# Overview of GPRS (General Purpose Research Simulator)

# Reduced Variable (RV) Method for Compositional Flow Simulation

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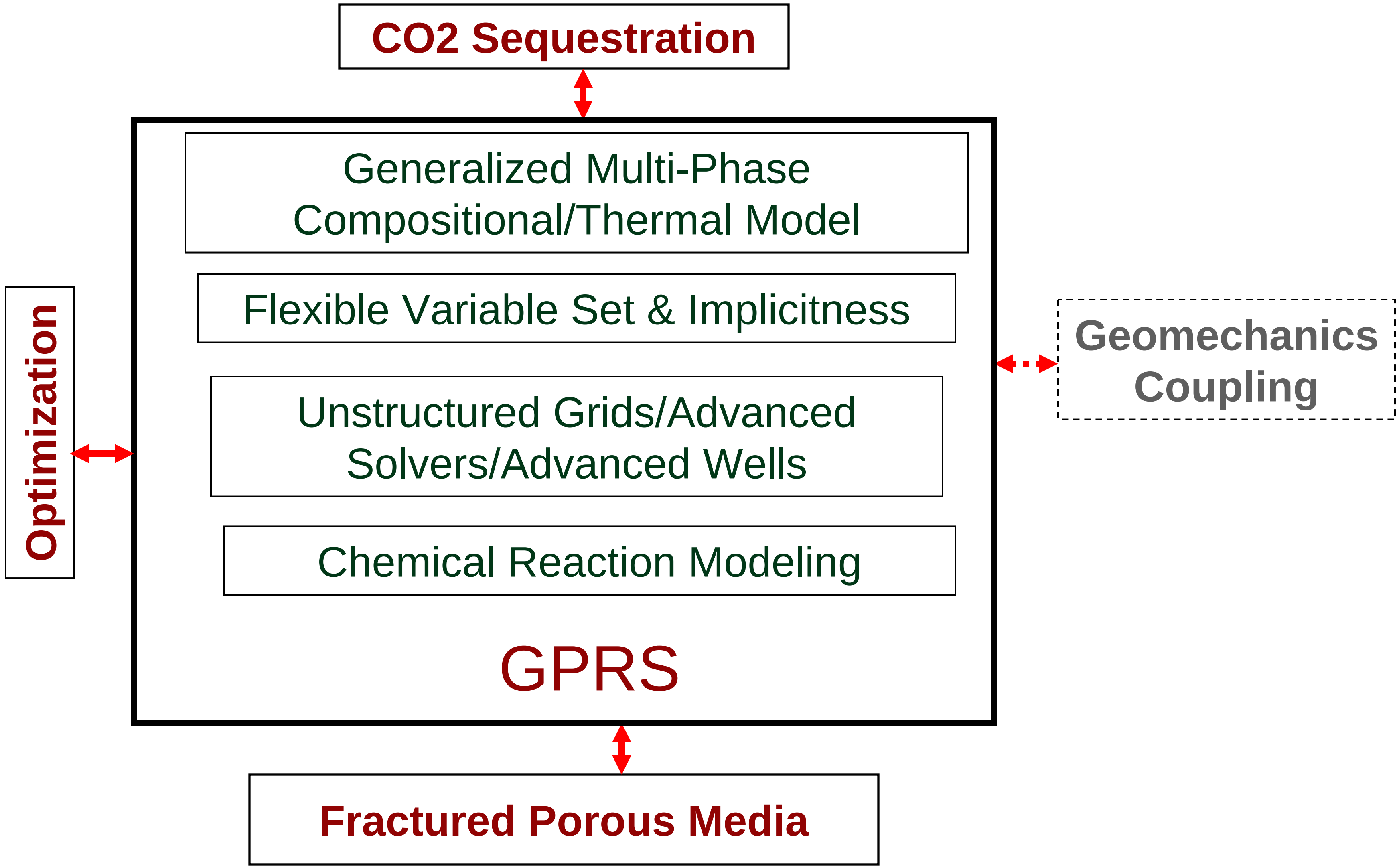
# GPRS: Research Platform



# GPRS Software Features

- Multiple platforms
  - Visual Studio 6/2005/2008
  - Linux
- Portable Source Code
  - Single standard C++ source code for all platforms

# Ongoing GPRS Research Projects

- Automatic Differentiation (AD) based GPRS
  - Compositional modeling with arbitrary number of phases
  - Connection based formulation with TPFA & MPFA
  - Flexible nonlinear formulations
  - Advanced nonlinear solvers
  - Flexible AIM
  - Advanced well & facility modeling
  - Thermal capability

# Ongoing GPRS Research Projects

- Reduced variable (RV) method
  - Efficient & robust implementation
  - Combine Michelson's bypass method with RV
- Chemical reaction modeling
  - Fully coupled with flow equations
  - Element-based approach
  - Application to CO2 sequestration, in-situ upgrading
- Heater well modeling

# Ongoing GPRS Research Projects

- Multi-Segment (MS) well modeling
  - Isothermal & thermal compositional MS model
  - Homogeneous & drift flux fluid model
- Plug-in MPFA module in GOCAD
  - Discretization layer for unstructured grids
  - Link to GPRS
- Integration with well optimization
  - Reduced-order modeling
  - Adjoint-enabled GPRS

# GPRS: Long-Term Goals

- ADET based GPRS framework
  - Automatic differentiation with expression templates
  - Compositional, thermal, reactions
  - General multiphase equilibrium (RV)
  - Tie-line based parameterization (CSAT)
  - Scalable multi-stage linear solvers
  - General nonlinear solvers
  - Geomechanics coupling
  - Adjoints
  - Parallel (openMP, MPI)

# GPRS Release

- GPRS1.0 (initial version, 2002)
- GPRS1.1 - 8/03
- GPRS1.2 - 6/04
- GPRS1.3 - 11/04
- GPRS1.4 – 11/05
- GPRS2.0 – 6/06
- GPRS2.1 – 2/07
- GPRS 2.2 – 5/2009

# New GPRS2.3 Release (July, 2010)

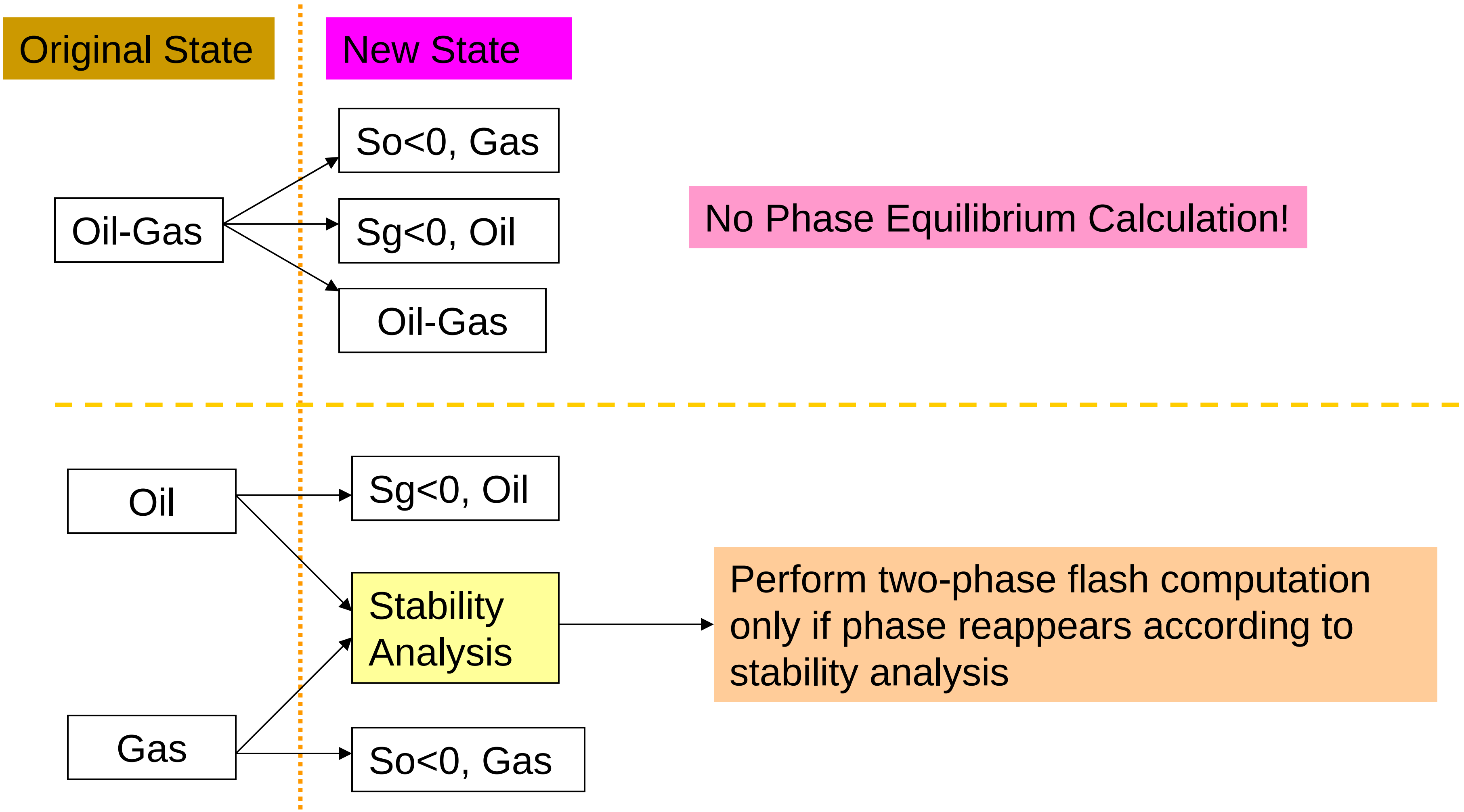
- Speedup compositional simulation
  - Efficient RV implementation
  - Michelsen’s bypass stability analysis (with RV)
- Improvements in chemical reaction modeling

# Reduced Variable (RV) Method for Compositional Simulation

# Phase Equilibrium Computations

- Stability analysis
  - Determine if a mixture is single- or two-phase
  - Nc - 1 nonlinear equations
  - Initial oil & gas
- Two-phase flash
  - Determine amount & compositions of gas & oil
  - Nc nonlinear equations
- Detailed models with large Nc: phase equilibrium computations can be very expensive

# Phase-State Determination



# Phase-Stability Analysis is Crucial

CPU time of stability analysis & flash computation using the standard method (top layer of SPE10):

| | Time (sec.) | | Time (stability) % |
|---|---|---|---|
| | Stability | Flash | |
| SPE5 (6 component) | 262 | 0.25 | 99.9 |
| SPE3 (9 component) | 2613 | 82 | 97.0 |
| Condensate2 (15 component) | 5225 | 35 | 99.3 |

# Fast Stability Analysis Approaches: RV and Bypass

- RV (Reduced Variables): fast iterative method to replace standard (Conventional Variables, CV) method
- Michelsen's bypass scheme: empirical method to avoid stability analysis computations
- RV-based bypass method

# Reduced Variables (RV) Method

- Based on Principal Component Analysis (PCA)
- Robust stability analysis:
  - Globally convergent Newton method
- Efficient for stability analysis & flash computation:
  - Fewer iteration variables
  - Fewer number of iterations

Pan & Firoozabadi: SPE J., 78-89 (2002); 380-391 (2003)

# RV Method

$$G = G(n, a, b) \qquad a(n_1^V, n_2^V \ldots\ldots, n_N^V)$$

**PCA:** $$a \approx \sum_{\alpha=1}^{M} \lambda_\alpha Q_\alpha^2$$

$\lambda_\alpha$'s Principal Eigenvalues;

$$G = G(n, Q_1, Q_2, \ldots\ldots, Q_M, b)$$

*M+1* for stability test, *M+2* for flash.

