and formula setups

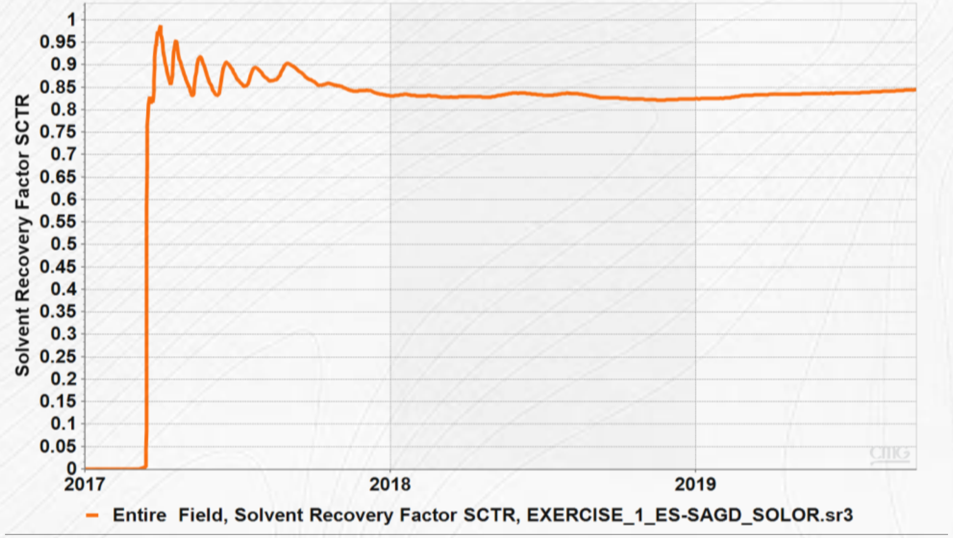
Net Non-Solvent Cumulative Oil Production

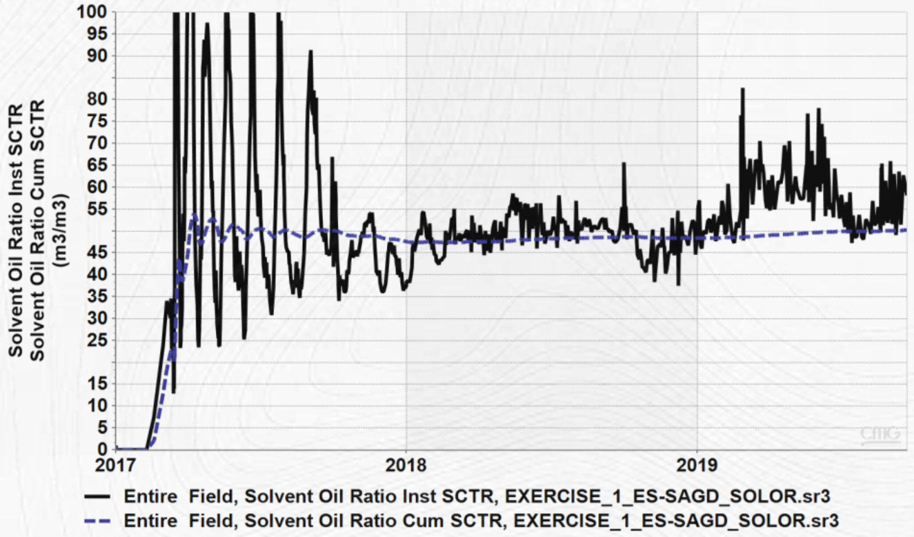




Produced Solvent Rate and Cumulative

Dynamic Solvent Recovery Factor





Instantaneous and Cumulative Solvent-Oil Ratio

Process Dynamics – Viscosity Mixing

Flexible input for a Generalized Viscosity Mixing Table Format into STARS. Different tables for each phase; pressure, temperature and composition effects.

