A Historical Perspective of HYDRAULIC FRACTURING

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S E I

SPE Mid Continent Section
Tulsa, Oklahoma
January 17, 2008

Thanks to SPE !!!

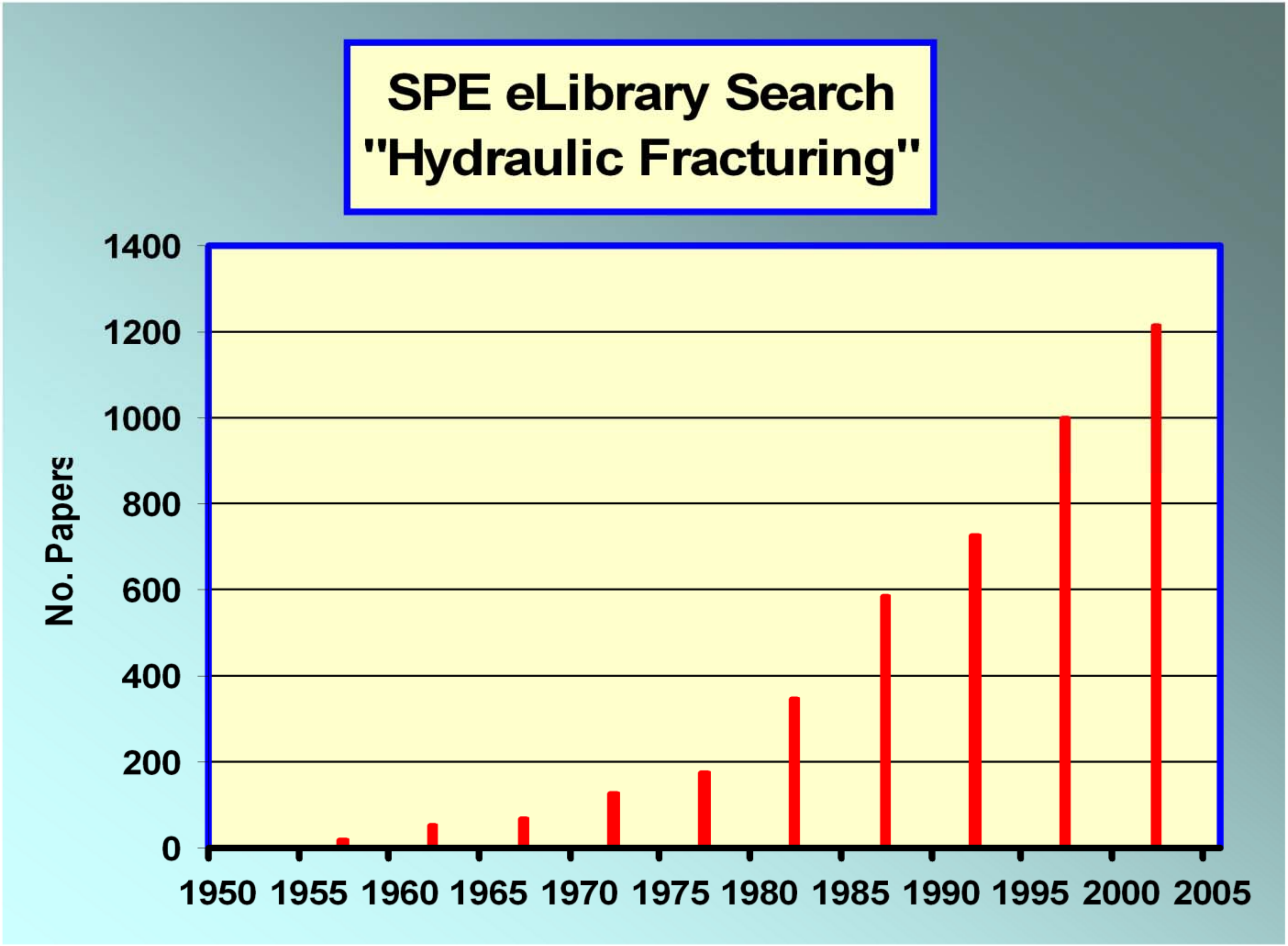
Without SPE, We Might Have Eventually Done It.

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)


SPE eLibrary Search
"Hydraulic Fracturing"
No. Papers
0
200
400
600
800
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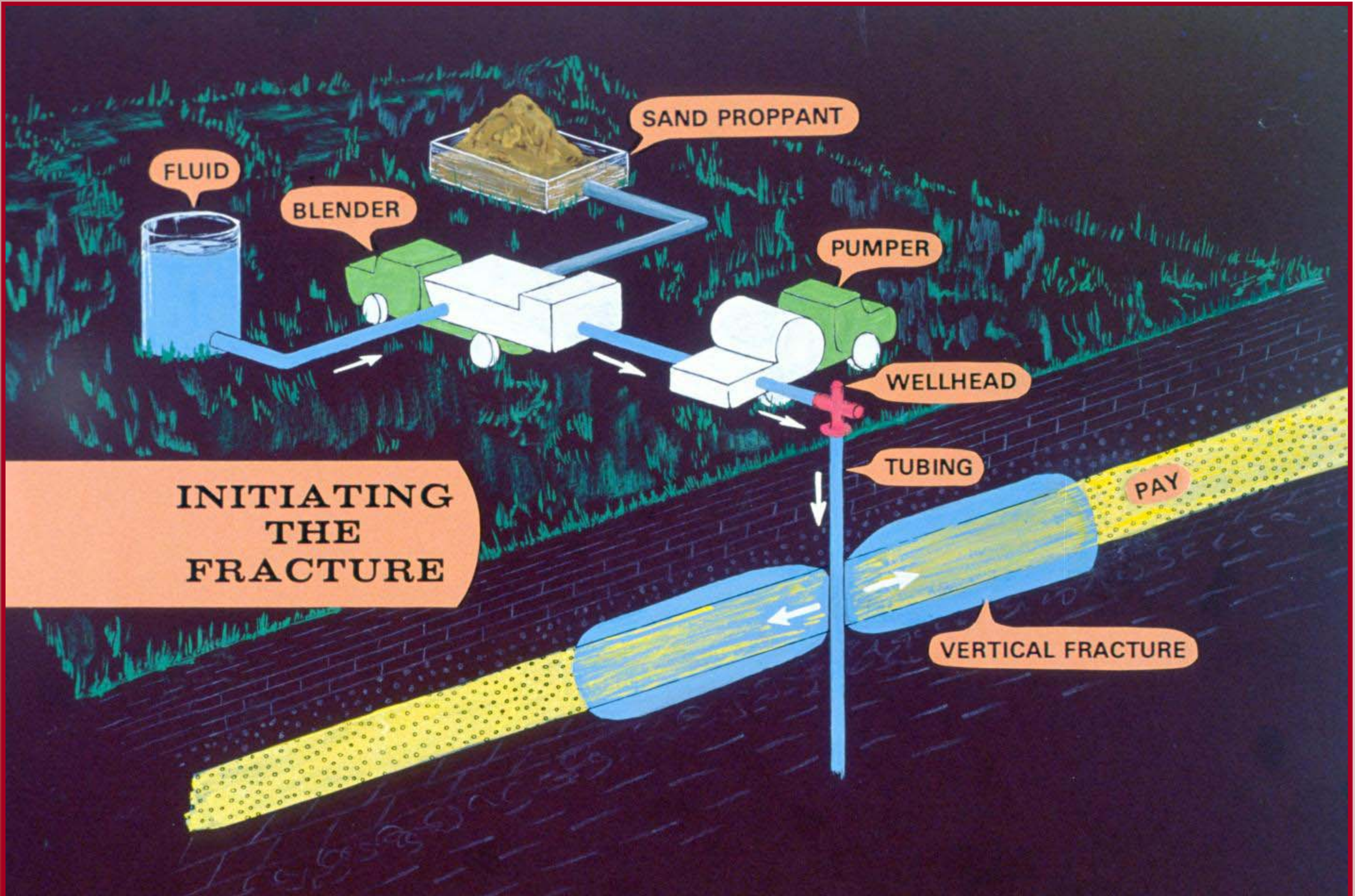
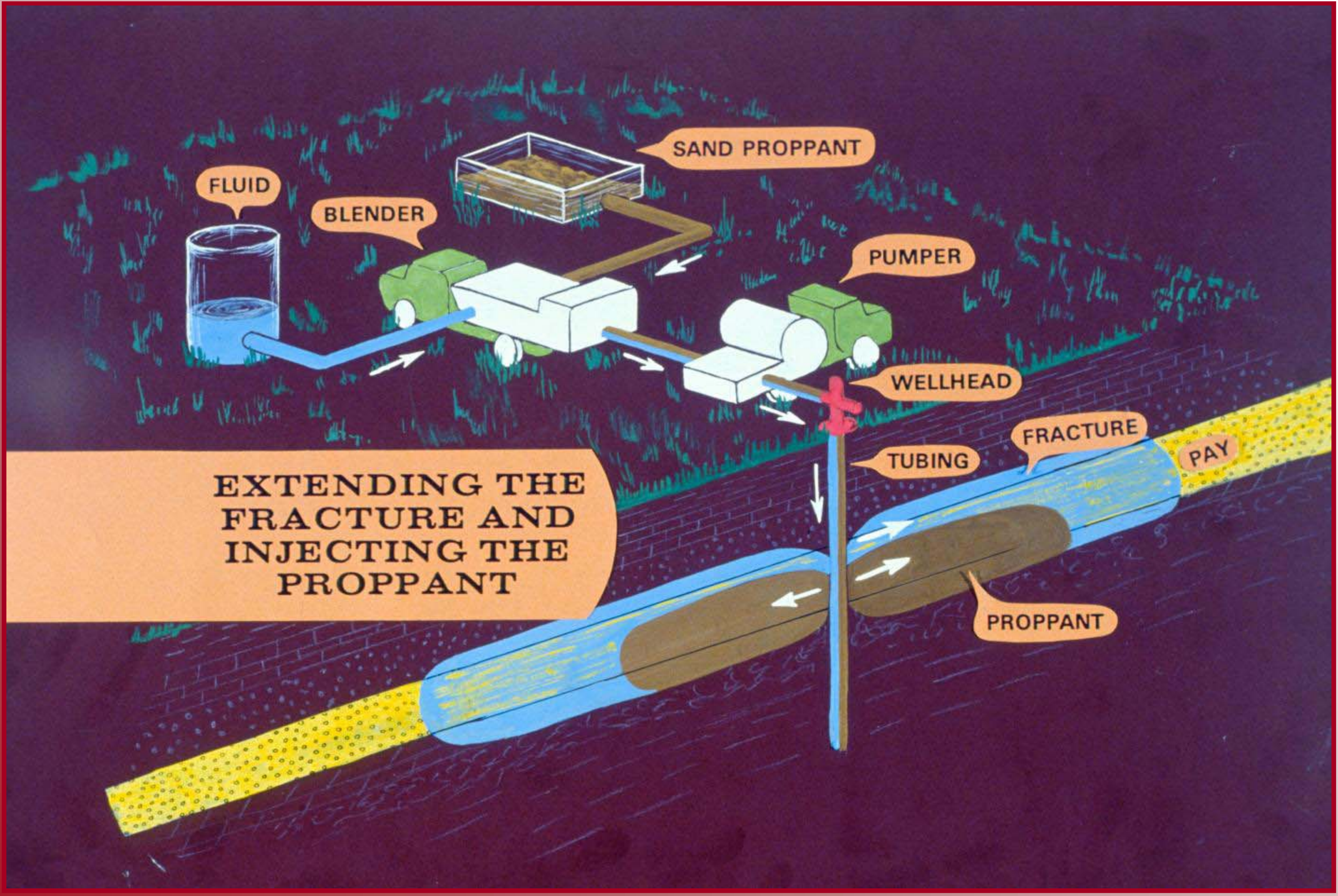
1200
1400
1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005

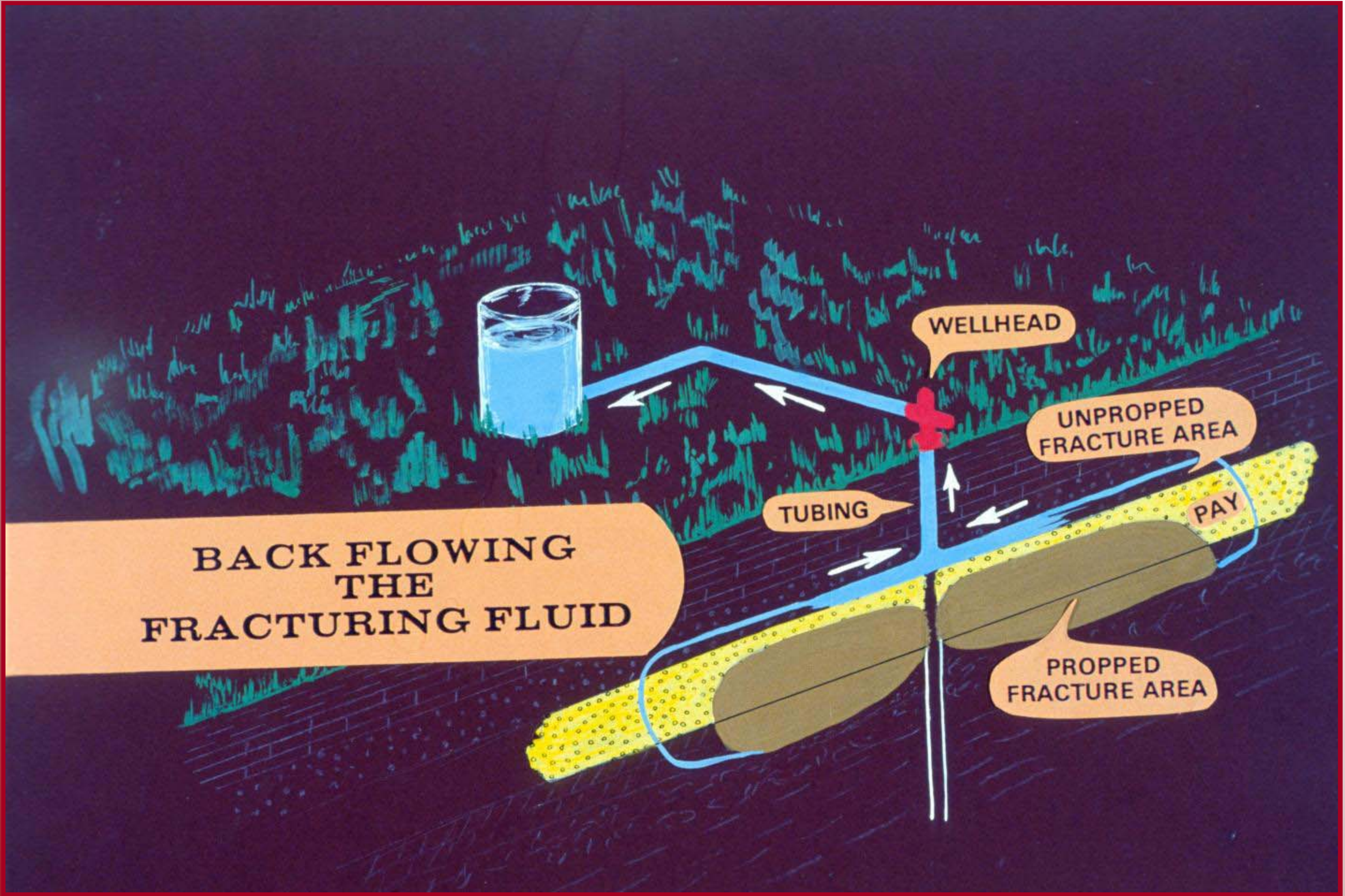
THE "TYPICAL" TREATMENT – STEP 1



THE "TYPICAL" TREATMENT – STEP 2



THE "TYPICAL" TREATMENT – STEP 1



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

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

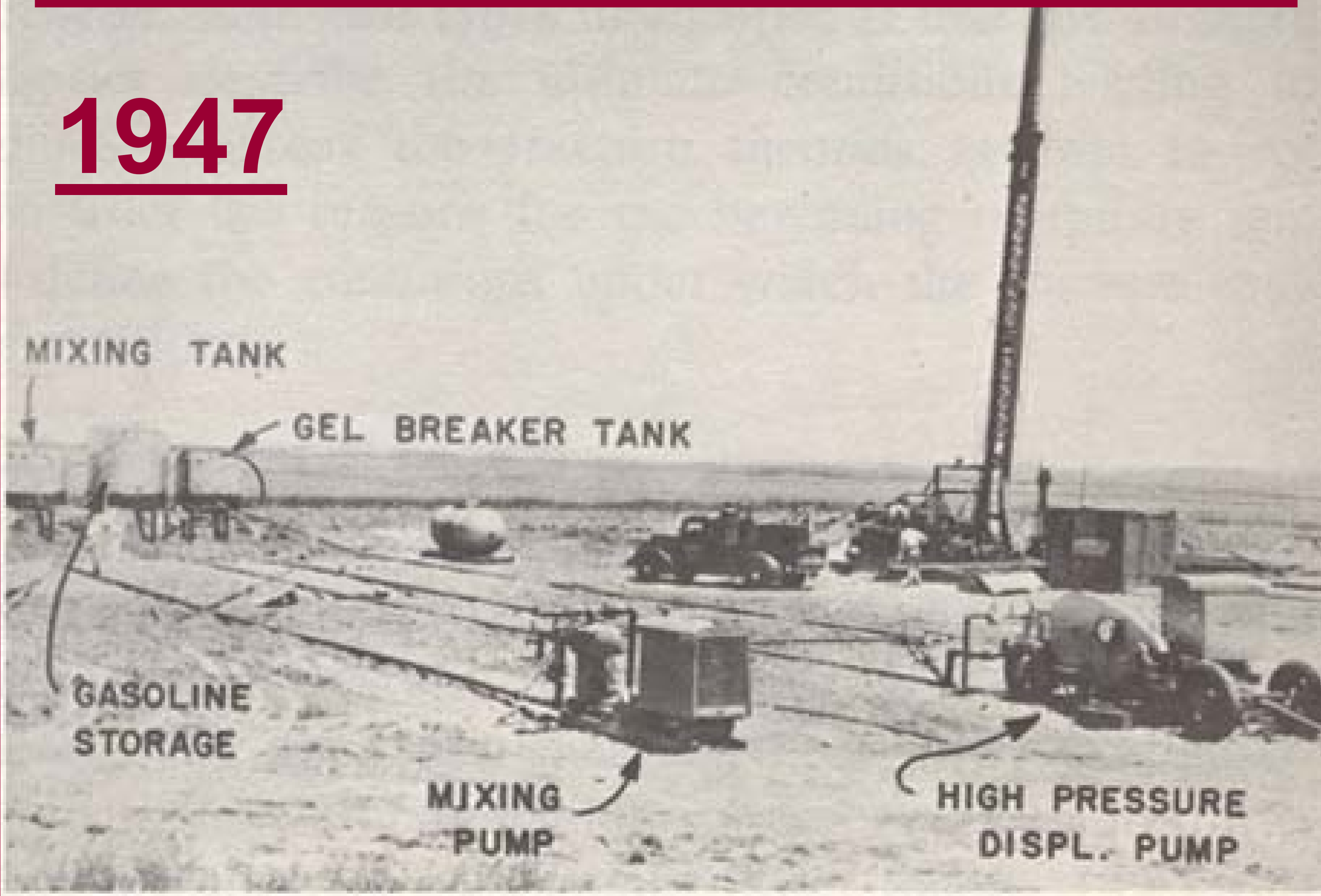
??Hydraulic Fracturing has generated more profit for the petroleum industry than any other process, except for exploratory & development drilling.??

