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Optimizing Wellbore Integrity in Well Construction

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Schlumberger Carbon Services

10/16/13

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Agenda

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1. General Observations
   Cementing over time
2. Zonal Isolation
   Cement from Placement to Abandonment
3. Cement Design
   Accounting for the unknowns
3. Looking forward

Evolution - Cementing

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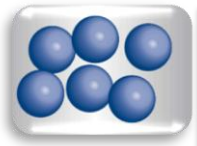


Early AD Clays, Quicklime, Pozzolans

1900
- **1824** Portland Cement Patent
- **1906** Portland Cement used in Oil Well

1920
- **1917** Oil Well Cements Commonly Available

1940
- **1948** API Code 32 “API Code for Testing Cements Used in Oil Wells

1960
- **1956** API Recommended Practice 10B - Tables

1980
- **1980** Basic Mechanism for annular fluid flow defined
- **1983** Gas Migration Design tools
- **1988** Computerized Cement Simulation

2000
- **1993** Basic Placement Simulators
- **2000** Mud Removal Simulations
- **2005** Poro-Mechanical Models

2010
- **2010** API Standard 65 Part 2
- **2012** Drilling Final Rule, Draft of API 90, Norsok D010, others

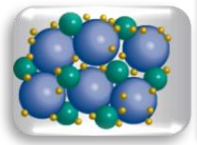
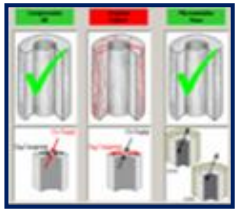
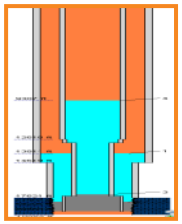
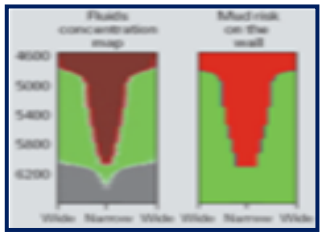


Table E.1 — Casing well-simulation tests

1	2		3		4		5		6		7	
	Temperature gradient, °C/100 m depth (°F/100 ft depth)											
Depth (h_{TOCTVD})	1,6	(0,9)	2,0	(1,1)	2,4	(1,3)	2,7	(1,5)	3,1	(1,7)	3,5	(1,9)
	Temperature											
	°C	(°F)	°C	(°F)	°C	(°F)	°C	(°F)	°C	(°F)	°C	(°F)
305 m (1 000 ft)	27	(80)	27	(80)	27	(80)	27	(80)	27	(80)	27	(80)
610 m (2 000 ft)	32	(89)	32	(89)	32	(90)	32	(90)	33	(91)	33	(91)
1 020 m (4 000 ft)	37	(99)	38	(100)	38	(101)	39	(102)	39	(103)	40	(104)
1 830 m (6 000 ft)	44	(112)	46	(114)	47	(116)	48	(118)	49	(120)	52	(126)
2 440 m (8 000 ft)	52	(126)	54	(129)	57	(135)	60	(140)	63	(146)	71	(160)
3 050 m (10 000 ft)	61	(141)	63	(146)	70	(158)	75	(167)	82	(180)	93	(200)
3 660 m (12 000 ft)	64	(148)	74	(165)	84	(183)	94	(201)	104	(219)	113	(236)
4 270 m (14 000 ft)	73	(164)	85	(185)	97	(207)	109	(228)	121	(250)	133	(271)
4 880 m (16 000 ft)	83	(182)	97	(207)	112	(233)	126	(258)	140	(284)	154	(309)
5 490 m (18 000 ft)	94	(201)	111	(231)	127	(261)	144	(291)	161	(321)	177	(350)
6 100 m (20 000 ft)	106	(222)	124	(256)	144	(291)	163	(326)	182	(360)	202	(395)
6 710 m (22 000 ft)	118	(244)	140	(284)	162	(324)	184	(364)	207	(404)	229	(444)







Cementing Fundamentals

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Types of jobs: Surface, Intermediate, Long String, Liner, Squeeze, Plug

Additives: Thick, Thin, Heavy, Light, Low fluid loss, Expanding, Temperature degradation, (Better cementing through chemistry)

Placement: Slow, Fast, In Between

Simulators: Flow Loops, Temperature, U-tube, Placement,

Jewelry and Control lines: Will become common DHG,DTS,DAS

Regulations: Post Deepwater Horizon, Gasland, Shale gas expansion, CO_2 Sequestration the world is changing

Wellbore Integrity will become more and more an issue

Cementing Failures

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Well Cementing is simply the displacement by cement of the drilling fluid in the well casing-open hole annulus, so why are there failures?

1. Execution
   Equipment, people
2. Incomplete Mud Removal (Design)
3. Flow after placement (Design)
4.. Inappropriate slurry (Design)

Cementing Failures

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Equipment and People

1. Poor selection; inappropriate supplier
2. Equipment failure: Maintenance, catastrophic, rig related
3. People failure: Training and competency, human error, lack of planning, QA/QC process

Design Failures

Not so simple, let's take a look

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Zonal Isolation

From Placement to Abandonment

Mud Removal - Centralization

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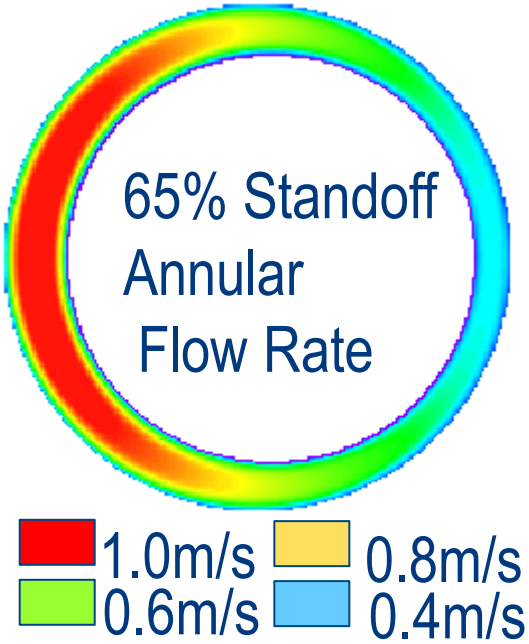
- Stand-off: measure for centralization
- 100%: casing in the middle of the hole
- 0%: casing touching one side of the hole

- Flow prefers wide side.
- Major influence on mud removal efficiency



7" Pipe in 8 .8" Hole @ 1000lpm

- **Standoff < 75% almost always guarantees a bad cement job**

Mud Removal - Laminar or Turbulent Flow?

