Mechanical Integrity Testing Workshop

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Oklahoma City, OK Sept 15th, 2019

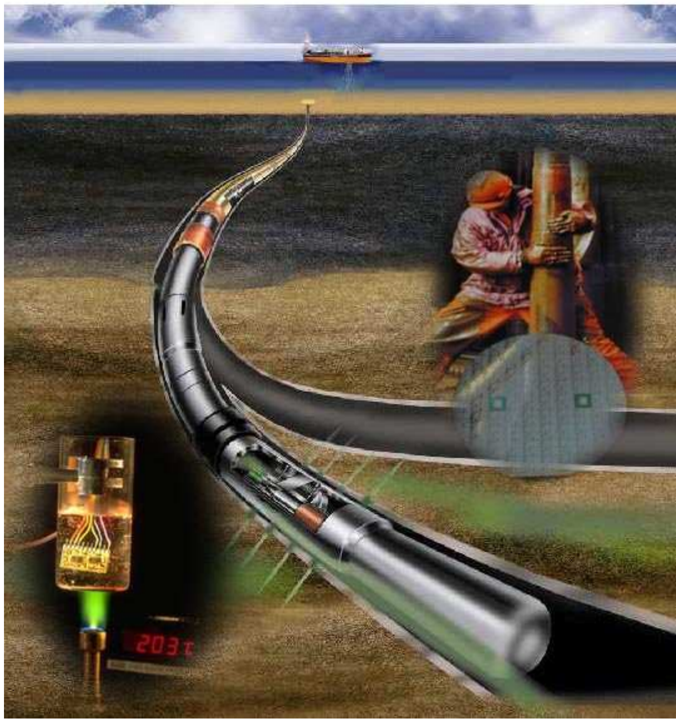
Safety Moment!

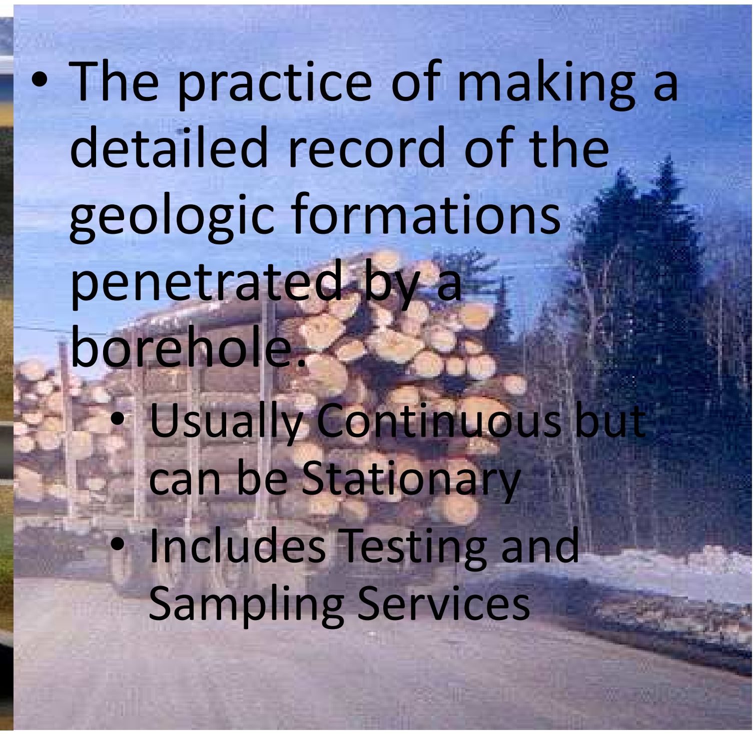
- With wild swings in Temperatures about to start happening this time of year.
- Keep your tire pressure within the recommended range for your vehicle.

Agenda

- Introduction to Open Hole Logging
- Primary Cementing 101
- Interpreting Cement Evaluation Tools
- Remedial Cementing 101
- Casing Inspection 101
- New Technologies

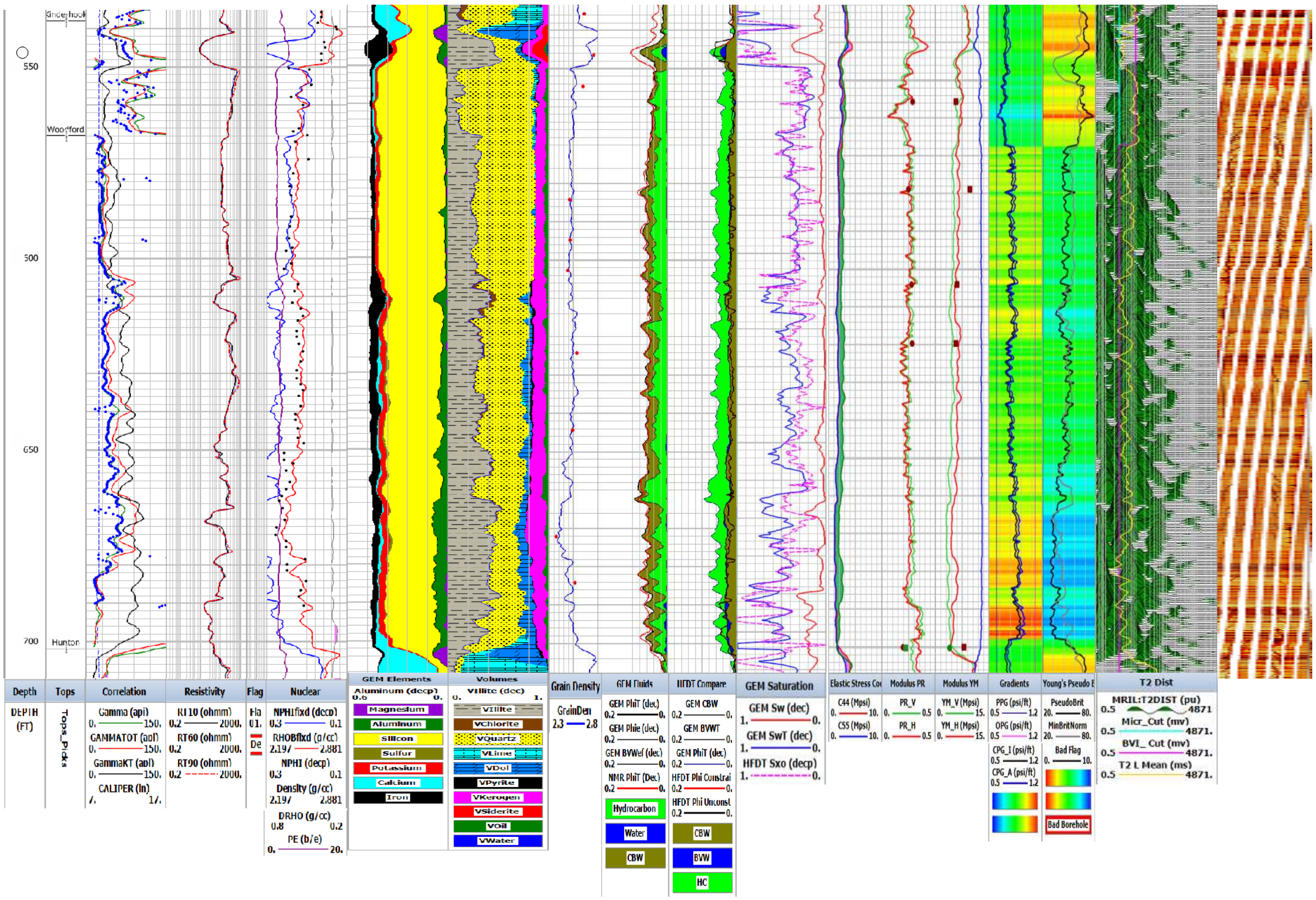
Introduction to Open Hole Logging
Electric Well Logging



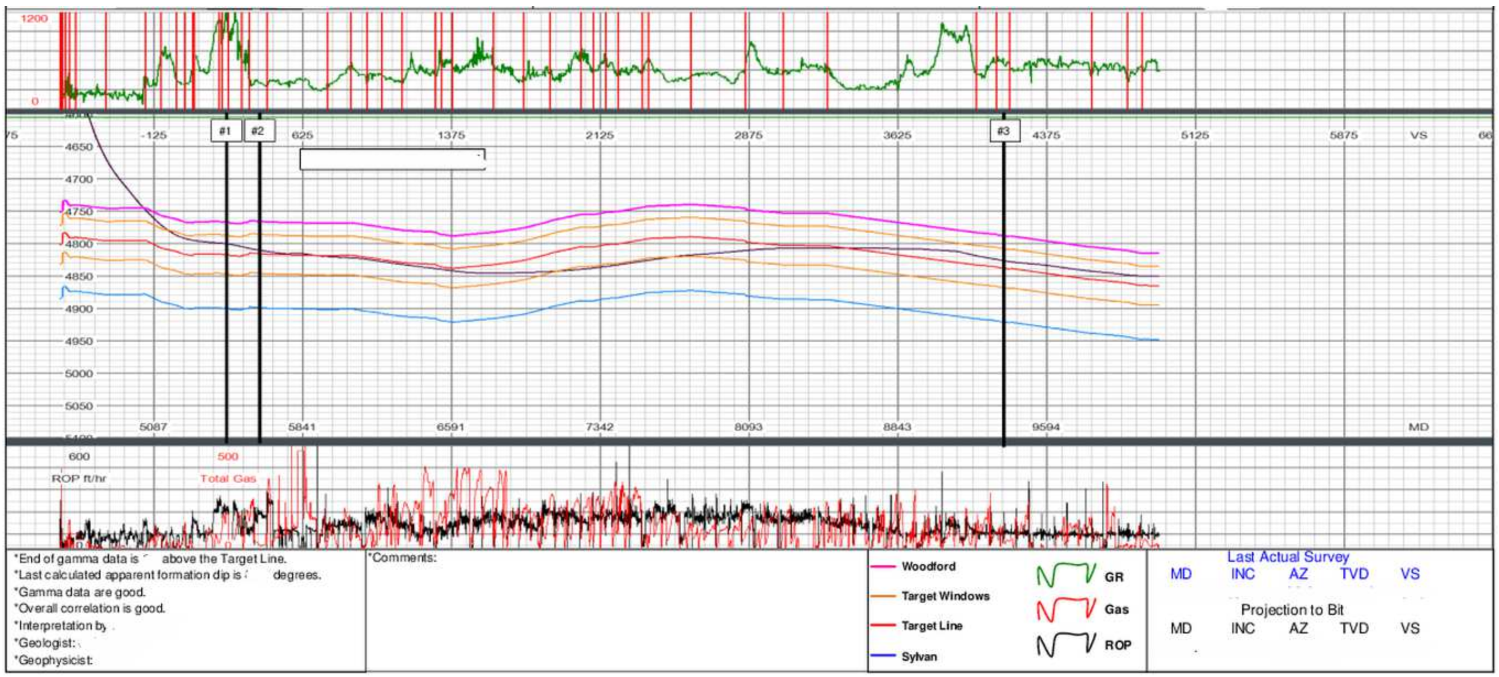


- The practice of making a detailed record of the geologic formations penetrated by a borehole.
  - Usually Continuous but can be Stationary
  - Includes Testing and Sampling Services

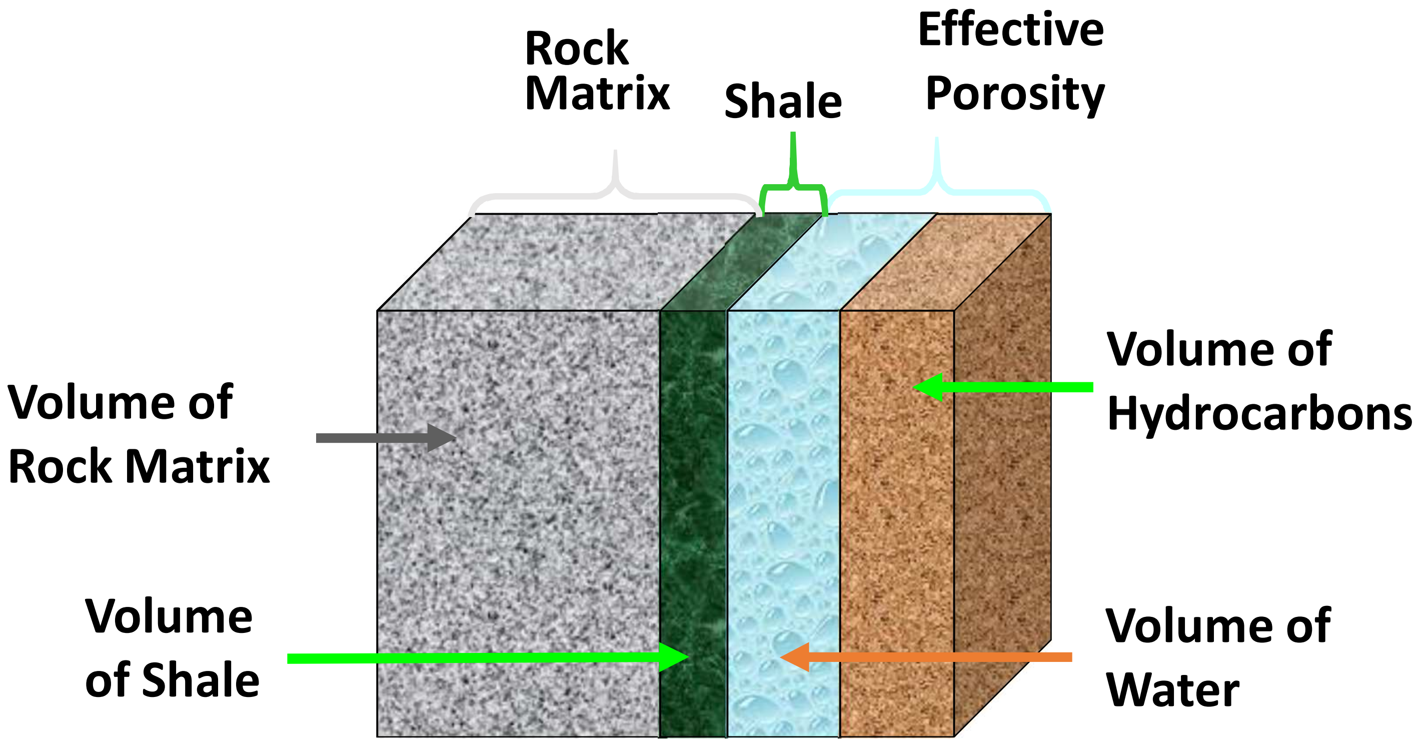
Open Hole Logs, What Information Do We Want To get. Everything!



What we usually get!

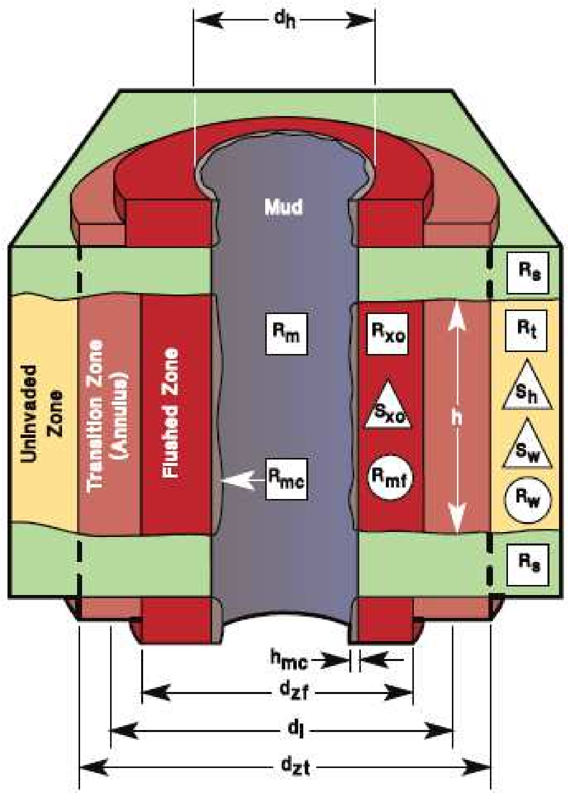


Traditional Rock - Shale Model (with Hydrocarbons)



$$Volume_{Total} = V_{RM} + V_{SH} + V_{W} + V_{HC}$$

Open Hole Borehole Conditions

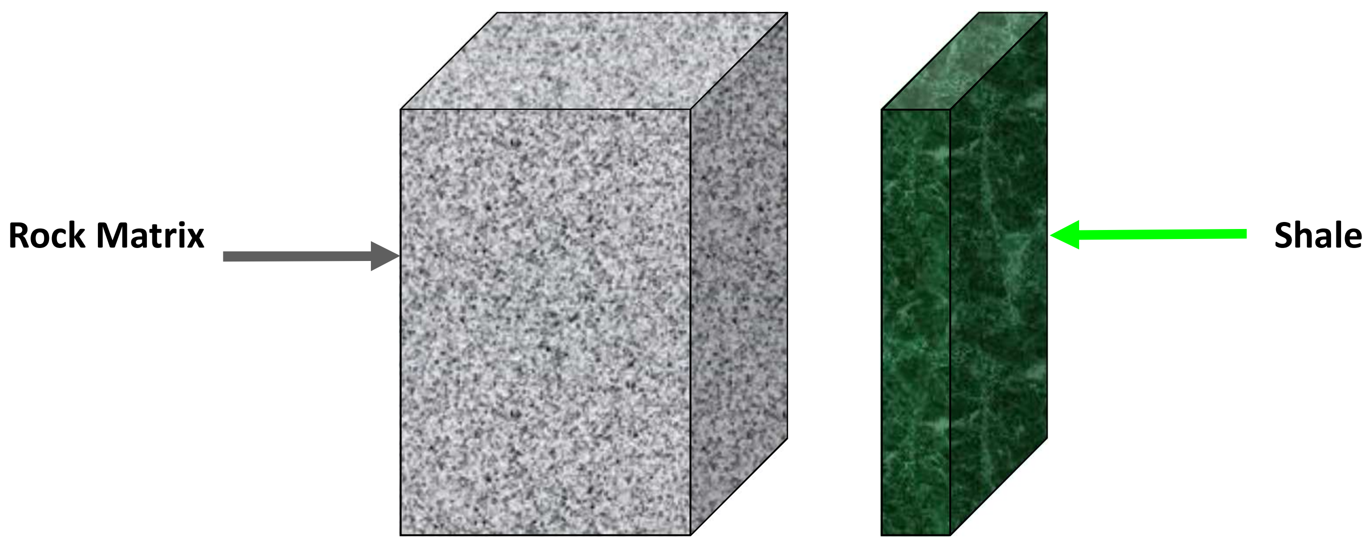


h : Bed Thickness
h_{mc} : Mudcake Thickness
d_i : Diameter of Invasion (step profile)
d_h : Borehole Diameter
d_{zf} : Diameter of Flushed Zone
d_{zt} : Diameter of Transition Zone

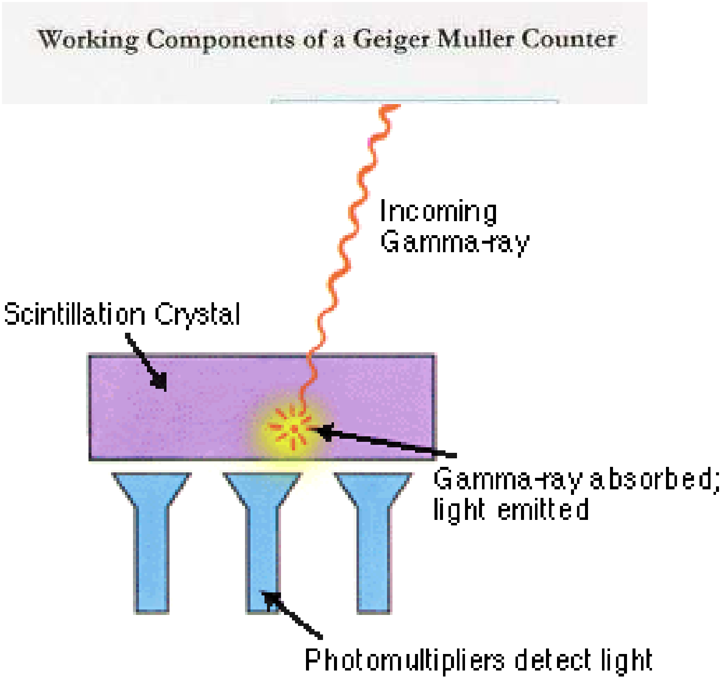
R_m : Mud Resistivity
R_{mc} : Mudcake Resistivity
R_{mf} : Mud Filtrate Resistivity
R_s : Adjacent Bed Resistivity
R_t : True Resistivity
R_{xo} : Flushed Zone Resistivity
R_w : Formation Water Resistivity

S_h : Hydrocarbon Saturation
S_w : Water Saturation
S_{xo} : Flushed Zone Water Saturation
S_{hr} : Residual Hydrocarbon Saturation