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

"Since 1980, industry experiences in water, chemical, miscible, thermal, etc., processes have not <u>Economically</u> 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)

1947



The Great Race
First Commercial Fracturing Treatment – 1949 (Pictured)
Stephens County, OK - Dwight K. Smith – Halliburton Engr.

Courtesy - Halliburton

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

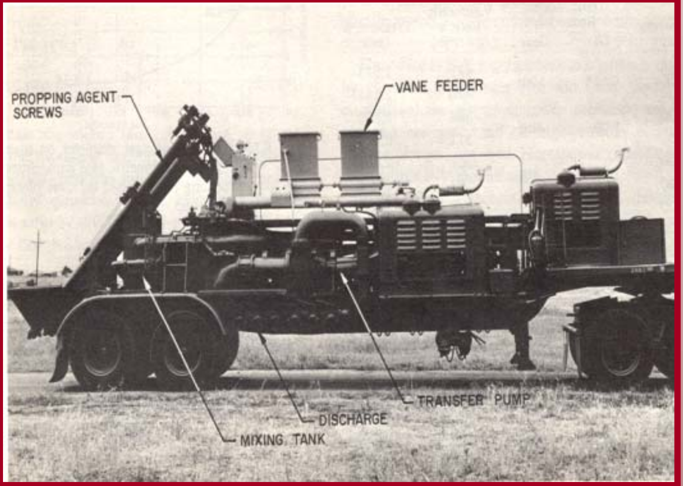
1950 – Fracturing with Cement Pumpers (SPE Monograph Vol. 2)

Mid 1960's – Fracturing Pumpers & Blenders (SPE Monograph Vol. 2)

Pumpers - Remote Controlled

Control Center

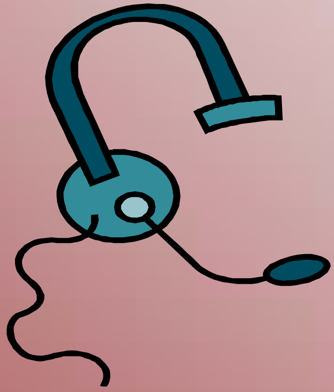
Blenders



1950's – Early 1960's: Treatment Orchestration

Communications

Data Collection

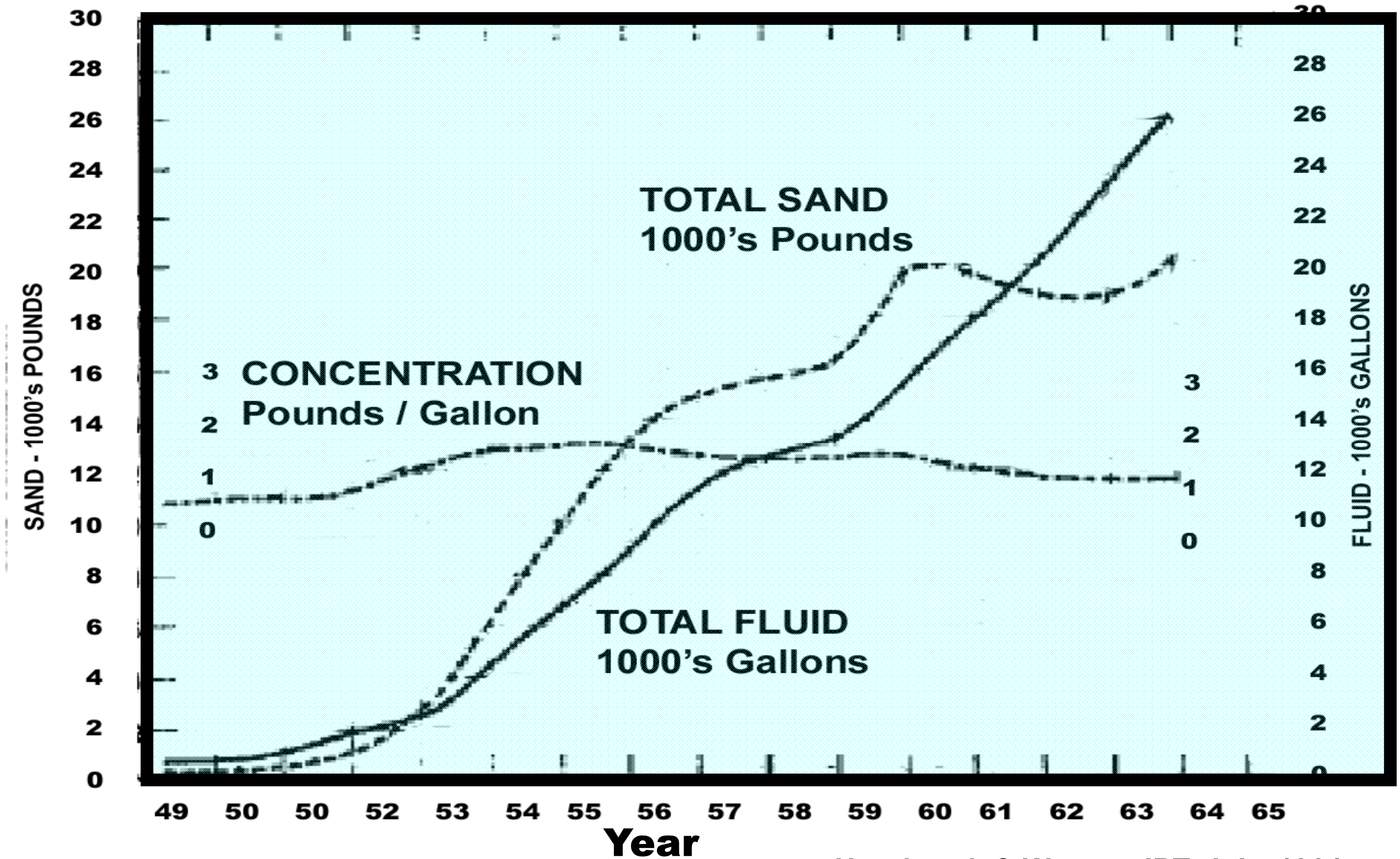


Mid 1960's – Some Fancy Manifolding (SPE Monograph Vol. 2)

From the Blenders to the Pumpers

From the Pumpers
To the Well

1949 – 1965 Fracturing Treatment Sizes



Hazebrook & Waters, JPT, July, 1964

<u>1950's & 1960's - Treatment Designs.</u>

Who Had the Final Say ?

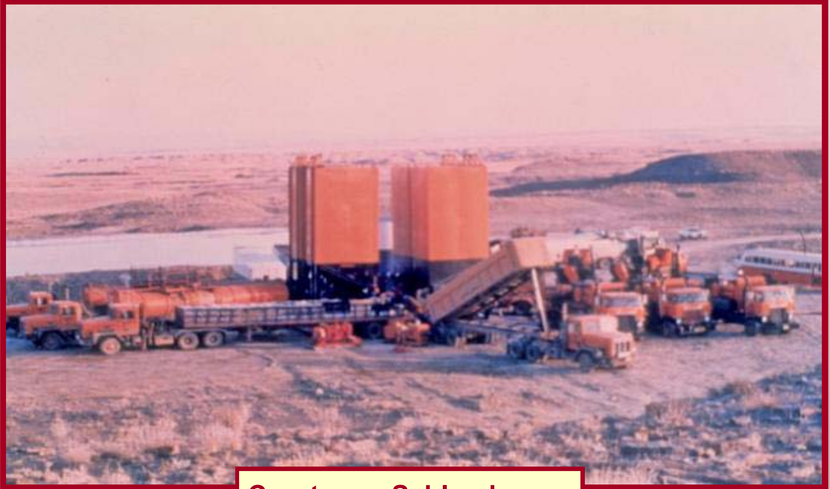
Often - The Area Superintendent.

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

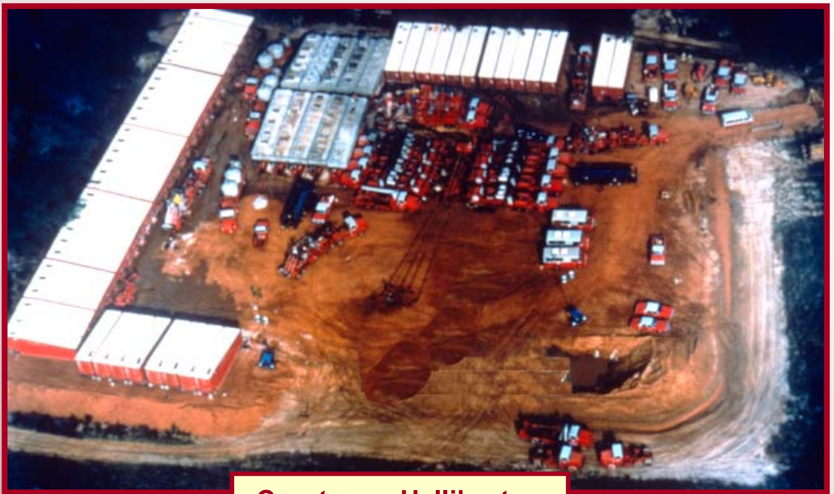
"And, DON'T Even LOOK at My GOOD Wells !!!"

Mid 1970's - The Showdown in TOMBSTONE (Rock, That is)

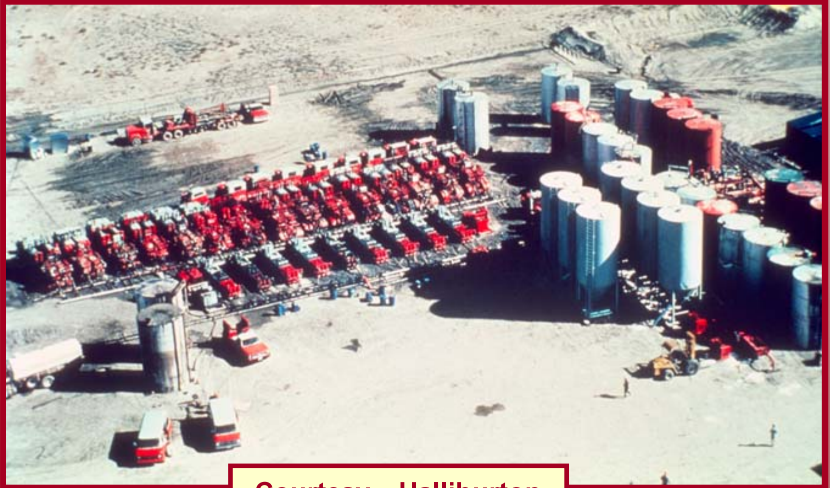
MASSIVE HYDRAULIC FRACTURING (M H F)



Courtesy – Schlumberger



Courtesy – Halliburton



Courtesy – Halliburton

Courtesy – BJ Services

MHF – Fracturing Treatments & Design Trends

1970's	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

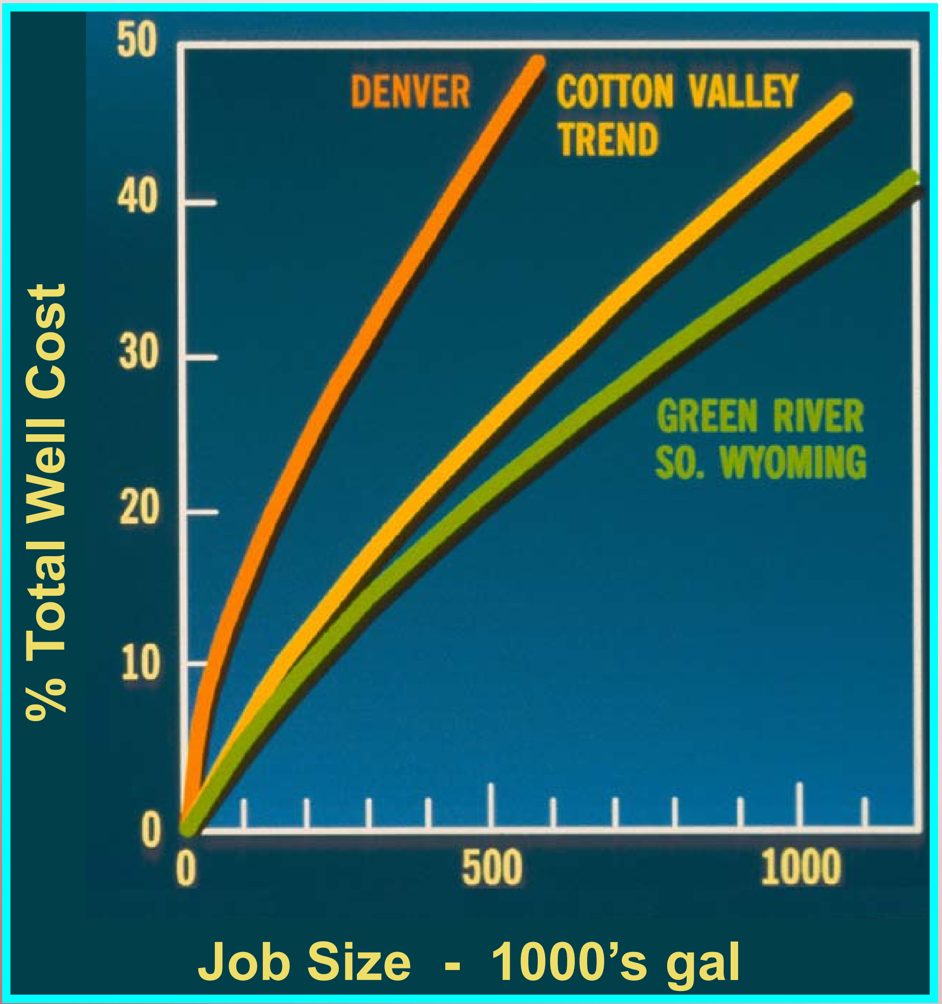
Relative Job Costs
Frac / Total Well

RC < 15% → RC > 50%

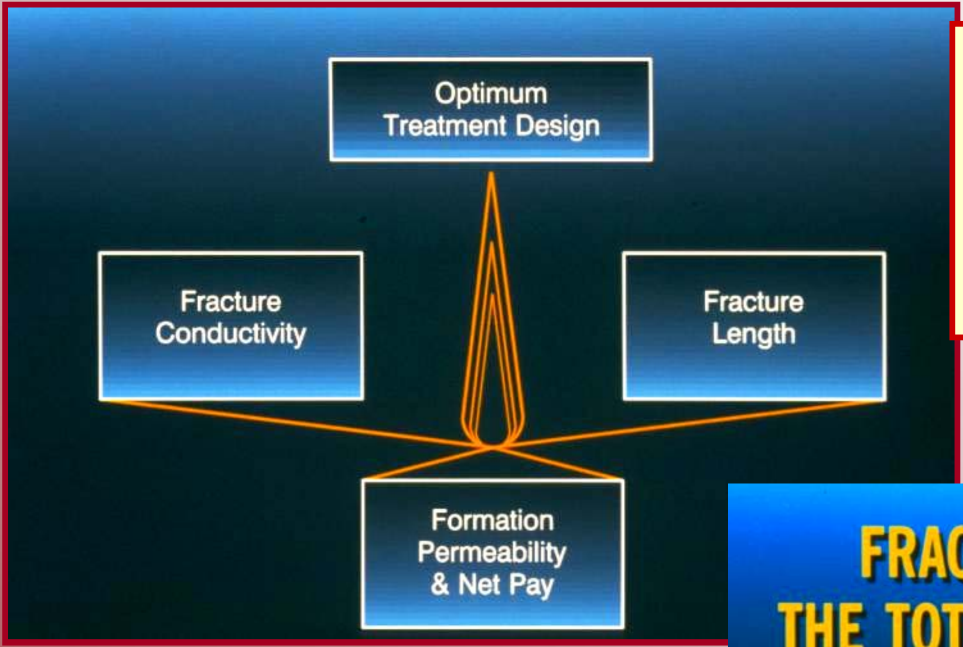
Design Strategy

Bigger → Smarter

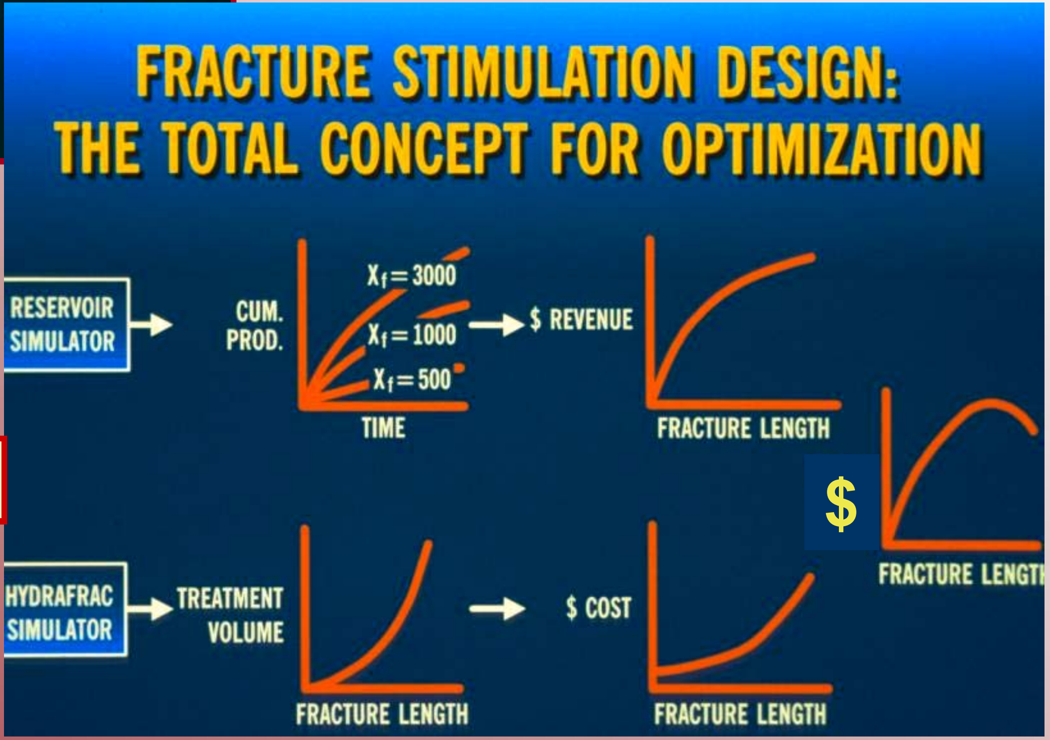
The Superintendents Got Out of The Treatment Design Business



