Case 6 (Single fracture in layered elastic media with complex fracturing fluids) using EFrac

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Hydraulic Fracture Models

- **Fracture complexity:**
  - Interaction between fractures (stress shadow)
  - Poroelastic effects
  - Non-planar fractures
  - Multi-stranded fractures
- **Rock complexity**
  - Creation of induced un-propped (IU) fractures
  - Rock heterogeneity
  - Interaction of fractures with natural fractures
  - Inelastic rock behavior
- **Fluid complexity**
  - Improper proppant transport models
  - Non-isothermal
  - Compressible fluids
  - Fluid leak-off models
  - Phase changes
  - Turbulent flow
- **Wellbore effects**
  - Proppant transport in wellbores
  - Proppant distribution in perforations / clusters

Hydraulic Fracturing Models At the University of Texas

- **EFRAC (FEM based, 3D planar, complex fluids)**
- MULTI-FRAC (FVM based, fully coupled poroelastic, multiple non-planar fractures, multiple wells)
- MULTI-FRAC-NF (DDM based, multiple non-planar fractures in naturally fractured reservoir)
- PERI-FRAC (Peridynamics based, multiple non-planar fractures in heterogeneous reservoirs)
- FRAC-PACK (FVM based, poro-elasto-plastic, fully 3D)

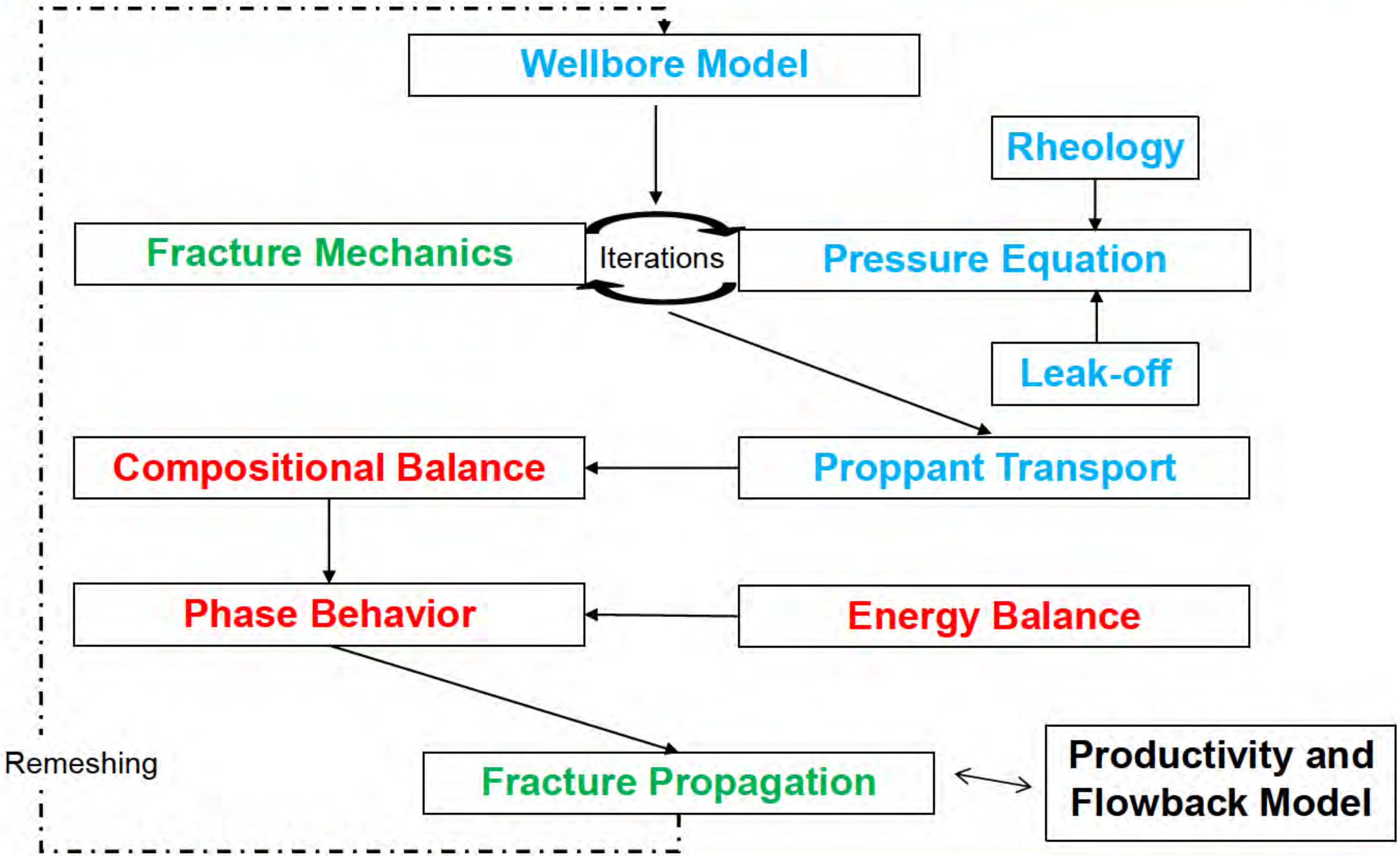
Case 6: Problem Description

Cases	Description
6a	Non-Newtonian fracturing fluid
6b	Energized fracturing fluid (CO_2 foam 70% quality)
6c	Energized fracturing fluid (gelled CO_2)

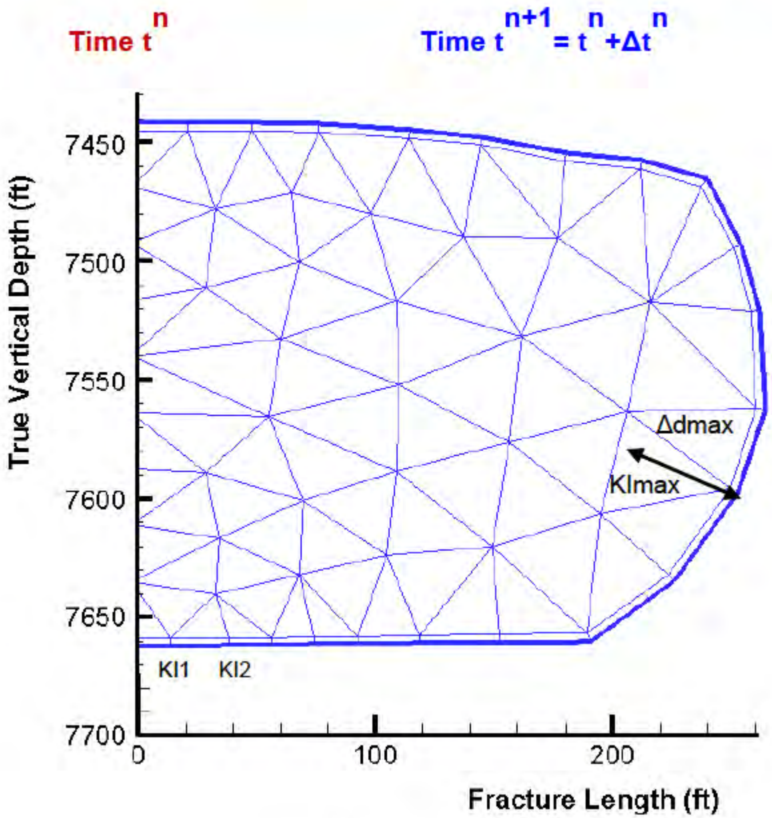
Additional modeling considerations for Case 6:

1. Fluid viscosity is not constant, but function of shear rate
2. Fracturing fluid composed of two components (CO_2 and water)
3. Density of CO_2 is function of pressure and temperature
4. Solve temperature (energy balance) within the fracture
5. Consider CO_2 solubility in aqueous phase

Modeling Approach (EFrac)



Fracture Propagation



$$\Delta d = \max\left(\Delta d_{\max}\left(\frac{K_I - K_{IC}}{K_{IC}}\right), 0\right)$$

$$K_I = \frac{G}{4\pi(1-\upsilon)}\sqrt{\frac{2\pi}{r}}w$$

Start Picard iterative loop:

$$w^{n(k+1)} = \alpha F\left[w^{n(k)}\right] + (1-\alpha) w^{n(k)}$$

Calculate time step:

$$\Delta t^n = \frac{\Delta m_{fracture} + \Delta m_{leakoff}}{m_{pumped}}$$

Solve Pressure:

$$\frac{\partial}{\partial t}\left\{w\left(\sum_{j=1}^{NP}\rho_j^* S_j^*\right)\right\} + \frac{\partial}{\partial x}\left\{\left(\sum_{j=1}^{NP}\rho_j^* A_j^* S_j^*\right)\frac{\partial P}{\partial x}\right\} + \frac{\partial}{\partial y}\left\{\left(\sum_{j=1}^{NP}\rho_j^* A_j^* S_j^*\right)\frac{\partial P}{\partial y}\right\}$$
$$+ \frac{\partial}{\partial y}\left\{\left(\sum_{j=1}^{NP}\rho_j^{*2} A_j^* S_j^*\right) g\right\} + \sum_{j=1}^{NP}\frac{2C_{w,j}\rho_j}{\sqrt{t-\tau}} = 0$$

Solve Width:

$$-P(x,y) + \sigma_{h\min}(x,y) = \frac{G}{4\pi(1-\nu)}\int_\Omega\left[\frac{\partial}{\partial x}\left(\frac{1}{r}\right)\frac{\partial w(x,y)}{\partial x'} + \frac{\partial}{\partial y}\left(\frac{1}{r}\right)\frac{\partial w(x,y)}{\partial y'}\right]d\Omega$$

Check error criteria:

$$\sum\left(\frac{w^{n(k+1)} - w^{n(k)}}{w^{n(k)}}\right) \le \varepsilon$$

Check for fracture propagation

Case 6: Inputs

Mechanical Layer Properties:

	Layer Top	Layer Thickness	Min Horiz Stress	Max Horiz Stress	Vertical Stress	Young's Modulus	Poisson's Ratio	KIc
	ft	ft	psi	psi	psi	MMpsi		psi-in$^{0.5}$
Layer 1	7700	200	5250	5550	7000	3.5	0.35	500
Layer 2	7900	200	5000	5300	7000	4	0.3	1000
Layer 3	8100	200	5250	5550	7000	4.5	0.25	1500

Porous Layer Properties:

	Layer Top	Layer Thickness	Permeability	Porosity	Pore Pressure
	ft	ft	mD		psi
Layer 1	7700	200	0.0005	0.05	3900
Layer 2	7900	200	0.001	0.1	4000
Layer 3	8100	200	0.002	0.15	4100

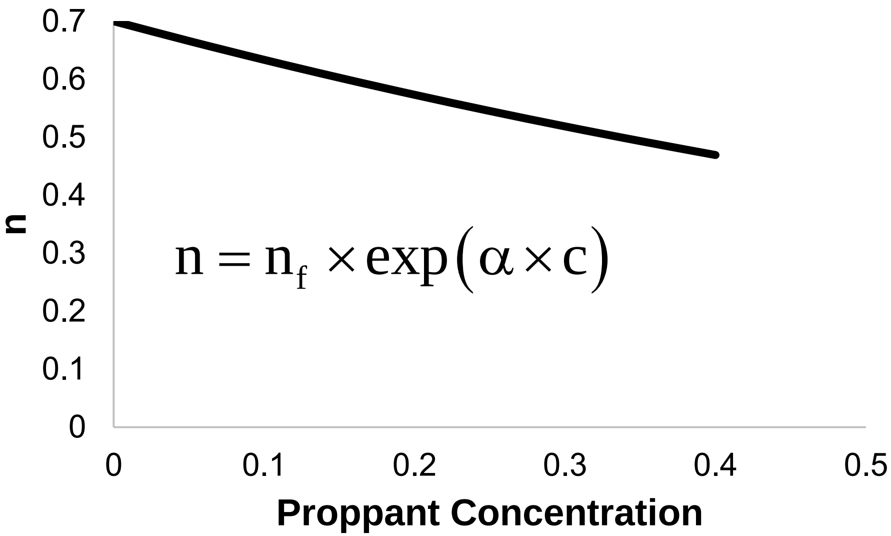
Fracturing Fluid Properties:

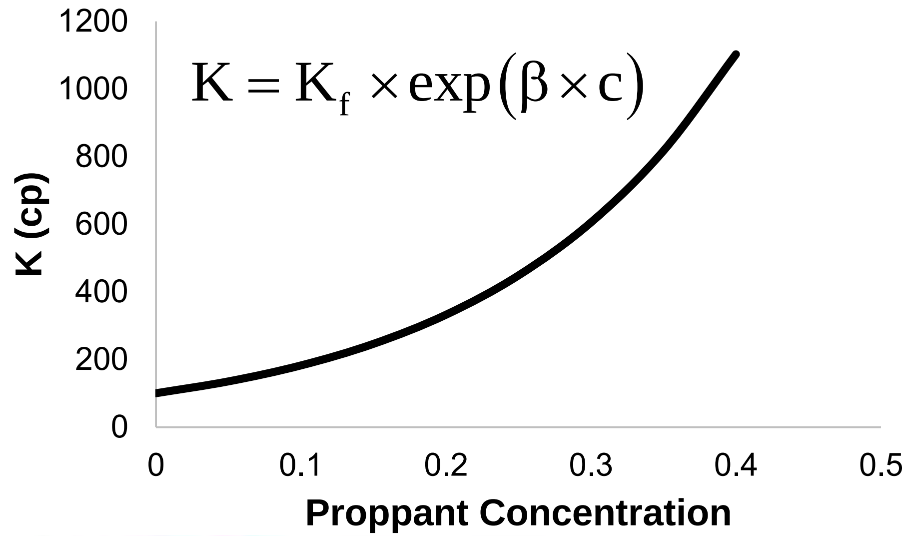
	Density	n	K
	lb/ft^3		cp
Non-Newtonian	62.4	0.7	100
CO_2 Foam	f(P,T)	0.7	100
supercritical CO_2	f(P,T)	0.7	30

