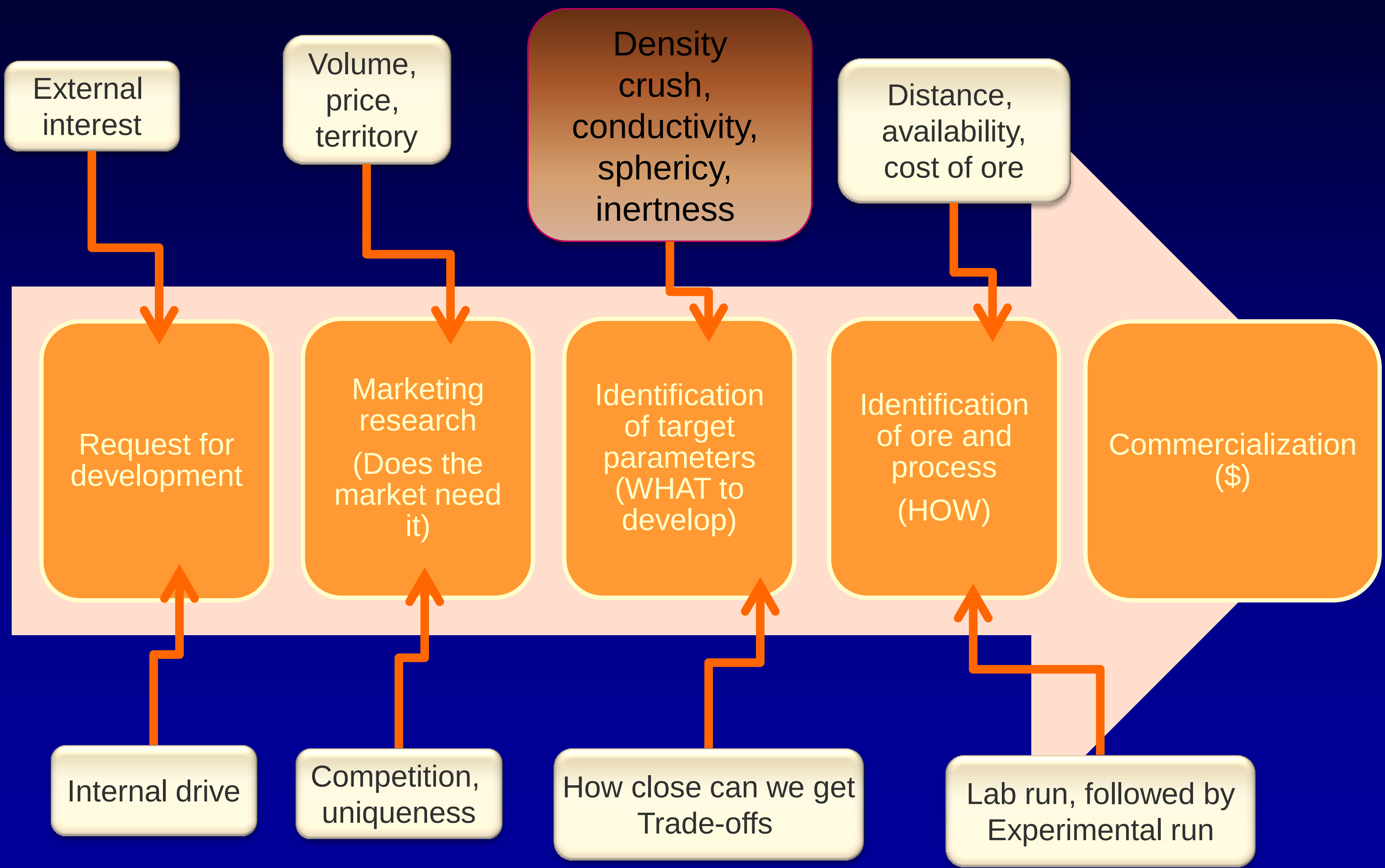
Value of API crush test for ceramic proppant evaluation and field studies on productivity in unconventional reservoirs

CARBO CERAMICS

Outline

- The need to critically review API crush test and misconceptions
- 10 Myths – SPE 119242
  - How to use and misuse crush data!
- Recommendations for proppant evaluation
- What matters when evaluating proppant quality
- Production behavior in fractures completed with different proppants - field studies

The development stages



What test methods in proppant deveopment to use?

- Testing according to ISO 13503-2 (2006)
- Identification of an easy-to-use method to quickly qualify or discard candidate proppants or mineral blends
- Where to test for varification
- External input (ea. fluid systems compatibility)

CARBO*RosLite*

- In 2010 TNK-BP asked Carbo to develop a «Ryabchek» proppant
- Initial research was done in Carbo’s research center in Houston
- A new product was developed in Russia, launched in 2013, **CARBO***RosLite*

How to distinguish a promising blend from a failure

- Crush test, SG and acid solubility for quick answers
- Run full API test on promising blends
- Identify best blend

PROBLEM!

What if Crush test results are misleading?

- From experience and SPE 119242 we know, that crush tests are of limited, or no use to conclude conductivity
- What matters is conductivity as a direct indicator for production rates
- It is technically impossible to run conductivity test on all blends

TNK-BP QAQC for light weight proppant

Fracture Closure Stress (psi/MPa)	Proppant Pack Conductivity (mD/ft)			
	10/14	12/18 - 12/20	16/20 - 16/30	20/40
2000 / 13,79	no data	35708	18270	8352
4000 / 27,58	no data	21091	12795	6538
6000 / 41,37	no data	8442	6445	4055
8000 / 55,16	no data	3775	2806	2324
10000 / 68,95	no data	1613	1198	1241
12000 / 82,74	no data	200	225	60
14000 / 96,53	no data	90	154	38

Test Pressure (psi/MPa)	Proppant Crush Test (% Fines)			
	10/14	12/18 - 12/20	16/20 - 16/30	20/40
5000 / 34,47	8,0	3,0	2,0	1,0
7500 / 51,71	22,0	19,8	13,0	6,0
10000 / 68,95	38,0	35,0	21,0	12,0
12500 / 86,18	48,0	43,0	33,0	24,0
15000 / 103,4	no data	49,0	39,0	31,0

Crush test vs conductivity

- *Please take reference to tables provided…*
- CARBO*RosLite* 12/18 crush is 2 x higher than specs BUT conductivity is in line or higher

SPE 119242

How to Use and Misuse Proppant Crush Tests – Exposing the Top 10 Myths

T. T. Palisch, M. Chapman, R. Duenckel,
S. Woolfolk, CARBO Ceramics, Inc.
M. C. Vincent, Insight Consulting

SPE International
Society of Petroleum Engineers

Crush Test Protocols

- Crush tests are cheap, fast, and data available
- API RP56 (1983) & RP60 – updated in ISO 13503-2 (2006)
  - “improve quality…delivered proppants”
  - “enable…to compare physical properties”
  - Original intent to help qualify sand sources
- “Crush results” and proppant selection
  - “qualified engineering analysis….required for their application to a specific situation”
  - SPE 11634 – Conductivity comparisons cannot be made on the basis of crush tests

***Yet many still select proppants based on crush results ***

Ten Myths to Investigate

1. Crush tests simulate realistic conditions

ISO 13503-2 Crush Test Procedure

- Proppant is pre-sieved to remove particles outside of stated mesh range.
- Dry proppant placed in steel cell at ~4 lb/sq ft (sand equivalent)
- Room temperature
- Proppant evenly distributed with level surface
- Load applied at uniform rate
- Constant stress maintained for two minutes

- Proppant is sieved post-crush. The weight percent which falls below the primary screen is reported.
  - For 16/20 proppant all material < 20 mesh is reported as “fines”
  - For 30/50 proppant all material < 50 mesh is reported as “fines”

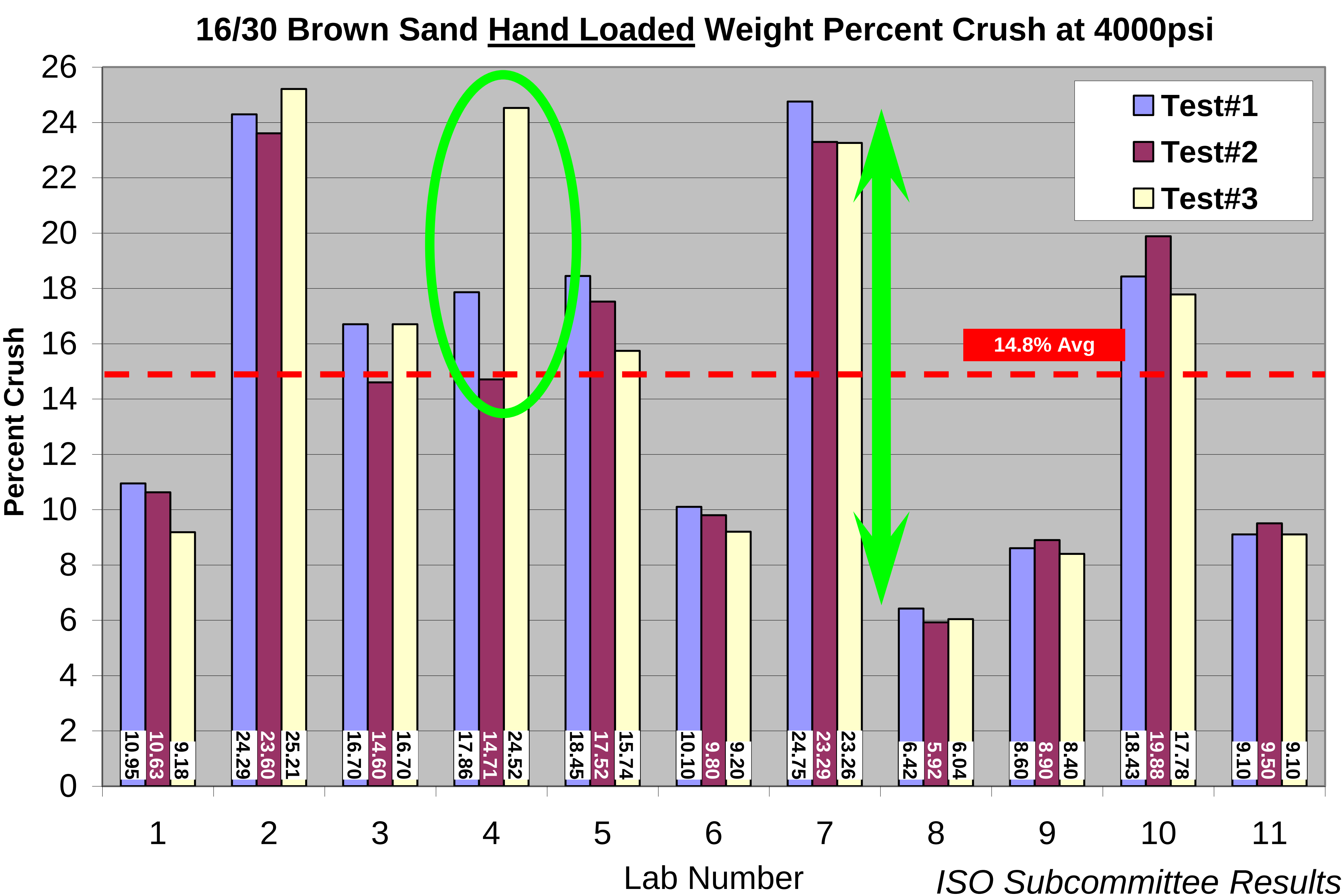
Are test conditions realistic?

- Proppant is pre-sieved.
- Proppant loading (pack width ~ ½”)
  - Sand/RCS/LWC ~4 lb/ft^2
  - IDC ~4.8 lb/ft^2
  - Bauxite ~5.2 lb/ft^2
- Smooth, steel plates – embedment?
- “Carefully loaded”
- Dry, room temperature
- 2000 psi/min, relaxed after 2 minutes
- Only the particles smaller than bottom screen are considered “fines” or “crush”

Ten Myths to Investigate

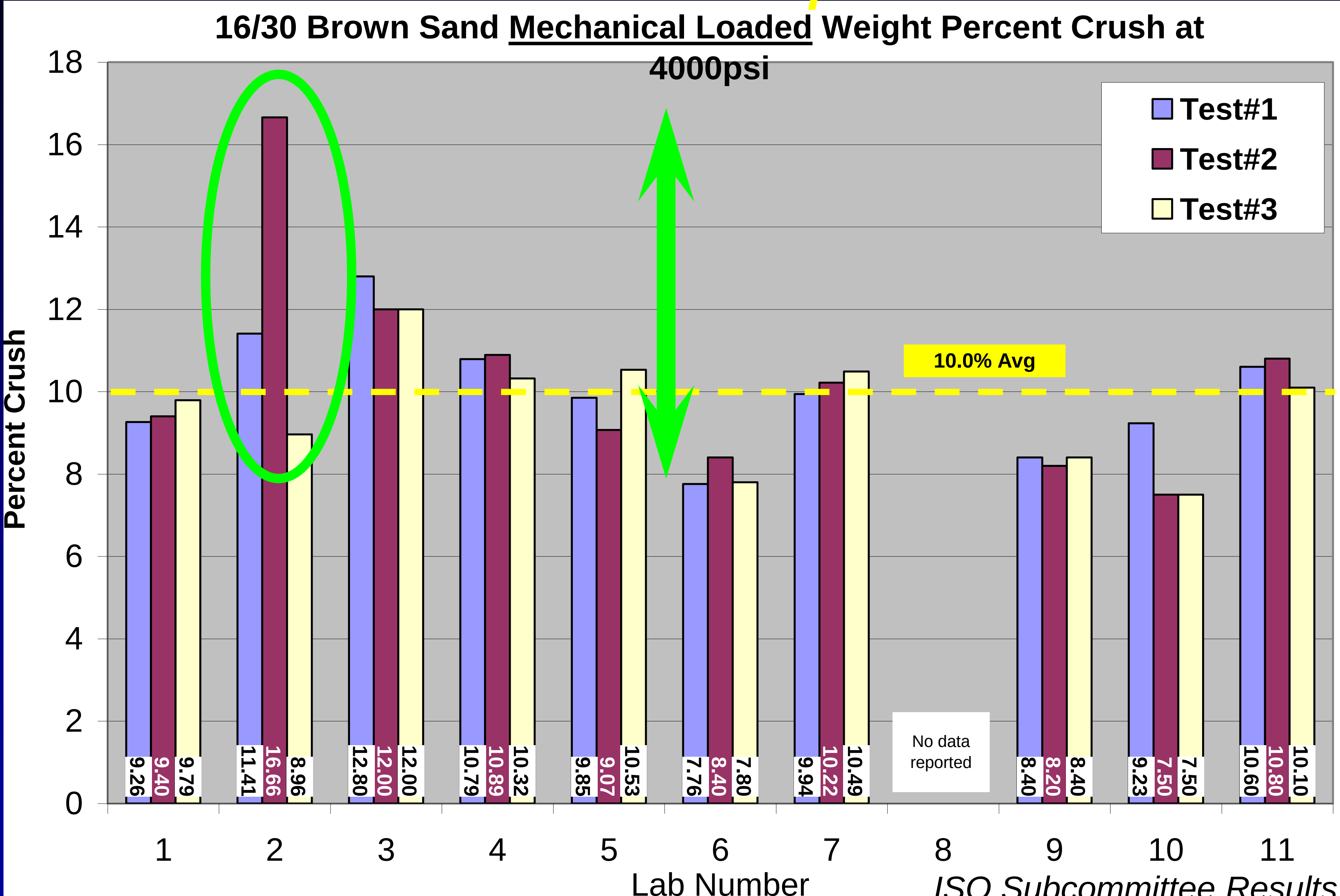
1. Crush tests simulate realistic conditions
2. Crush tests are reliable/repeatable

Are the results repeatable?



