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Advanced Dynamic Formation Stimulation

DEM Modeling Of High Strain Rate Well Bore Fracturing Via High Pressure Pulsed Gas Combustion

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5th International Itasca Symposium

Vienna, Austria, Feb. 17-20, 2020

Outline

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- Pulsed Gas Fracturing For Complex Fracture Generation
- Well Bore Fracture Pattern vs. Pressurization Rate
- PFC2D & Strain Rate Dependent Tensile Strength Fracturing Simulations
- PFC3D Fracturing Simulations vs Experiments
- Conclusions & What's Next
- Contacts & Questions

Pulsed Gas Fracturing Technology

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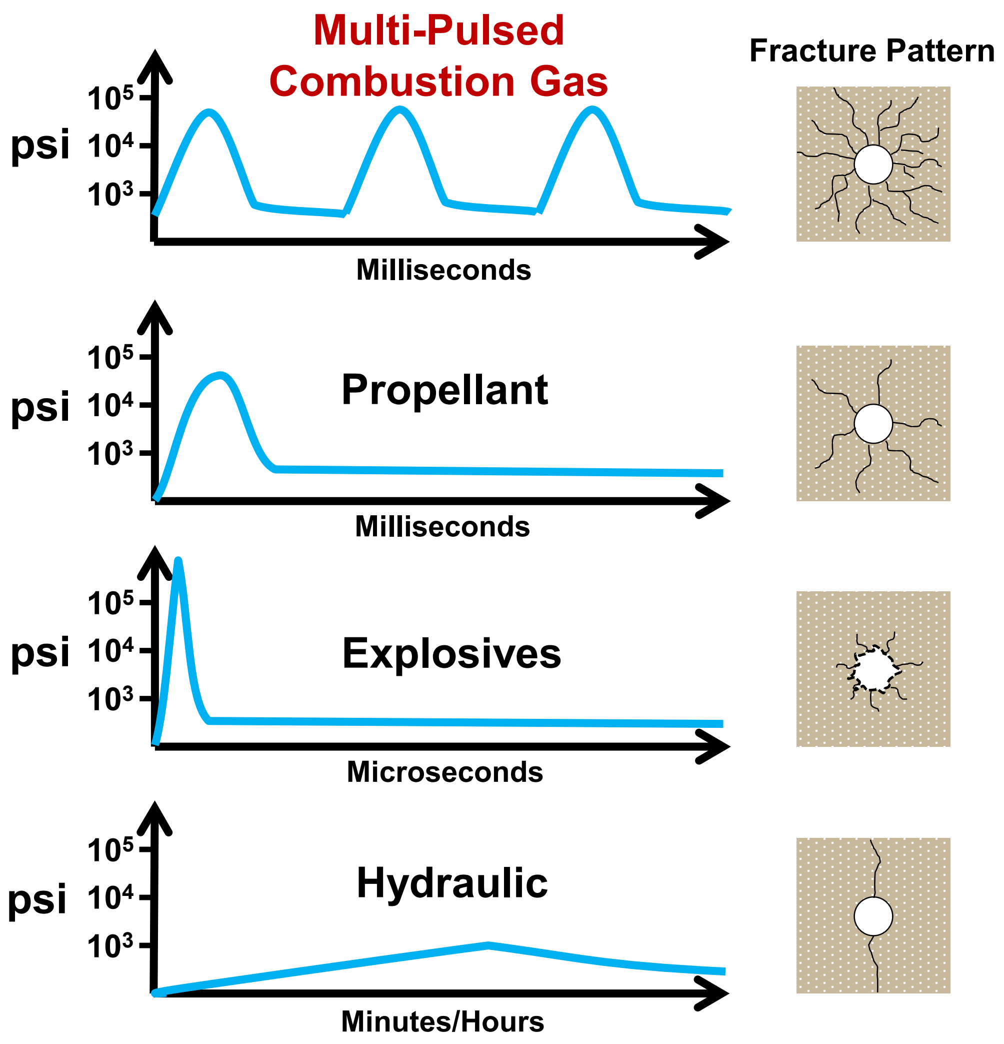
- **Formation Fracturing Via Repetitive High Pressure Combustion-Based Down-Hole Pulsed Gas Generation**
  - Static + Dynamically Applied Pressures
- **Optimized Peak Pressures & Rise Rates**
  - Enhanced Fracture Pattern Complexity w/o Formation Destruction
- **Dynamically Adjustable And Controllable Process**
  - Repetition Rate, Pressure Peak, Rise Times/Strain Rates, etc.
- **Capable Of Extreme Shock Pressures If Needed**
  - ~5:1 to ~30:1 Pressure Amplification
- **Highly Configurable/Adaptable Tool Operation & Technology**
  - Full Fracturing & Fluids/Proppant Injection
  - Crack Initiation/Crack Starter
  - Clean-Out/Re-Stimulation/Remediation



Creating Complex Fractures: Optimal Loading & Strain Rate

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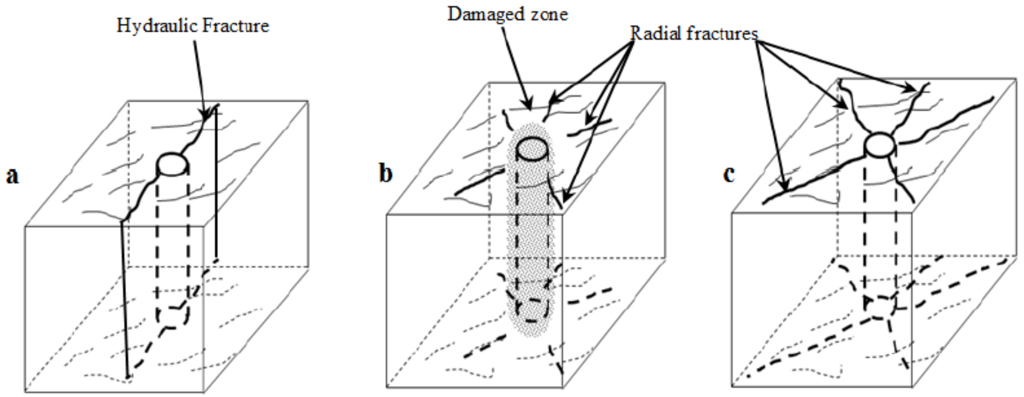
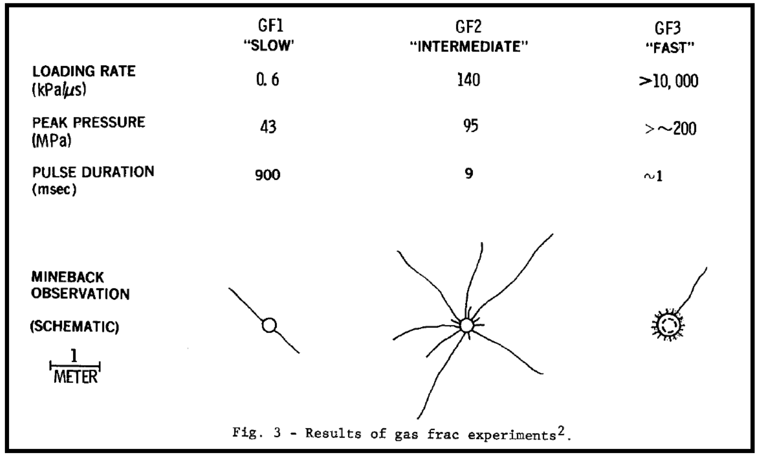
URTeC 1579760
Pulsed Fracturing in Shale Reservoirs: Geomechanical Aspects, Ductile-Brittle Transition and Field Implications
M. Reza Safari*, Raju Gandikota, Uno Mutlu, Weatherford , Missy Ji, Jonathan Glanville, ANSYS , Hazim Abass, ARAMCO



Comparison of fracture patterns from a variety of techniques: (a) hydraulic (b) explosive (c) pulsed gas fracturing

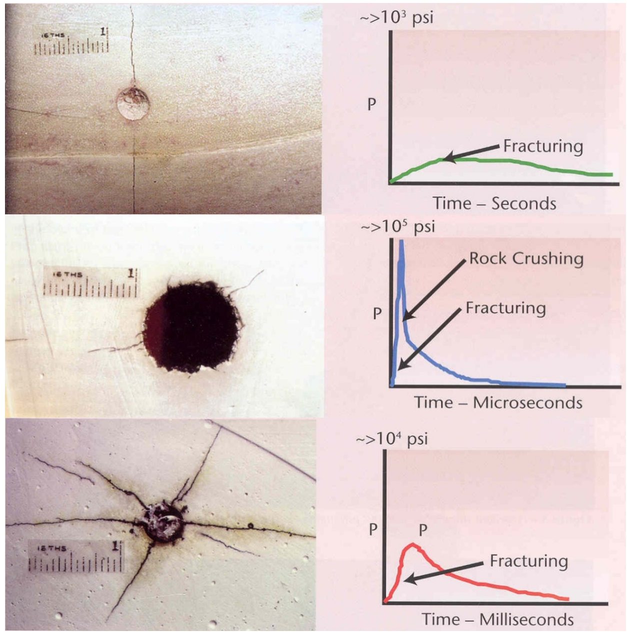
SPE/DOE 8934 SPE Society of Petroleum Engineers
IN SITU EVALUATION OF SEVERAL TAILORED-PULSE WELL-SHOOTING CONCEPTS
by Richard A. Schmidt, Norman R. Warpinski and. Paul W. Cooper, Sandia National Laboratories



	GF1 "SLOW"	GF2 "INTERMEDIATE"	GF3 "FAST"
LOADING RATE (kPa/μs)	0.6	140	>10,000
PEAK PRESSURE (MPa)	43	95	>~200
PULSE DURATION (msec)	900	9	~1

Fig. 3 - Results of gas frac experiments[2].