Proppant Properties:

	Density	US Mesh Size	Proppant Loading
	lb/ft^3		ppa
Proppant 1	165	40/70	2

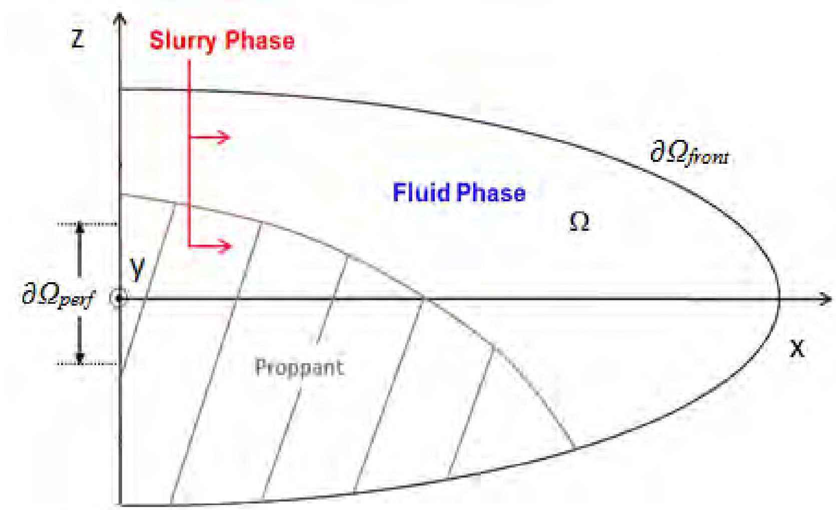
Non-Newtonian Fluids



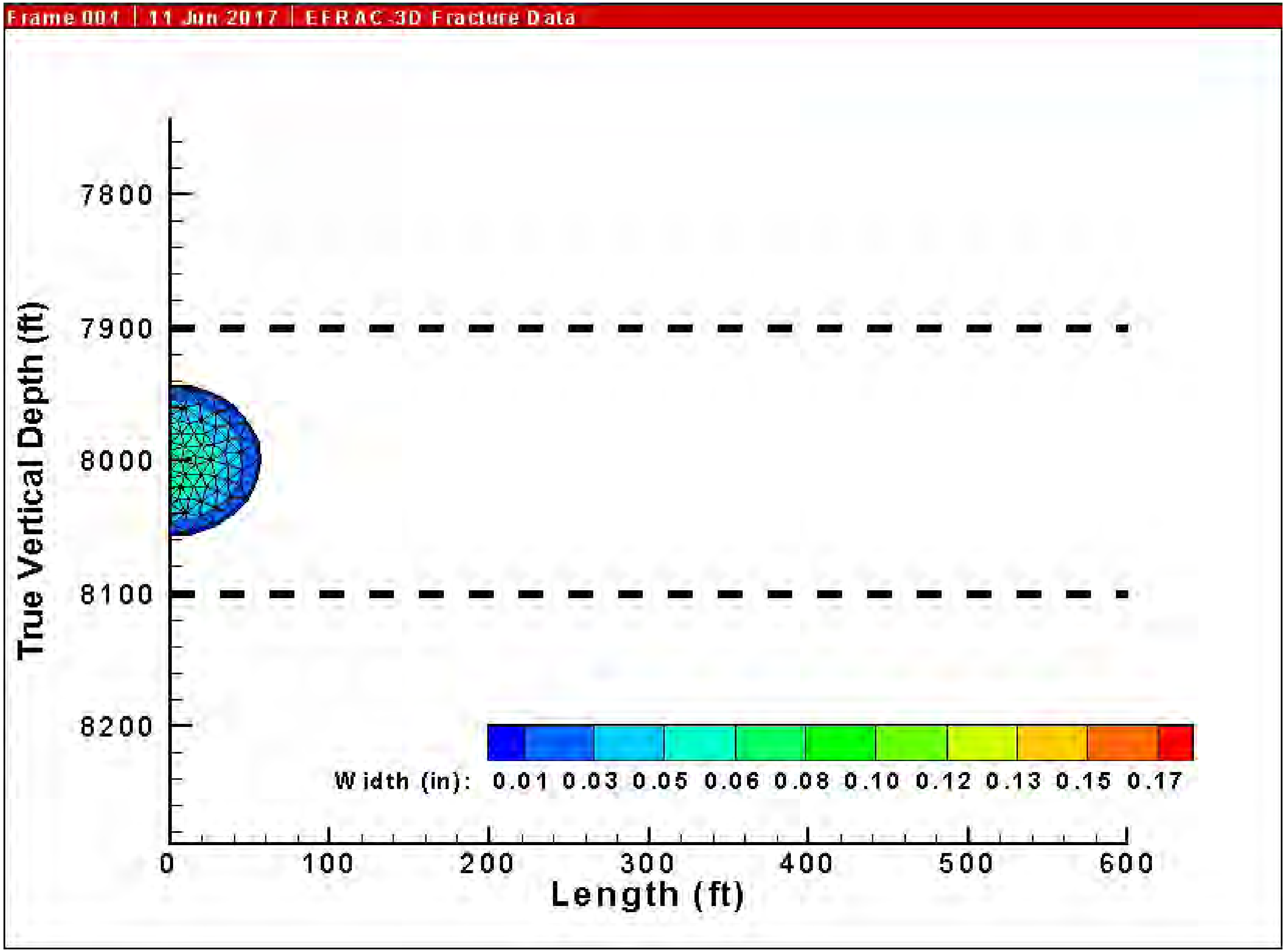


$$\mu_{app} = \frac{2n+1}{3n} K^{1/n} \left(\frac{w}{2} \left| \nabla P - \rho g \right| \right)^{n-1/n}$$

