Results from ARMA Hydraulic Fracturing Code Comparison 2017 using Resfrac (code described in SPE-182593-MS)

Benchmark Problem 6 (a,c)

Note: We also did an “extended” 6c with 10 days of shut-in, followed by 90 days of production, to show the large changes that occurs *after* shut-in

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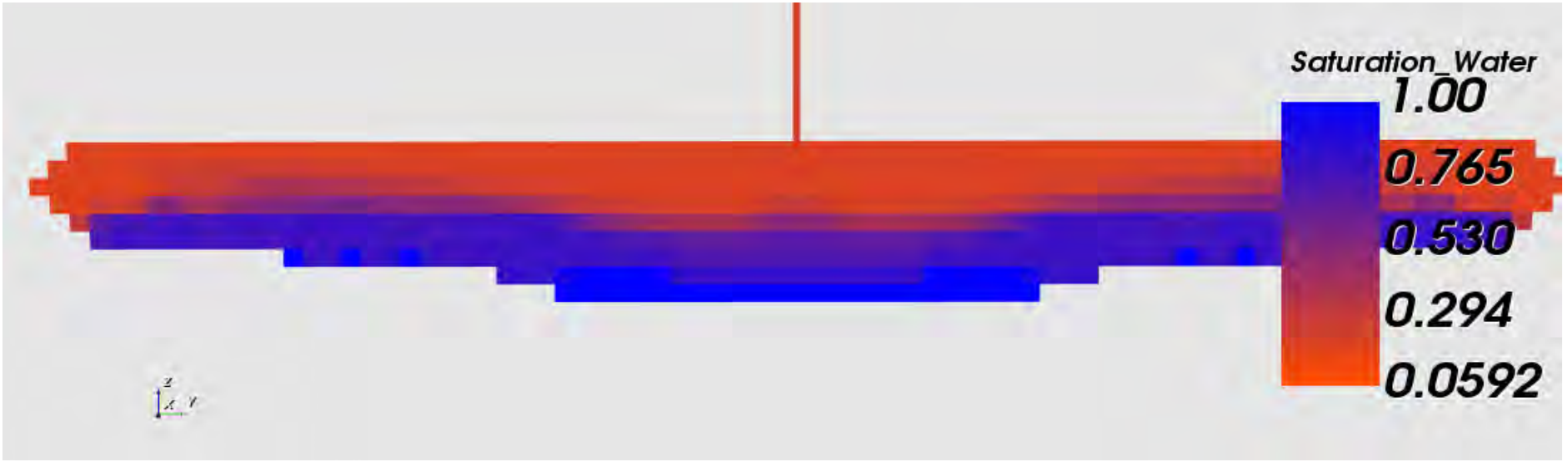
GEOMECHANICS

Resfrac

SPE 182593-MS

- Full coupling between wellbore, reservoir, and hydraulic fracturing
- A *true* hydraulic fracturing simulator and a *true* reservoir simulator
- Ability to capture fracture closure, either with or without proppant, and smoothly transition between constitutive equations
- Thermal and compositional (three-phase)
- Proppant transport: gravitational settling, hindered settling, jamming, transition to Darcy flow, gravitational convection



Multiphase Forcheimer flow with gravity and non-Newtonian fluid
Handles closure, with or without proppant

$$\frac{\Delta\Phi_p}{\Delta x} = -\frac{q_{p,o}}{W}\left(\frac{12\mu_{p,s}}{E^3 k_{rp,cro}}\right) + sgn\left(\Delta\Phi_p\right)\left(\frac{q_{p,o}}{WE}\right)^2 \beta_{cro}\beta_{rp,cro}\rho_{p,s}$$

$$\frac{\Delta\Phi_p}{\Delta x} = -\left(\frac{q_{p,c}}{W}\right)\frac{1}{M_{p,cr}+M_{p,b}} + sgn\left(\Delta\Phi_p\right)\left(\frac{q_{p,c}}{WE}\right)^2 \rho_p \frac{M_{p,cr}+M_{p,b}}{\frac{M_{p,cr}}{\beta_{cr}\beta_{rp,cr}}+\frac{M_{p,b}}{\beta_b\beta_{rp,b}}}$$

$$\gamma_f = \frac{E_{open}}{0.1\left(E_0 + E_{pr} + E_{res}\right) + E_{open}}$$

$$q_p = \gamma_f q_{p,o} + \left(1-\gamma_f\right)q_{p,c}$$

$$\Phi_p = P_p - gz(\gamma_f\rho_p + (1-\gamma_f)(C_{pr}\bar{\rho}_{pr} + \left(1-C_{pr}\right)\rho_p))$$

$$\mu_a = \frac{\mu_0}{1+\frac{\mu_0}{K}(\dot{\gamma})^{1-n}} = \frac{\mu_0}{1+(\frac{\dot{\gamma}}{\dot{\gamma}_{1/2}})^{1-n}}$$

Modified power-law fluid (similar to an Ellis fluid)

$$\mu_a = \frac{\mu_0}{1 + \frac{\mu_0}{K}(\dot{\gamma})^{1-n}} = \frac{\mu_0}{1 + \left(\frac{\dot{\gamma}}{\dot{\gamma}_{1/2}}\right)^{1-n}}$$

Behaves like a power-law fluid at high shear rate, but has a low-shear rate plateau.

Solute concentration and temperature related to rheological parameters.

Smoothly captures transition from Newtonian to non-Newtonian fluid as solute concentration increases.

Can set parameters to behave similar to power law.

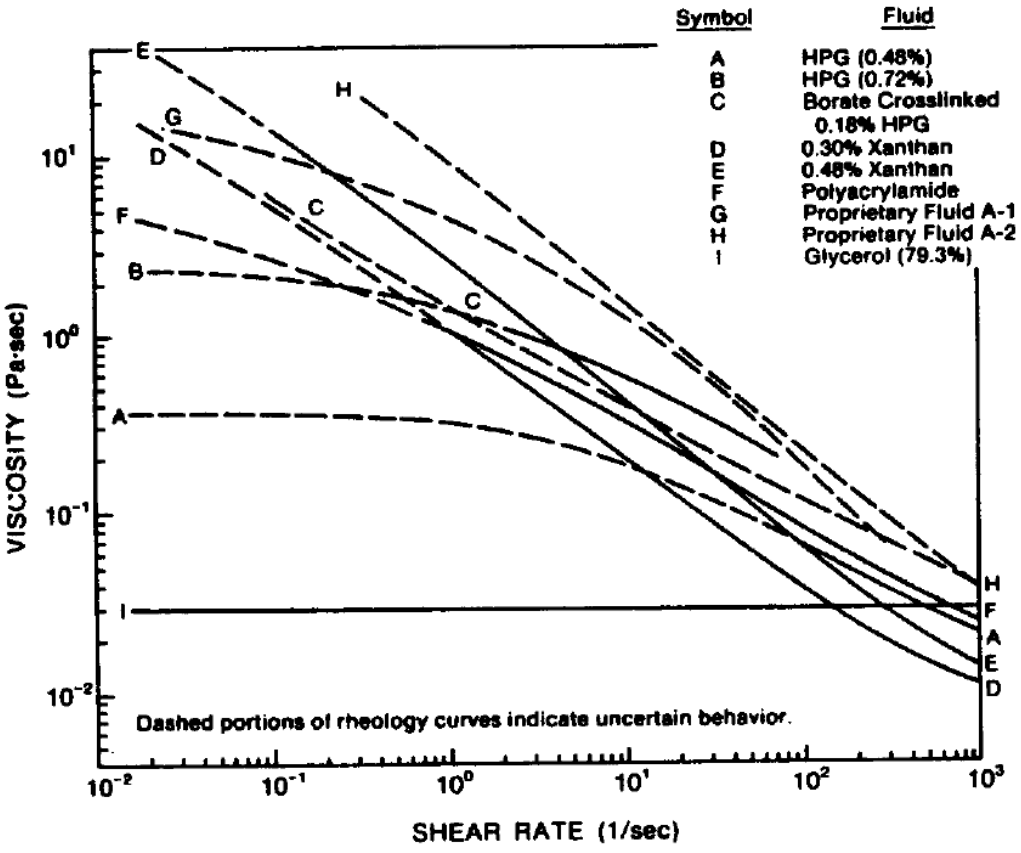


Figure 7. Rheological characterization of fluids.

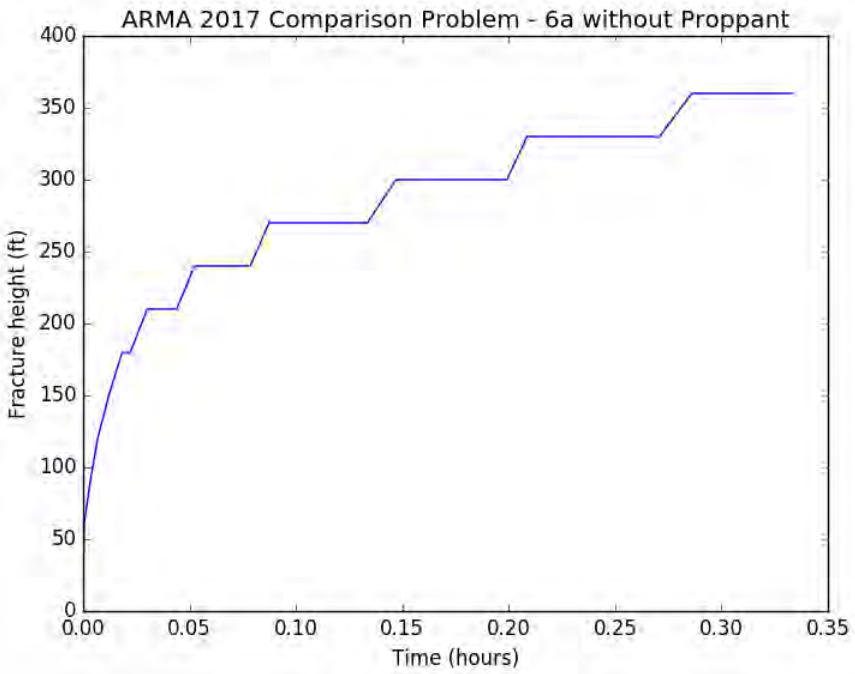
Kirkby and Rockefeller (1985)