ISO Subcommittee Results

Are the results repeatable?



ISO Subcommittee Results

Are the results repeatable/reliable?

Crush Cell Loading critical

- “variance in crush results….associated with method of loading…”
- Significant efforts ongoing on ISO Committee and StimLab to alleviate variations in results
  - Loading technique thought to be the cause
  - Lab to lab, technician to technician, equipment to equipment

Ten Myths to Investigate

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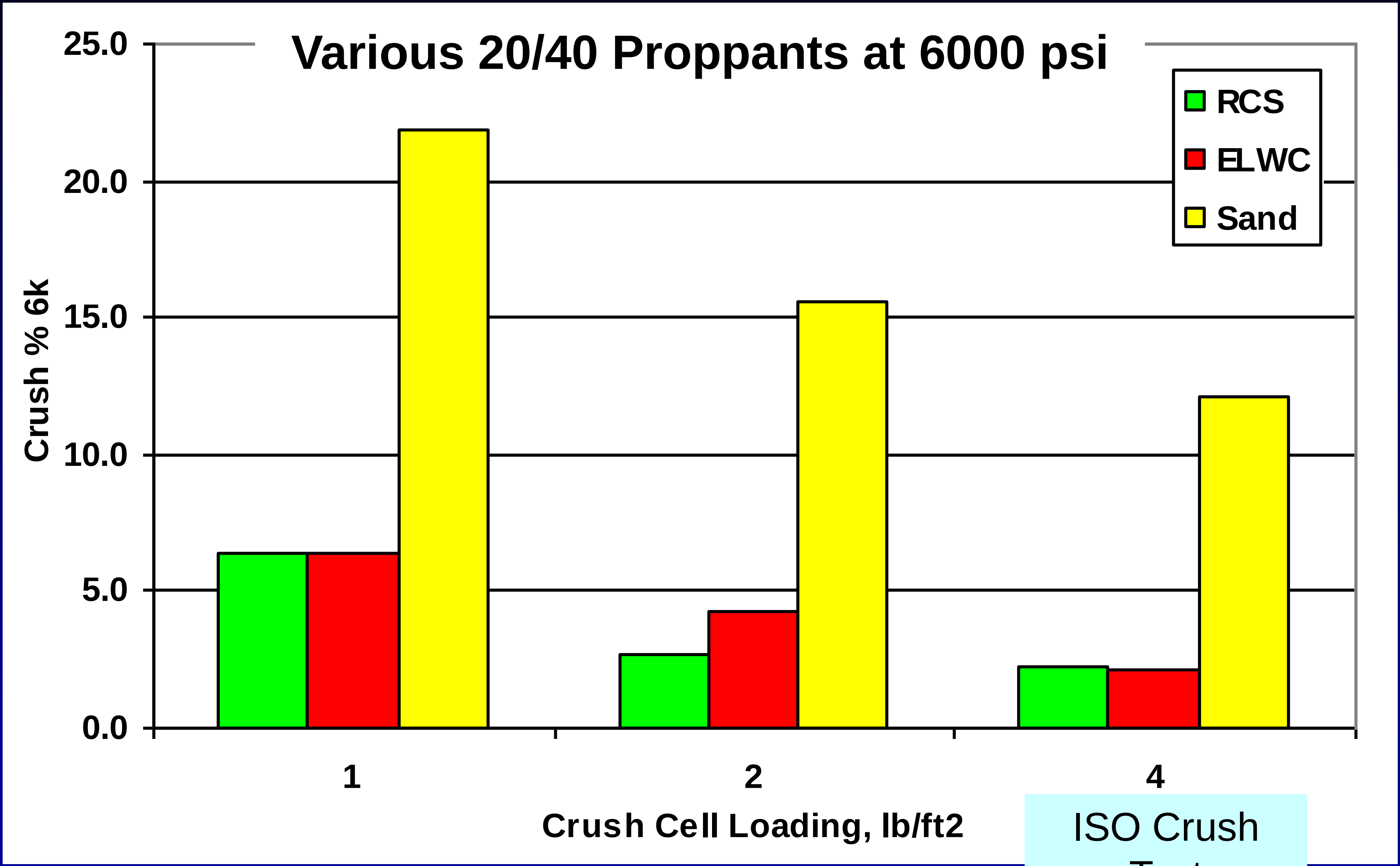
3. Fracture width doesn't affect proppant crush

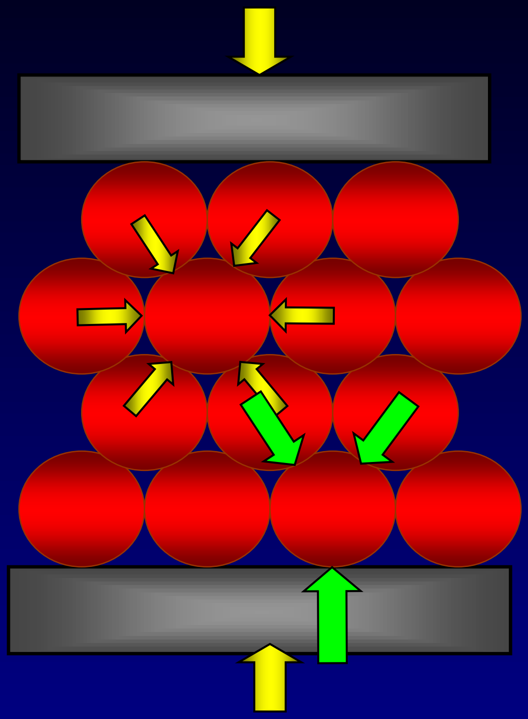
Does Fracture Width Affect Crush?



ISO Crush Test Conditions

Does Fracture Width Affect Crush?

- Interior grains loaded “evenly”
- Exterior grains have fewer load points
- Crush increases significantly as proppant loading decreases



- For a 20/40 proppant, there are approximately 24 layers of proppant in standard 4 lb/ft^2 crush test.
  - *8% are exterior grains*
- 1 lb/ft^2 is ~6 layers of 20/40 proppant
  - *33% are exterior grains*

Ten Myths to Investigate

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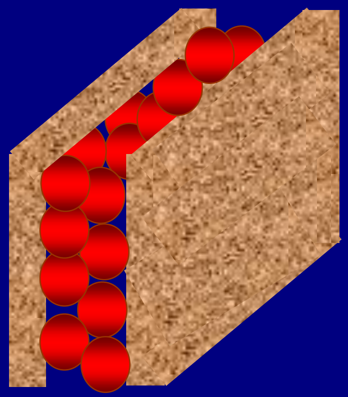
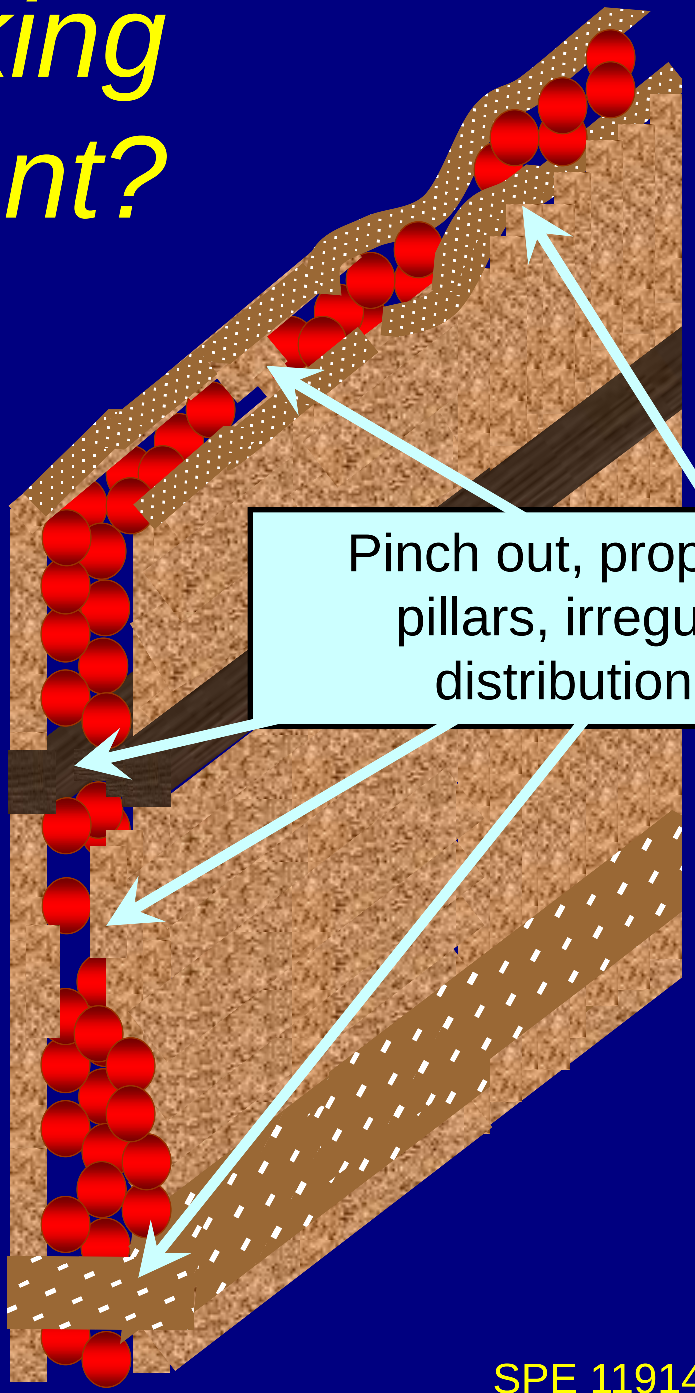
4. Uniform particle arrangement is realistic

Uniform Packing Arrangement?

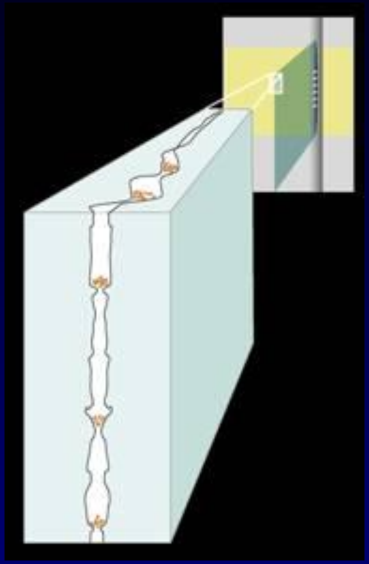


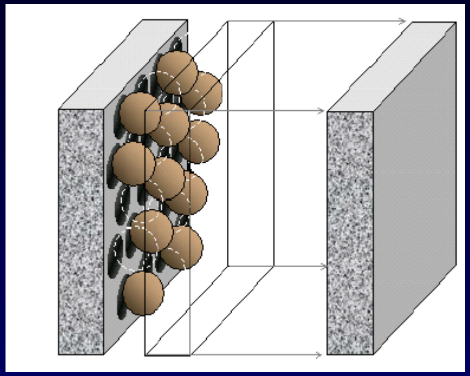


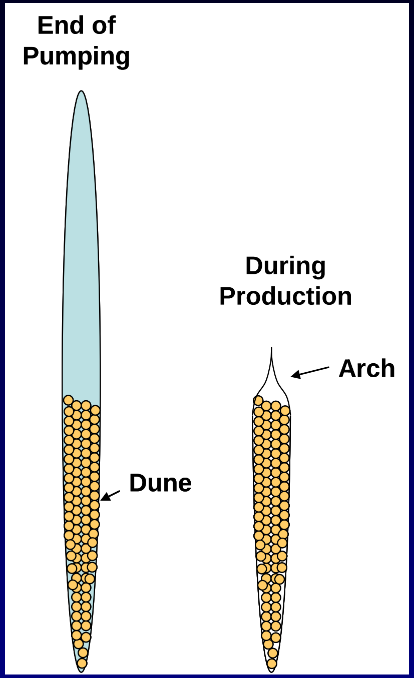
Is this ribbon laterally extensive and continuous for hundreds or thousands of feet?