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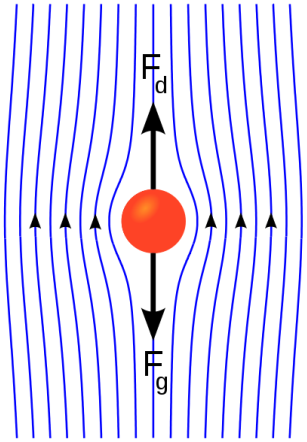
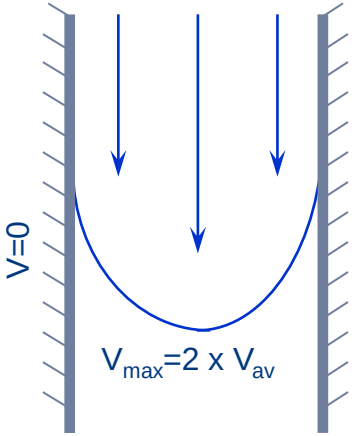
Laminar Flow

- Streamline flow, no mingling of parallel layers.
- Flow velocity at solid surface is zero
- Highest flow velocity furthest from surface
- Only shear stress acts at the surface

NEED **HIGH** RHEOLOGY FLUIDS!!!

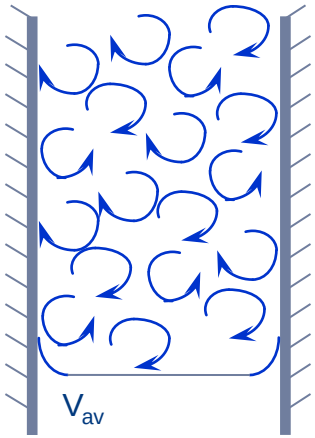




Turbulent Flow

- Eddies are random in size and direction
- Average direction is the mean flow
- Incident and Shear forces act at the surface

NEED **LOW** RHEOLOGY FLUIDS



Cementing Design – Turbulence

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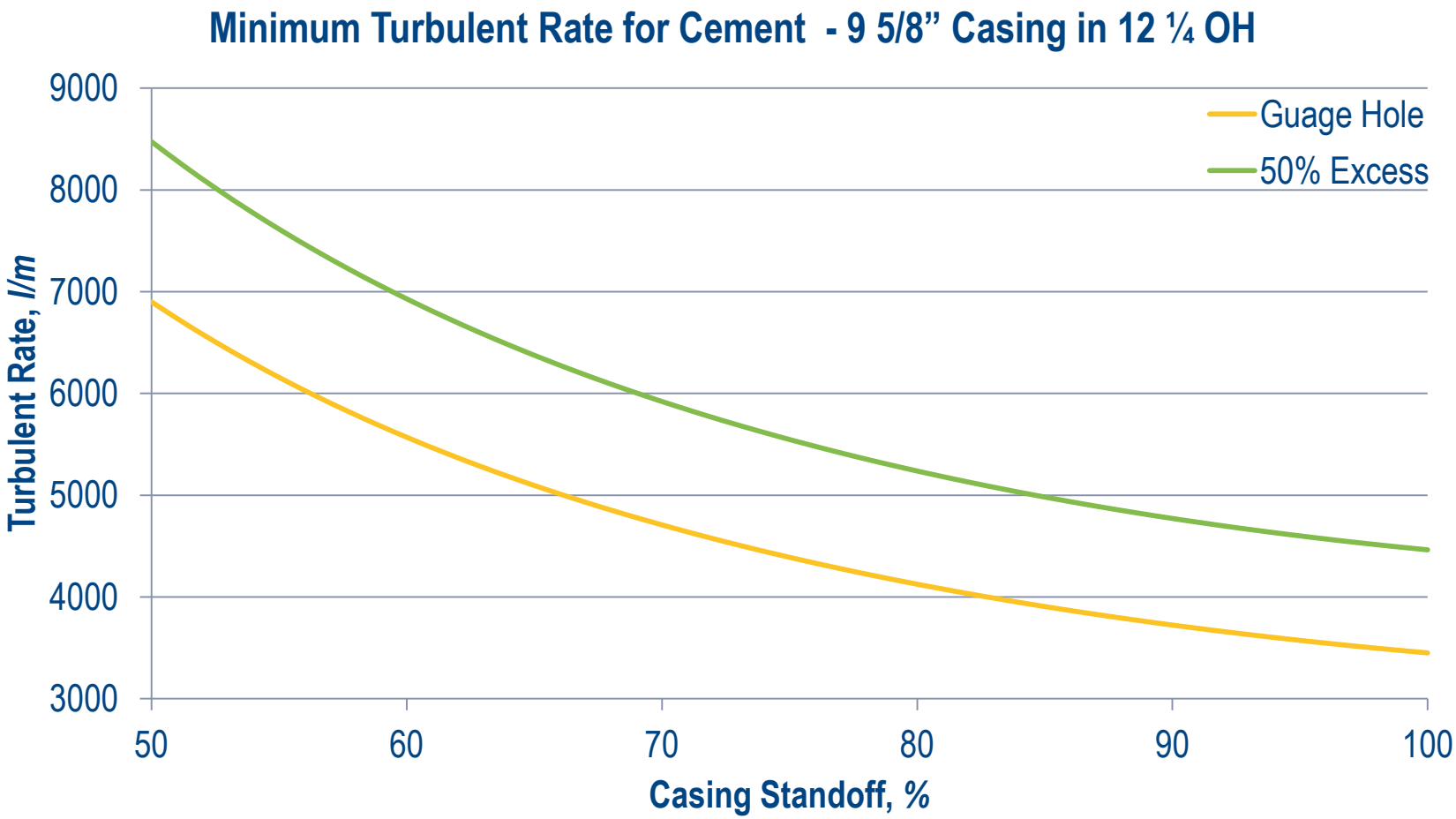

Cementing Design – What if?

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Turbulent Flow Regime	Laminar Flow Regime
Hole Size is Bigger Than Expected	
• Won't Be Turbulent – Mud Channel	• Probably OK
Formation Weaker Than Expected	
• Can't Slow Down – Losses	• Slow Down
Problems Reaching Desired Rate	
• Won't Be Turbulent – Mud Channel	• Probably OK

Slurry and Spacer Design Critical to be based on actual well conditions !!!!!!!