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

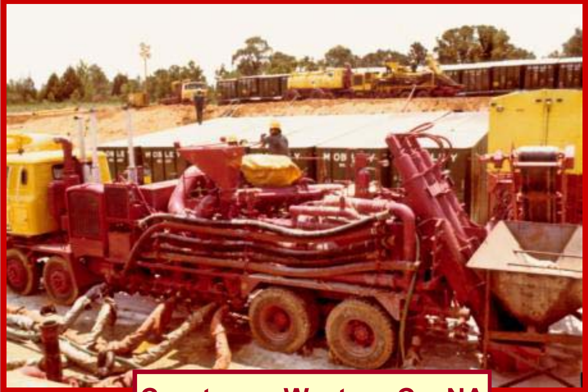
Steroid Pumpers – Bigger, Stronger, Faster

Courtesy – Halliburton

Courtesy - BJ Services

Big Throated, Bulimic Blenders

Courtesy – Schlumberger



Courtesy – Western Co. NA

Courtesy - BJ Services

Proppant to the Blenders - The Early Days vs The Later Daya

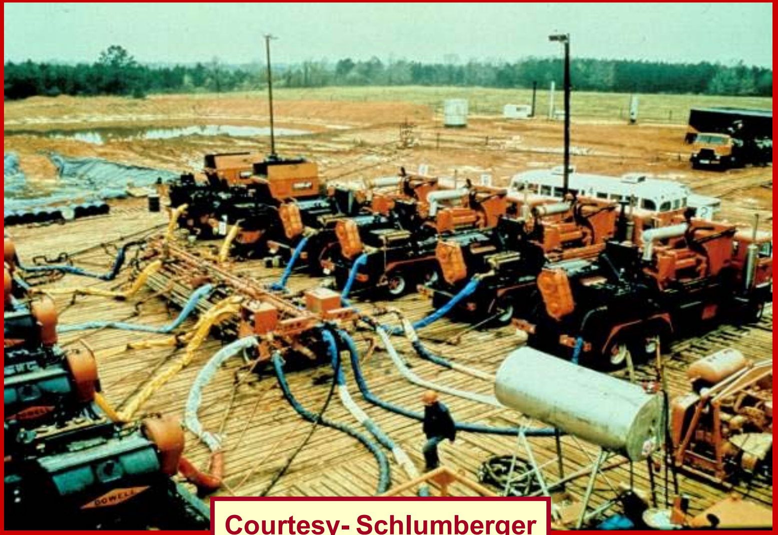
Courtesy- Halliburton

Courtesy- Schlumberger

Courtesy- BJ Services

Manifolding: Design Basis – Plug & Play

Blenders to Pumpers



Courtesy- Schlumberger

Courtesy- BJ Services

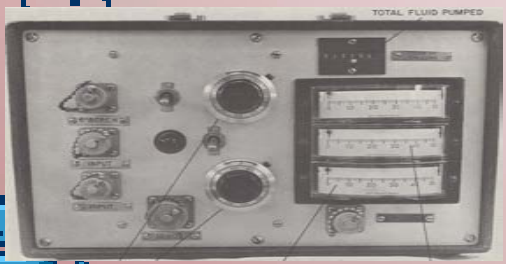
Pumpers to Well

Courtesy- Western Co. NA

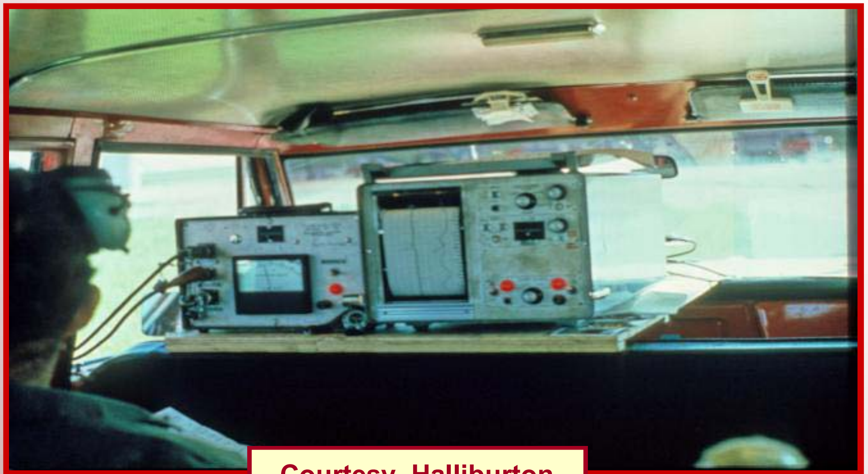
Courtesy- Halliburton

Job Control, Monitoring, Data Collection & Processing - Evolutions

Knobs & Dials & Clip Boards



Paper Strip Charts

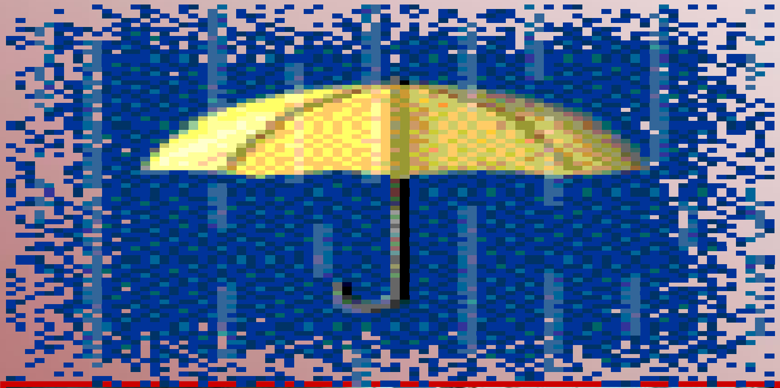


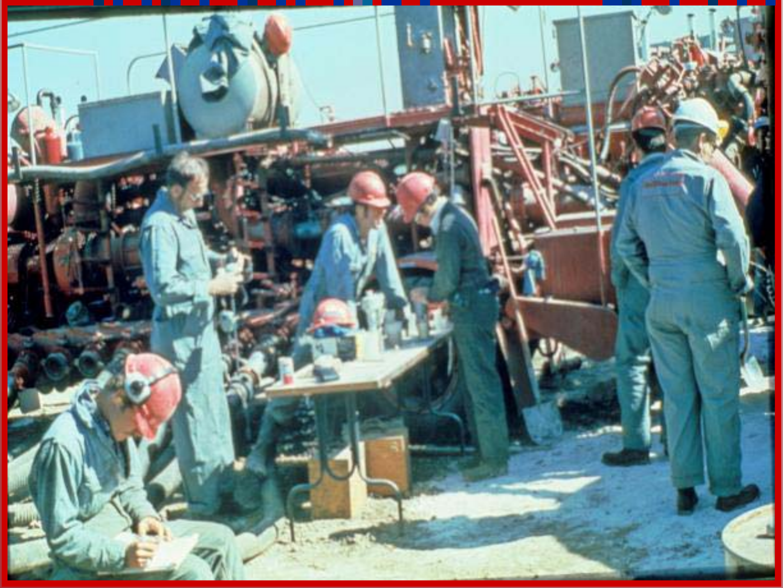
Courtesy- Halliburton

Electronic - Computerized

Courtesy- Schlumberber

Quality Monitoring & Control - Evolutions





Courtesy- BJ Services

With In-Line Flow Loop Rheometers

Meanwhile – Both MHF & Non-MHF - Other Things Emerged

Coiled Tubing Fracs

Courtesy- Halliburton

Courtesy- BJ Services

Courtesy- Schlumberger

Frac Navies

Courtesy- Halliburton

H o r i z a l W e l l s

The AMAZING Evolution of
FRACTURE PROPAGATION GEOMETRY

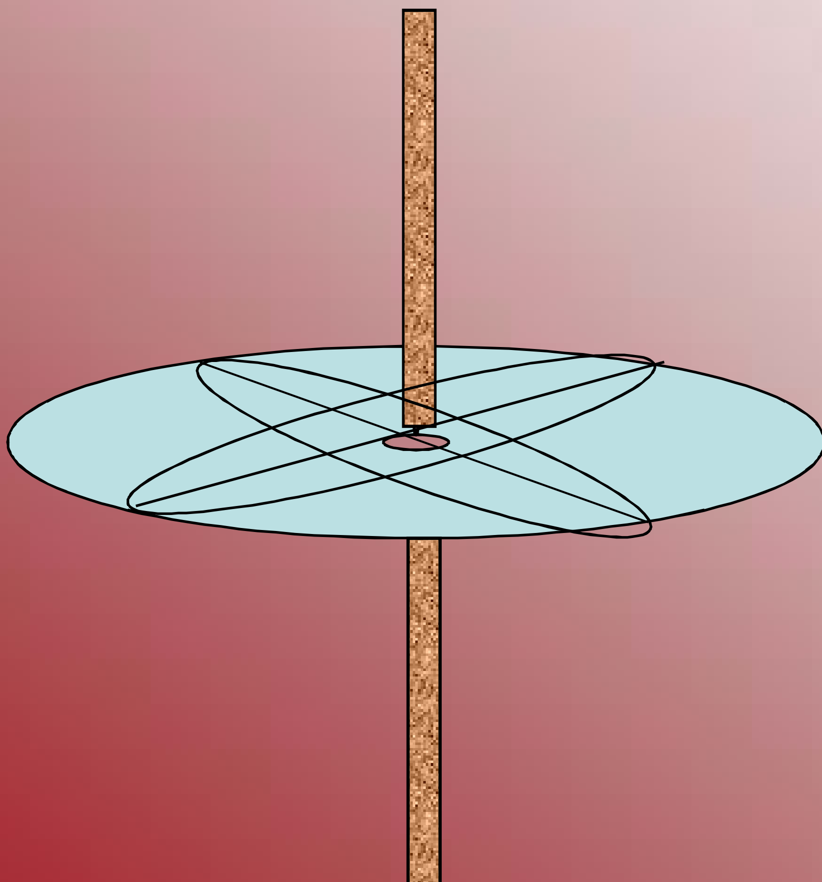
Our Perceptions of
Fracture Propagation Geometry
Were NEVER Wrong.

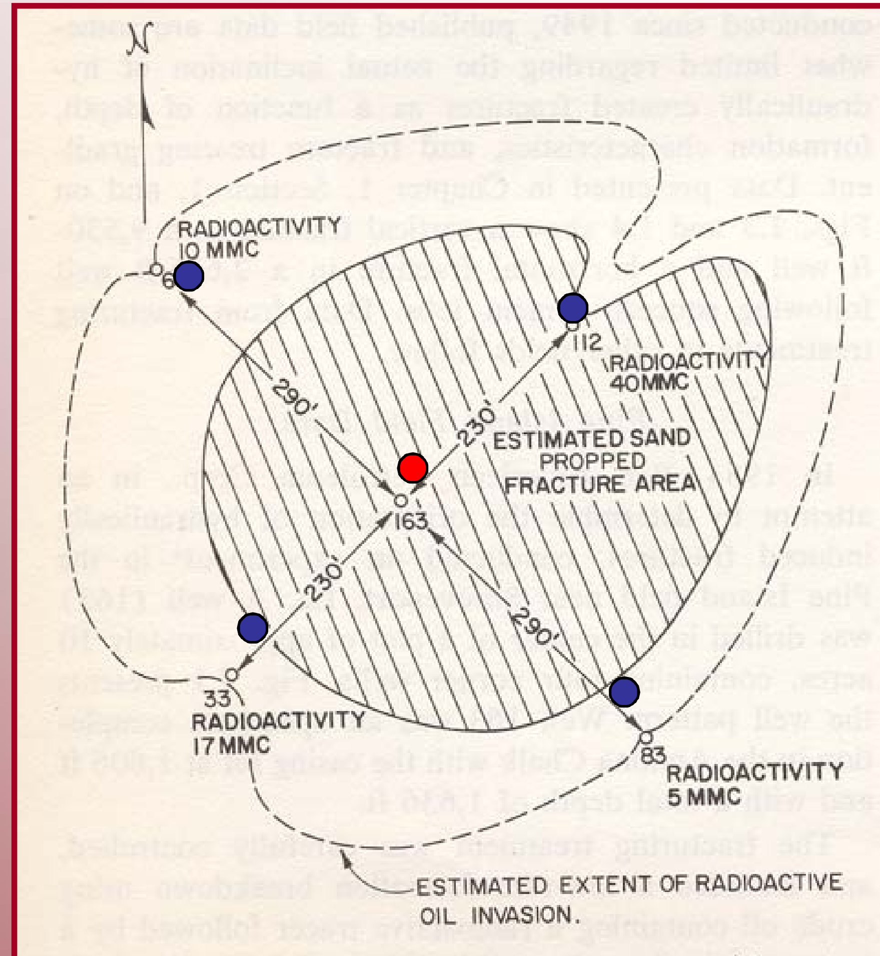
It was the Fractures Themselves that Changed

Just When We Had Them Figured Out,
They Would Mutate – Again and Again

Fracture Geometry: 1947 - 1957

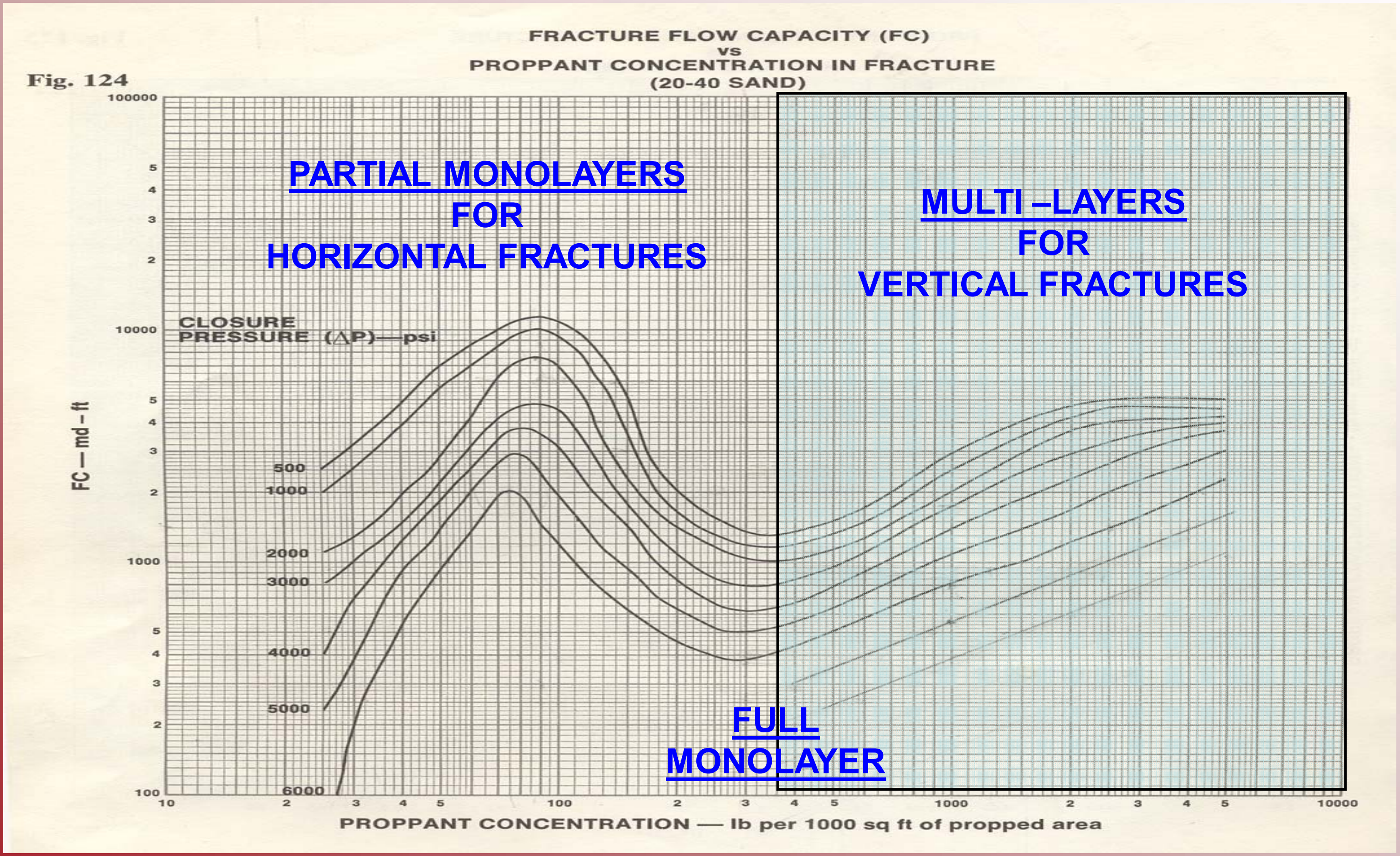
HORIZONTAL





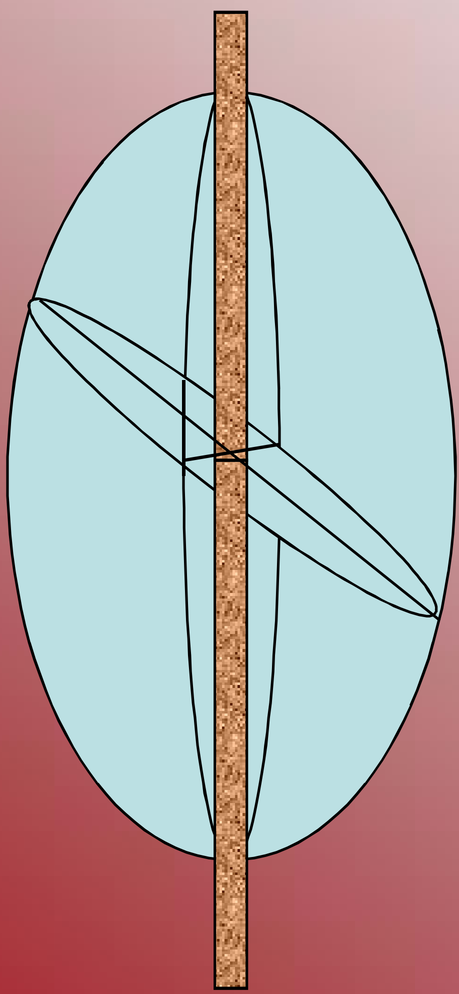
Pine Island Field, LA - 1954
Howard, G. C., Pan American Petroleum

