Perforation Flow Laboratory:
The Past, The Present, The Future

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Perforating Flow Laboratory – 60th Year

- Historical context
- Capability evolution
- Advances & milestones
  - relevance to field, benefit to industry
- Common themes
- Outlook for the future
Perforating Flow Laboratory – Historical Context

Field perforating techniques

Mechanical (knife cutter)

Bullet 1932 Niche applications

Shaped Charge 1948 >95% of all perforating

Hydraulic (abrasive jetting)

Niche applications

1920 1940 1960 1980 2000

Laboratory perforating standards

Perforating flow laboratory introduced 1953
RP43 1st ed 1961
2nd ed. 1971
3rd ed. 1974
4th ed. 1985
5th ed. 1991
RP 19B 1st ed 2001
2nd ed 2006

2012 International Perforating Symposium IPS-12-24
Perforating Flow Laboratory – Evolution of Test Standards

Radial flow also conducted
Bell et al. 1972
Regalbuto et al. 1985
Liu et al. 1988
Deo et al. 1989

Concrete: Core Flow Efficiency (CFE)
Linear flow

WellFlow Index (WFI)
Linear flow

Core Flow Efficiency (CFE)
Radial or Linear flow

Halleck et al. 1997

1920 1940 1960 1980 2000

Section 1
Concrete: penetration

Section 2
Rock: penetration & flow

Then…

2012 International Perforating Symposium
IPS-12-24
Perforating Flow Laboratory – Evolution of Lab Capabilities

- Independent control of confining, wellbore P
- Perforating gun system (multiple charges)
- Transient pressure measurements
- Transient pressure control
- Precision flow control
- Automation
- Flow visualization

1940
1960
1980
2000

Flow visualization

2012 International Perforating Symposium
Productivity & skin

Importance of reducing skin
Productivity & skin

Natural completions
- Shot density
- Phasing
- Penetration depth
- Perforation damage

Stimulated completions
- Weak rocks – sand control (GP / FP)
- Tight rocks – hydraulic fracturing
- Carbonates - acidized
Perforating Flow Lab - Fundamental Advances in Industry Knowledge

Penetration related

Formation stress effect

Wellbore pressure effect

Formation strength effect

Perforator/rock interaction, comparison vs. bullets (plugging, etc.)

Penetration depth = f (formation strength, stress, reservoir pressure, etc.)
Perforating Flow Lab - Fundamental Advances in Industry Knowledge

Cleanup, skin, & completion related

Perforating strategies for stimulated completions

1920 1940 1960 1980 2000

- Fracturing (late 80's)
- Weak rocks (1990s)
- Carbonates / Acidizing (2000s)
- Integrated perf + fluids (2004-5)
- Static underbalance skin (1991)
- Optimum static underbalance (1995)
- Dynamic underbalance discovered (~2001)
- Multiple perfs (all perfs are NOT created equal) (1994)
- Static UB known to be important since 50's
- Fundamental nature of perf damage (2011)
- Static UB not required!!

Production through the perforations. **High productivities are indicated when jet perforating in oil or salt water with pressure differentials into the well bore using a perforator which does not cause carrot plugging.**

*Allen & Worzel (1956)*
Milestones

- **Bullets, jets**
  - Penetration & plugging
  - Well fluid & pressure differential effect on flow

### First work
- Allen & Atterbury (1953) – SPE 319
- Allen & Worzel (1956) – API 56-112
- Krueger (1956) – API 56-126
- Bell, et al. (1959) – API 59-249

### Penetration
- Thompson (1962) – API 62-191
- Saucier & Lands (1978) – SPE 6758
- Halleck et. al. (1988) – SPE 18245
- Behrmann & Halleck (1988) – SPE 18243
- Harvey et al. (2011) – SPE 181546

### Perf cleanup & Flow regimes
- Bell, Brieger & Harrigan (1972) – SPE 3444
- Deo, Tariq, & Halleck (1989) – SPE 16896
- Halleck & Deo (1989) – SPE 16895
- Hsia & Behrmann (1991) – SPE 22810
- Behrmann (1996) – SPE 30081
- Walton et al. (2001) – SPE 71642

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**Perforating Today — A Science†**

W. T. Bell,* M. P. Lersch,* AND J. Bradbury

... so it is, axiomatically, that one simple test method will not satisfy all testing requirements. It remains that to realistically evaluate gun-perforator performance, the test conditions must approach those under which the perforator will ultimately be applied.
Milestones

- System effects, heterogeneity, etc.
  - Mason et al. (1994) – SPE 28554

- Weak sands & sand control (sand production, GP impairment, etc.)
  - Blok et al. (1996) – SPE 36481
  - Behrmann et al. (1997) – SPE 38639
  - Venkitaraman et al. (1997) – SPE 38144
  - Walton et al. (2001) – SPE 71458
  - Walton et al. (2004) – SPE 90123

- Fracturing
  - Behrmann & Elbel (1991) – SPE 20661

- Acidizing
  - Bartko et al. (2007) – SPE 105022

- Perf system / fluid / formation interactions
  - Chang et al. (2004) – SPE 82203
  - Chang et al. (2005) – SPE 94596
Common Theme & Goals

- **Theme**
  - Perforating is a SYSTEM operation

- **Goals:**
  - Understand reservoir response
  - Understand wellbore & completion responses

System = gun + charges + wellbore + reservoir
Keys to Success

- Know what to measure & control
- Measure & control it
- Interpret, and ultimately apply to downhole
- Integration

System = gun + charges + wellbore + reservoir
Recent & Future Trends

- More accurately replicate downhole environment
  - Rock properties (UCS, porosity, perm) – reservoir core sample ideal
  - Static conditions (stress, P, T)
  - Dynamic conditions
  - Fluids (both reservoir and wellbore)
  - Drilling damage

- Harsher environments (HP, HT)

- Prove product (and system) performance, validate models

- "test drive" perforating techniques, before / in conjunction with field testing

Ultimate goals remains the same

Maximize well productivity & operational efficiency

Minimize risk to field operations and completion equipment
By the way...

**Predictions (Behrmann, 2007):**

- Slow down in increasing Section 1 penetration.
- Focus shift to reservoir rock under downhole conditions.
- Focus shift to well productivity (away from Section 1 performance).
- Openhole perforating
- Systems optimized for specific reservoirs and completion types.
- Systems integrated with completions, stimulation operations.
- “One trip well”.
Summary

- Perforating flow laboratory, 6 decades of:
  - Fundamental discoveries
    - Penetration depth
    - Perforation cleanup
  - Field techniques developed / demonstrated / refined
    - Natural completions
    - Sand control
    - Hydraulic Fracturing
    - Acidizing
  - Predictive models developed / validated / calibrated

Integration essential (multidisciplinary; expts+modeling)
Reduce risk & uncertainty for field operations
Relevance to field is key!
Outlook

All of this will continue – and become more important in the future, as:

- **Field conditions get more severe**
- **Accurate prediction of downhole performance becomes more critical**
- **Operations get less risk-tolerant**
- **Laboratory testing can be essential piece of the puzzle:**
  - Ensure the optimal technology is selected for field application
  - Improve confidence in expected field performance

Integration essential (multidisciplinary; expts+modeling)
Reduce risk & uncertainty for field operations
Maximize well productivity & operational efficiency
Minimize risk to field operations and completion equipment

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