SPE 119143

Potential Proppant Arrangements



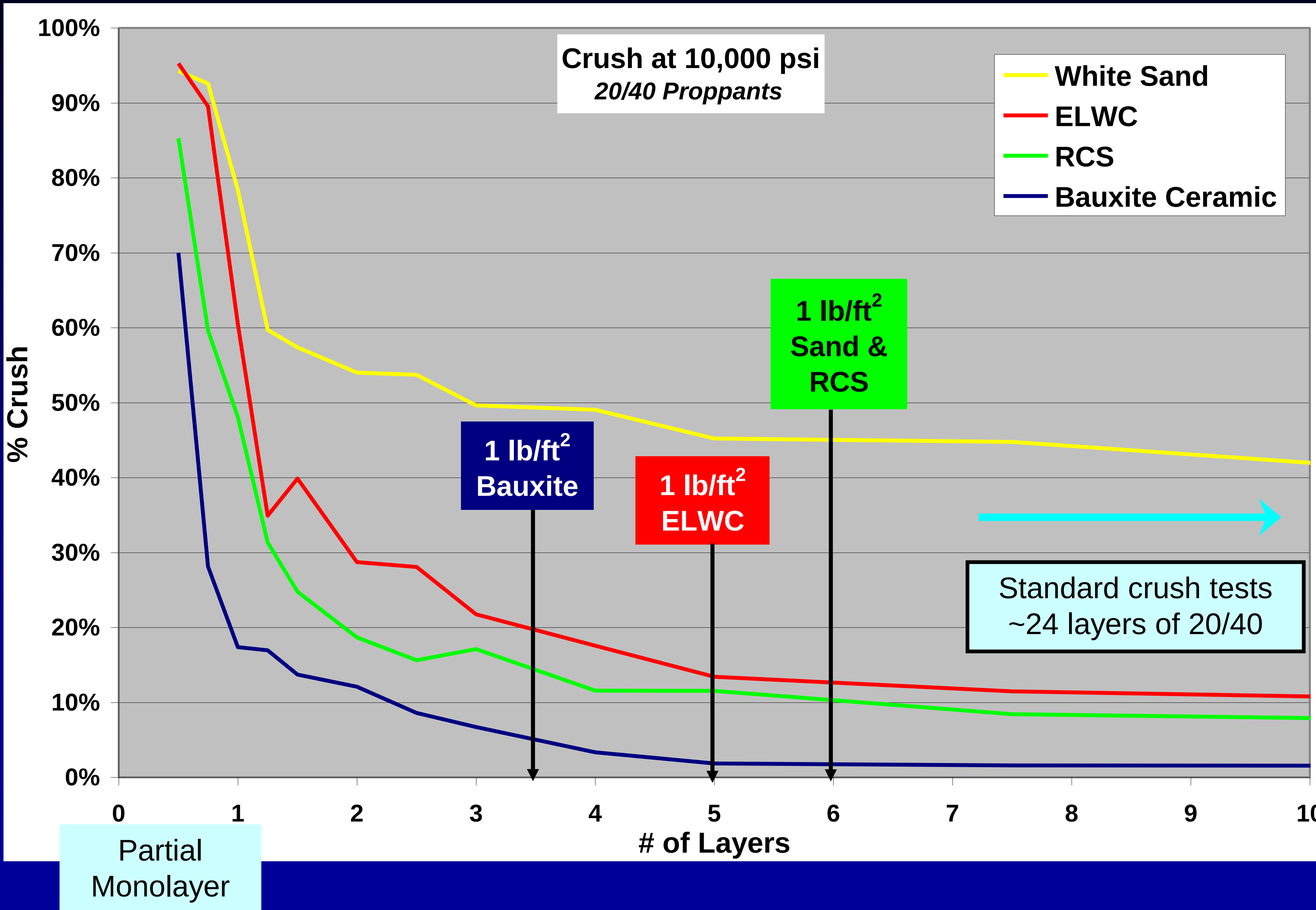




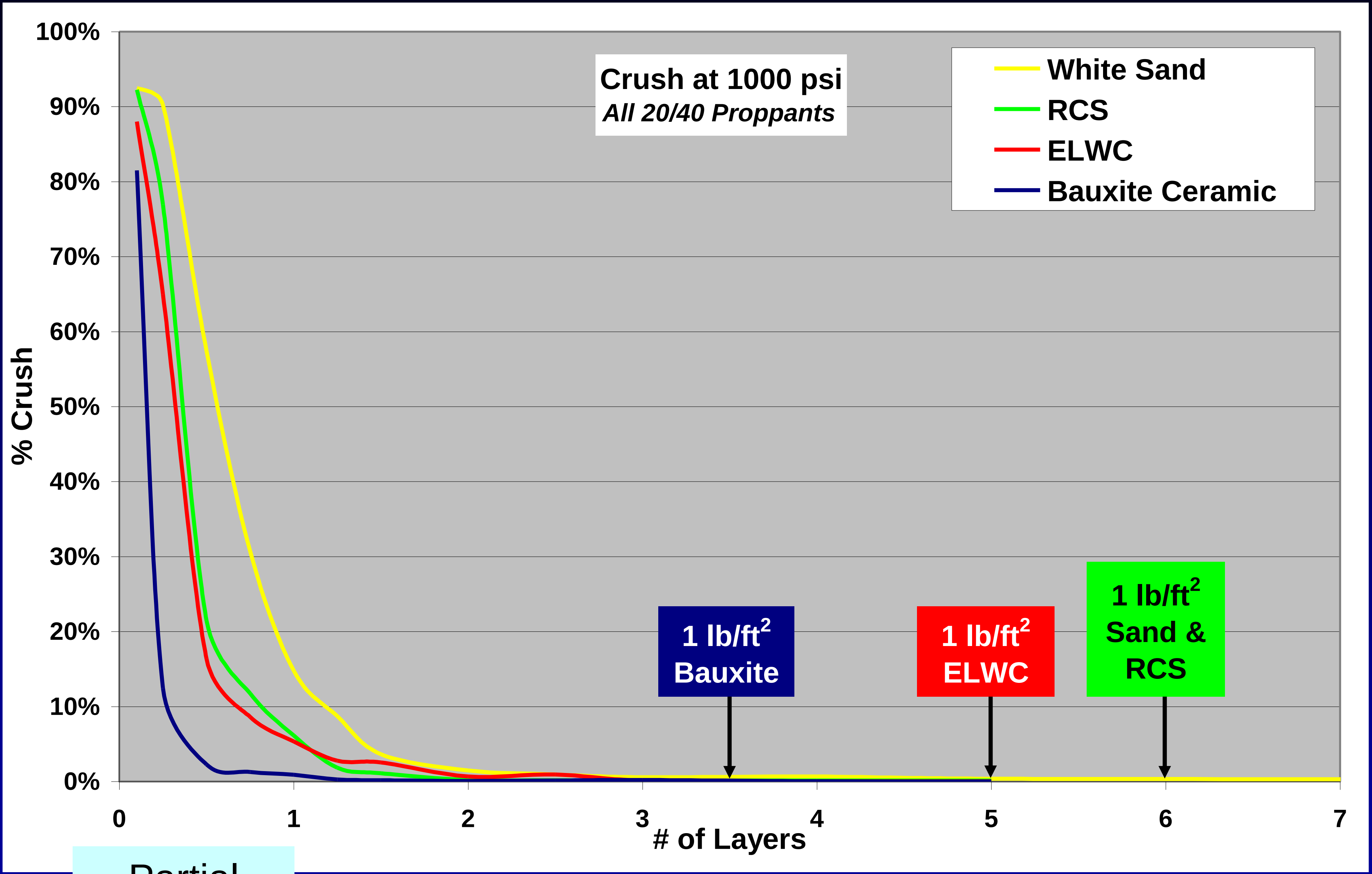
- 45 t of proppant contains ~125 billion particles
- Most every arrangement we can envision likely exists somewhere in a frac
- All arrangements cause higher stress concentration on proppant than our “idealized” testing on uniform wide packs
- In series, the flow capacity limited by poorest arrangement, not the average

SPE 115769, 114173, 115766, 90698

10,000 psi Crush vs # Layers



1000 psi Crush vs # Layers



Partial
Monolayer

Ten Myths to Investigate

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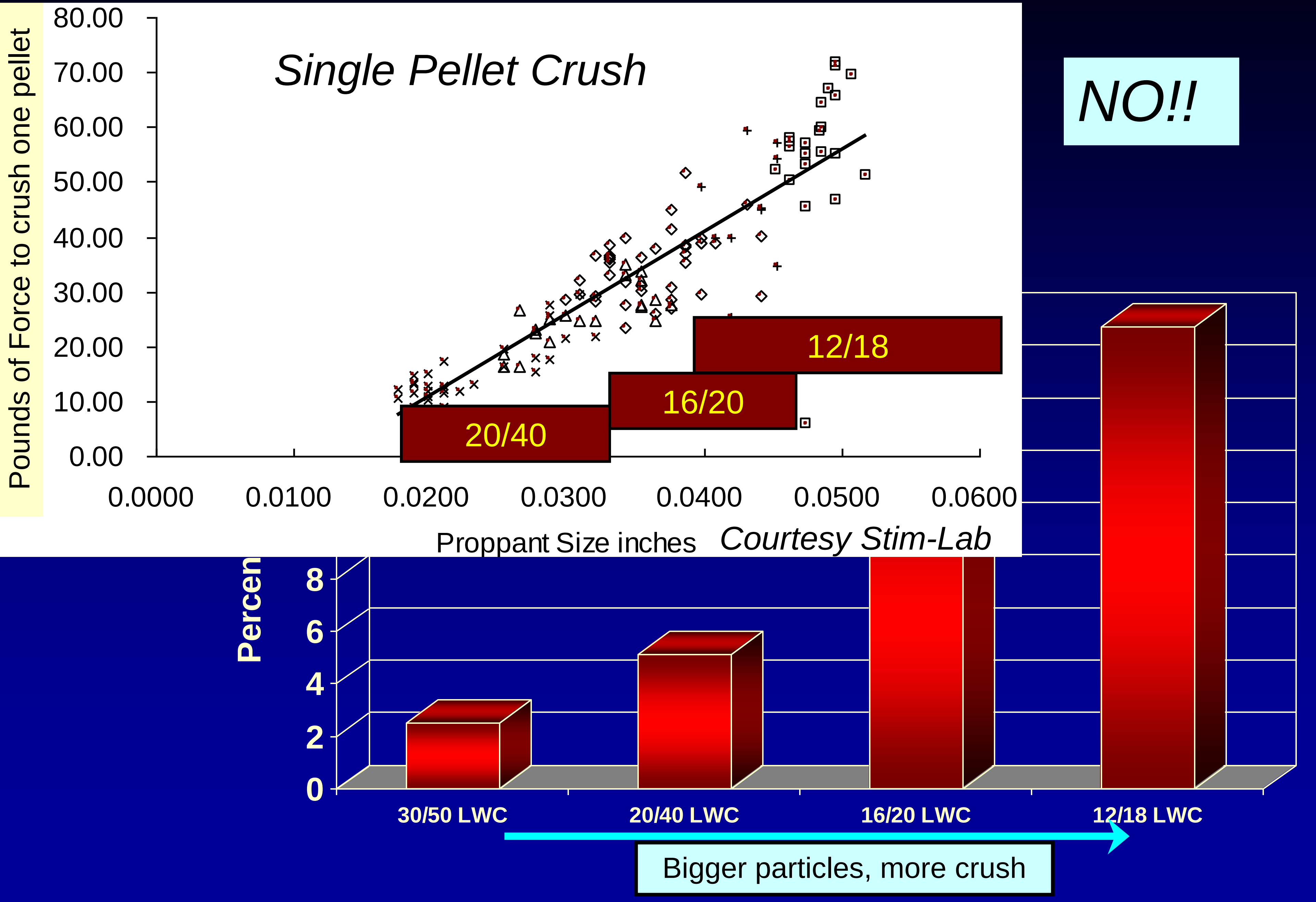
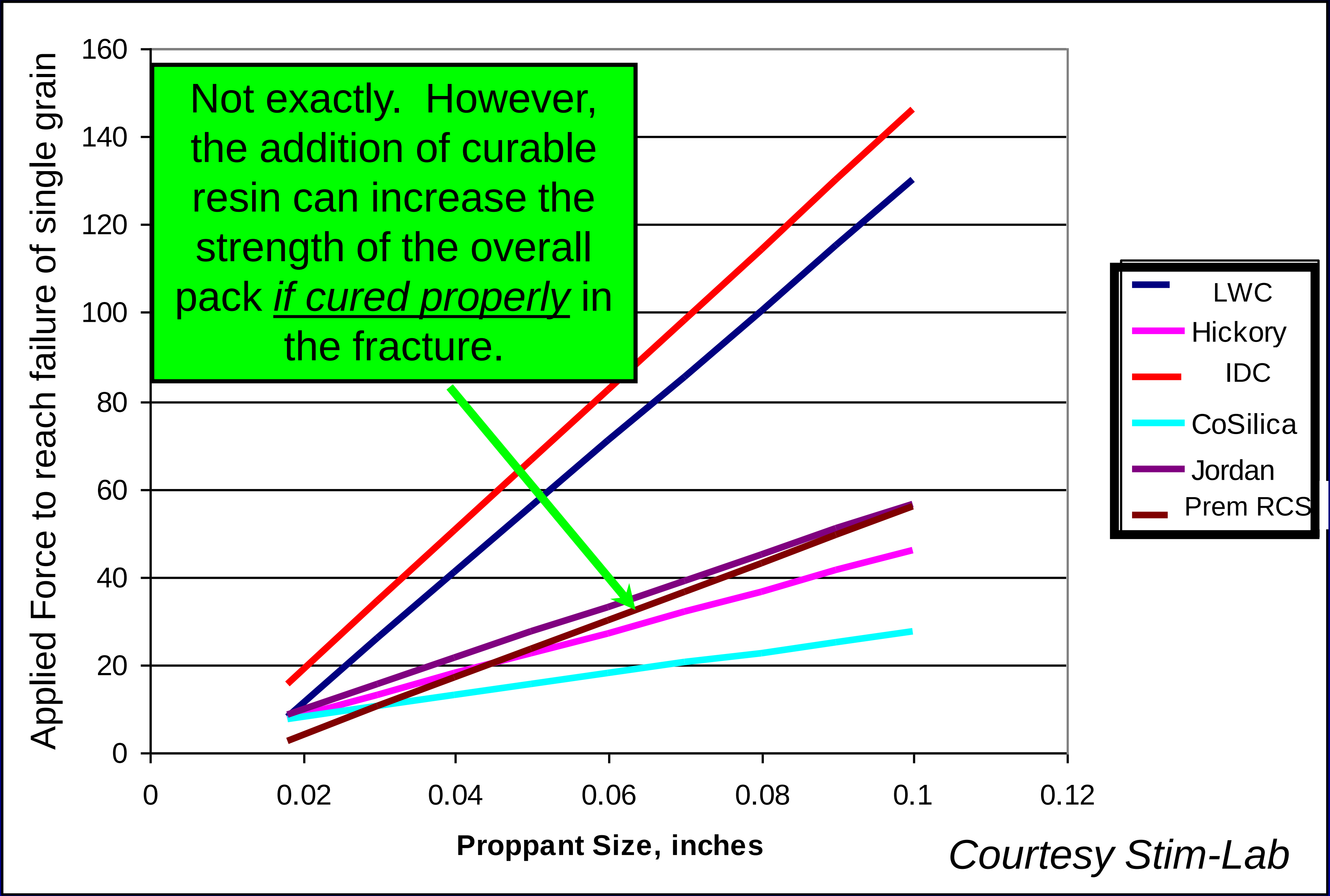
5. Small particles are stronger