Fracture patterns from "slow", "medium", and "fast" propellant gas loading rate



Optimum Strain Rate & Peak Strain For A Given Bore Diameter & Formation Characteristics To Produce A Complex Initial Fracture Network From A Fast Rising Gas Pulse

Pulsed Gas Fracturing Tool Design Depends Upon Prediction Of Formation Response To Pressure Rise Rate & Amplitude

Dynamic Fracture Simulation Tool Must Give Good Quantitative Prediction Of Fracture Generation Under Prescribed Conditions

Numerical Fracture Modeling Validation

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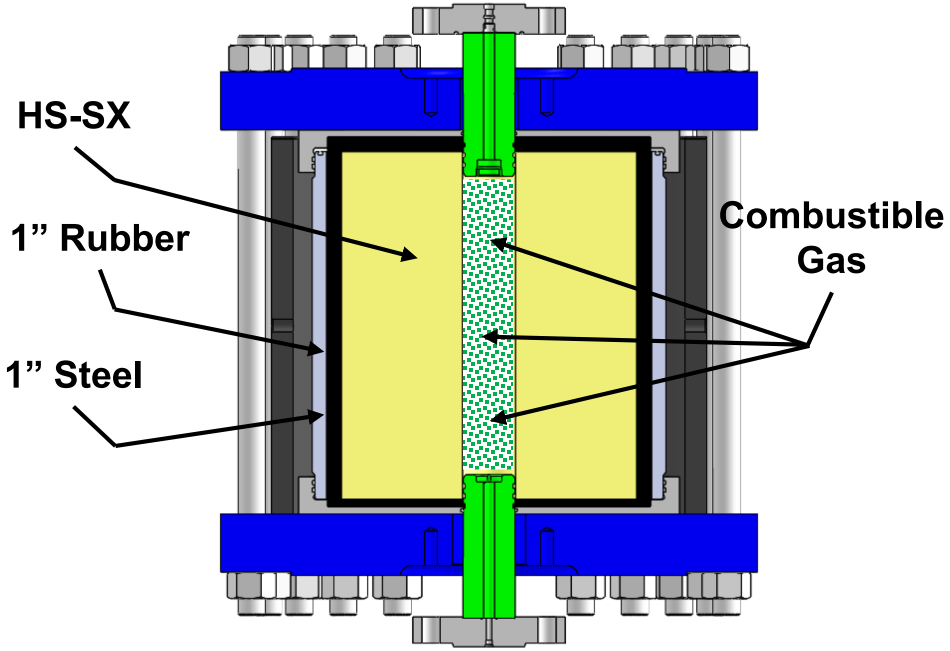

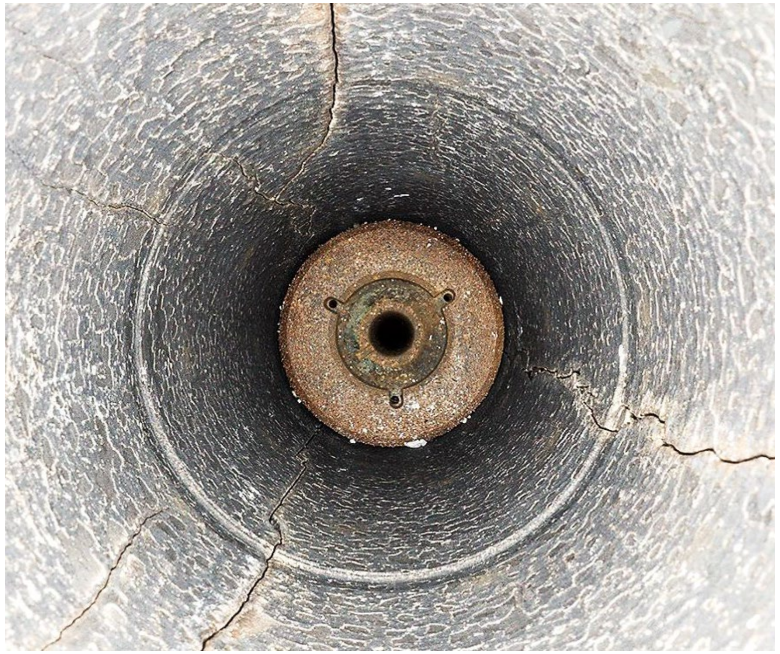

PFC2D Dynamic Fracture Modeling Qualitatively Matches # Of Initial Major Fractures vs. Pressure Rise Time

Slower Pressure Rise Rate

Faster Pressure Rise Rate

PFC2D Confined Lab & Unconfined Far-Field Sims

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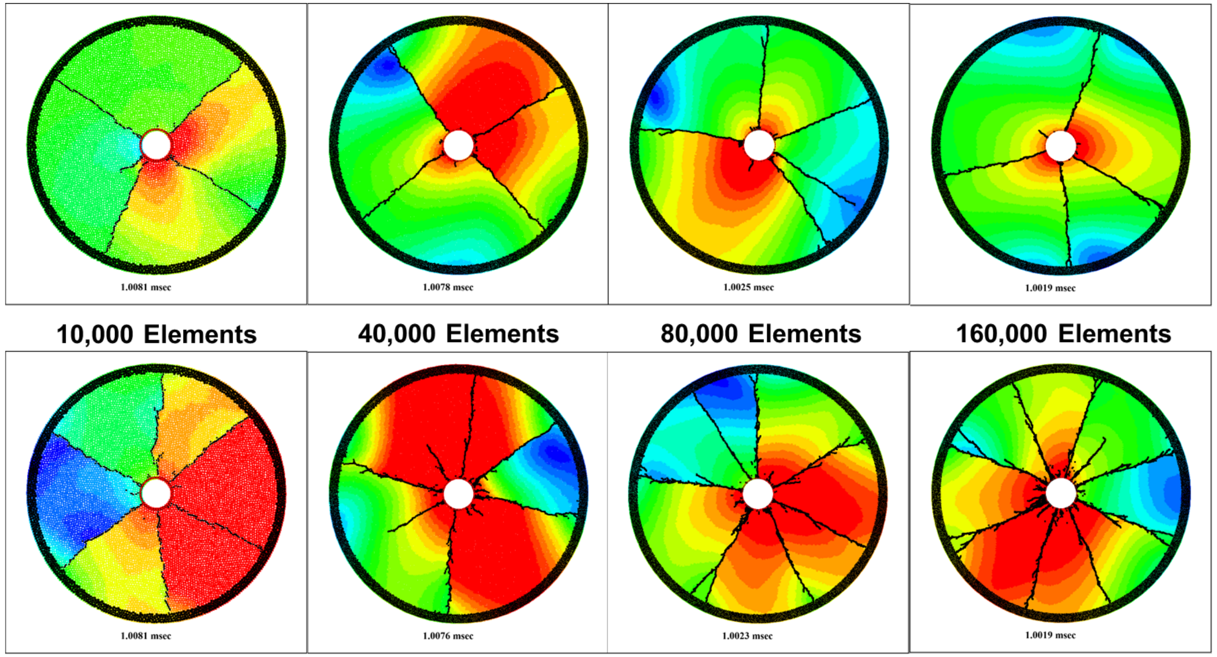
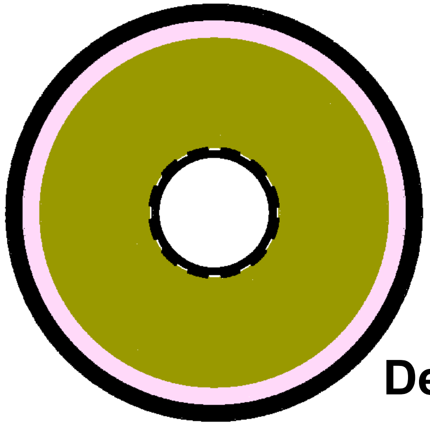
0.5msec Rise Time

0.025msec Rise Time





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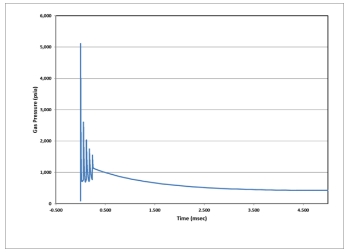
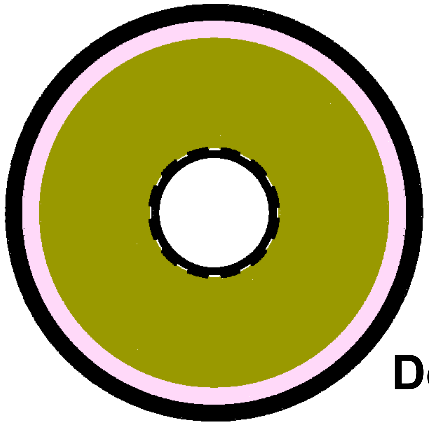


Detonation



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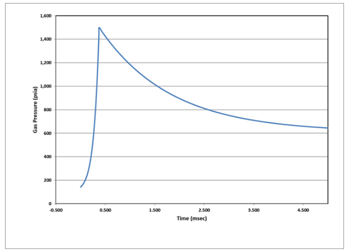
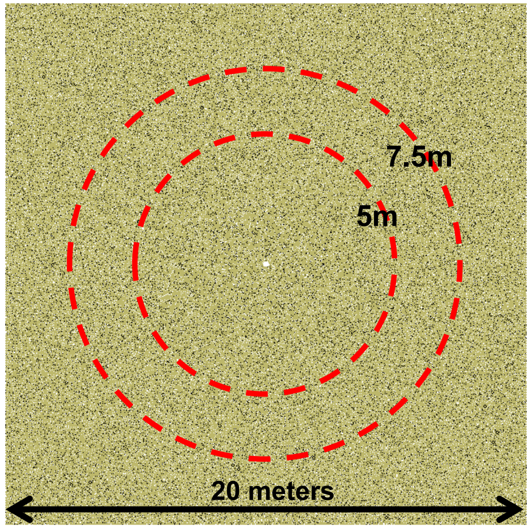