2025 Q1

- Beginning development (including detailed research into methodologies)

2025 Q2

- **Released (2025.20)** – Additional Viscosity Mixing Correlations

2025 Q3+

- Generalized Viscosity Mixing Tables in STARS
- Considerations for any additional, specific details or correlations (would require direct information – correlations/papers/data)

Process Dynamics – Viscosity Mixing

Prior to 2025.10

- Linear
- Non-Linear
    - Log-Log
    - Mole or Mass-Fraction based

New in 2025.20

- Bingham
- Cragoe
- Mehrotra
- Chirinos
- Power-Law
- Arrhenius
- Expanded-Fluid (EF)

Linear	$\mu_{mix} = \sum_{i=1} x_i \mu_i$
Power-law	$\mu_{mix}^n = \sum_{i=1} x_i \mu_i^n$
Arrhenius	$\ln(\mu_{mix}) = \sum_{i=1} x_i \ln(\mu_i)$
Double-double log	$\log(\log(\mu_{mix}+1)) = \sum_{i=1} x_i \log(\log(\mu_i+1))$
Kendel	$\frac{1}{3}\ln(\mu_{mix}) = \sum_{i=1} \frac{1}{3} x_i \ln(\mu_i)$
Bingham	$\frac{1}{\mu_{mix}} = \sum_{i=1} \frac{x_i}{\mu_i}$
Crago	$\frac{1000\ln(20)}{\ln\left(\frac{\mu_{mix}}{5\times10^{-4}}\right)} = \sum_{i=1} x_i \frac{1000\ln(20)}{\ln\left(\frac{\mu_i}{5\times10^{-4}}\right)}$
Forth-root	$\mu_{mix}^{-0.25} = \sum_{i=1} x_i \mu_i^{-0.25}$
Wilkie	$\mu_{mix} = \frac{\sum_{i=1} x_i \varphi_i \mu_i}{\sum_{i=1} x_i \varphi_i}$
Mehrorta	$\log(\mu_{mix}+0.7) = \sum_{i=1} x_i \frac{M_i}{M_{mix}} \log(\mu_i+0.7)$
Refutas	$A\log(\log(\mu_{mix}+0.8)) + B = \sum_{i=1} (Ax_i \log(\log(\mu_i+0.8)) + B)$
Chirinos	$\log\left(\log\left(\frac{\mu_{mix}}{\rho_{mix}}+0.7\right)\right) = \sum_{i=1} x_i \log\left(\log\left(\frac{\mu_i}{\rho_i}+0.7\right)\right)$

Process Dynamics – Viscosity Mixing

```
GENVISTABLE    OIL
     PRESS               2000   3000   4000
     TEMP                50     100
     MFRAC     'C3'      0.1    0.2    0.3    0.4    0.5    0.6    0.7

** P   T   FR (C3)       0.1    0.2    0.3    0.4    0.5    0.6    0.7
   1   1                 590    470    390    270    230    190    180
   1   2                 550    450    370    260    210    170    140
   2   1                 600    490    400    282    241    199    187
   2   2                 559    458    380    267    217    182    149
```

Process Dynamics – Rate Dependent Dissolution/Exsolution, Asphaltene Modelling, & Compositional-Dependent Rel Perms

Validation of current capabilities to known data and enhancements for easier setup and more stable simulations.

2025 Q3

- ODE Integrator (Begin Development) – greater stability/speed for reaction modelling

2025 Q4

- ODE Integrator (*Release in STARS*)
- ODE Integrator – scoping for GEM implementation

2026 Q1+

- Process-Wizard for simplifying setup of rate-dependent dissolution/exsolution, Asphaltene Modelling, and Compositional/Temp-Dependent Rel Perms
- Improved mechanistic modelling of asphaltenes from C3-C4 solvents (requires 4-phase capabilities for multi-oleic phase considerations)

Advanced Well Dynamics

Enhancing extensibility of simulators to work with complex well controls and scripts.
Consideration of strong wellbore modelling module.