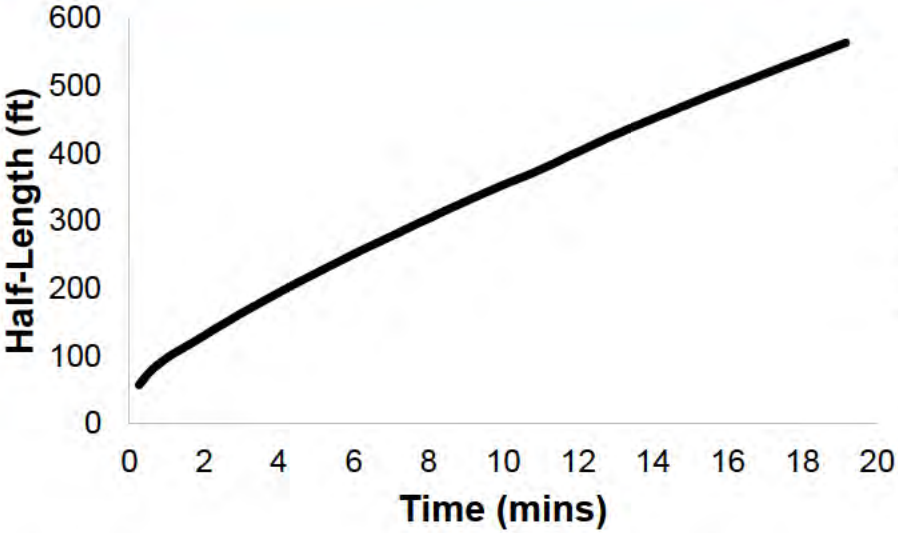
$$\text{velocity} = \frac{w^2}{12\mu_{app}} \left(\nabla P - \rho g \right)$$

