A Historical Perspective of HYDRAULIC FRACTURING

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S E I

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Thanks to SPE !!!

Without SPE, We Might Have Eventually Done It.

But We Wouldn’t Have Done It As Fast.

Done What ?

Made the Progress that We Have
In
Hydraulic Fracturing Technology
Over the Past 60 Years

( 7000+ SPE Fracturing Papers Since 1949 )
THE "TYPICAL" TREATMENT – STEP 1

INITIATING THE FRACTURE
THE "TYPICAL" TREATMENT – STEP 2

EXTENDING THE FRACTURE AND INJECTING THE PROPPANT
THE “TYPICAL” TREATMENT – STEP 1

BACK FLOWING THE FRACTURING FLUID
The Birth of HYDRAULIC FRACTURING
Born 1947, Hugoton Field, Grant County, Kansas
Final Patent Issued 1953 to Stanolind Oil & Gas,
(Bob Fast, George Howard, Floyd Farris, Joe Clark)
Since then it has Turned the World GREEN with MONEY

Hugoton, KS
A. B. Waters, Halliburton Co., circa 1980:
(Paraphrased)

“Hydraulic Fracturing has generated more profit for the petroleum industry than any other process, except for exploratory & development drilling.”

Veatch, S E I, circa 2007:
(Observation)

“Since 1980, industry experiences in water, chemical, miscible, thermal, etc., processes have not Economically competed with Hydraulic Fracturing.”
Klepper Gas Unit No. 1, Hugoton field, Kans. The first well to be hydraulically fractured to increase well productivity. (SPE Monograph Vol. 2)
The Great Race
First Commercial Fracturing Treatment – 1949 (Pictured)
Stephens County, OK - Dwight K. Smith – Halliburton Engr.

Second Commercial Fracturing Treatment – 1949 – 2 Hours Later
Archer County, TX - A. B. Waters – Halliburton Engr.

1949

Courtesy - Halliburton
1950 – Fracturing with Cement Pumpers  (SPE Monograph Vol. 2)
Mid 1960’s – Fracturing Pumpers & Blenders (SPE Monograph Vol. 2)

Pumpers - Remote Controlled

Control Center

Blenders
1950’s – Early 1960’s: Treatment Orchestration

Data Collection

Communications
Mid 1960’s – Some Fancy Manifolding  (SPE Monograph Vol. 2)

From the Blenders to the Pumpers

From the Pumpers To the Well
1949 – 1965 Fracturing Treatment Sizes

Hazebrook & Waters, JPT, July, 1964
1950’s & 1960’s - Treatment Designs.

Who Had the Final Say?

Often - The Area Superintendent.

“Give It a $15,000 Job.”
or
“Pump 20,000 Pounds.”

“And, DON’T Even LOOK at My GOOD Wells !!!”
Mid 1970’s - The Showdown in TOMBSTONE (Rock, That is)

MASSIVE HYDRAULIC FRACTURING (M H F)
MHF – Fracturing Treatments & Design Trends

1970’s vs. 1980’s
1,000’s gal → MM’s gal
1,000’s lbs → MM’s lbs
$1000’s → $MM’s

2 – 5 ppg → 5 – 10+ ppg

Relative Job Costs
Frac / Total Well
RC < 15% → RC > 50%

Design Strategy
Bigger → Smarter

The Superintendents
Got Out of The
Treatment Design
Business

% Total Well Cost

Job Size - 1000’s gal

DENVER COTTON VALLEY TRENDS
GREEN RIVER SO. WYOMING
Economic Optimized Treatment Design Came into the Picture
to Balance Fracture Length & Conductivity with Formation Permeability & Rock Properties
to Maximize - THE MONEY!
The Equipment - It GREW

Steroid Pumpers – Bigger, Stronger, Faster

Big Throated, Bulimic Blenders

Courtesy – Halliburton

Courtesy - BJ Services

Courtesy – Schlumberger

Courtesy – Western Co. NA

Courtesy - BJ Services
Quality Monitoring & Control - Evolutions

With In-Line Flow Loop Rheometers

Courtesy - BJ Services
Meanwhile – Both MHF & Non-MHF - Other Things Emerged

Coiled Tubing Fracs

Frac Navies

Courtesy- Halliburton

Courtesey- BJ Services

Courtesy- Schlumbergerr

H o r i z a l W e l l s
The AMAZING Evolution of
FRACTURE PROPAGATION GEOMETRY

Our Perceptions of
Fracture Propagation Geometry
Were NEVER Wrong.