Designing a Cement Job

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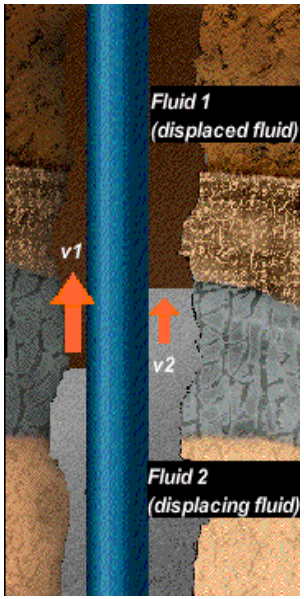
- **Check for an efficient mud removal to prevent mud channeling and to ensure good zonal isolation**

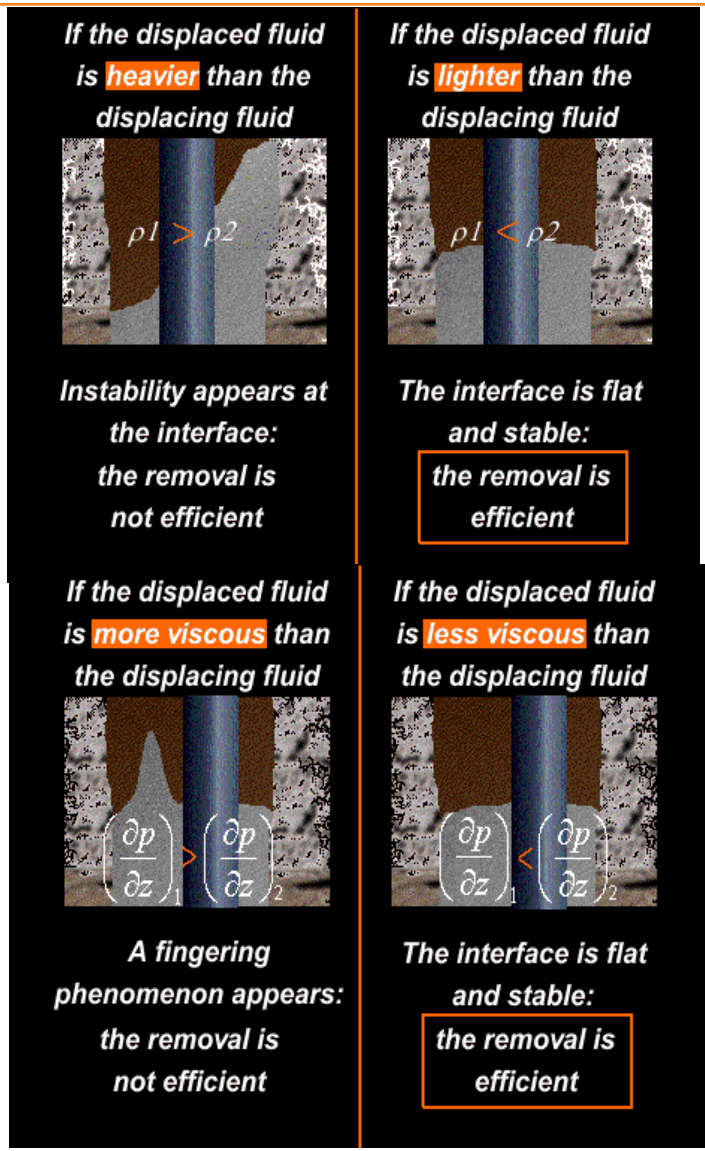
  Ensure a flat interface between fluids

  Avoid stationary mud around the annulus

  Ensure good wall cleaning



- *Optimize fluid properties (density, viscosity hierarchy)*
- *Optimize the pumping rate/velocity, yield stress and PV*
- *On the way down : Mechanical plugs*
- *Optimize casing centralization*
- *Optimize pre-flushes contact time, volume, velocity and flow rate*



Mud Removal – Density-Viscosity Hierarchy (Ryan et al. 1992)

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Slurry density/viscosity > Spacer density/viscosity > Mud density/viscosity

- Flattens fluid interface and improves interface stability.
- Minimum density difference of 10%.
- Best spacer density halfway between mud and slurry density.
- Less effective in highly deviated sections
- Counterproductive in pipe – Use Wiper Plugs

Mud Removal – Industry Solution

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- 1-D Laminar Flow Design Criteria (SPE 24977) 1992
- 2-D Computational Fluid Dynamics (SPE 68959) 2002
- Future will be Integrated Model 2014
  Rheology, Geometry, Temperature

Zonal Isolation – Cement Phases

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End of Job

Cement set

1. Placement	2. During Set	3. Post-set
Liquid	*Semi Solid*	*Solid*
Minutes	Hours→Days	Months → Years
Mud Removal	**Fluid Migration**	**Mechanical Properties**
1. Centralisation 2. Rheology 3. Density	1. CSGS 2. Additives	1. Compressive Strength?? 2. Youngs' Modulus

Gas Migration – Critical Static Gel Strength

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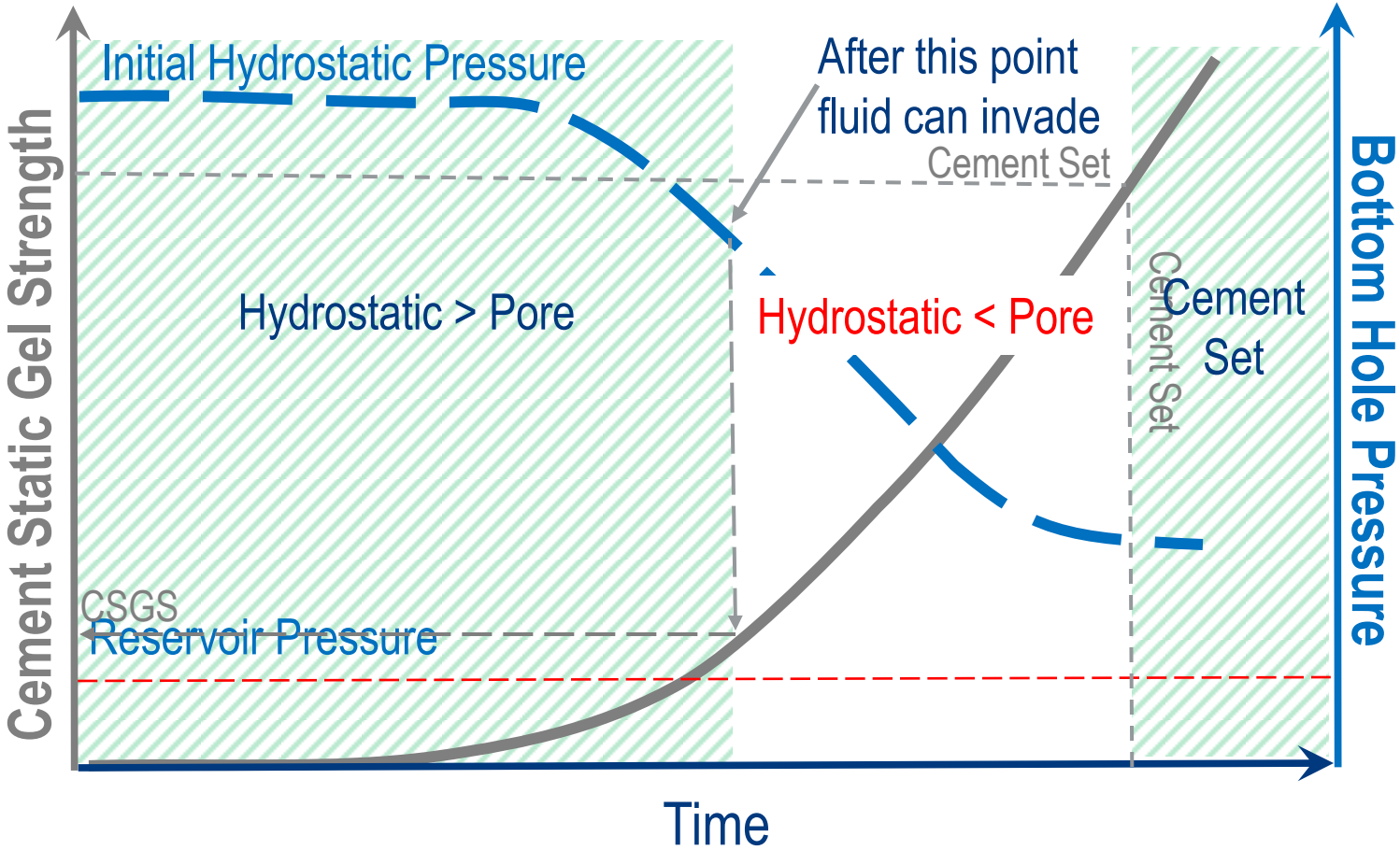