Gamma Ray

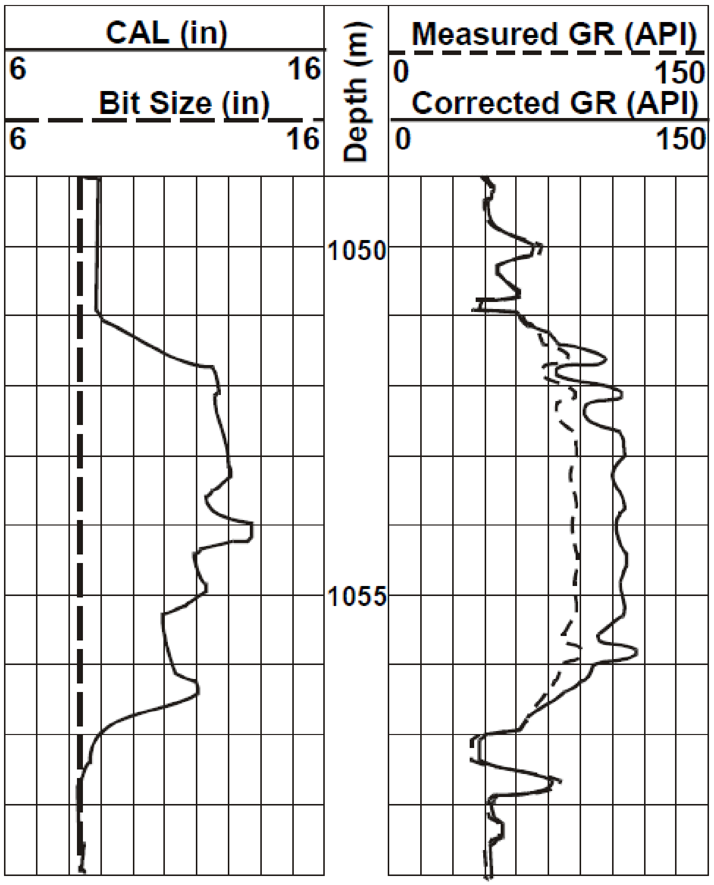


Gamma Ray Detection



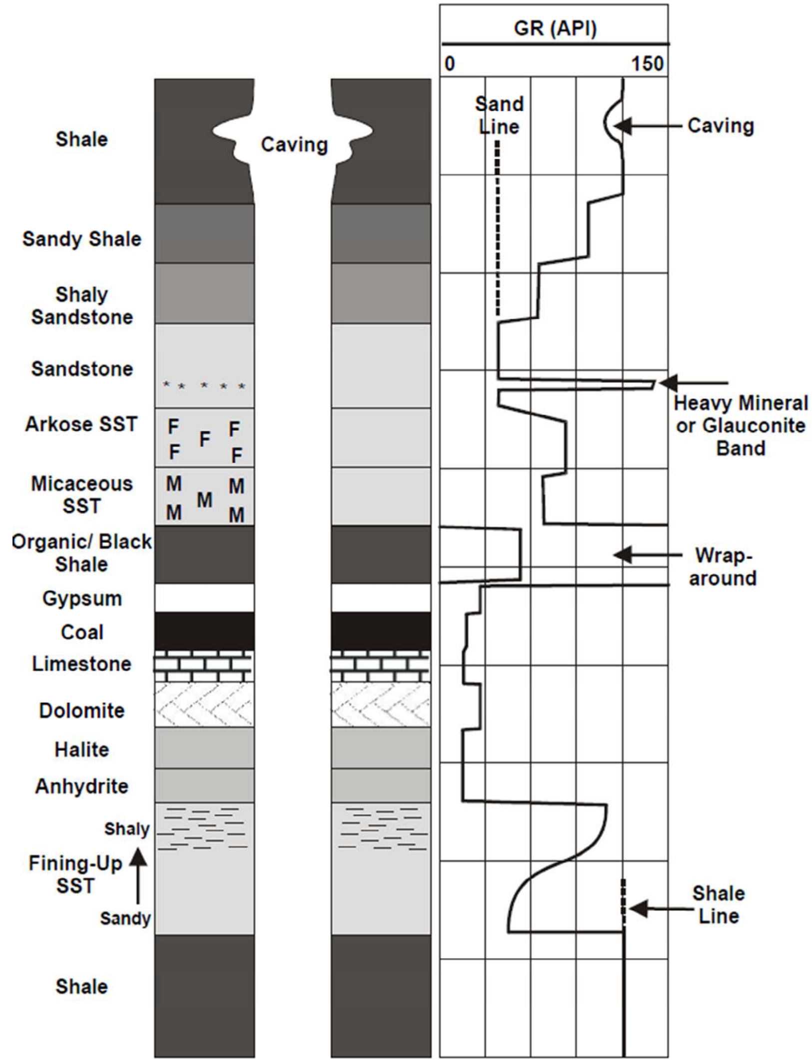
- Passive Detection
  - Geiger-Mueller Detectors
  - Scintillation Detectors
    - Detect Naturally Occurring Gamma Ray

GR Environmental Corrections



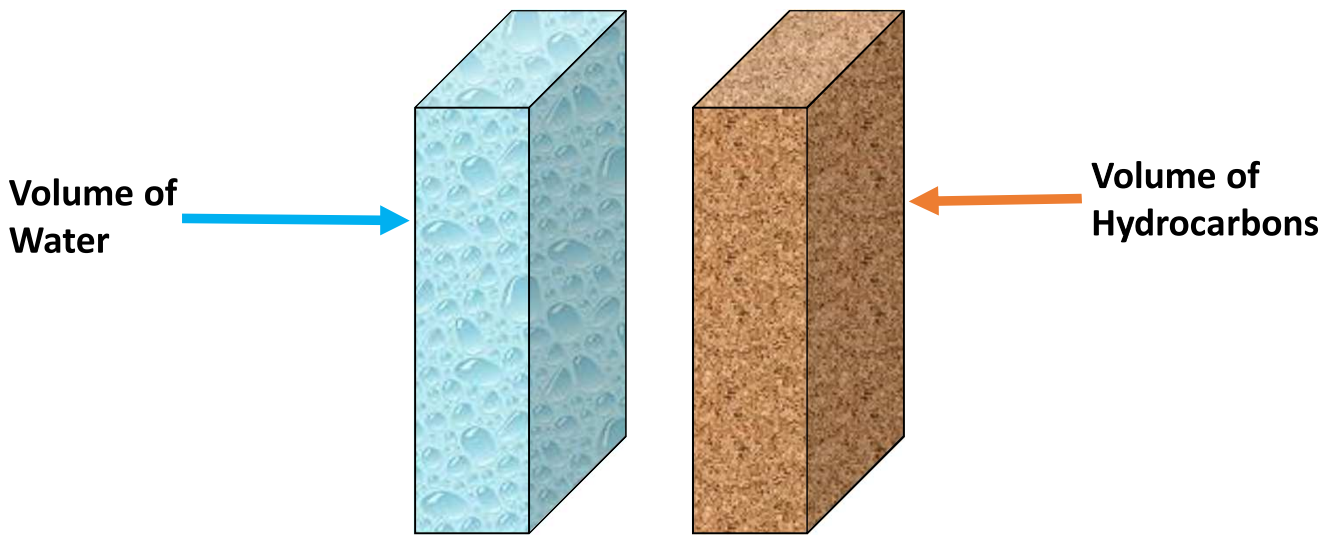
- Corrections
  - Borehole Diameter
  - Mud Weight
  - Washout
  - Standoff
  - Tool Position

Gamma Ray

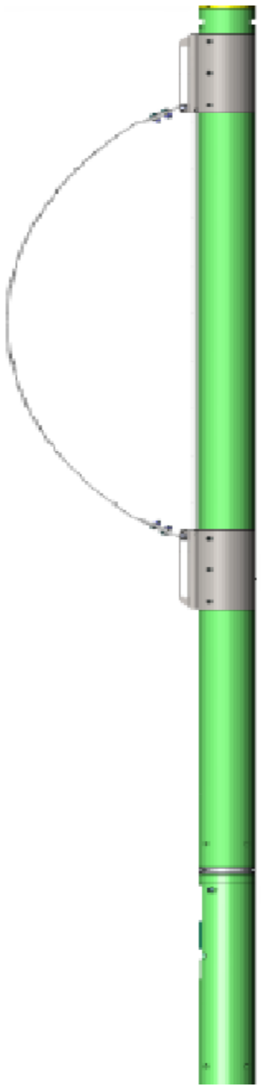


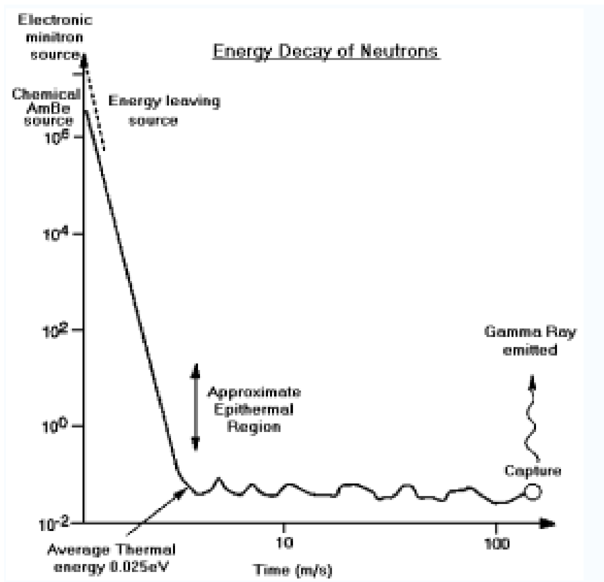
GR (API)
0
150
Shale
Caving
Sand Line
Caving
Sandy Shale
Shaly Sandstone
Sandstone
Heavy Mineral or Glauconite Band
Arkose SST
Micaceous SST
Organic/ Black Shale
Wrap-around
Gypsum
Coal
Limestone
Dolomite
Halite
Anhydrite
Shaly
Fining-Up SST
Sandy
Shale Line
Shale

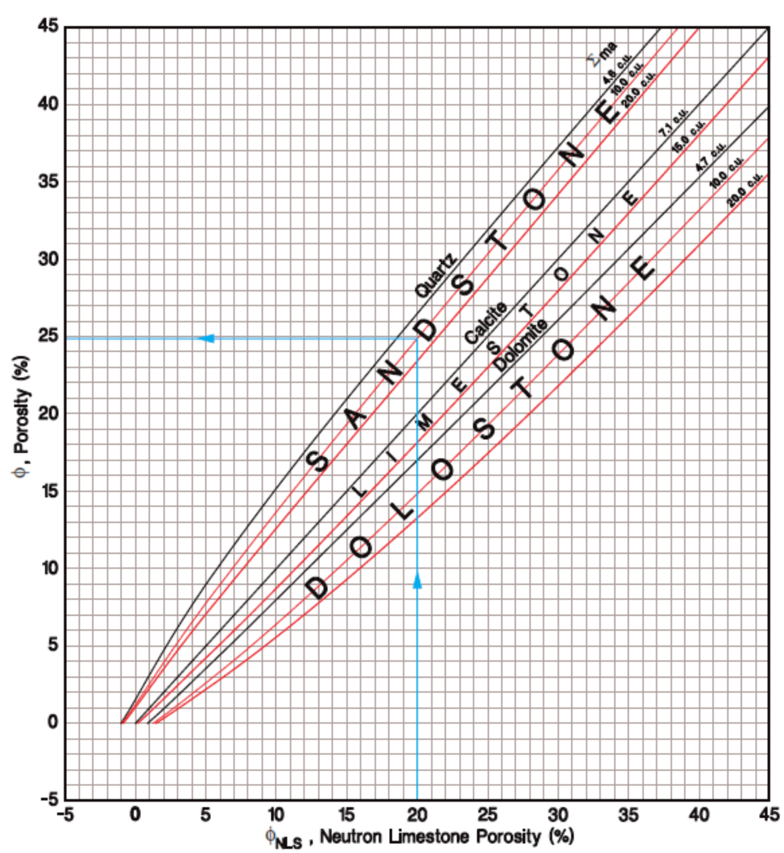
Porosity



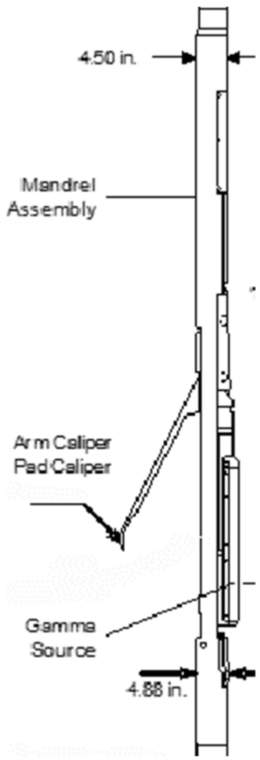
Neutron Apparent Porosity

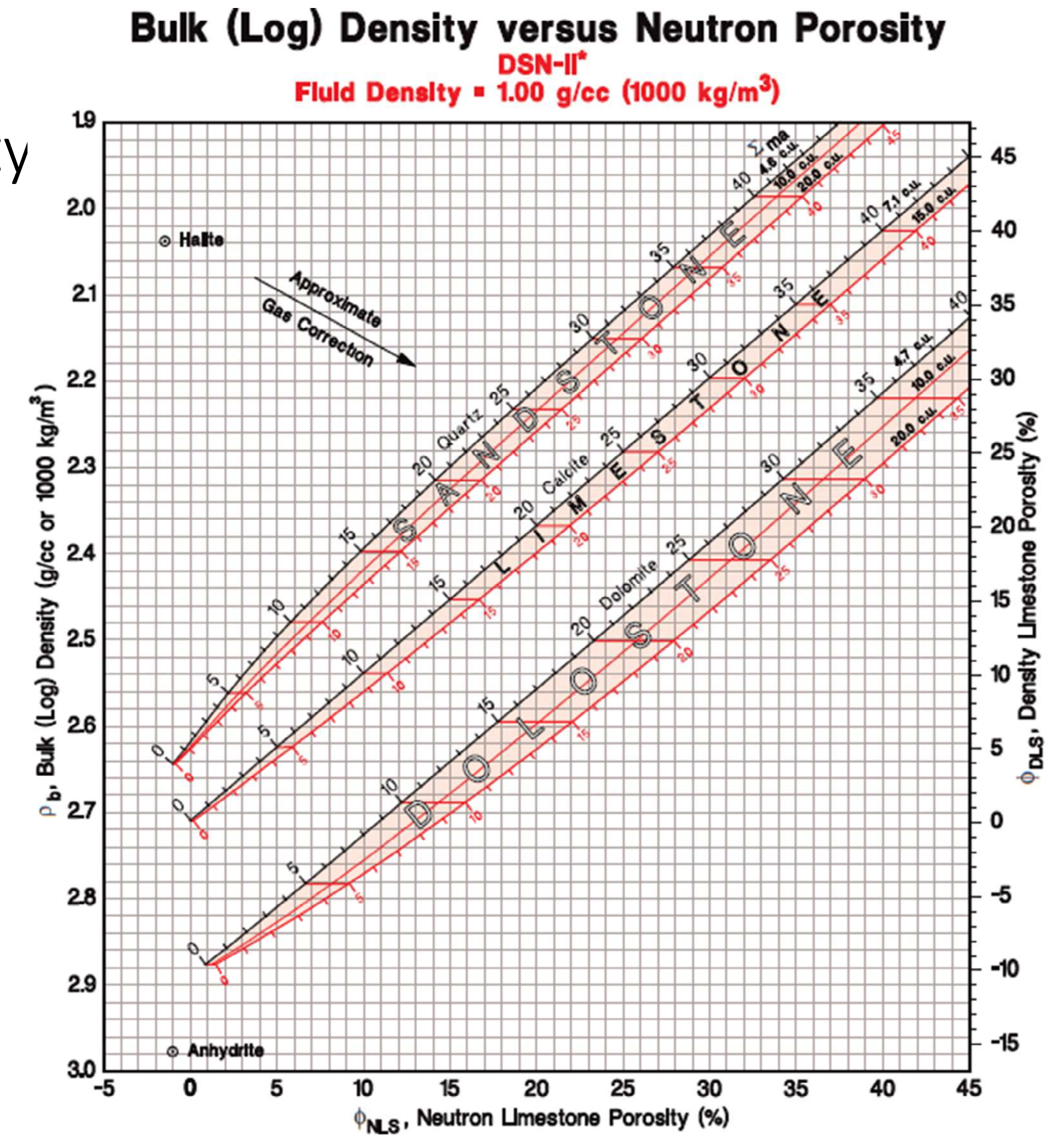




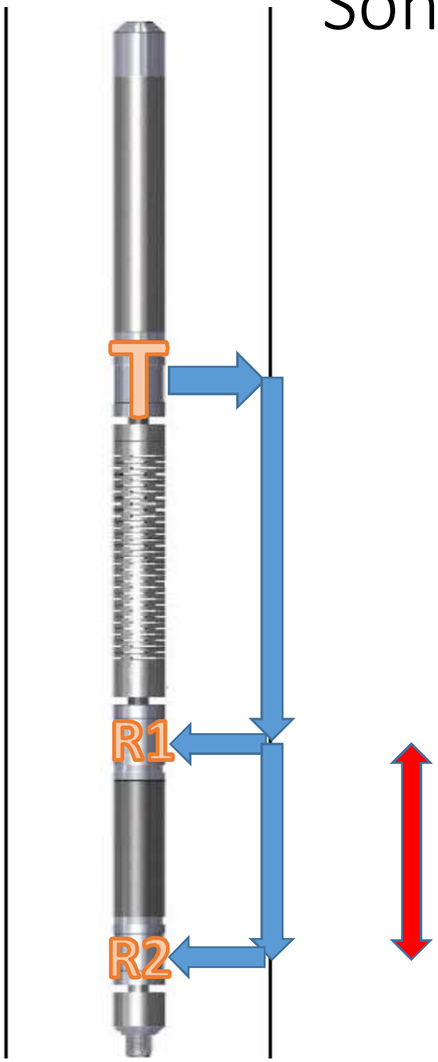


Density Apparent Porosity





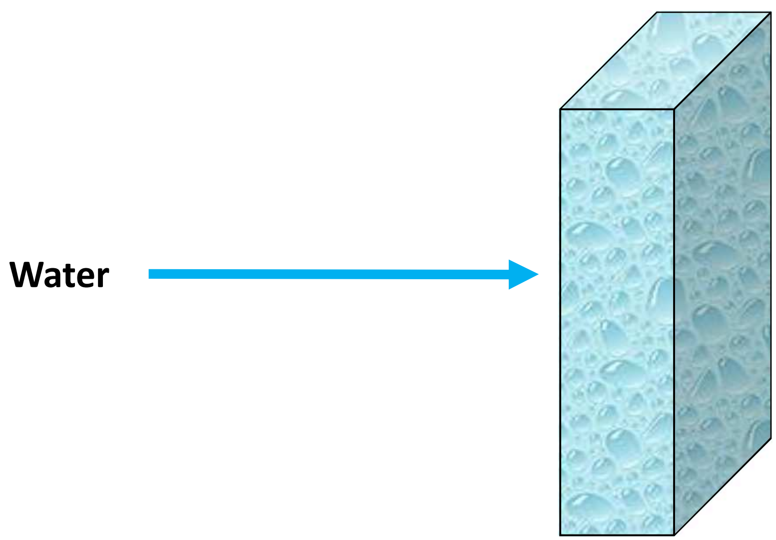
Sonic Apparent Porosity



- Measures Sound Travel Time
  - ΔTc is Delta Time for P-wave
  - ΔTs is Delta Time for S-wave

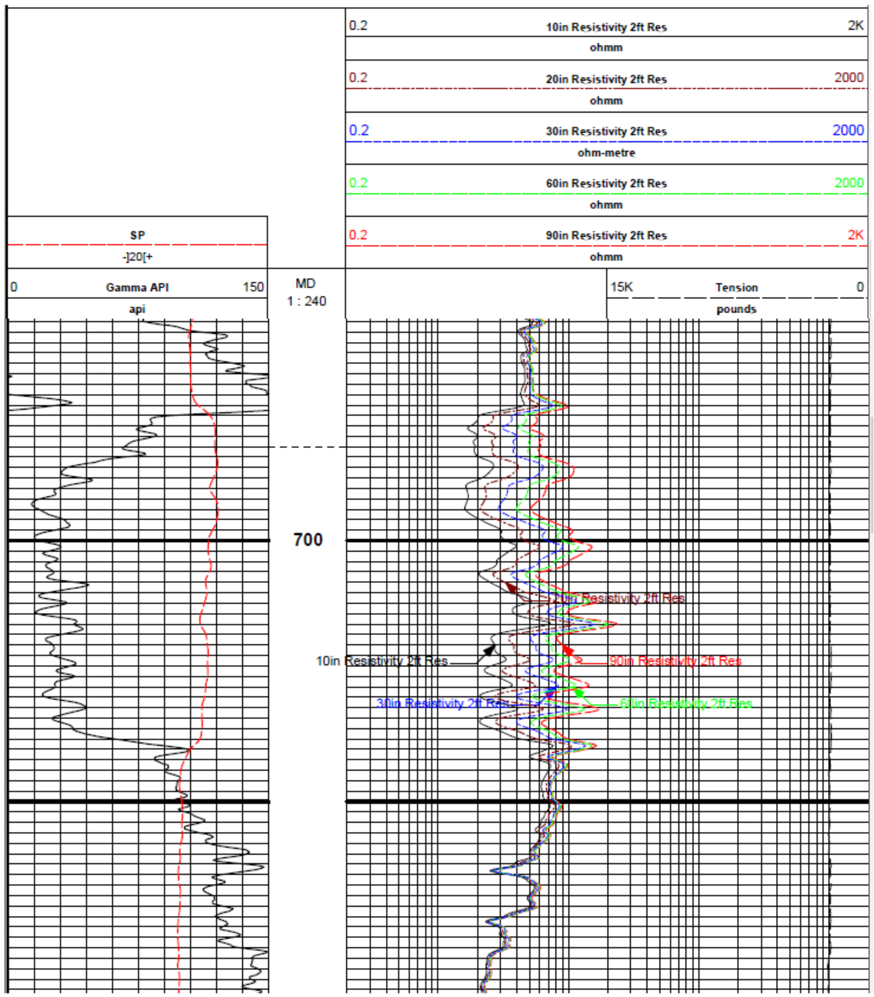
$$\emptyset_{Sonic} = \frac{\Delta tLog - \Delta tMatrix}{\Delta tFluid - \Delta tMatrix}$$

