2012 International Perforating Symposium

The Woodlands Resort and Conference Center, Houston, Texas
April 26th-28th, 2012

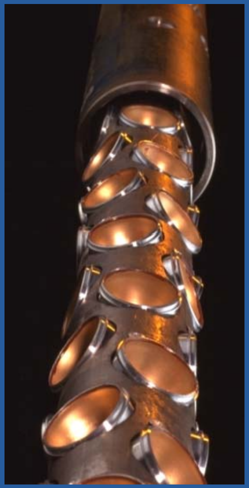
Design and Qualification of an Ultra-High Pressure Perforating System

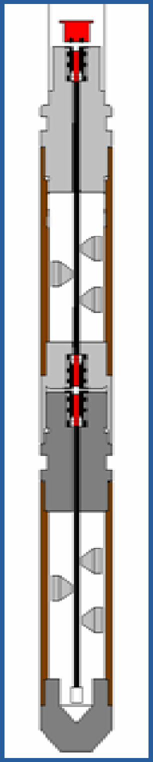
Nauman Mhaskar, Baker Hughes
Mark Sloan, Baker Hughes
William Myers, Baker Hughes
William Harvey, Baker Hughes

Presented By,
Nauman Mhaskar, Baker Hughes

Introduction

- Perforating Gun System
  - Shaped Charges
  - Strip to hold Shaped Charges
  - Detonating Cord and Boosters
  - Expendable Hollow Carrier
  - Firing Head, Connectors, Plugs
  - Misc.

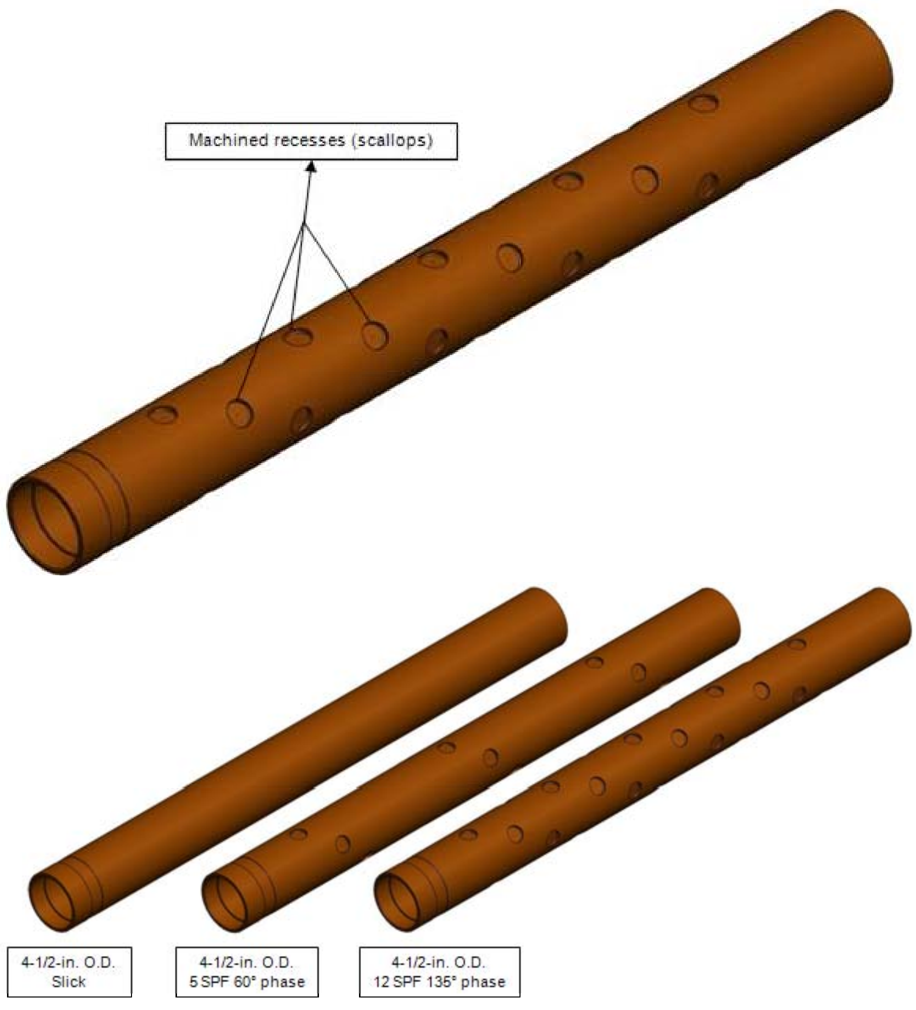




Expendable Hollow Carriers

- Differentiating factors are,
  - Outside diameter
  - Length
  - Shots per foot (number of scallops)
  - Phasing (orientation)