2024

- Development of Drift-Flux formulation for FlexWell
- PyControl Enhancements to support external scripts

2025 Q1

- **Released** - Drift-Flux formulation in FlexWell, Phase 1 (Co-Current)
- **Released** - Pump with Segregation Enabled in FlexWell

2025 Q2+

- **Released (2025.20)** Drift-Flux, Phase 2 (Counter-Current, Liquid Level); Emulsion-Dispersion
- Downhole Separator with FlexWell
- Further stability of FlexWell to provide greater performance
  - New linear solver, compute velocity implicitly, parallelization of FlexWell

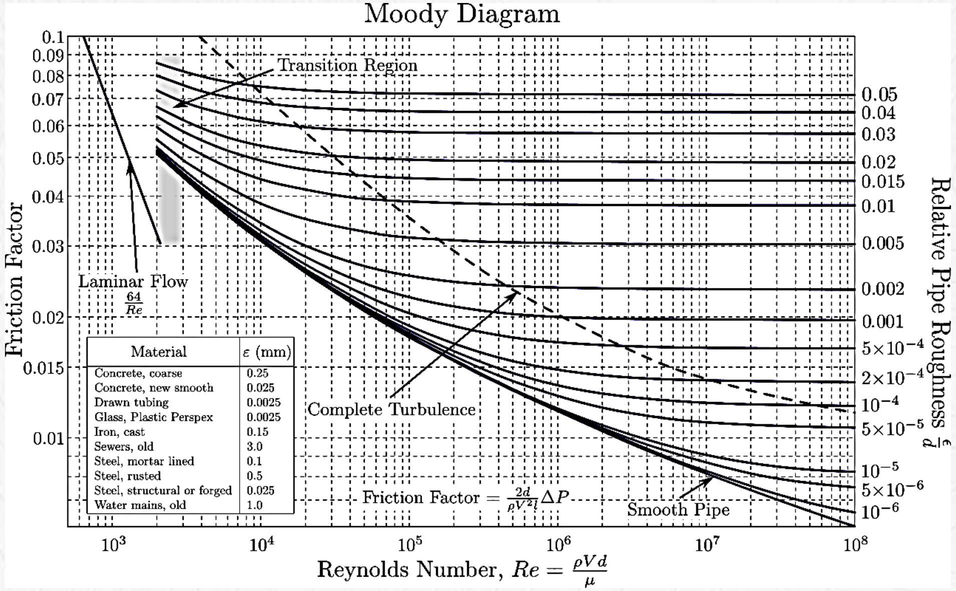
Original Formulation

$$f_D = \begin{cases} \dfrac{64}{Re} & \textit{Laminar} \\ \left(\dfrac{-0.5}{\log_{10}\left(\dfrac{(\varepsilon/D)}{3.7} + \dfrac{2.51}{Re\sqrt{f_D}} \right)} \right)^2 & \textit{Turbulent} \end{cases}$$

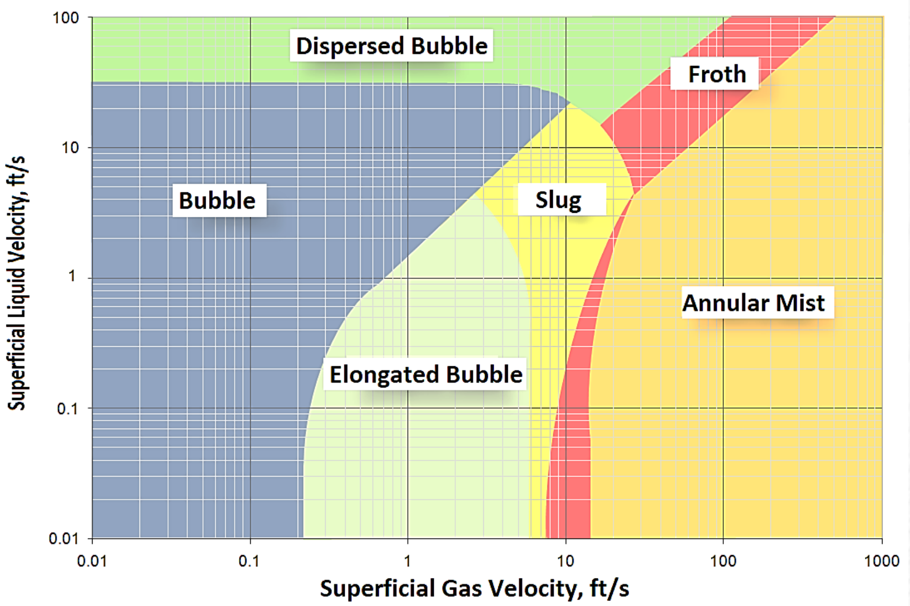
$$\Delta\Phi = \frac{\rho f_{cor} f_D v|v|}{2} L/D = K_{cor} v \quad (\text{per phase})$$