Resistivity



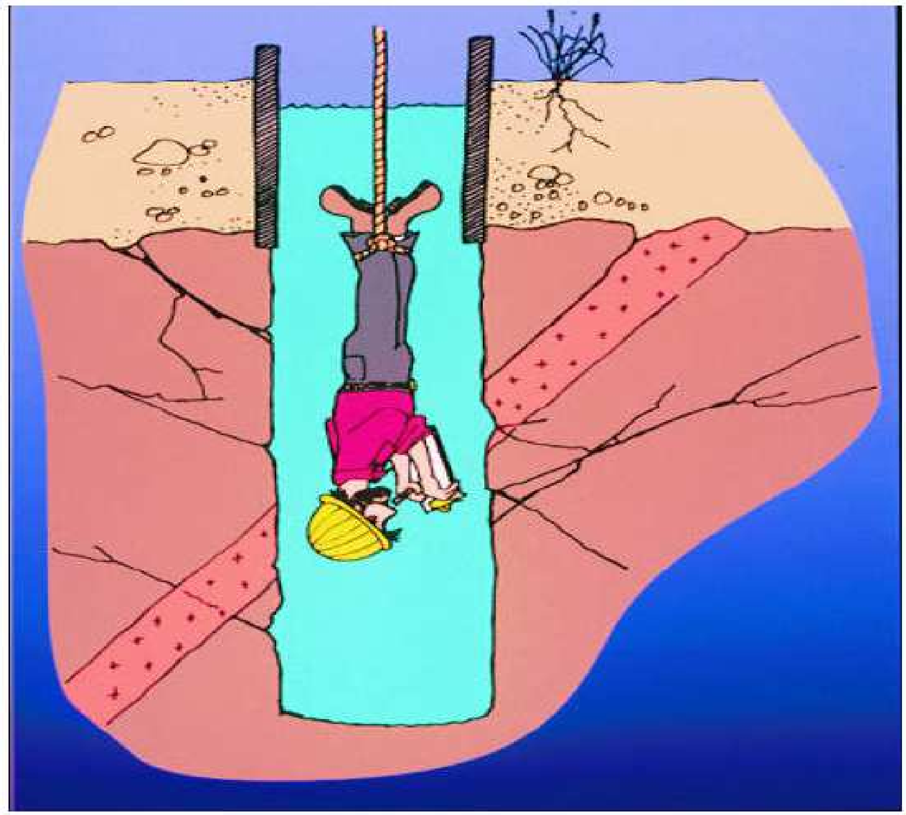
Resistivity

- Matrix material High resistivity
- Oil High resistivity
- Gas High resistivity
- Formation waters <u>Usually</u> Low resistivity
- Water-based mud filtrate can be Low or High resistivity
- Oil-based mud filtrate High resistivity

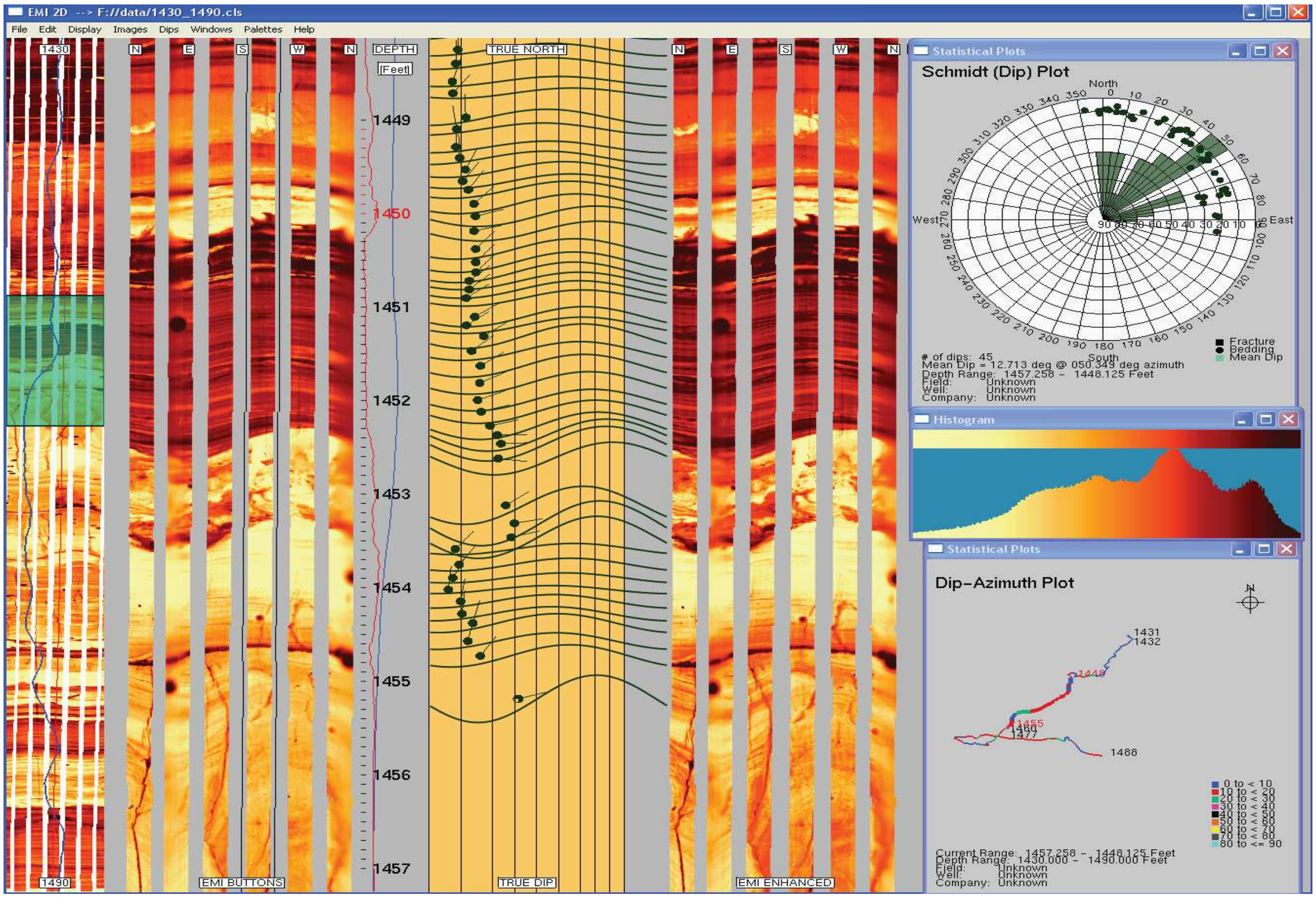


- Resistivity
  - Hydrocarbon Indicator
  - Invasion Indicator
  - Shale Indicator
- Rt
  - Environmentally Corrected Deep Resistivity

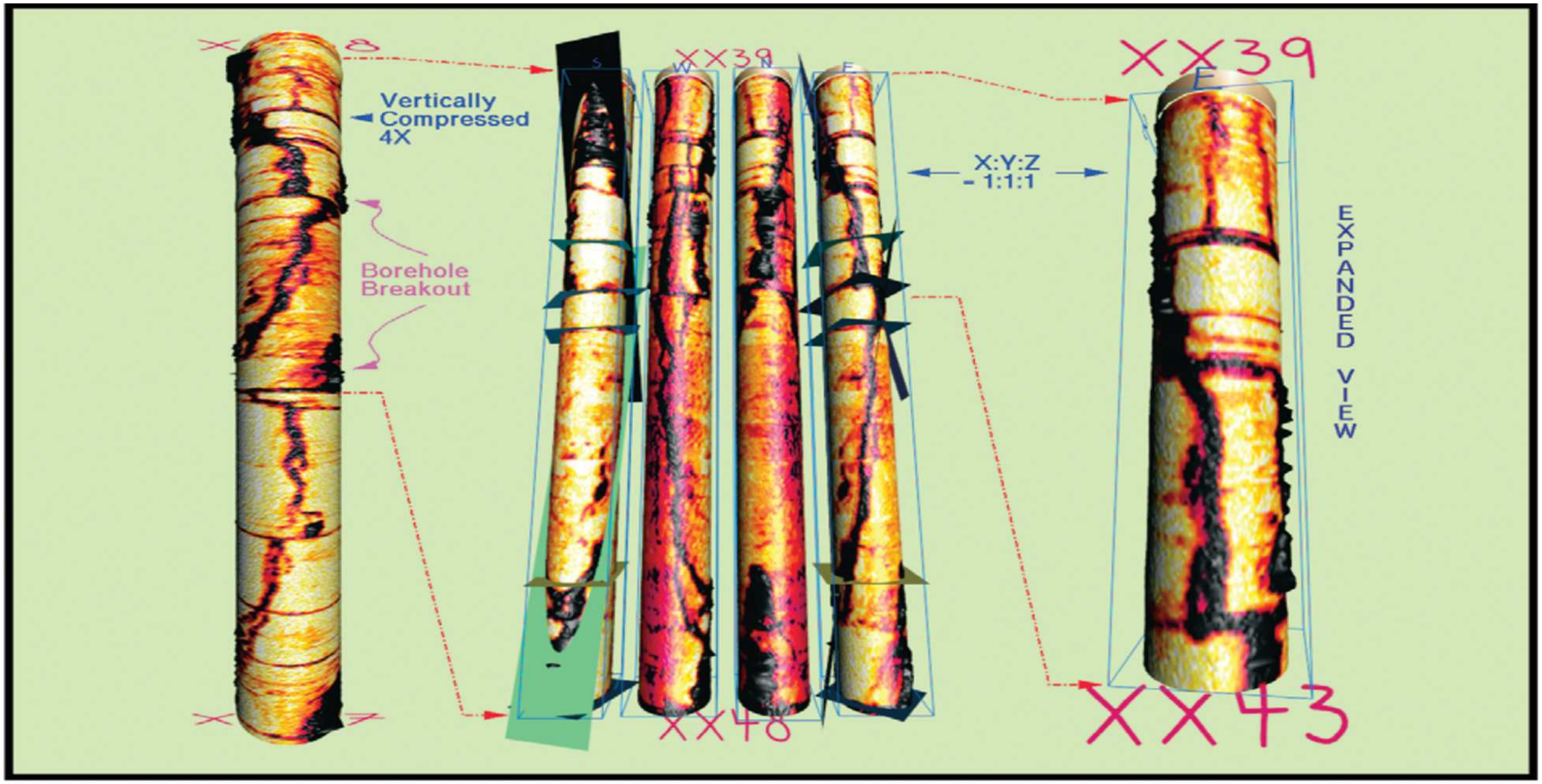
Formation Dip, Imaging, etc.

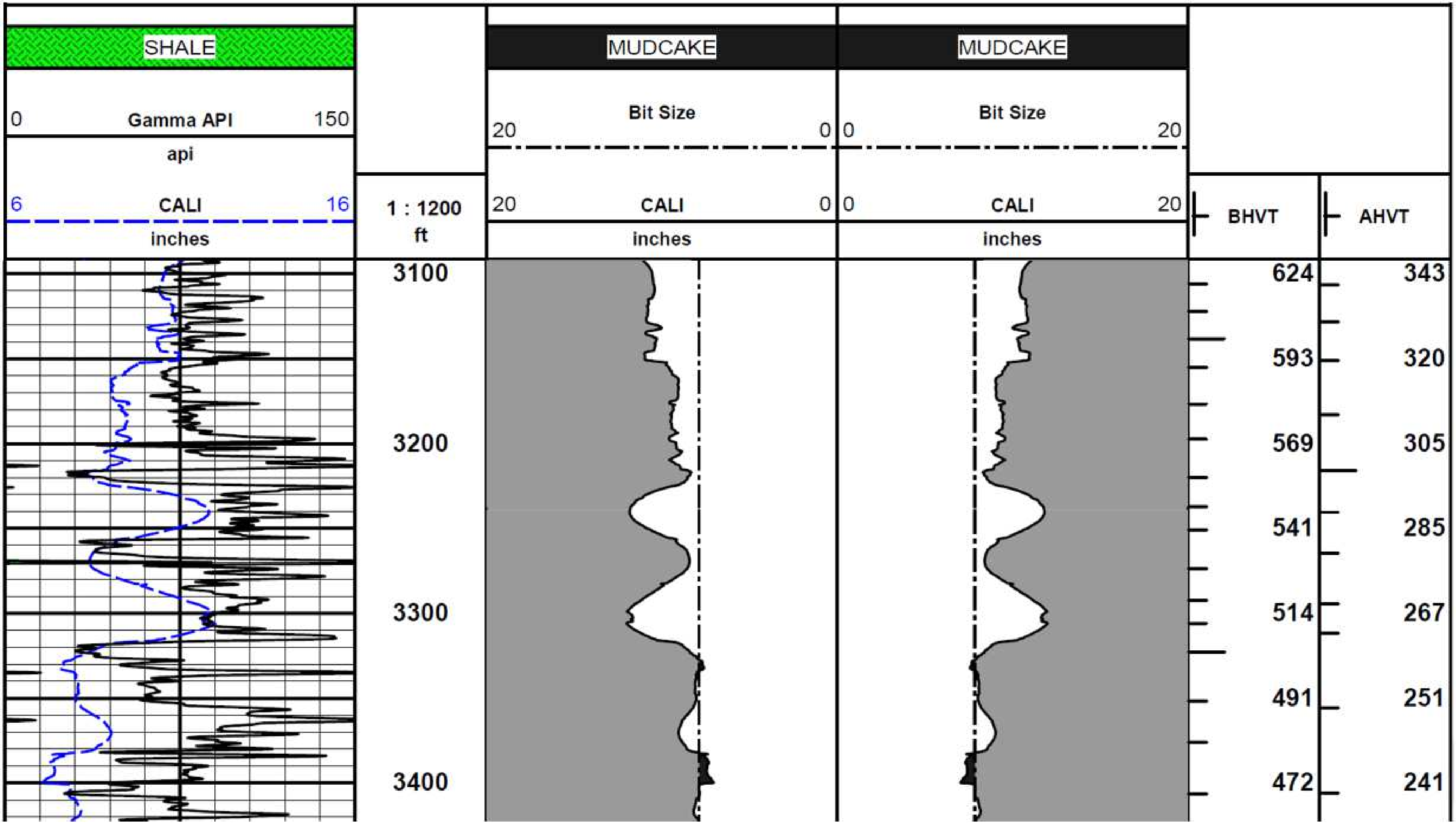


Micro Imager



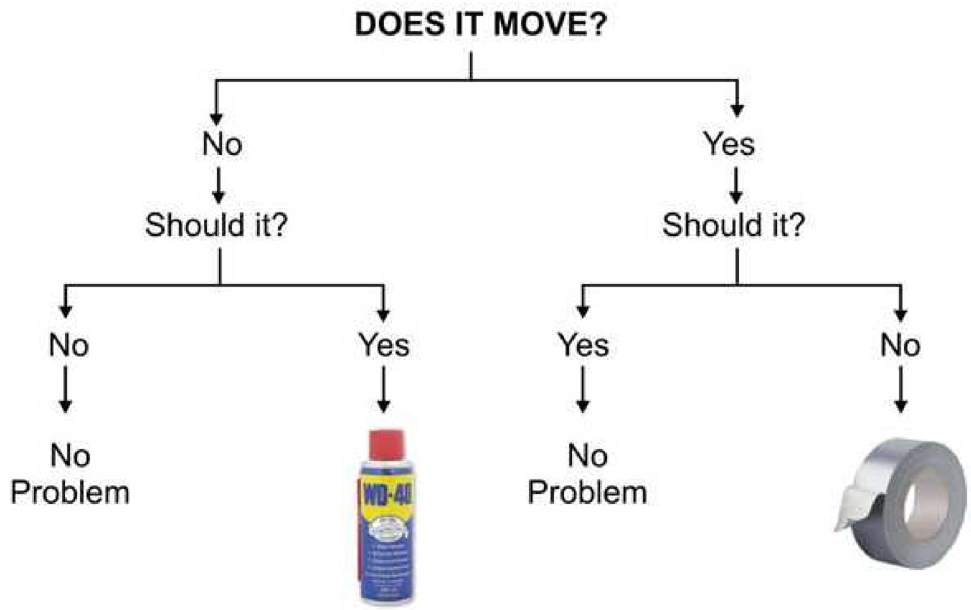
Circumferential Acoustic Scanning





SHALE
0
Gamma API
150
api
6
CALI
16
inches
1 : 1200
ft
MUDCAKE
Bit Size
20
0
CALI
20
0
inches
MUDCAKE
Bit Size
0
20
CALI
0
20
inches
BHVT
AHVT
3100
3200
3300
3400
624
593
569
541
514
491
472
343
320
305
285
267
251
241

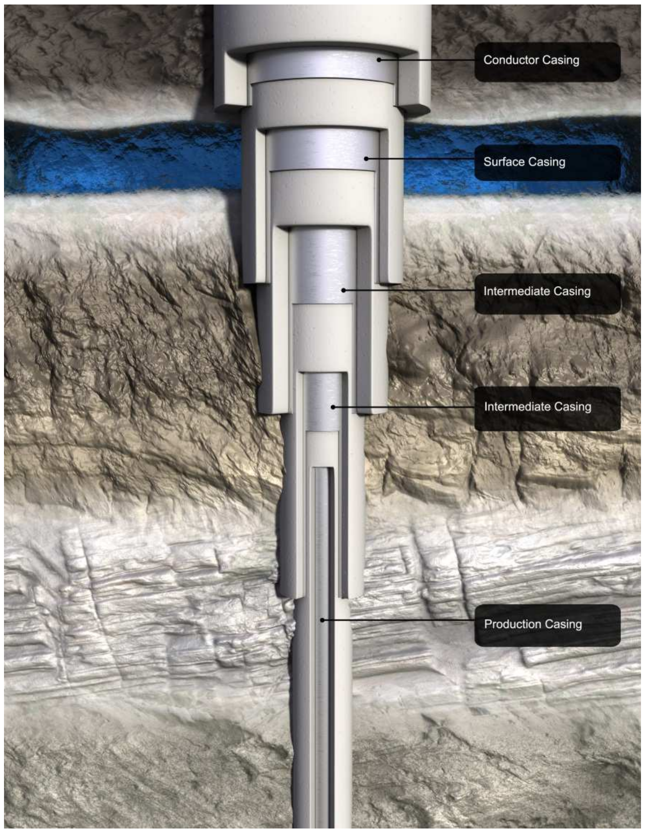
If There is a Problem Production Engineering Will Fix It!