Horizontal Fracs - Proppant EMBEDMENT & PARTIAL Monolayers Were VERY Important In Treatment Design



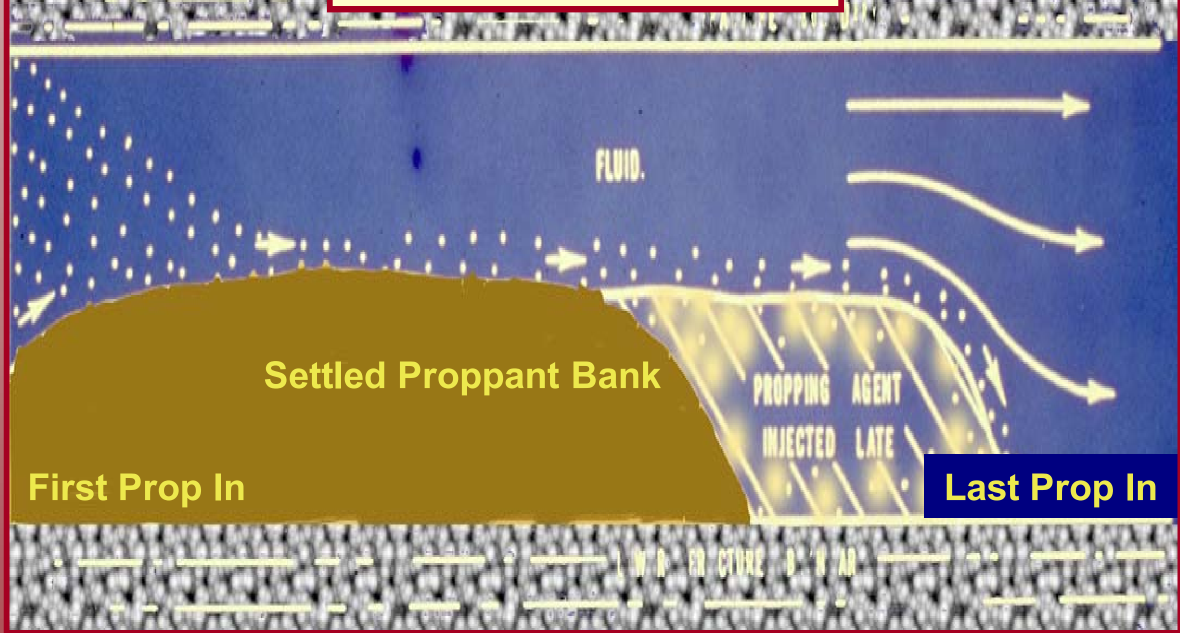
Halliburton – “fracbook”, 1971

Mid 1950's Fracture Geometry
Per – Hubbert & Willis, Trans AIME, 1957
Fractures Reoriented Vertically



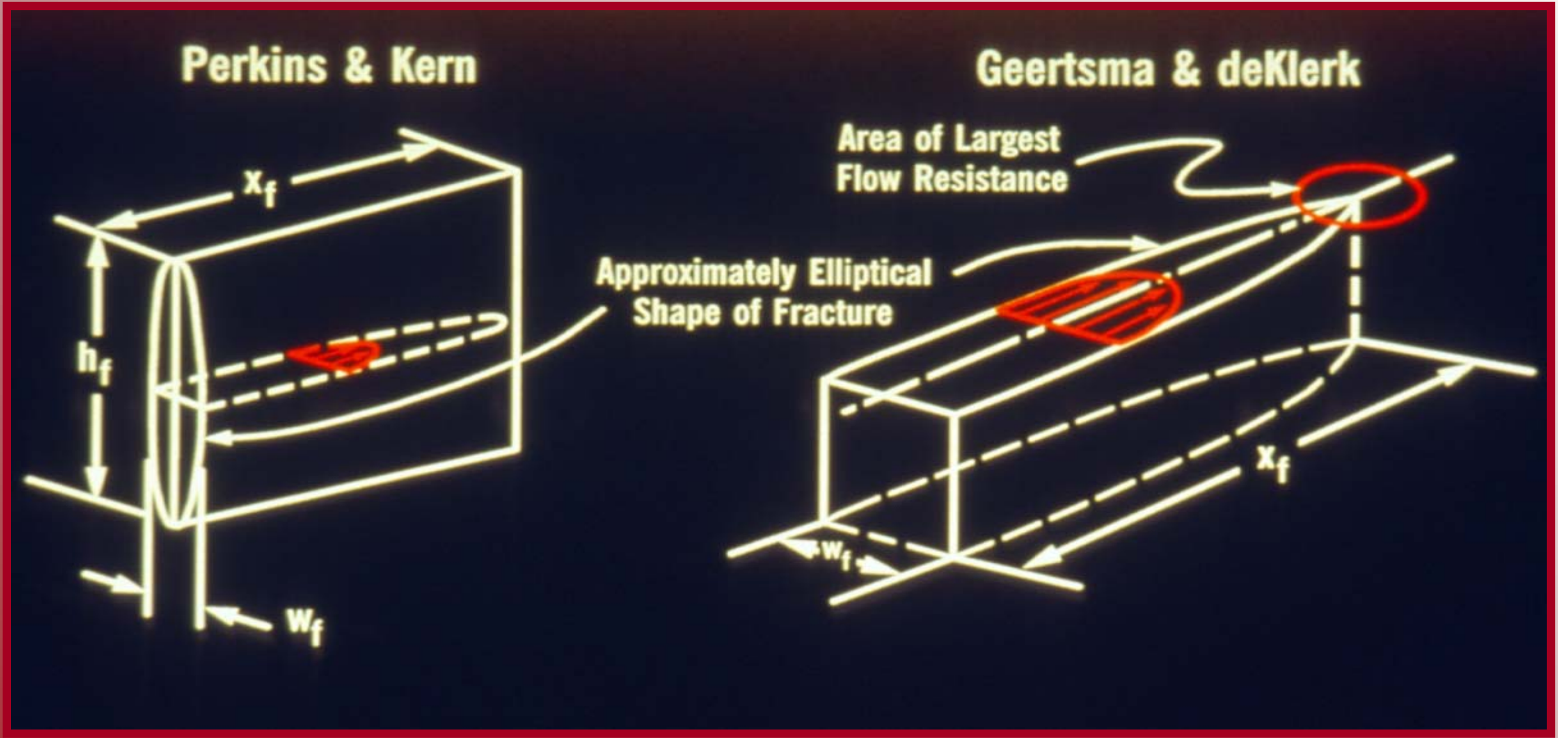
And, Proppant TRANSPORT
Equilibrium Banking
vs
"Perfect" Transport
Became a BIG Design Issue.

Equilibrium Banking



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!!!!

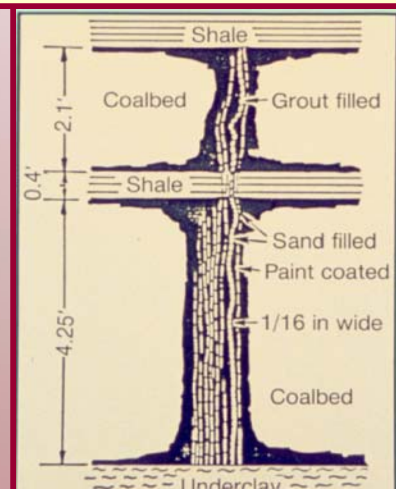


For a While: Height = Perf Span. But Later On Fracs Started to Grow

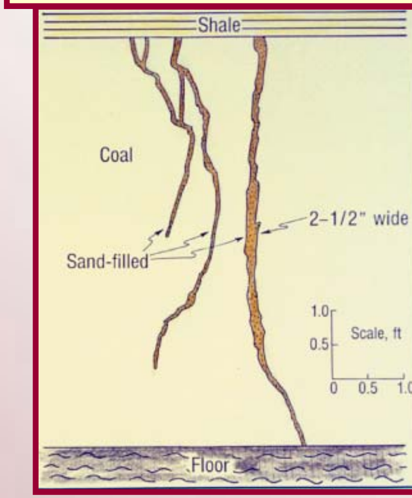
In the Late 1970's and Early 1980's, Fractures Began Misbehaving. Since Then. They Have Gotten Almost Completely Out of Control.

Multi Nodal

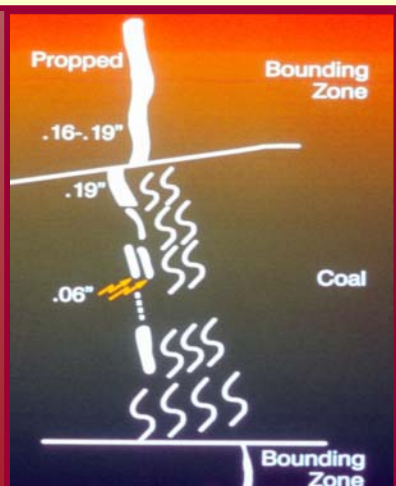
Weird X-Sections



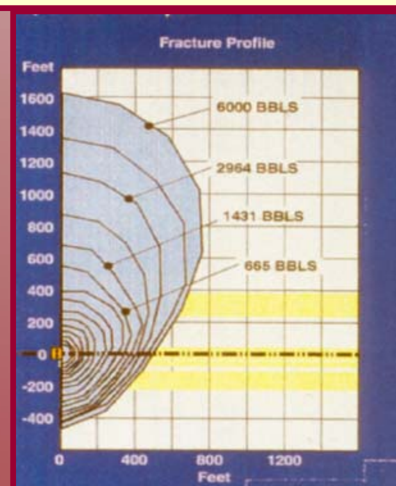
Multiple Frac Wings



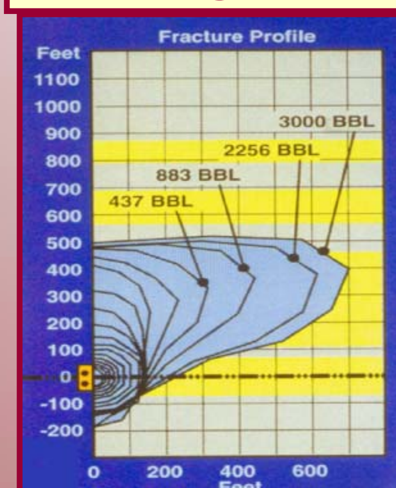
Vertical Dog Legs



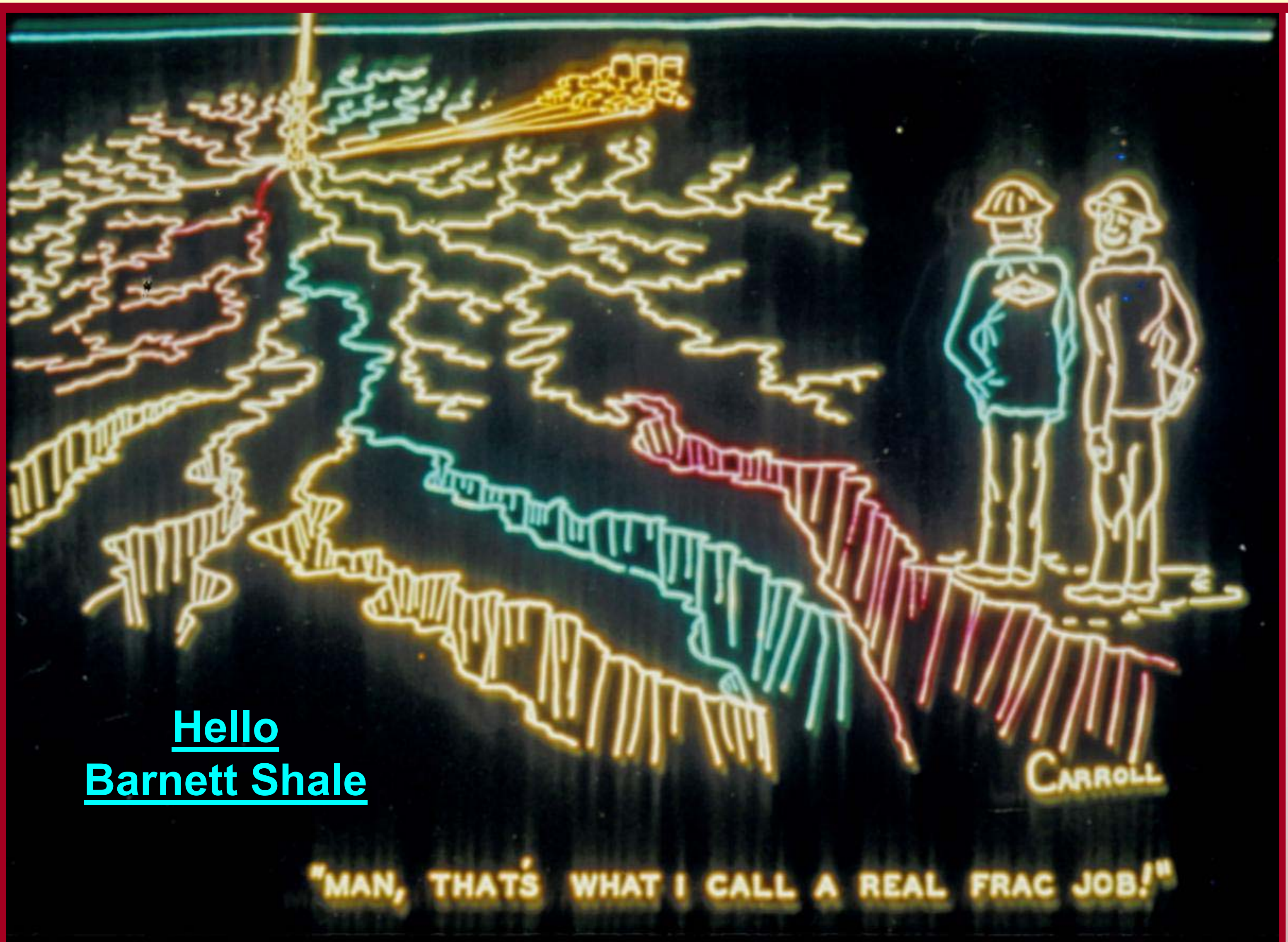
Out of Zone



Wrong Zone



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

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

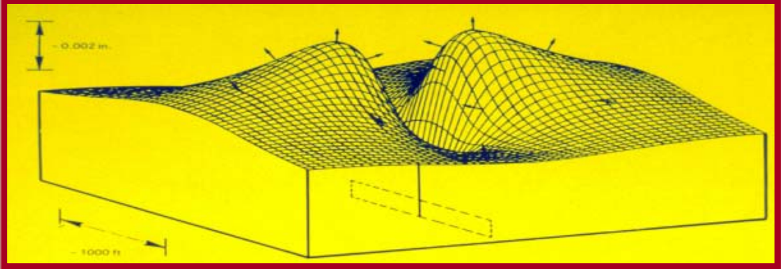
- Borehole Elongation Orientation
- Geoseismic
  - Cross Wellbore
  - Single Well
- Impression Packers
- Insitu Stress Profiles
- Micro-Seismic
- Post Frac Temperature Profiles
- Television – Televiewers
  - Optical, Sonic
- Tri-Axial Sonic