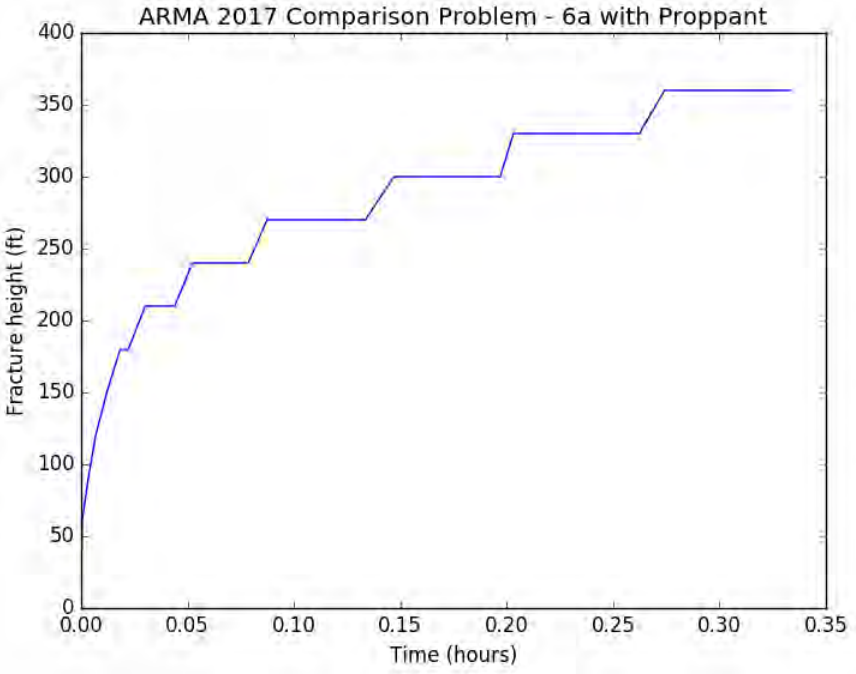
Numerical Methods

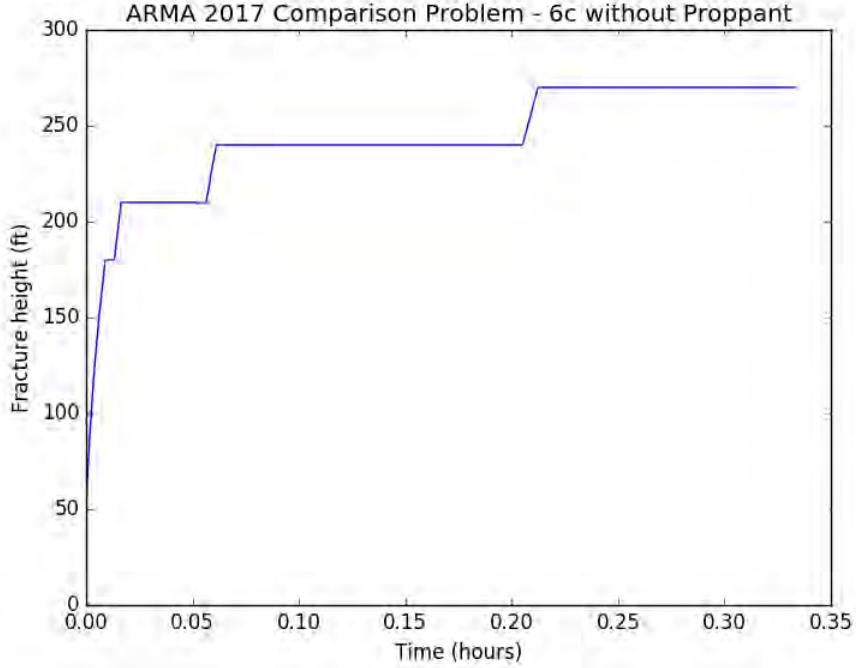
- Finite volume method for transport
- Boundary element method for mechanics

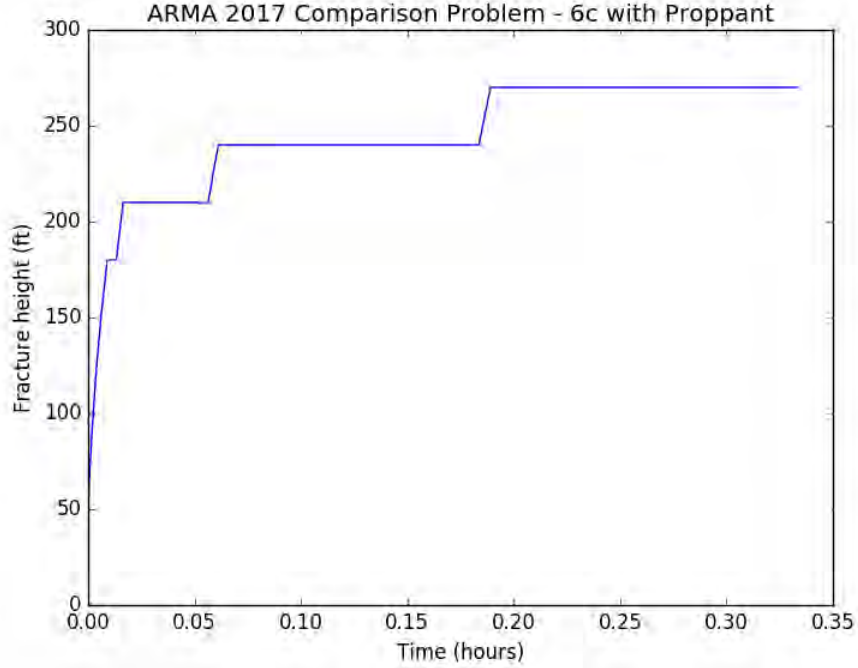
- Non-Newtonian flow in 6a (Newtonian fluid in 6c)
- In 6c, CO_2 density calculation with Peng-Robinson equation of state, CO_2 viscosity set constant to 15 cp

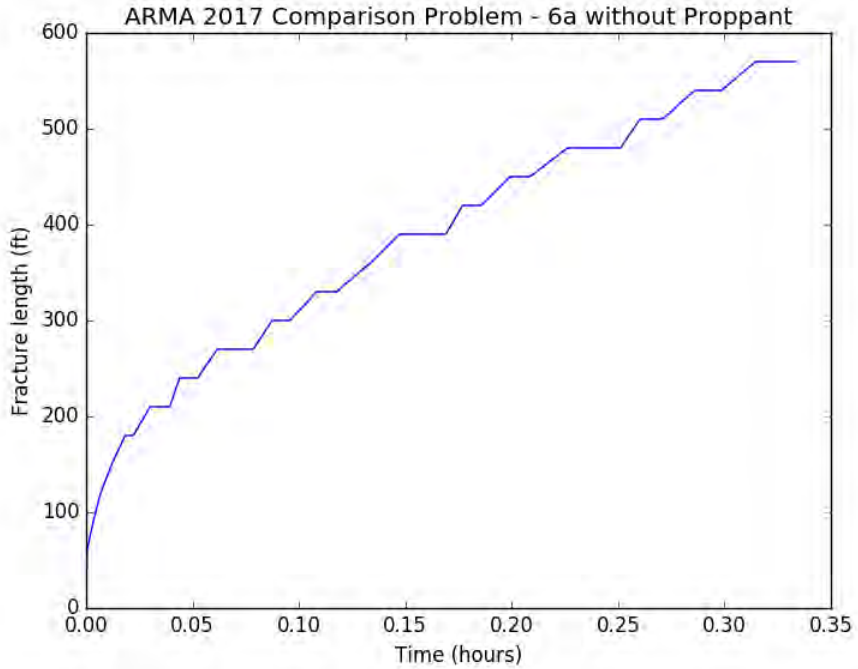
- Injection rate:
  - "20 bpm" was assumed to refer to reservoir volume
  - For CO_2, this was converted to 50 Mscf/min

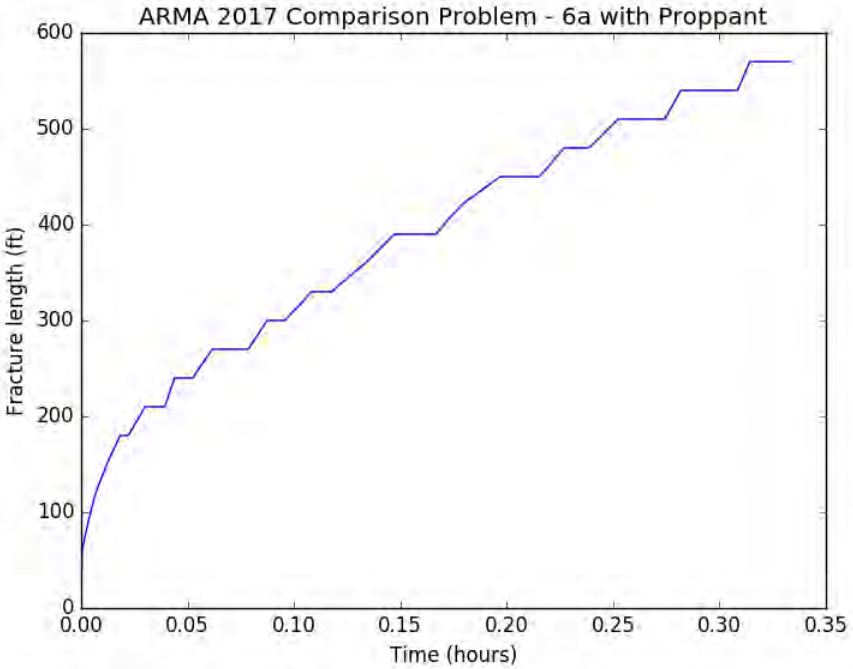

ARMA 2017 Comparison Problem - 6a without Proppant
Fracture height (ft)
Time (hours)
0
50
100
150
200
250
300
350
400
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35

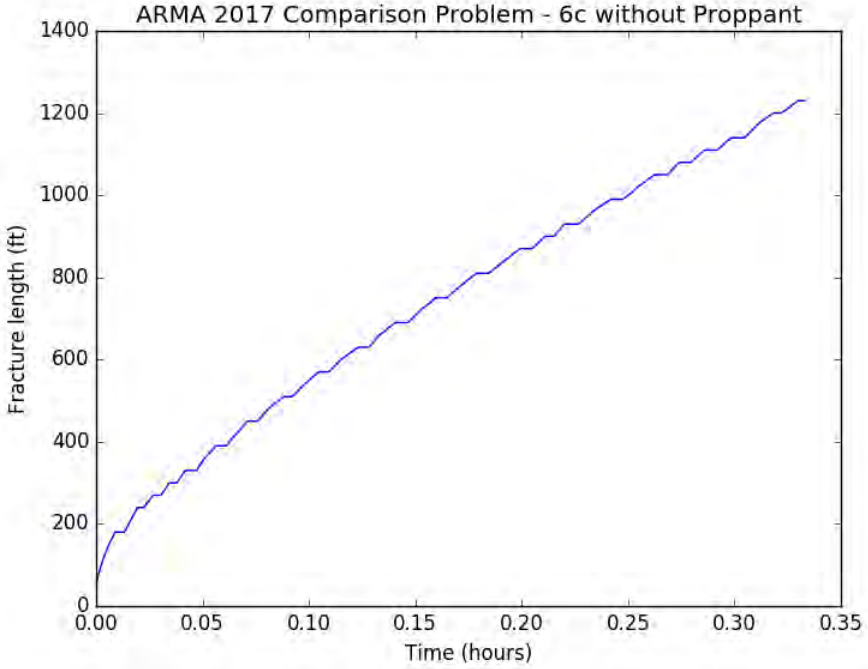

ARMA 2017 Comparison Problem - 6a with Proppant
Fracture height (ft)
Time (hours)
0
50
100
150
200
250
300
350
400
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35