Cementing 101

HALLIBURTON

Oil and Gas Well Cementing Reasons



- Restrict fluid movement between formations
  - Manage formation pressures
  - Seal off zones (i.e. water, thief, producing)
- Bond and support the casing
  - Protect from corrosion
  - Protect from shock loads

Source: Society of Petroleum Engineers, Cementing Monograph Volume 4, 1990

Cement History

- Egypt
  - Plaster of Paris ($CaSO_4$ + Heat)
- Greece
  - Lime ($CaCO_3$ + Heat)
- Roman Empire
  - Pozzolam-lime reactions
- England
  - Natural Cement (1756)
  - Portland Cement (1824)
- United States
  - Portland Cement (1872)

Raw Materials

- Calcareous Material – Source of lime ($CaCO_3$)
  - Limestone, Chalk, Coral, Cement Rock, Marble, Seashells
    - 70 to 80%
- Argillaceuos Material – Source of silica (SiO_2)
  - Clay, Sand, Shale, Fly Ash, Volcanic Ash, Blast furnace slag
    - 20 to 30%
- Gypsum ($CaSO_4{\cdot}2H_20$)

Chemical Compounds in Portland Cement

Compound	Formula	Standard Designation
Tricalcium aluminate	$3CaO \cdot Al_2O_3$	C_3A
Tricalcium silicate	$3CaO \cdot SiO_2$	C_3S
B-dicalcium silicate	$3CaO \cdot SiO_2$	C_2S
Tetracalcium aluminoferrite	$3CaO \cdot Al_2O_3 \cdot Fe_2O_3$	C_4AF

API Classifications of Cements

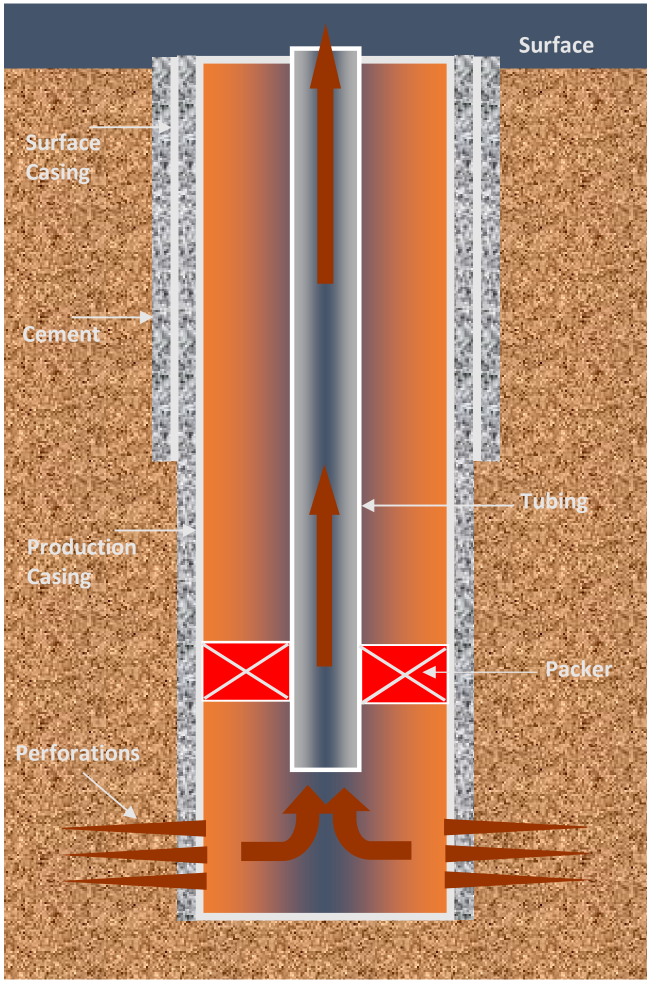
API Classification	Mixing Water (gal/sk)	Well Depth (feet)	Static Temp (°F)
A (Portland)	5.2	0 – 6000	80 – 170
B (Portland)	5.2	0 – 6000	80 – 170
C (High Early Strength)	6.3	0 – 6000	80 – 170
D (Retarded)	4.3	6,000 – 12,000	170 – 260
E (Retarded)	4.3	6,000 – 12,000	170 – 260
F (Retarded)	4.5	10,000 – 16,000	230 – 320
G (Basic)	5.0	0 – 8,000	80 – 200
H (Basic)	4.3	0 – 8,000	80 – 200
J	4.9	12,000 – 16,000	260 – 330

Slurry Additives

- Accelerators
- Retarders
- Fluid Loss
- Dispersants
- Light Weight
- Heavy Weight
- Defoamers
- Lost Circulation
- Free Water
- Bond Improving

Purpose of Cementing

- Zonal Isolation
  - Well Control
  - Protects the environment
  - Prevents blowouts
- Casing protection against
  - Corrosion
  - Drilling Shocks
  - Burst/Collapse
- Strengthen Casing
- Plug/Abandonment



Material Storage

- Bulk Silos
- Sacks/Pallets

Scale and Blending

- Cement and additives are measured by weight
- Scale Tanks have scales to monitor tank weight
- Bend tanks used as “Mixing pots”

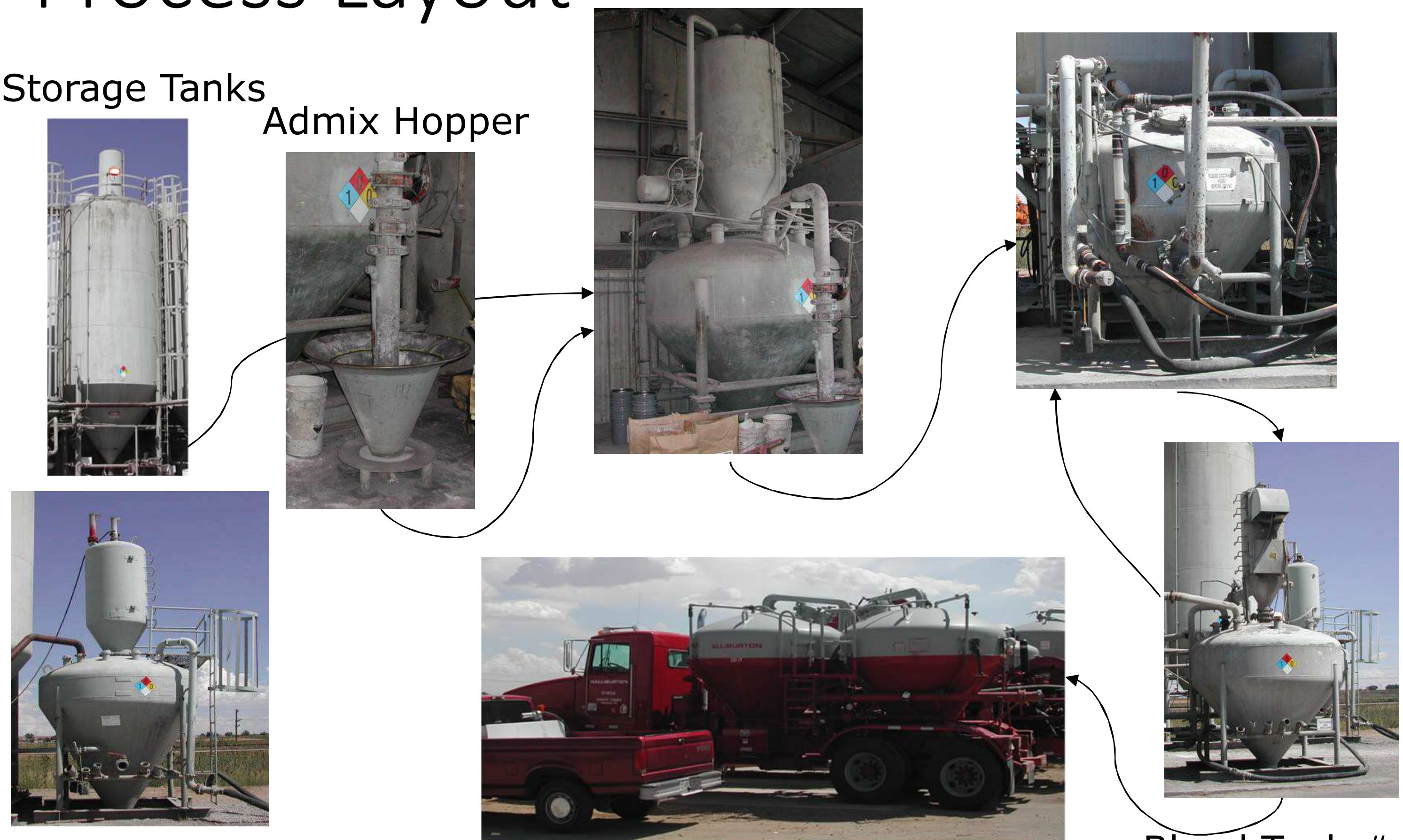
Admix Hopper

- The additives that are not stored in bulk are added to the scale tank threw the admix hopper
- Material dumped via bag directly into hopper
- Uses vacuum to move materials over to the scale tank.

Control System

- Entire process controlled from one station
- PLC Controlled – fully automated
- Air Compressors
  - one to pressure up the tanks
  - one to pull vacuum
  - a high pressure compressor to open and close valves

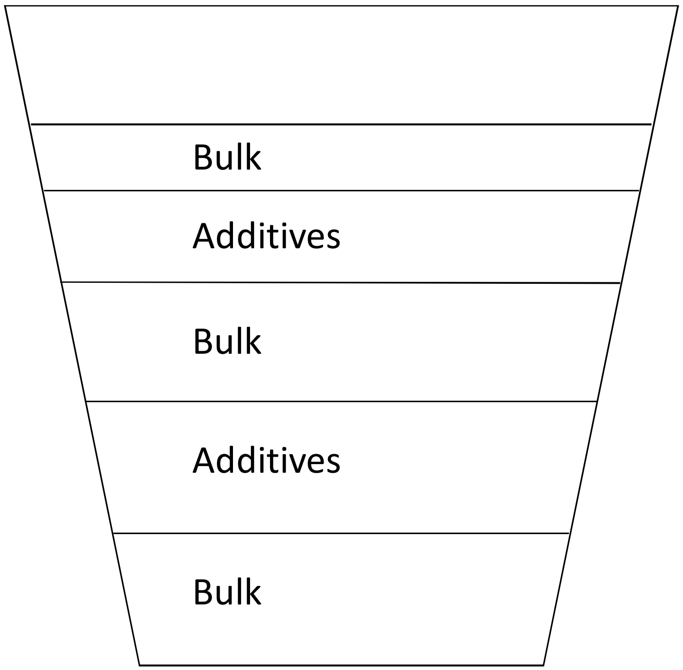
Process Layout



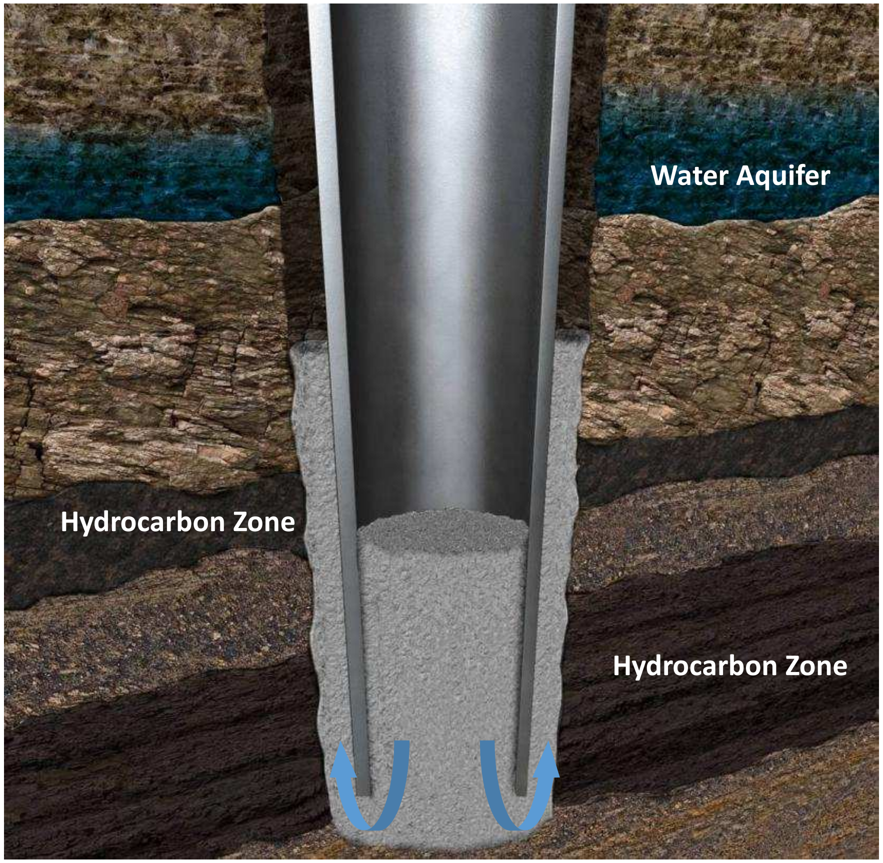
Loading Procedure

The 1/3, 1/2, 1/3, 1/2, 1/3 Loading Method

“Sandwich”

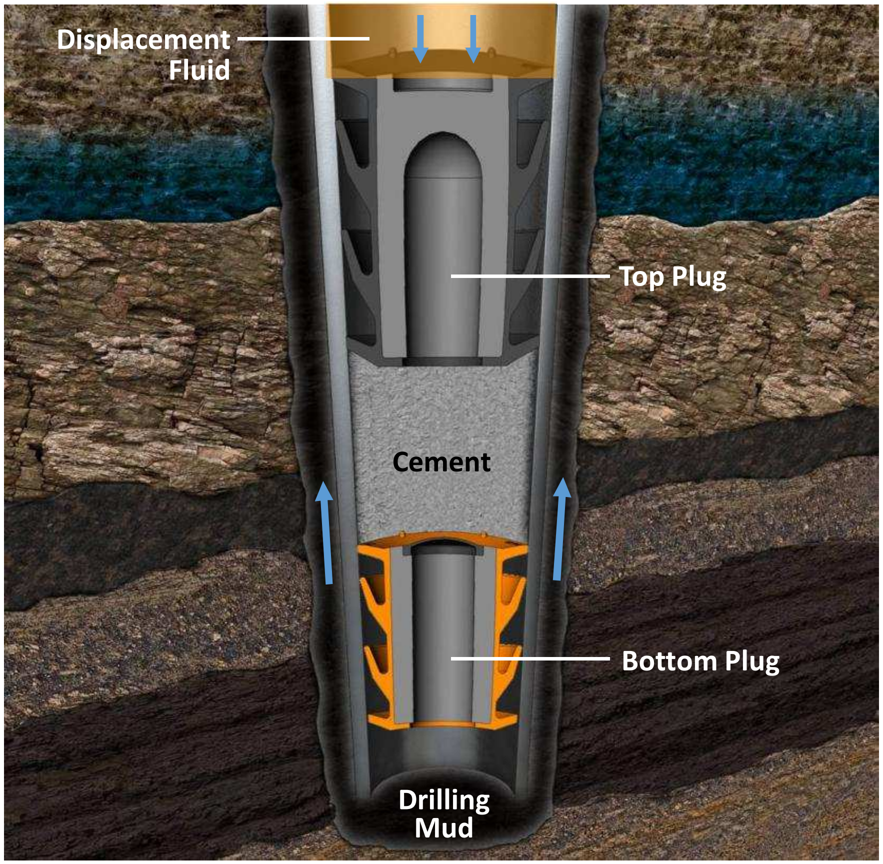


Cement Placement: Process Basics



- High-rate mixer blends cement, water and chemicals into a slurry
- The slurry is pumped down through steel casing, then up through the annulus

Cement Placement: Process Details

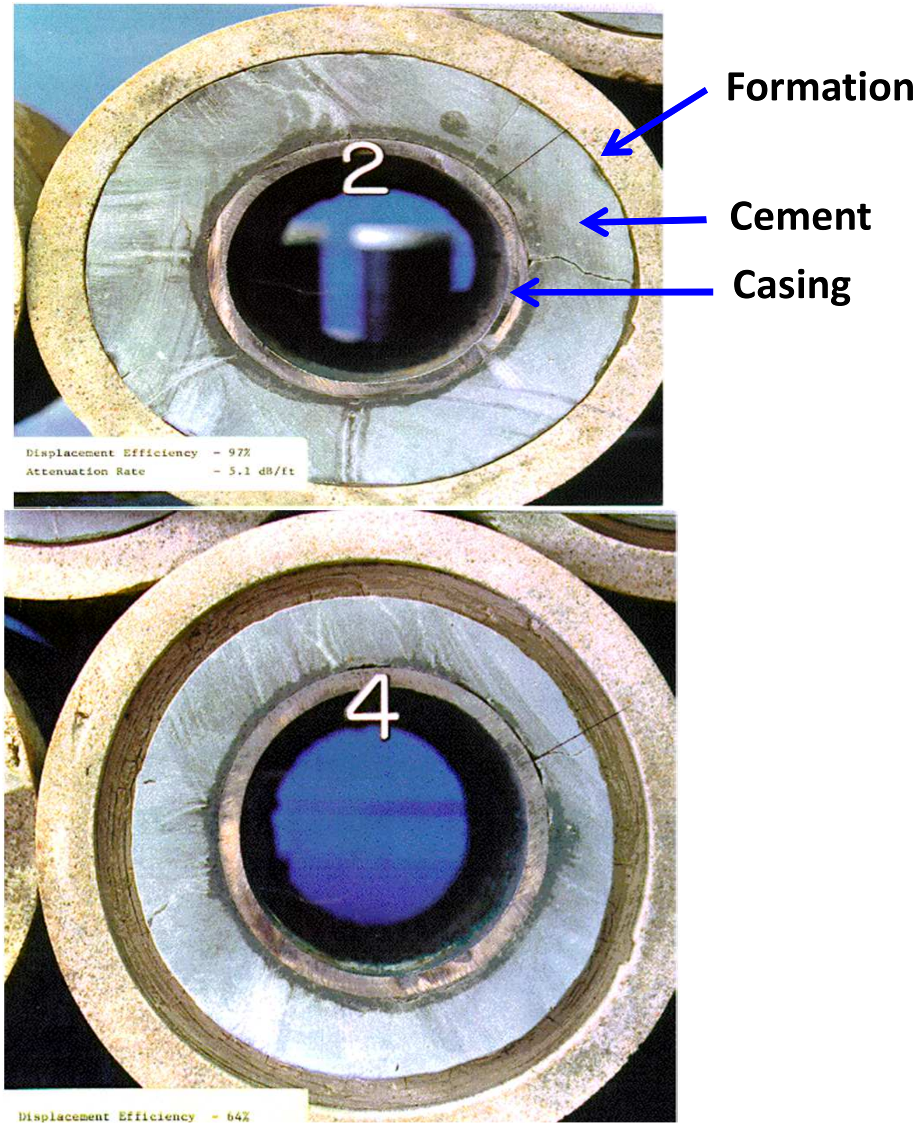


- Plug separates cement slurry from the well fluids to keep it from being contaminated
- Like a squeegee, plug helps displace the cement, forcing it cleanly through casing

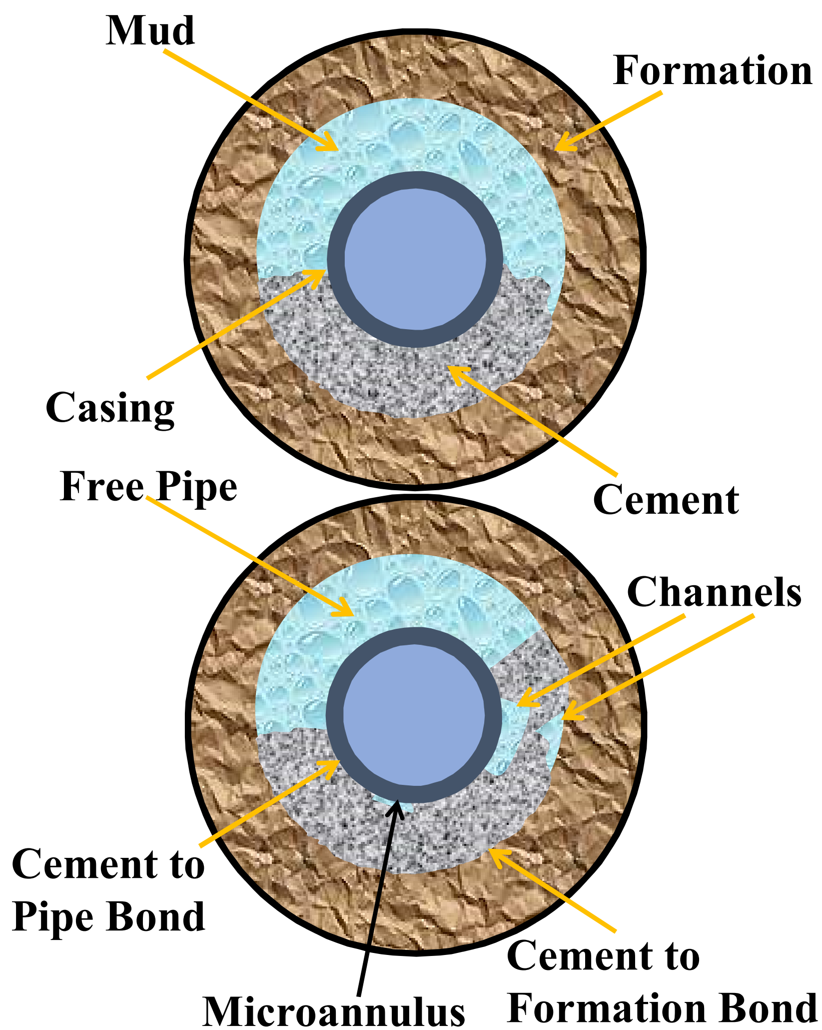
Society of Petroleum Engineers, Cementing Monograph Volume 4, 1990

Equipment

Interpreting Cement Evaluation Tools



Formation
Cement
Casing
2
Displacement Efficiency - 97%
Attenuation Rate - 5.1 dB/ft
4
Displacement Efficiency - 64%



Mud
Formation
Casing
Cement
Free Pipe
Channels
Cement to
Pipe Bond
Microannulus
Cement to
Formation Bond

Cement Bond Types and Tools

- Two basic cement bonds
  - Pipe to cement bond
  - Cement to formation bond
- Two basic types of cement evaluation tools
  - Sonic
    - Conventional cement bond log (CBL)
      - Cement to formation bond
      - Cement to casing bond
    - Modified CBLs for expanded casing to cement evaluation.
  - Ultrasonic
    - Casing to cement bond and Casing Inspection