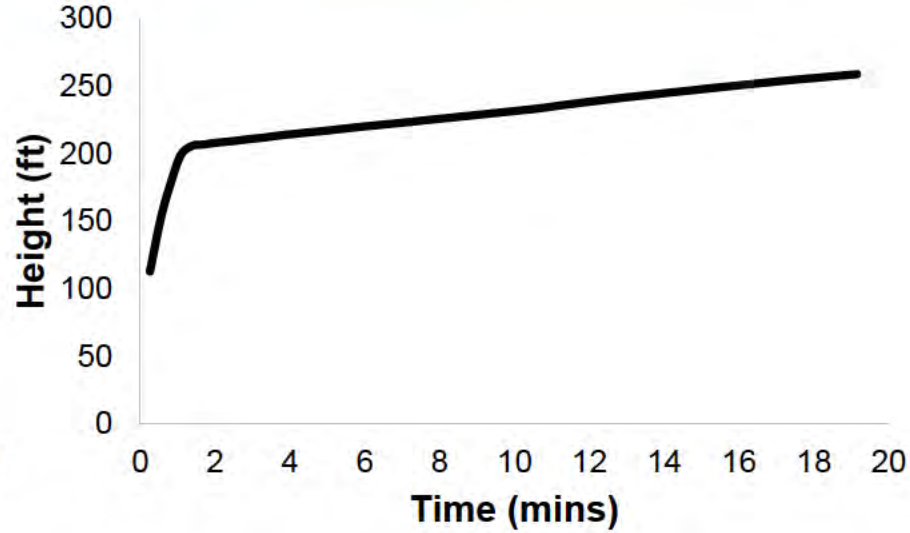


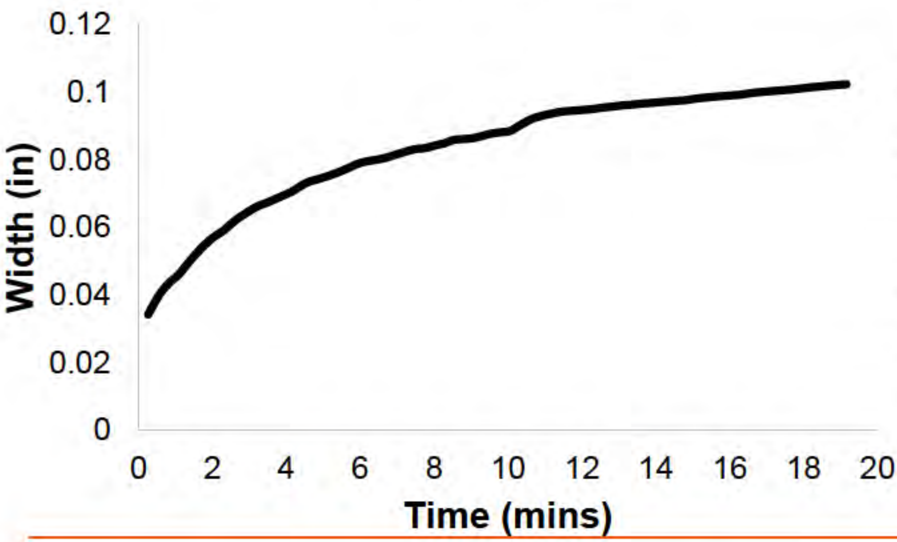
Case 6a: Fracture Width

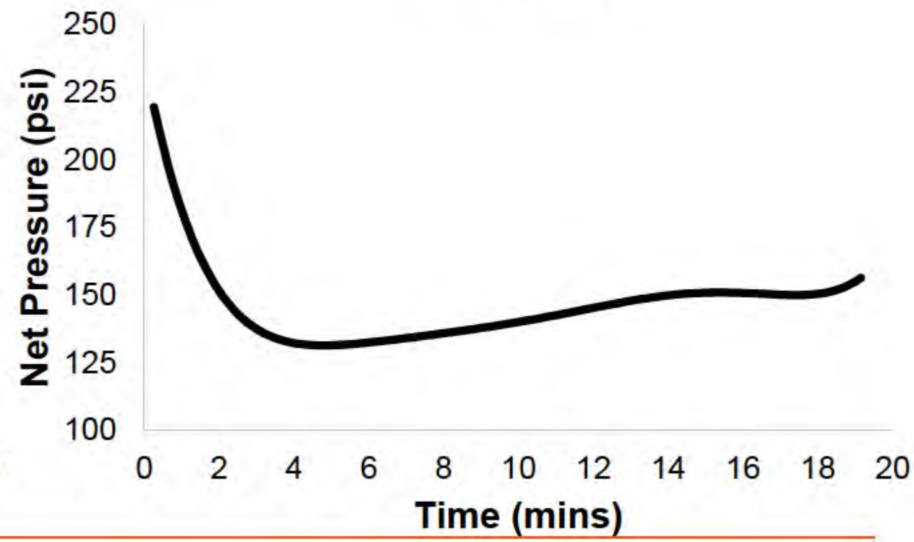


Case 6a: X-Y Plots

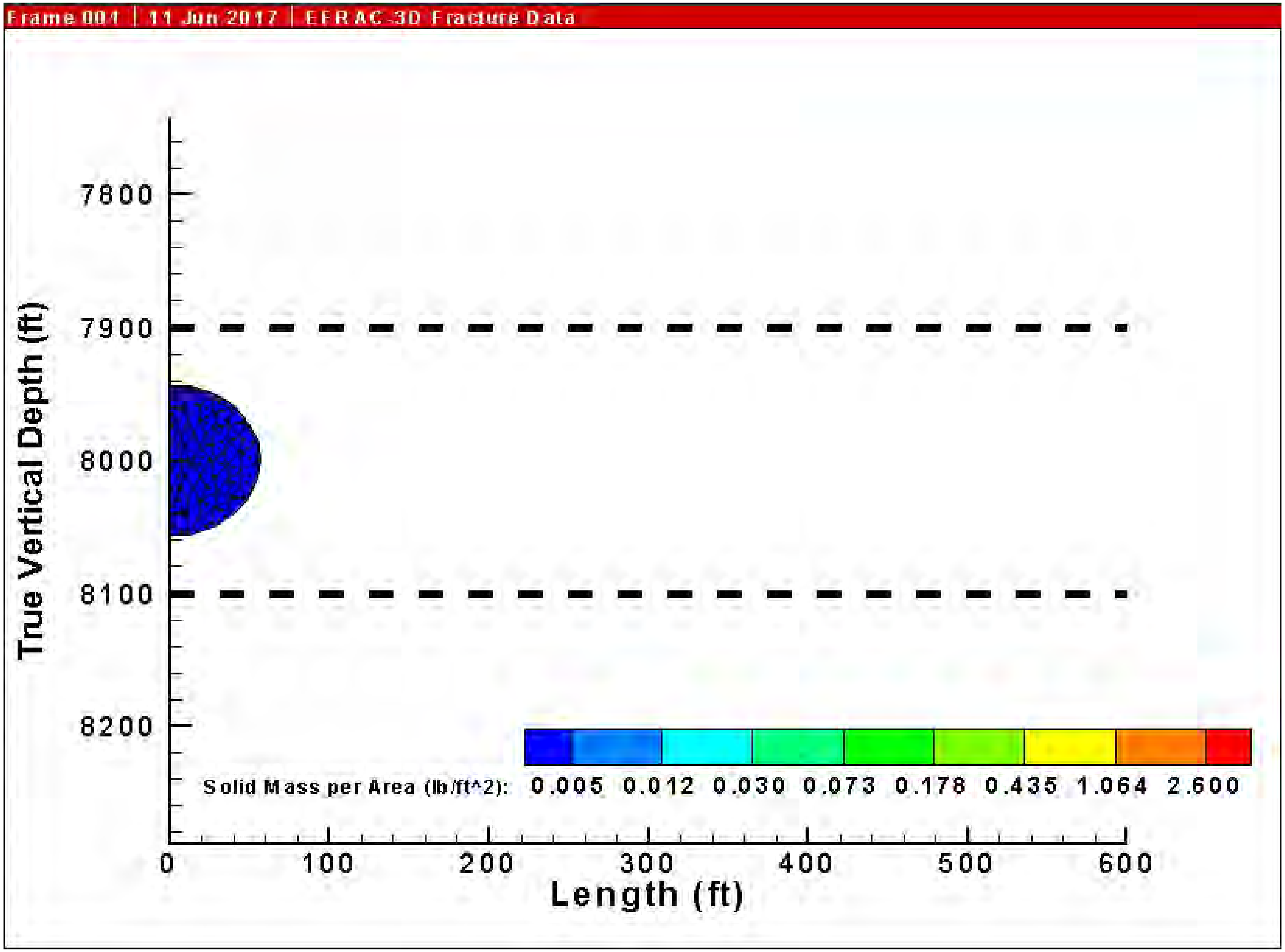




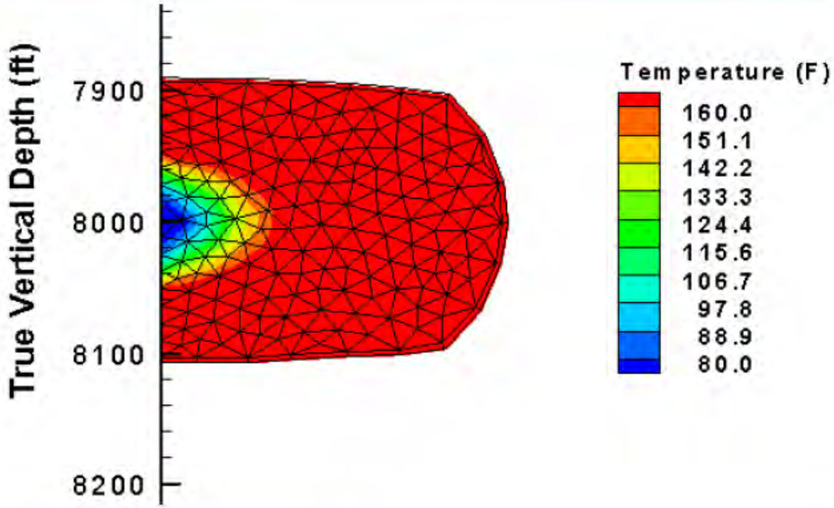


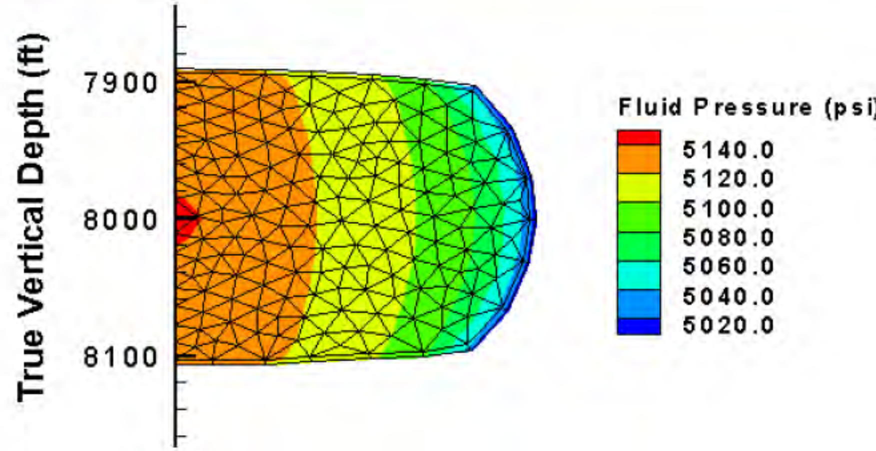