- Multi-phase momentum Eqs.
- Flow regime calculation
- High fidelity pressure drop
- Discontinuous correlations

f_D



f_{cor}



Updated Formulation

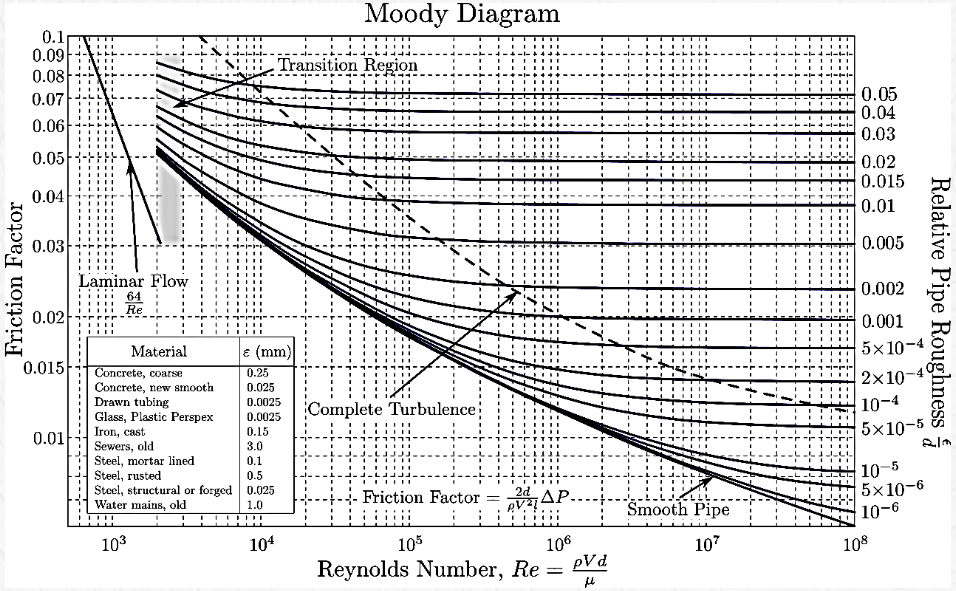
$$f_D = \begin{cases} \frac{64}{Re} & Laminar \\ \left(\frac{-0.5}{\log_{10}\left(\frac{(\varepsilon / D)}{3.7} + \frac{2.51}{Re\sqrt{f_D}} \right)} \right)^2 & Turbulent \end{cases}$$