Standard Cement Bond Tools

- Cement Bond Log (CBL)
  - Circumferential averaged bond
  - Cement-to-Pipe bond
    - Amplitude
    - Attenuation
    - Acoustic waveform
  - Cement-to-Formation
    - Acoustic waveform
- Radial Bond Log
  - Amplitude

Cement Bond Log CBL

- Cement Bond Log (CBL)
  - Single transmitter
  - Two receivers
  - Circumferential averaged data
    - Omni-directional transmitter and receivers
    - No indication of radial continuity of bonding or channels
- Physics of measurement
  - Transmitted energy
  - No practical mud weight limitation

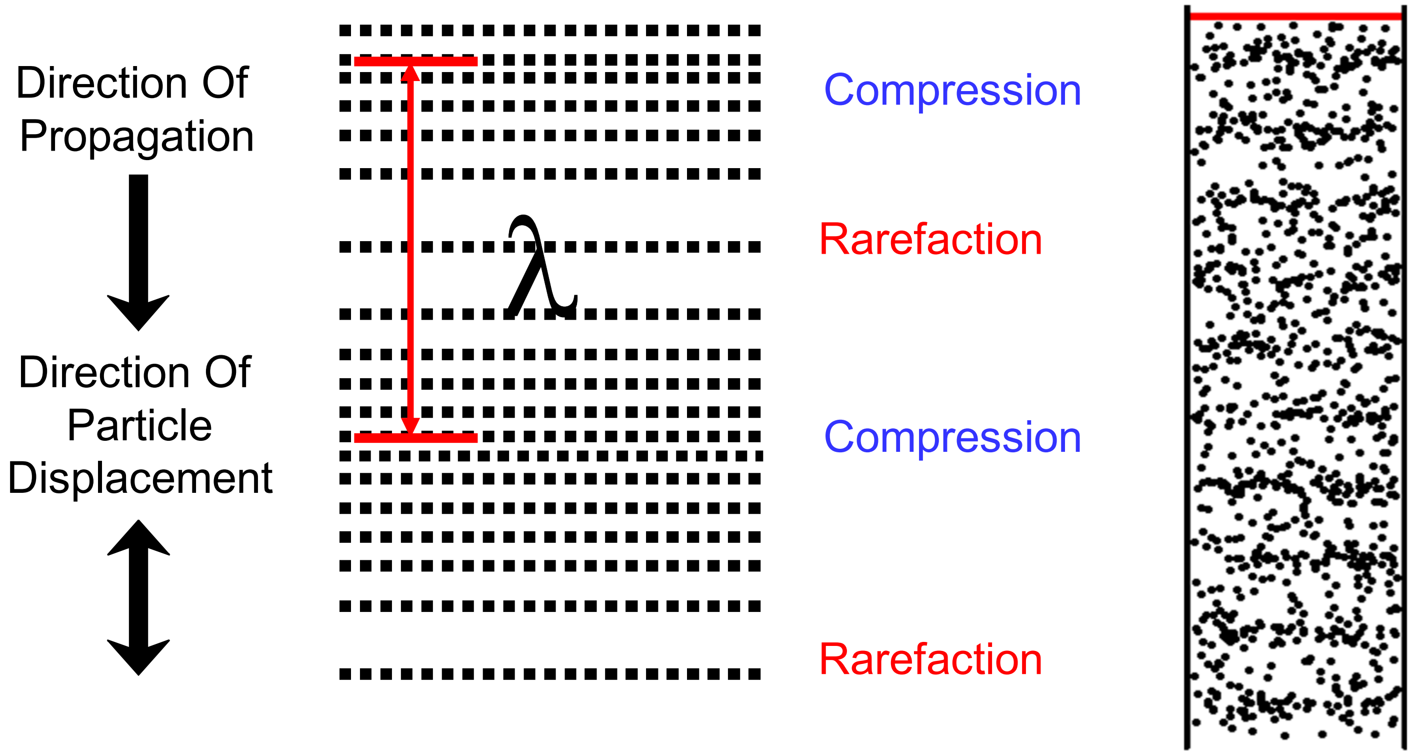
Cement Bond Log (CBL) Measurements

- Data from the 3 foot receiver
  - Pipe amplitude
  - Attenuation
  - Transit time or travel time

- Data from the 5 foot receiver
  - Waveform data

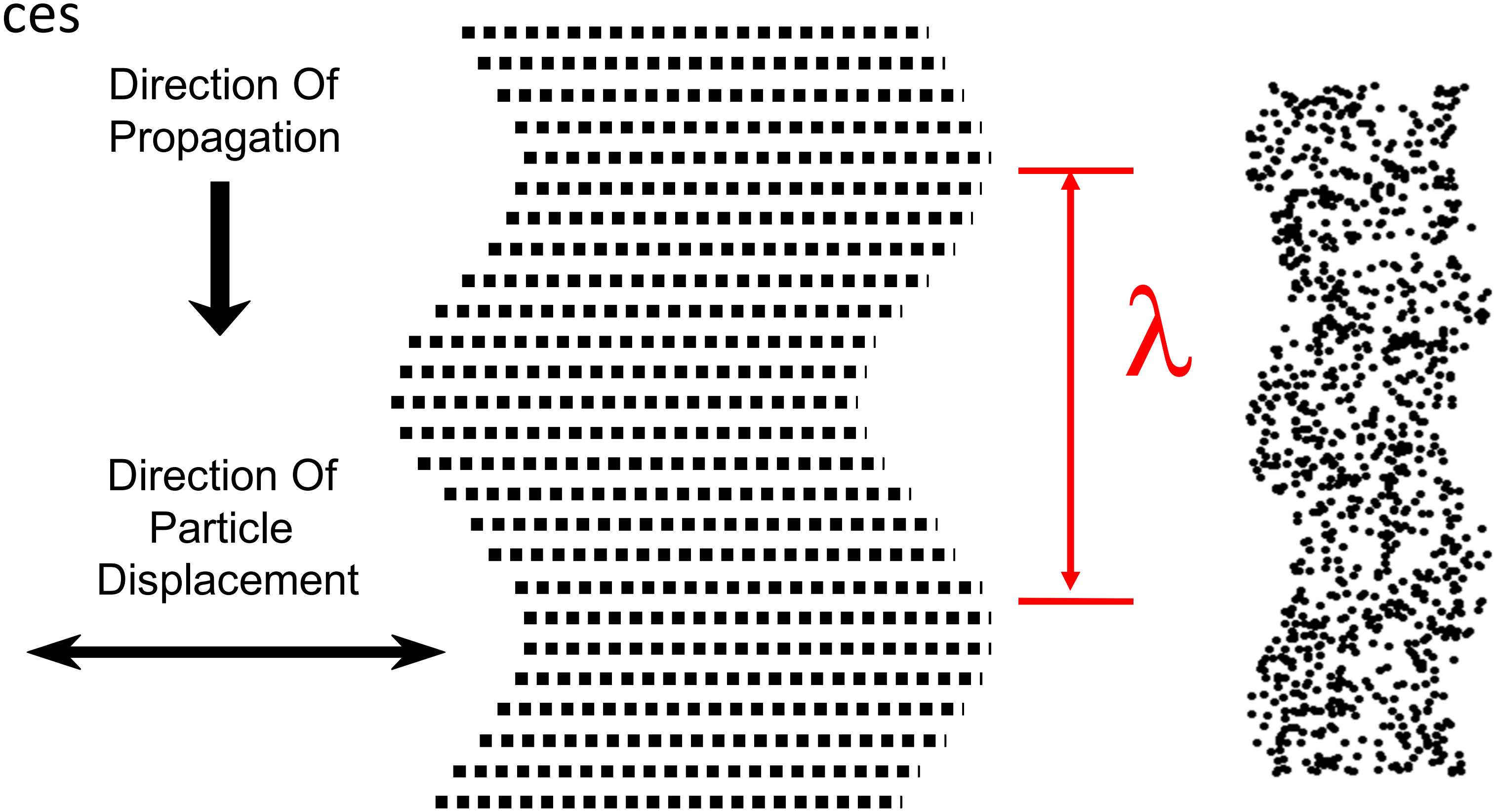
Compressional Wave P-Waves

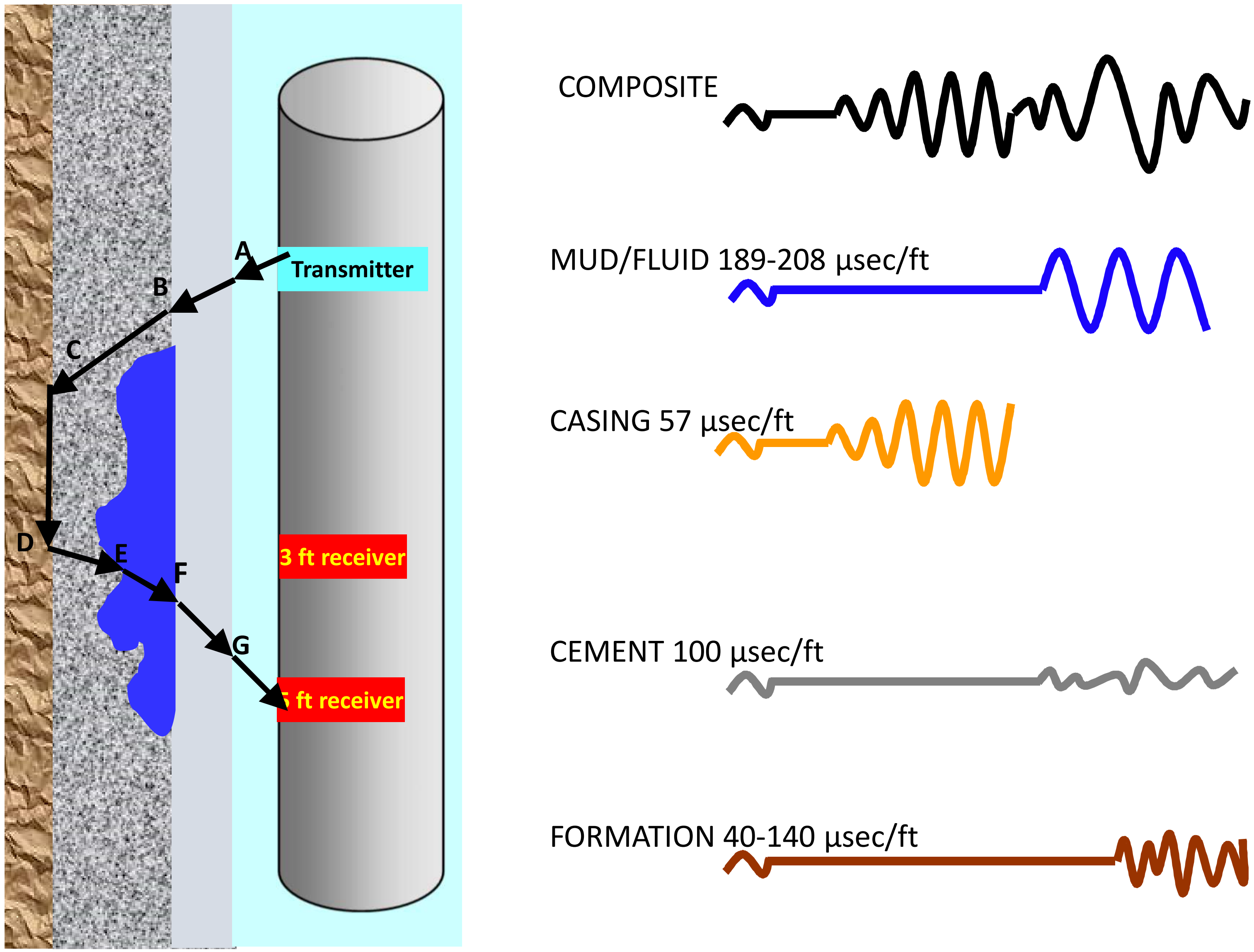
- The only mechanism of acoustic energy transport in gases and liquids.



Shear Wave S-Waves

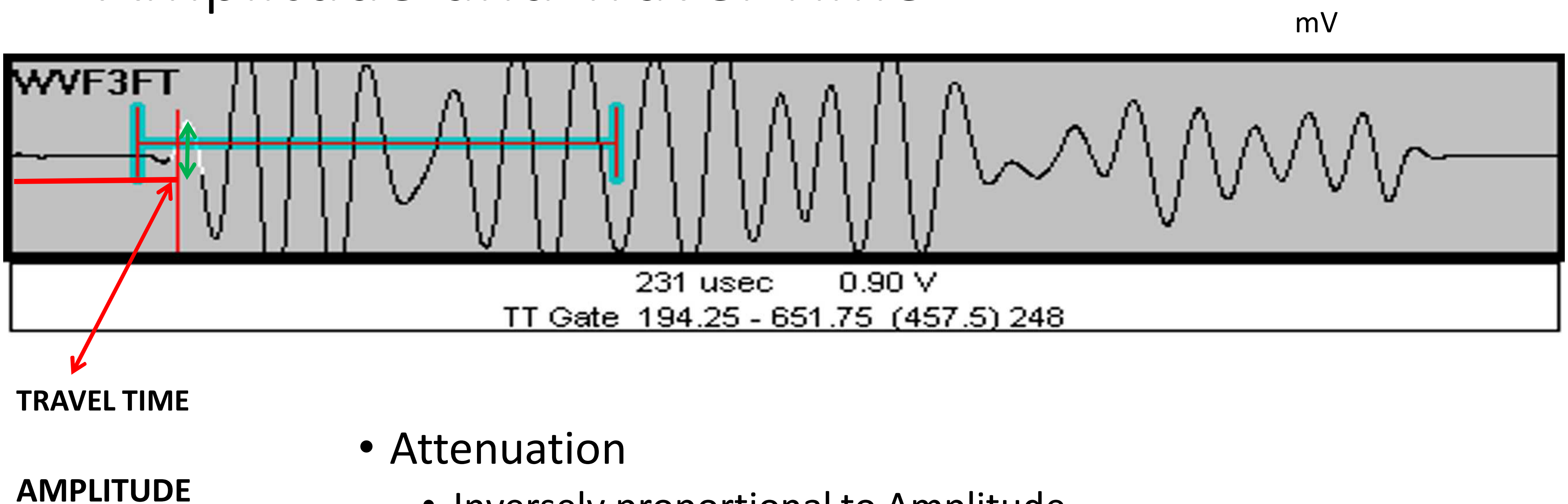
- Common mechanism of energy transport for ridged bodies and for surfaces





A
B
C
D
E
F
G
Transmitter
3 ft receiver
ft receiver
COMPOSITE
MUD/FLUID 189-208 µsec/ft
CASING 57 µsec/ft
CEMENT 100 µsec/ft
FORMATION 40-140 µsec/ft

Amplitude and Travel Time



- Attenuation
  - Inversely proportional to Amplitude
  - How fast the signal will die out
    - Low Attenuation = lack of cement
    - High Attenuation = cement

Amplitude

- Measured at one receiver 3 feet away from the transmitter
- Indication of pipe to cement bond
- Used in determination of cement bond index

$$BI = \frac{\log(A_{fp}) - \log(A_{ls})}{\log(A_{fp}) - \log(A_{100\%})} \qquad BI_{linear} = \frac{(A_{fp} - A_{ls})}{(A_{fp} - A_{100\%})}$$

BI = bond index
Afp = free pipe amplitude
Als = the measured amplitude
A100% = what is considered to be 100% bonding

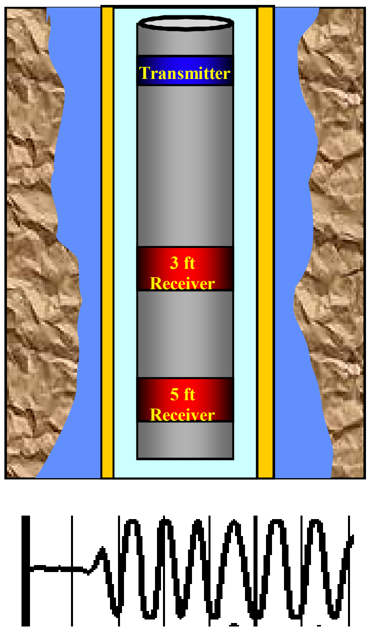
Typical Amplitude and Travel Time Readings

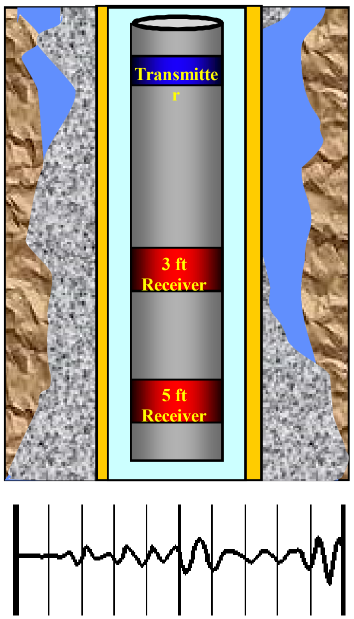
CASING SIZE (in)	CASING WEIGHT (lb/ft)	TRAVEL TIME (μs)		AMPLITUDE (mV)
		1-11/16" TOOL	3-5/8" TOOL	
4-1/2	9.5	252	233	81
	11.6	250	232	81
	13.5	249	230	81
5	15.0	257	238	76
	18.0	255	236	76
	20.3	253	235	76
5-1/2	15.5	266	248	72
	17.0	265	247	72
	20.0	264	245	72
	23.0	262	243	72
7	23.0	291	271	62
	26.0	289	270	62
	29.0	288	268	62
	32.0	286	267	62
	35.0	284	265	62
	38.0	283	264	62
7-5/8	26.4	301	281	59
	29.7	299	280	59
	33.7	297	278	59
	39.0	295	276	59
9-5/8	40.0	333	313	51
	43.5	332	311	51
	47.0	330	310	51
	53.5	328	309	51
10-3/4	40.5	354	333	48
	45.5	352	332	48
	51.0	350	330	48
	55.5	349	328	48

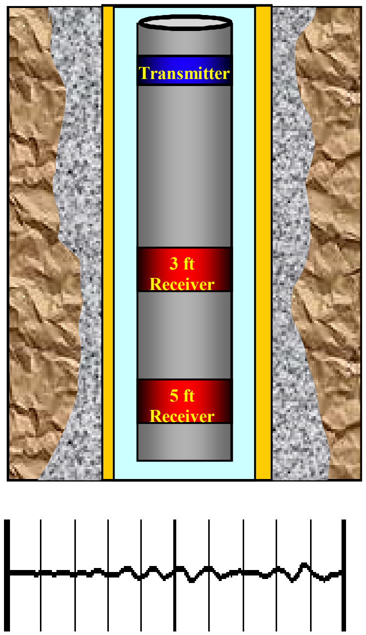
Waveform Data

- Provides the basic data for evaluating the quality of the cement sheath
- Delineate cemented from non-cemented sections by interpreting waveforms of acoustic signals
- Horizontal measurement is in time