Case 6a: Proppant Distribution



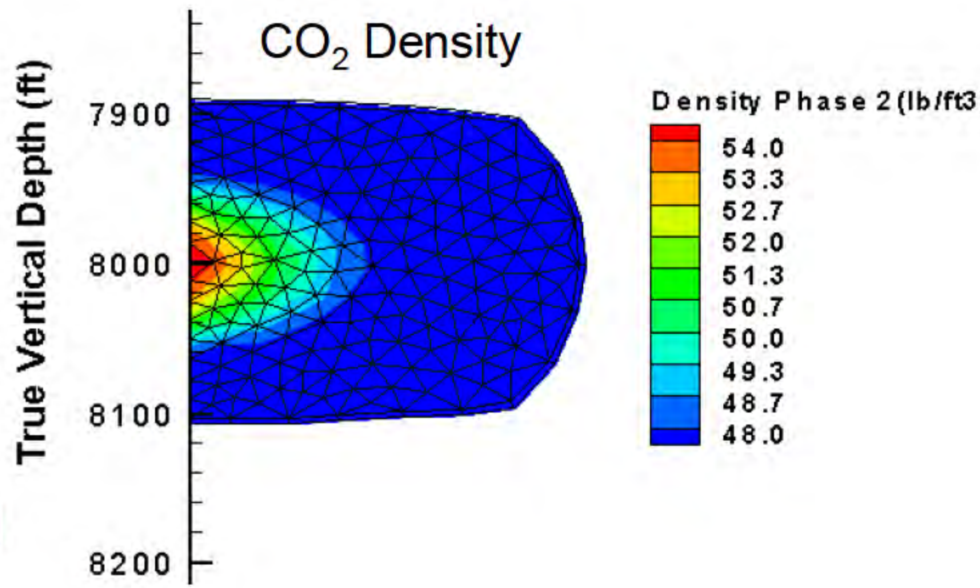
Compressible Fluids





CO_2 Density

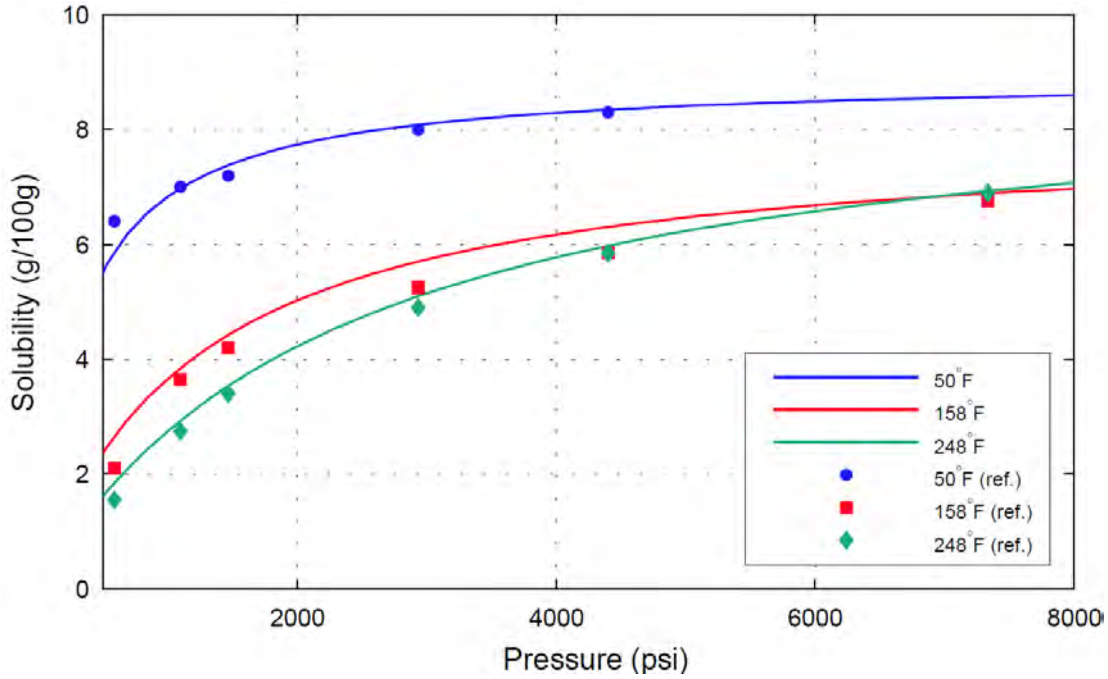
$$\rho(P,T) = \frac{M_w P}{Z(P,T)RT}$$



Water Density:

$$\rho(P,T) = \rho_0 \times e^{\left[-\alpha_T (T-T_0)\right]} \times e^{\left[c_f (P-P_0)\right]}$$