*M* is small in practice

# RV Method

- Research on standalone phase equilibrium computations
- Limited integration with compositional flow simulation
  - Different RV method (transform kij to h & g)
  - 2D, 400 cells with IMPEC simulation
- Extensive study of RV based compositional flow simulations in large reservoir models with complex fluids & large time steps is key for practical use

Okuno, R., Johns, R.T., and Sepehrnoori, K. 2008: Use of a Reduced Method in Compositional Simulation. Paper presented at the 11th ECMOR, Bergen, Norway, 8-11 September.

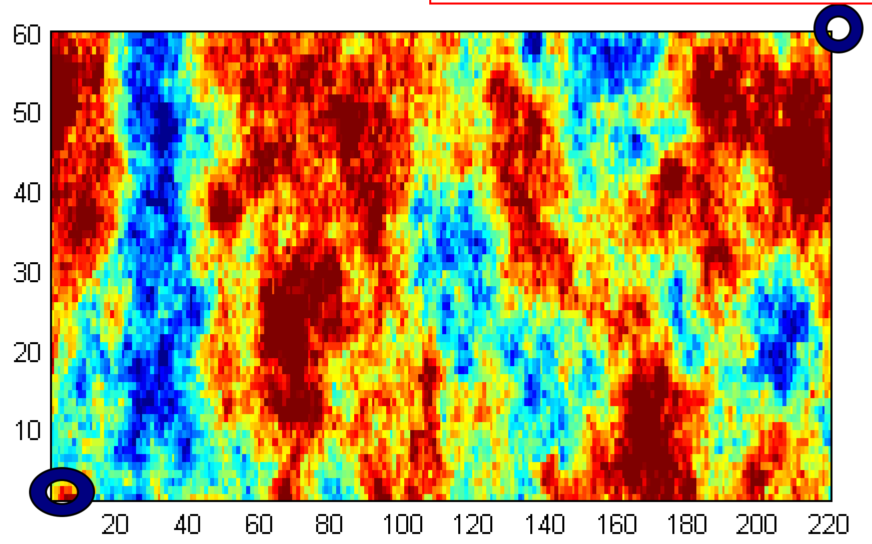
# Fluids & Eigenvalues

| Fluid | SPE3 | SPE5 | Oil1 | Condensate1 | Condensate2 |
|---|---|---|---|---|---|
| Nc | 9 | 6 | 26 | 8 | 15 |
| M=1 | 8.586 | 5.964 | 25.39 | 7.723 | 14.46 |
| 2 | 0.3323 | 0.07022 | 0.4385 | 0.2101 | 0.4179 |
| 3 | 0.1932 | -0.03379 | 0.1854 | 0.09831 | 0.1205 |
| 4 | -0.09432 | | 0.08774 | -0.02971 | 0.07151 |
| 5 | -0.0233 | | -0.07572 | -1.865e-3 | -0.05175 |
| 6 | 9.158e-3 | | -0.03192 | -1.471e-3 | -0.01916 |
| 7 | -3.590e-3 | | 0.02191 | 1.27e-3 | 2.722e-3 |
| 8 | | | -0.01892 | -5.57e-6 | |
| 9 | | | 1.546e-3 | | |
| 10 | | | -2.1e-4 | | |
| 11 | | | -1.49e-5 | | |

# Reservoir I

Top layer of SPE 10, 220 x 60 =13,200 cells

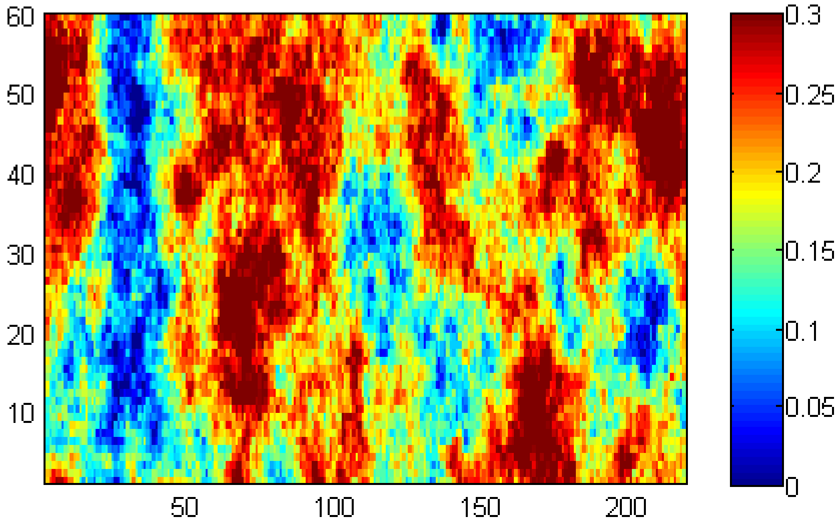
Production well: BHP control




Injection well: BHP control

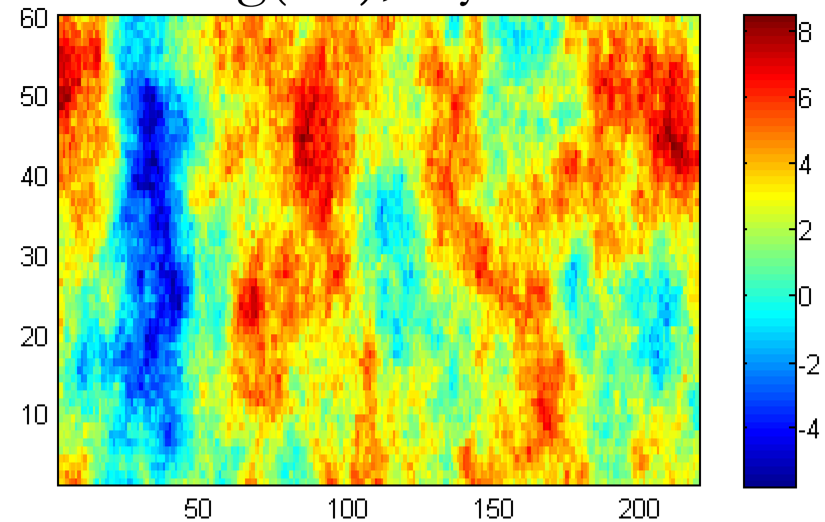
Stream: separator gas at standard conditions