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



Mineback Experiments

Mid 1980's – Revelation – Insitu Stress vs Depth is a Very Wiggly Function

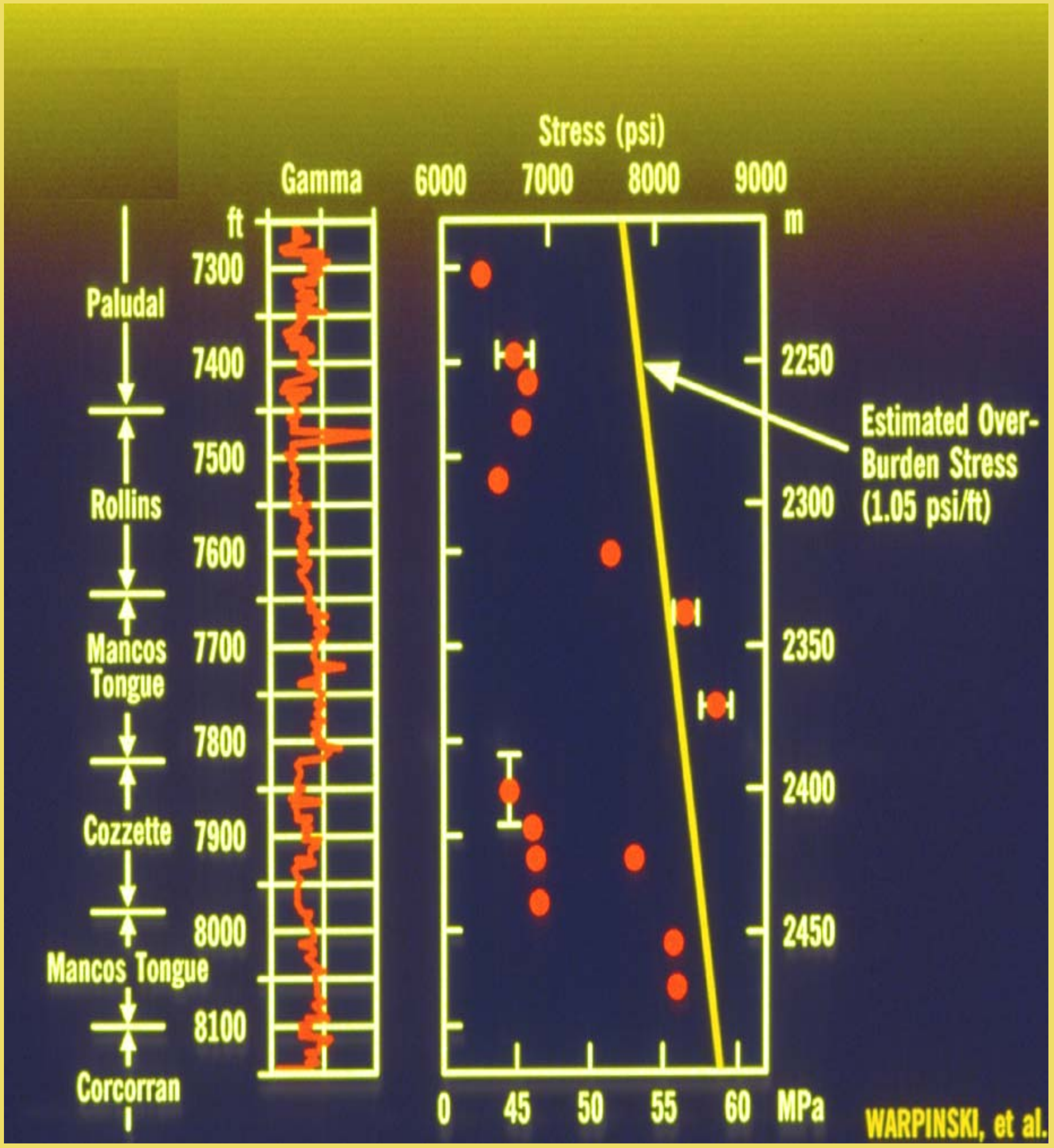
Example

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
<u>2001 Odessy</u> - 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

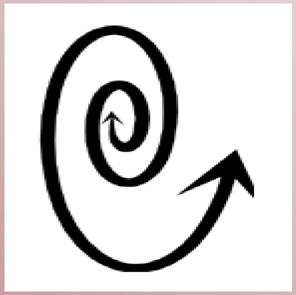
Alcohol

Acid

Crosslinked Aqueous

Linear Aqueous

Liquid Emulsions



Lease Crude

Aqueous Foam

Refined Oils

Liquid CO2

Napalm-gelled Gasoline

Environmentally Green

Crosslinked Oils

Hydrocarbon Foam

Nitrogen Gas

Surfactants

Hairy Stranded

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

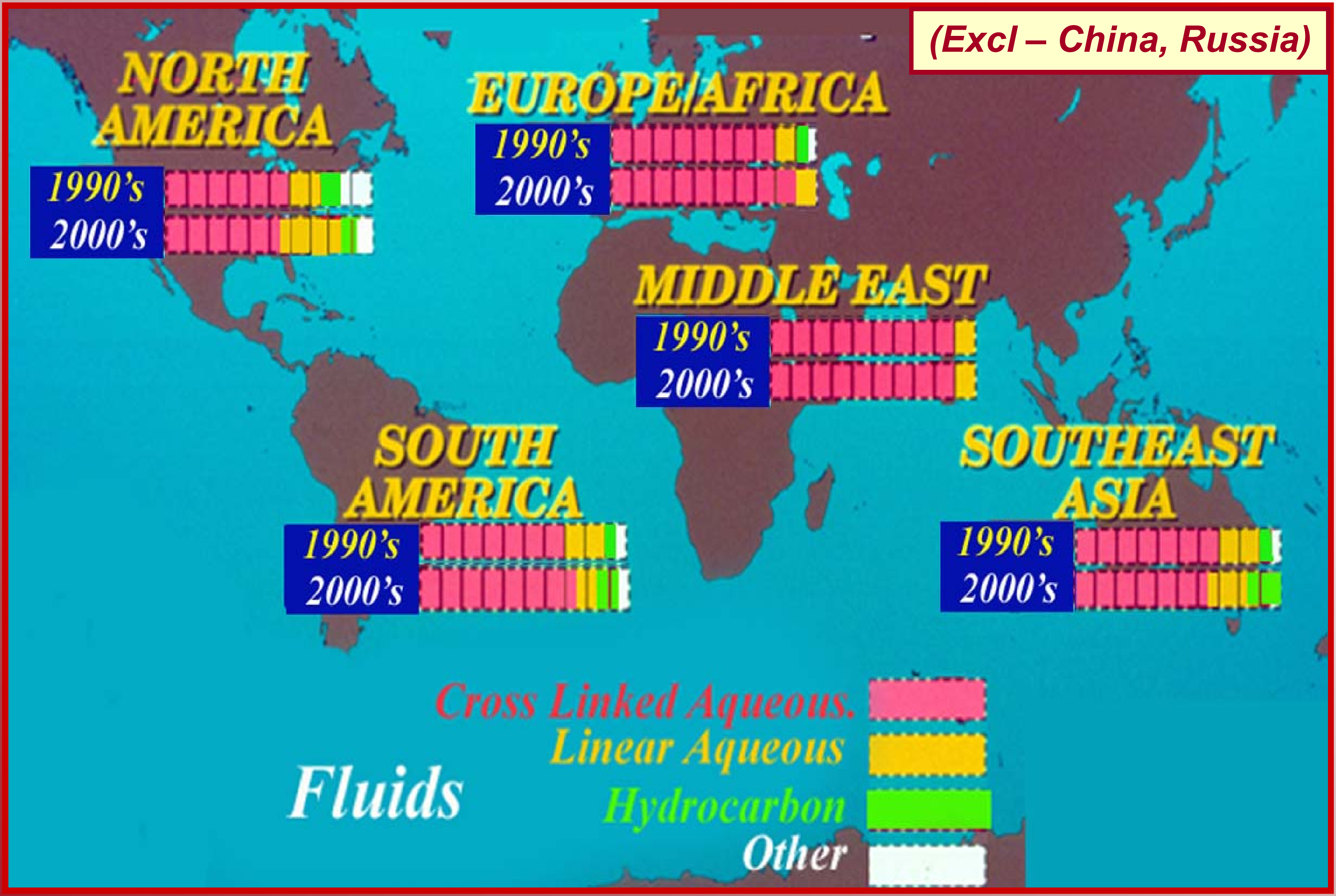
Cross Linking Agents

Aluminum
Antimony
Boron
Chromium
Titanium
Zirconium
Etc.

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.

Fracturing Fluids – Percent Usage – 1990's vs 2000's

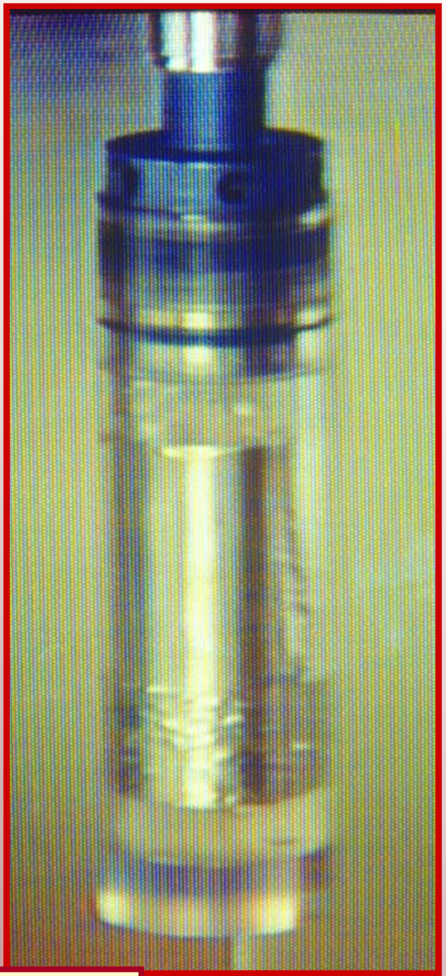


Cross Linked Fluids – The Strange and Mysterious Globs

J. R. Cameron, 1990

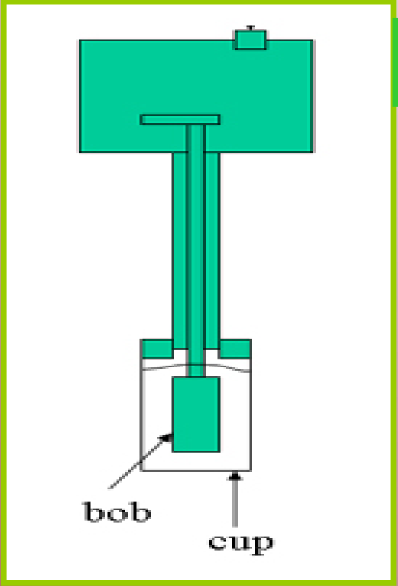
Testing Cross Linked Fluids – Some Problems

Observed in the Bob & Cup



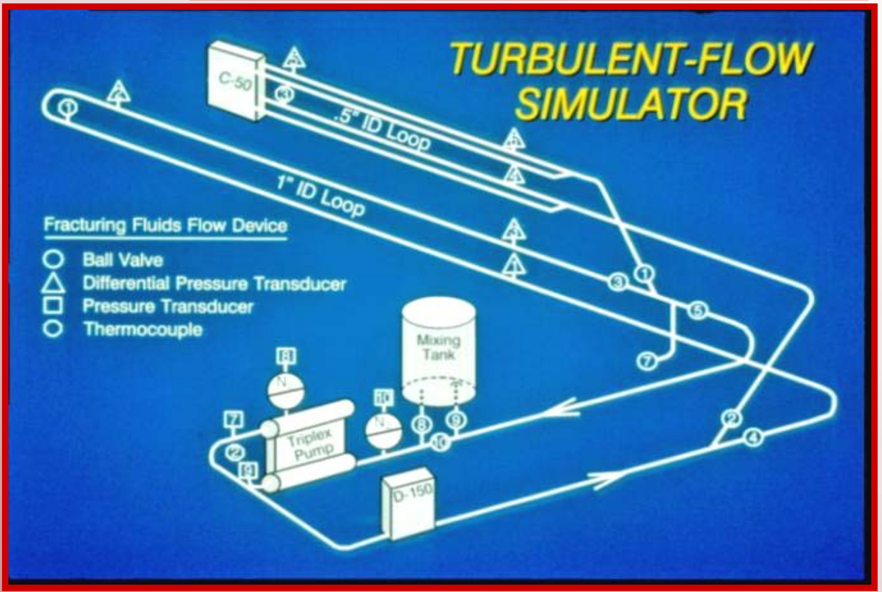
J. R. Cameron, 1990

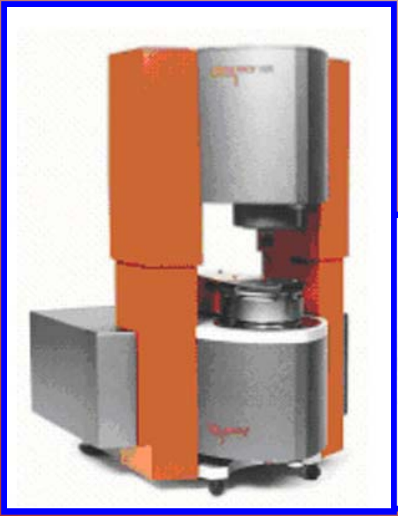
Instruments Required to Characterize – Many Visco-Elastic Fluids



Couette – Rotary – Multiple Cups & Bobs

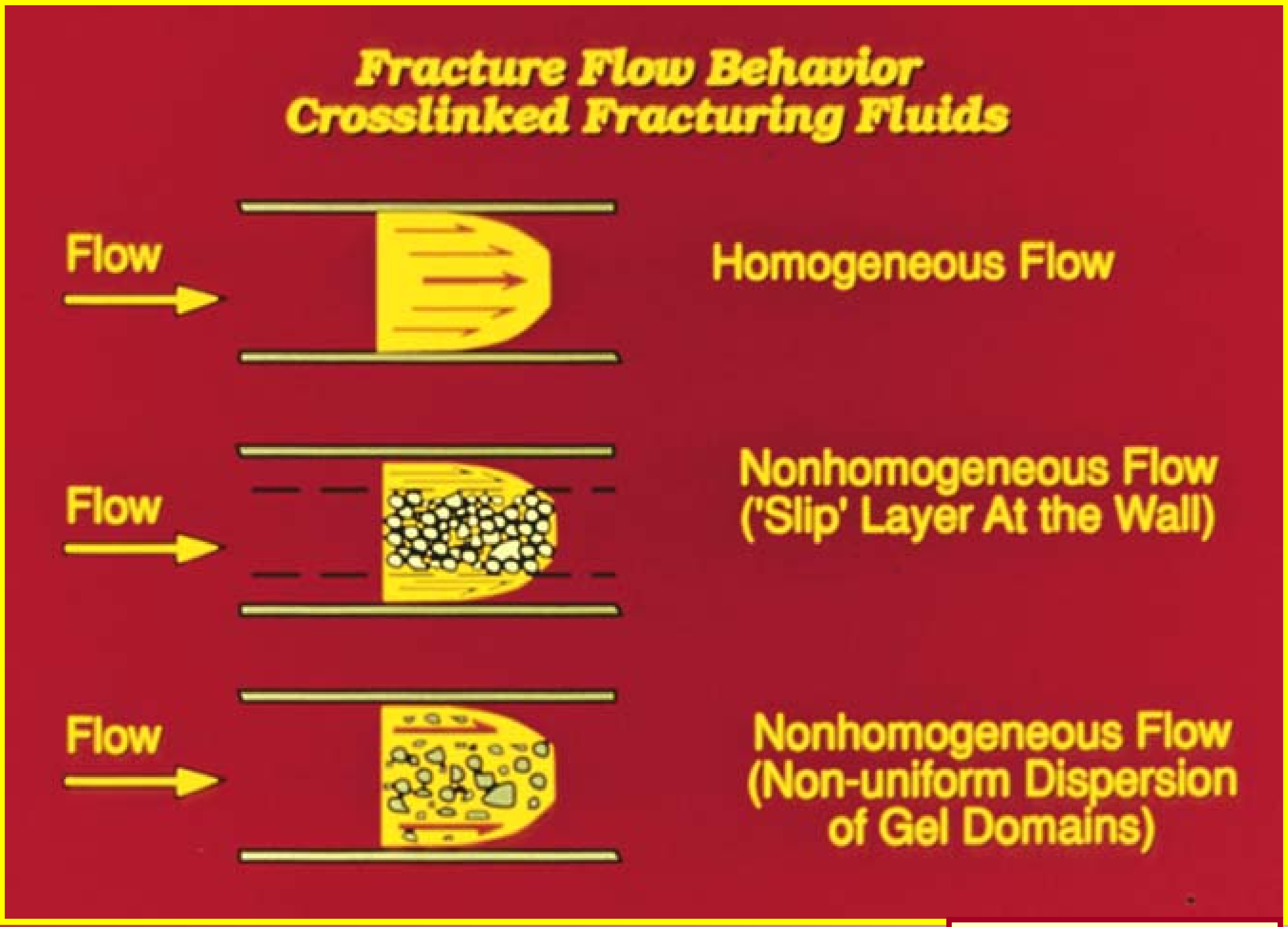
Multiple Pipe Flow Systems





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

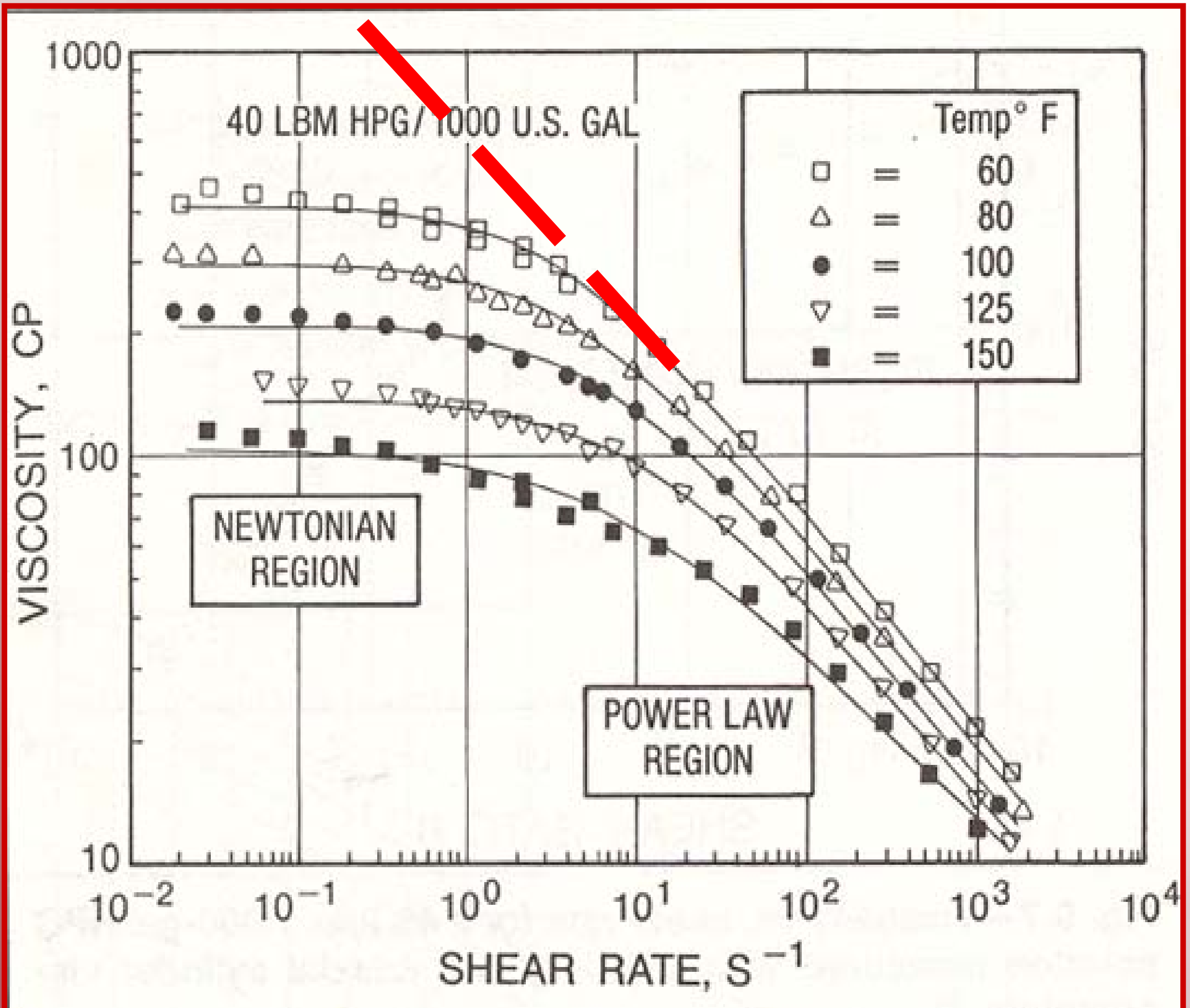
Mid 1980's – Rheology Revelations - Power Law Behavior ? ?