Deflagration



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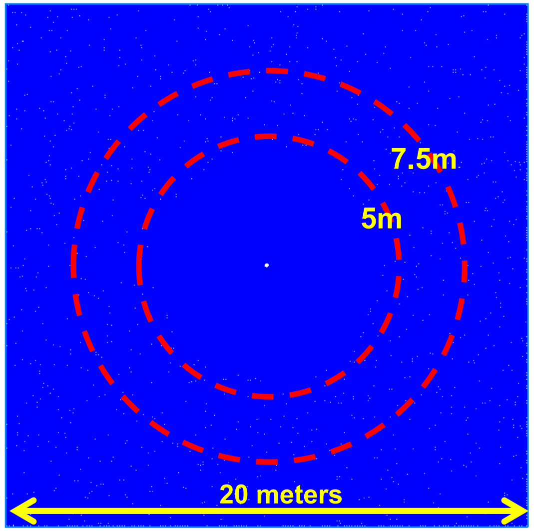

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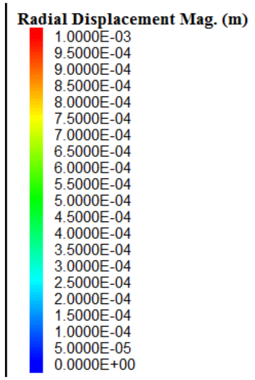

Detonation vs Slow(er) CV Combustion

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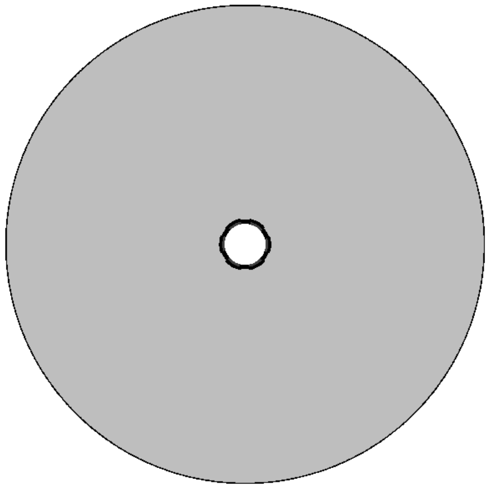
Detonation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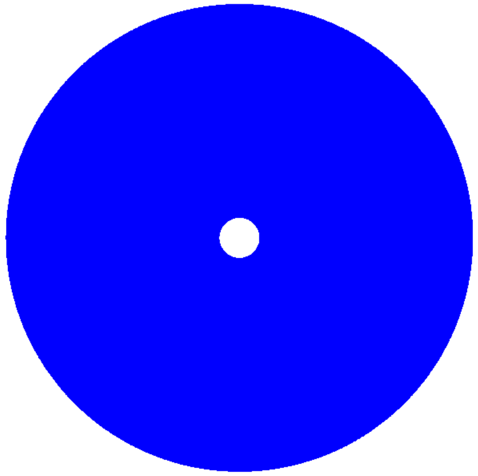
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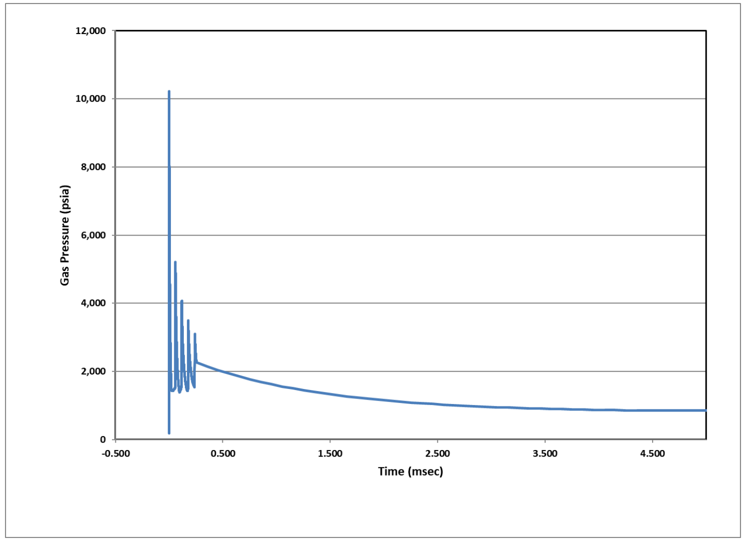
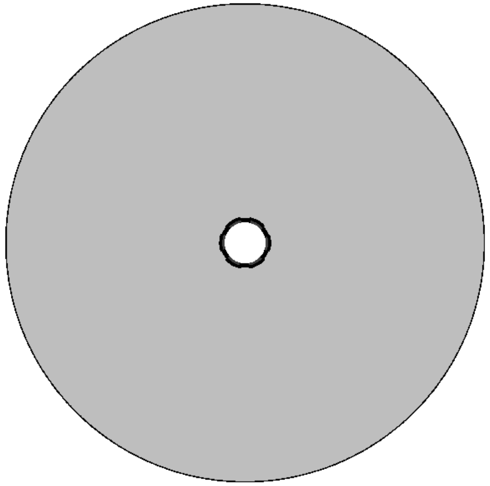


Slow CV Combustion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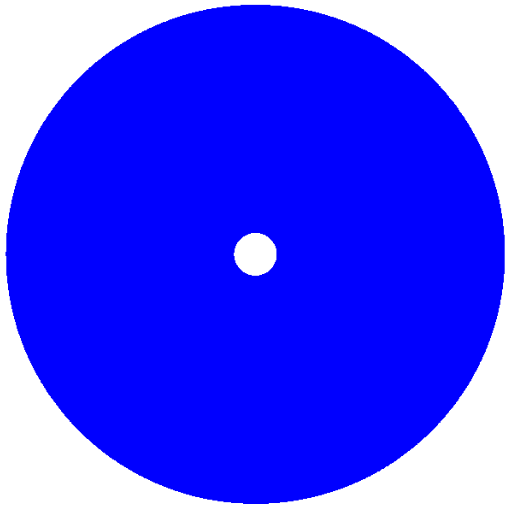
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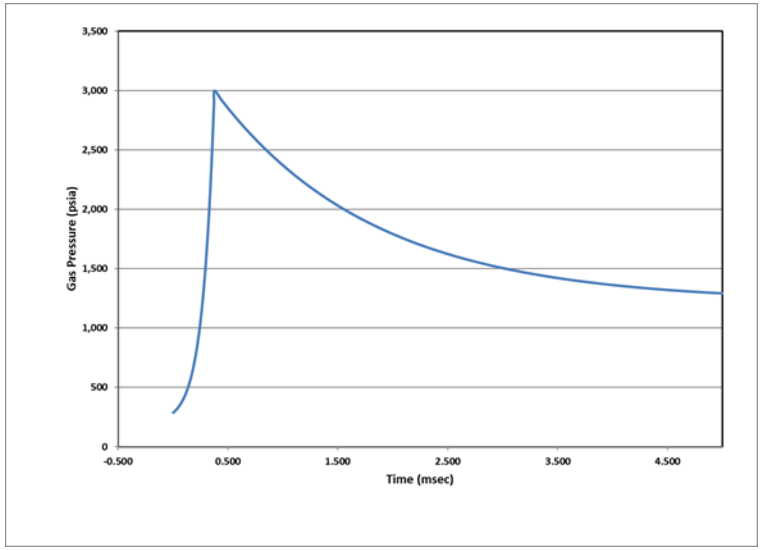
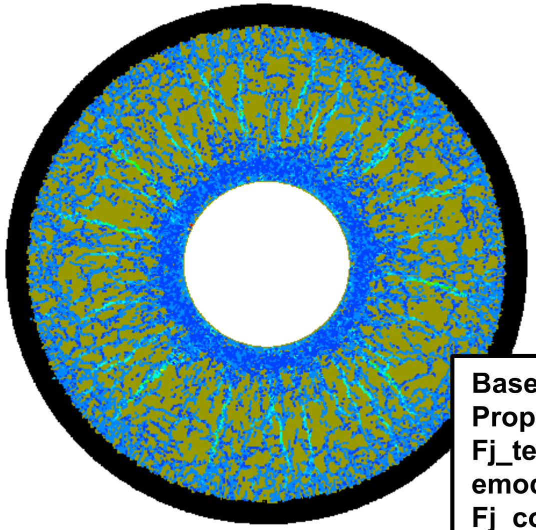


Material: HydroStone Super-X w/ Measured BTS Strength

Tensile Strength and Elastic Modulus Variations

Unrealistic

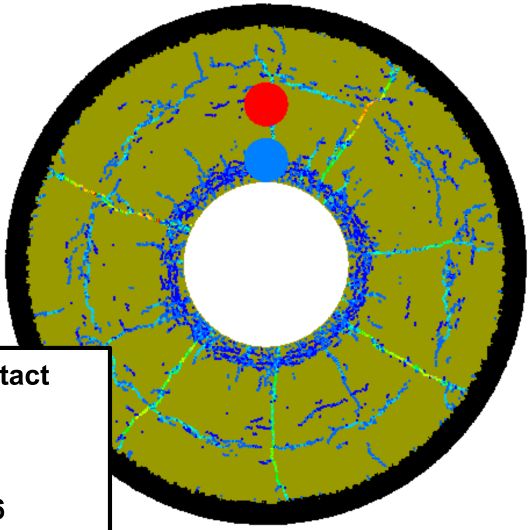


0.1506 msec

3000 psi CV detonation
1x tensile strength
1x modulus

Baseline Contact Properties:
Fj_ten 8.62e6
emod 18.8e9
Fj_coh 82.8e6
Fj_fa 0
Fj_fric 0.577