# Reservoir I: Properties

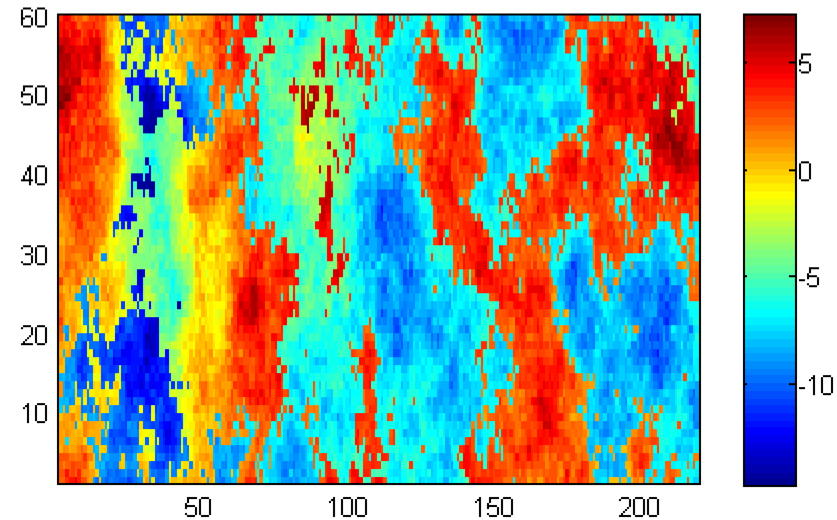



Porosity

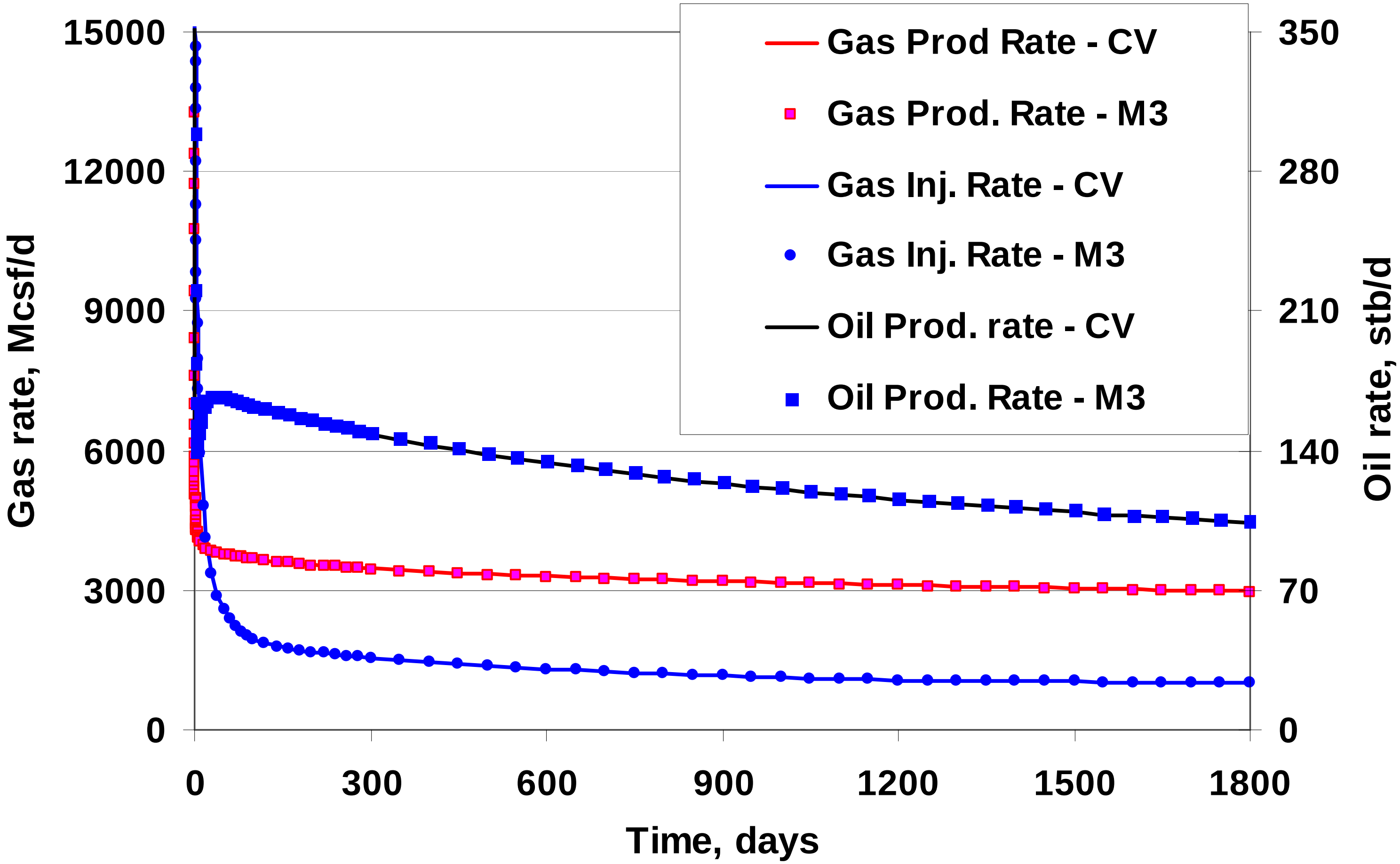
Log(Kx), Ky=Kx



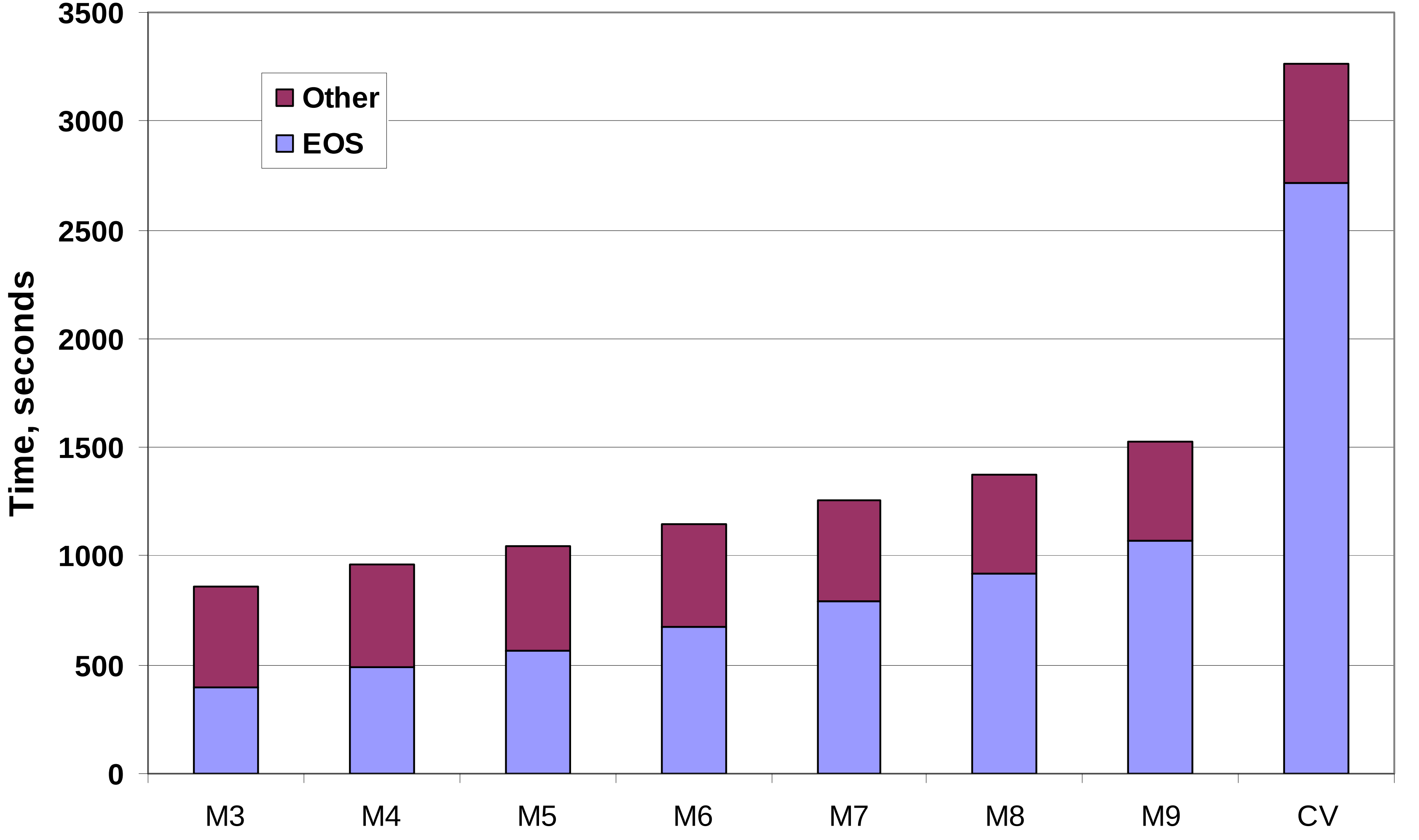

Log(Kz)