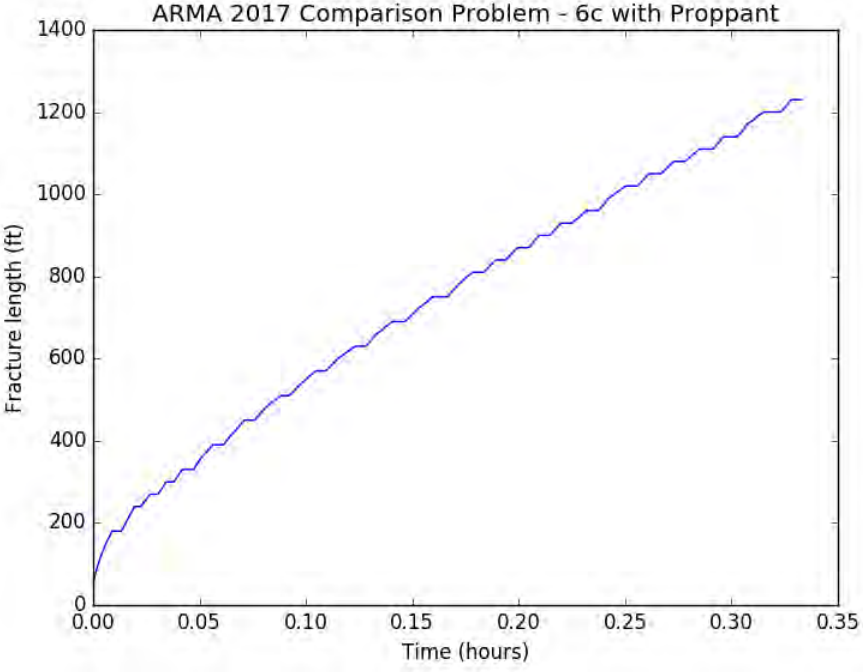

ARMA 2017 Comparison Problem - 6c without Proppant
Fracture height (ft)
Time (hours)
0
50
100
150
200
250
300
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35

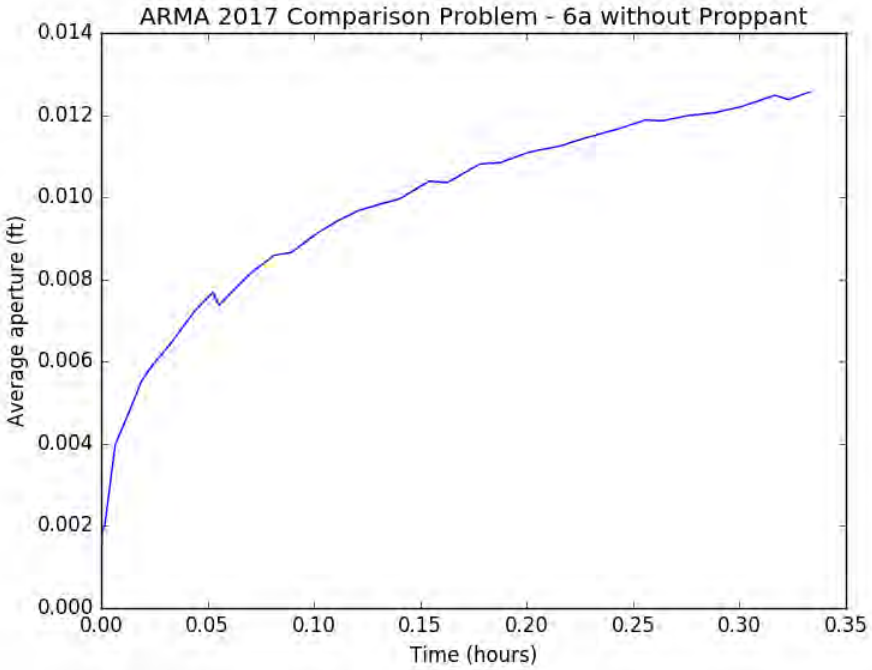

ARMA 2017 Comparison Problem - 6c with Proppant
Fracture height (ft)
Time (hours)
0
50
100
150
200
250
300
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35

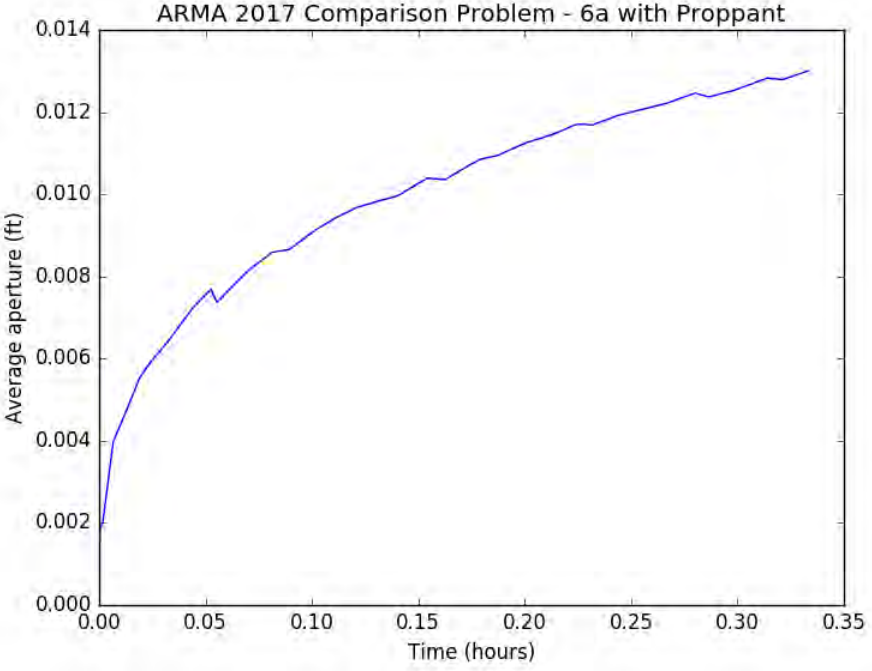

ARMA 2017 Comparison Problem - 6a without Proppant
Fracture length (ft)
Time (hours)
0
100
200
300
400
500
600
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35

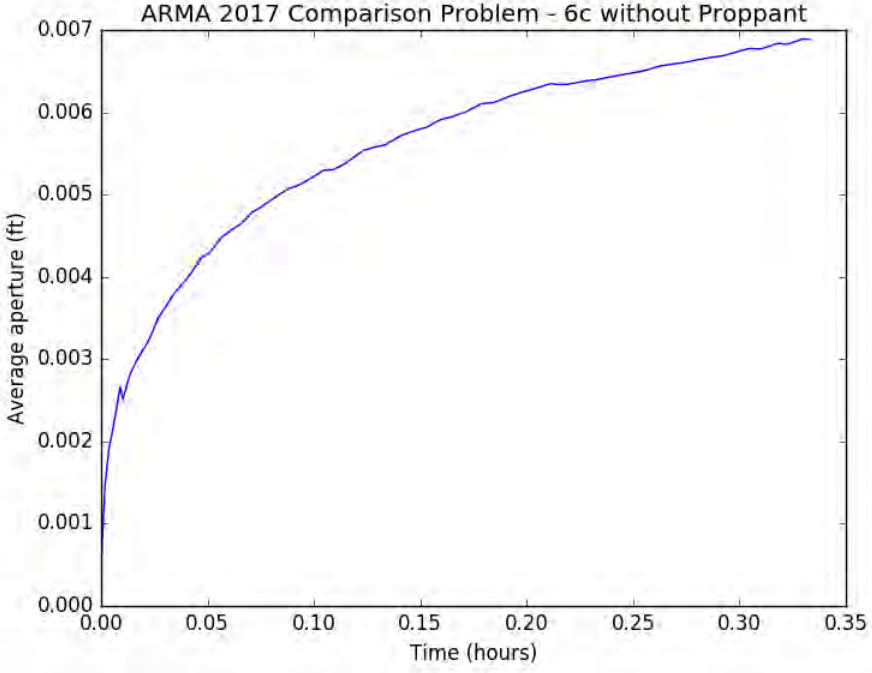

ARMA 2017 Comparison Problem - 6a with Proppant
Fracture length (ft)
Time (hours)
0
100
200
300
400
500
600
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35


ARMA 2017 Comparison Problem - 6c without Proppant
Fracture length (ft)
Time (hours)
0
200
400
600
800
1000
1200
1400
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35


ARMA 2017 Comparison Problem - 6c with Proppant
Fracture length (ft)
Time (hours)
0
200
400
600
800
1000
1200
1400
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35


ARMA 2017 Comparison Problem - 6a without Proppant
Average aperture (ft)
Time (hours)
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35


ARMA 2017 Comparison Problem - 6a with Proppant
Average aperture (ft)
Time (hours)
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35