Fluid Migration – Critical Static Gel Strength

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$$CSGS = \frac{OBP \times 300 \times D_{eff}}{L}$$

OBP	*Overbalance Pressure*
300	*Conversion Factor*
L	*Length of Cement Column*
D_{eff}	*Effective Diameter*

$$D_{eff} = D_{OH} - D_C$$

D_{OH}	*Open Hole Diameter*
D_C	*Casing Diameter*

Fluid Migration – Slurry Design

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1. Faster liquid to Solid Transition
    - Dispersants
    - Antigelling agents

2. Prevent Downhole Pressure Loss
    - Foamed cement
    - Downhole gas generation

3. Reduce Permeability of Semi Solid Cement
    - Latex
    - Microsilica

Gas Migration – Industry Solution

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- Identify Mechanism of Invasion (*SPE 11982*) C. 1980
- Invasion Risk Software (SPE18622) C. 1989
- Slurry Design for High Risk Zones (SPE 17258) C.1988

Zonal Isolation – Cement Phases

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End of Job

Cement set

1. Placement

Liquid

Minutes

Mud Removal

1. Centralisation
2. Rheology
3. Density

2. During Set

Semi Solid

Hours→Days

Gas Migration

1. CSGS
2. Additives

3. Post-set

Solid

Months → Years

Mechanical Properties

1. Compressive Strength??
2. Youngs' Modulus

Why Mechanical Analysis?

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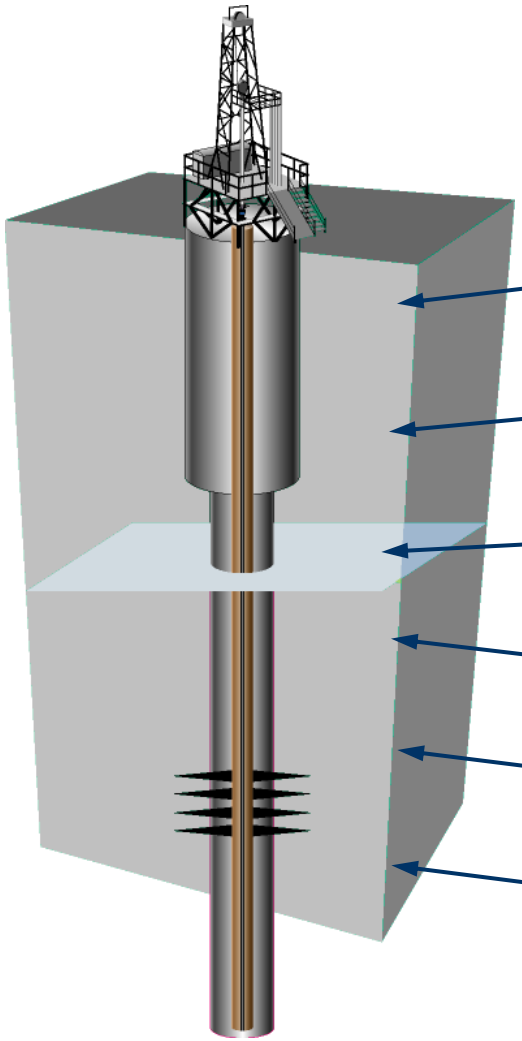

A well is a stressful environment

- Production/Injection
- Temperature changes in upper casings during production/injection
- Pressure changes: drilling, production injection
- Permanent well abandonment
- Formation changes/tectonic activity
- Well completion/perforation/stimulation

Stresses on the Cement Sheath

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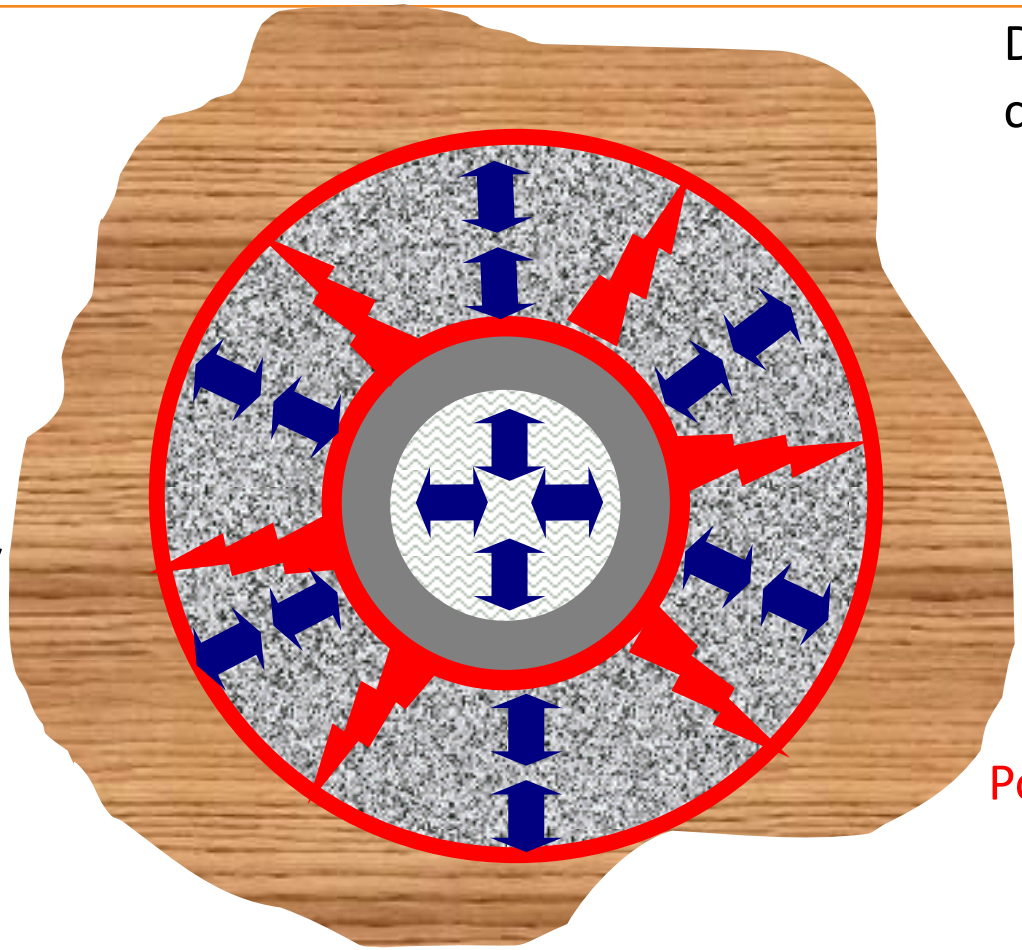
Tensile cracks