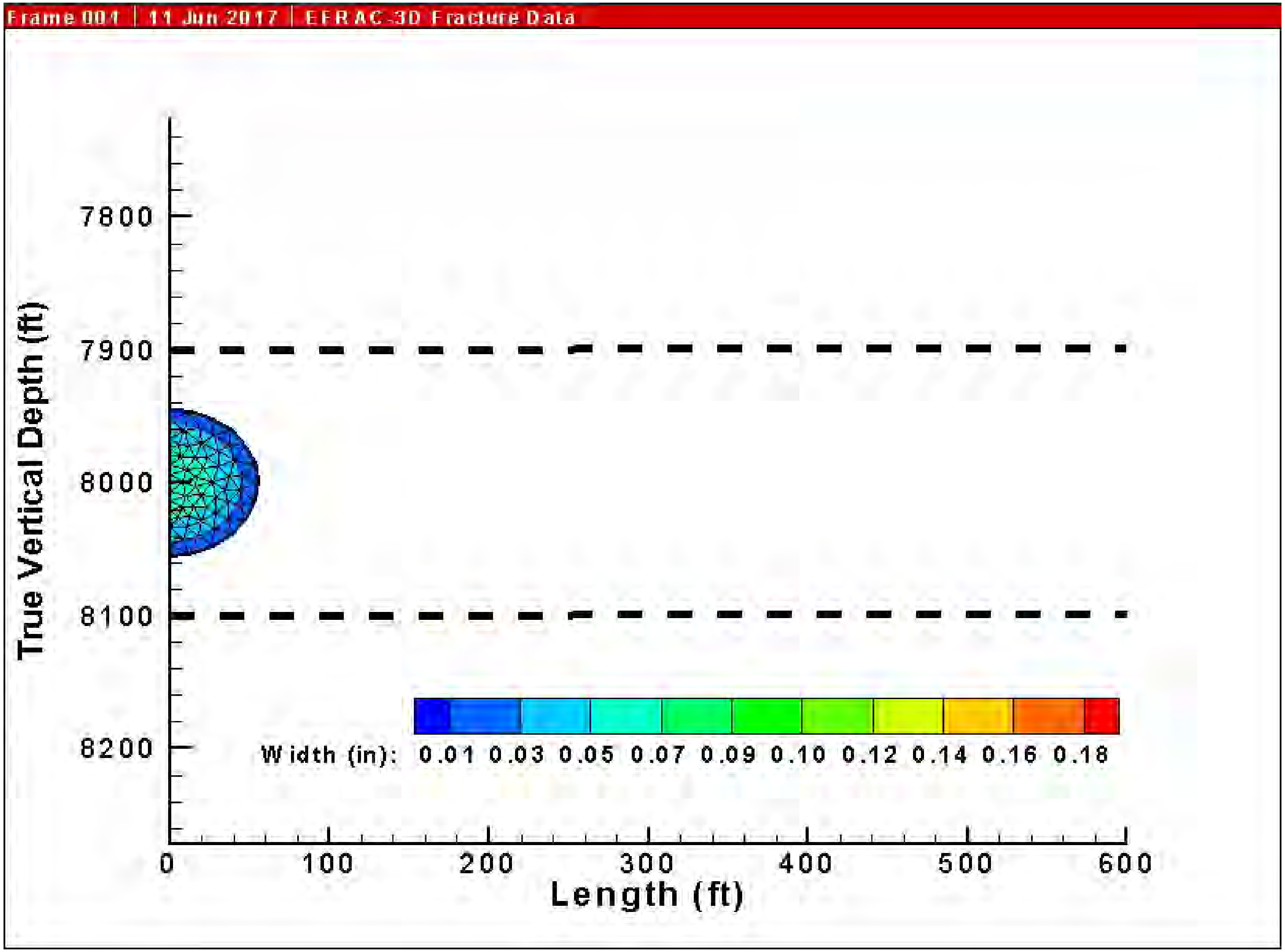
Phase Behavior



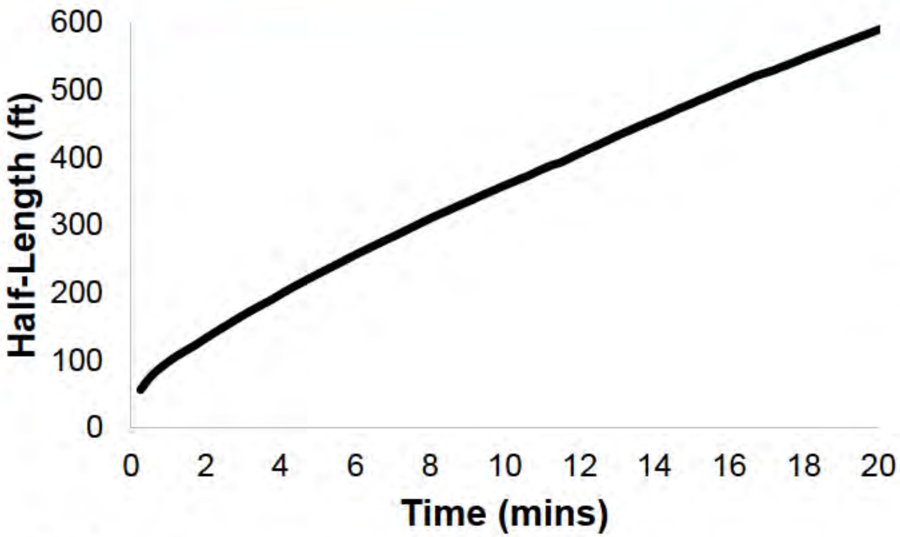
Solubility of CO_2 in water: comparison between our model and experimental data

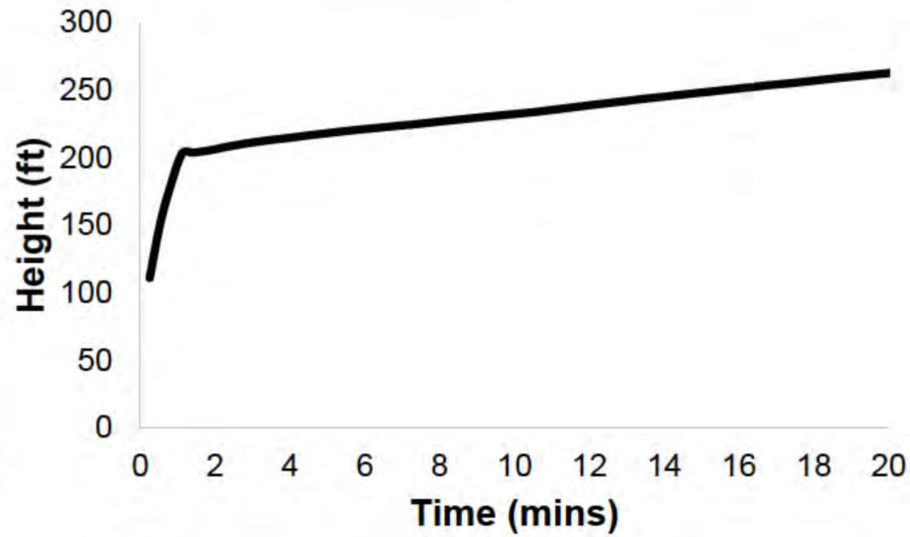
$$x_{i,sol} = \beta(T)\frac{\alpha(T)P}{1+\alpha(T)P} \quad \text{and} \quad x_i = \frac{x_{i,sol}}{100 + x_{i,sol}}$$