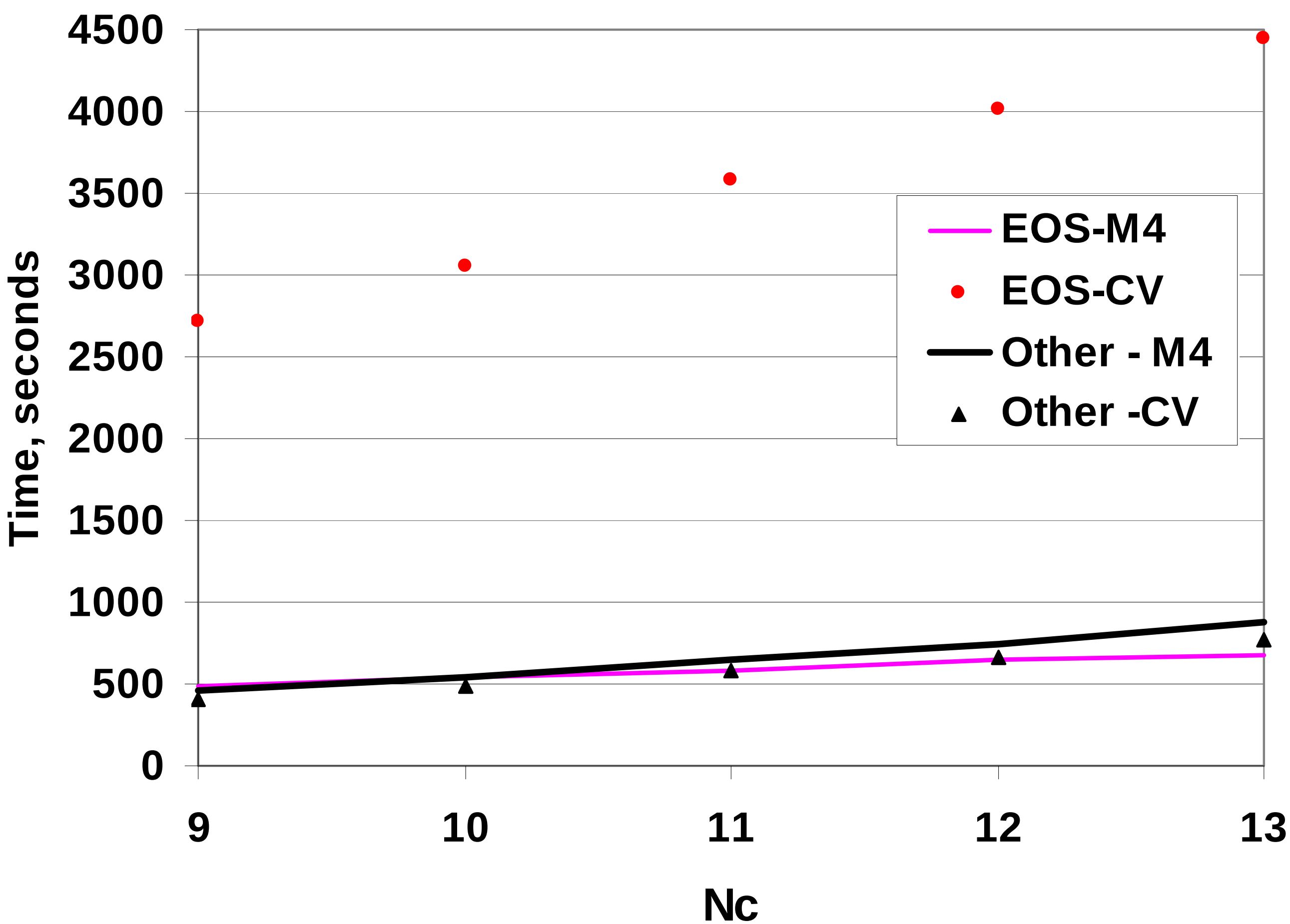
# SPE3: Well Flow Rates



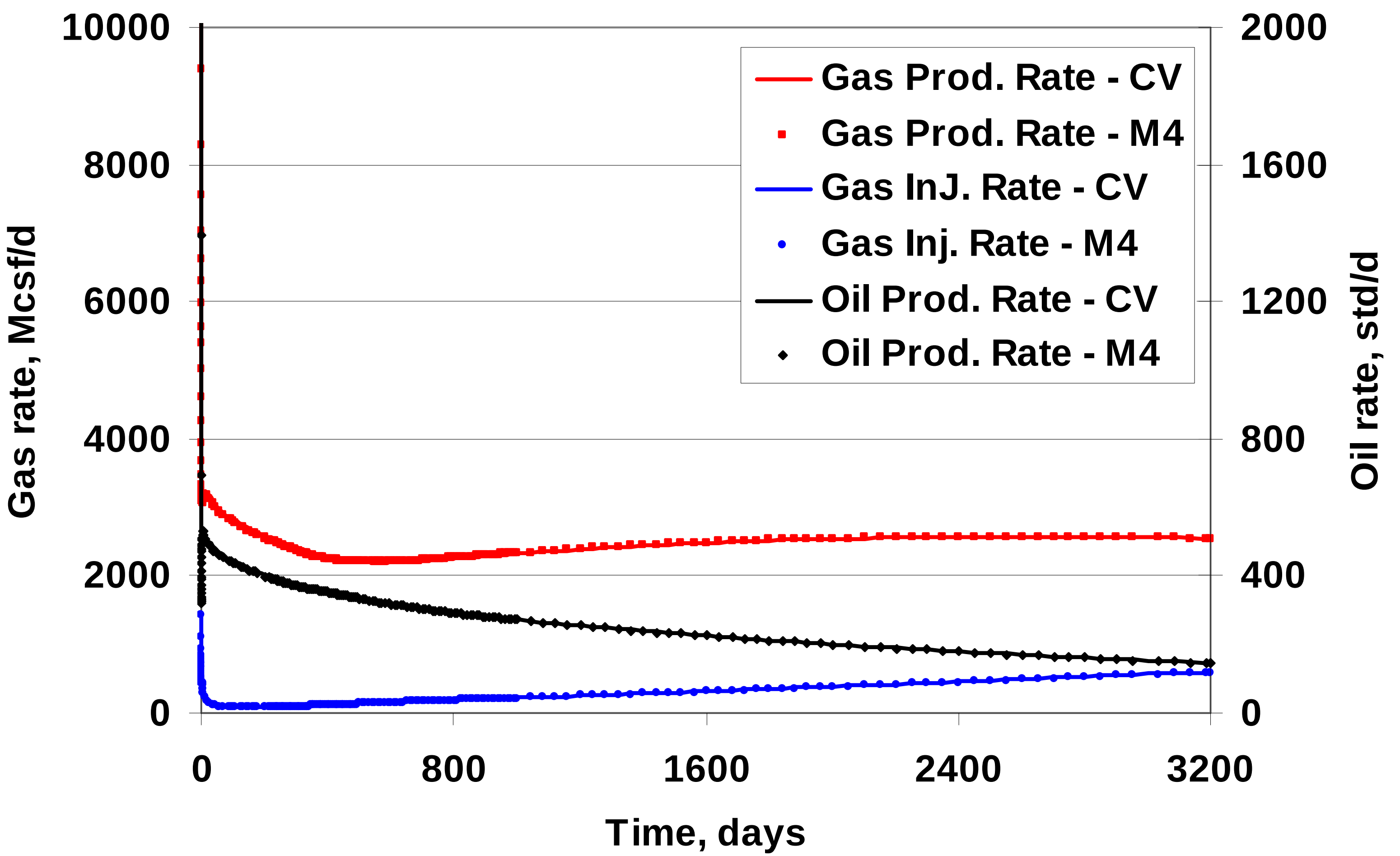
# SPE3: Execution Time



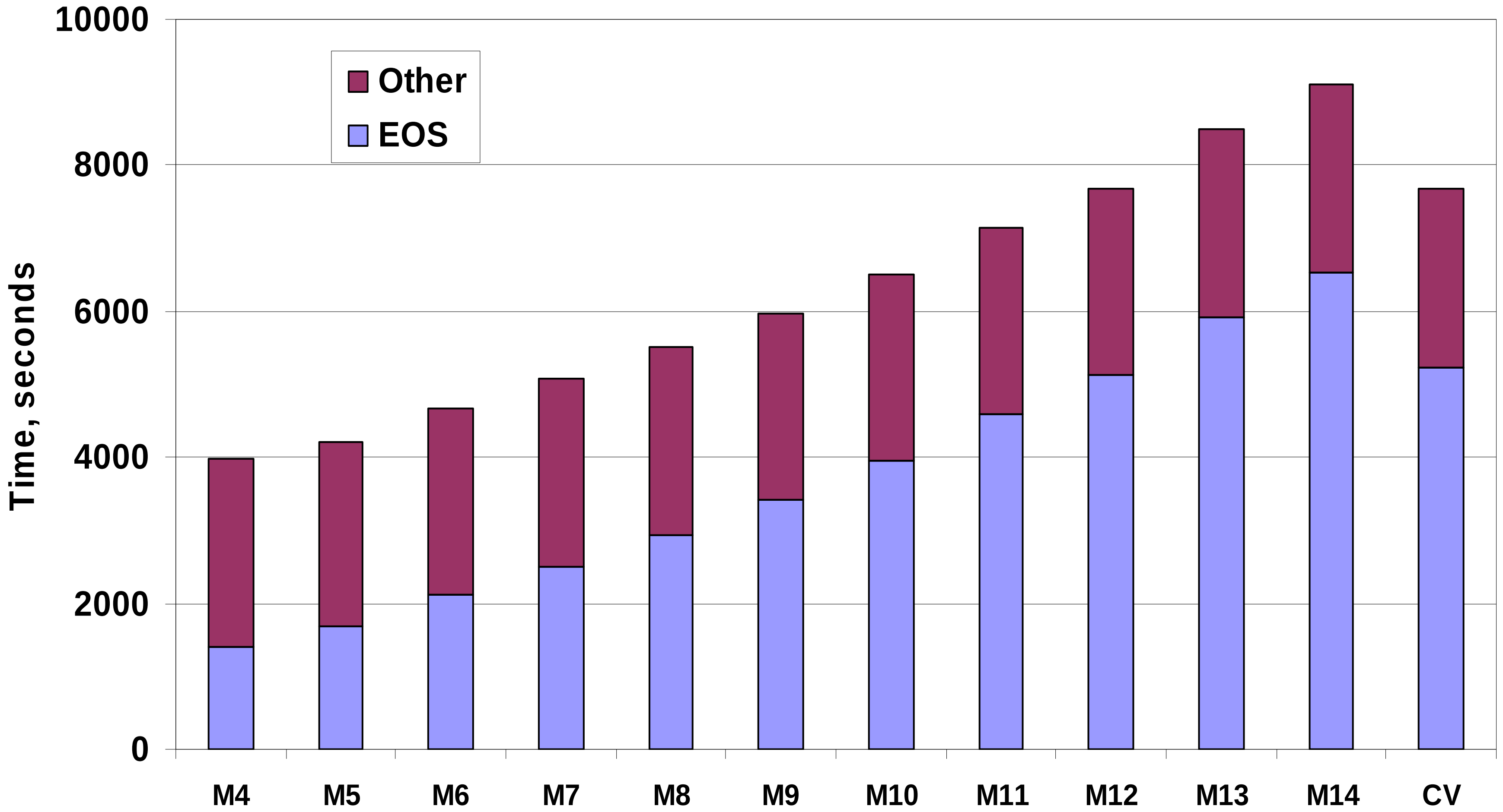
# SPE3: CPU Time vs. Number of Components (Nc)



# Condensate2: Well Flow Rates



# Condensate2: Execution Time



# Condensate2: Performance

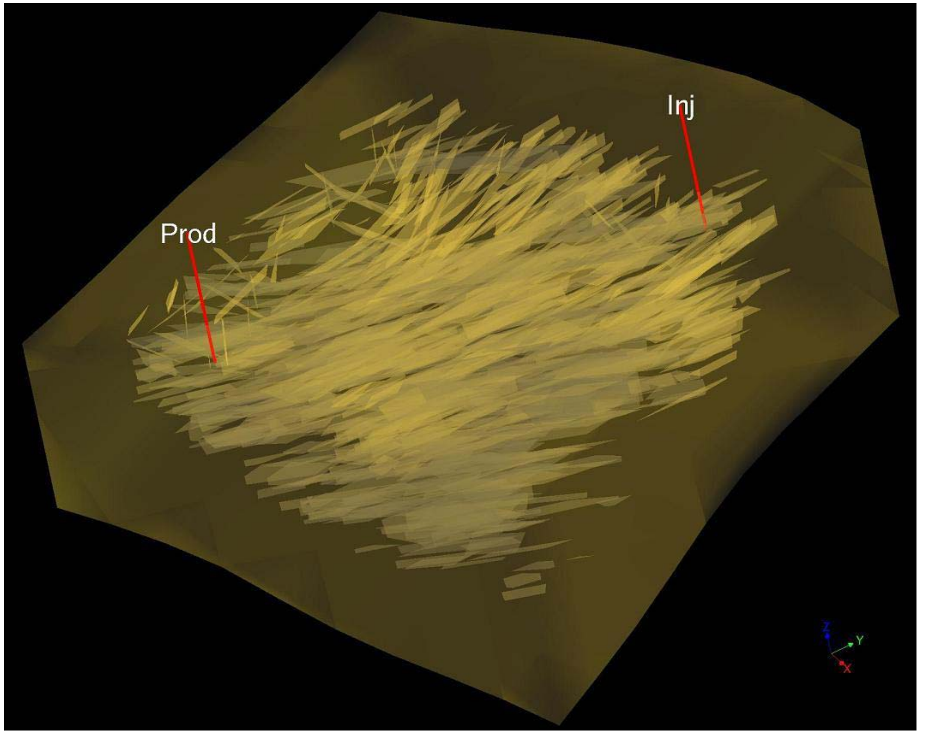
CV vs. RV performance for Stability Analysis (SA) & Flash Computation (FC)

| Method | CV | RV-M4 |
|---|---|---|
| Number of SA | 9,131,772 | 9,139,801 |
| Time (second) of SA | 5,225 | 1,480 |
| Time (second) per 10000 SA | 5.72 | 1.62 |
| Number of FC | 12,351 | 13,508 |
| Time (second) of FC | 35 | 14 |
| Time (second) per 10000 FC | 28.34 | 10.36 |

# Reservoir II

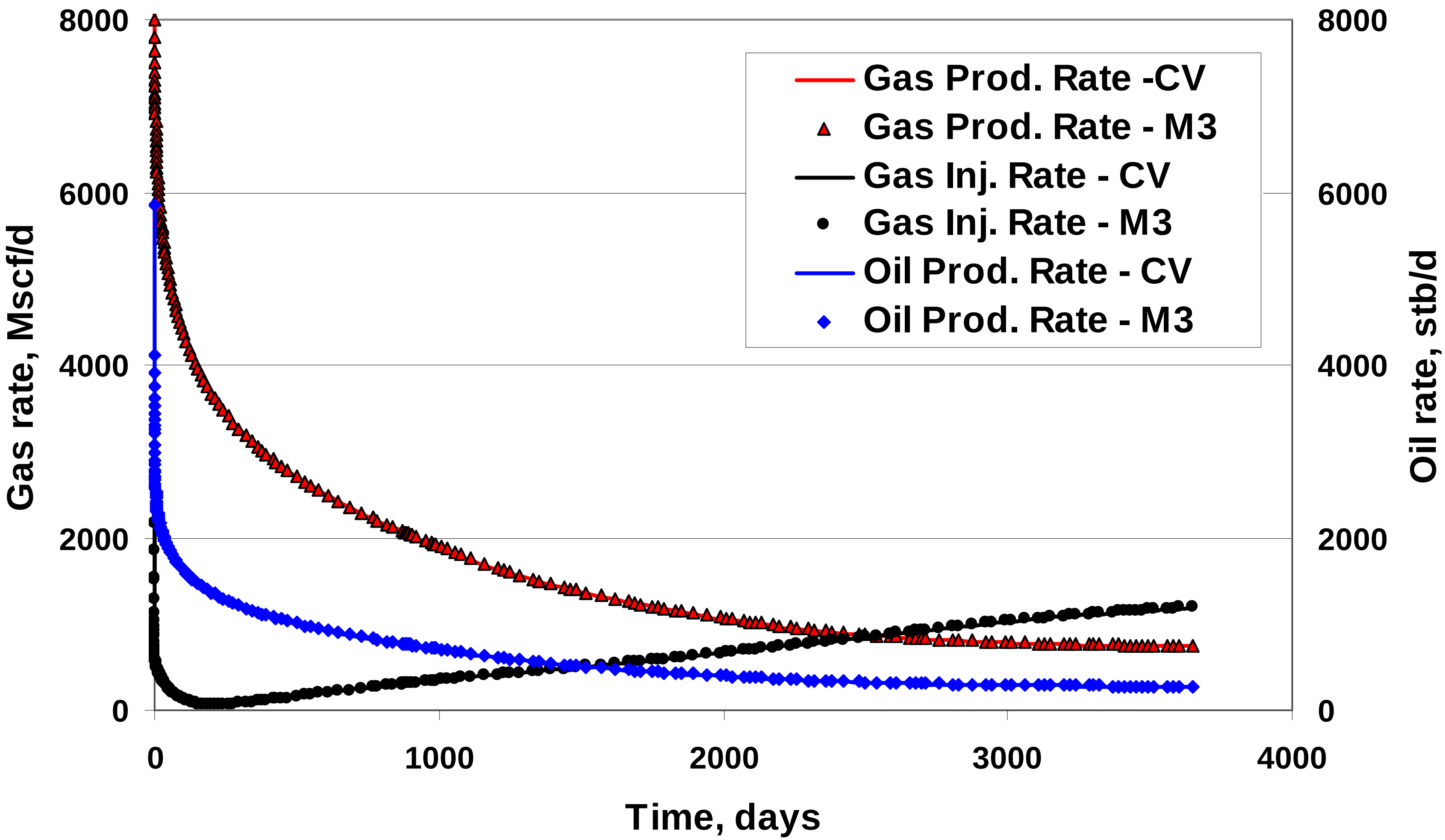
- 5,227 discrete fracture cells
- Permeability: 0.1 ~ $10^6$ md
- Porosity: 0.25 ~ 1.0
- Volume: $10^{-3}$ ~ $10^3$ $ft^3$