Wellbore and Waveform Response

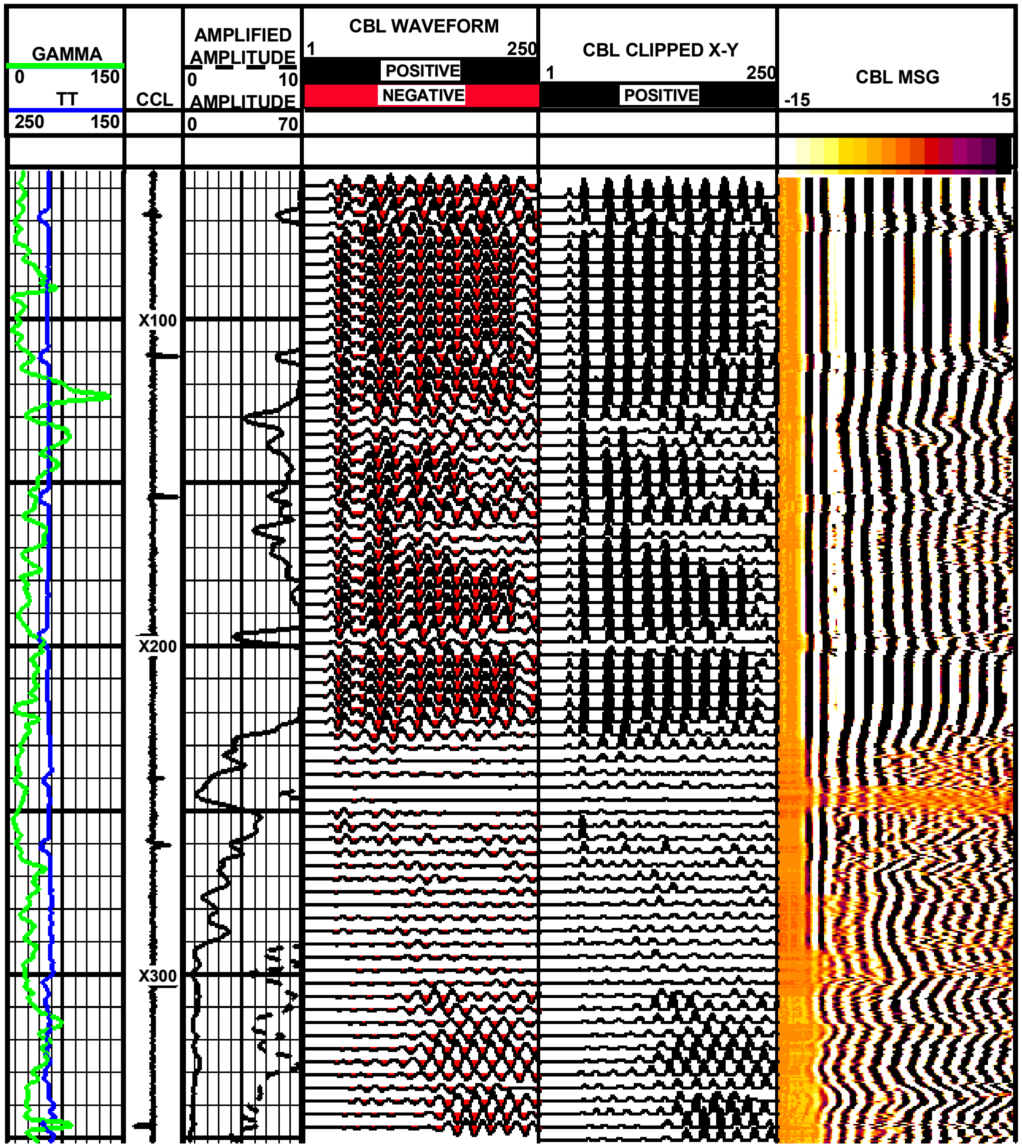






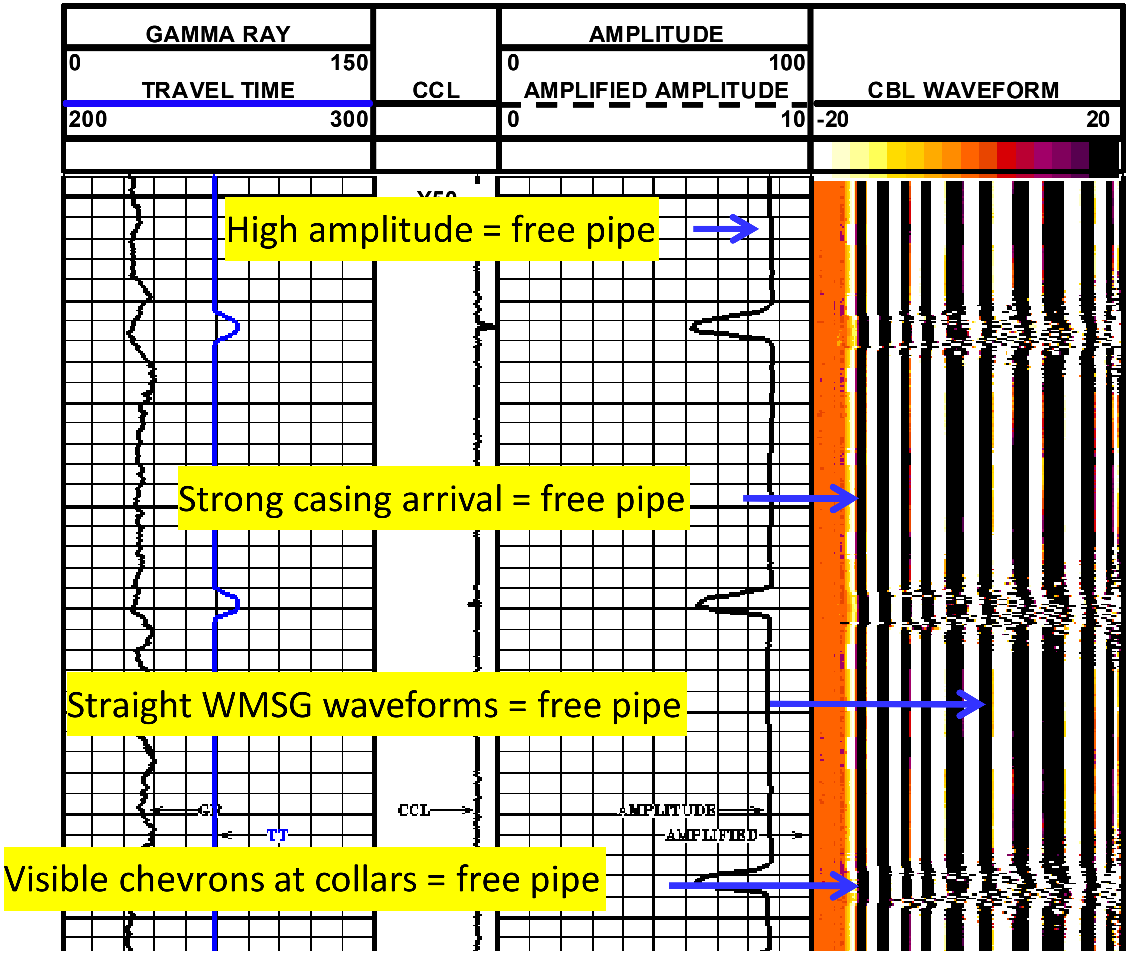
Traditional CBL Waveform Displays

- CBL Waveform
- Clipped Travel Time
- MicroSeismicGram (MSG) or Variable Density Log (VDL)

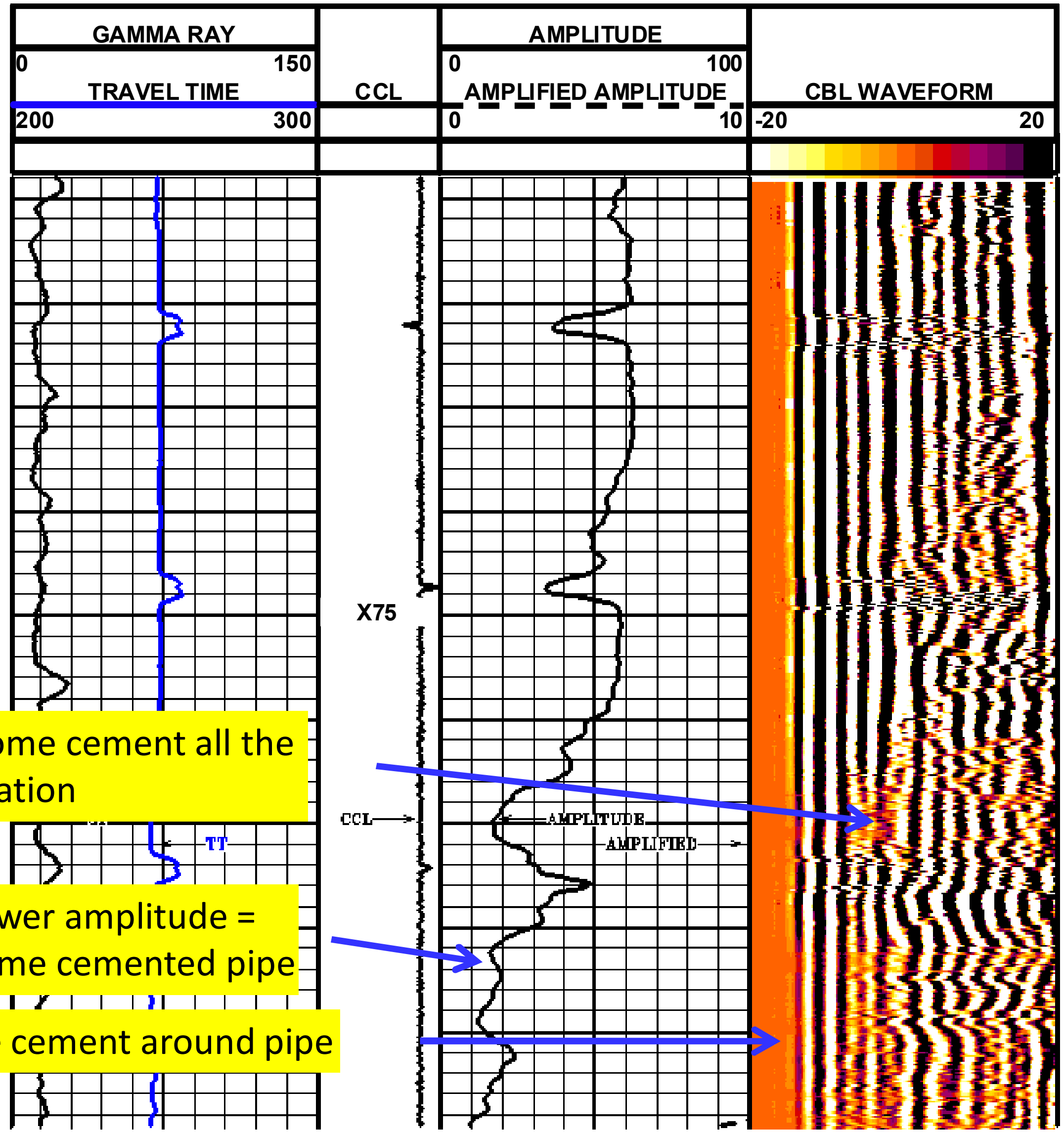


Free Pipe

- Travel time indicates free pipe and good centralization



Free to Bonded Pipe



WMSG waveforms = some cement all the way from pipe to formation

Lower amplitude = Some cemented pipe

Weaker casing arrival = some cement around pipe

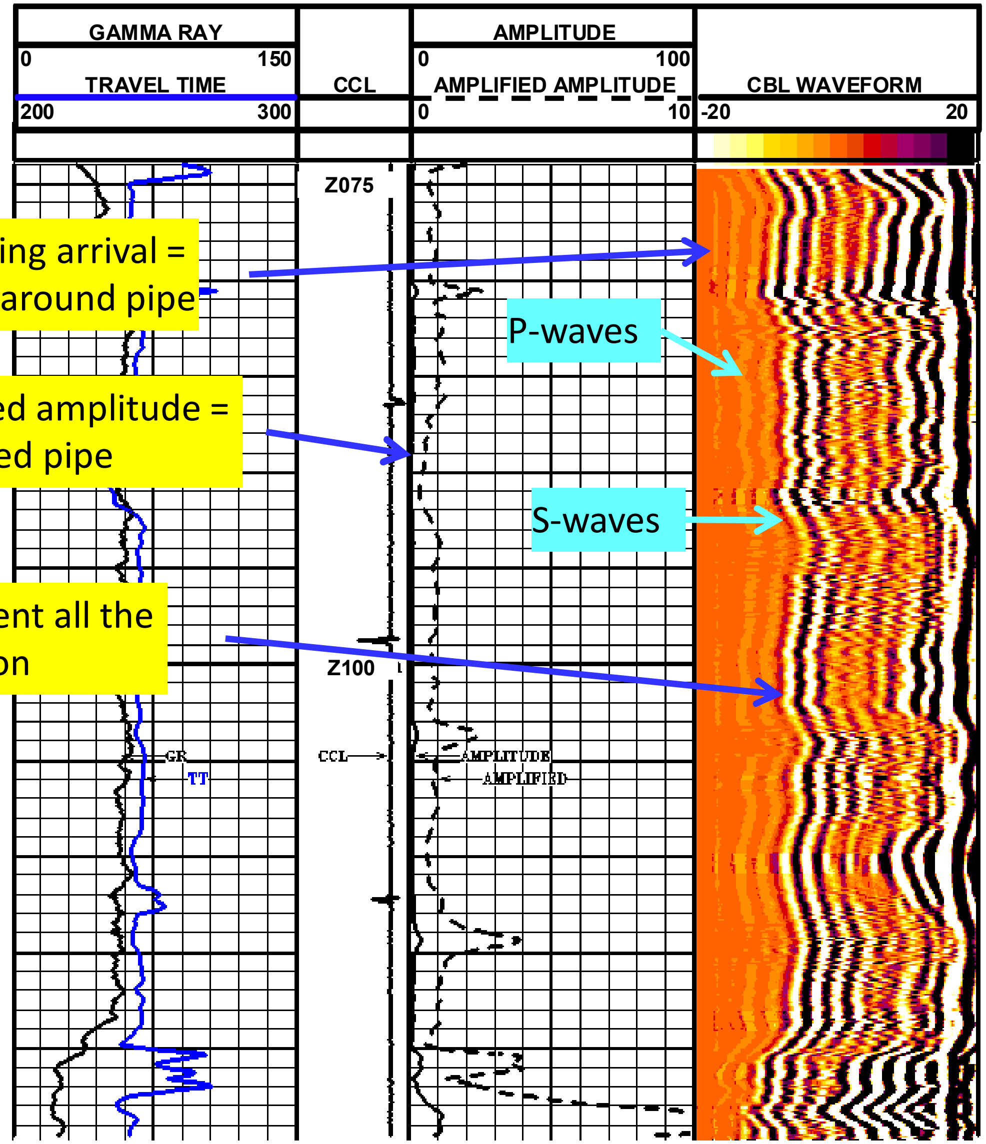
Excellent Cement Bond

Very weak casing arrival = Good cement around pipe

Amplified amplitude = cemented pipe

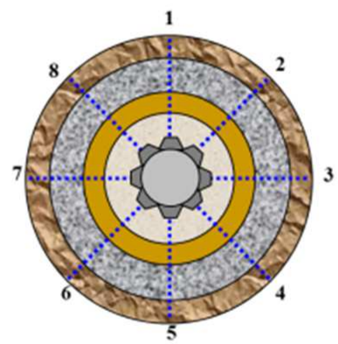
WMSG waveforms = cement all the way from pipe to formation

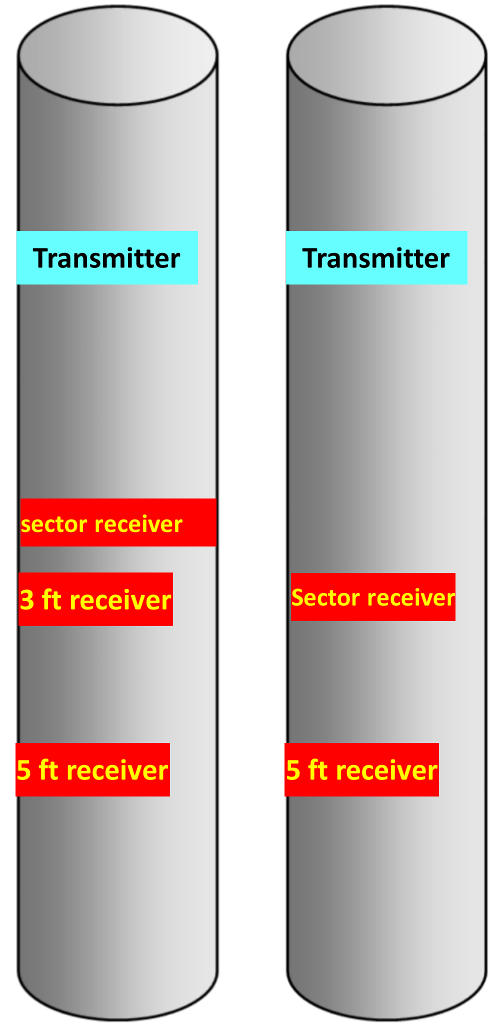
Changes in waveform response correspond to changes in gamma ray, indicating good cement all the way to the formation



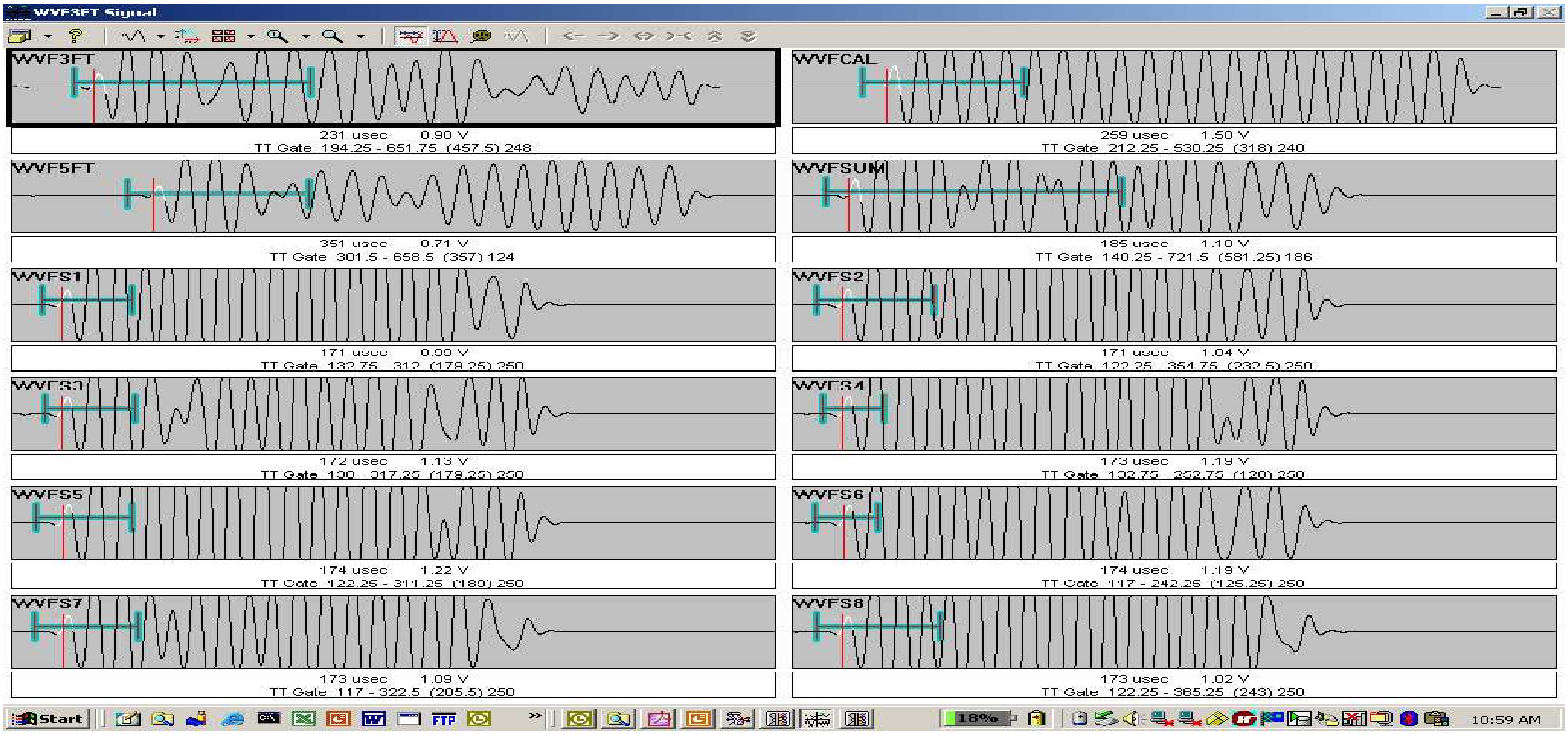
Radial Bond Log

- CBL with an additional sectored receivers
- Provides information on radial continuity of bonding or channels
- Depending upon the above
  - Sectors roughly 2 feet from source
  - 3 ft from source
- Six radial amplitude measurements for 1 11/16" tool.
- Eight radial amplitude measurements for larger tool 3 1/8" tool.
- Some tools have relative bearing sensor
  - High side and low side of hole determination