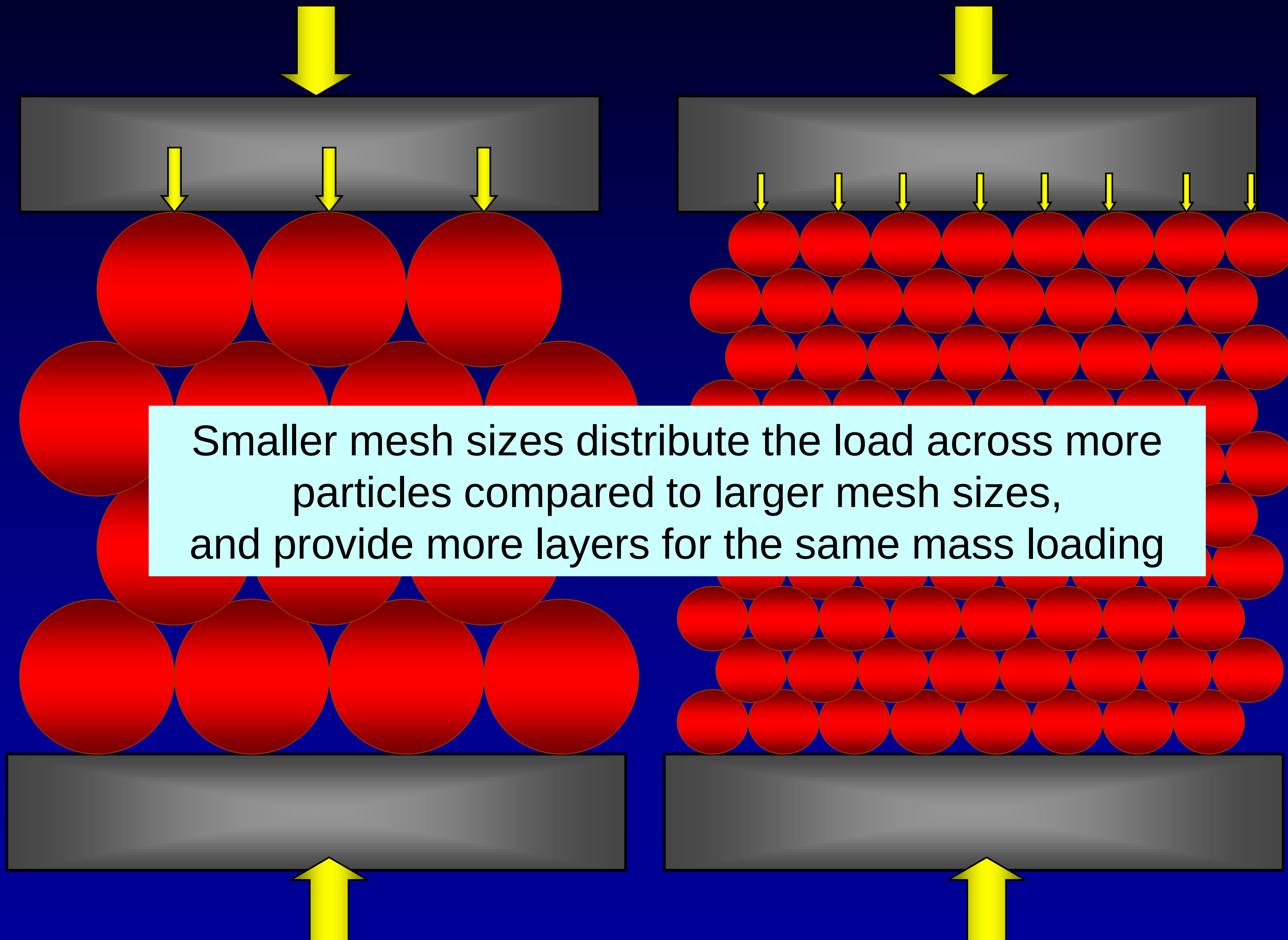
Are Large Particles weaker than Small?



For all proppant types, larger grains have greater individual strength.



“There’s Strength in Numbers”



Ten Myths to Investigate

1. Crush tests simulate realistic conditions
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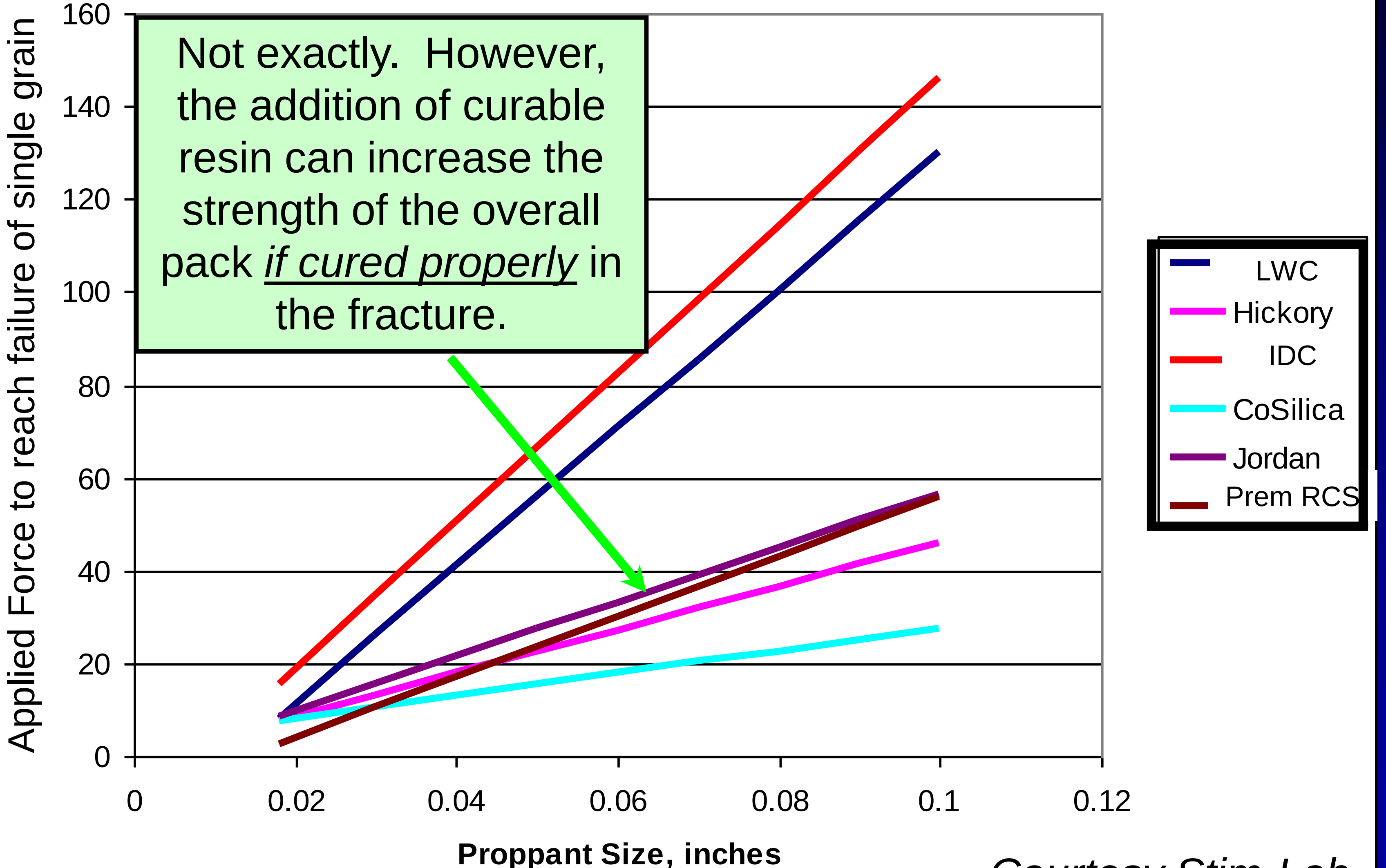
5. Small particles are stronger
6. Resin coating improves particle strength

Does the application of resin increase Particle Strength?



Courtesy Stim-Lab

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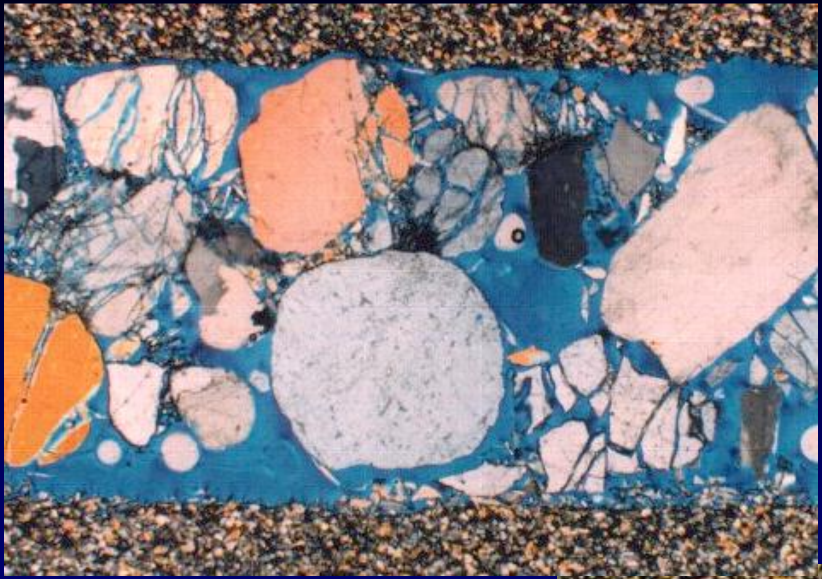
7. All proppants fail (crush) in the same way

Do all Proppants Fail in the Same Manner?

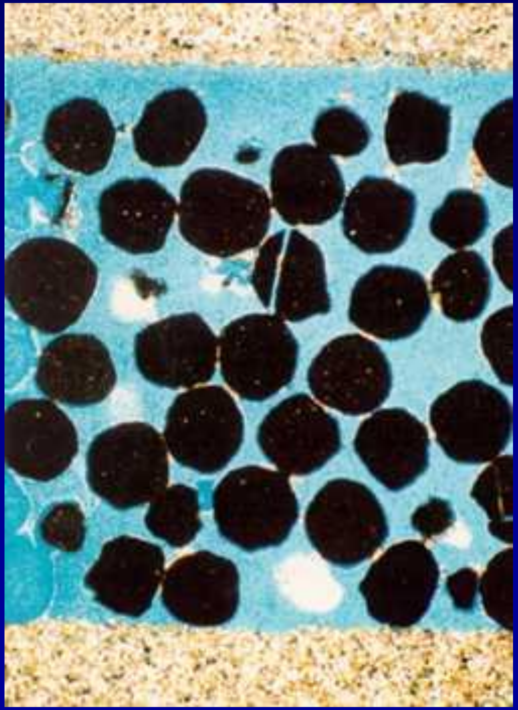


When they fail…

- Sands shatter like a glass
- Ceramics cleave like a brick
- Resin Coated products "deform"; fines captured

Brown Sand at 6k psi.

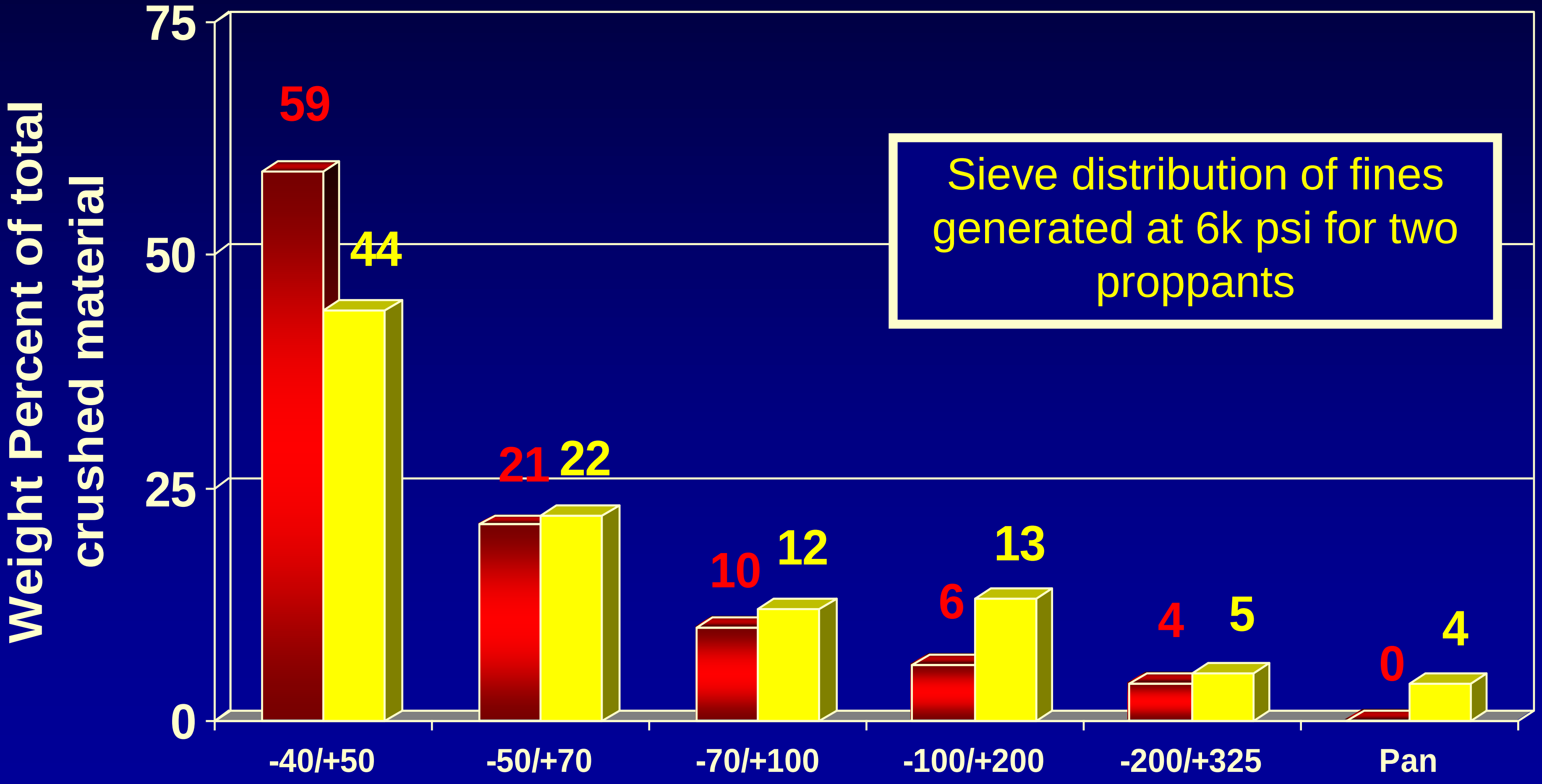
RCS at 8k psi.