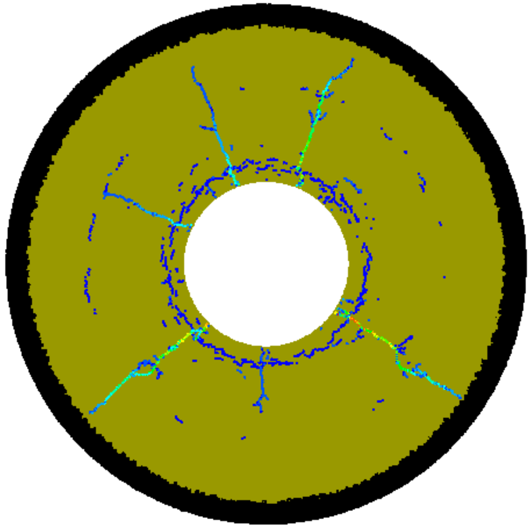
Close To Observed



0.1506 msec

3000 psi CV detonation
2.5x tensile strength
1x modulus

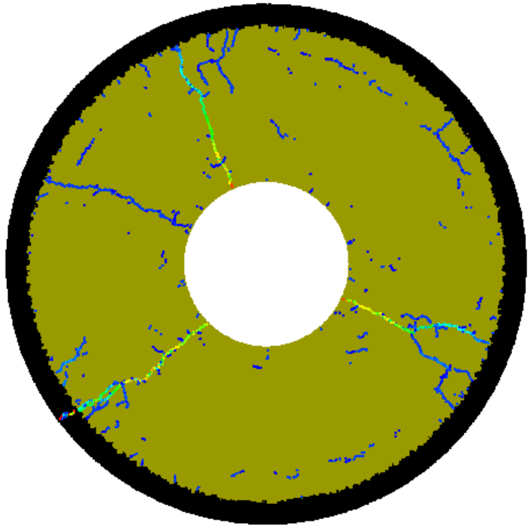
Unrealistic



0.3312 msec

3000 psi CV detonation
5x tensile strength
1x modulus

Unrealistic



0.2810 msec

3000 psi CV detonation
5x tensile strength
2x modulus

- Increasing Bond tensile strength reduced the number of fractures
- At 2.5 and 5x Fj_ten, a ring of damage due to a rarefaction wave was still present
- 10x multiplier (not shown) resulted in no fractures.

Lab Scale Fracture Demonstrations

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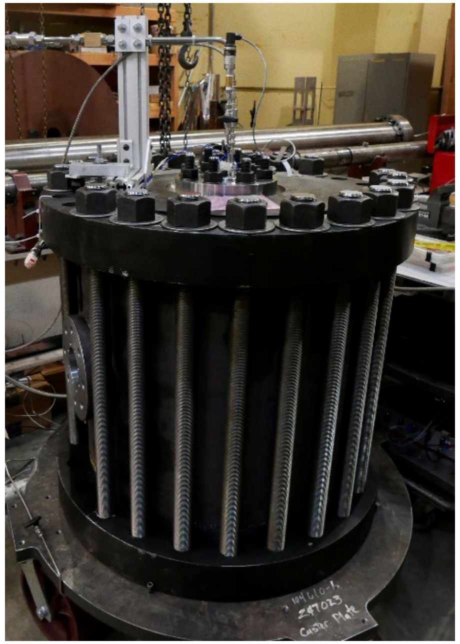
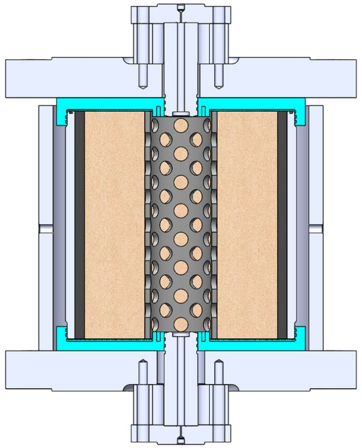
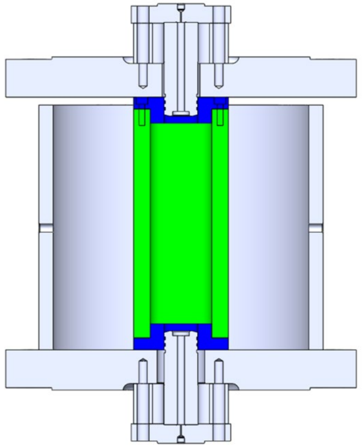


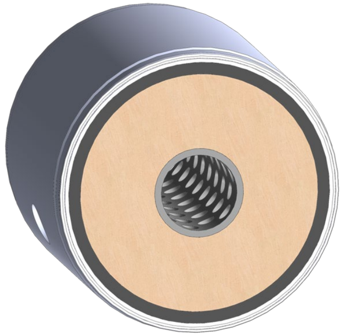


Installed Sample



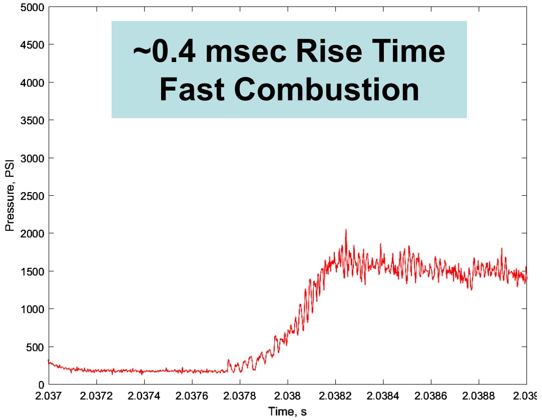
Calibration Config.

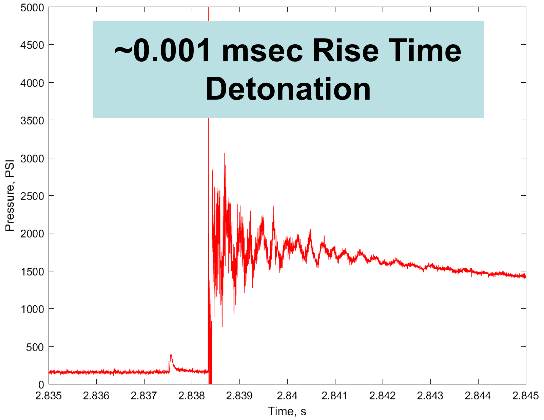
- Cast HydroStone-SX Material
- 24” OD x 24” L x 6.5” ID Sample
- 1” Steel Shell + 1” Rubber
- 7-5/8” OD P-110 Pre-Perforated Casing
- Lab Test For BTS, Density, Vp, E, ν, etc.
- Practice Cylinder For Calibrating Gas Pulse Generation System



1” Steel + 1” Rubber Shell
Hydrostone-SX Sample

Pressure Rise Time Variations





Combustion Pressure Rise Rate Tunable By >400x Range
PFC2D/3D Used To Predict Fracture Pattern In Confined Sample

PFC3D Lab Scale Dynamic Fracture Modeling Path

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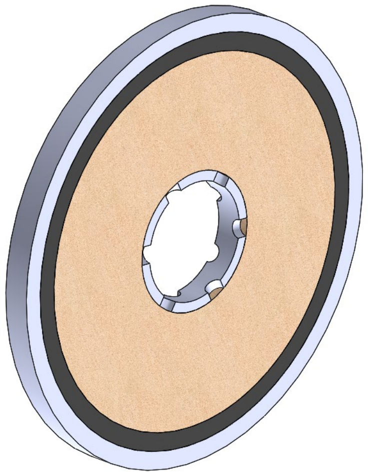
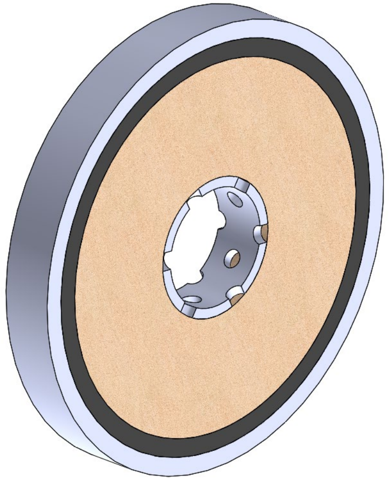
Too Thin:
All Perforations
On Boundaries



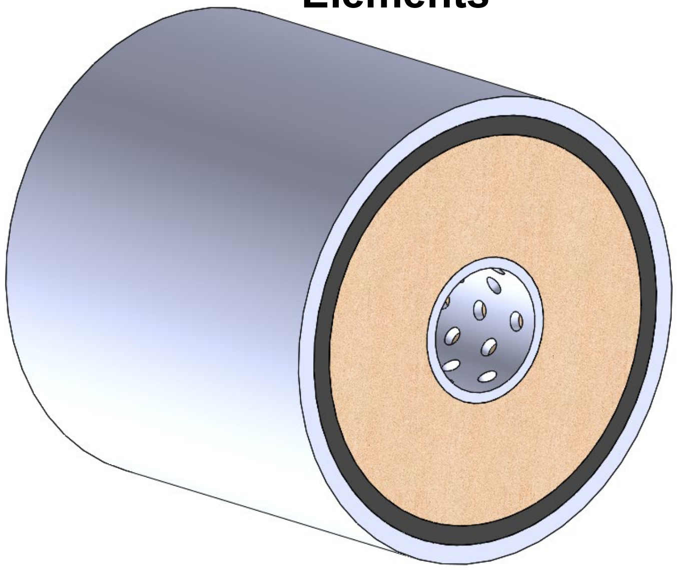
Thin 3D Slice

Minimum Thin:
1 Set Of Whole
Perforations On Center



Thick 3D Slice

Full 3D:
Too Many
Elements



Full 3D Sample

Actual Lab Sample:
Real Ductile &
Elastomeric Materials

University Of Washington
Lab Hydro-Stone Super-X
Test Article

- **Verify/Anchor 3D Fracturing Model In HS-SX + Perforations: 360 deg. Perforations & Directional Perforations – Vary Perf Density & Open Area**
- **Extend To Near-Field Un-Constrained "Real Rock" & Anisotropic Stress**
- **Multi-Pulse & Far-Field Fracture Propagation**