$$\Delta \Phi = \frac{\rho f_D v|v|}{2} L/D = K_{cor} v$$

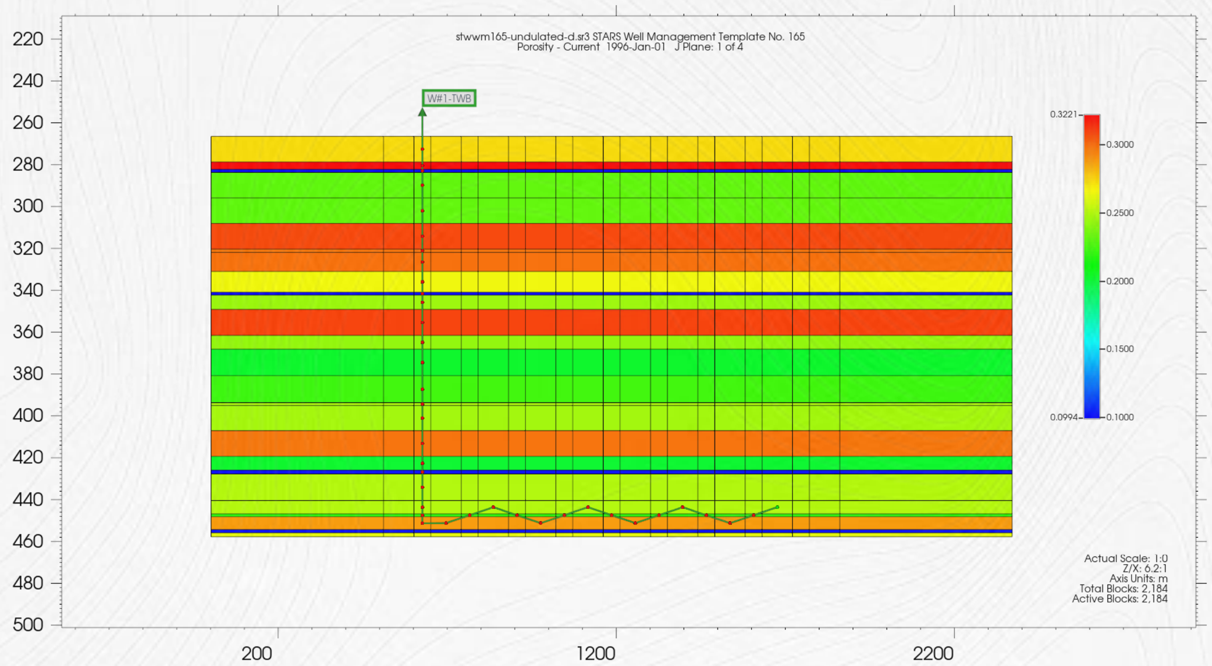
$$v_g = C_0 v + v_d \qquad v_l = \frac{(v - s_g v_d)}{s_l}$$

- Unified momentum Eqs.
- Smooth correlations for friction
- More robust for horizontal, undulated, vertical wells
- Pressure drop model used for NOSLIP and DRIFT-FLUX

f_D

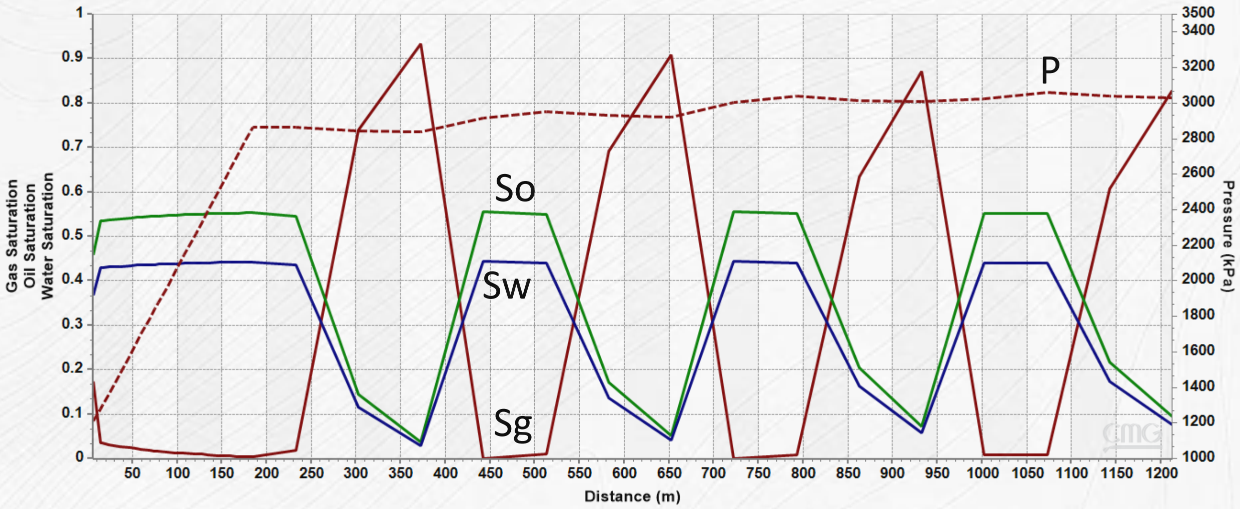


T. Hewei, W. J. Bailey, T. Stone, and J. Killough. "A unified gas/liquid drift-flux model for all wellbore inclinations." *SPE Journal* 24, no. 06 (2019): 2911-2928.