- Wellbore pressure increase
- Wellbore temperature increase
- Cement shrinkage

De-bonding cement/ rock interface

- Formation stress decrease
- Wellbore pressure decrease
- Hydraulic fracturing
- Cement shrinkage



De-bonding steel/ cement interface

- Wellbore pressure decrease
- Temperature decrease
- Casing movement
- Cement expansion

Potential Results

- Loss of Well Integrity
- Sustained Casing Pressures
- Collapsed Casing

Cement Mechanical Failure

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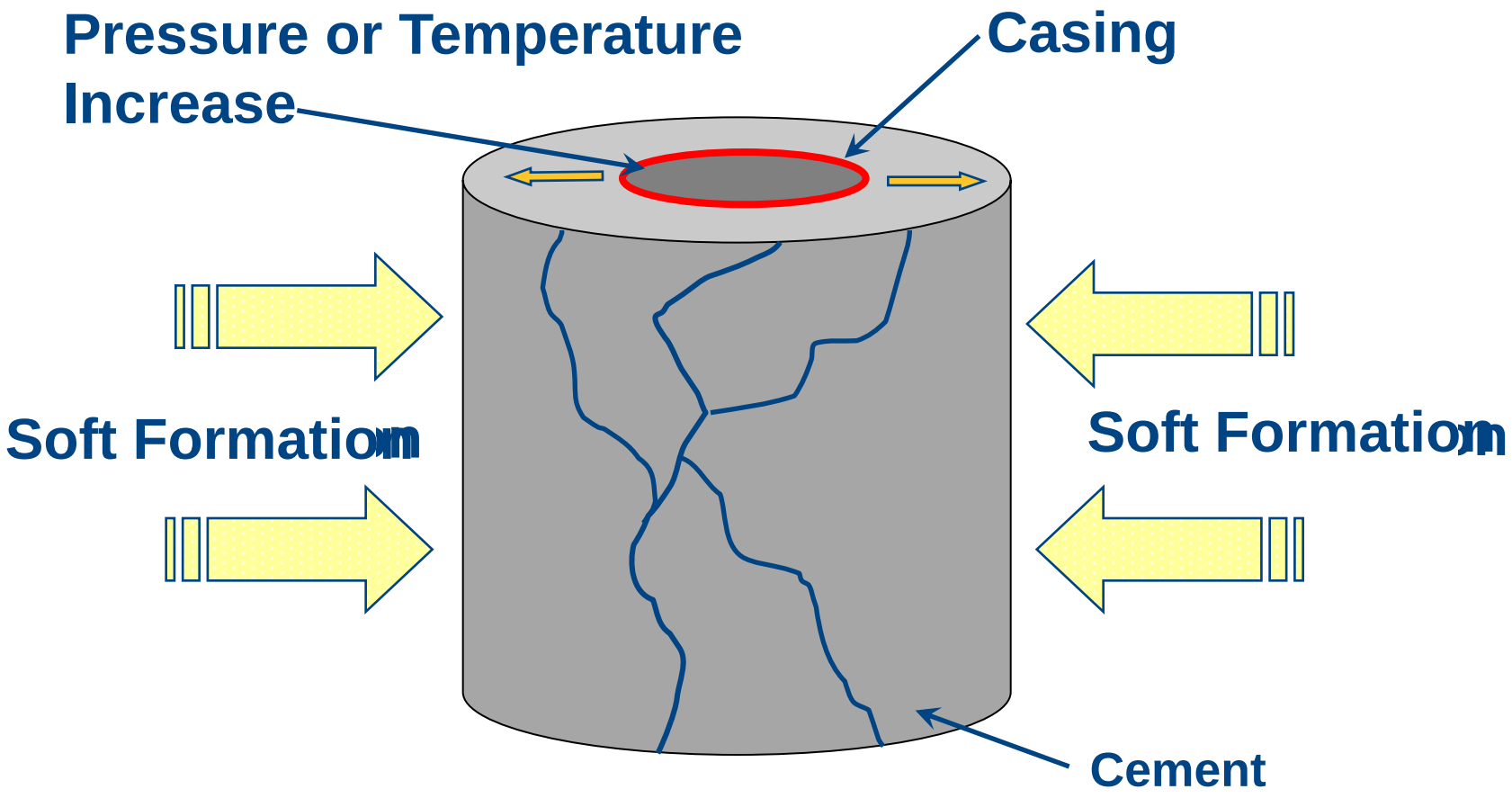

Work Goes on to Improve Cement Slurries

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Understanding of Nano/Microstructure of set cements enables our capabilities to create next generation of materials

- First Result: Solution to Coarsening Effect in HPHT cement has potential for HO and Geothermal applications
- Composite materials (Organic-Inorganic) = (Elasticity-Strength) -> Self Sealing

Expanding cement combined to Poro-Mechanical Model -> Sealing Properties

Slurries designed for specific purpose (CO_2 Resistance)

Better understanding of the temperature/pressure profile of setting cement

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Well Cementing Design

Accounting for the unknowns

Simulation

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Flow Loops 1940s *First indication of the importance of mud removal*