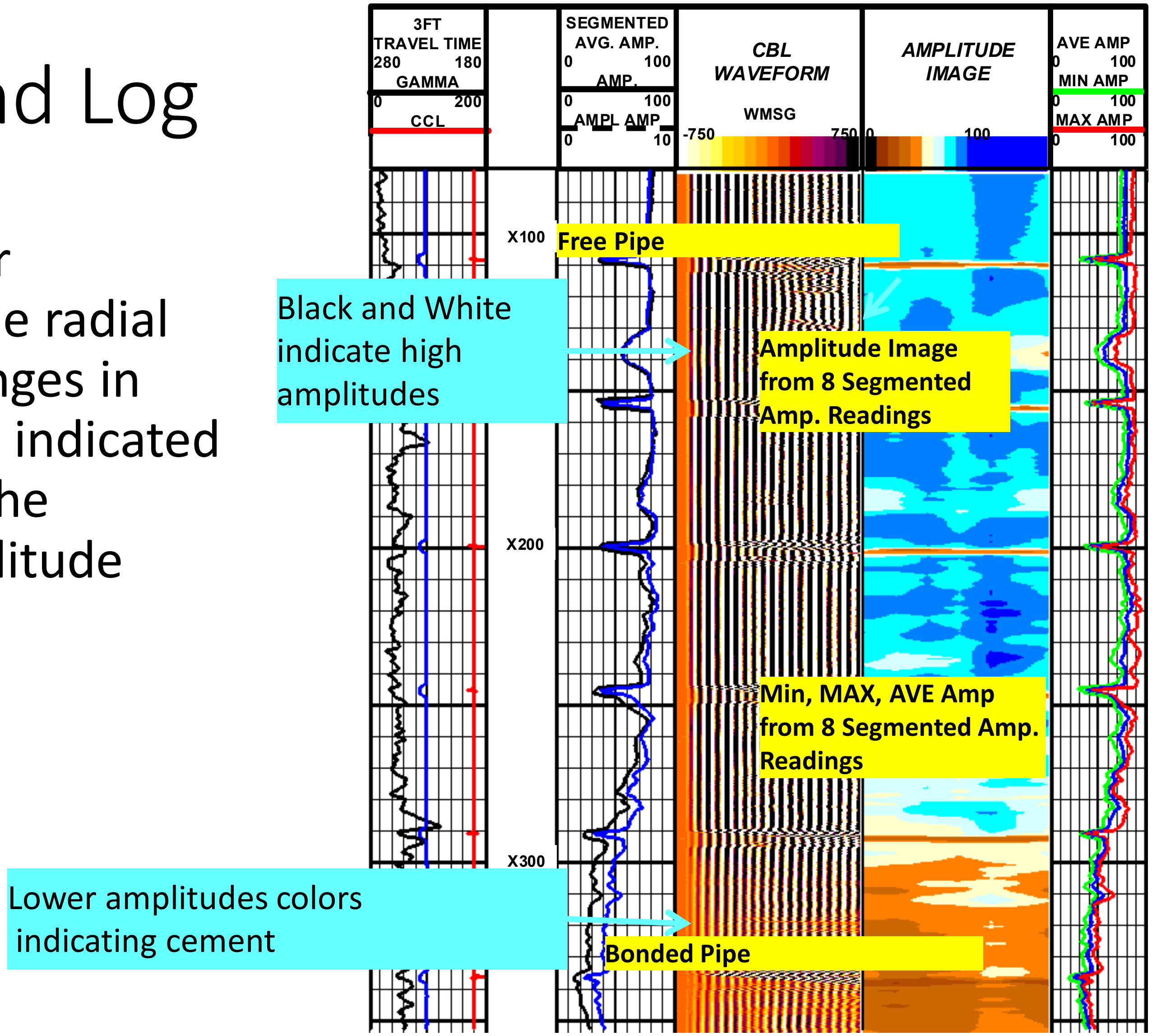


Radial Bond Tool Waveforms



Radial Bond Log

- With the higher frequency of the radial bond tool, changes in the cement are indicated by changes in the waveform amplitude



Advanced Cement Bond Tools Rotating Ultrasonic Transducers

- CAST-F, CAST-M, USIT
  - Cement and casing inspection
    - Azimuthal cement-to-pipe bond
    - Casing inspection
      - Casing internal radius
      - Casing thickness
  - Extensive horizontal coverage
    - 100% horizontal coverage (CAST-F, CAST-M)
    - 36, 72, or 100 Measurements Per Depth (USIT, CAST-V)

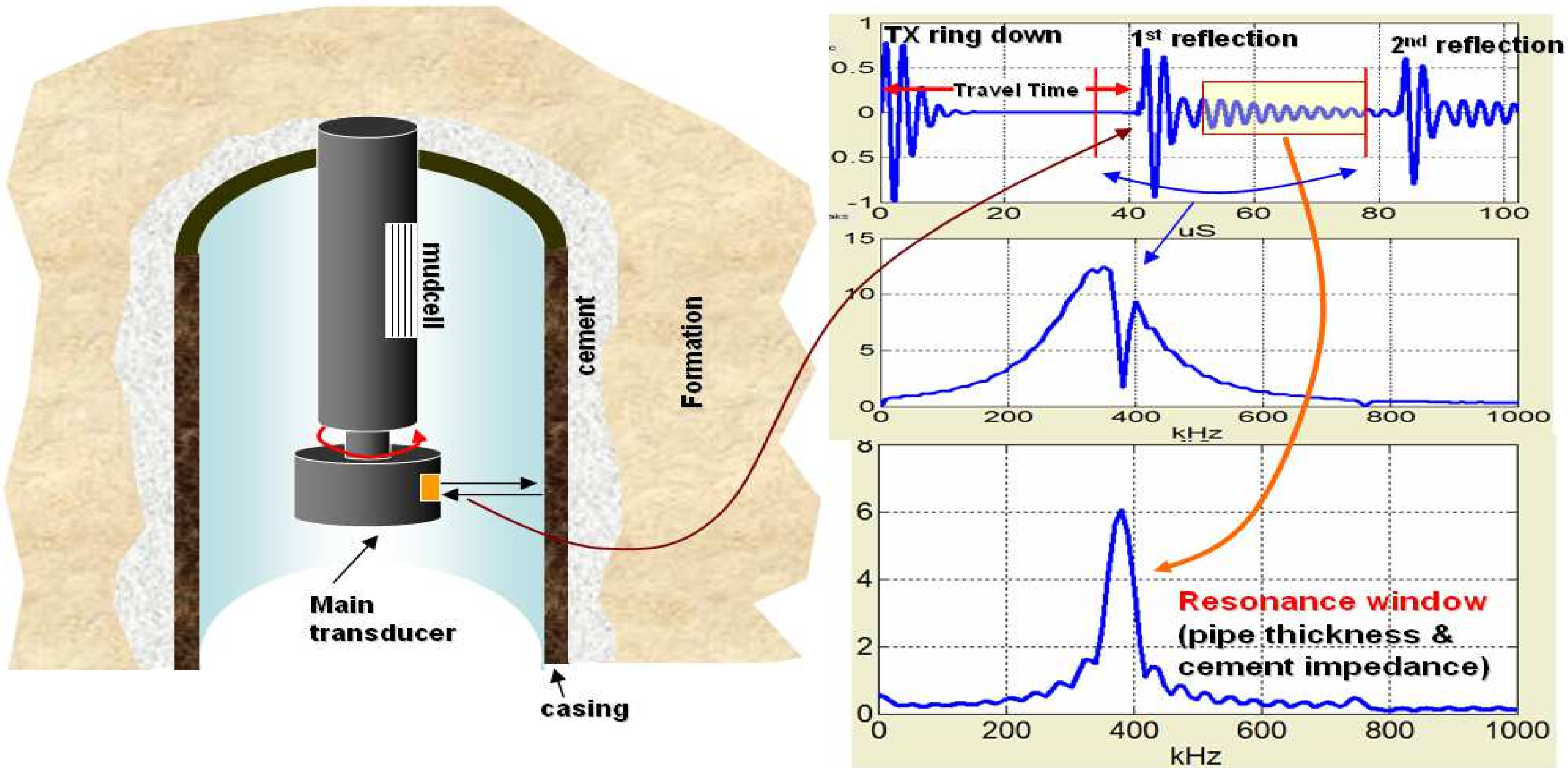
Ultra Sonic Cement Evaluation Tools

- Physics of Measurement

- Reflected Ultrasonic energy
  - Two way travel time
    - Casing radius
  - Amplitude of reflected waveforms
    - Casing inspection
  - Frequency of reflected waveforms
    - Casing thickness
  - Evaluation of reflected waveforms
    - Cement evaluation

- Mud weight and type limitation
  - Solids weighting material attenuates the ultrasonic signal
  - Signal attenuation in OBM ≈14-16 ppg.

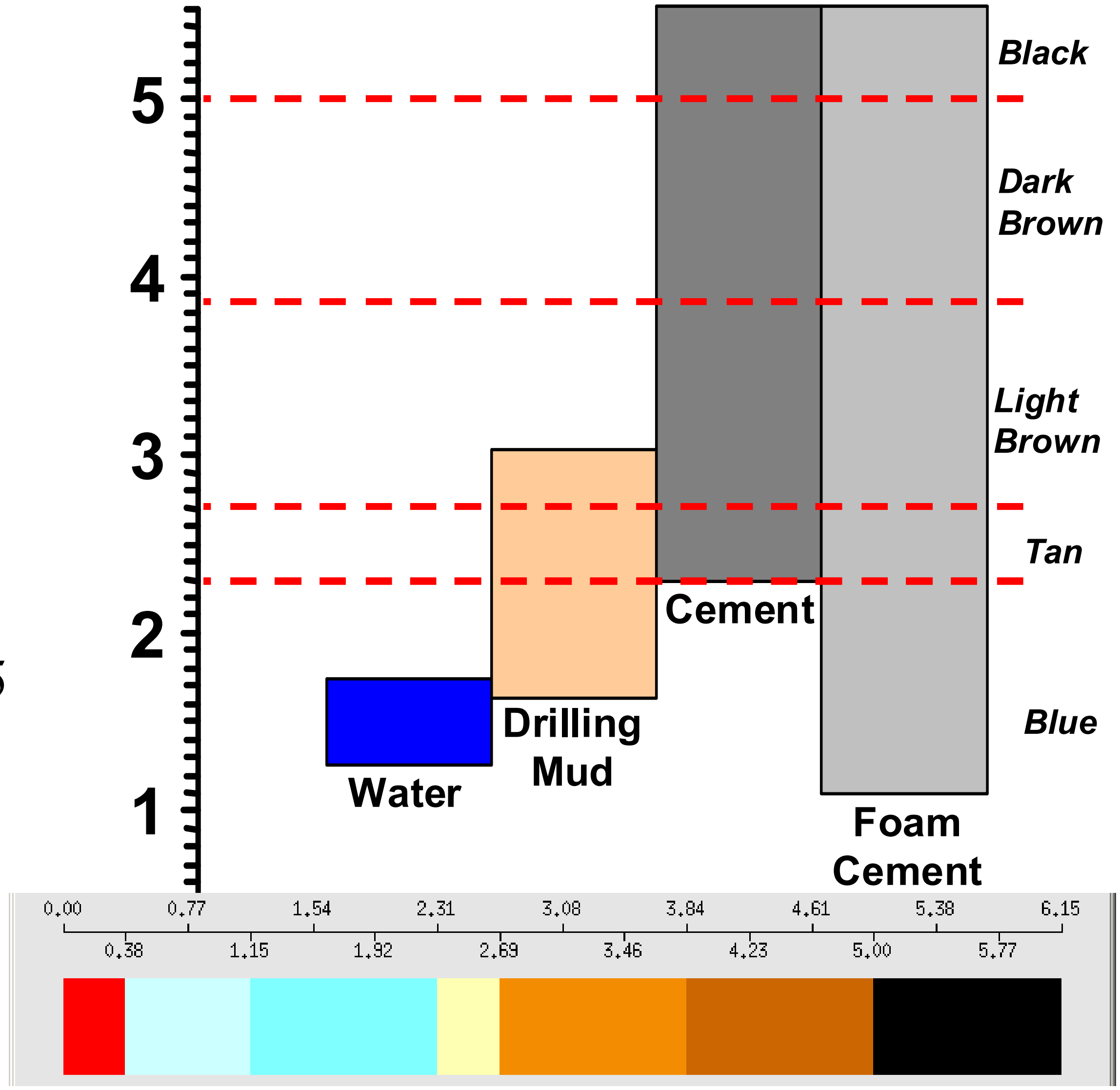
Ultrasonic Wave Propagation



Impedance Values

$$Z = \rho \times V$$

$$Z = (\rho_{ppg} / \Delta T_{\mu sec/ft}) \times 365$$

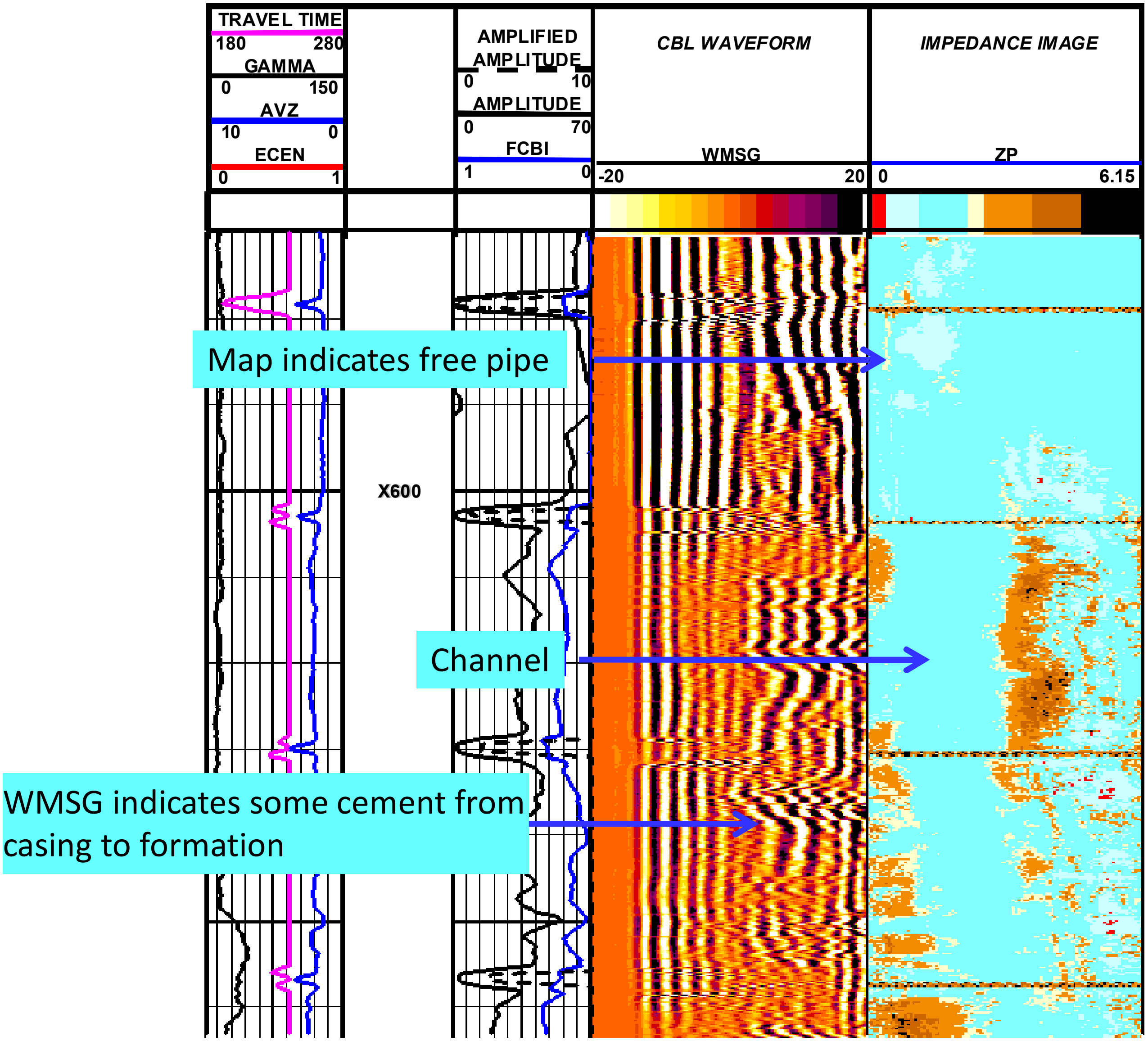


Impedance Values

Table 10-1 Acoustic parameter values

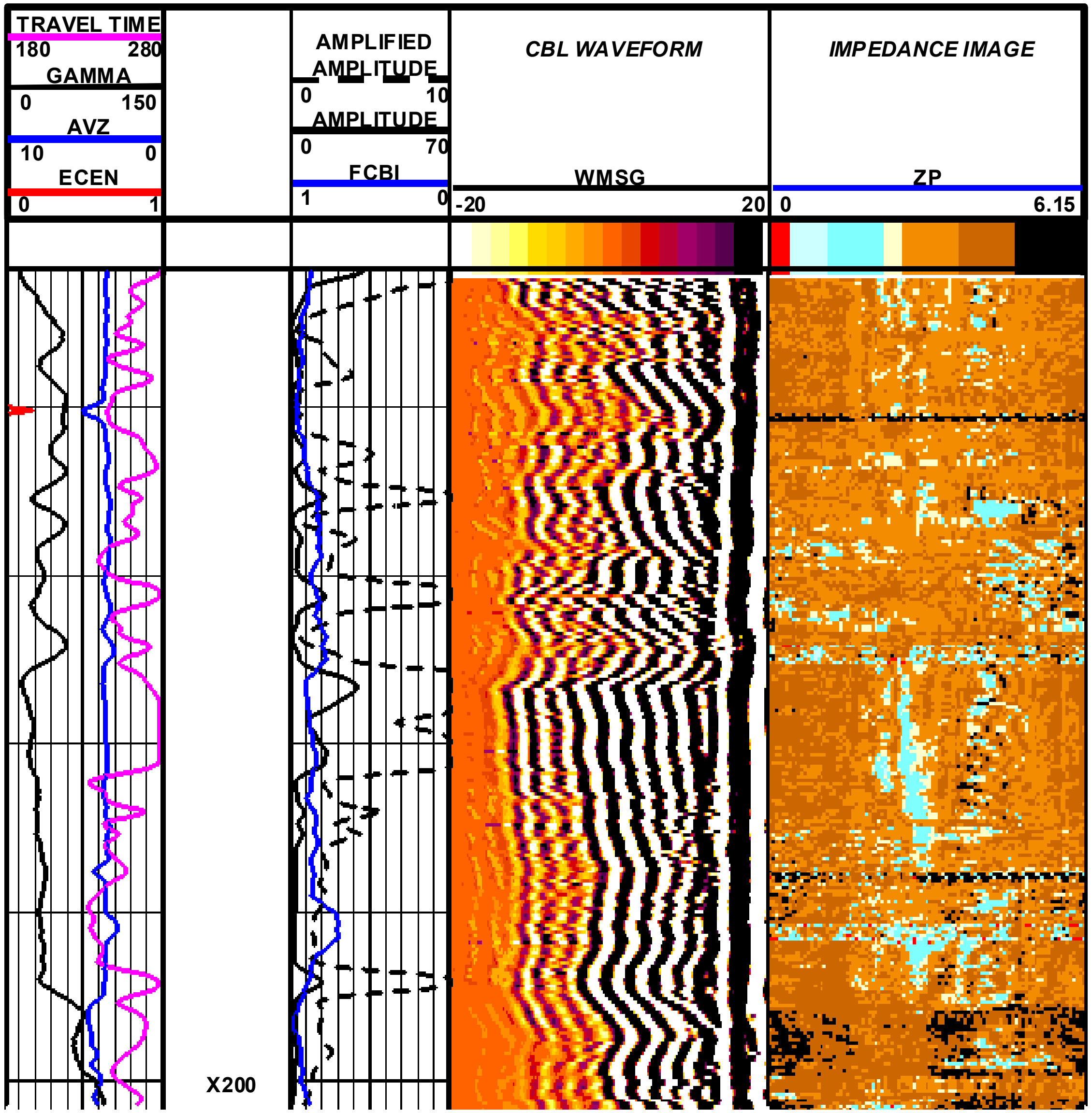
Material	V_p (km/s)	V_s (km/s)	ρ_b (gm/cc)	Z (MRayls)
Fresh water	1.52	0	1.00	1.52
Salt water (200 Kppm)	1.74	0	1.14	1.98
Diesel oil	1.25	0	0.80	1.00
Mineral oil	1.45	0	0.83	1.2
Free gas (mostly methane)	0.38	0	0.001	0.1
Water-based drilling fluid (8 lb/gal)	1.44	0	0.96	1.38
Water-based drilling fluid (16 lb/gal)	1.40	0	1.92	2.69
Oil-based drilling fluid (8 lb/gal)	1.34	0	0.96	1.29
Oil-based drilling fluid (16 lb/gal)	1.20	0	1.92	2.30
10% Porosity sandstone	4.66	2.91	2.49	11.60
30% Unconsolidated sands	3.31	1.94	2.16	6.42
10% Porosity limestone	4.91	2.73	2.54	12.47
10% Porosity dolomite	5.24	3.06	2.68	14.04
Class H cement (12 lb/gal)	3.1	1.8	1.55	4.8
Class H cement (16.6 lb/gal)	3.20	1.90	1.94	6.21
Lightweight cement (9 lb/gal)	3.10	1.80	1.55	4.81
Steel	5.90	3.23	7.70	45.43

CAST and CBL



TRAVEL TIME
180 280
GAMMA
0 150
AVZ
10 0
ECEN
0 1
X600
AMPLIFIED AMPLITUDE
0 10
AMPLITUDE
0 70
FCBI
1 0
CBL WAVEFORM
WMSG
-20 20
IMPEDANCE IMAGE
ZP
0 6.15
Map indicates free pipe
Channel
WMSG indicates some cement from casing to formation

Bonded Pipe


TRAVEL TIME
180 280
GAMMA
0 150
AVZ
10 0
ECEN
0 1
AMPLIFIED AMPLITUDE
0 10
AMPLITUDE
0 70
FCBI
1 0
CBL WAVEFORM
WMSG
-20 20
IMPEDANCE IMAGE
ZP
0 6.15
X200