- Needs to be designed for,
  - External hydrostatic pressure
  - Ballistic load
  - Tensile load



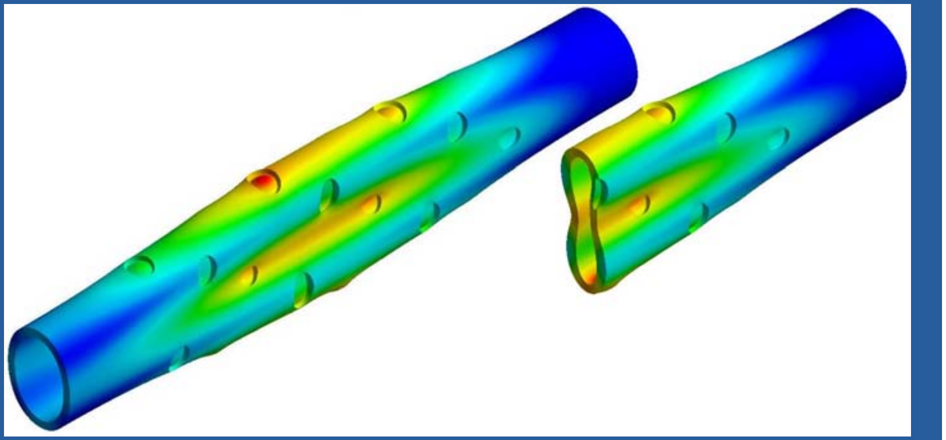
Designing for External Pressure

- It is difficult to analyze cross-sectional collapse of tubing with realistic imperfections using analytical methods.

- **Linear Finite Element Method (ANSYS):**

- Eigenvalue-buckling analysis gives the theoretical buckling strength and mode shapes of an ideal linear elastic structure.

- Geometry imperfections prevent most real-world structures from achieving their theoretical buckling strength.



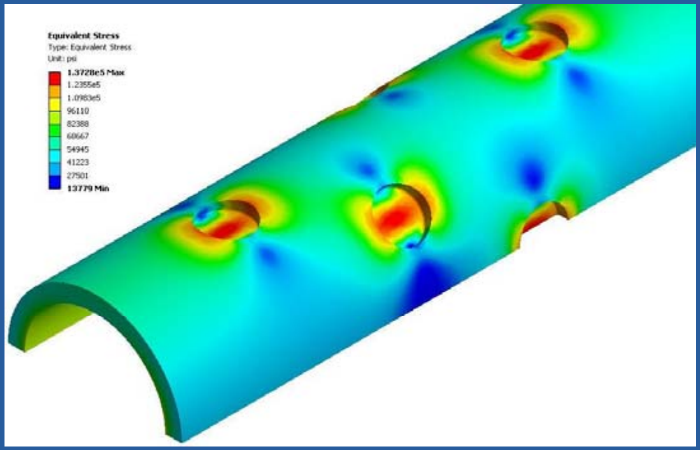
Mode shape from Eigenvalue-buckling analysis.

- Using the inception of yield as a criterion for collapse underestimates the failure pressure.