ARMA 2017 Comparison Problem - 6c without Proppant
Average aperture (ft)
Time (hours)
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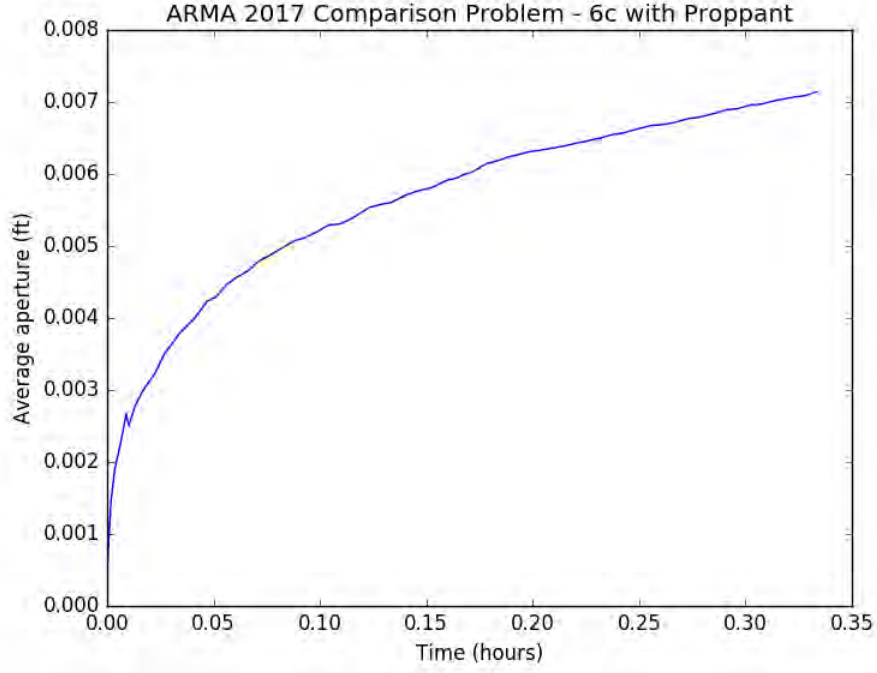
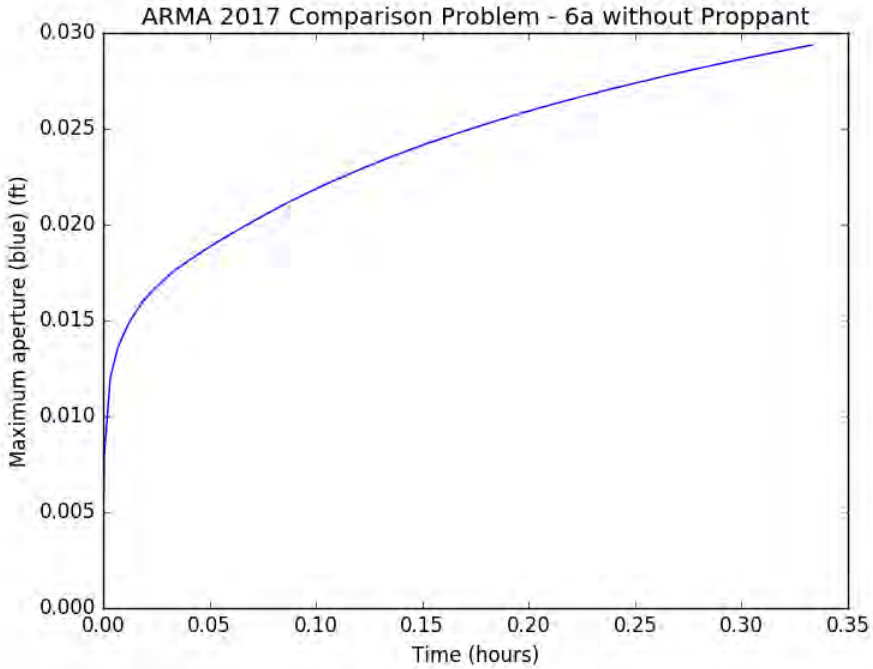
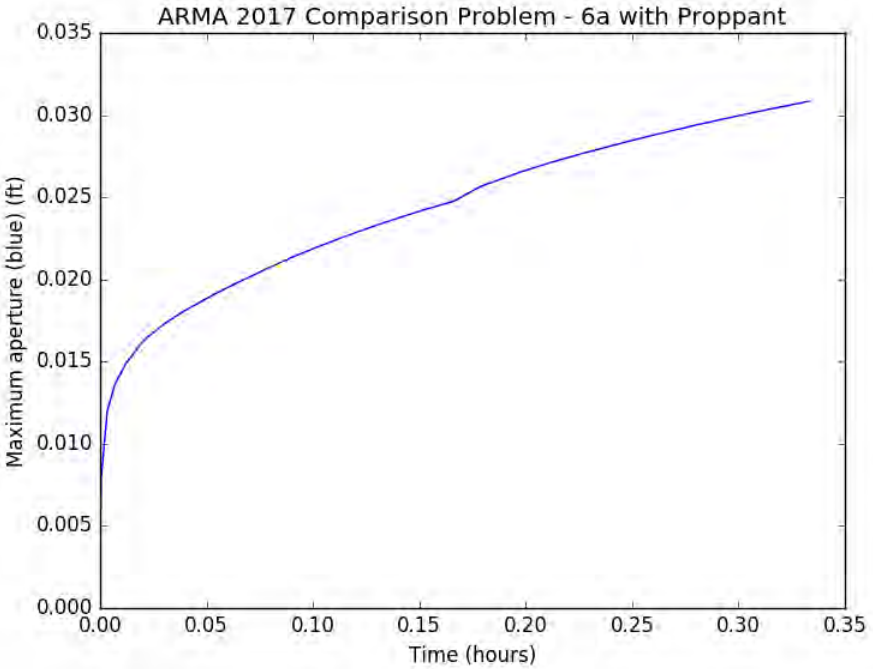
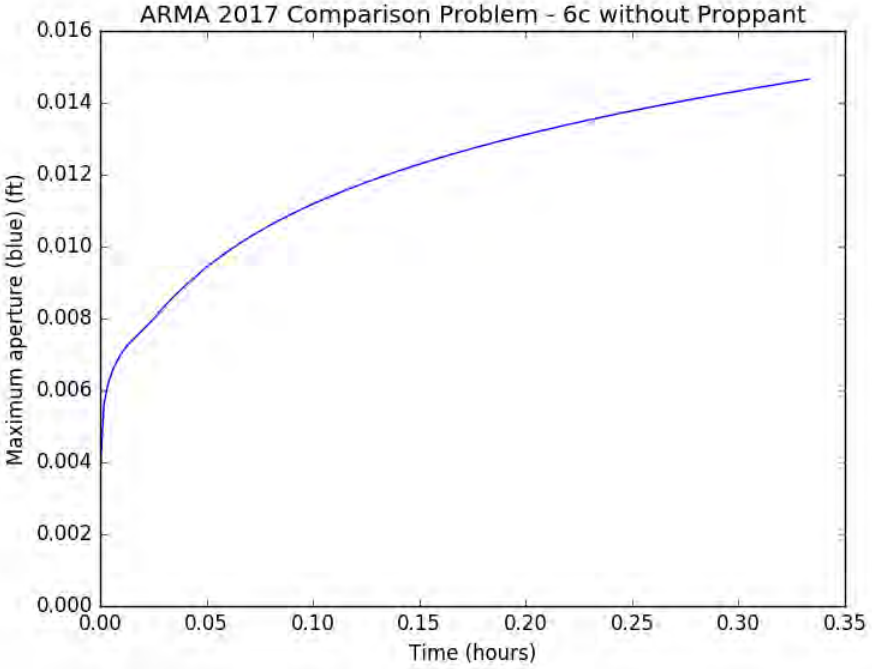
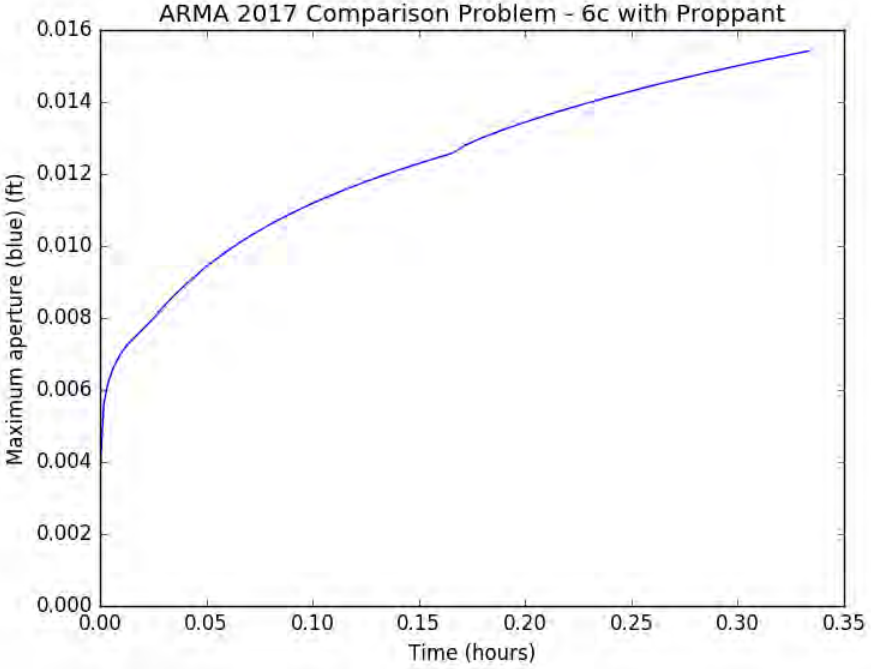
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35

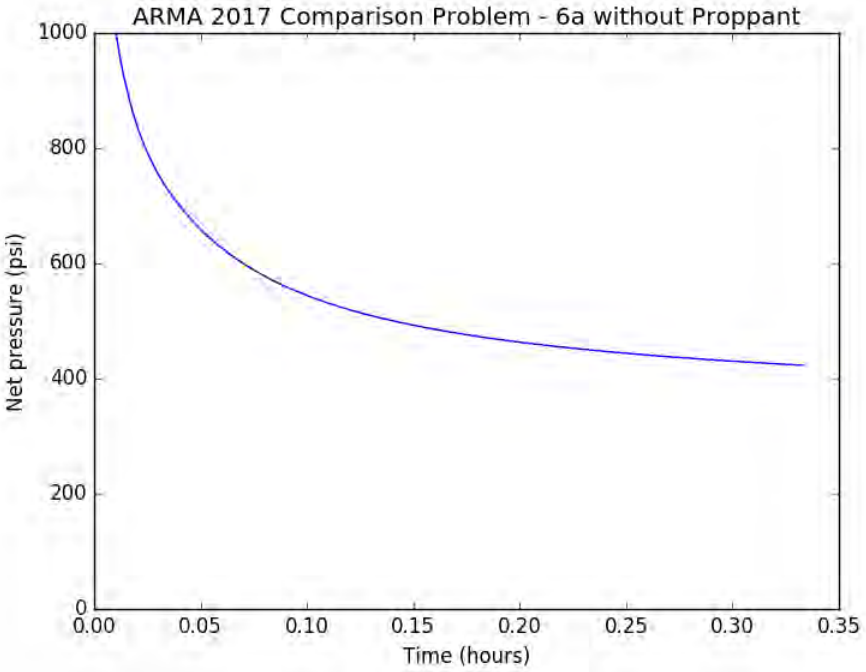

ARMA 2017 Comparison Problem - 6c with Proppant
Average aperture (ft)
Time (hours)
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35

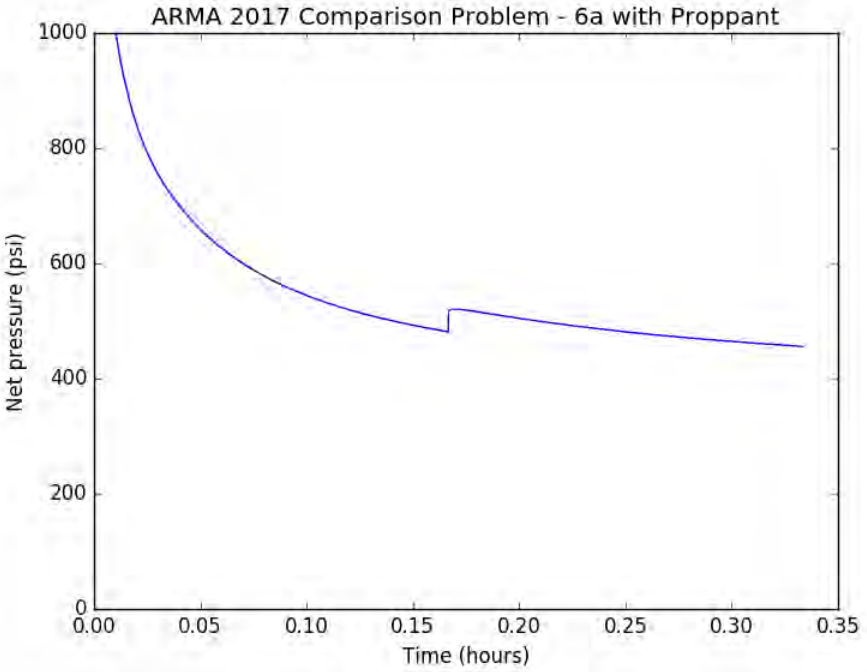

ARMA 2017 Comparison Problem - 6a without Proppant
Maximum aperture (blue) (ft)
Time (hours)
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35


ARMA 2017 Comparison Problem - 6a with Proppant
Maximum aperture (blue) (ft)
Time (hours)
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35


ARMA 2017 Comparison Problem - 6c without Proppant
Maximum aperture (blue) (ft)
Time (hours)
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.016
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35


ARMA 2017 Comparison Problem - 6c with Proppant
Maximum aperture (blue) (ft)
Time (hours)
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.016
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35


ARMA 2017 Comparison Problem - 6a without Proppant
Net pressure (psi)
Time (hours)
0
200
400
600
800
1000
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35