IDC at 8k psi.

Do all Proppants Fail/Crush the Same?

Remember that 5% crush on a 20/40 proppant could be a 5g of 50 mesh particles or 5g of 200 mesh particles.



Source: CARBO Analyses Nov 1998

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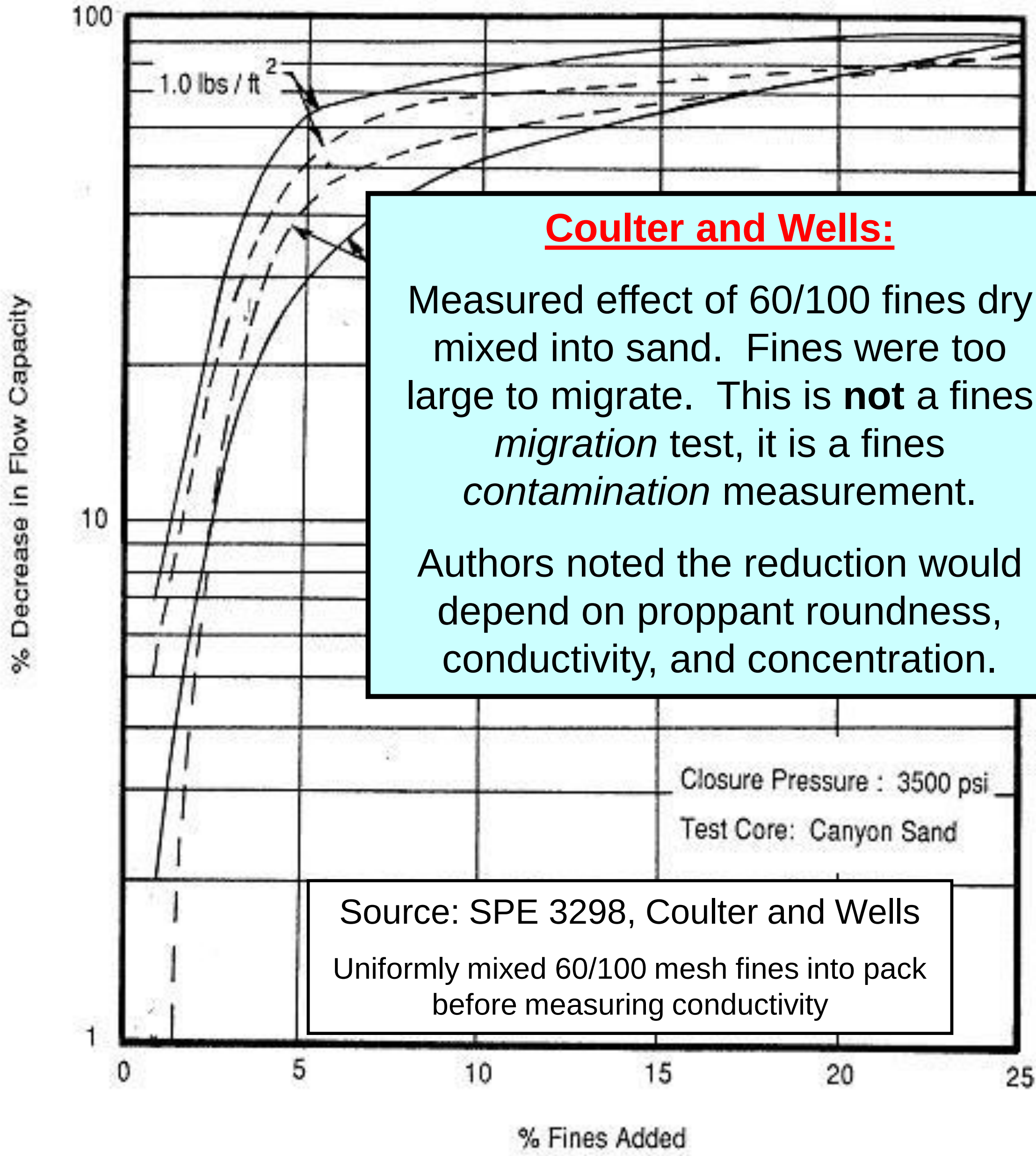
7. All proppants fail (crush) in the same way
8. 5% crush damages all proppants similarly

Do fines affect all proppants similarly?



Coulter and Wells:

Measured effect of 60/100 fines dry mixed into sand. Fines were too large to migrate. This is **not** a fines *migration* test, it is a fines *contamination* measurement.

Authors noted the reduction would depend on proppant roundness, conductivity, and concentration.

Source: SPE 3298, Coulter and Wells

Uniformly mixed 60/100 mesh fines into pack before measuring conductivity

CAUTION: There is little doubt that most fines have the potential to affect the flow capacity of the fracture. However, to use this chart, one must assume:

- **All reported crush is in the 60/100 range**
- **Pore geometry of 20/40 Brady at 3500 psi is identical to the product of interest**
- **Fines are equally damaging to sand, RCS, ceramic**
- **Fines will be uniformly distributed as in test**

Conductivity testing can account for crushed material/fines in a hot, wet environment, and demonstrate that this correlation doesn't work for all proppants!

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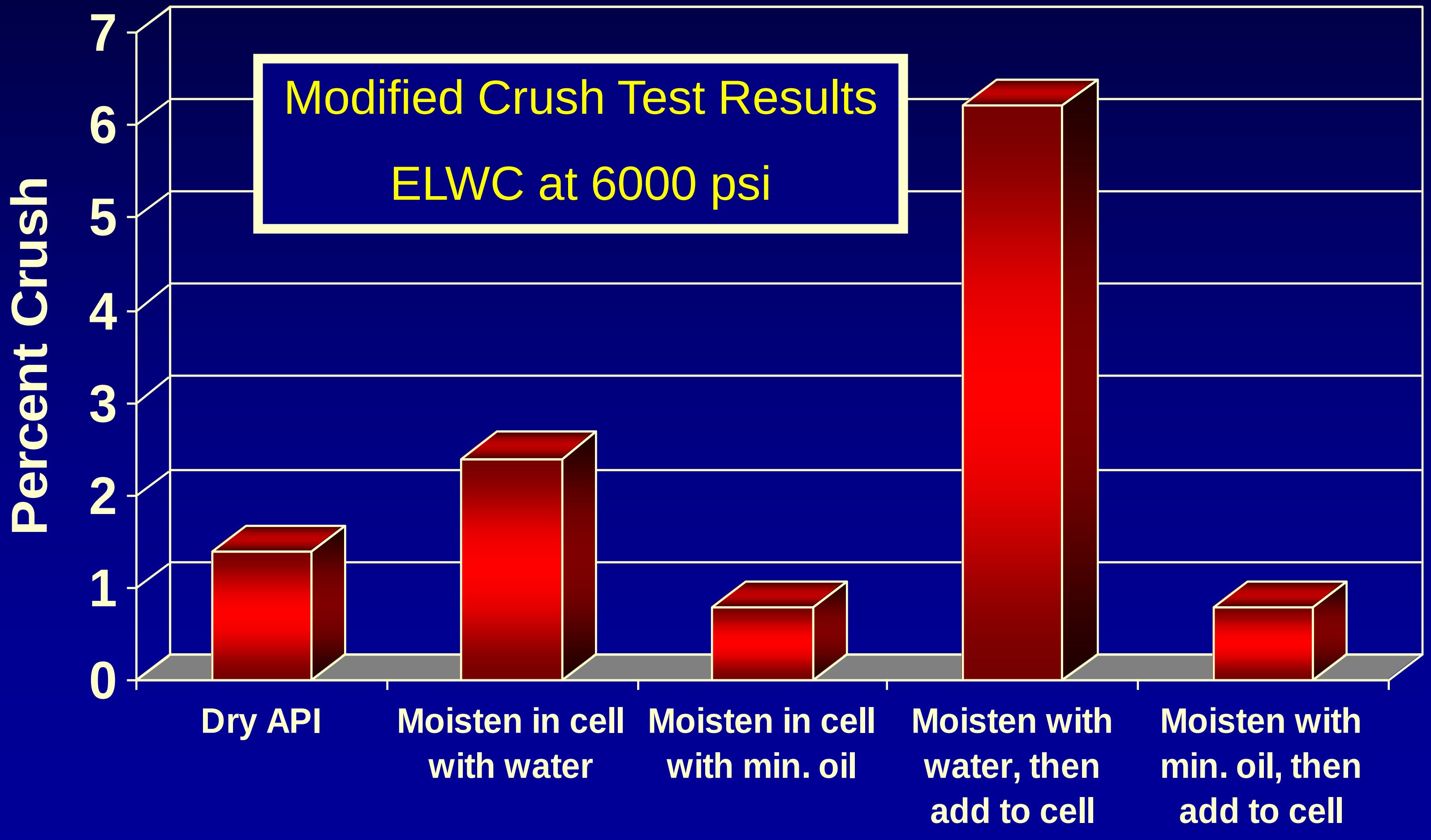
9. Hot/wet crush tests provide adequate understanding

Fluid Effects

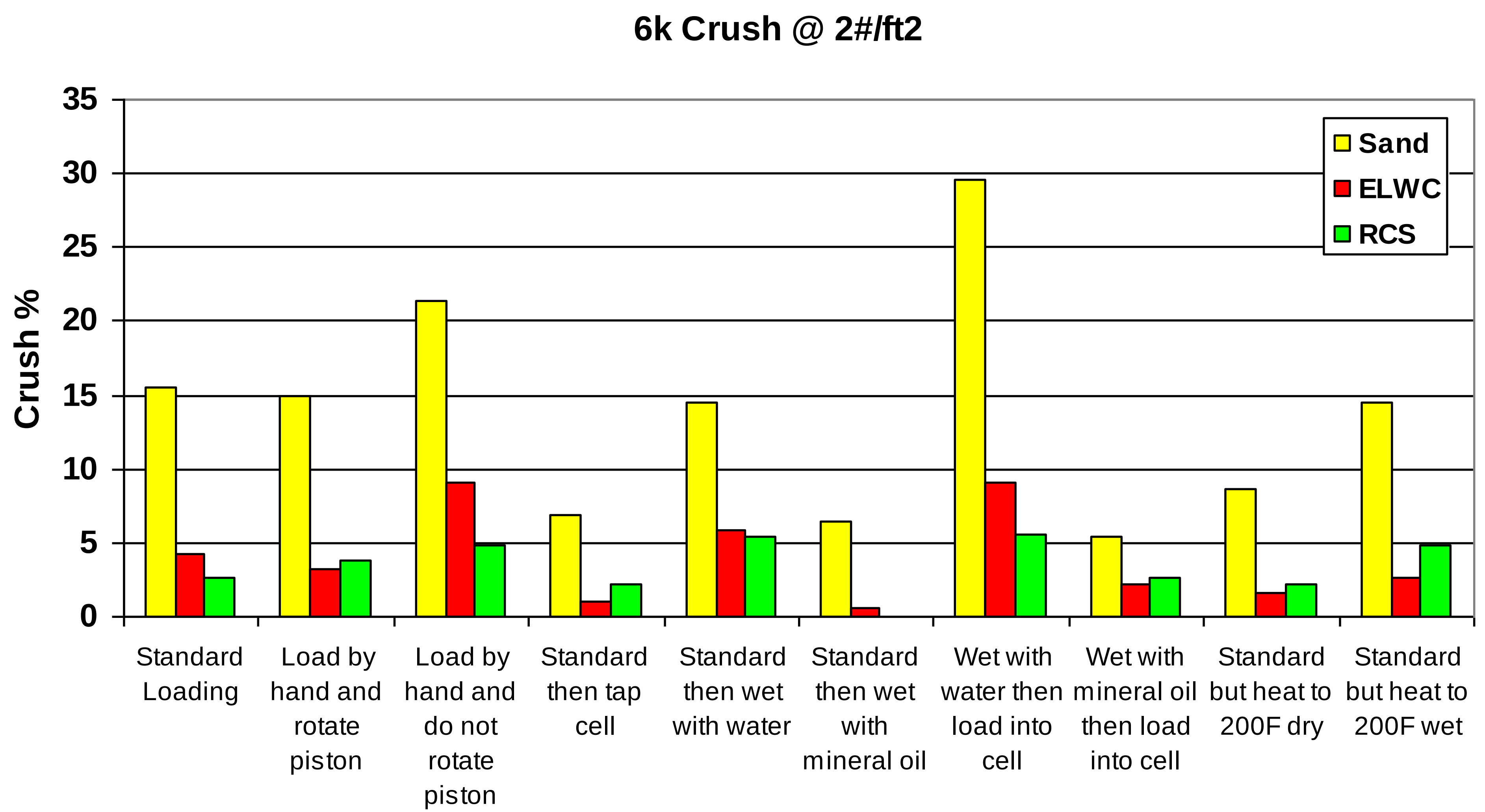
- Crush testing is performed dry. What if the proppant is saturated?



Source: CARBO Tech Brochure 3/4/96

Is one set of Test Conditions superior to another?