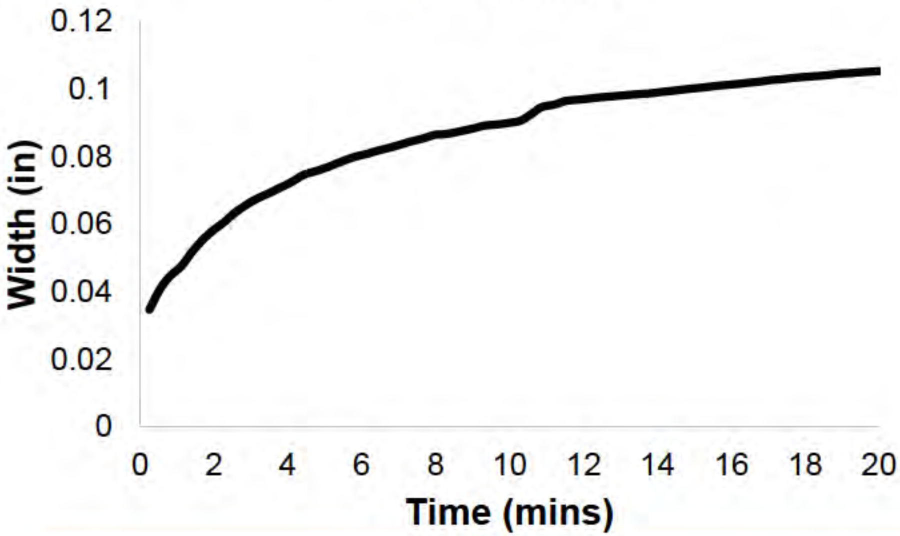
Case 6b: Fracture Width

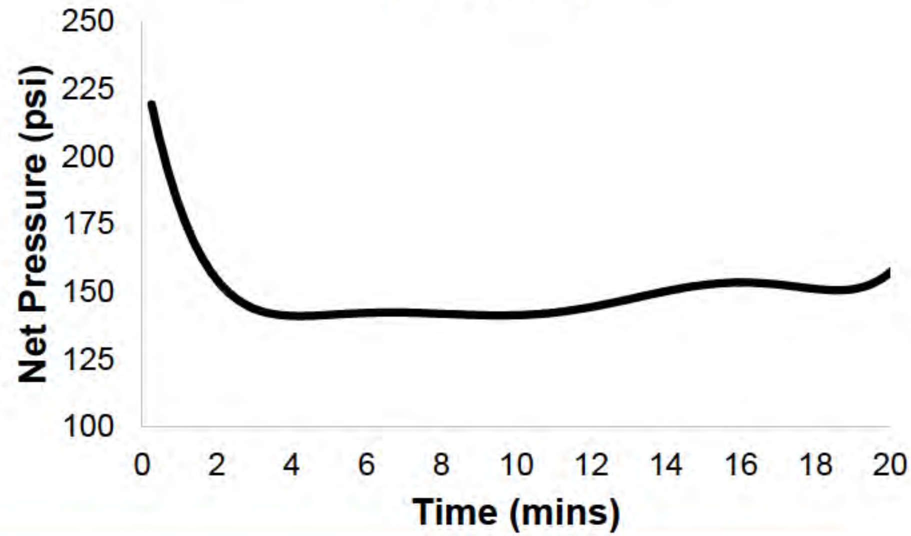


Case 6b: X-Y Plots

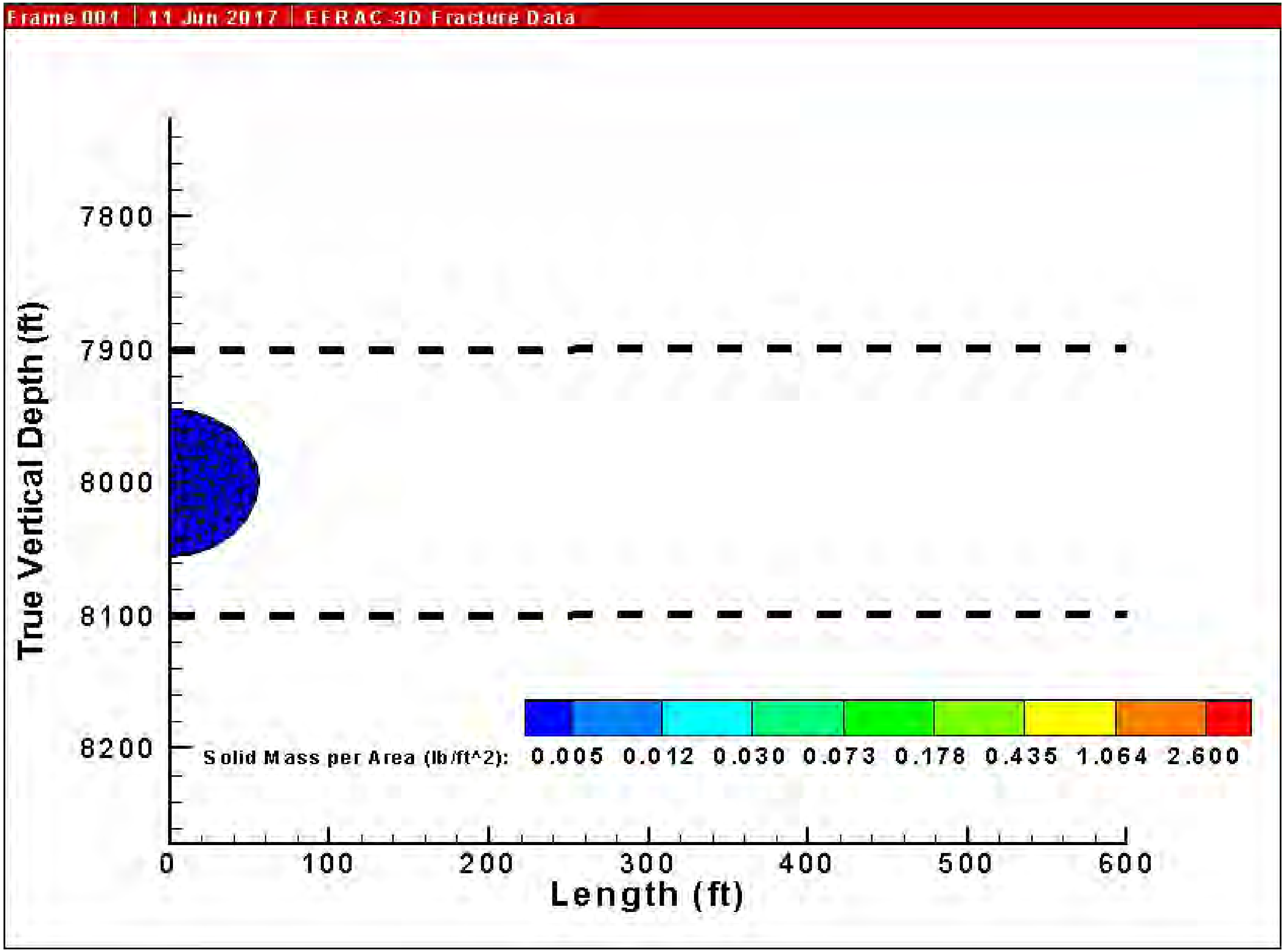








Case 6b: Proppant Distribution



Case 6: Conclusions

Case	6a	6b	6c	2b
Half-Length (ft)	570	590	750	1012
Height (ft)	259	262	247	225
Width (in)	0.102	0.105	0.08	0.06
Net Pressure (psi)	153	155	122	87
Propped Length (ft)	120	130	150	190