ARMA 2017 Comparison Problem - 6a with Proppant
Net pressure (psi)
Time (hours)
0
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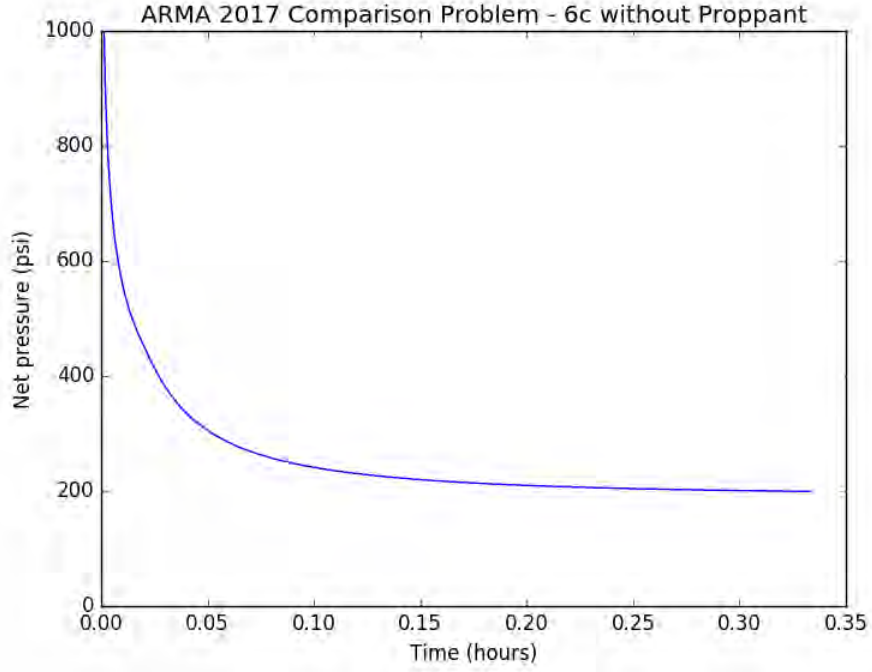
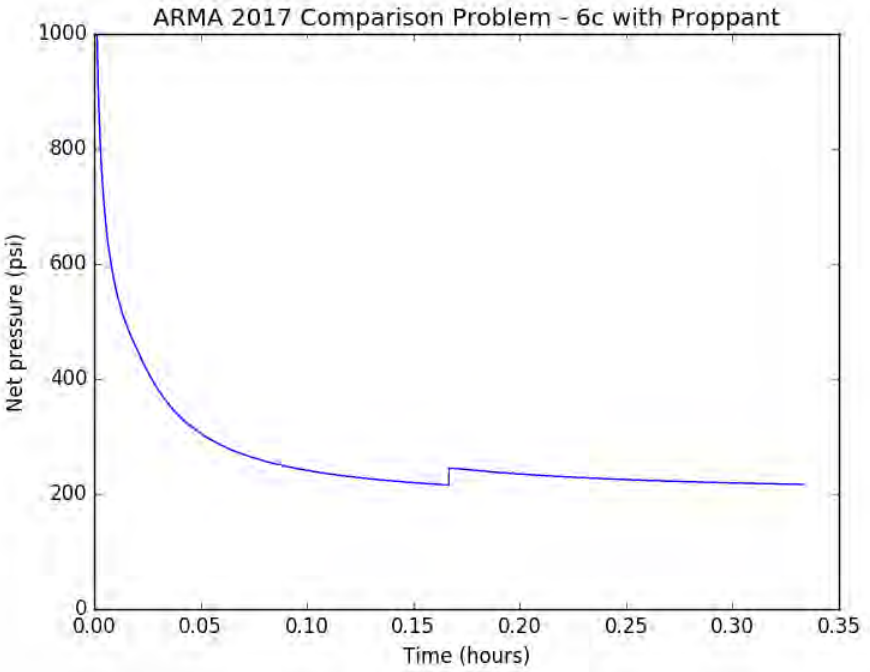
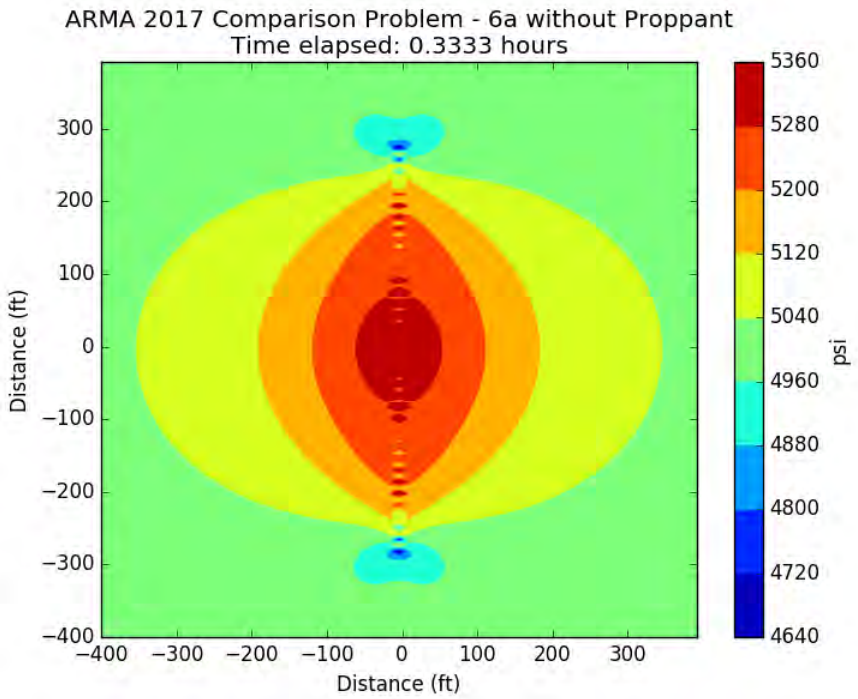
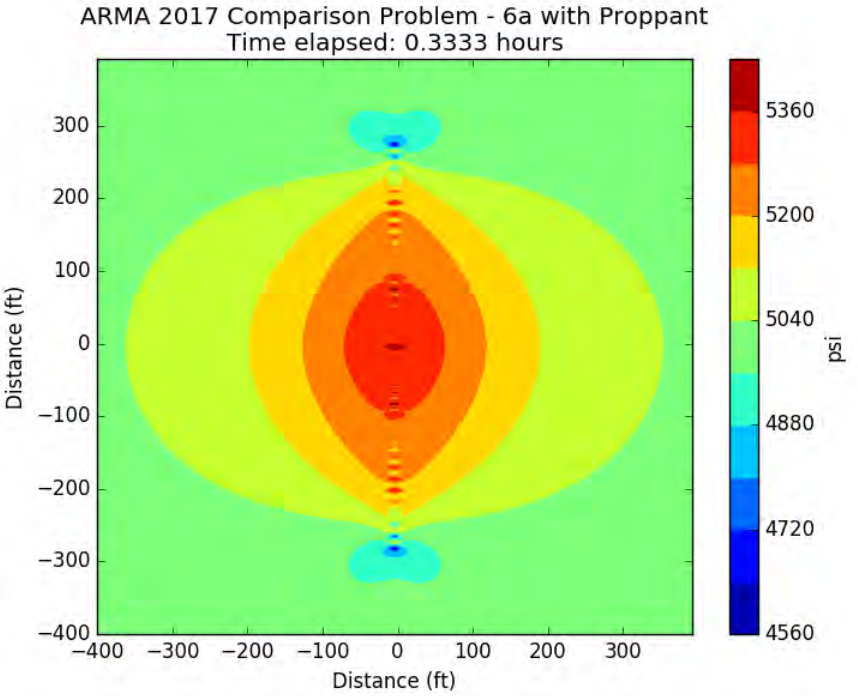
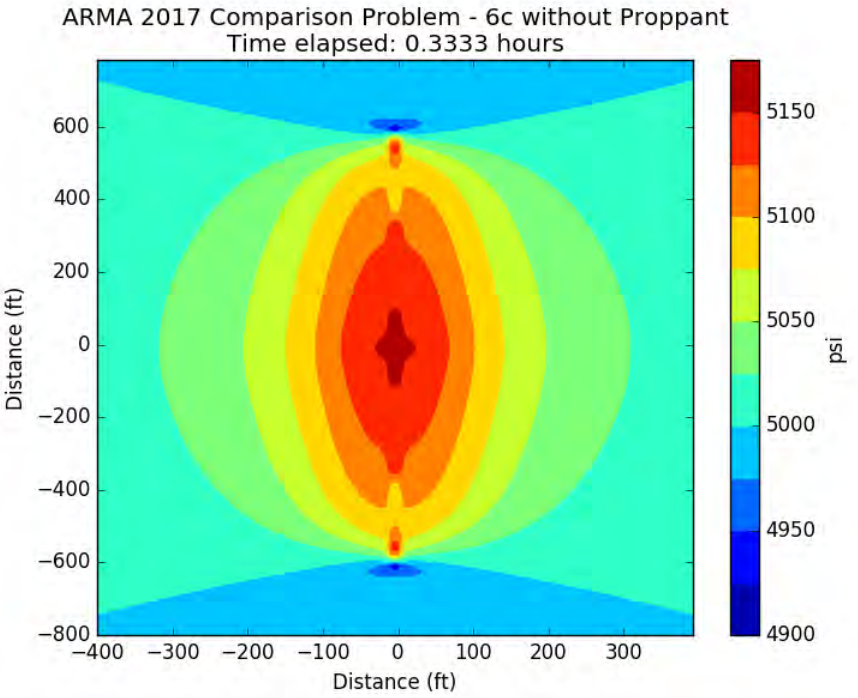
400
600
800
1000
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35

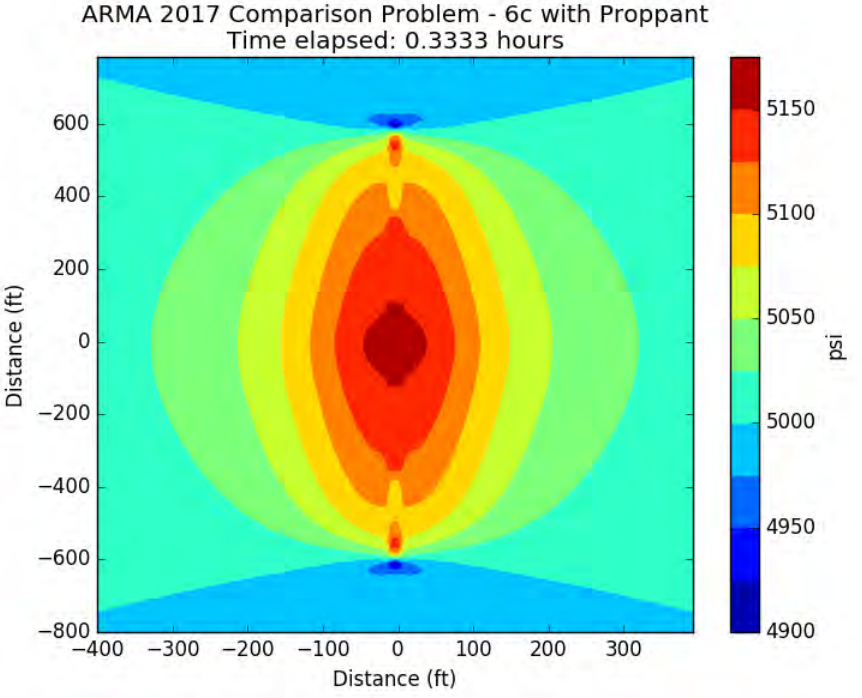

ARMA 2017 Comparison Problem - 6c without Proppant
Net pressure (psi)
Time (hours)
0
200
400
600
800
1000
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35