Circulating Temperature equations

U – tube simulator 1970s

1-D Flow simulation 1980

Gas Migration late 1980s

2-D Simulators 1990

2-D Computational Fluid Dynamics 2001

Building the complete model 2013 *Still trying to understand mud removal*

It's all the unknowns that are hard to simulate

Effects of Ovality on Zonal Isolation

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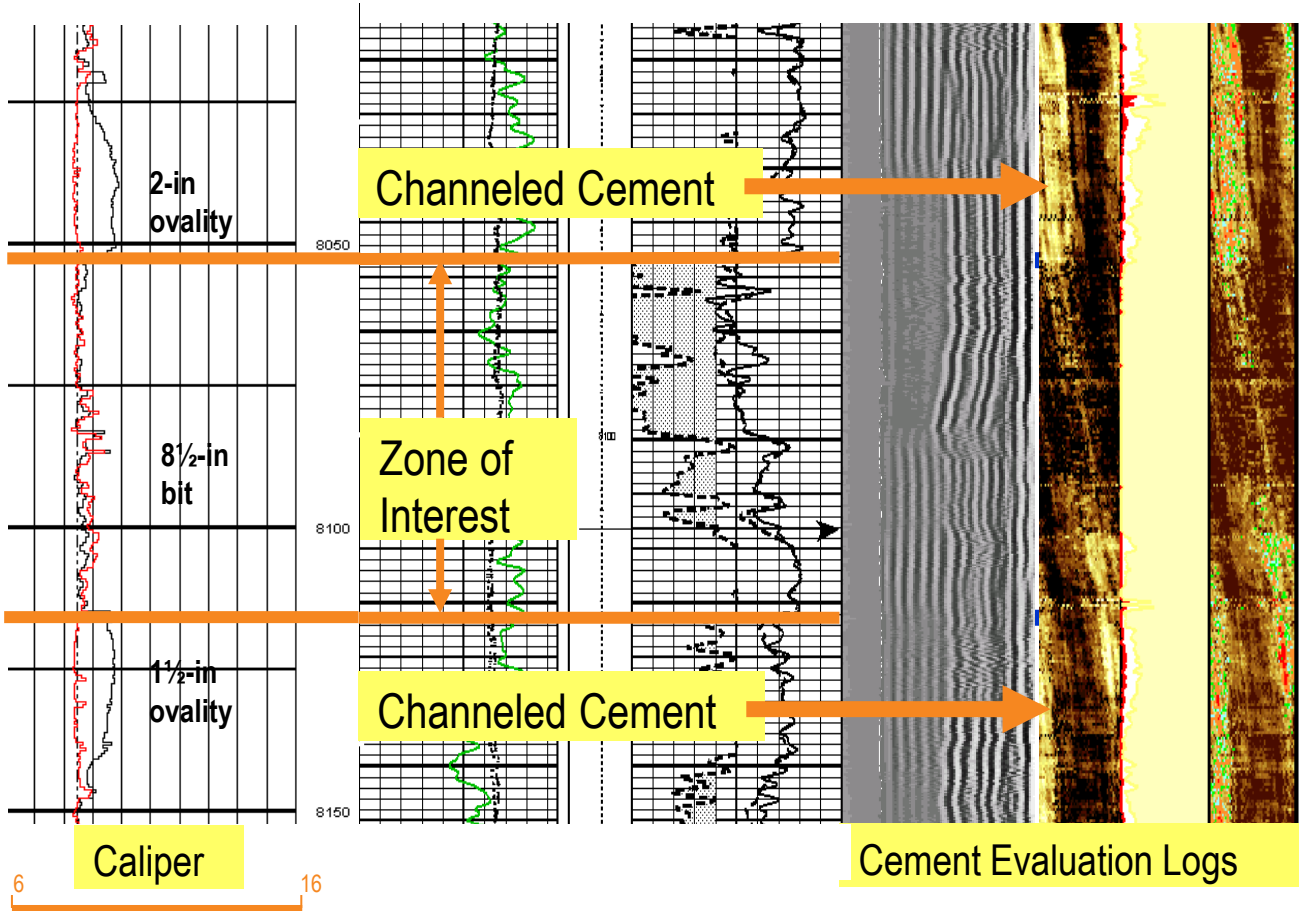

Quantitative Assessment of Ovality/Washout

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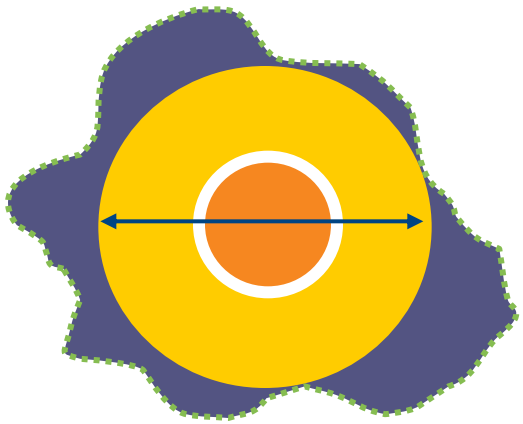

Outside hole (OH) diameter = 8 3/4-in bit

Casing diameter = 7 in

Average rugosity = 5/8 to 3/4 in

- Annular volume per foot:
  - **8 3/4-in OH = 0.0268 bbl/ft**
  - **9 3/8-in OH = 0.0378 bbl/ft**
  - **9 1/2-in OH = 0.0401 bbl/ft**

- Annular volume per 20-ft interval:
  - **8 3/4-in OH = 0.536 bbl**
  - **9 3/8-in OH = 0.756 bbl** **+ 41%**
  - **9 1/2-in OH = 0.802 bbl** **+ 50%**

Conventional Free-Standing Model

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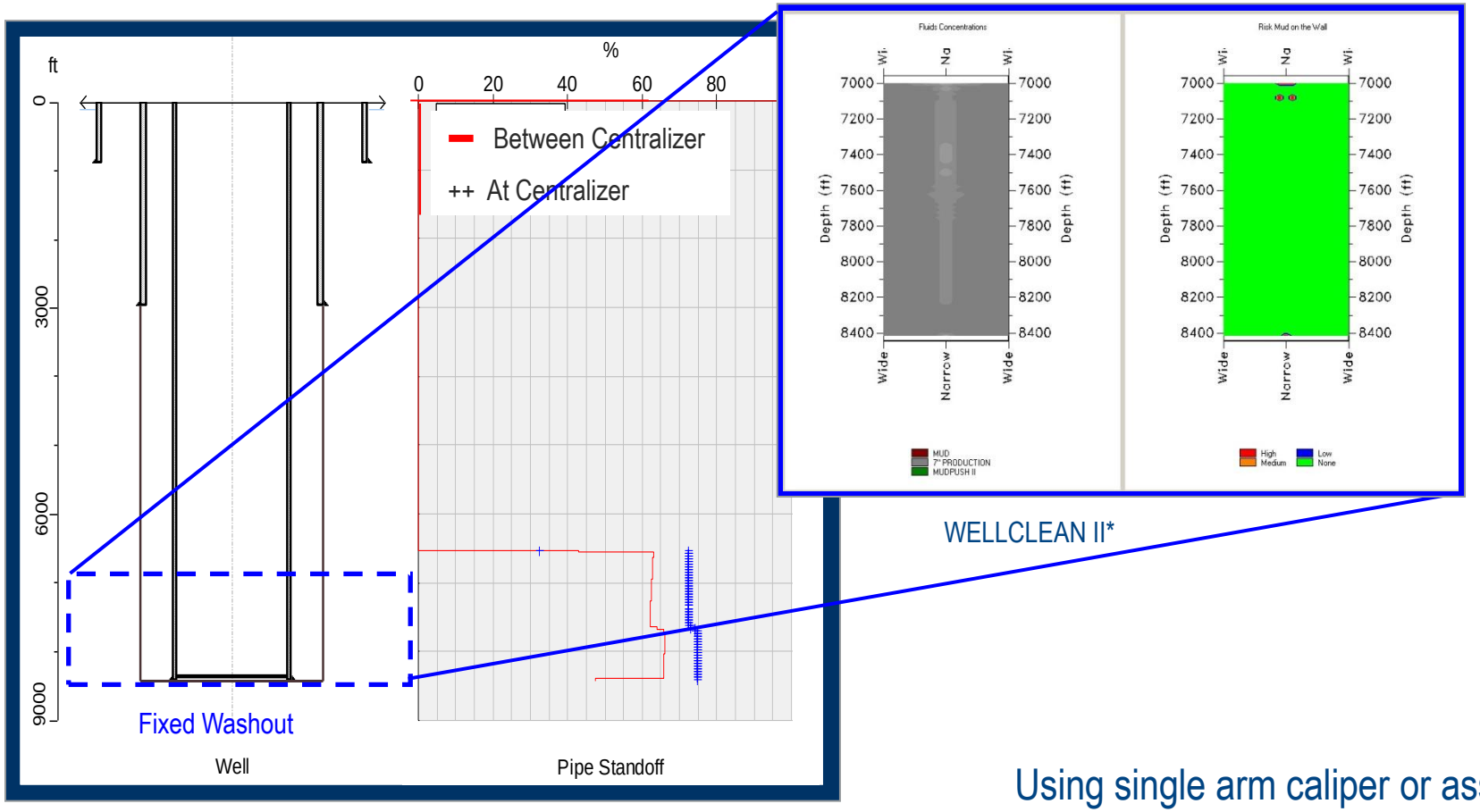