HS-SX Tensile Strength In Numerical Models Increased ~2.5x To Match Experiments

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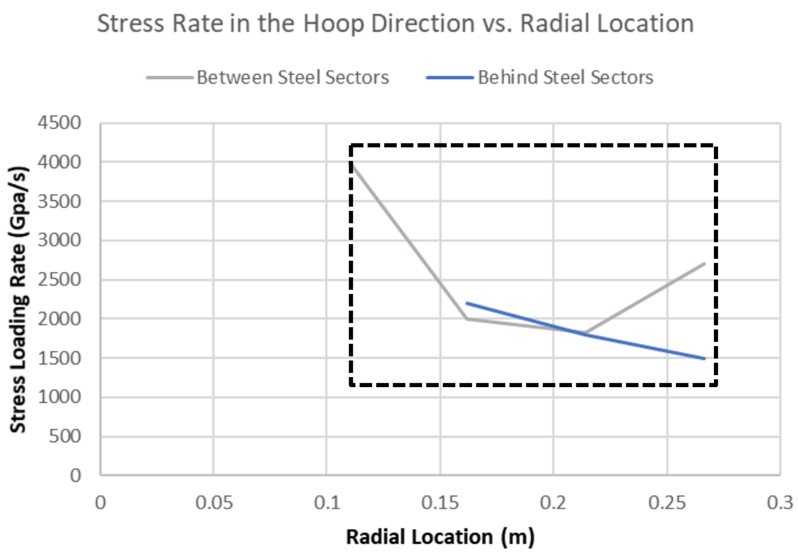

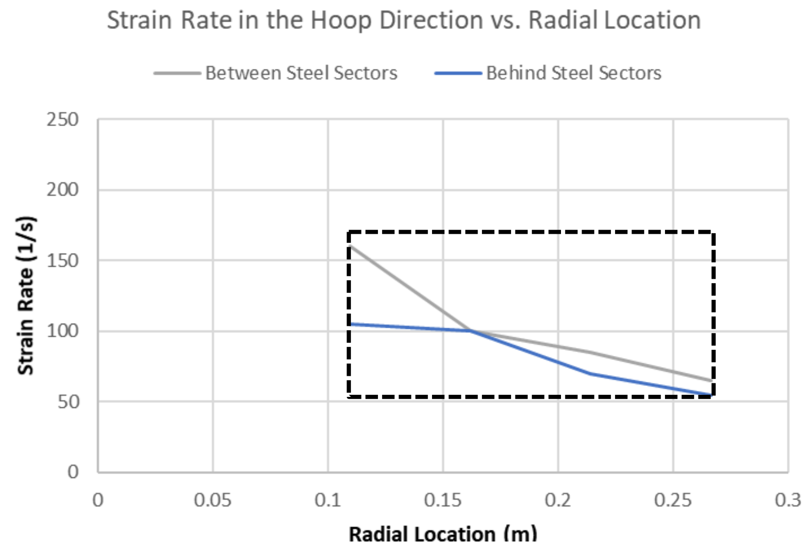

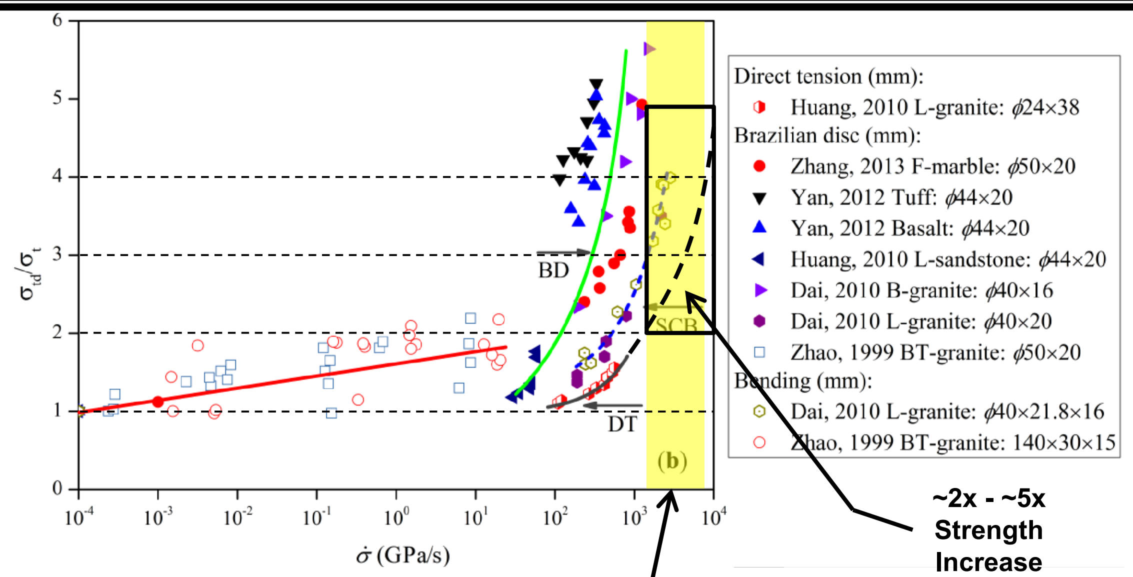

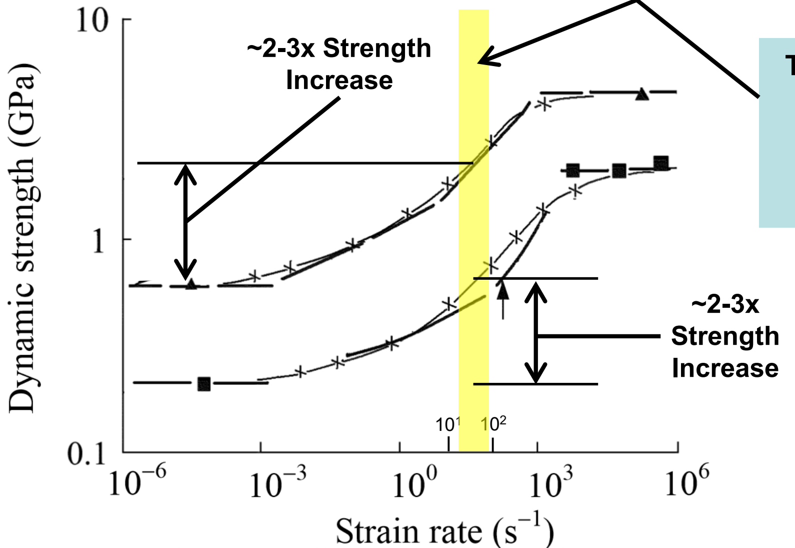

(b) Granodiorite and dolomite.

Typical Strain & Loading Rates For Dynamic Pulsed Fracturing

~2.5x Tensile Strength Increase Required To Match HS-SX Perforation Experiments Is Consistent With Empirical Rock Data: This Behavior Must Be Inherent In Model!

- **At High Loading Rates We Should Expect The HS-SX To Exhibit ~2.5x-~5x Static Strength**
- **At Moderate Loading Rates ~1.0x to ~2x Strength**

Fracture Comparison – Pressure Pulse and HS-SX BTS Strength Variation vs. Lab Experience

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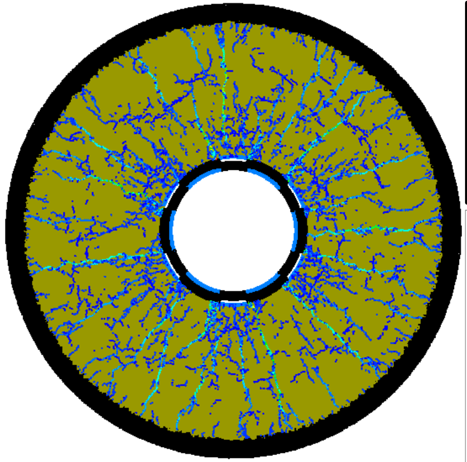
2,000 psi CV Pressure Detonation | 3,000 psi CV Pressure Detonation

1x Measured HS-SX BTS Tensile Strength 1x Measured Tensile Modulus

This Fracture Pattern Has Too Much Fine Scale Damage – We Do Not See This In Tests

2,000 psi CV Pressure Detonation



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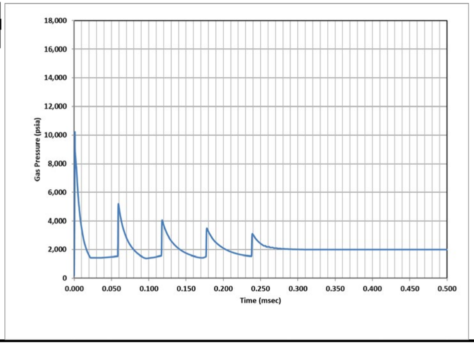
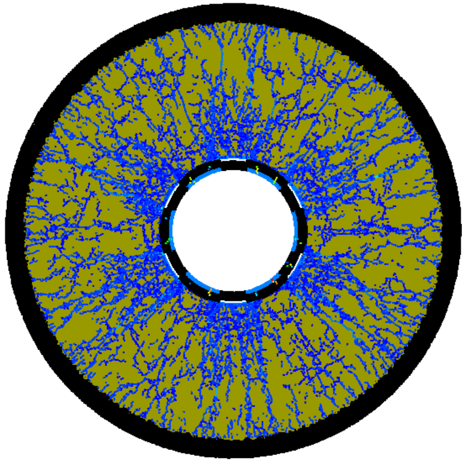
Fj_fa 0
Fj_fric 0.577