Dry, wet, hot, room temperature, water or oil…
is one method more realistic than another?



Source: SPE 119242

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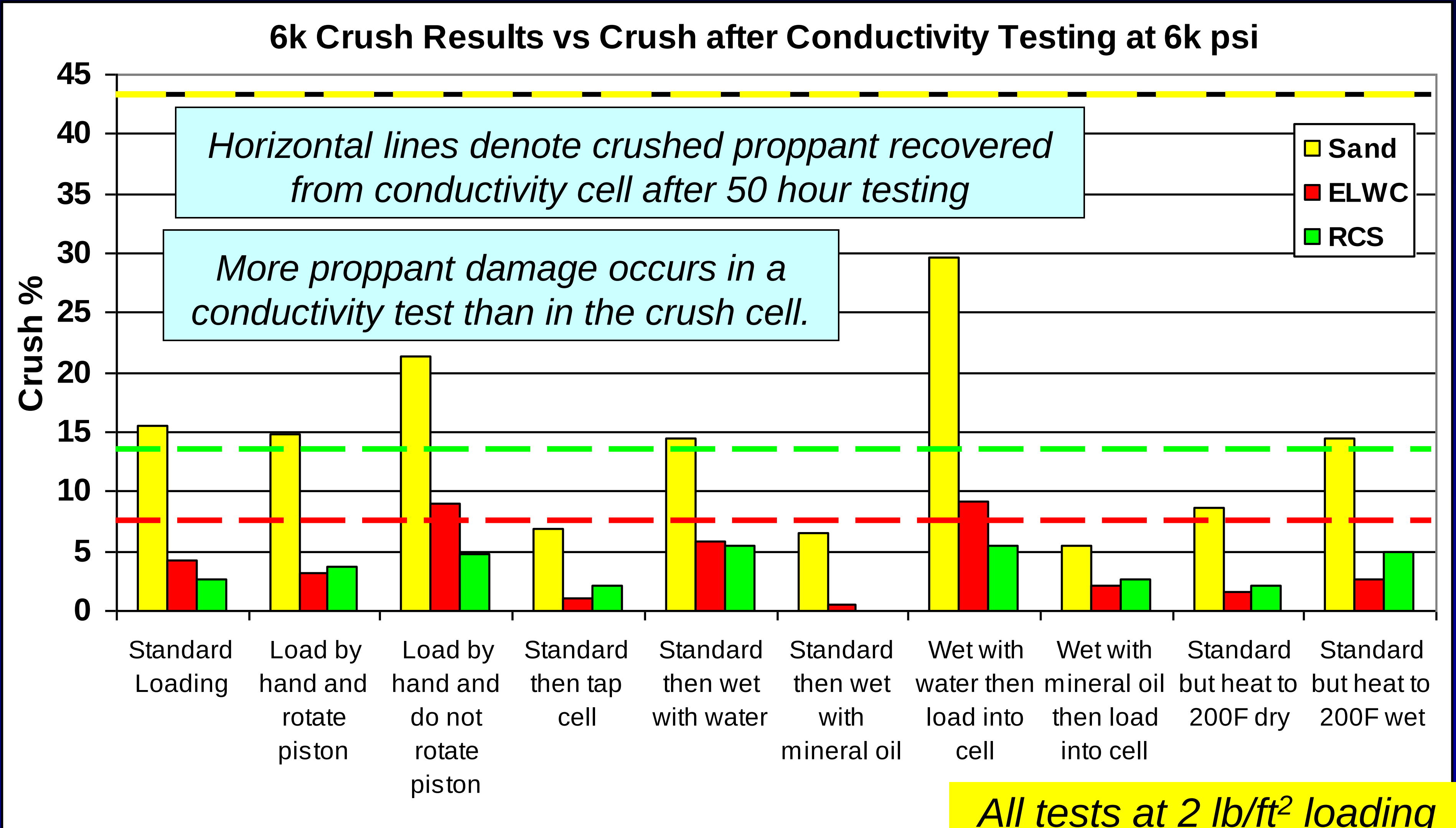
9. Hot/wet crush tests provide adequate understanding
10. Crush tests correlate with conductivity

Can Crush results be Correlated to Conductivity?

Test Differences

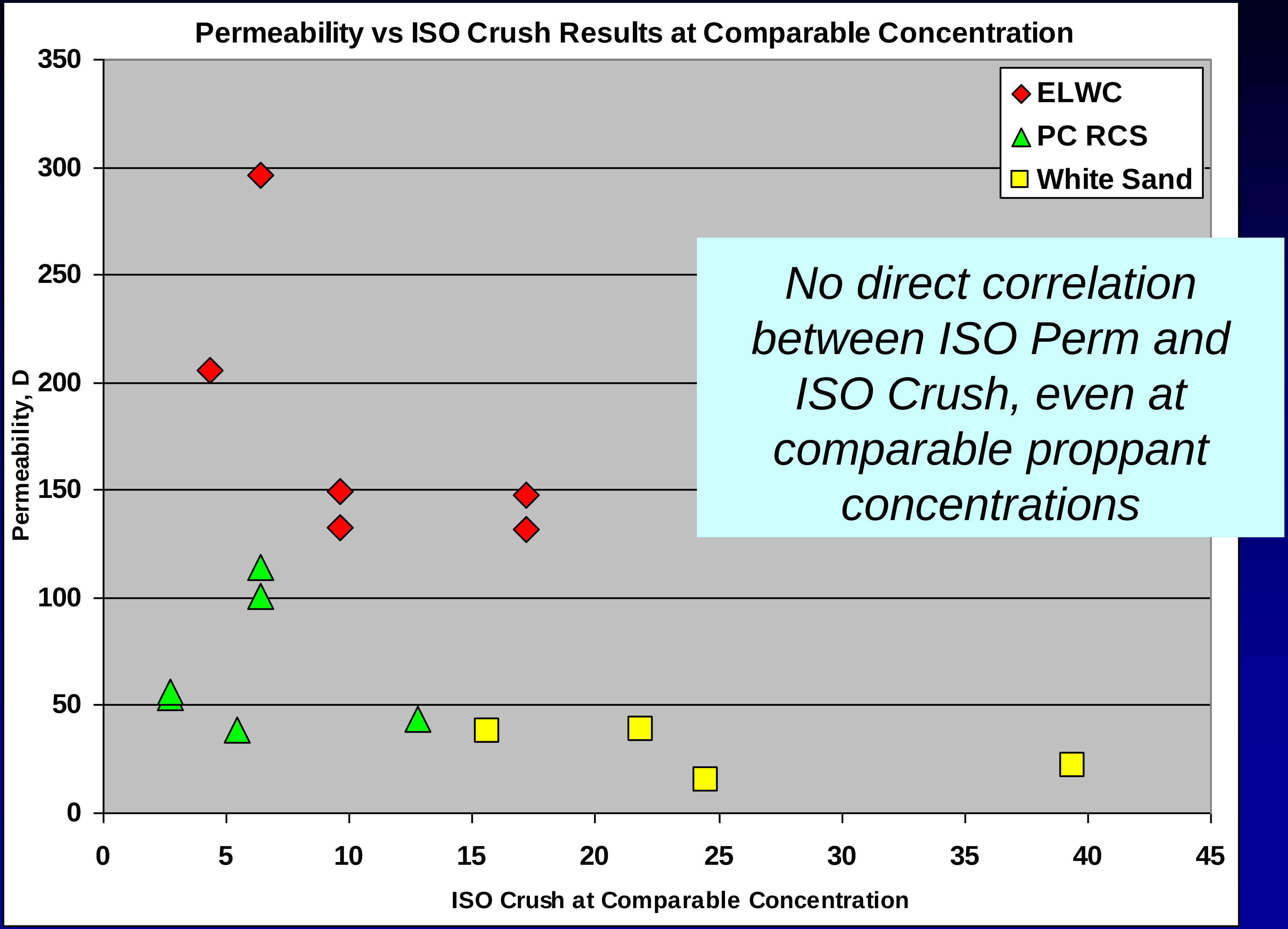
Conductivity Test	Crush Test
Proppants evaluated as received	Remove out of spec particles
Equivalent *mass* loading 2 lb/ft^2	Equivalent *volume* loading ~4 – 5.2 lb/ft^2
Sandstone shims	Steel pistons
Flow brine through pack	Dry
Elevated temperature (150° to 350° F)	Room temperature
Stress held for at least 50 hours	Stress held for 2 *minutes*

Does proppant damage in the conductivity cell correlate to damage with other loading procedures?



All tests at 2 lb/ft² loading

Can Crush results be Correlated to Flow Capacity?



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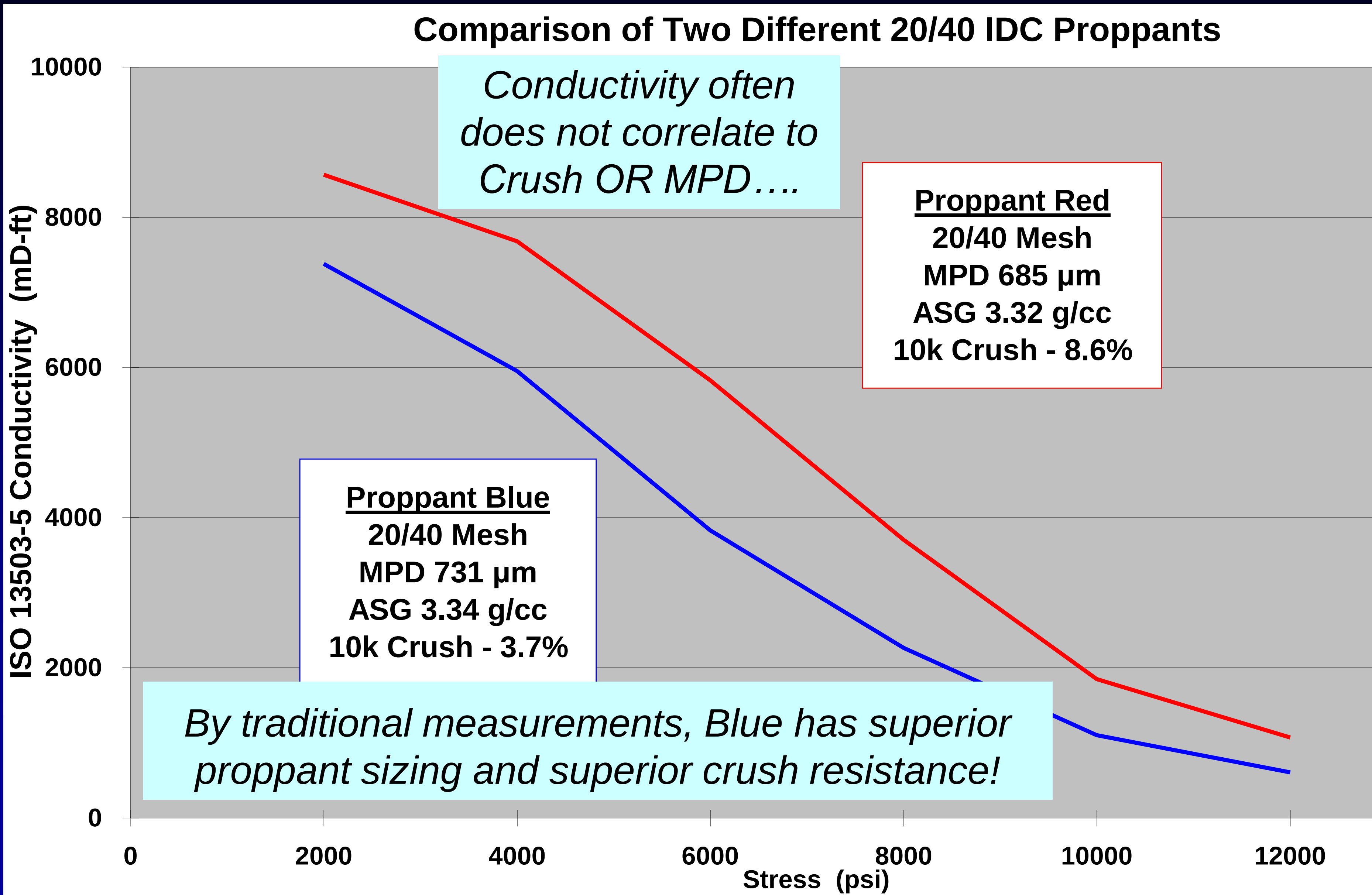


Are Crush results Useful?