It was the Fractures Themselves that Changed

Just When We Had Them Figured Out,
They Would Mutate – Again and Again
Fracture Geometry: 1947 - 1957

Pine Island Field, LA - 1954
Howard, G. C., Pan American Petroleum
Horizontal Fracs -
Proppant EMBEDMENT & PARTIAL Monolayers
Were VERY Important In Treatment Design

Halliburton – “fracbook”, 1971
Mid 1950’s Fracture Geometry
Per – Hubbert & Willis, Trans AIME, 1957
Fractures Reoriented Vertically

And, Proppant TRANSPORT
Equilibrium Banking vs
“Perfect” Transport
Became a BIG Design Issue.

Equilibrium Banking

Settled Proppant Bank
First Prop In
Last Prop In
Then Along Came Tom - 1961 & Along Came John (Jahns) – 1969, Where Fractures Maintained a Constant Height from Wellbore to Tip.

And With These, Came the Table Pounding Between the PERKINIUMS and the GEERTSMACRATS
Perkins is RIGHT! He is NOT, Geertsma IS!
Is NOT! Is TOO! Is NOT!! Is TOO!! Is NOT!!! Is TOO!!!!

For a While: Height = Perf Span. But Later On Fracs Started to Grow
In the Late 1970’s and Early 1980’s, Fractures Began Misbehaving. Since Then. They Have Gotten Almost Completely Out of Control.
They Began Curving, and Zig-Zagging About. Some Would Even Propagate Dendritically (Just Like Othar Kiel Told Us in the Late 1970’s --- What Did He Know?)

Hello
Barnett Shale

"MAN, THAT'S WHAT I CALL A REAL FRAC JOB!"
A Lot of Folks Got Involved to Address these Issues

- Equipment Manufacturers
- Government Laboratories
- Industry Associations
- Industry Consortiums
- Private Technology
- Product Suppliers
- Production Companies
- Service Companies
- Universities

They Developed:
- Equipment
- Processes
- Techniques

To Keep Up With Those Pesky Fractures

They Built Design Tools & Computer Models - to Tell The Fractures How to Behave !!!!
Some Ways to Get a Hint of Prospective Fracture Propagation Behavior

Nolte-Smith – Net Pressure vs Time Curves

**Downhole Tools**
- Borehole Elongation Orientation
- Geoseismic
  - Cross Wellbore
  - Single Well
- Impression Packers
- In situ Stress Profiles
- Micro-Seismic
- Post Frac Temperature Profiles
- Television – Televiwers
  - Optical, Sonic
  - Tri-Axial Sonic

**Laboratory – Core**
- Compressional/Shear Wave
- Differential Strain Relaxation
- Point Loading
- Residual Stress Overcoring
- Strain Relaxation
- Thermal Expansion

**“Surface” Mapping**
- Electro Potential
- Geo- & Micro-seismic
- Tiltmeters
Mid 1980’s – Revelation – Insitu Stress vs Depth is a Very Wiggly Function

Example

Mesa Verde, Rifle, CO

2000 psi Stress Change Over a 100 ft Interval

Subsequent Experience

Often More a Rule Than an Exception.

Warpinski, Brannagan & Wilmer, JPT, March, 1985
Fracture Treatment Design Tools

50’s - 60’s

60’s - 70’s

90’s - 2000’s

70’s - 80’s - 90’s
Fracturing Simulators – Now Available, At Your Finger Tips

Simple (PKN, GDK, Elliptical)
Lumped Parameter
Planar Finite Difference, Pseudo 3D” – Vertical Growth by 2D Elasticity
Planar Finite Element 3D” – ALL Growth by 3D Elasticity

2001 Odessy - 3D Simulators – Coupled Finite Difference & Finite Element
  2D - 3D Fluid Flow and Proppant Transport
  Angularly Oriented – Laterally
  Multi-Nodal
  Non-Planar
  Non-Symmetrical
Varying Properties – Both Laterally and Vertically
  Elastic Modulli
  Fluid Loss
  Formation Pressures
  Insitu Stresses
  Poisson’s Ratios,
  Stress Intensity Factors
  Brick Piles

Which One to Use?  - However You Want to Tell the Fractures to Behave.
PS – They May Not Be as Obedient as You Would Like !!!
The AROUND & AROUND World of Fracturing Materials:

Fracturing Fluid Systems & Propping Agents – Proppants

One Thing That Really Keeps Going ‘Round & ‘Round:

Our Perpetually Repetitious Comments

“We Used Those Back in the ___’s, and Here They Come AGAIN?.”
The “Circulating” - Fracturing Fluid Systems

Polymer Free

Alcohol

Acid

Linear Aqueous

Crosslinked Aqueous

Liquid Emulsions

Aqueous Foam

Liquid CO2

Napalm-gelled Gasoline

Hydrocarbon Foam

Nitrogen Gas

Crosslinked Oils

Environmentally Green

Surfactants

Hairy Stranded

Lease Crude

Refined Oils
# Fracturing Fluid Systems – a Plethora of Choices – All it Takes is MONEY