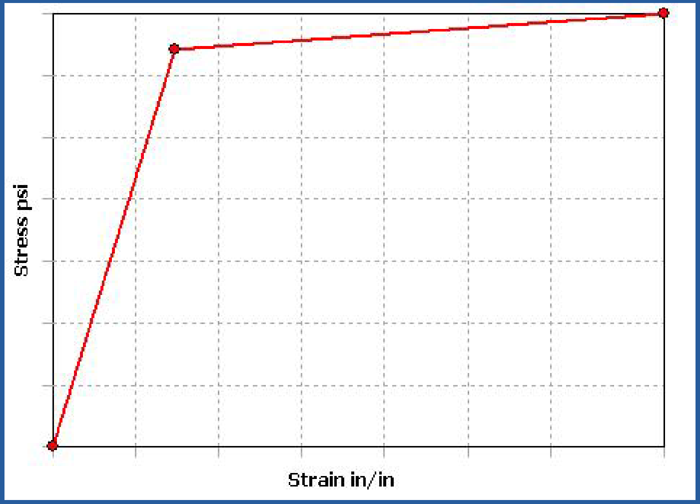
Designing for External Pressure

- **Non-Linear Finite Element Method (ANSYS):**

- Geometry
  - Three-dimensional solid with ovality to account for geometric imperfections.
  - Use of symmetry.
  - 10-node tetrahedral solid elements