At Low Shear Rates, Power Law Equations Do Not Describe Behavior,

Some Systems Have Upper Viscosity Limits

(Laser Anemometry Tests)

POWER LAW

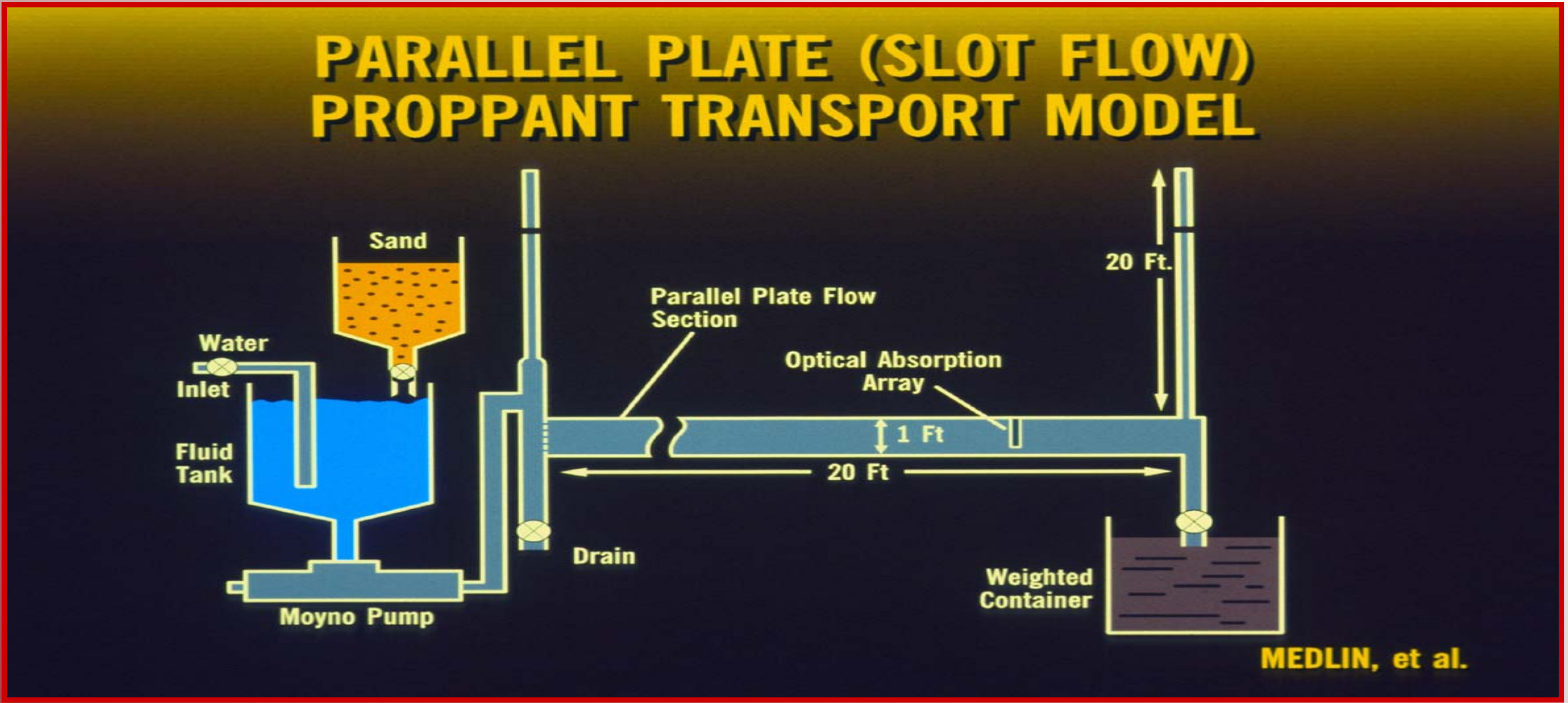


Guillot & Dunand, SPEJ, Feb, 1985

Mid 1980's – Proppant Transport

Medlin, Sexton & Zumwalt: SPE, 1985

Roodhart: SPE, 1985



1990's – 2000's: Life-Size Test Facilities.

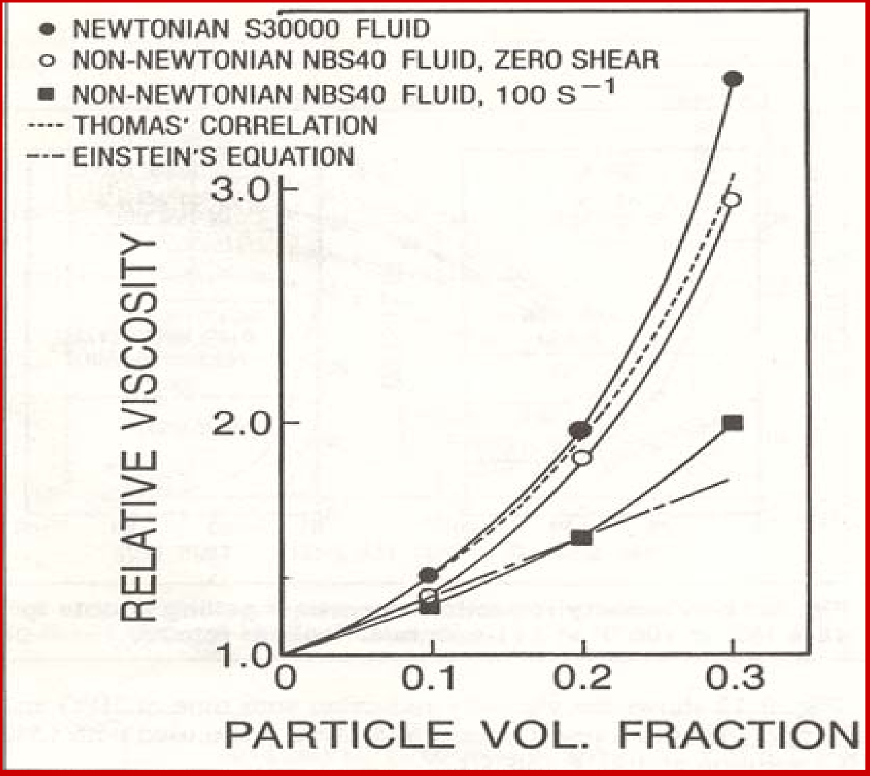
@ Elevated Temperature & with: Fluid Loss, Particle Tracking, etc.

Consortiums & Service Companies

Mid 1980's - Proppant Concentration & Fluid System Viscosity

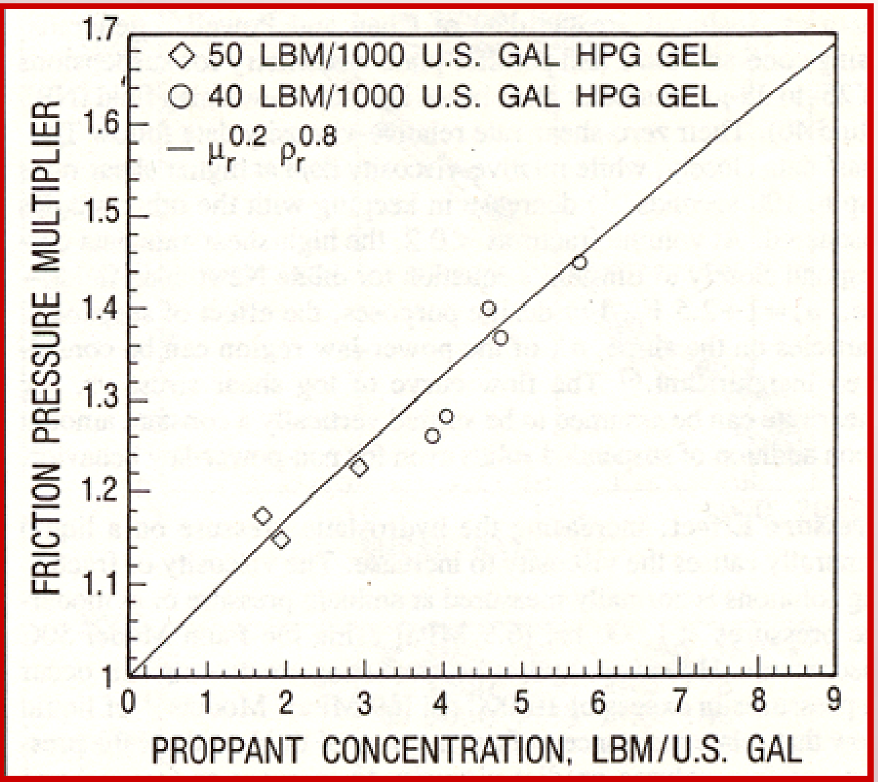
Proppant Concentration & Size Distribution Can Significantly Increase Fluid System Viscosity

Low Shear Rates



Chan & Powell , 1984

Turbulent Flow



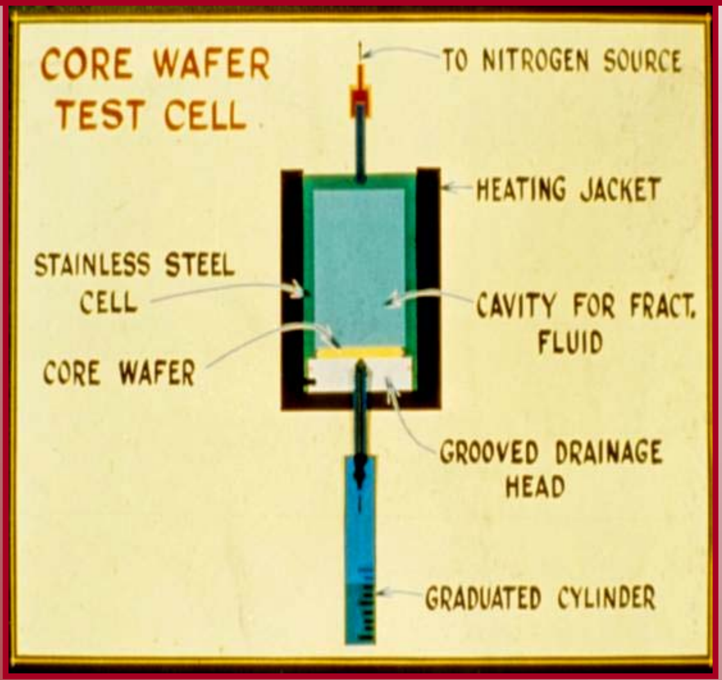
Hannah, Harrington & Lance , 1983

Fracturing Fluids – A BIG Revolution

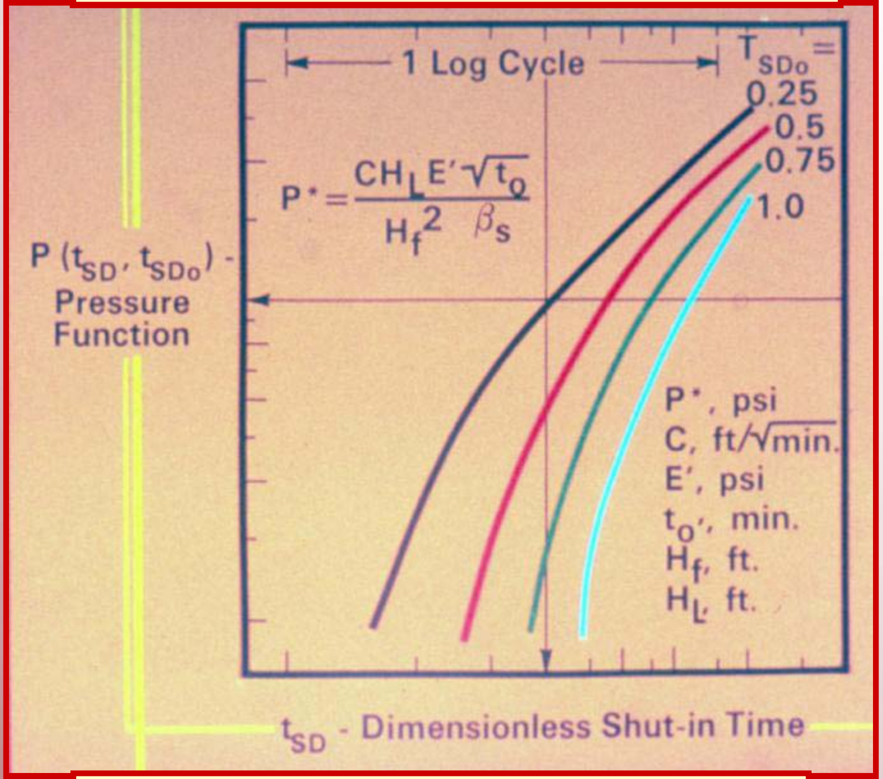
1970's -1980's		1990's -2000's
POWDERS	→	LIQUID CONCENTRATES
Hydroxy Propyl Guars Gel Concentrations 50 – 60+ gal / 1000	→	Improved Guars Gel Concentrations 15 – 30 gal / 1000
Cross Linkers (Metallic Bonded) Titanium Zirconium 300 – 350+ F	→	Cross Linkers (Hydrogen Bonded) New Borates 100 – 300+ F

Fluid Loss Behavior - Static

1950's – 2000's Laboratory



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



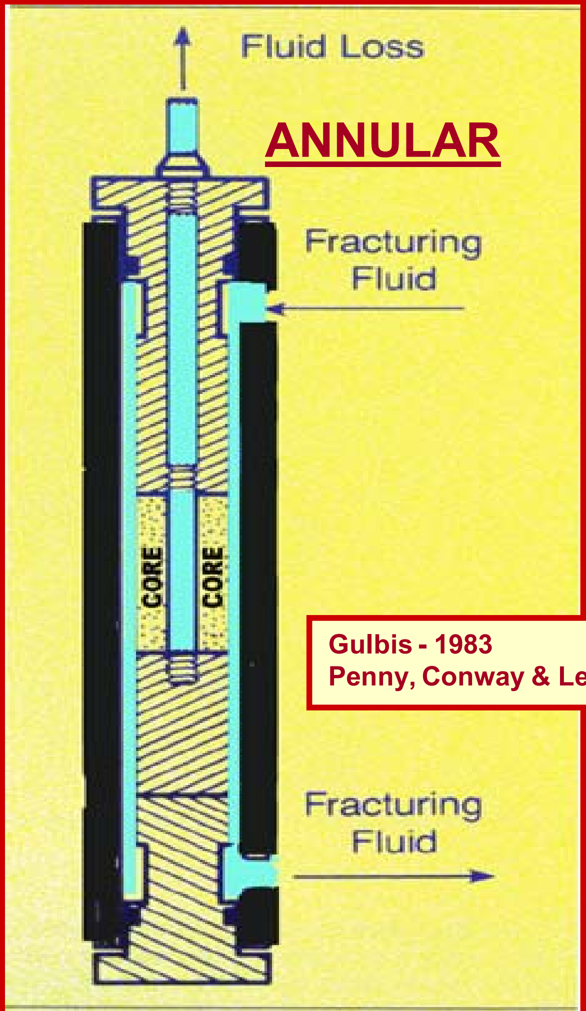
Followed by - " G-Functions"

SIPD Almost Put Laboratory Static Testing Out of Business

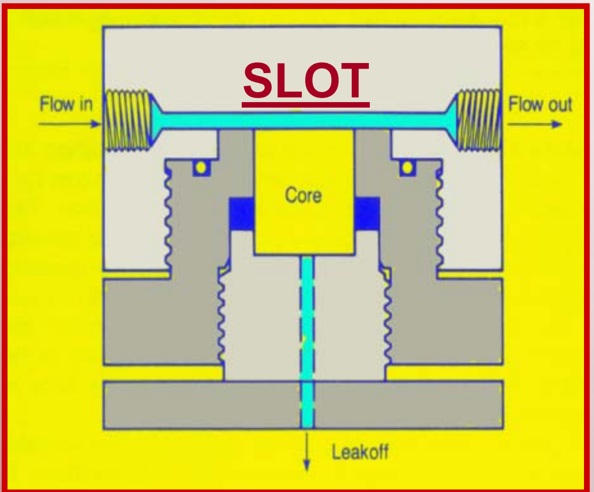
Mid 1960's - Fluid Loss Behavior - Dynamic