## System Gelling Agents
- Cellulose
  - Carboxy Methyl
  - Hydroxy Ethyl
- Guar
  - Natural
  - Derivatized
  - Modified
  - Improved
- Napalm (Oils)
- Soaps (Oils)
- Sodium Bicarbonate (Oils)
- Surfactants
- Xanthan

## Functional Additives
- Antifoaming
- Bacteria Control
- Breakers (Viscosity)
- Buffers
- Clay Stabilizing
- Defoamers
- Demulsifying
- Dispersing
- Emulsifying:
  - Flow Diverting, Blocking
- Fluid Loss
- Foaming
- Friction Reducing
- Inhibitors
- pH Control
- Scale Inhibitors
- Sequestering
- Surfactants
- Temperature Stabilizing
- Water Blockage
- Etc.

## Cross Linking Agents
- Aluminum
- Antimony
- Boron
- Chromium
- Titanium
- Zirconium
- Etc.
Fracturing Fluids – Percent Usage – 1990’s vs 2000’s

(Excl – China, Russia)
Cross Linked Fluids – The Strange and Mysterious Globs

J. R. Cameron, 1990
Testing Cross Linked Fluids – Some Problems

Couette Rheometer

Observed in the Bob & Cup

J. R. Cameron, 1990
Instruments Required to Characterize – Many Visco-Elastic Fluids

- **Couette – Rotary – Multiple Cups & Bobs**
- **Multiple Pipe Flow Systems**
- **Oscillating – Parallel Plate**
Flow Regimes for These Fluids – In the Fracture - Can Change Back and Forth Dramatically Throughout the Job Depending on Time, Changing Shear Rate, Temperature, etc.

J. R. Cameron, 1990
At Low Shear Rates, Power Law Equations Do Not Describe Behavior, Some Systems Have Upper Viscosity Limits (Laser Anemometry Tests)

Guillot & Dunand, SPEJ, Feb, 1985
Mid 1980’s – Proppant Transport
Medlin, Sexton & Zumwalt: SPE, 1985
Roodhart: SPE, 1985

@ Elevated Temperature & with: Fluid Loss, Particle Tracking, etc.
Consortiums & Service Companies
Proppant Concentration & Size Distribution Can Significantly Increase Fluid System Viscosity

Mid 1980’s - Proppant Concentration & Fluid System Viscosity

Low Shear Rates

Turbulent Flow

Chan & Powell, 1984

Hannah, Harrington & Lance, 1983
Fracturing Fluids – A BIG Revolution

1970’s -1980’s

Hydroxy Propyl Guars
Gel Concentrations
50 – 60+ gal / 1000

Cross Linkers
(Metallic Bonded)
Titanium
Zirconium
300 – 350+ F

1990’s -2000’s

Improved Guars
Gel Concentrations
15 – 30 gal / 1000

Cross Linkers
(Hydrogen Bonded)
New Borates
100 – 300+ F

POWDERs

LIQUID CONCENTRATES
Fluid Loss Behavior - Static

1950’s – 2000’s Laboratory

1979 - In the Field – Nolte Shut-In Pressure Decline (SIPD) Type Curves

Followed by - “G-Functions”

SIPD Almost Put Laboratory Static Testing Out of Business
Mid 1960’s - Fluid Loss Behavior - Dynamic
Hall & Dollarhide, JPT, May, 1964

1980’s

Gulbis - 1983
Harris & Penny - 1989

1990’s + Consortiums & Service Companies

McDaniel - 1985
Harris - 1985 & 1987
The Circuitous World of Propping Agents - Proppants

- Bio-Degradable
- No Proppants – 3rd Cycle
- Plastic Beads
- Nut Shells
- Aluminum Pellets
- Adhesive Pellets
- Glass Beads
- Deformables
- Resin Coated Sand
- Custom-Shapes
- Sintered Bauxite
- Resin Coated Nut Shells
- Zirconium Pellets
- River Sand
- Mined Sand
- Resin Coated Ceramics
- Lt Weight Ceramics
Early 1980’s - An “API” Fracturing Sand

It Took Only Six (that’s 6) Years
For a
30+ Member Industry Committee
To
Come to a “Consensus”
Of What
Constitutes
an

“API Fracturing Sand”

“API RP-56, 1983”