# Reservoir II: Wells

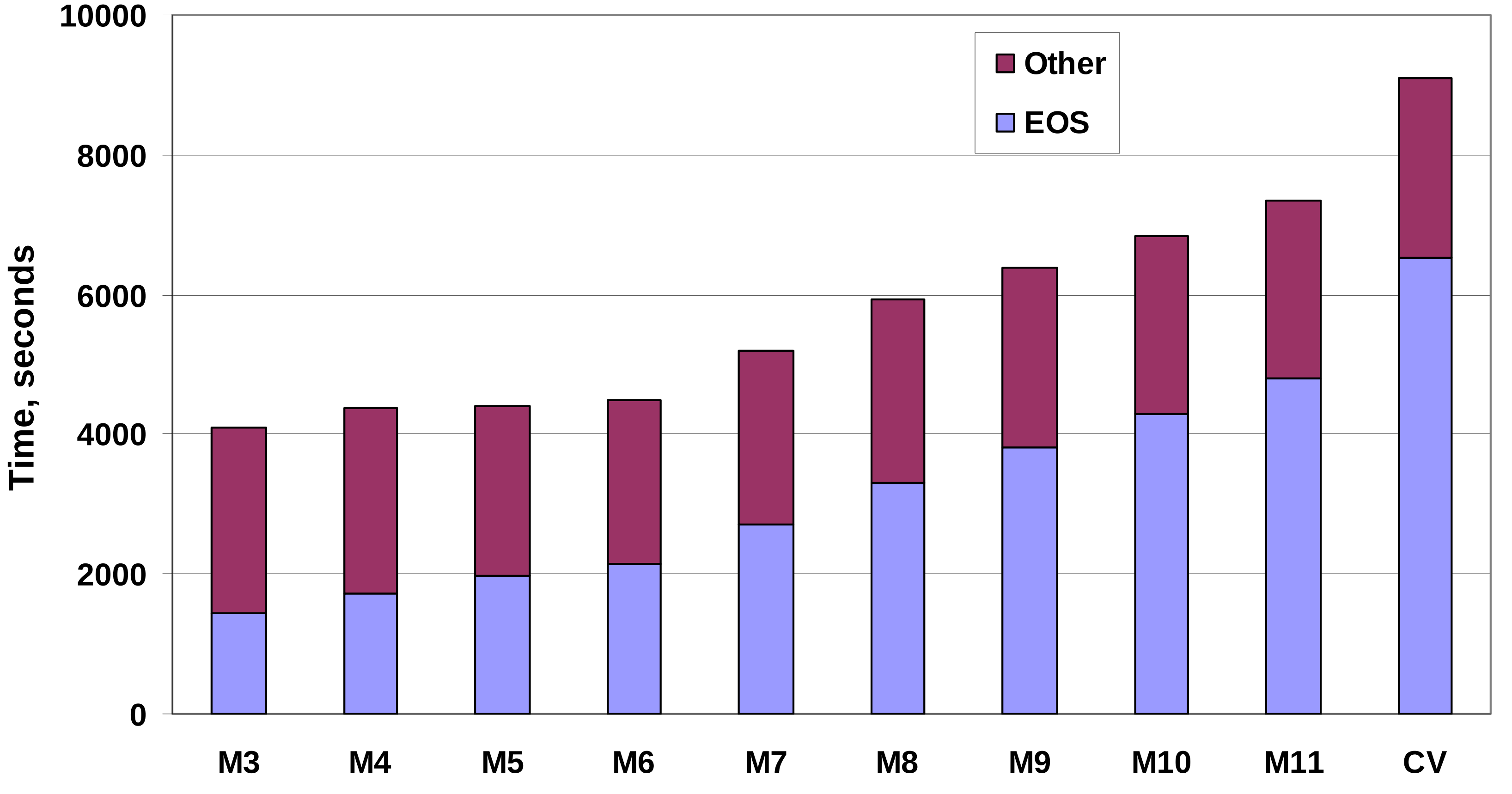



Injection stream: separator gas at standard conditions

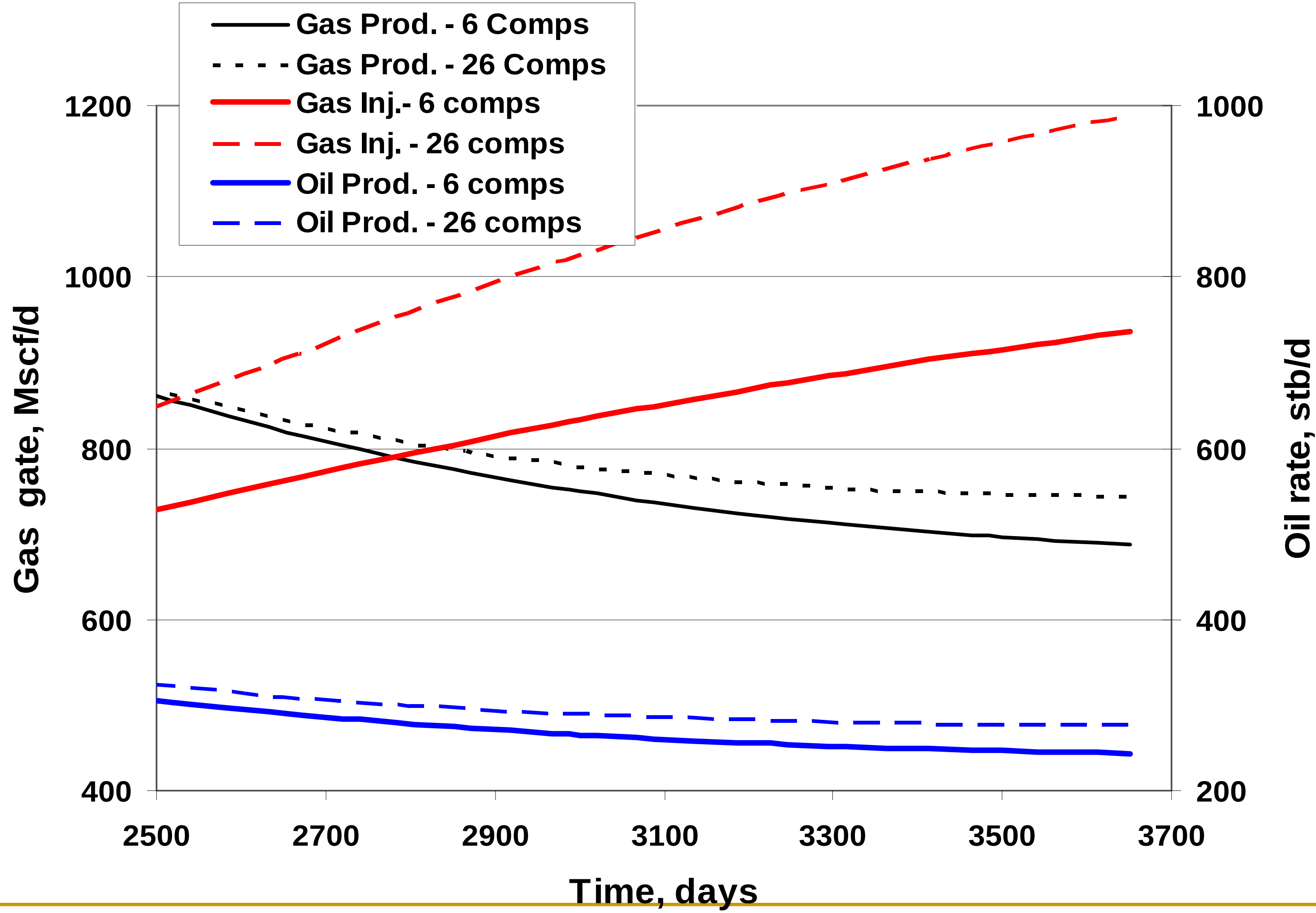
# Oil1: Well Flow Rates



# Oil1: Execution time



# Oil1: Well Flow Rates for 6 & 26 components



# Advantages of RV over CV

- Much better nonlinear behavior
  - Linear increase of CPU time with number of RV
  - Very slow increase of CPU time with increase of number of components
- Fewer variables
- Significant CPU-time reduction

# How Many Eigenvalues ($M$) to Keep?

| Fluid | SPE3 | SPE5 | Oil1 | Condensate1 | Condensate2 |
|---|---|---|---|---|---|
| Nc | 9 | 6 | 26 | 8 | 15 |
| M=1 | 8.586 | 5.964 | 25.39 | 7.723 | 14.46 |
| 2 | 0.3323 | 0.07022 | 0.4385 | 0.2101 | 0.4179 |
| 3 | 0.1932 | -0.03379 | 0.1854 | 0.09831 | 0.1205 |
| 4 | -0.09432 | | 0.08774 | -0.02971 | 0.07151 |
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| 8 | | | -0.01892 | -5.57e-6 | |
| 9 | | | 1.546e-3 | | |
| 10 | | | -2.1e-4 | | |
| 11 | | | -1.49e-5 | | |