WELLCLEAN II*

Using single arm caliper or assuming gauge hole

Utilizing OH Caliper to Optimize Design

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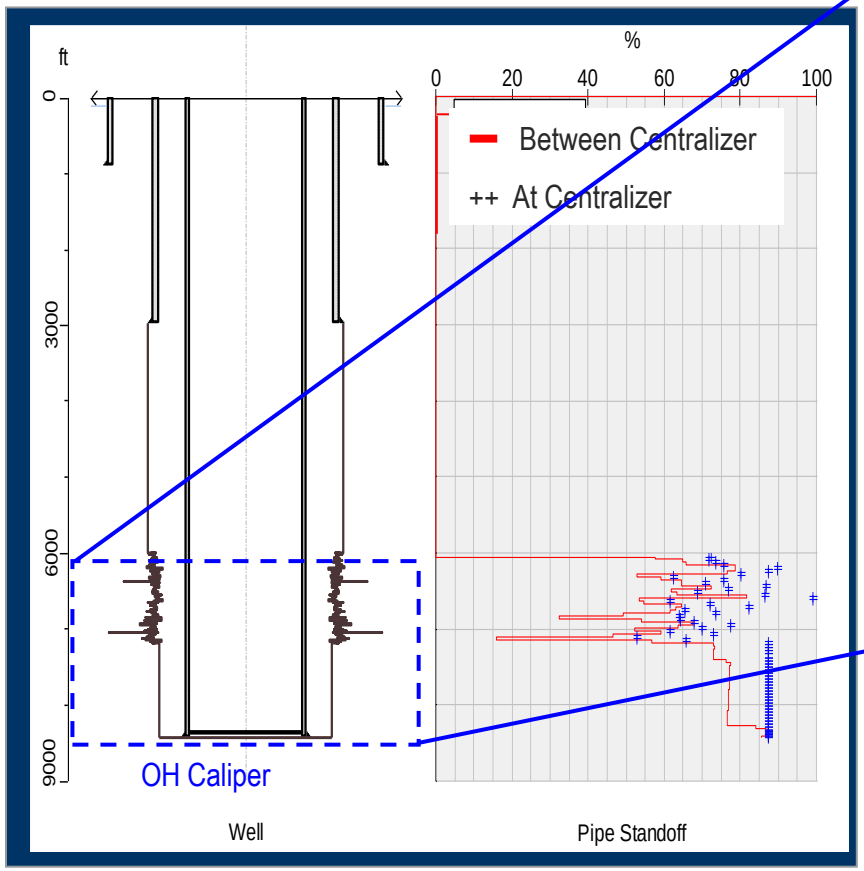