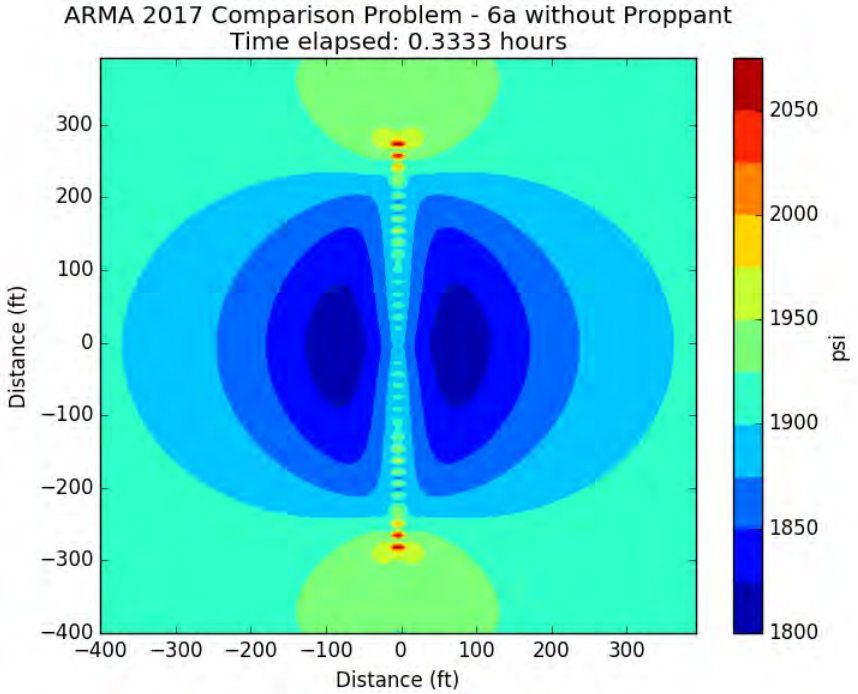

ARMA 2017 Comparison Problem - 6c with Proppant
Net pressure (psi)
Time (hours)
0
200
400
600
800
1000
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35

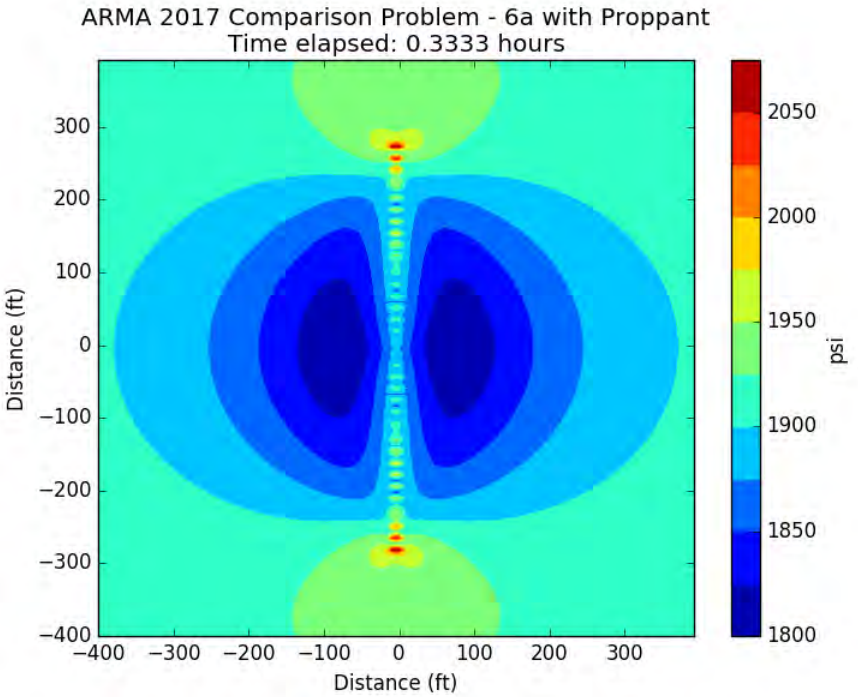

ARMA 2017 Comparison Problem - 6a without Proppant
Time elapsed: 0.3333 hours
Distance (ft)
Distance (ft)
psi
5360
5280
5200
5120
5040
4960
4880
4800
4720
4640

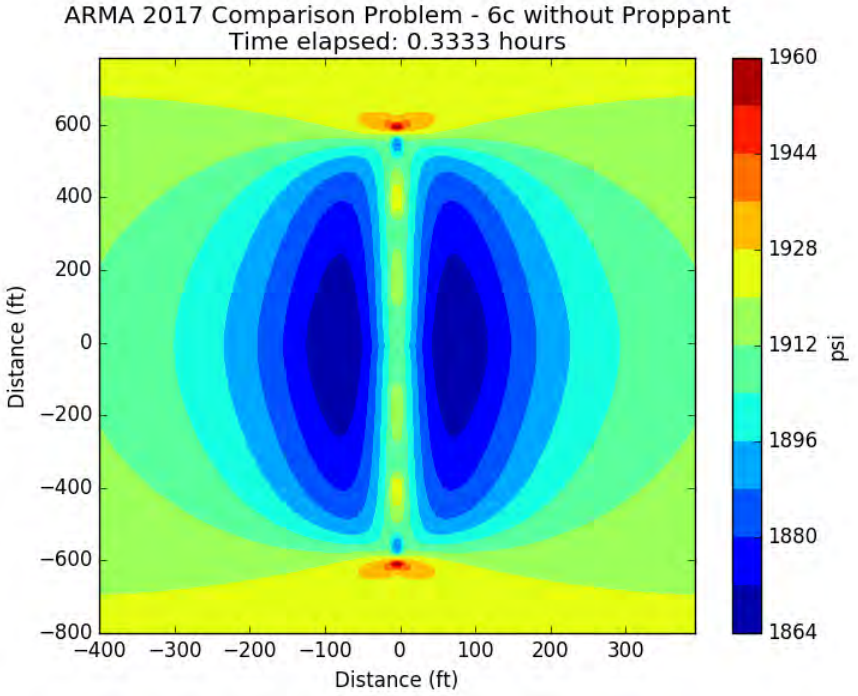

ARMA 2017 Comparison Problem - 6a with Proppant
Time elapsed: 0.3333 hours
Distance (ft)
Distance (ft)
psi
5360
5200
5040
4880
4720
4560

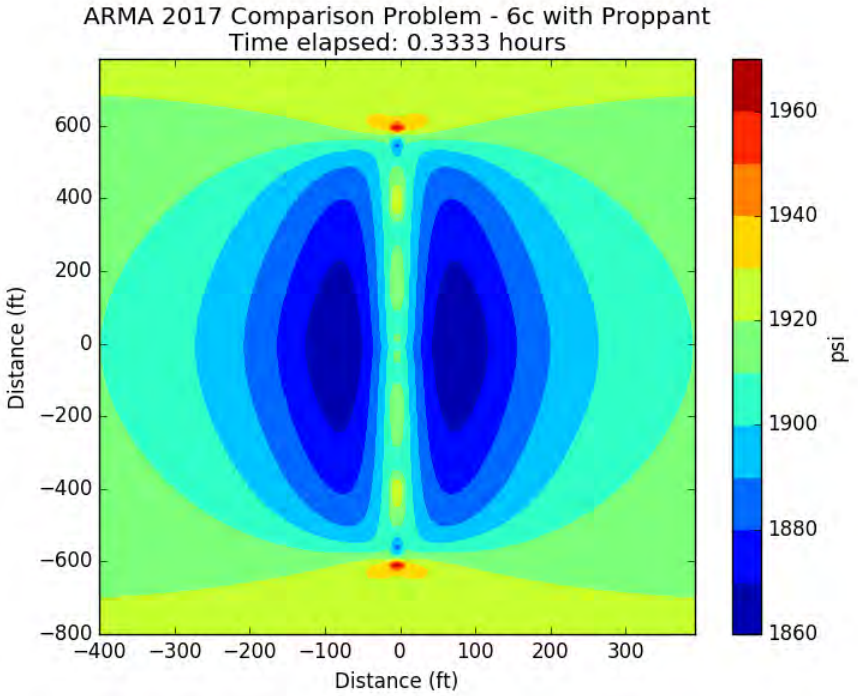

ARMA 2017 Comparison Problem - 6c without Proppant
Time elapsed: 0.3333 hours
Distance (ft)
Distance (ft)
psi
5150
5100
5050
5000
4950
4900


ARMA 2017 Comparison Problem - 6c with Proppant
Time elapsed: 0.3333 hours
Distance (ft)
Distance (ft)
psi
5150
5100
5050
5000
4950
4900

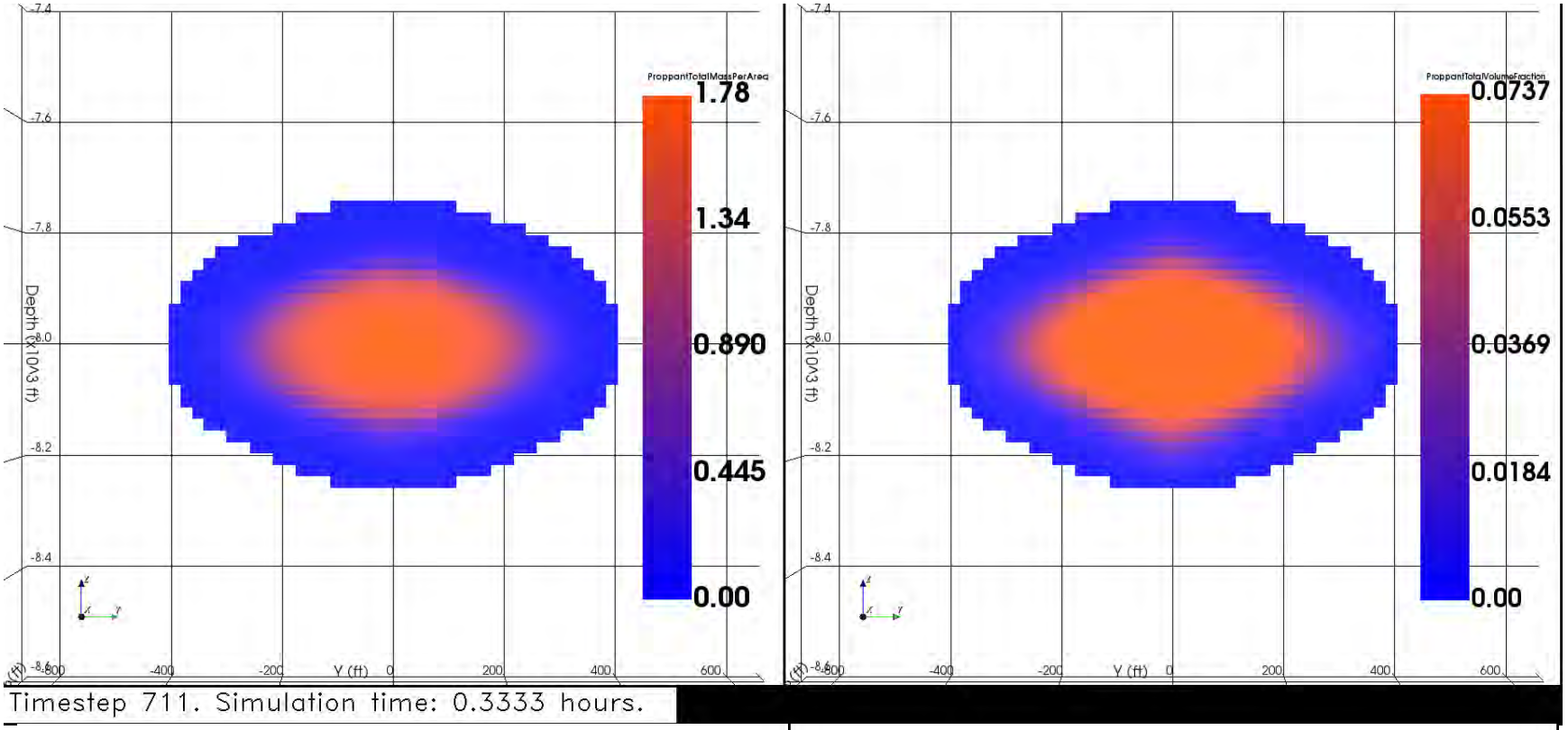

ARMA 2017 Comparison Problem - 6a without Proppant
Time elapsed: 0.3333 hours
Distance (ft)
Distance (ft)
psi
2050
2000
1950
1900
1850
1800