$$Abs(\lambda_\alpha) > 0.07$$

# How to Determine *M*?

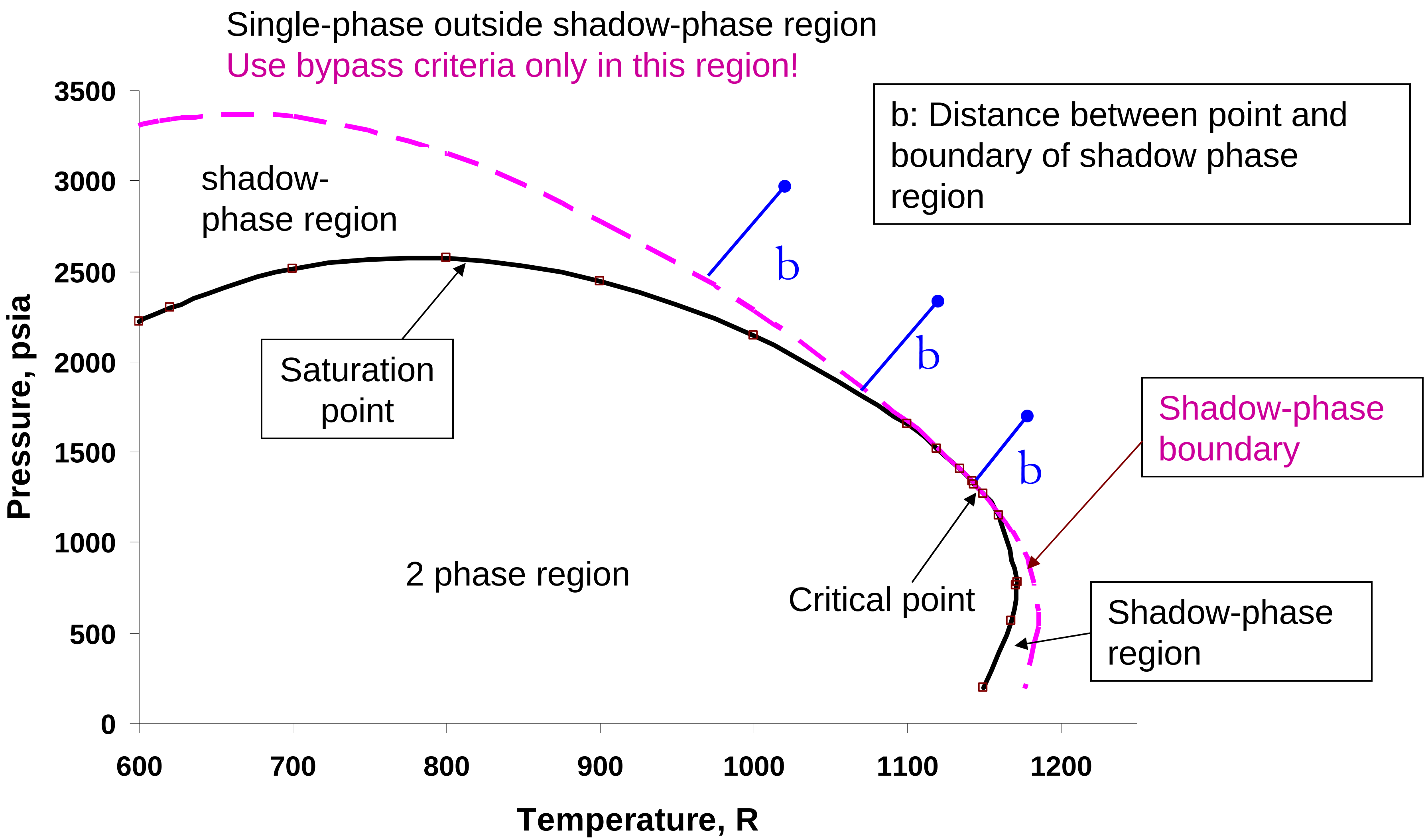
- *M* depends strongly on the complexity of the phase behavior of the reservoir fluid
- Reservoir properties (porosity, perms. etc.) have little effect
- Results from compositional flow simulations with the target fluid system in a small homogenous model (e.g., hundreds of cells) provide good estimate of *M*

# Michelsen's Bypass Method

- Empirical method to bypass stability analysis
- Standalone testing without flow simulation results
- Integrate with compositional flow simulation
- Develop an RV based version of the method

Rasmussen C.P., Krejbjerg K., Michelsen M.L., Bjurstrom K.E. 2006 Increasing of Computational Speed of Flash Calculations with Applications for Compositional, Transient Simulations, *SPE Res Eval & Eng*, **9**(1): 32-38..

# Michelsen's Bypass Method



# Michelsen's Bypass Criteria

$$\left| z_i - z_{i,old} \right| < b_{old} / 10$$

$$\left| P - P_{old} \right| < P b_{old} / 10$$

$$\left| T - T_{old} \right| < 10 b_{old}$$

b: smallest eigenvalue of matrix B

$$B_{ij} = \delta_{ij} + \sqrt{n_i n_j} \left( \frac{\partial \ln \phi_i}{\partial n_j} \right)_{P,T}$$

$$\delta_{ij} = 1 \quad i = j$$

$$\delta_{ij} = 0 \quad i \neq j$$

# Extend Bypass Criteria to RV

$$B_{ij} = \delta_{ij} + \sqrt{n_i n_j}\left(\frac{\partial \ln \phi_i}{\partial n_j}\right)_{P,T}$$

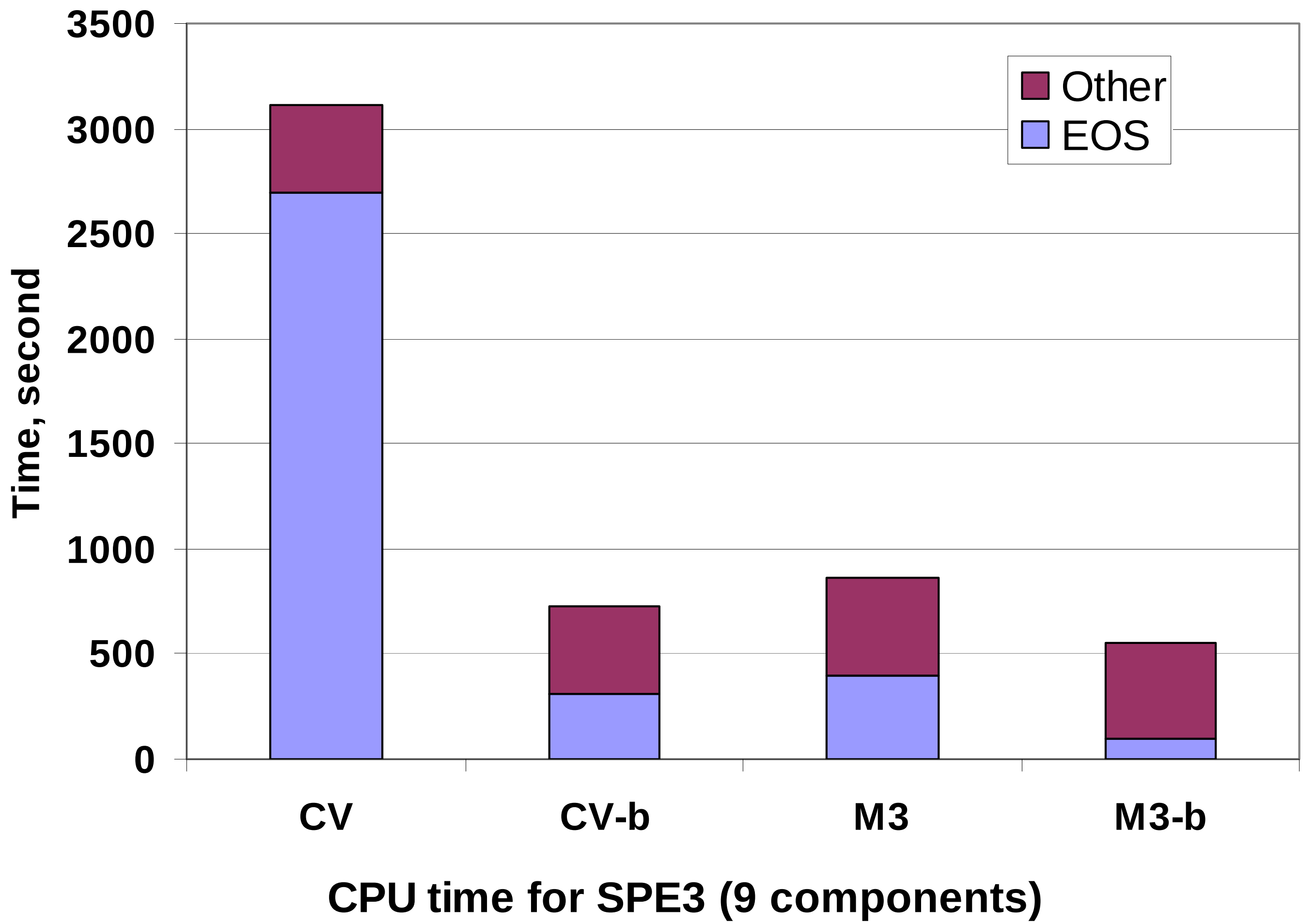
Chain rule to calculate matrix B in RV method:

$$\left(\frac{\partial \ln \phi_i}{\partial n_j}\right) = \sum_{\alpha=1}^{M+1}\left(\frac{\partial \ln \phi_i}{\partial Q_\alpha}\right)\left(\frac{\partial Q_\alpha}{\partial n_j}\right)$$

# Simulations & Results

- Reservoir I (top layer of SPE10, 13,200 cells)
- Wells: one injector & one producer
- Fluids: SPE3, Condensate2
- Methods: CV, CV-b, RV, RV-b
- Simulation results:
  - No accuracy deterioration from bypass method
  - Deviation of well flow rate (injection, production) <0.1%

# SPE3 (9 Components): CPU Time

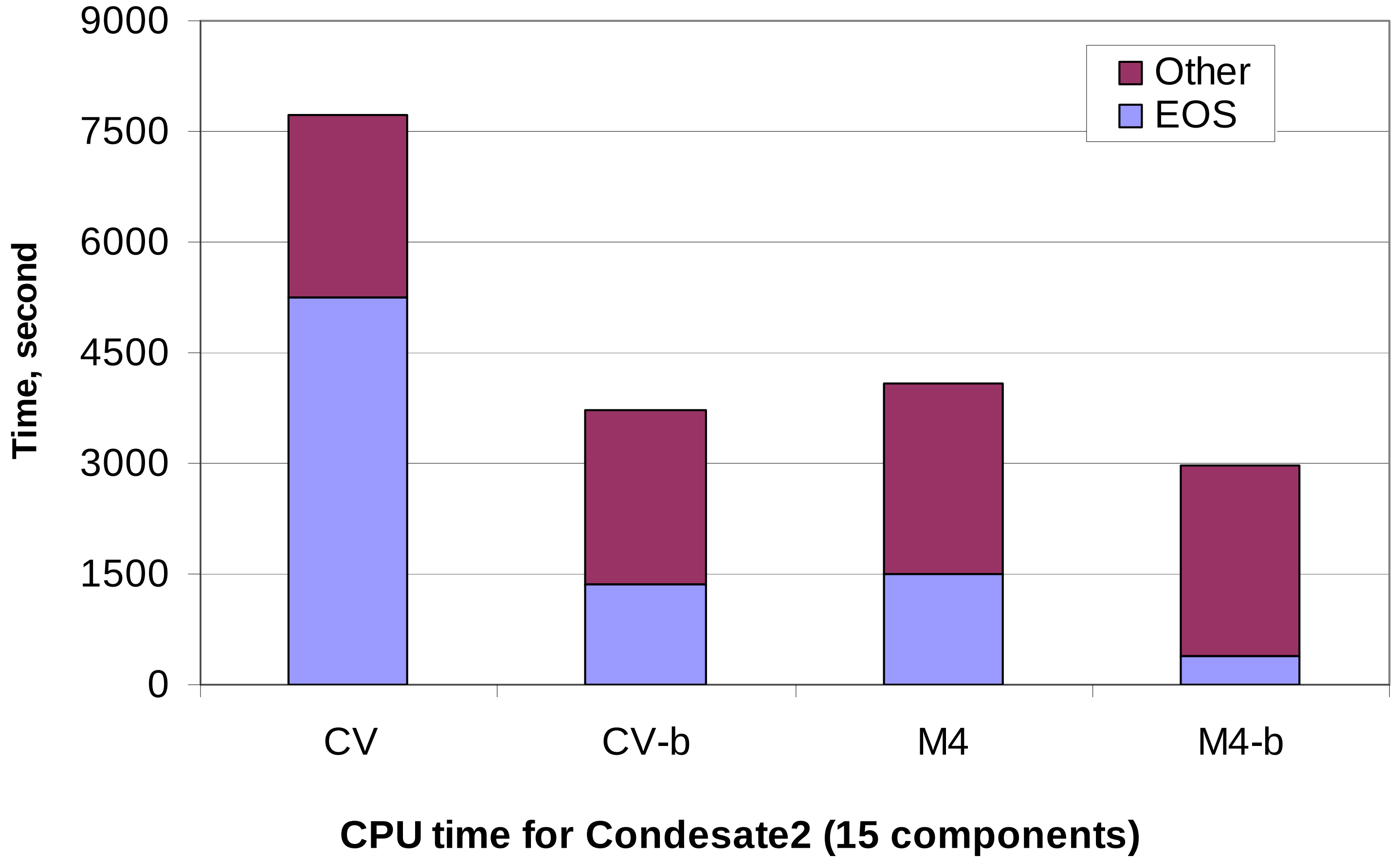


# SPE3: Stability Analysis Performance

Number of Stability Analysis (SA)