3,000 psi CV Pressure Detonation



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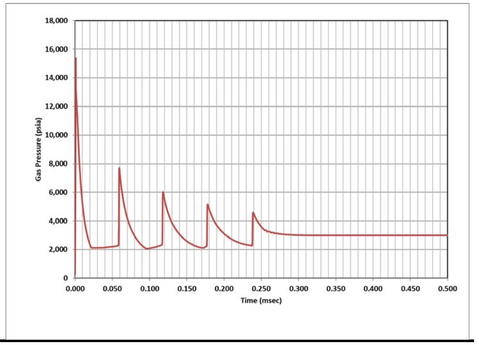
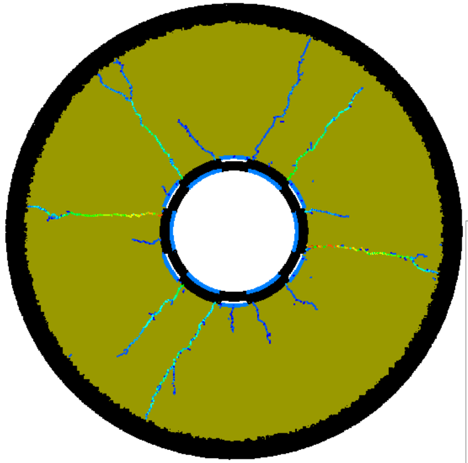


2.5x Measured HS-SX BTS Strength & 1x Meas. Tens. Modulus

This Fracture Pattern Is Consistent With What We Observer In The Laboratory Tests

2,000 psi CV Pressure Detonation



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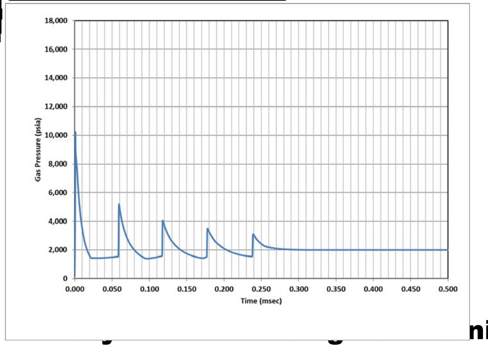
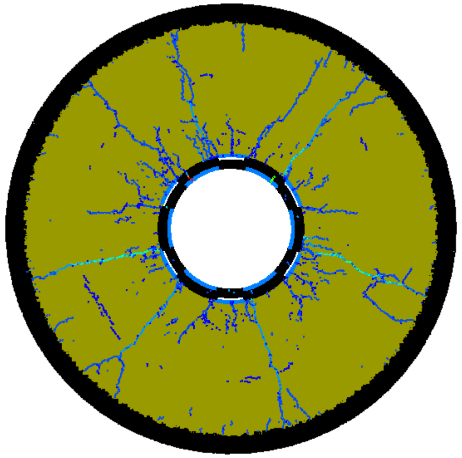


3,000 psi CV Pressure Detonation



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emod 18.8e9 (1x)
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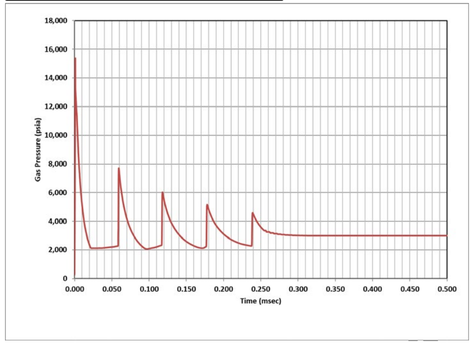
Fj_fric 0.577



PFC3D Constrained 24” OD HS-SX + Rubber-Lined + Perforated Steel Casing Fracturing Model

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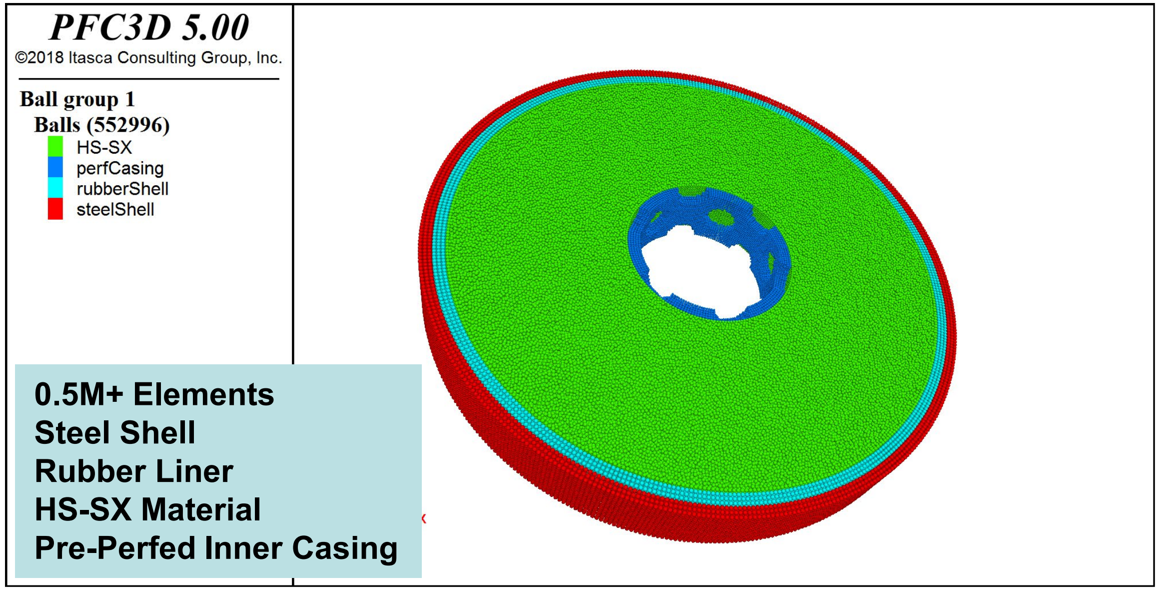
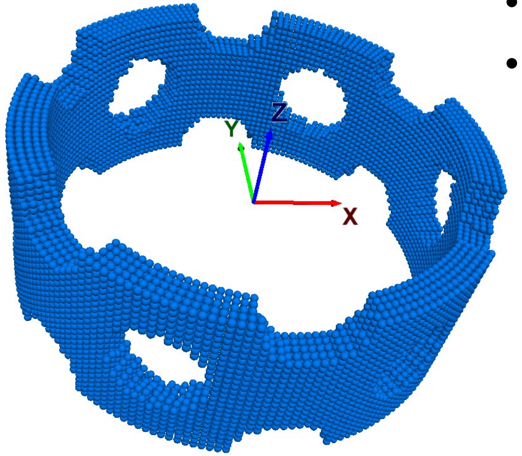
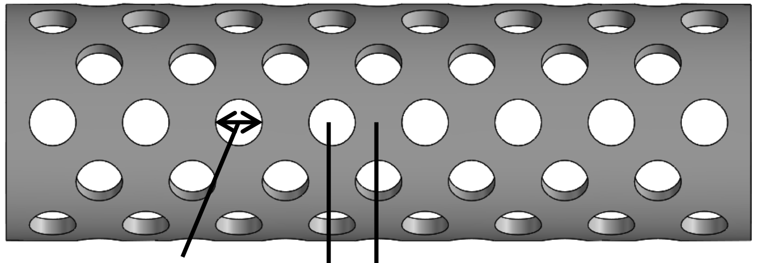
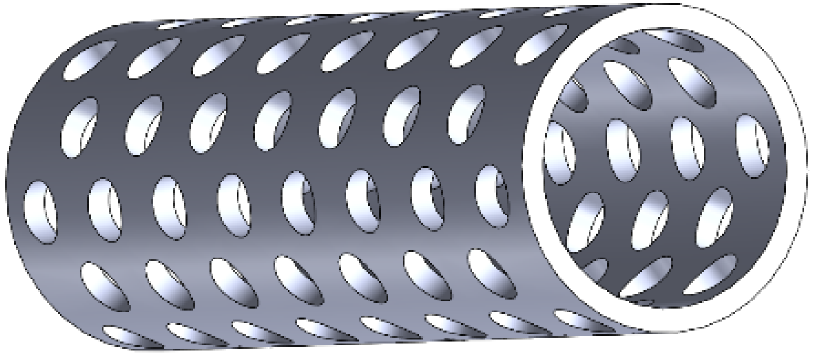


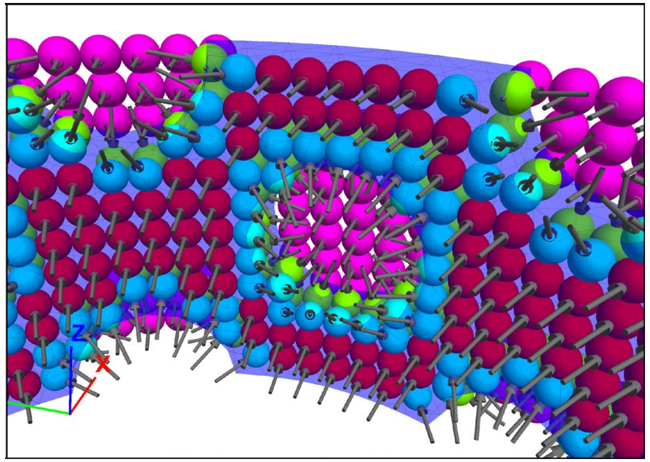
0.5M+ Elements
Steel Shell
Rubber Liner
HS-SX Material
Pre-Perfed Inner Casing