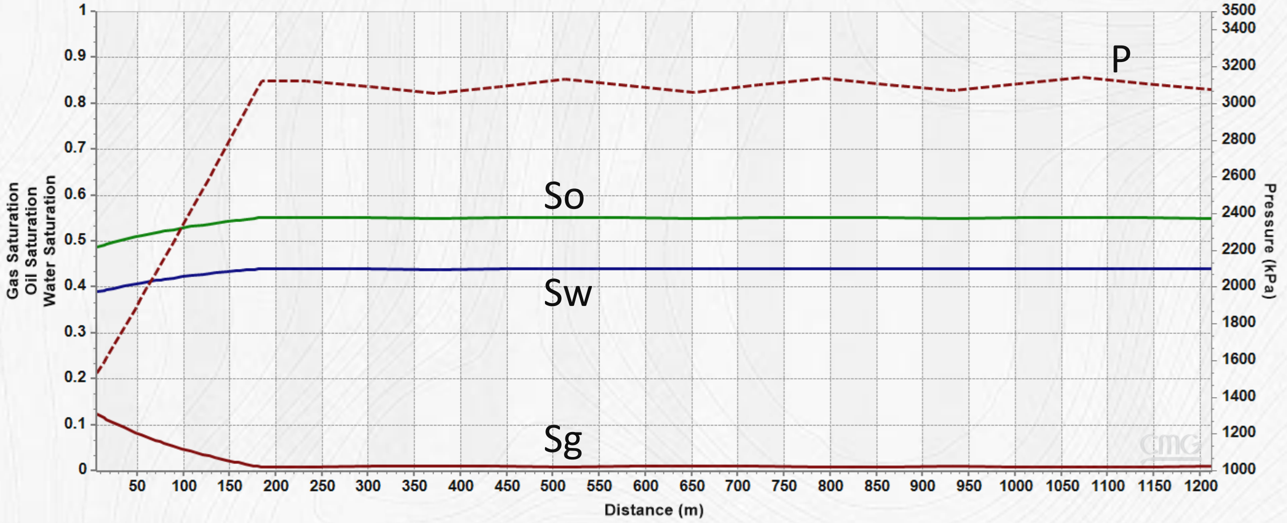


- A preliminary version of DF model has been completed in STARS
- Initial outcomes show that this model can capture the slippage between gas and liquid phases.
- Further tests will be conducted to improve the physics and efficiency of the DF model.

Drift Flux



NOSLIP



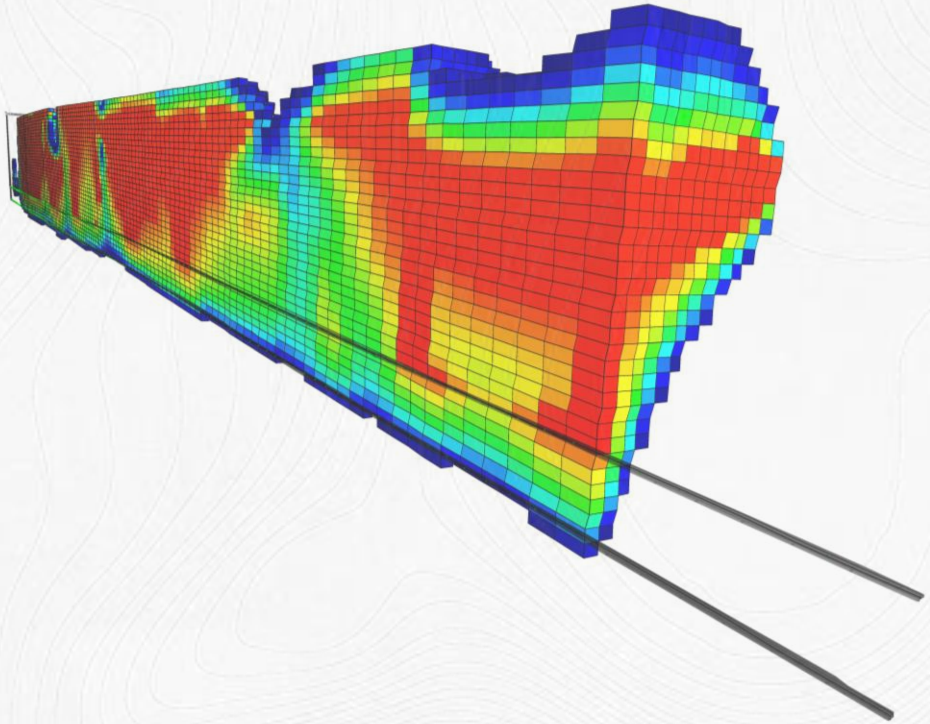
Advanced Pump Model with All Segregation Options