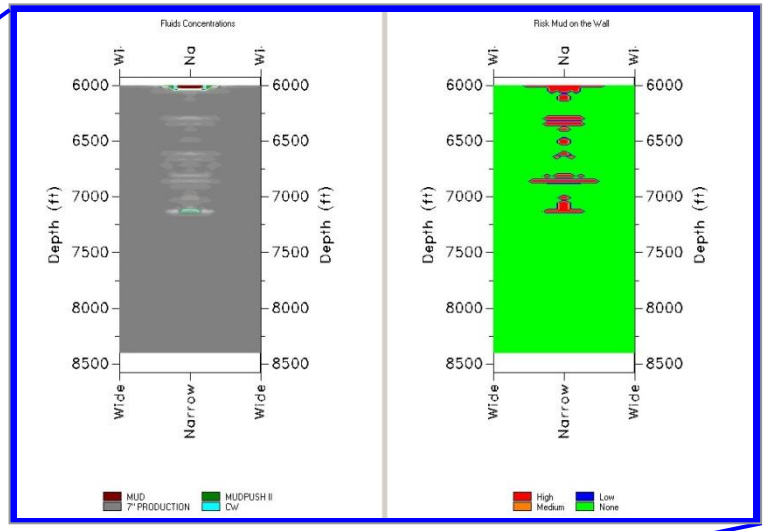

WELLCLEAN II

Using multi- arm caliper

Cement Design Flow Path

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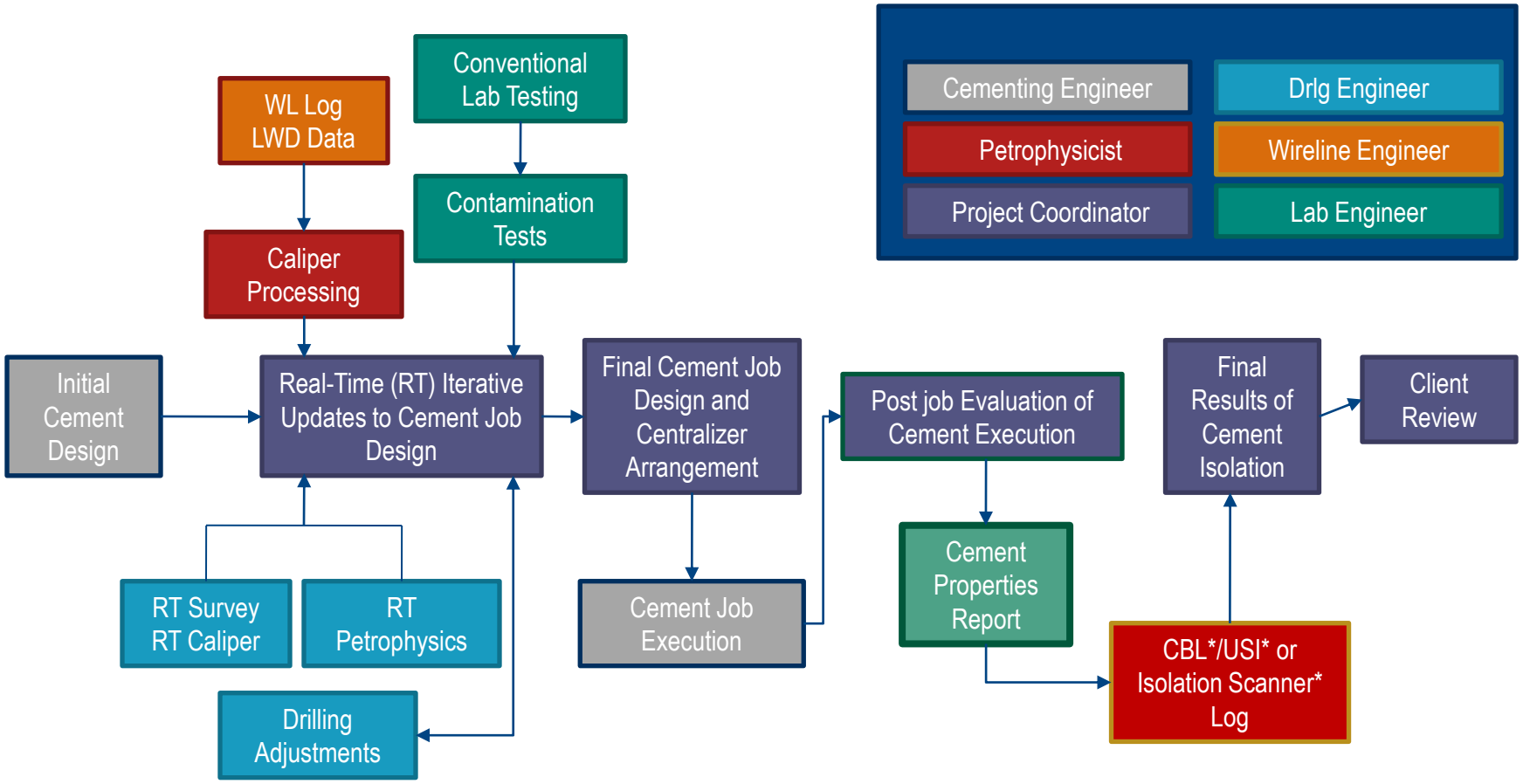

Integrated Solution to Zonal Isolation

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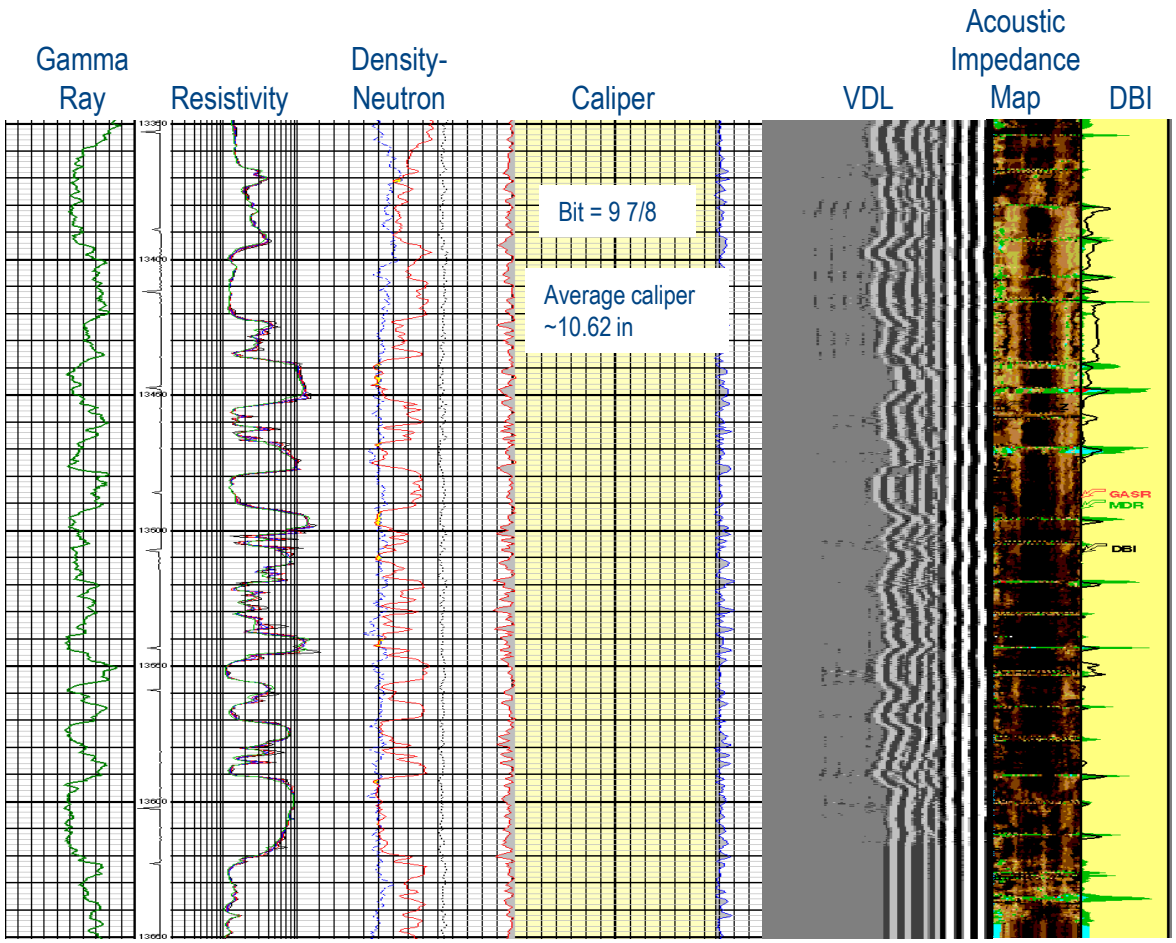

TD at 13,788 ft

Results when integrating all known information into the cementing design

Where Are we Going?

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1. Work remains in understanding cement placement including circulating temperature
2. Instrumentation external to casing will help in improving the above
3. Research in molecular and nano technologies will improve slurry robustness
4. Regulations will only become stricter with more oversight
5. Greater accountability for both operators and service providers

Questions?