Hall & Dollarhide, JPT, May, 1964

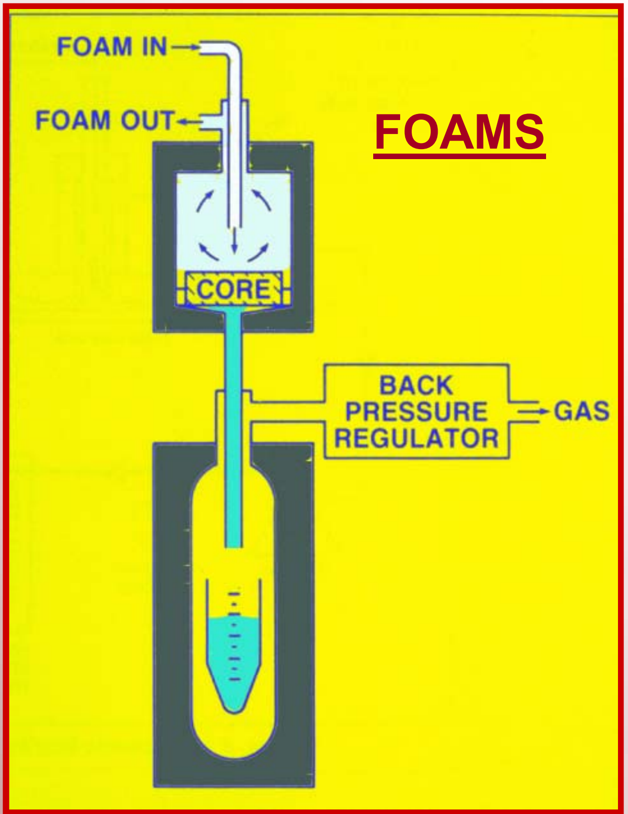
1 9 8 0 's



Gulbis - 1983
Penny, Conway & Lee – 1989



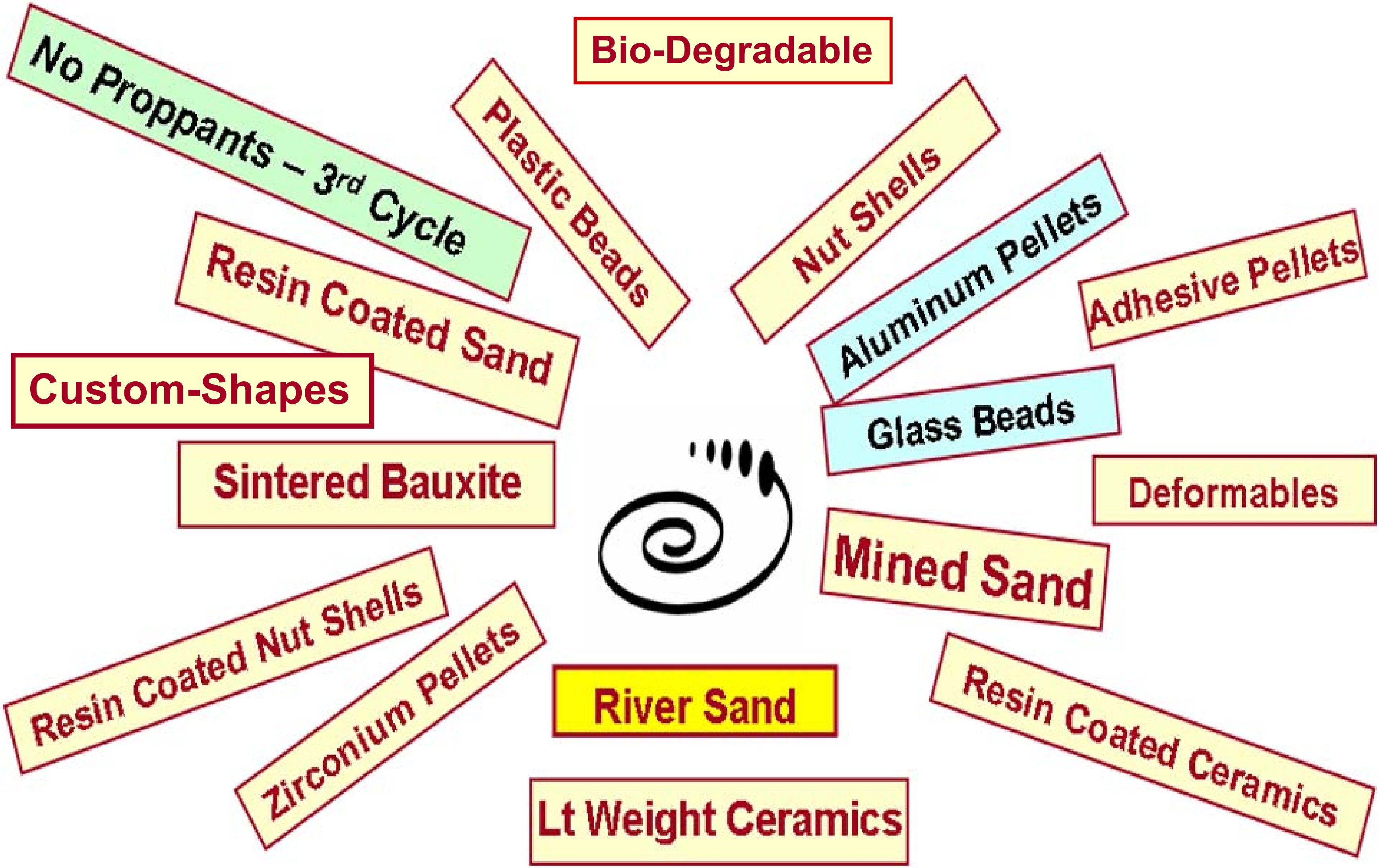
McDaniel – 1985
Harris & Penny - 1989



Harris – 1985 & 1987

1990's + Consortiums & Service Companies

The Circuitous World of Propping Agents - Proppants



Early 1980’s - An “ API “ Fracturing Sand

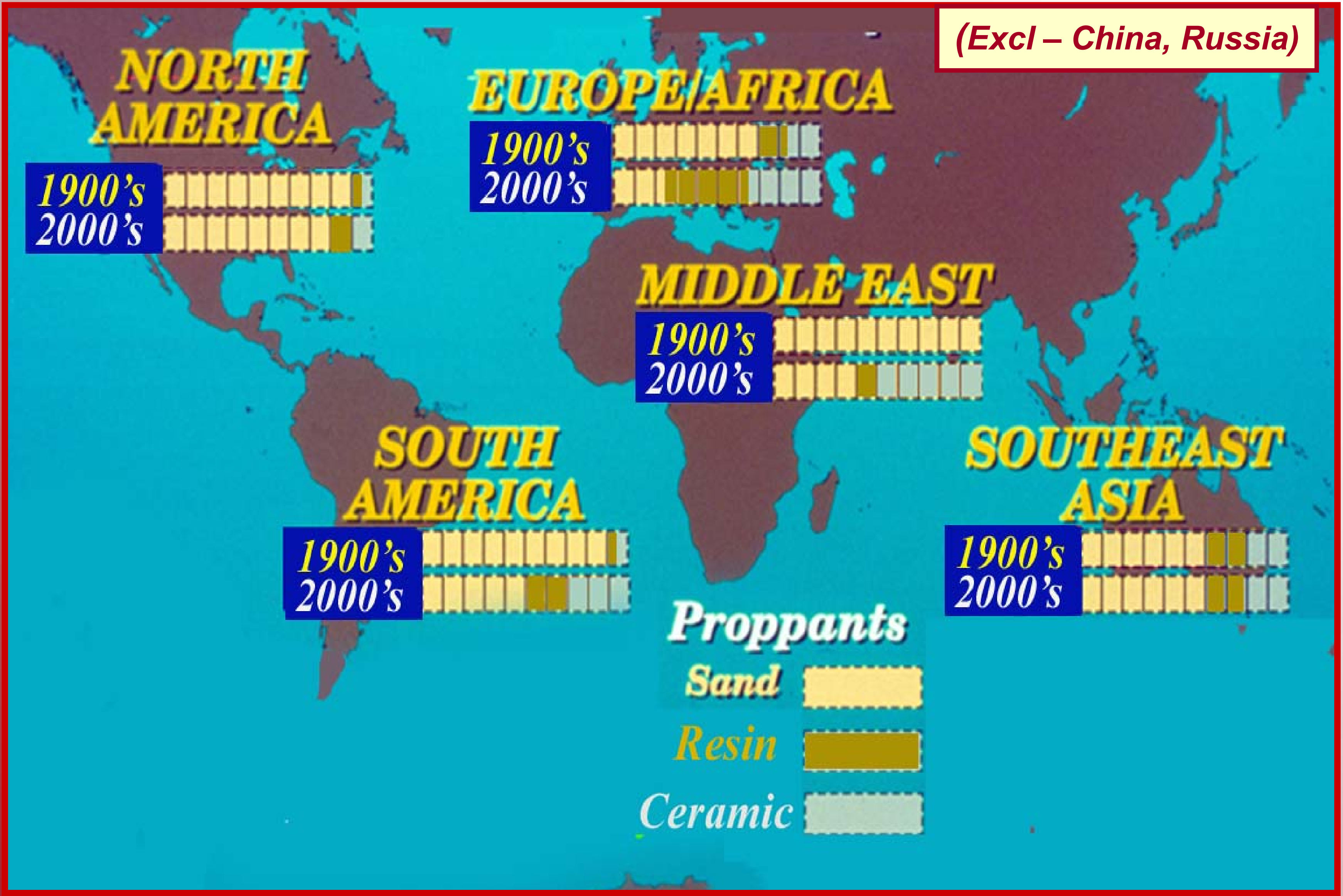
It Took Only Six **(that’s 6)** Years
For a
30+ Member Industry Committee
To
Come to a “Consensus”
Of What
Constitutes
an

“API Fracturing Sand”

“API RP-56, 1983”

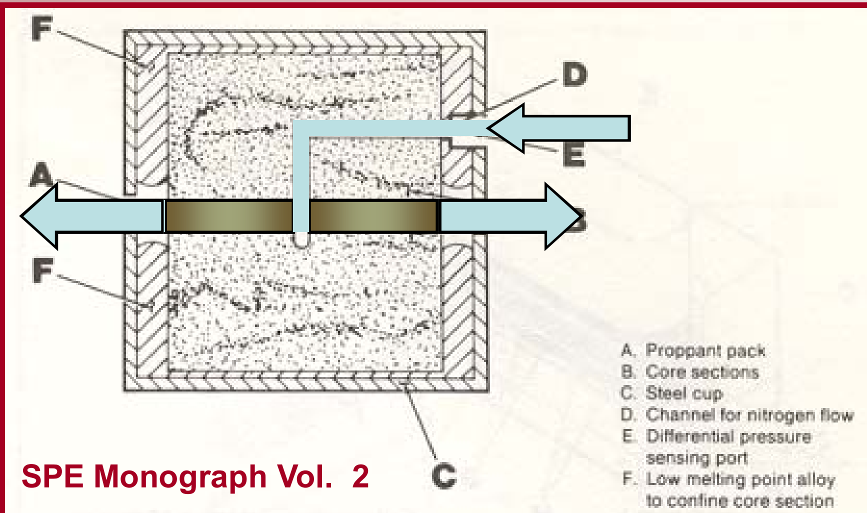
(Whew !!!)

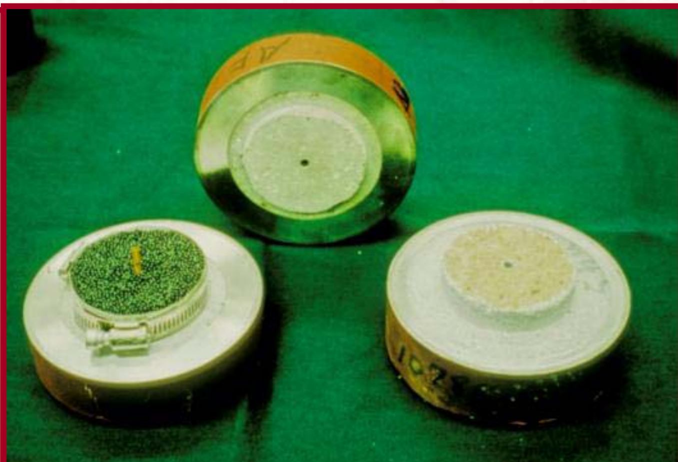
Propping Agents – Percent Usage – 1990's vs 2000's



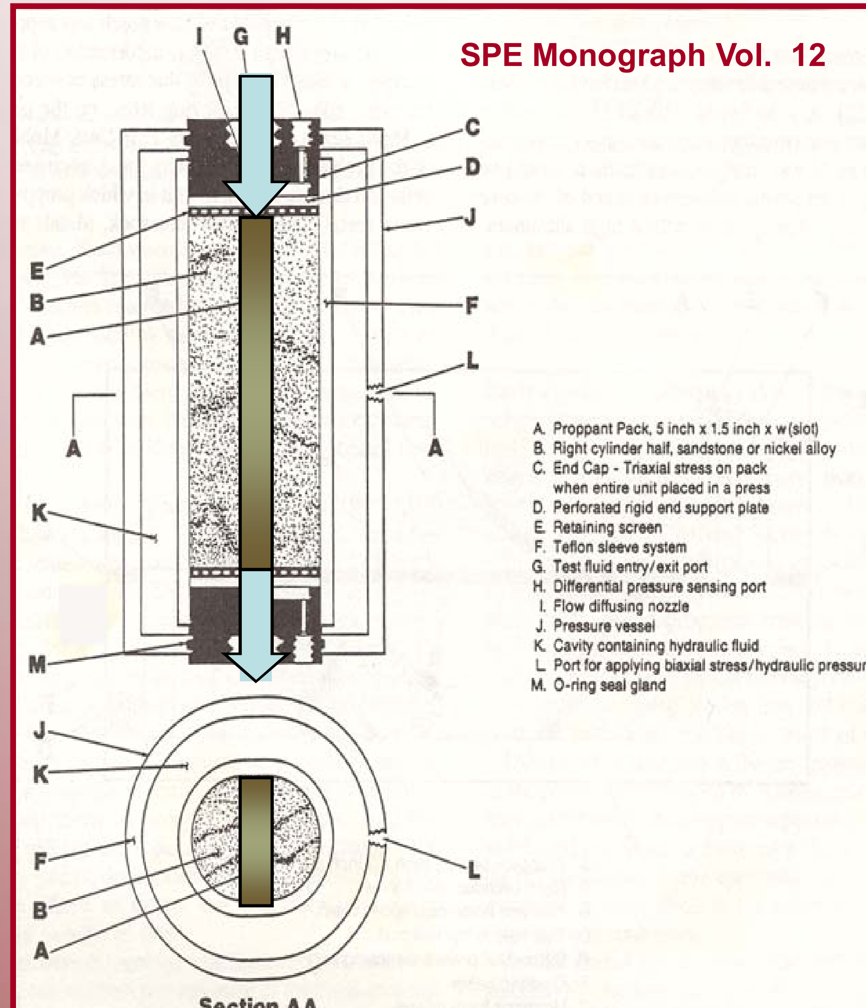
Fracture Conductivity Testing - the Good Old Days