ARMA 2017 Comparison Problem - 6a with Proppant
Time elapsed: 0.3333 hours
Distance (ft)
Distance (ft)
psi
2050
2000
1950
1900
1850
1800

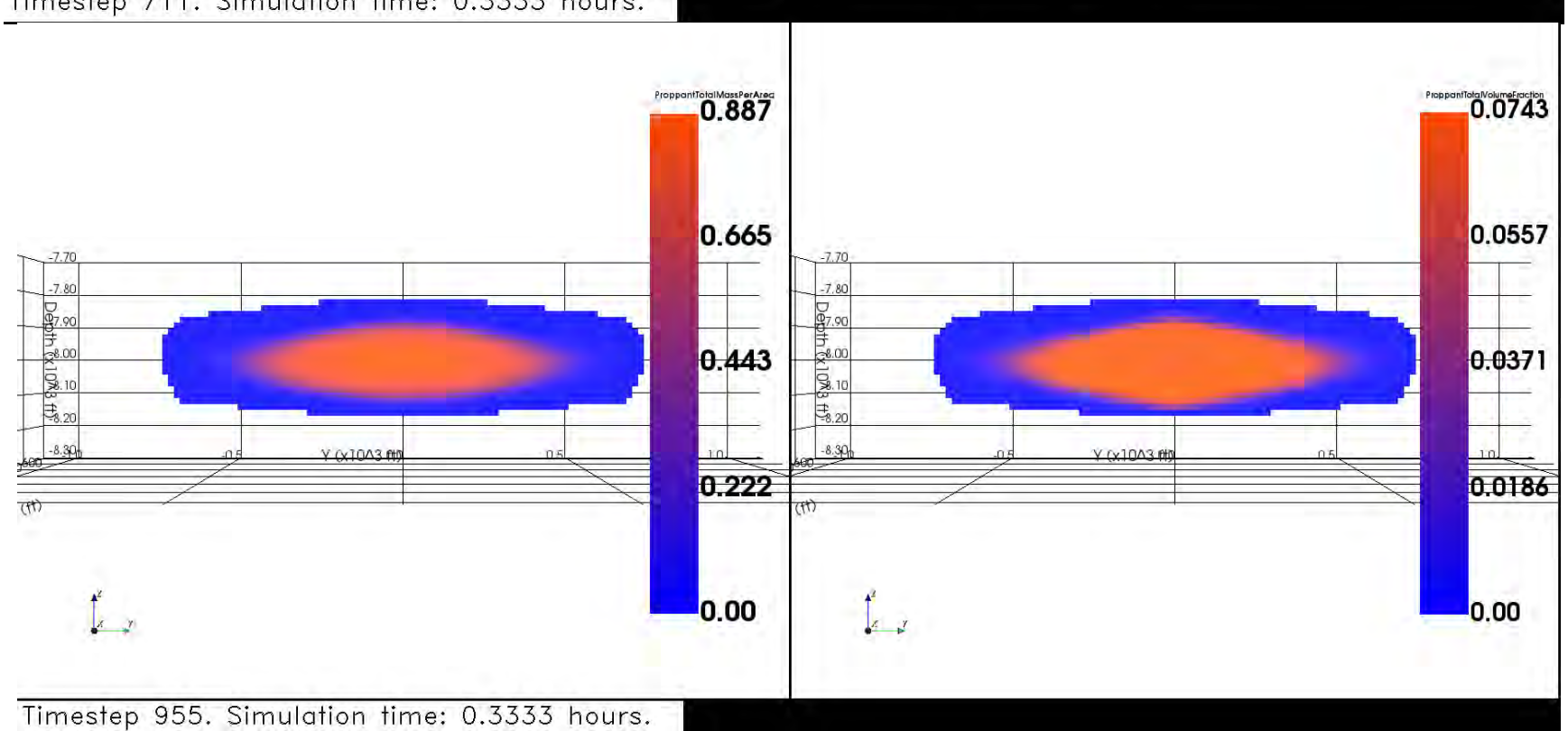

ARMA 2017 Comparison Problem - 6c without Proppant
Time elapsed: 0.3333 hours
Distance (ft)
Distance (ft)
psi
1960
1944
1928
1912
1896
1880
1864


ARMA 2017 Comparison Problem - 6c with Proppant
Time elapsed: 0.3333 hours
Distance (ft)
Distance (ft)
psi
1960
1940
1920
1900
1880
1860

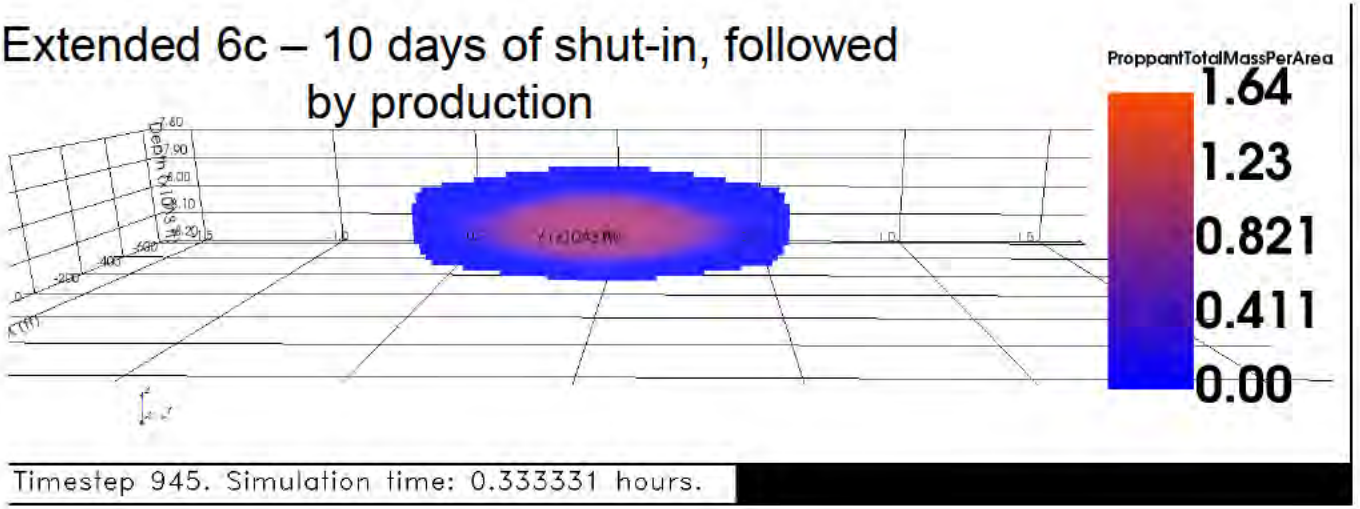
6a

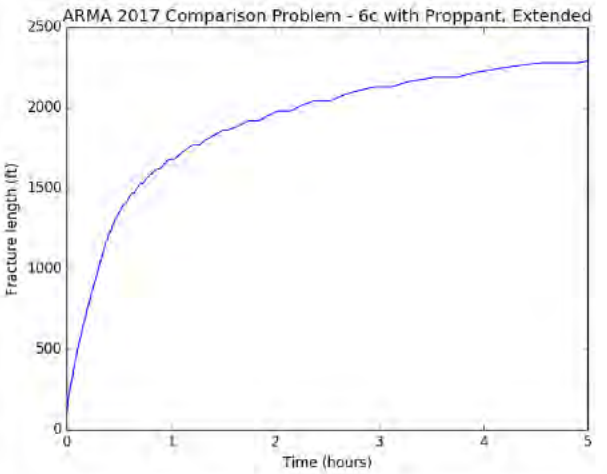

ProppantTotalMassPerArea
1.78
1.34
0.890
0.445
0.00
ProppantTotalVolumeFraction
0.0737
0.0553
0.0369
0.0184
0.00
Depth (x10^3 ft)
Y (ft)
Timestep 711. Simulation time: 0.3333 hours.

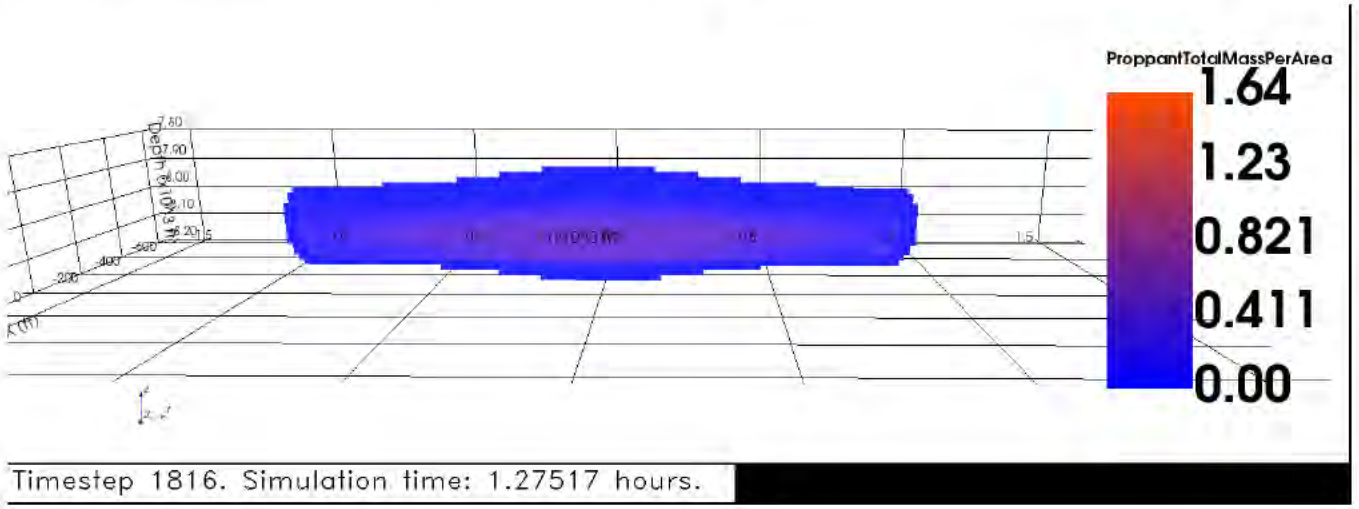
6c

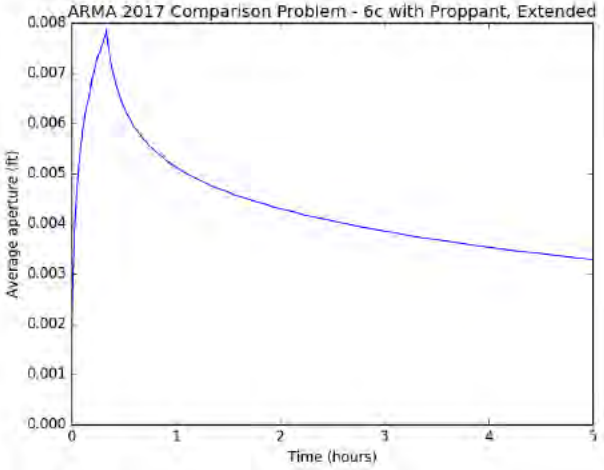

ProppantTotalMassPerArea
0.887
0.665
0.443
0.222
0.00
ProppantTotalVolumeFraction
0.0743
0.0557
0.0371
0.0186
0.00
Depth (x10^3 ft)
Y (x10^3 ft)
Timestep 955. Simulation time: 0.3333 hours.