Pump Power Correlation

- Power is a function of volumetric flow rate of liquid and differential pressure across the pump
- Define a max power and pressure

Table Input

- Rates versus Differential Pressure
- Similar to FCD Table setup
- Optional dependencies on Inlet:
  - Temperature
  - Pressure
  - Water Cut
  - Gas Fraction



Released in 2024 -
Greater Understanding of Complex Thermal Well Dynamics

Improve accuracy of energy transfer with new Fluid Thermal Resistance calculation

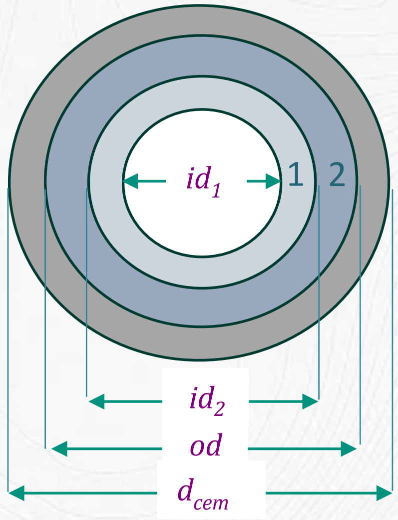
More accurate thermal resistance values through the fluid film near to the tubing and casing walls.

$$res(fl) = \frac{D_h}{\pi N_u K D_{to} L} = \frac{D_{ci} - D_{to}}{\pi N_u K D_{to} L}$$

Better tuning to field operations with Radial Heat Transfer Outputs in FlexWell

Consider Intermediary temps and heat transfer changes **radially outwards**

- Define multiple concentric casing layers
- Output and plot the temperature along the intermediary points
- **Useful in matching thermal conduction with sensor data** (e.g. insulation or cemented zones)



Better Fluid Modelling Accuracy for Thermal Runs

Improved Default Enthalpy for gas-based enthalpy and Lee-Kesler thermal models

Default values of CPG, HVR, and EV are now based on library values of hydrocarbon components with the *nearest molecular mass* (C1 - C20)

- **Greater accuracy for thermal models**
- New defaults can be activated by the option ***CPG_LIB**

Faster STARS runs with PVT K-Value Smoothing Option in WinProp

- Modified P-smoothing approach
- Best for Gas-Liquid K-value tables
- Also useful for liquid-liquid tables

Modelling More Than 3-Phases – Phase 1

Providing ability to model LLV conditions with steam (2 oleic phases). Proposed development to support included comprehensive developments to both STARS and WinProp in 2-phases.

2024 Q4

- Started implementation of CPA into WinProp

2025 Q1

- Cont. implementation of CPA into WinProp (convergence with 4-phase flash)

2025 Q2

- Cont. implementation of CPA in WinProp (support for generating 2nd HC liquid tables)

2025 Q3

- Release - CPA in WinProp (support for generating 2nd HC liquid tables)
- Start implementation of Liquid Activity Model (est. 3 quarter development)
  - UNIQUAC EOS and NRTL EOS

Implementation of CPA

1. Research conducted to understand the underlying formulae
2. Implemented:
    a) Calculate molar-volume for one associated component (H2O) with EOS’
    b) CPA Logic for two associated components
    c) Ability to read in association energy and volume for association components
3. Current work:
    a) Enhance general EOS calculations to work with CPA
    b) Enhance multi-phase flash to work with CPA

Modelling More Than 3-Phases – Phase 2

Providing ability to model LLV conditions with steam (2 oleic phases). Proposed development to support included comprehensive developments to both STARS and WinProp in 2-phases.