- In Manufacturing
  - CARBO performs >70,000 crush tests per year!
  - With automated sampling and crush equipment, can achieve extremely repeatable data
  - Excellent QC gauge for ensuring a consistent quality product is being produced
  - But results are not predictive of conductivity (CARBO has ~ dozen conductivity cells running 24/7/365)

- For Proppant Selection
  - By itself, <u>CAUTION</u> should be used.
  - May be used for qualitative observations.
  - Conductivity testing a much better way to determine proppant value

From API test to practice

- We understand that API test is giving misleading, or at best incomplete answers
- Conductivity tests are closer to reality and a better tool to select a proppant
- Now lab meets reality: How much conductivity is really there and how proppant quality impact productivity

Proppant in UCR

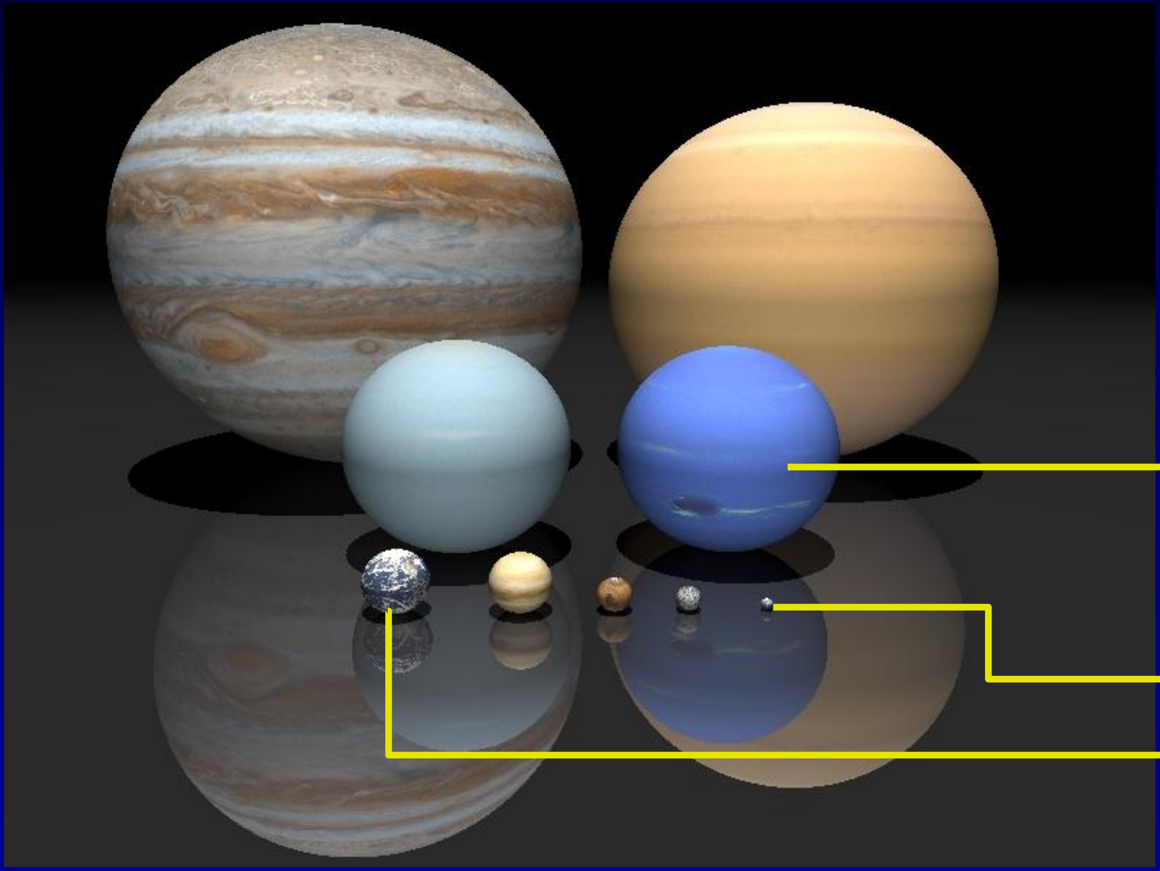
The Challenge of Tight/Unconventional reservoirs:

- EXTREAMLY low permeability formations

Applying key technologies driving UCR development:

- Advanced horizontal drilling and completion
- Multi stage fracturing to dramatically increase reservoir contact

Permeability (pore throat) visualization



Neptune (conventional)

Pluto (tight)

Earth

Territory of Moscow represents shale!

Fracture Optimization

- Wellbore placement and lateral length
- Completion hardware and isolation techniques
- Fracture spacing and number of fracs
- Fracture geometry and conductivity

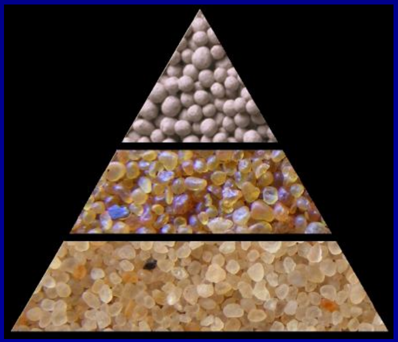
How can we increase fracture conductivity?

- Larger proppant volumes
- Higher proppant concentration
- Larger diameter proppant (depending on quality)
- Cleaner fluids
- Higher tier/Quality proppant

In most cases, increase in conductivity will lead to an increased investment

Proppant selection process

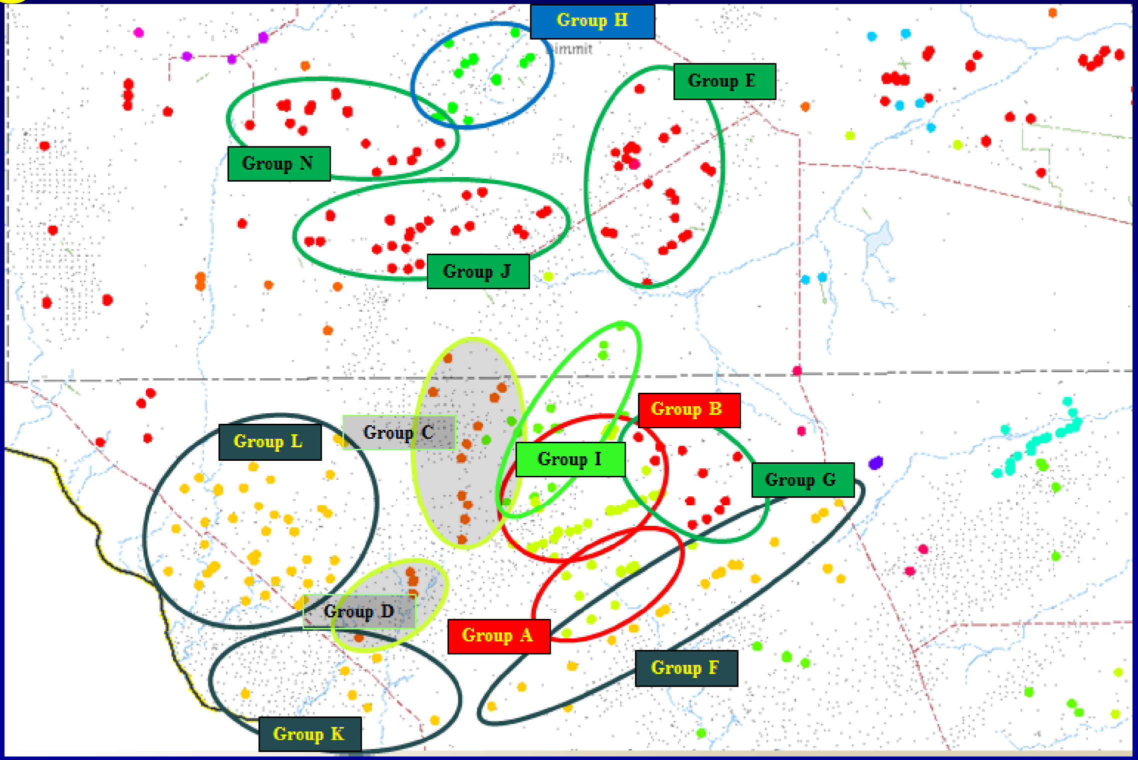
- Predict the fracture Conductivity at Realistic Conditions
  - *Several sophisticated Frac Models will do this*
- Run sensitivities to determine optimal Conductivity
  - *Provides the highest return on investment*
- Validate with field results
  - *Do the results match the model? Recalibrate?*



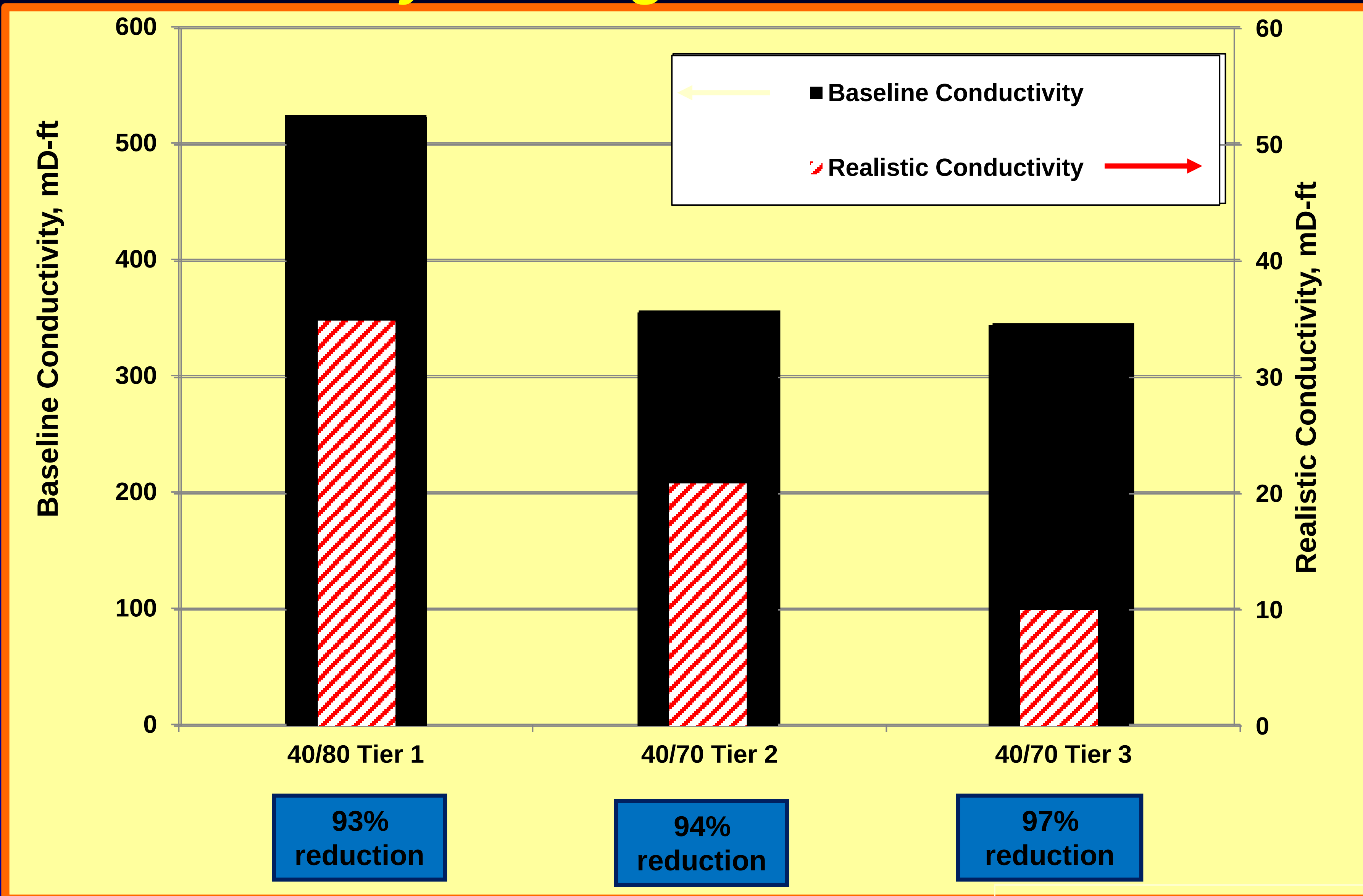
Eagle Ford Shale

Webb County operator

- Evaluated Tier 1 vs Tier 3 proppants
- Compared to internal wells, as well as offset operators