(Whew !!!)
Propping Agents – Percent Usage – 1990’s vs 2000’s

(Excl – China, Russia)
Fracture Conductivity Testing - the Good Old Days

Radial Flow Cell

Hassler Sleeve – Linear Flow

@ “Crunch” Stress, @ Room Temperature, With Water, 30+ Minutes

SPE Monograph Vol. 12
Late 1980’s - Fracture Conductivity Testing - the API Cell

@ “Crunch” Stress & Temperature,
With the Fracturing Fluid,
For a Long Time

“API RP-60 1989”
Fracture Conductivity – Short Term Tests vs Long Term @ Insitu Conditions

Short Term Test
- Ambient Temperature
- Newtonian Fluid

Long Term – Insitu
- Insitu Temperature
- Fluid Gel Damage
- Silica Solution
- Non-Darcy Flow
- Relative Permeability
- Formation Particulates
- Cyclic Loading
- Etc., Etc., Etc.

20/40 Good Sand

Fracture Conductivity \( \text{md - ft} \)

Stress - 1000’s psi
Hydraulic Fracturing Applications – They Expanded

1950’s – 1960’s (SPE Monograph Vol. 2)
- Overcome Wellbore Damage
- Increase Well Productivity
- Improve Secondary Recovery Injectivity
- Increase Brine Disposal Rate

1970’s – 2000’s (the Above, Plus)
- Increase Recoverable Reserves (MHF in Tight Formations)
- Blowout Well Control (Frac from a Directional Offset)
- Sand Control (e.g., Frac-n-Pack)
- Sweep & Conformance Improvement
- Fire & Steam Flooding
- Geothermal Energy Extraction (Hot Dry Rock Circulation)
- Drilling Mud Disposal (Environmentally Unfriendly)
- Nuclear Waste Disposal
- Etc., Etc.
Service Company:
Pumped Everything Away With No Breakdowns or Fluid Problems
Bar B Q Impressed the Company’s Field Supervisor
Promised More Jobs

Field Operating Personnel:
Service Company Arrived on Schedule,
   Adequately Staffed, and With All Equipment & Materials as Specified
Pumped the Treatment Per the Job Prognosis
Didn’t Destroy Any Lease Roads or Company Property
Frackers Left Before Dark, With All They Brought In, Especially Trash
No One Hurt or Killed
Service Company Bought Supper After the Job

The Frac Design Engineer's:
Production Response Better than the Boss Expected
Computer and Data Collection/Analysis Budgets were Increased

Operating Company Management:
Can Triple the Booked Reserves and NPV Sales Value of the Well
Hydraulic Fracturing
WORLD WIDE
A GLOBAL PERSPECTIVE
OF
ACTIVITY
1990’s & 2000’s
Mid 1990’s Annual Fracturing Jobs & Costs (Excl – China, Russia)

- **NORTH AMERICA**
  - Jobs: 87%
  - Cost: 81%

- **EUROPE/AFRICA**
  - Jobs: 2%
  - Cost: 8%

- **SOUTH AMERICA**
  - Jobs: 9%
  - Cost: 6%

- **MIDDLE EAST**
  - Jobs: 1%
  - Cost: 4%

- **SOUTHEAST ASIA**
  - Jobs: 1%
  - Cost: 1%

- **WORLD TOTAL**
  - No. Jobs: 10,000
  - Cost: $US 830 MM
Mid 2000’s Annual Fracturing Jobs & Costs (Excl – China, Russia)

- **NORTH AMERICA**: 85% Jobs, 85% Cost
- **EUROPE/AFRICA**: 1% Jobs, 2% Cost
- **MIDDLE EAST**: 2% Jobs, 3% Cost
- **SOUTH AMERICA**: 9% Jobs, 7% Cost
- **SOUTHEAST ASIA**: 3% Jobs, 3% Cost

- **WORLD TOTAL**: 23,000 Jobs, $US 2,200 MM
FRAC ENGINEERS Face A Somewhat Daunting Challenge. They Have To Work With A System Created By Nature. One That They Cannot See, They Cannot Touch, And That They Did Not Build So Where Are We Today In The Technology?
After 60 Years of Hydraulic Fracturing Research, Technology Development & Experience We Can Safely Say That We Know Everything There Is To Know About Hydraulically Created Fractures EXCEPT

- How Deeply They Penetrate
- Their Vertical Extents
- Their Symmetries About the Wellbore
- Whether They Are Planar or Multi-stranded
- Their Geometries At The Perimeter
- Which Directions They Go
- What Their Conductivities Are

OTHER THAN THAT – WE’VE GOT IT DOWN PAT

BUT – THEY STILL MAKE A LOT OF MONEY
Hydraulic Fracturing

GO FOR IT!

JOIN:
Fracturing Research Consortiums
&
The Society of Frac Dogs of America
(Carl Montgomery, Omnipotent Potentate)
Thank You For Coming!

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Questions?