| Method | CV | CV-b | RV-M3 | RV-M3-b |
|---|---|---|---|---|
| Total Number of SA | 3,939,240 | 3,939,240 | 4,289,425 | 4,289,425 |
| Number of Bypassed SA | 0 | 3,627,210 | 0 | 3,831,448 |
| Number of Calculated SA | 3,939,240 | 312,030 (8%) | 4,289,425 | 457,977 (11%) |
| Time (second) of SA | 2,613 | 231 | 349 | 44 |

# Condensate2: CPU Time

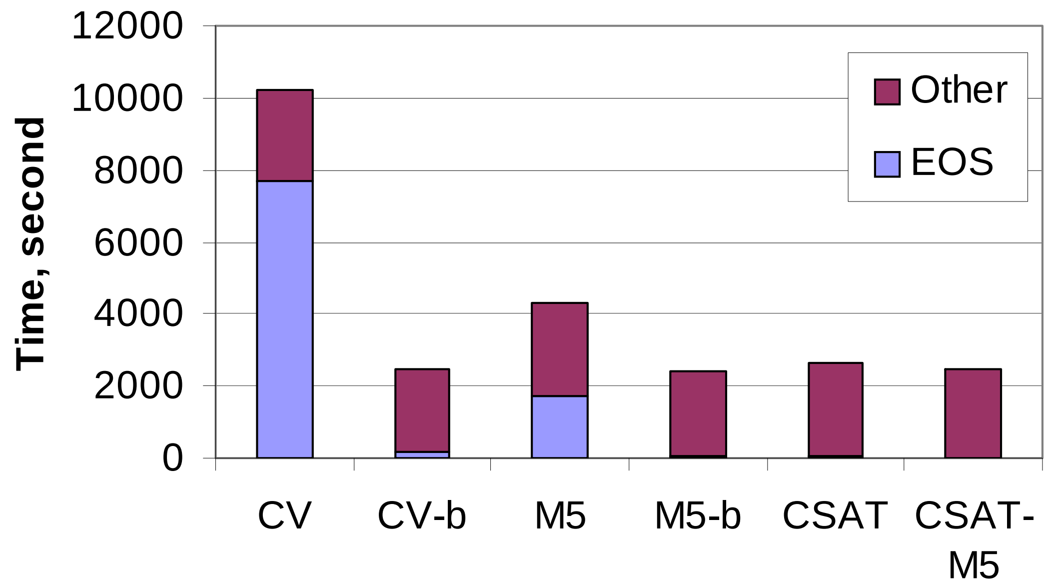


# Condensate2: Stability Analysis Performance

Number of Stability Analysis (SA)

| Method | CV | CV-b | RV-M4 | RV-M4-b |
|---|---|---|---|---|
| Total Number of SA | 9,084,864 | 9,084,864 | 9,092,585 | 9,092,585 |
| Number of Bypassed SA | 0 | 7,311,421 | 0 | 7,218,734 |
| Number of Calculated SA | 9,084,864 | 1,773,443 (19.5%) | 9,092,585 | 1,873,850 (20.6%) |
| Time (second) of SA | 5,225 | 1,232 | 1,480 | 360 |

# CPU Time: Various Methods Oil1 (26 Components) in a Model with Discrete Fractures (5,227 Cells)




Simulation time: 10 years

Time steps: 186

Newton iterations: 805

# Future Work: Extend RV & Bypass Methods to Three-Phase Systems

- Three phases
  - Hydrocarbons
  - Thermal with steam
- Expect more efficiency gains for three-phase compared with two-phase systems

# Remarks

- Significant GPRS based research activities
- Reduced Variables (RV) method is superior to Conventional Variables (CV) for phase equilibrium computations in compositional flow simulation
- Bypass method is robust & greatly improves simulation performance
- Fully integrated RV with Michelsen's bypass method into GPRS

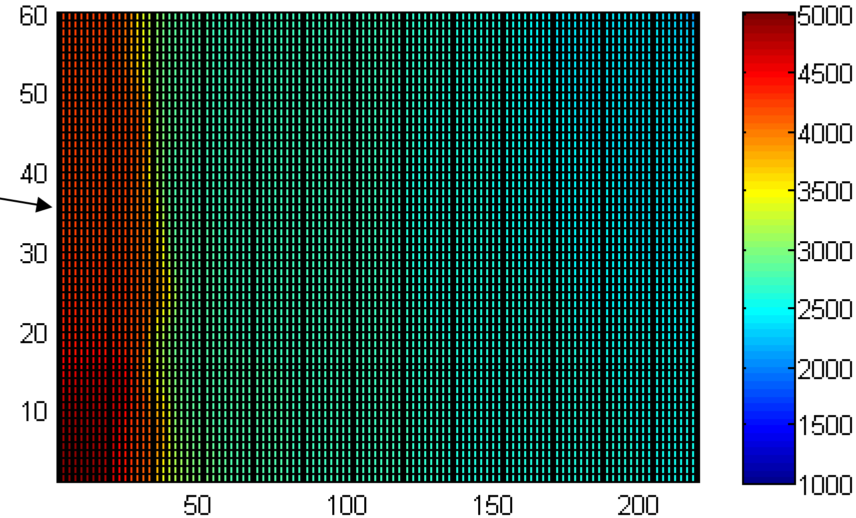
# Remarks

- Extensive simulation studies with complex fluids and reservoir models confirm efficiency & robustness of both RV and the bypass methods in compositional flow simulation
- Combined RV & bypass strategy shows best performance
- RV & bypass have great potential for thermal simulation & three-phase systems