Radial Flow Cell



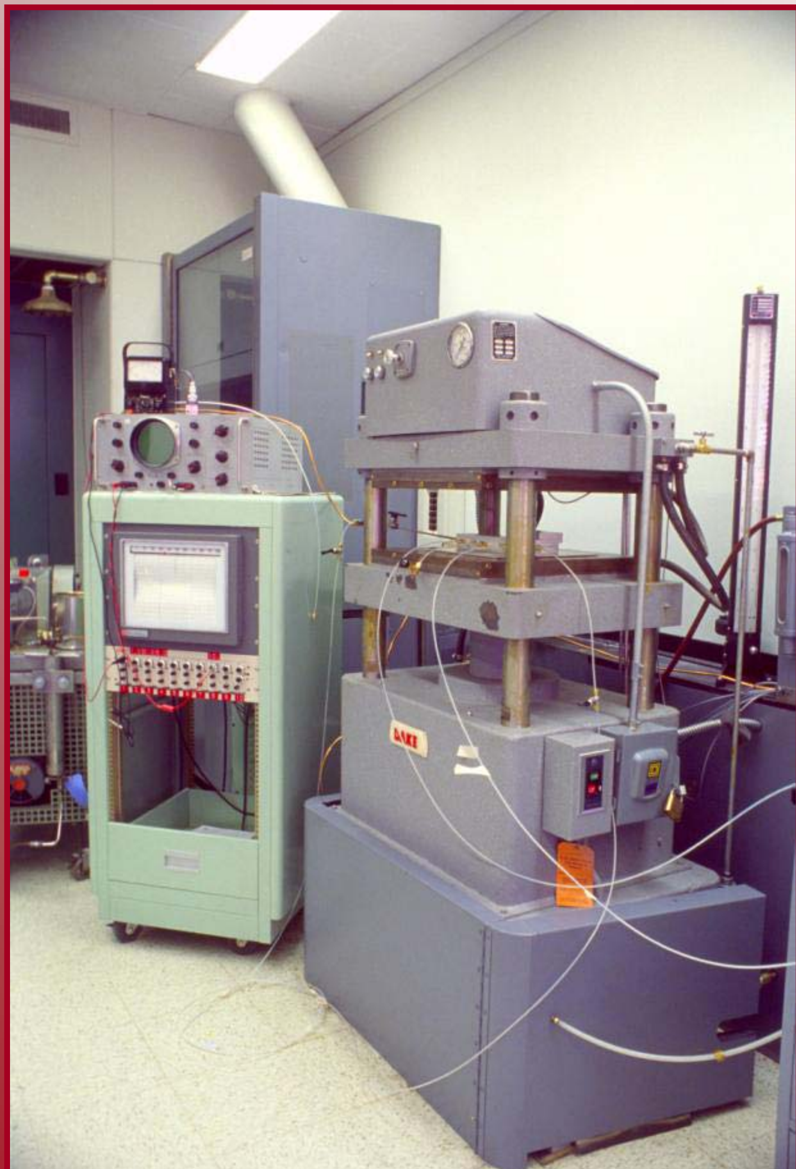


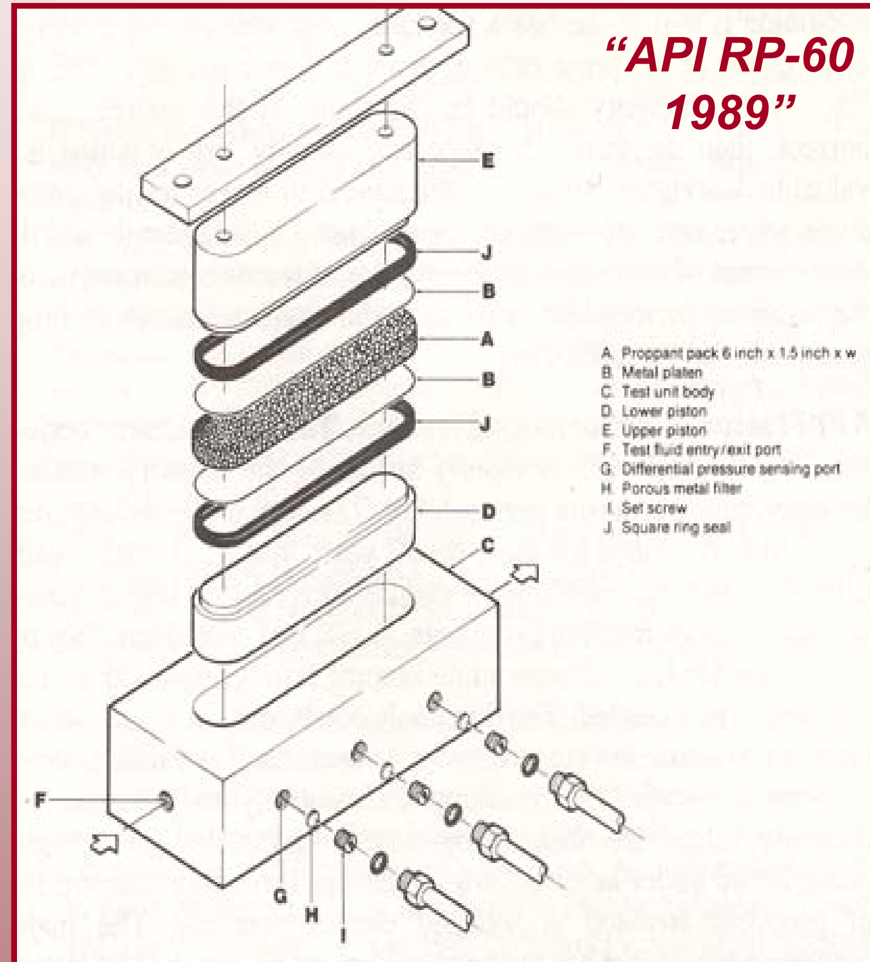
Hassler Sleeve – Linear Flow



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

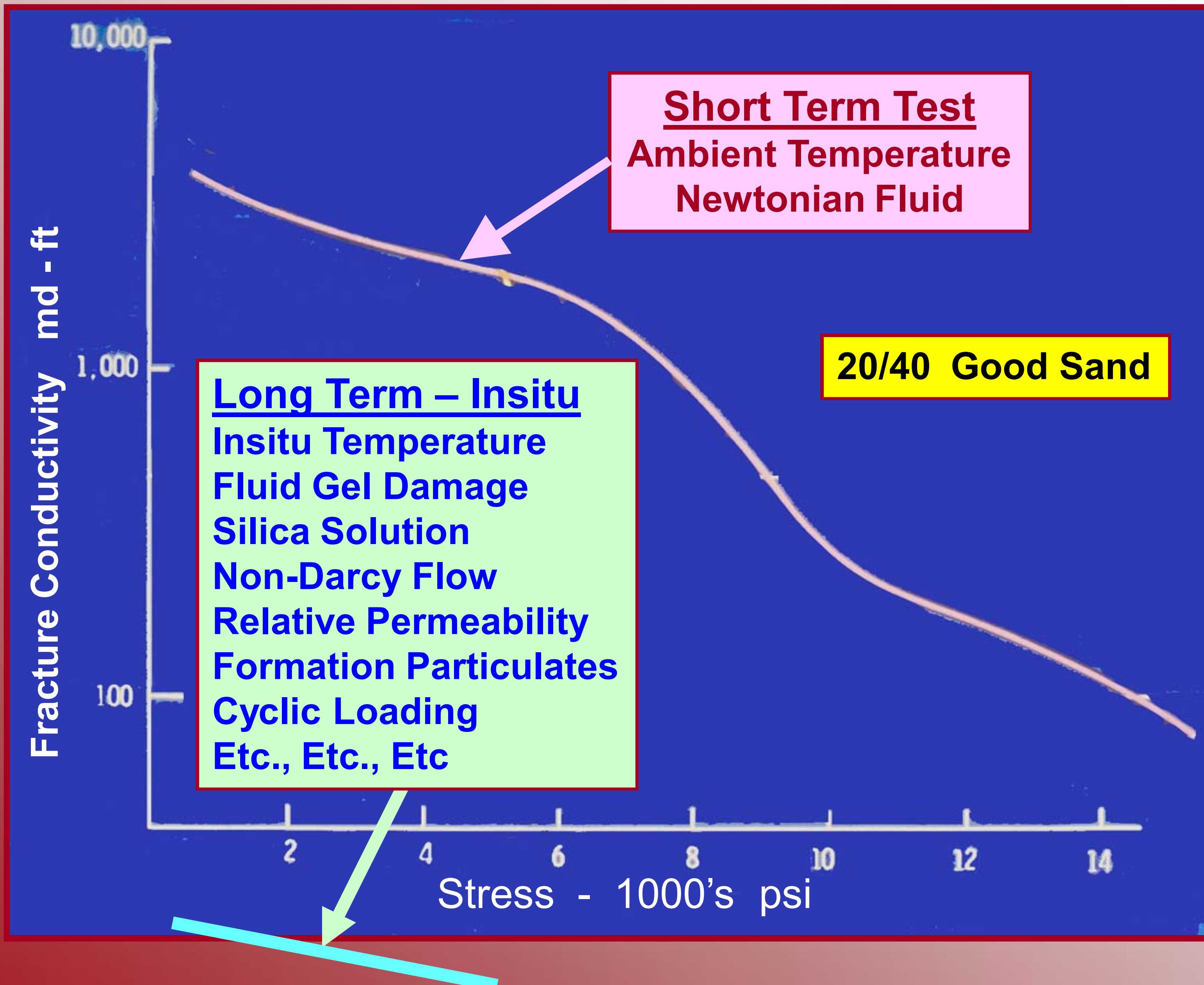
Late 1980's - Fracture Conductivity Testing - the API Cell





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

Fracture Conductivity – Short Term Tests vs Long Term @ Insitu Conditions



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.

1950's – 2000's: A Successful Treatment - Perceptions Still Vary

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
Fraccers 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

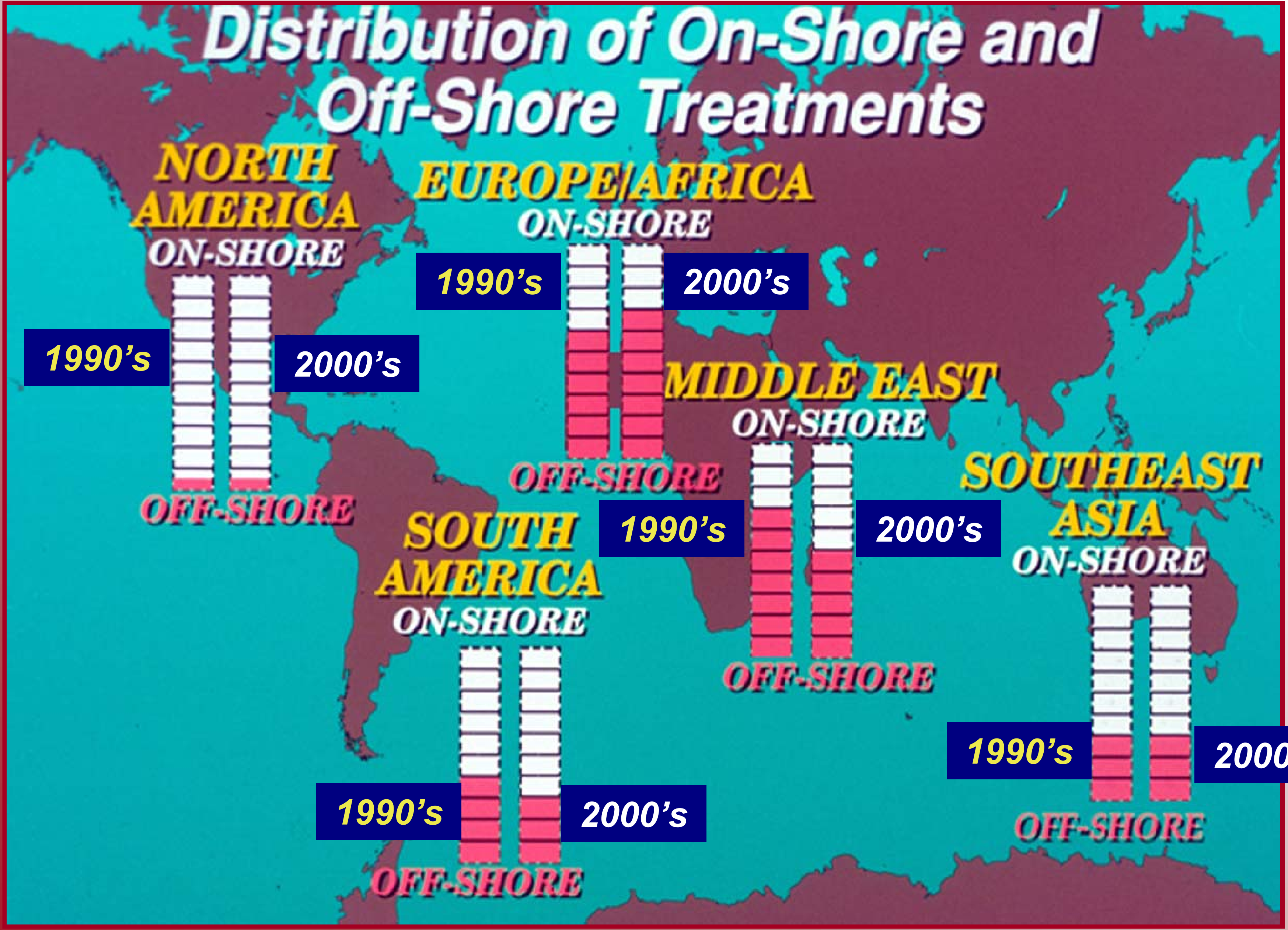
A GLOBAL PERSPECTIVE

OF

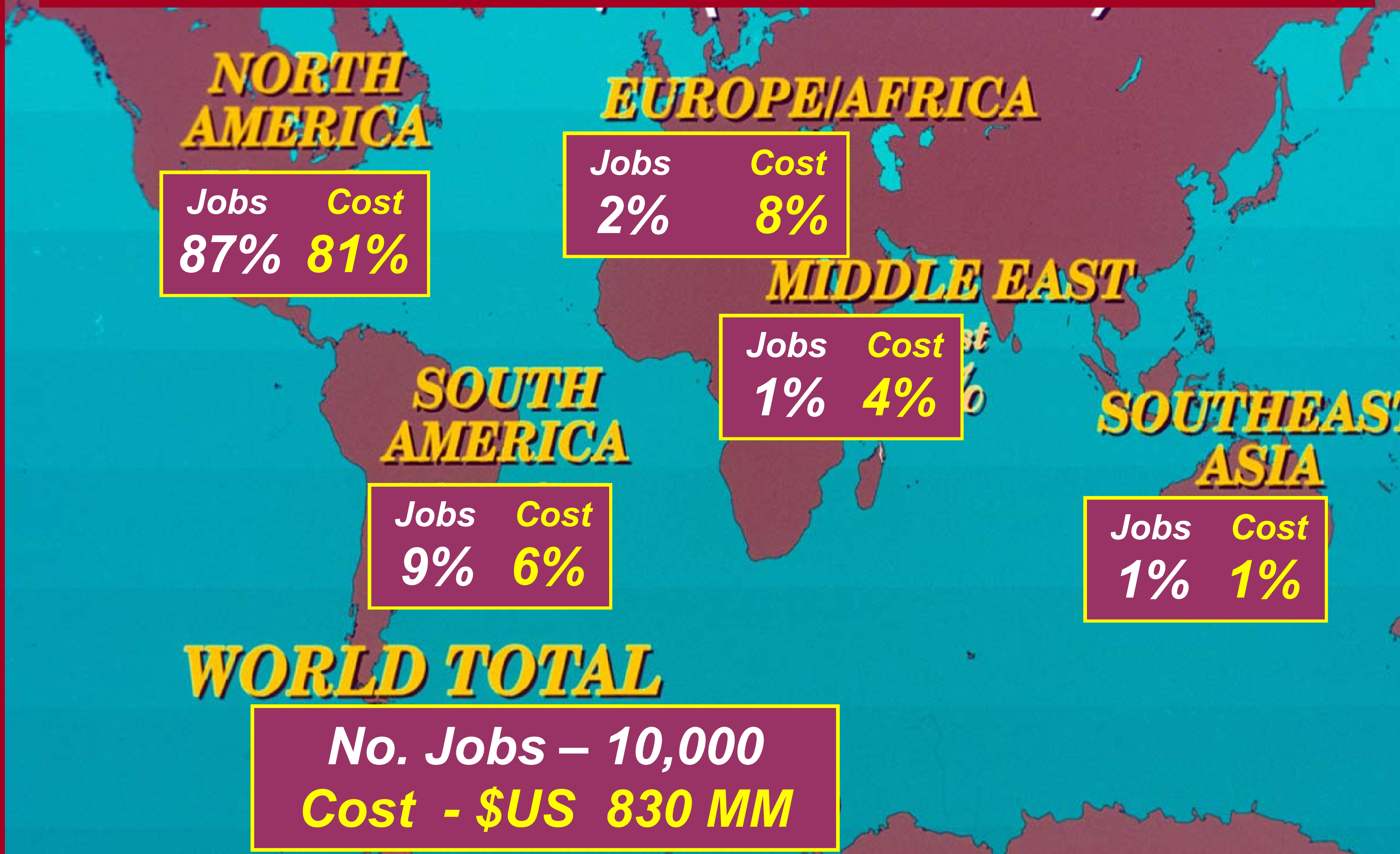
ACTIVITY

1990's & 2000's

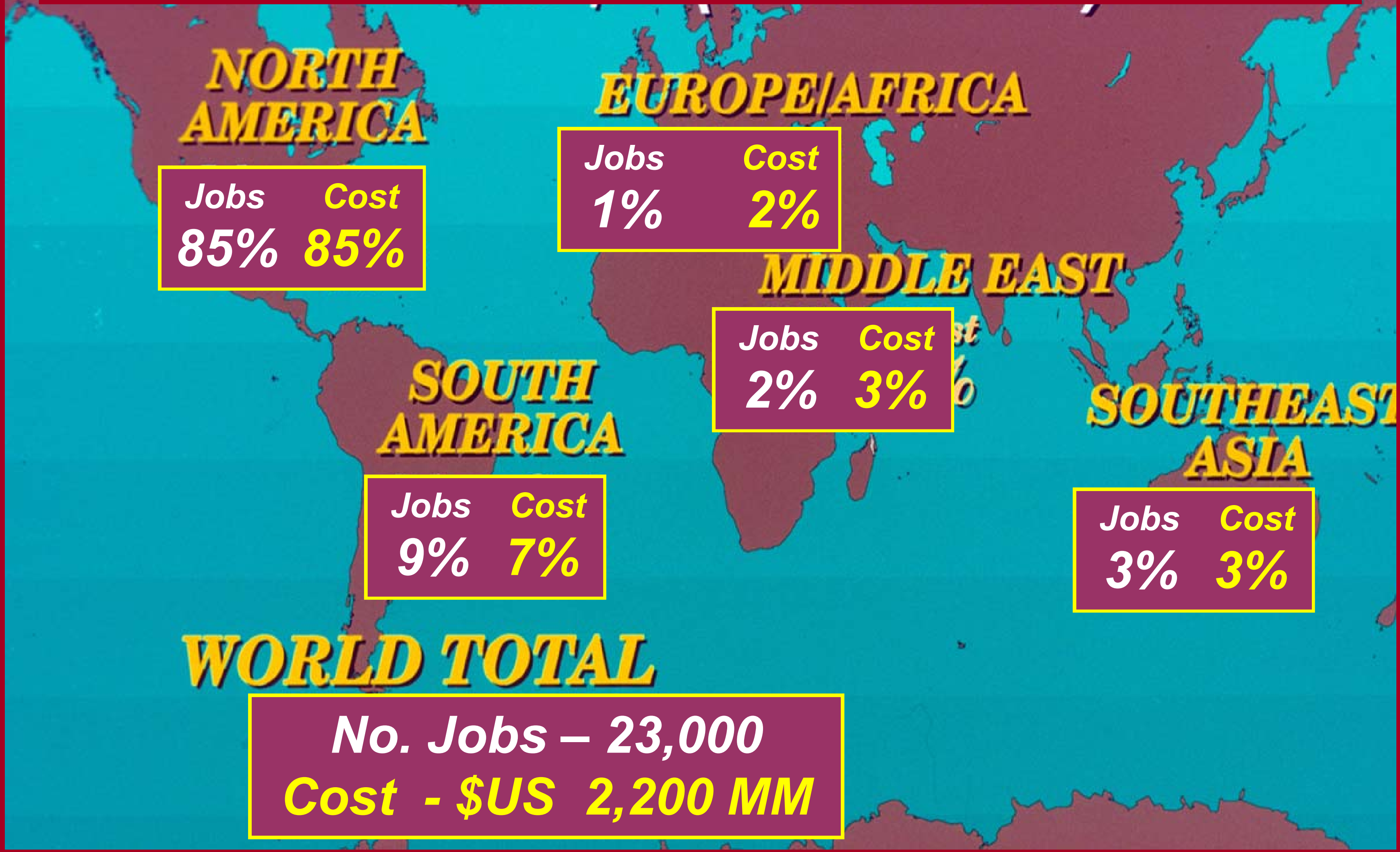
Onshore & Offshore Fracturing



Mid 1990's Annual Fracturing Jobs & Costs (Excl – China, Russia)



Mid 2000's Annual Fracturing Jobs & Costs (Excl – China, Russia)



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!

Questions?