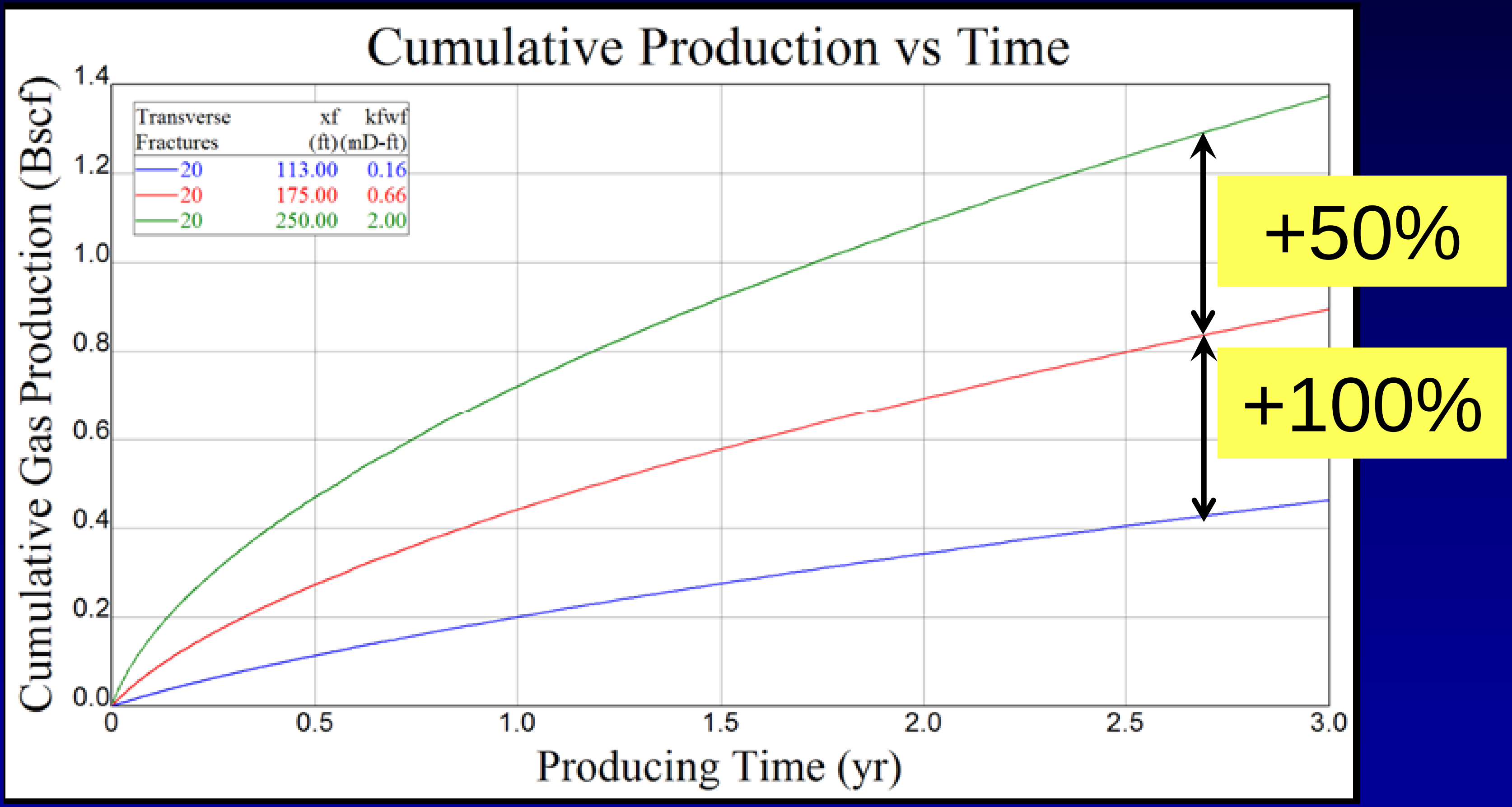


Conductivity at Eagle Ford Conditions

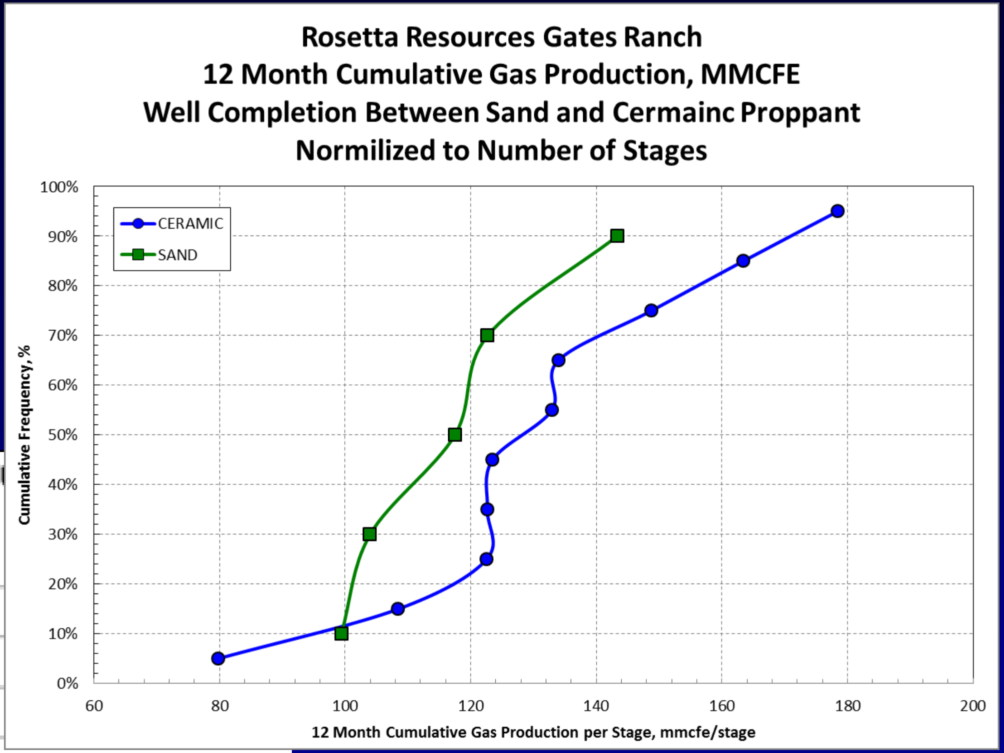


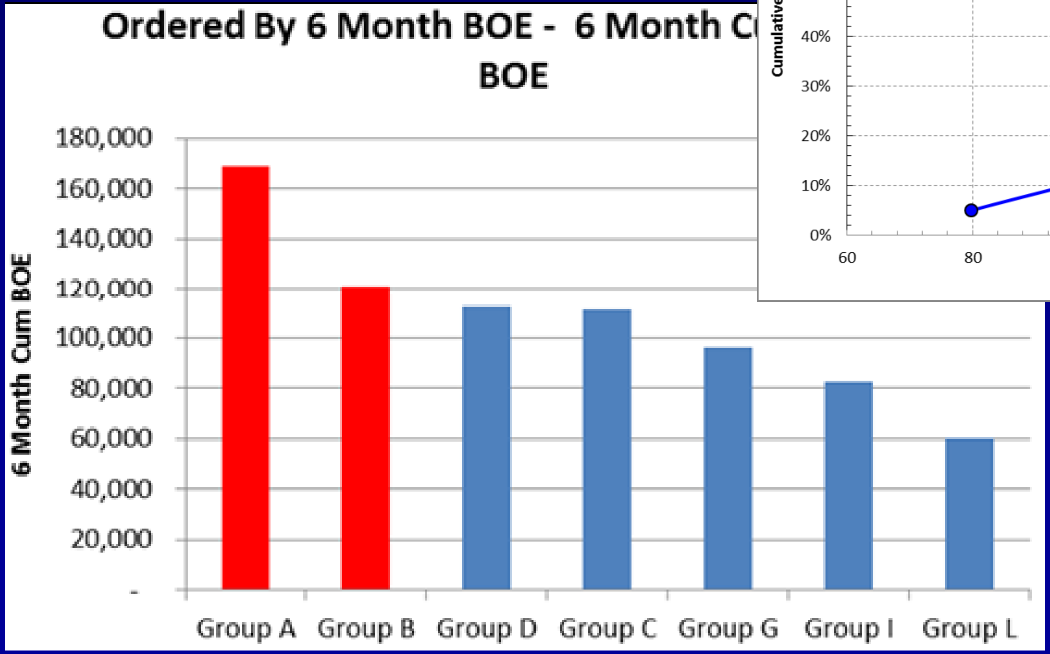
SPE 155779

Eagle Ford Production Match/Modeling



Production impact of conductivity



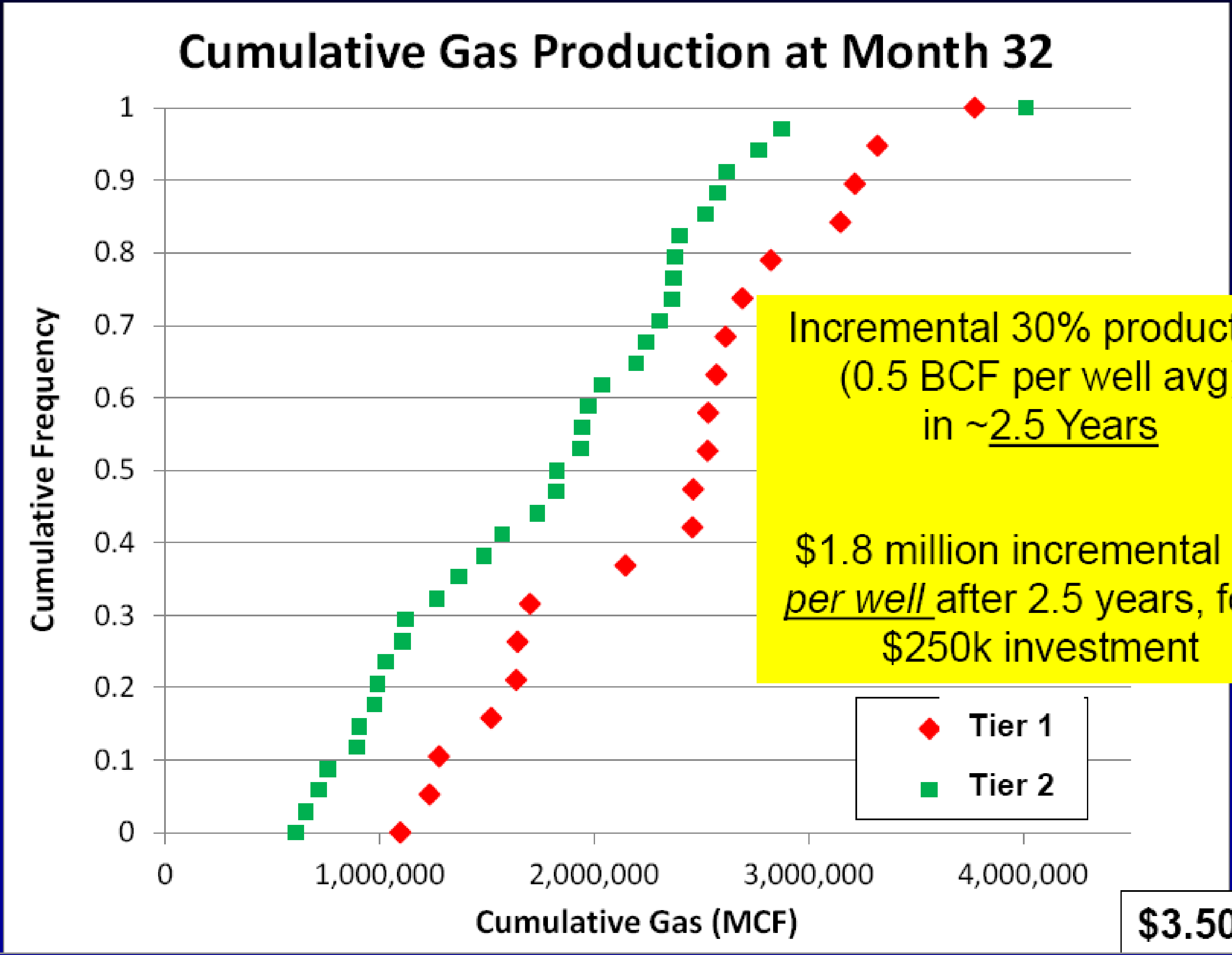


Haynesville Shale

Haynesville Shale

- *Desoto/Caddo Parish by one operator*
- *55 Wells – 20 utilized Tier 1 proppant, 35 utilized Tier 2*
- *All drilled/completed similarly in similar time frame*

Actual production after 2,5 years

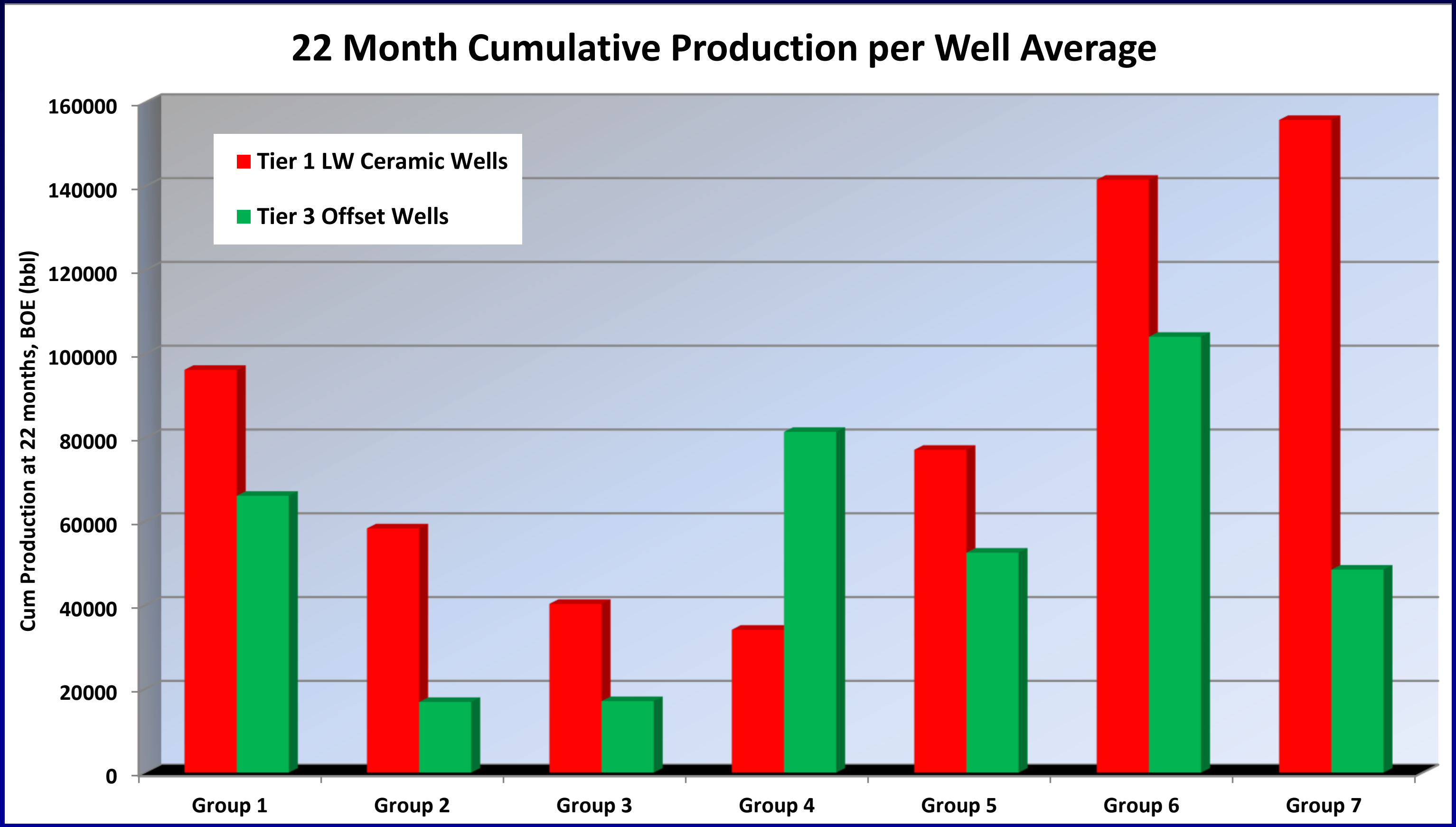


Incremental 30% production
(0.5 BCF per well avg)
in ~2.5 Years

$1.8 million incremental PV *per well* after 2.5 years, for a $250k investment

$3.50/mcf

Bakken Trial



What impacts proppant pack conductivity from a proppant perspective

- Improved roundness equals to improved “space to flow”
- Shape and form of fines
- Ability of fines to migrate
- Proppant uniformity and strength
- Resistance to cyclic loads, chemicals and temperature

Key Take Away Messaging

- The HF process provides two things – reservoir contact and conductive pathway.
  - *It is the critical (only) link between the reservoir and the wellbore*
- Proppant is the conductivity pathway.
- Hydraulic fractures are Conductivity Limited…period.
  - *The more you have, the more you make*
  - *One must estimate the conductivity of the fracture at realistic conditions*
- •Proppant Selection cannot be made based on depth, stress, mean particle diameter or what the last engineer did.
  - *It must be designed specifically to the deliverability of a given well*
- Proppant Selection is a Cost vs Benefit decision
  - *You must determine the economic benefit of increasing the conductivity via frac modeling and field validation*

Summary

- Availability and cost impacting proppant selection
- Unconventional reservoir developments, when taking off, will require massive volumes
- Fluid selection and Conductivity should drive proppant selection
- Best completion practice require a realistic estimate of conductivity
- The economical impact can be tremendous

Questions?

- Presentation based on SPE 119242 and 160206
- Contributors: T. Palish, M. Chapman, J. Godwin, R. Dunckel S. Woolfolk, M.C Vincent