# Backup Slides

# SPE3: Pressure

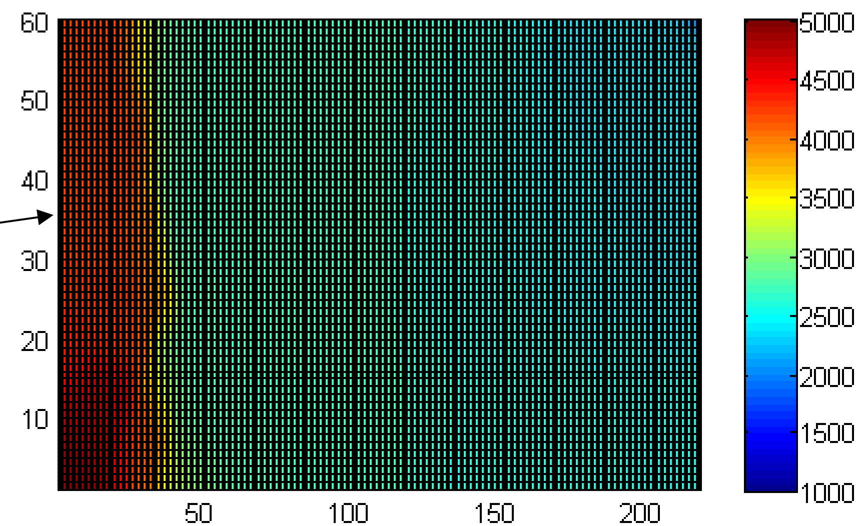
CV




**Simulation Time:**

**1,800 Days**

RV-M3



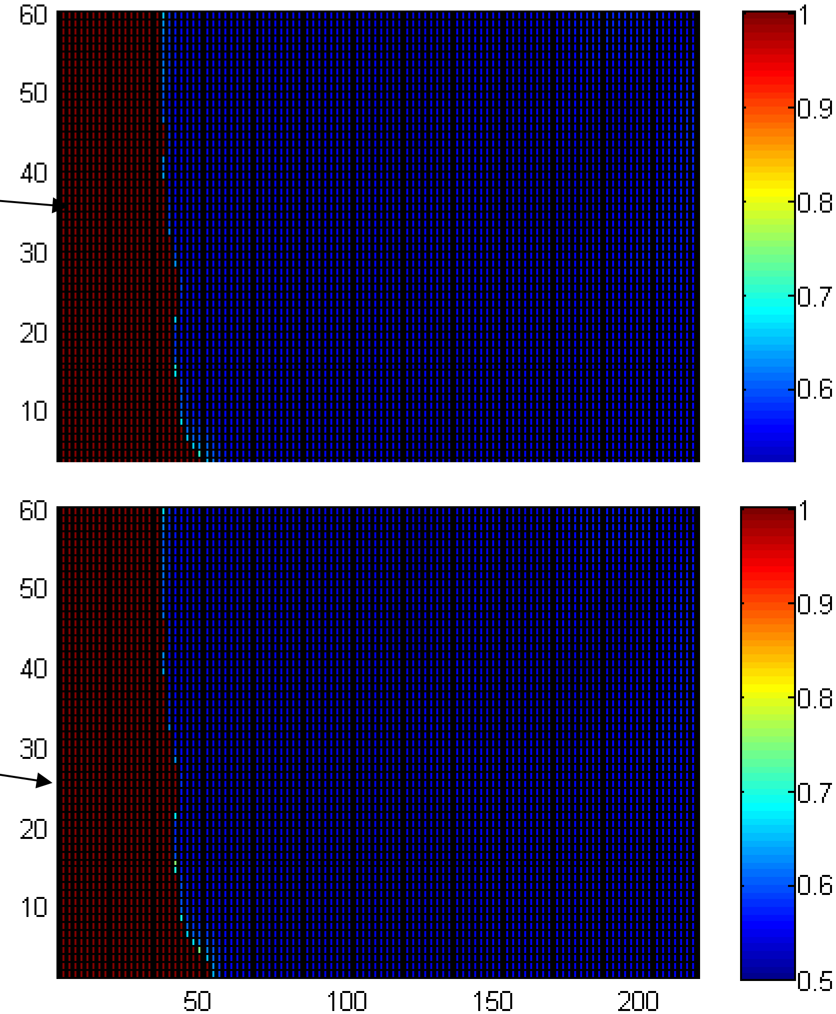
# SPE3: Gas Saturation

**Simulation Time:**

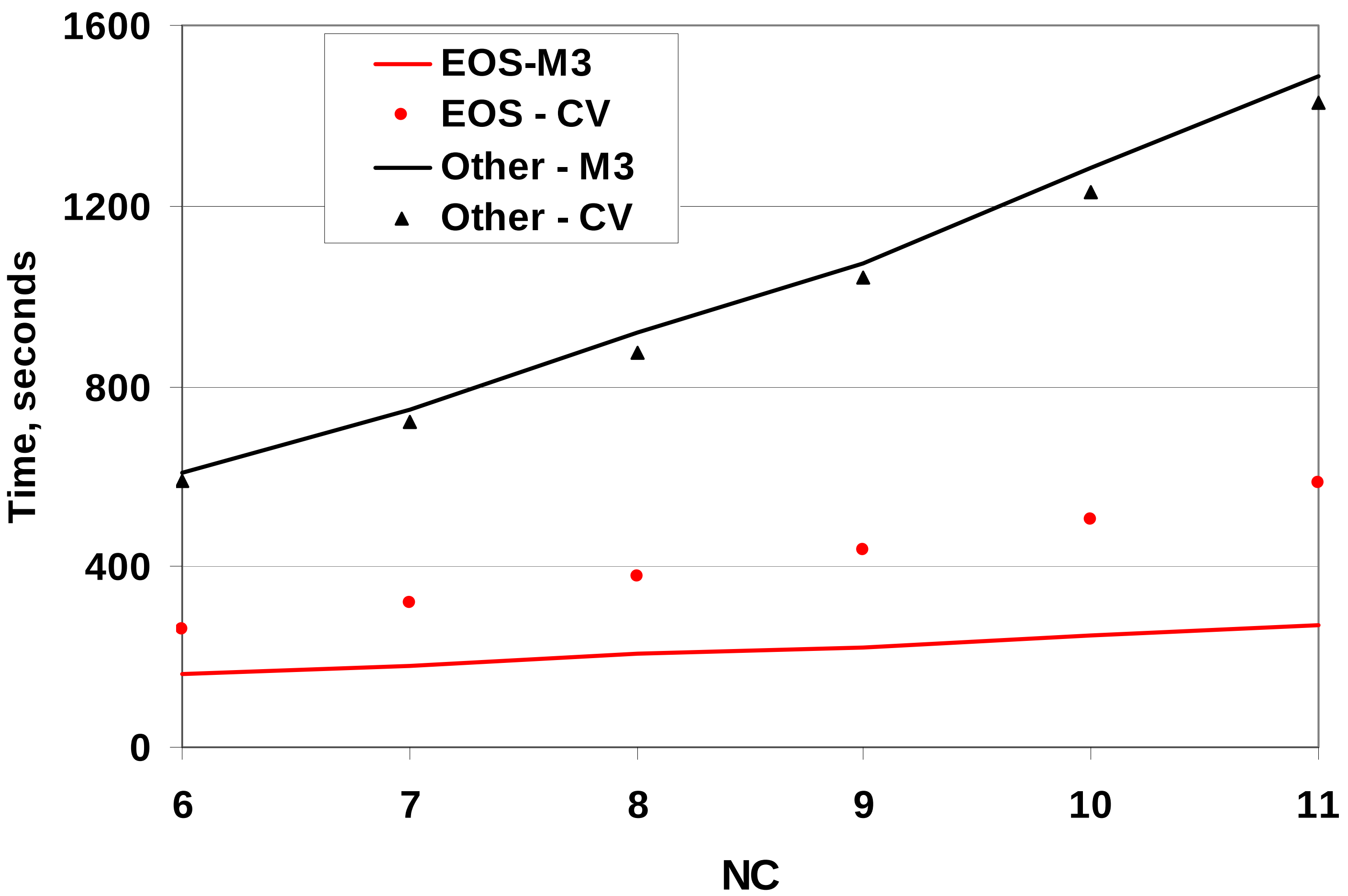
**1,800 Days**

CV

RV-M3

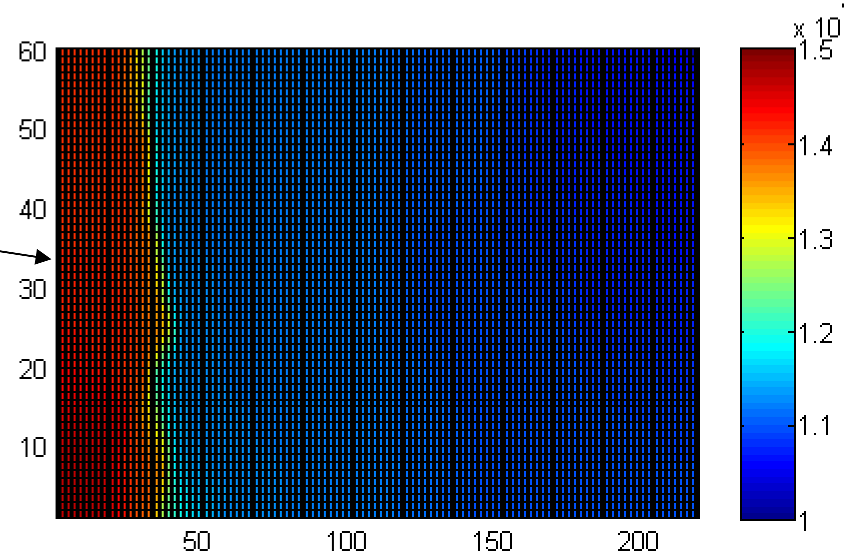


# SPE5: Execution Time vs. Nc



# Condensate2: Pressure

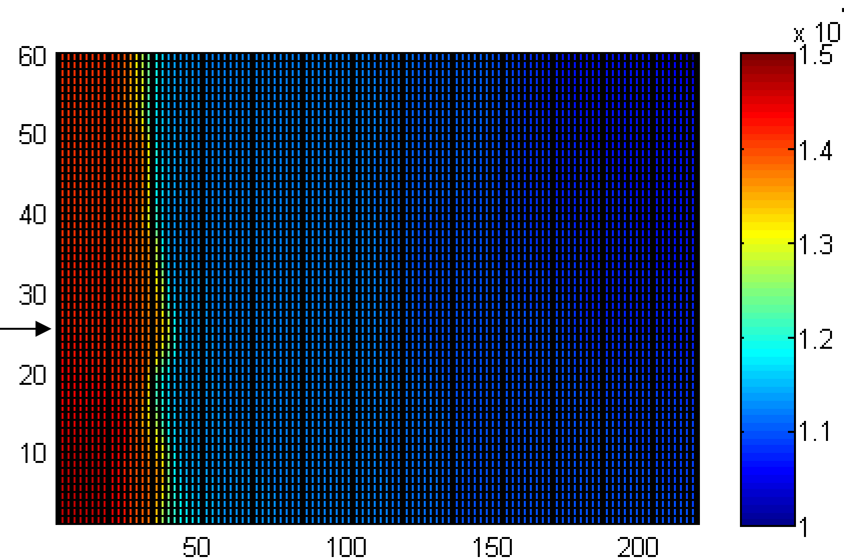
CV




**Simulation Time:**

**3,200 Days**

RV-M4



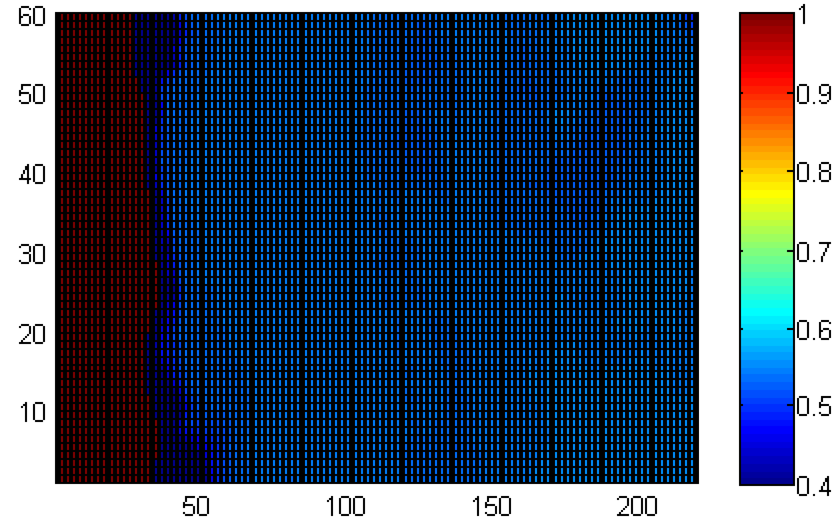
# Condensate2: Gas Saturation

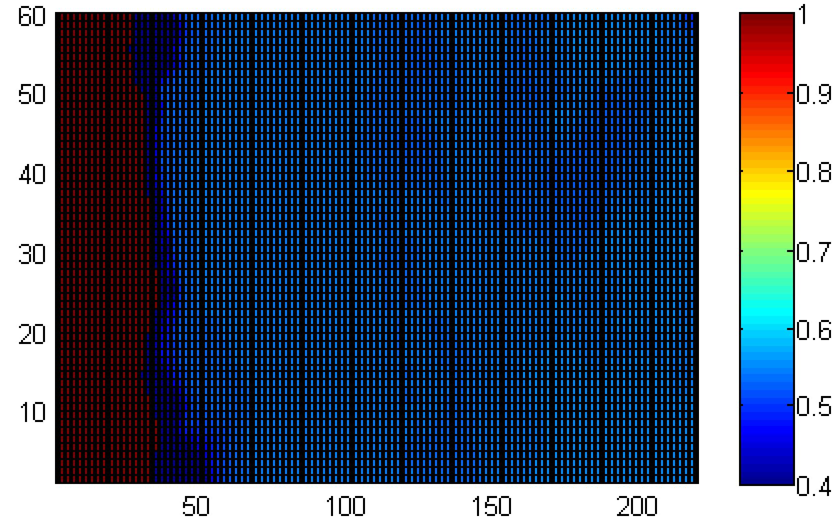
CV

**Simulation Time:**

**3,200 Days**

RV-M4



# Simple Simulations to Determine *M*

| Fluid | SPE3 | SPE5 | Condensate2 |
|---|---|---|---|
| Dimension (ft x ft x ft) | **10000x1000x50** | **15000x15000x100** | 10000x1000x50 |
| Number of Cells | **10x10x5** | **30x30x3** | 10x10x5 |
| Kx (mD) | **100** | **100** | 100 |
| Ky (mD) | **100** | **100** | 100 |
| Kz (mD) | **10** | **25** | 10 |
| porosity | **0.1** | **0.3** | 0.1 |
| W-I location* | **(1,1,1)** | **(1,1,1)** | (1,1,1) |
| W-P location* | (10,10,5) | (30,30,3) | (10,10,5) |

***W-I: Injection Well W-P: Production Well**

- Simulation: multi-contact miscible displacement
- *M* value is the same as in Reservoir I

  $M=3$ (SPE3), $M=2$ (SPE5), $M=4$ (Condensate2)