2025 Q2

- Common NIST data library
  - **Released (2025.20)** – CO_2 library properties and Visc vs Pressure option
- Start integration of second hydrocarbon phase table in STARS

2025 Q3

- Cont. integration of second hydrocarbon phase table in STARS

2025 Q4

- **Release** – second hydrocarbon phase table in STARS
- Combined liquid flow for hydrocarbons in STARS

Accelerating Decisions

Speed & Stability Enhancements

PyControl Enablement with MPI

With the PyControl tool you can script simple-to-complex controls with Python that the simulators can use when running

With this latest extension to MPI, even the largest of models can leverage the external scripting and capabilities that PyControl workflows provide.

AWS Datacentre
https://aws.amazon.com/compliance/data-center/data-centers/

Faster Distributed Runs with the Combinative Solver

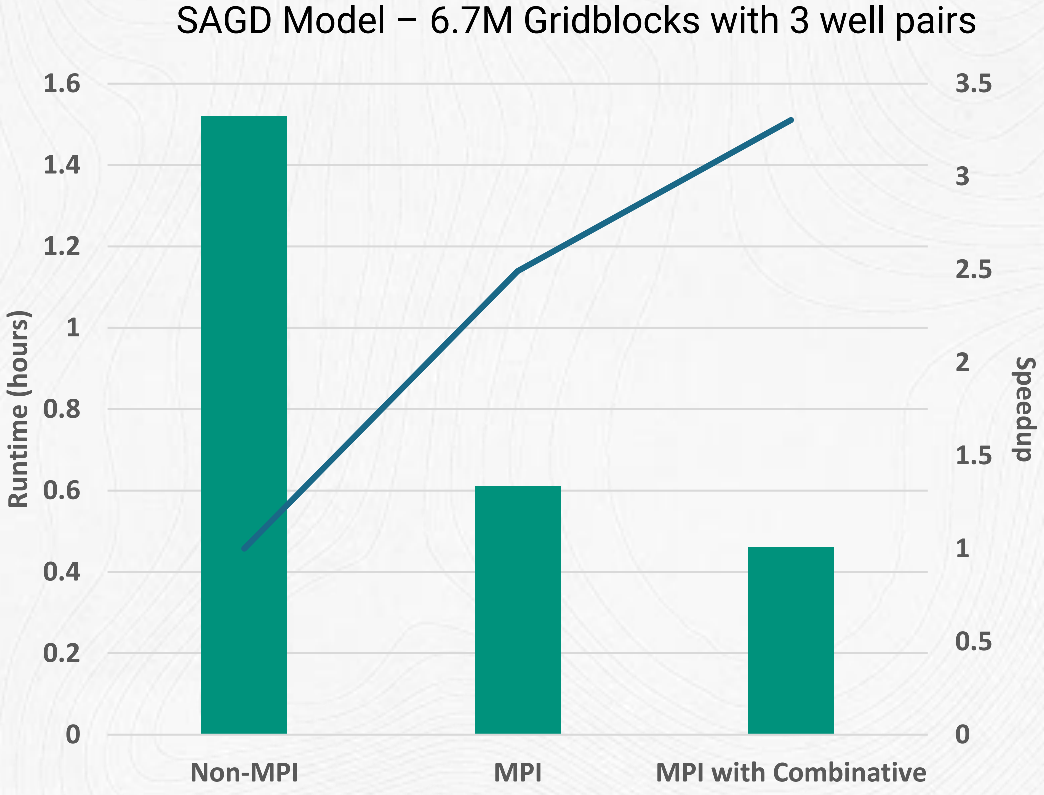
- Impactful with frontal-based processes
- Combinative previously available in IMEX, GEM, and STARS OpenMP (Shared Memory)
- Now Available in IMEX, GEM and STARS MPI (Distributed)
  - Combinative ILU currently deployed in MPI

Coming Soon:

- Combinative AMG Option for STARS-MPI

Average 40+% Speedup

In benchmark models with Combinative Solver + MPI



Thank you!

Questions?