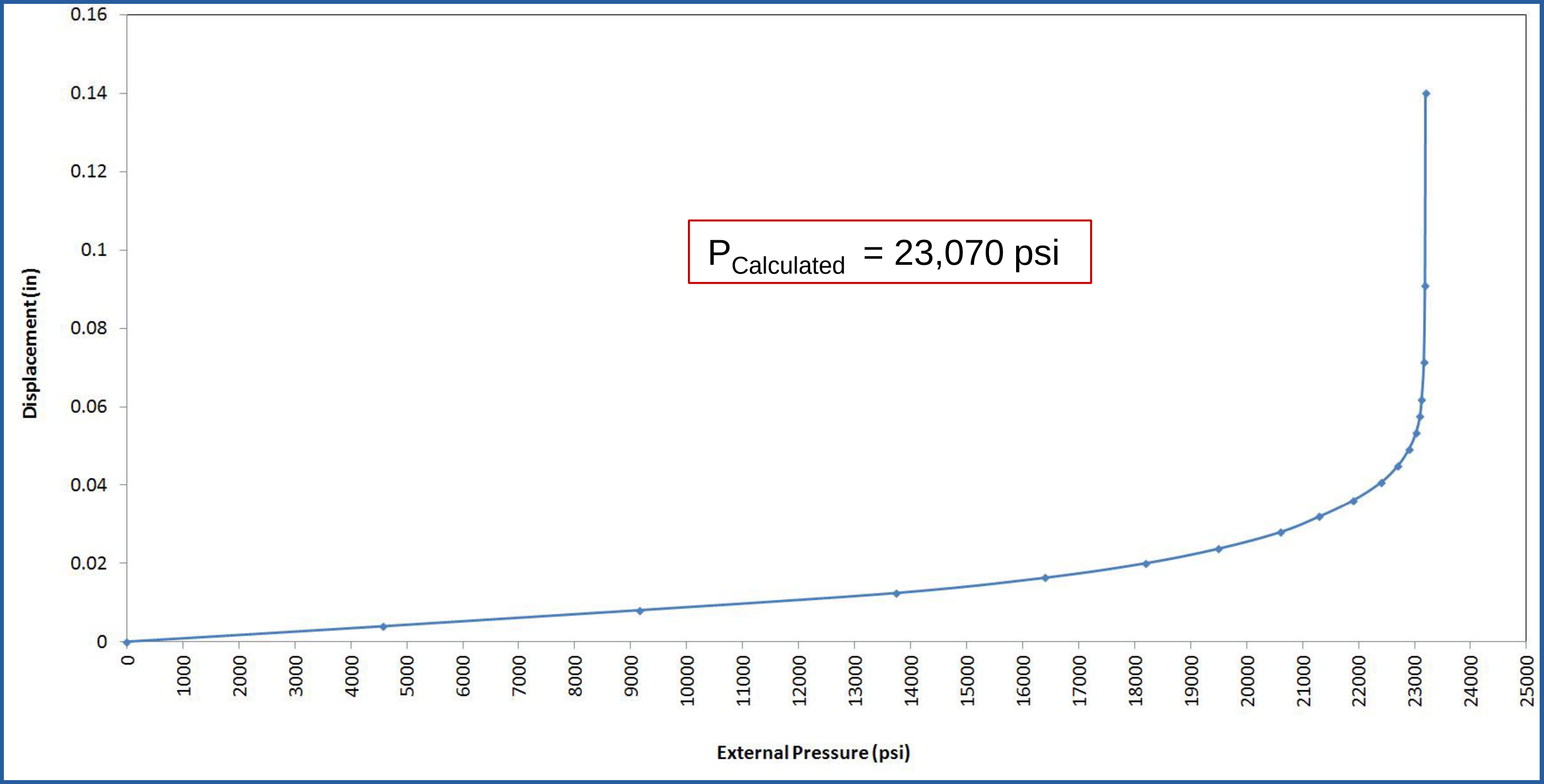


- Material
  - Von-Mises yield criteria coupled with an isotropic work hardening assumption.
  - Temperature effects.
  - Alloy Steel.



Designing for External Pressure

- Non-linear response



Pressure-Displacement Graph (4-1/2” 12 SPF 135° Phased Hollow Carrier)

Designing for External Pressure

- Results (Physical Testing)

- Testing Parameters:
  - 7-ft long Hollow Carriers capped at both ends to eliminate effect of slenderness ratio.
  - Material provided from the same batch or heat of raw material.
  - External pressure at 400° F was increased until a sudden pressure drop was observed.

Designing for External Pressure

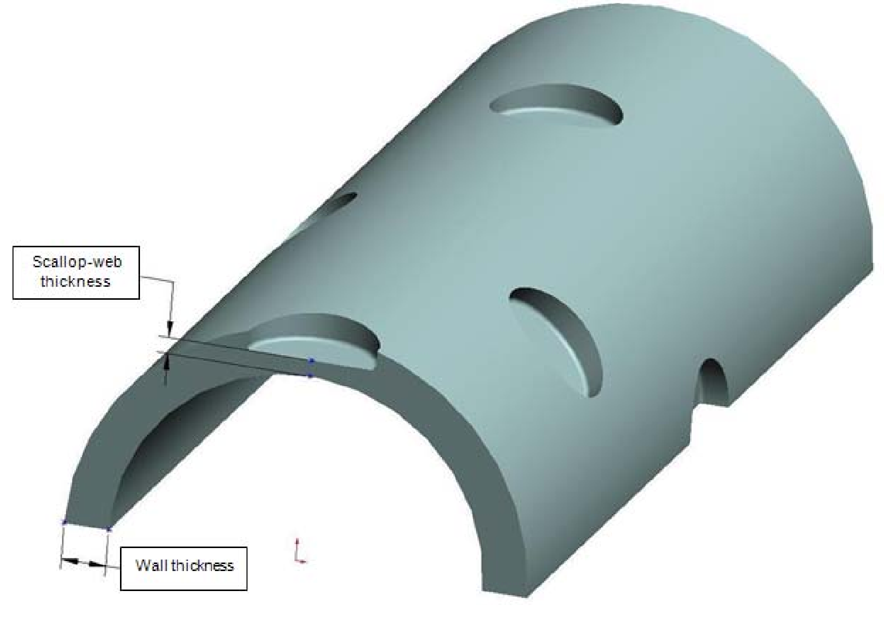
- Results (Validation)

	Yield Strength at ambient temperature (psi)	FEM Collapse Pressure at 400° F (psi)	Test Collapse Pressure at 400° F (psi)	Difference
4-1/2-in. O.D. Slick	135,040	26,400	25,595	1.7%
4-1/2-in. O.D. Slick	135,040	26,200	25,515	2.6%
4-1/2-in. O.D. 5 SPF 60° Phase	135,040	25,151	24,500	2.6%
4-1/2-in. O.D. 5 SPF 60° Phase	135,040	25,151	24,590	2.2%
4-1/2-in. O.D. 12 SPF 135° Phase	135,040	23,070	22,836	1.0%
4-1/2-in. O.D. 12 SPF 135° Phase	135,040	23,060	22,520	2.3%

	Yield Strength at ambient temperature (psi)	FEM Collapse Pressure at 400° F (psi)	Test Collapse Pressure at 400° F (psi)	Difference
6-1/2in. O.D. 16 SPF 140° Phase	139,300	13,390	13,700	2.3%
6-1/2in. O.D. 16 SPF 140° Phase	139,300	12,990	13,300	2.3%

Designing for External Pressure

Important parameters
Wall-thickness-to-scallop-web-thickness ratio
Inclusion of geometric imperfections
Selection of the material model



- Based on this methodology, and combined with API recommendations for pressure qualification (API RP 19B), a 7-in. O.D. 16 SPF 140° phase Hollow Carrier was designed with appropriate safety factors for an operating pressure and temperature of 30,000 psi and 400° F.