- **P-110 Alloy, 7-5/8” Casing @ 42.8 lb/ft**
- **7.625” OD x 6.50” ID**







Fracturing Geometry 1:

- 24$^{3}/_{8}$” Steel Outer Shell x 1” Thk.
- 1” Thk Rubber
- HS-SX With 7$^{5}/_{8}$” ID
- 7$^{5}/_{8}$” Perforated Casing With 1½” Holes
- Pressure Is Applied To HS-SX Thru Perforations & To Initially Exposed Surfaces Of Casing
- No Gas Pressure In Fractures – Results Shown Here Are Conservative

PFC3D 1,000 psi CV Pressure Detonation Model

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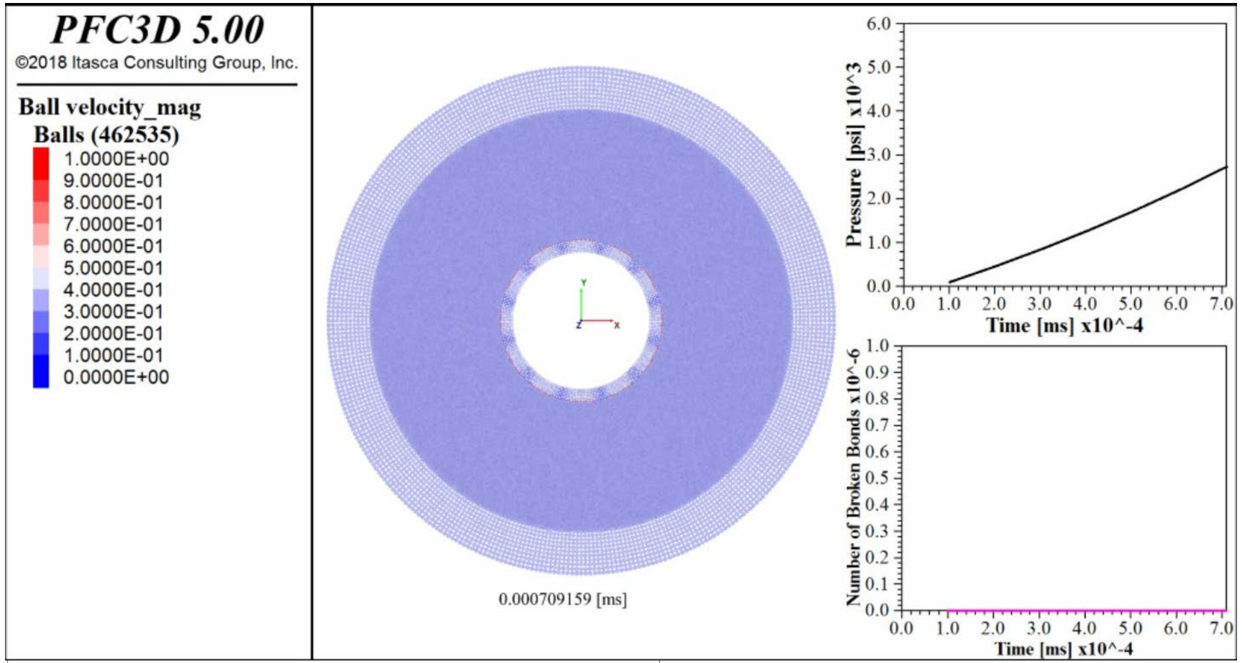
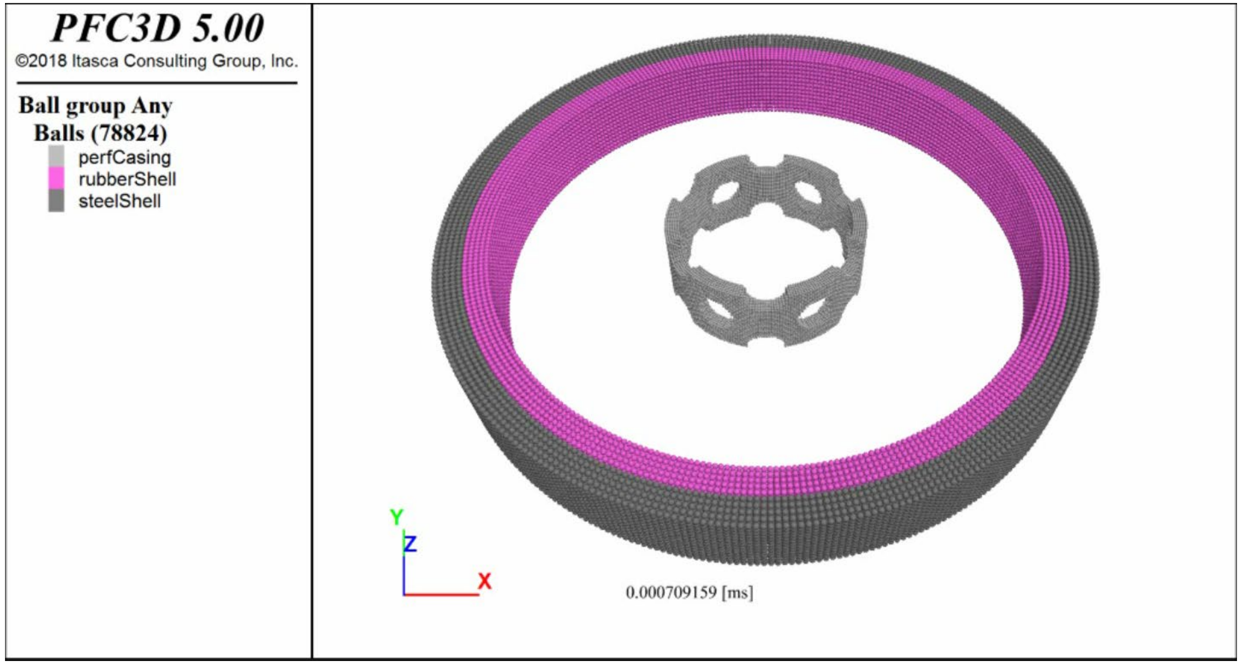
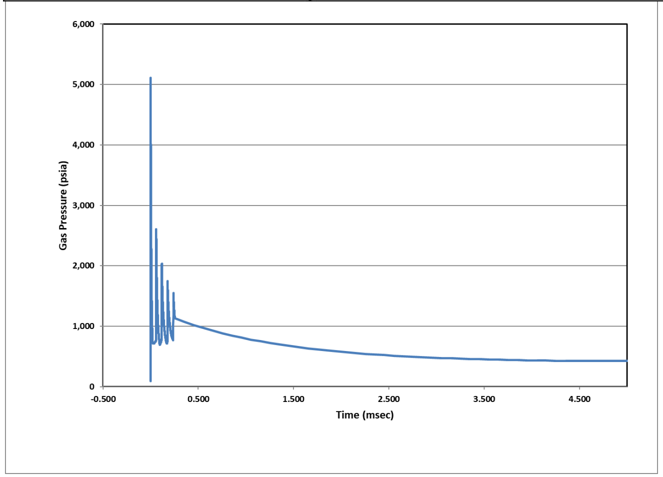
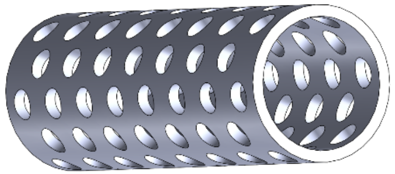