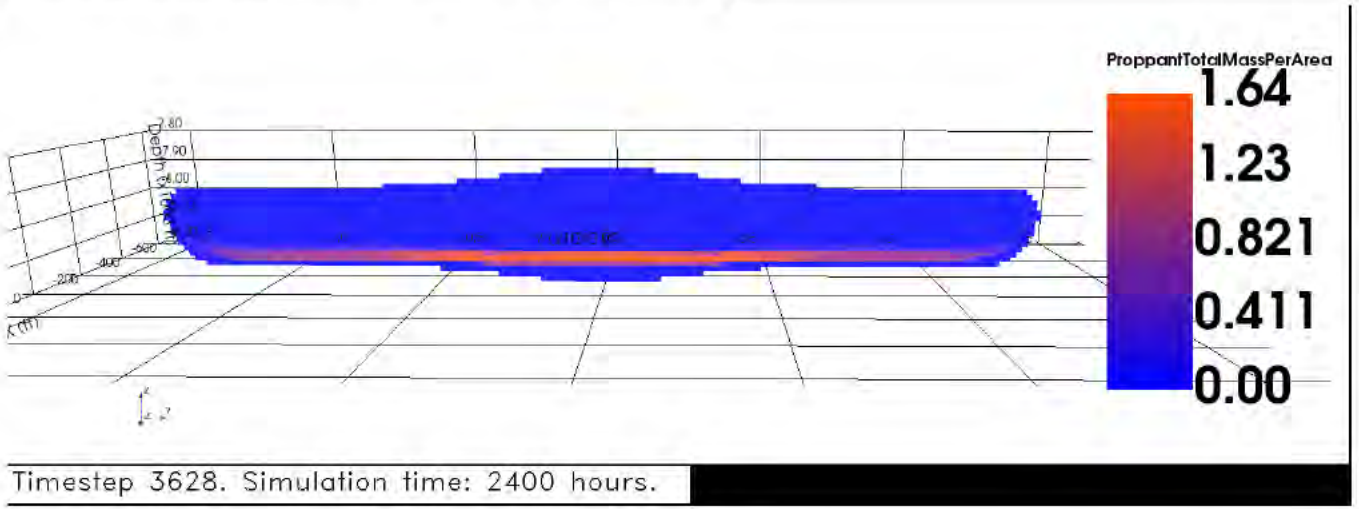
Extended 6c – 10 days of shut-in, followed by production

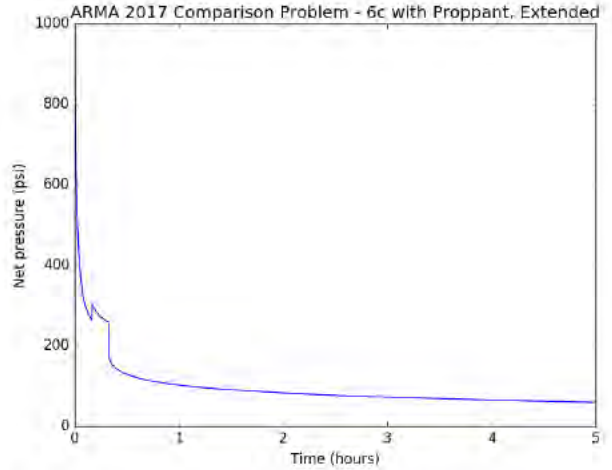




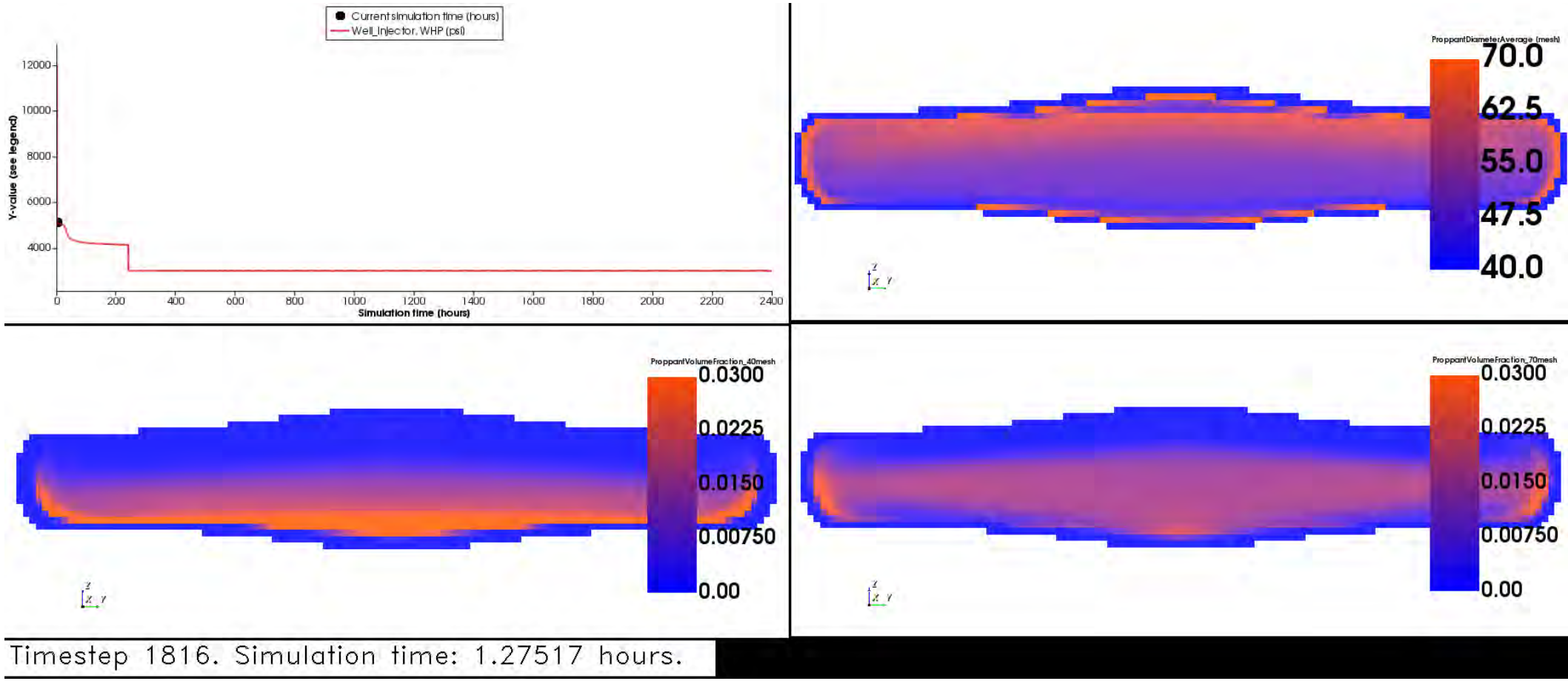
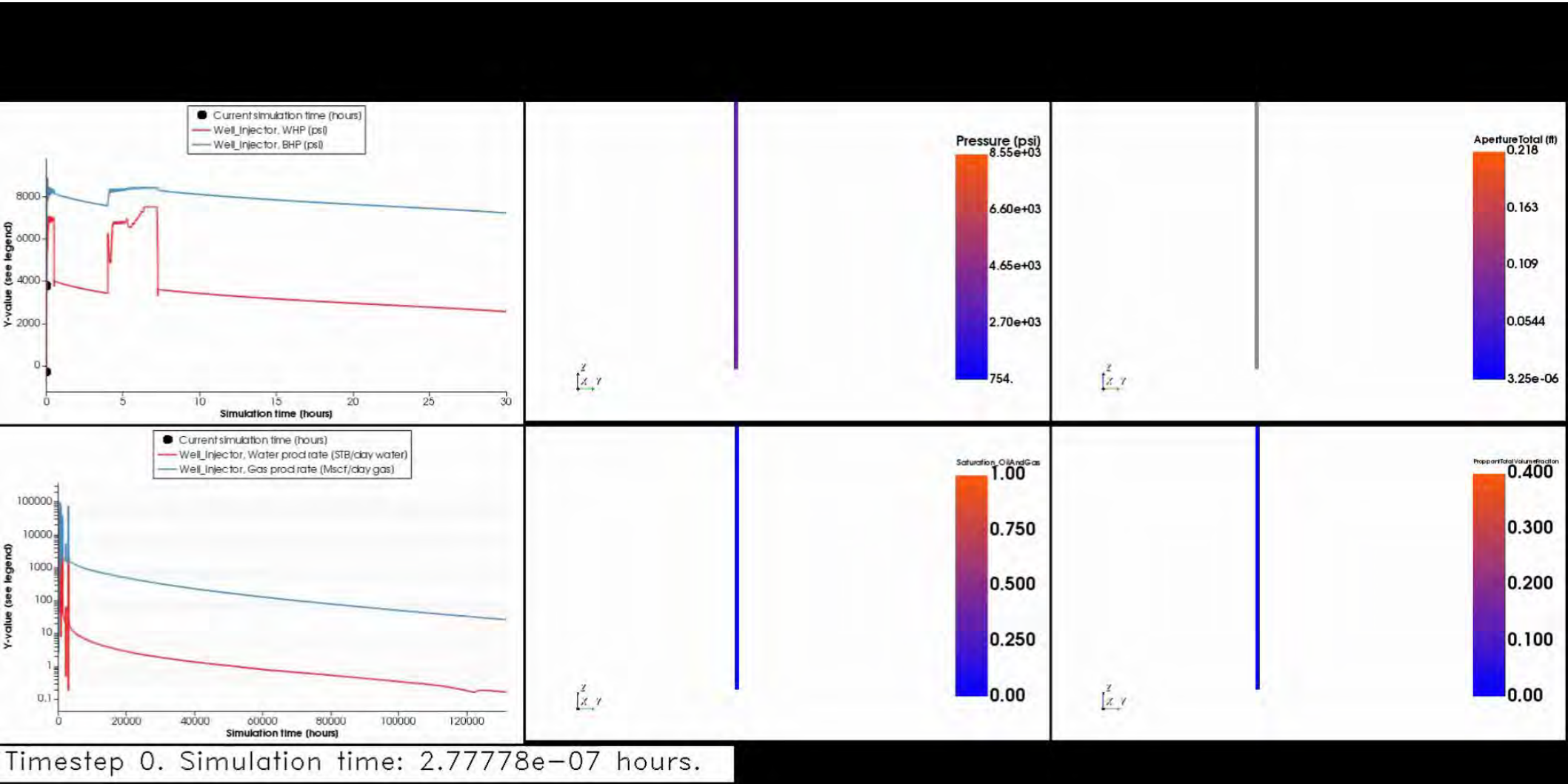








Mass balance is solved for four types of proppant: 40, 50, 60, and 70 mesh. This figure shows the gravitational segregation that occurs during shut-in (before closure) due to different settling velocities. Lower left is proppant volume fraction of 40 mesh. Lower right is proppant volume fraction of 70 mesh. Upper right is average proppant mesh as a function of position.



Example of field-scale hydraulic fracturing and production