Response to Ballistic Loading

- Will the ballistic event cause unacceptable damage to the Hollow Carrier?

Failure Modes	
Excessive swelling	Swell of Hollow Carriers post-detonation exceeding the specified diametric tolerances.
Splitting	Hollow Carriers that have been fractured with large cracks or splits due to the detonation of the explosives.

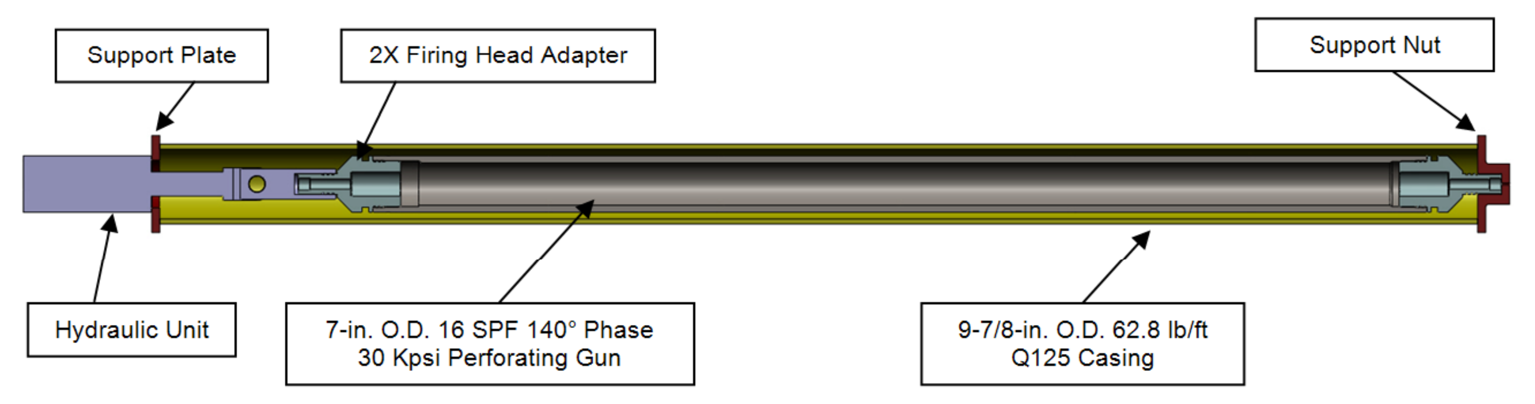
Response to Ballistic Loading

- Ballistic testing with the 7-in. O.D. 16 SPF 140° phase perforating gun system.

Phase I (Standard)	• A 7-ft long perforating gun was loaded with 47 grams RDX shaped charges and shot with fluid (water) surrounding the Hollow Carrier inside 9-7/8-in. O.D. 62.8 lb/ft Q125 casing.
Phase II (Uploaded)	• The second phase of survival testing used the same setup as Phase I, but shaped charges with an additional 2 grams of explosive (49 grams RDX per charge). • The additional 2 grams of explosive per shaped charge extended the survival-safety factor