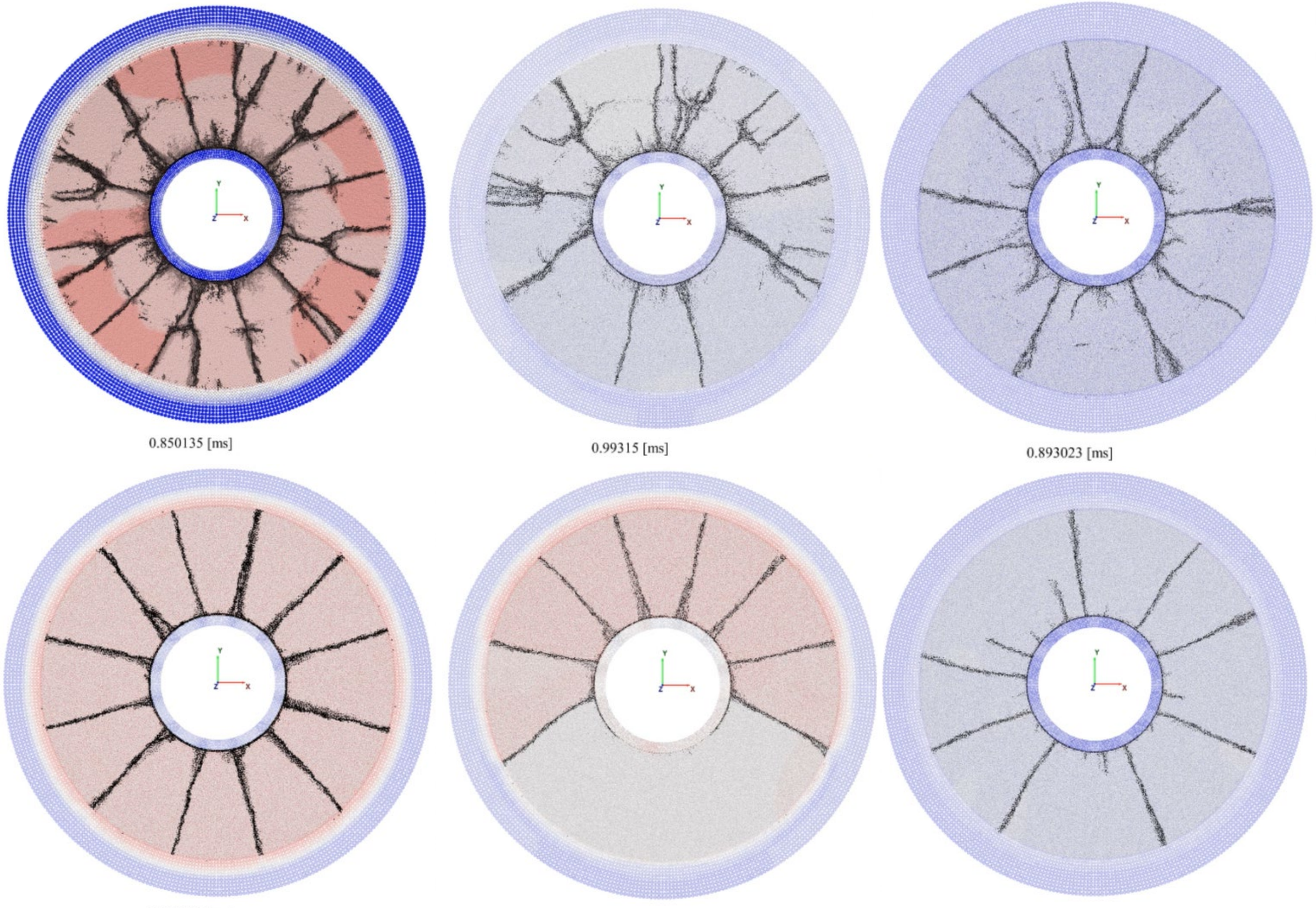
360˚ 1.5” Perforations

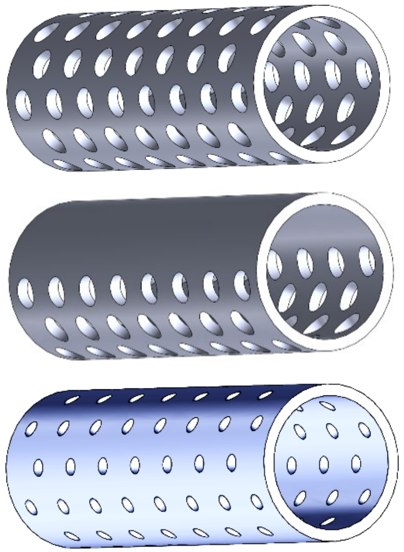
3D Micro Properties Were Recalibrated To Produce Same Measured Macro Properties (w/2.5x Fj_ten Value) As 2D Due To Simulation Differences Between 2D (Infinite Circular Rods) & 3D (Discrete Spherical Balls)

HS-SX 3D Fracturing Summary Results – Quantitative Predictions

NaturaFrac™ Advanced Dynamic Formation Stimulation

	360˚ 1.5” Perforations	180˚ 1.5” Perforations	360˚ 0.83” Perforations
1,000 PSI CV Radial Reflected Detonation	0.850135 [ms]	0.99315 [ms]	0.893023 [ms]
1,500 PSI Constant Volume Combustion	0.993393 [ms]	0.962486 [ms]	0.993421 [ms]

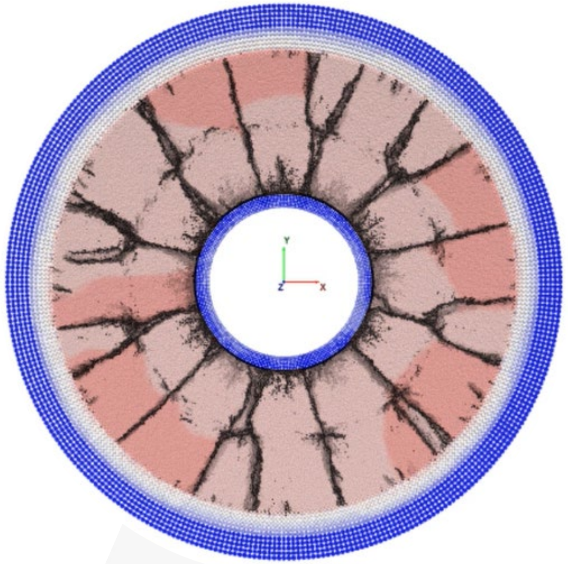


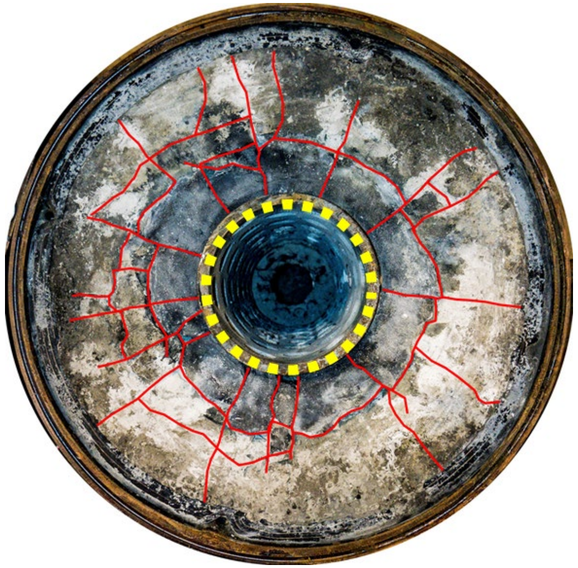


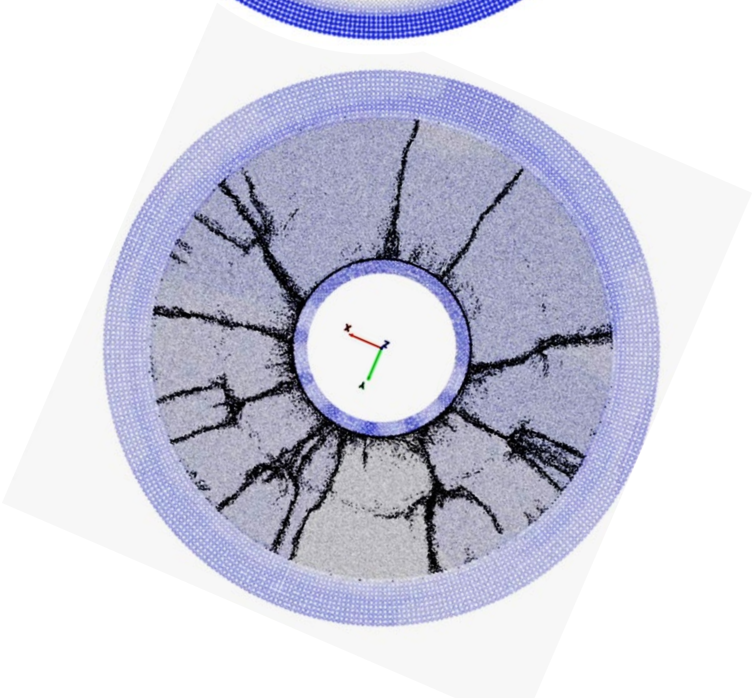
PFC3D Fracture Modeling Tool Shows Ability To Predict Complex Fracture Initiation Through Perforated Steel Casing With Adjustments to HS-SX Tensile Strengths

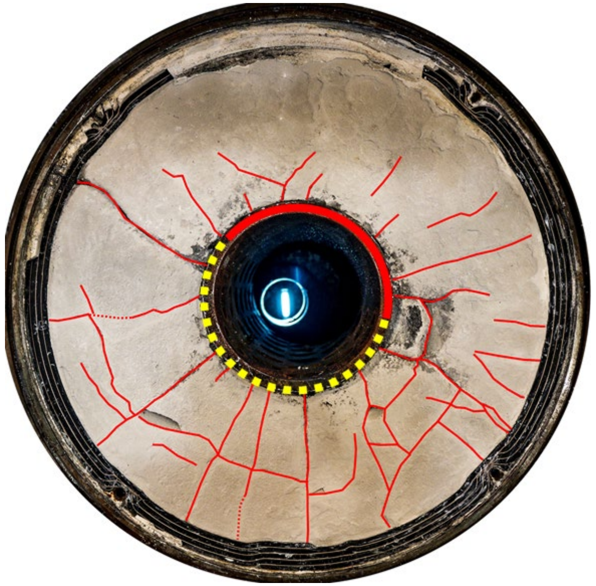
Very Good Agreement Between Experiments vs. Simulations With Modified Material Properties

NaturaFrac™
Advanced Dynamic Formation Stimulation









- **Experiment Results & *Pre-Test* Fracture Simulations Show Excellent Qualitative Agreement**
  - Fracture Complexity
  - Directionality Effects
- **Further Modeling Refinements & Tests Can Optimize Tool Operation For Desired Effects**
  - Fracturing Complexity
  - Degree Of Directionality
  - Etc.
- **Near Bore Strain Rate Dependent Material Properties Are Necessary For Successful Dynamic Fracture Simulations In PFC2D/3D**
- **Can Now Proceed To Free-Field/Large Scale Fracturing Modeling**

Conclusions

- **Pulsed Gas Fracturing Capable Of Producing Complex Fracture Patterns**
  - Fracture Type & Number Follow Theoretical Trends vs. Pressurization Rate & Peak Value
  - 2DPFC Fracture Models Show The Same Trends
- **2D & 3D PFC Successfully Modeled Lab Demonstrated Fracturing Patterns**
  - Multi-Material, Confined Synthetic Fracturing Samples
  - Modified Material Characteristics At High Loadings/Strain Rates Necessary
  - Love To Have Auto-Strain-Rate Dependent Fj_ten In PFC
- **Further Modeling Challenges**
  - Model Sizes/Element Counts For Full Scale (6ft Diam Samples)
  - Real Formation Fabric Modeling
  - Dynamic Gas In Fractures Effects
  - Existing Fractures/Multiple Pulse Fracturing
  - Thermal Effects

Thanks & Questions?

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