Response to Ballistic Loading

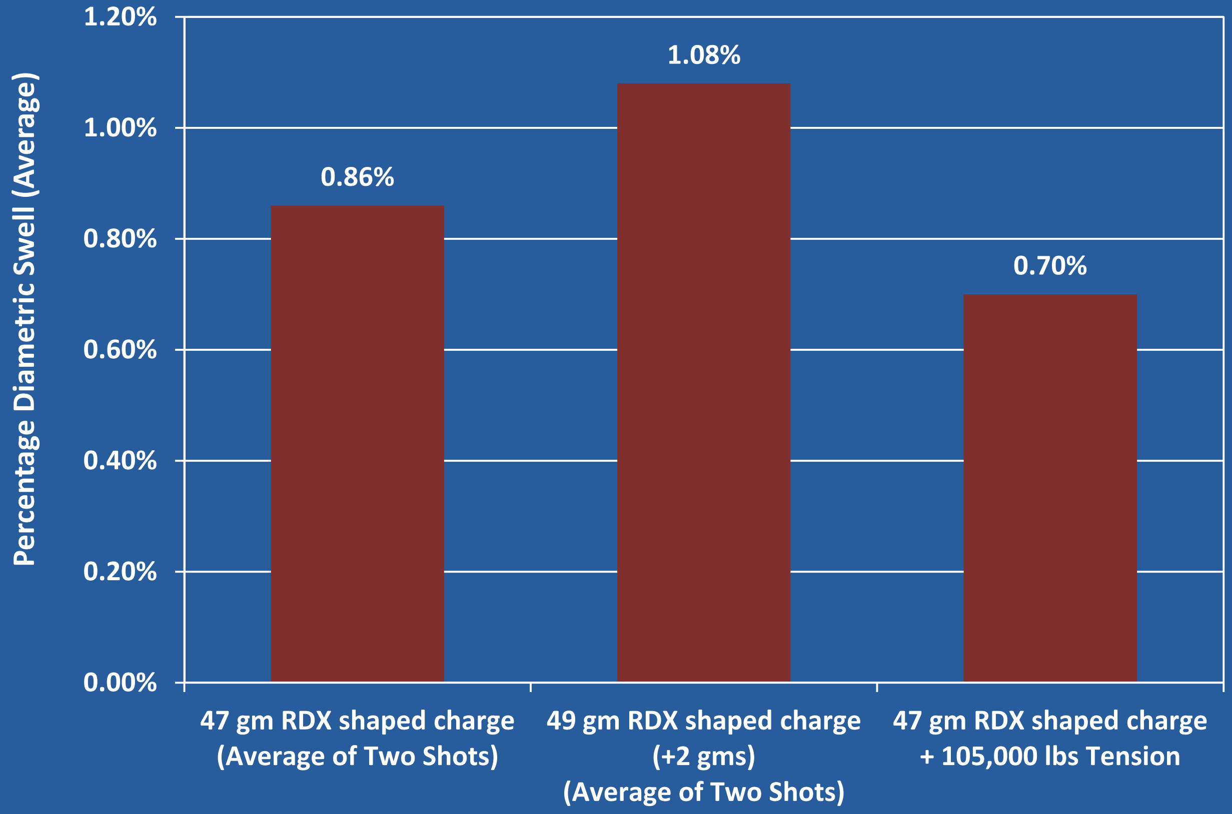
Phase III (Tensile Load)	• A 105,000 lb tensile load was applied to the Hollow Carrier. • This load represents the weight of a 1,500-ft long perforating string. • An 11-ft long perforating gun was capped at both ends inside 9-7/8-in. O.D. 62.8 lb/ft Q125 casing. • Tensile load was applied to the Hollow Carrier by a hydraulic unit using threaded end connectors and support members. • 47 grams RDX shaped charges.



Response to Ballistic Loading

- Results

- The percentage increase in O.D. is the swell of the hollow carrier.



Performance

System	• 7-in. O.D. 16 SPF 140° phase • Casing: 9-7/8-in. O.D. 62.8 lb/ft Q125 • Operational pressure and temperature = 30,000 psi and 400° F
API 19B (Section 1)	• Total Target Penetration = 5.6-in. • Exit Hole Diameter = .82-in. • Area Open to Flow = 8.45-in^2 per foot

Summary

- The collapse of Hollow Carriers due to external pressure can be predicted using nonlinear finite-element methods.
- These methods were validated with physical testing.

- Two approaches were introduced that include safety factors for performing ballistic tests on perforating guns:
  - -The addition of explosives to the standard gram load and,
  - - The imposition of a tensile load for the ballistic test.

- Based on the methodology reported, a 7-in. O.D. 16 SPF 140° phase perforating gun was designed for an operating pressure and temperature of 30,000 psi and 400° F.

Questions?