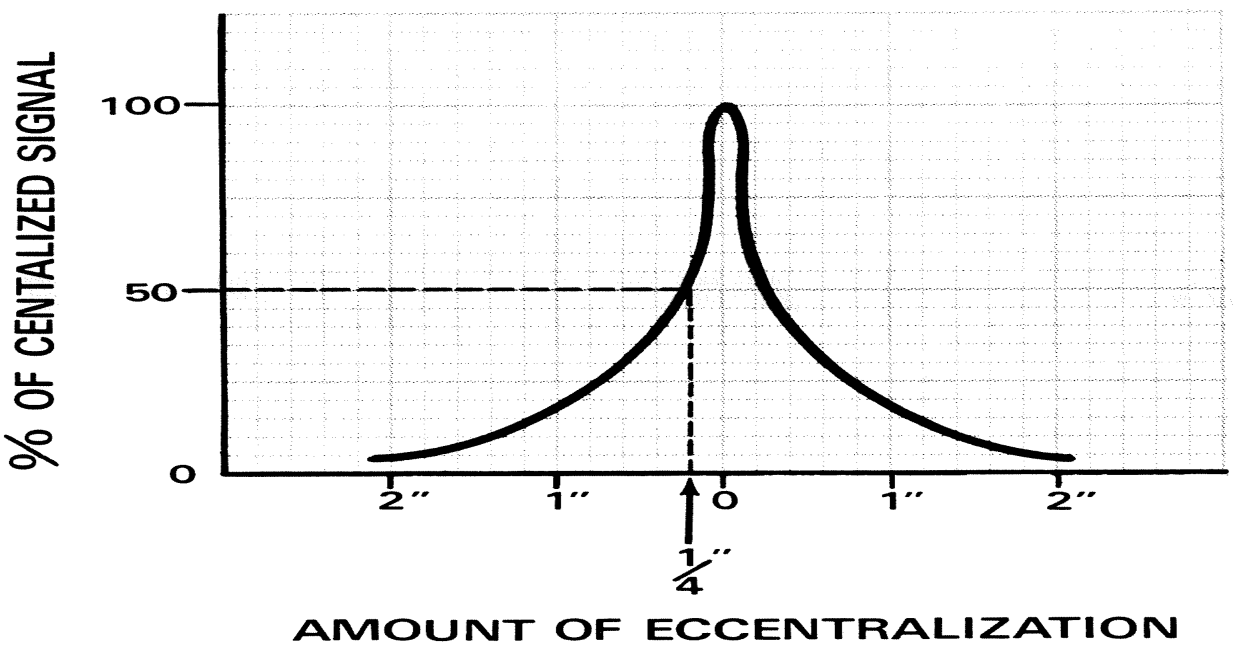
Cement Evaluation Theory (*ART)

- CBL, Sonic
  - Amplitude
    - High indicates free pipe
    - Low indicates cement
  - Waveform
    - High activity indicates cement
    - Low activity (railroad tracks) indicates free pipe
- Ultrasonic Tools
  - Impedance
    - High impedance indicates cement
    - Low impedance indicates free pipe

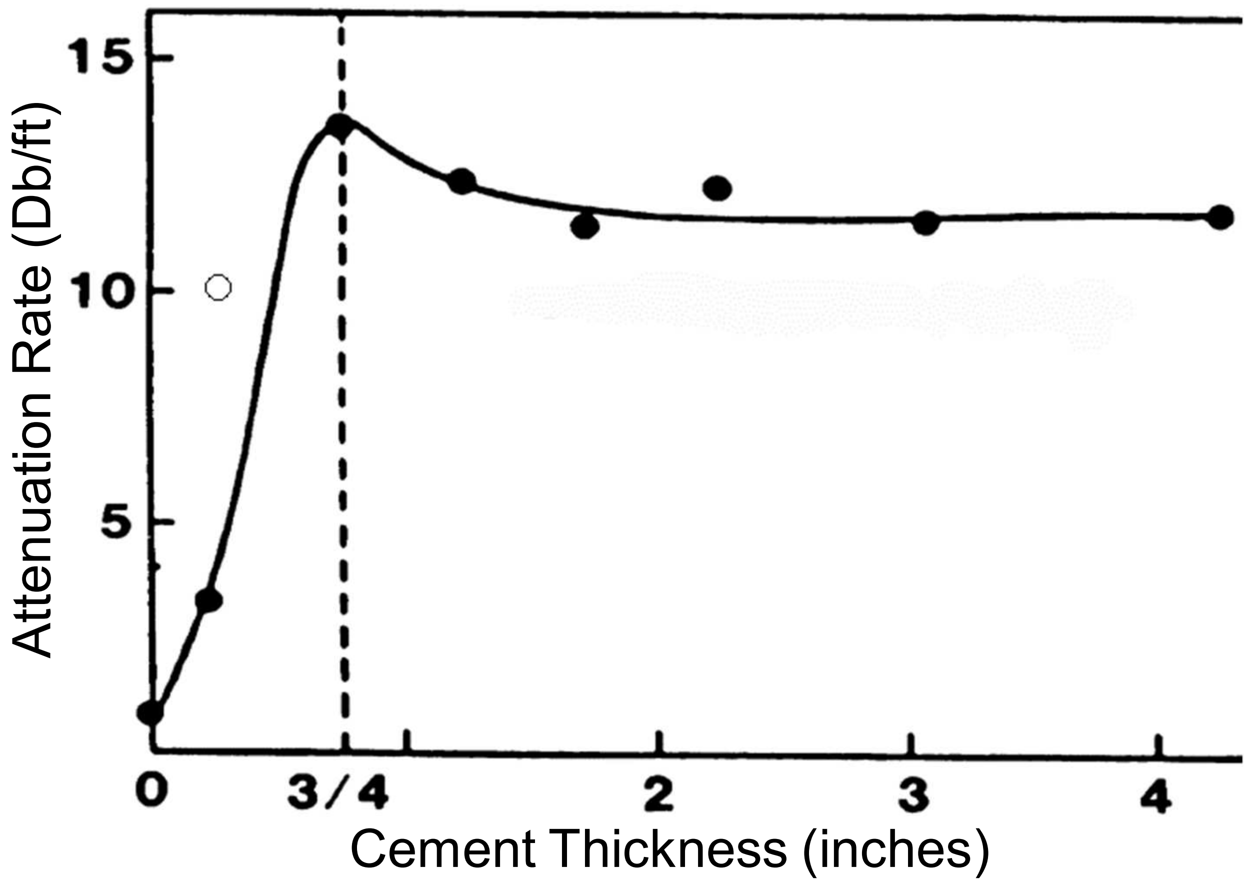
Quality Control for Cement Evaluation Tools

- All tools need to be very well centralized
- Each tool will have traces that will relate to QC
- Environmental Effects on Logs
  - Thin cement sheaths
  - Microannulus
  - Borehole shape
  - Fast formations
  - Cement curing time
- Garbage in = Garbage Out

Tool Decentralization Effects
for 1-11/16" CBL Tool

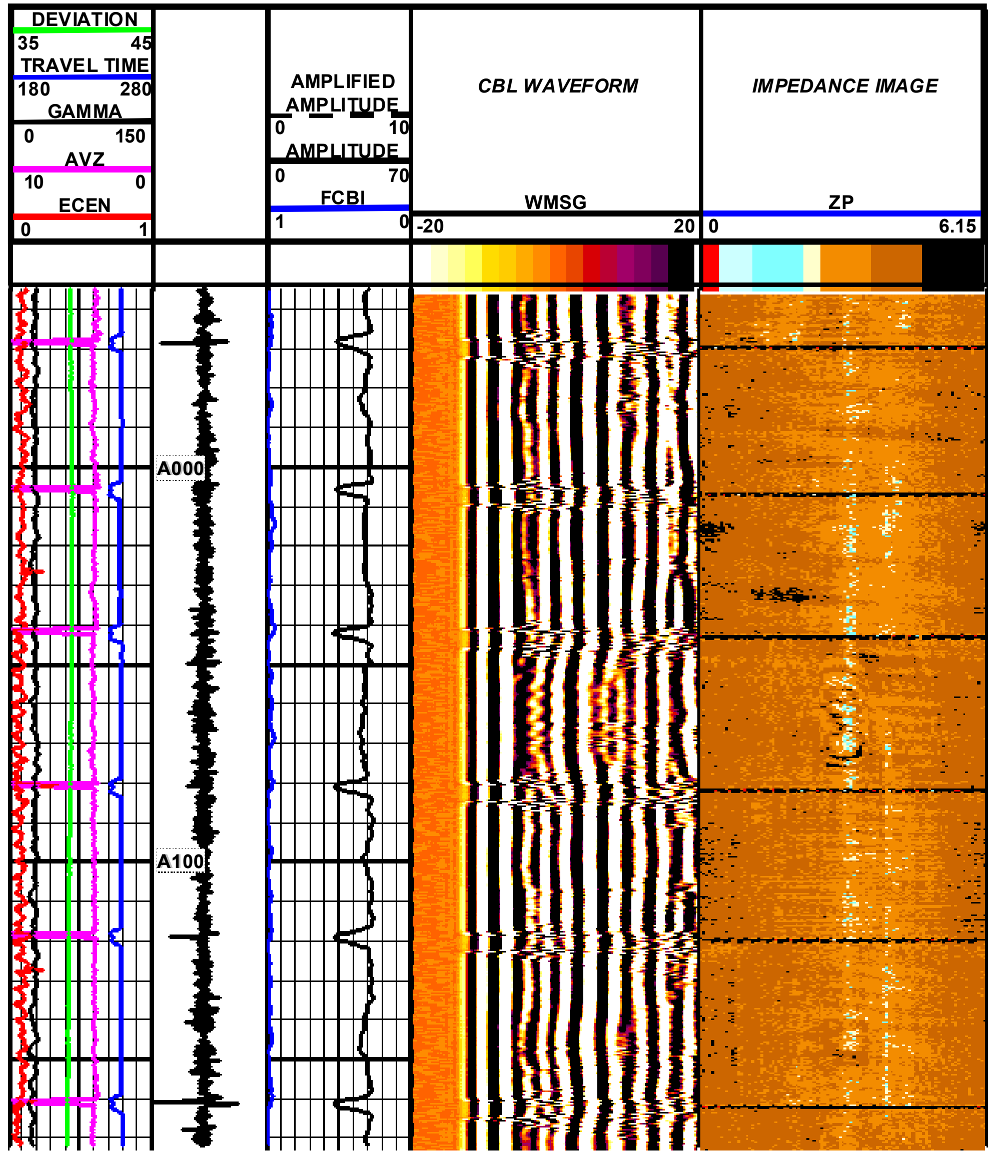


Attenuation Rate vs. Cement Thickness

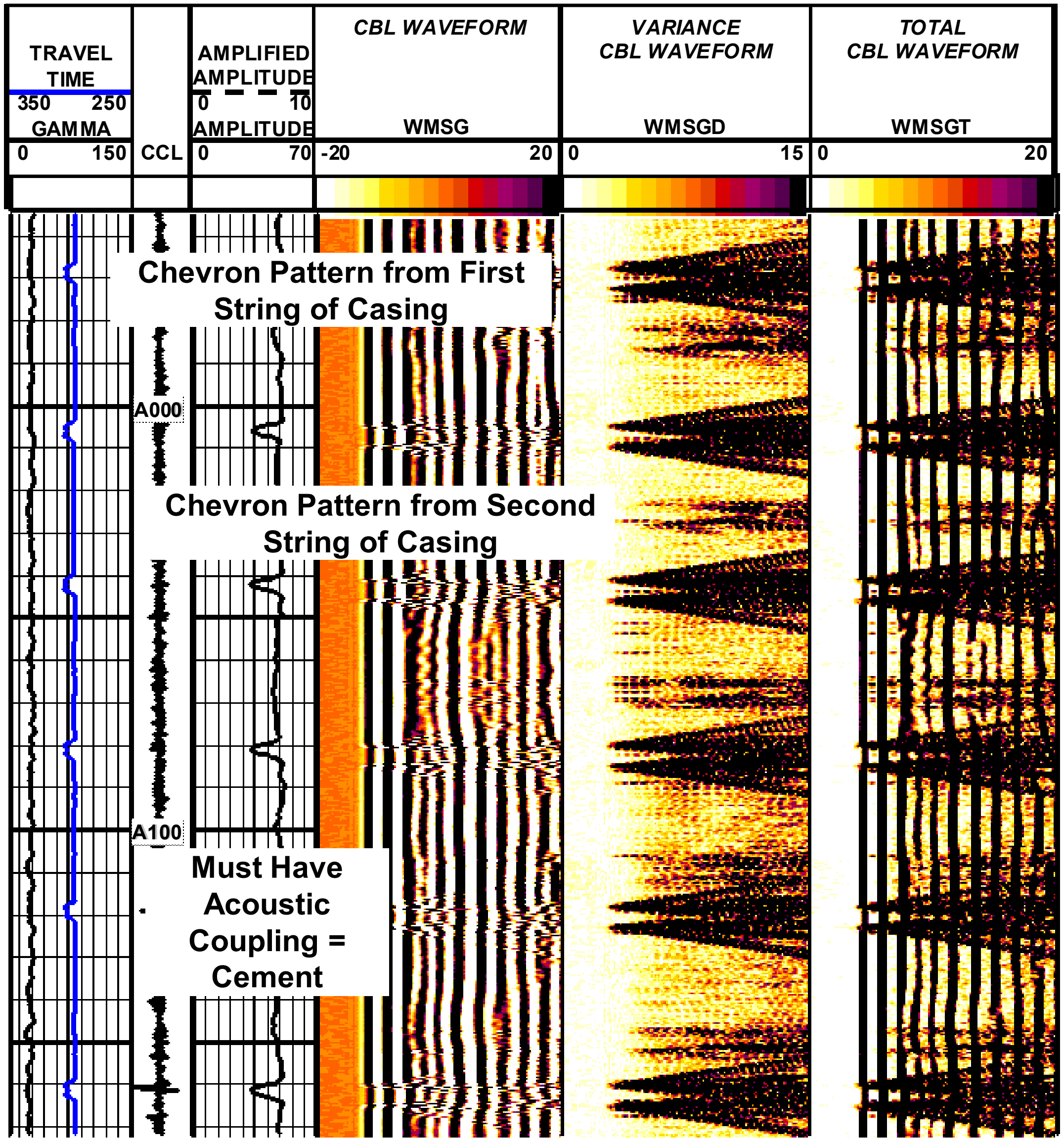


Which Cement Evaluation Log is Correct?

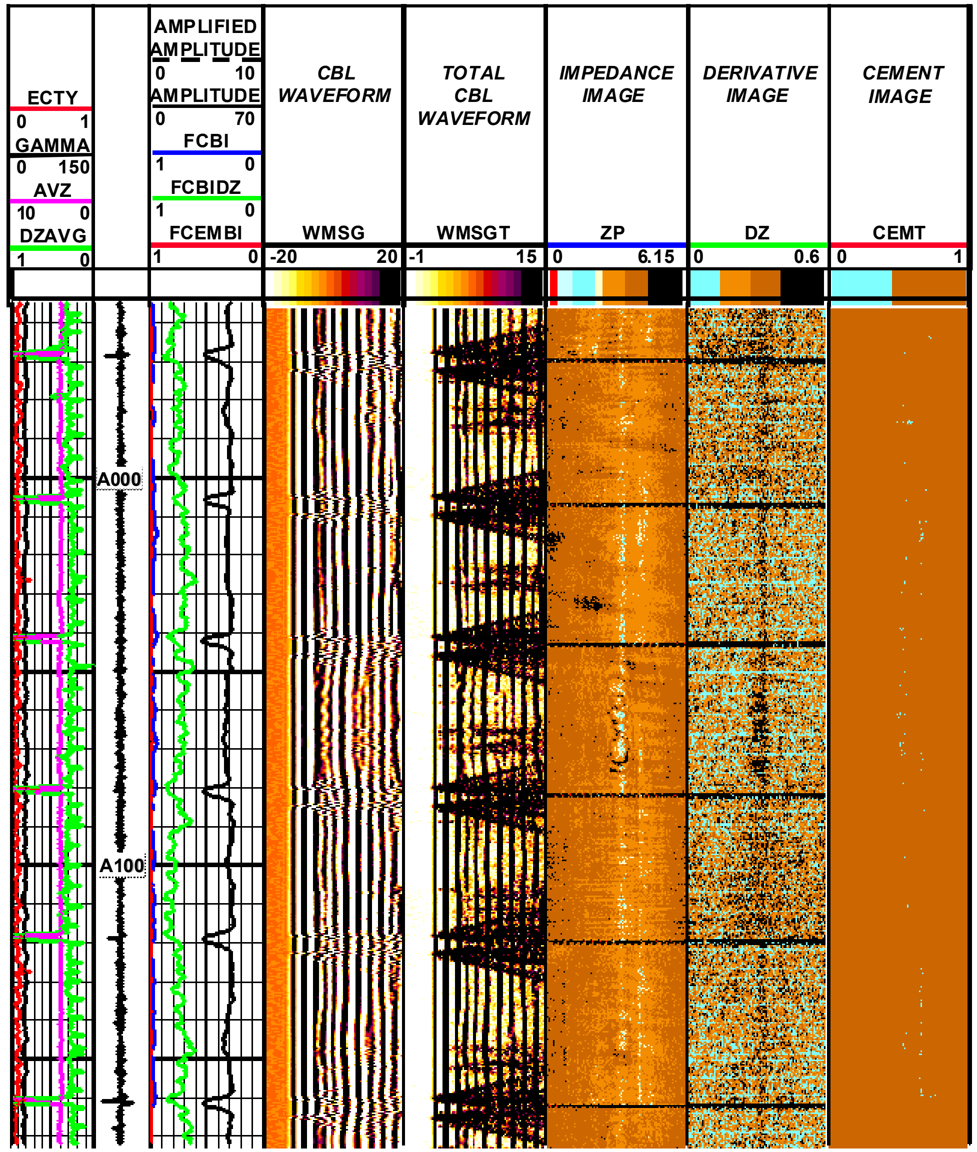
The CBL or Scanner?



Both!
Cement Sheath IS Very Thin.

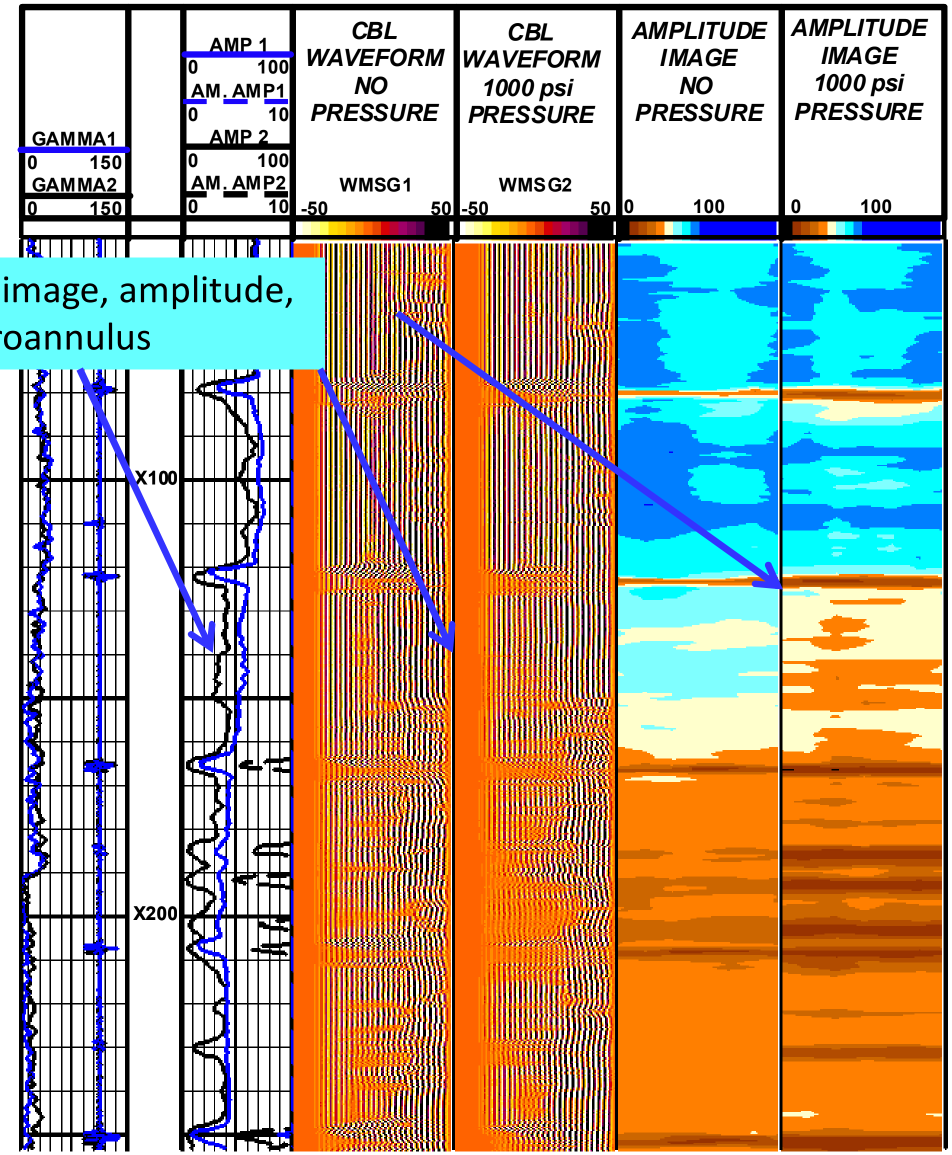


ACE Analysis



Radial Bond Microannulus

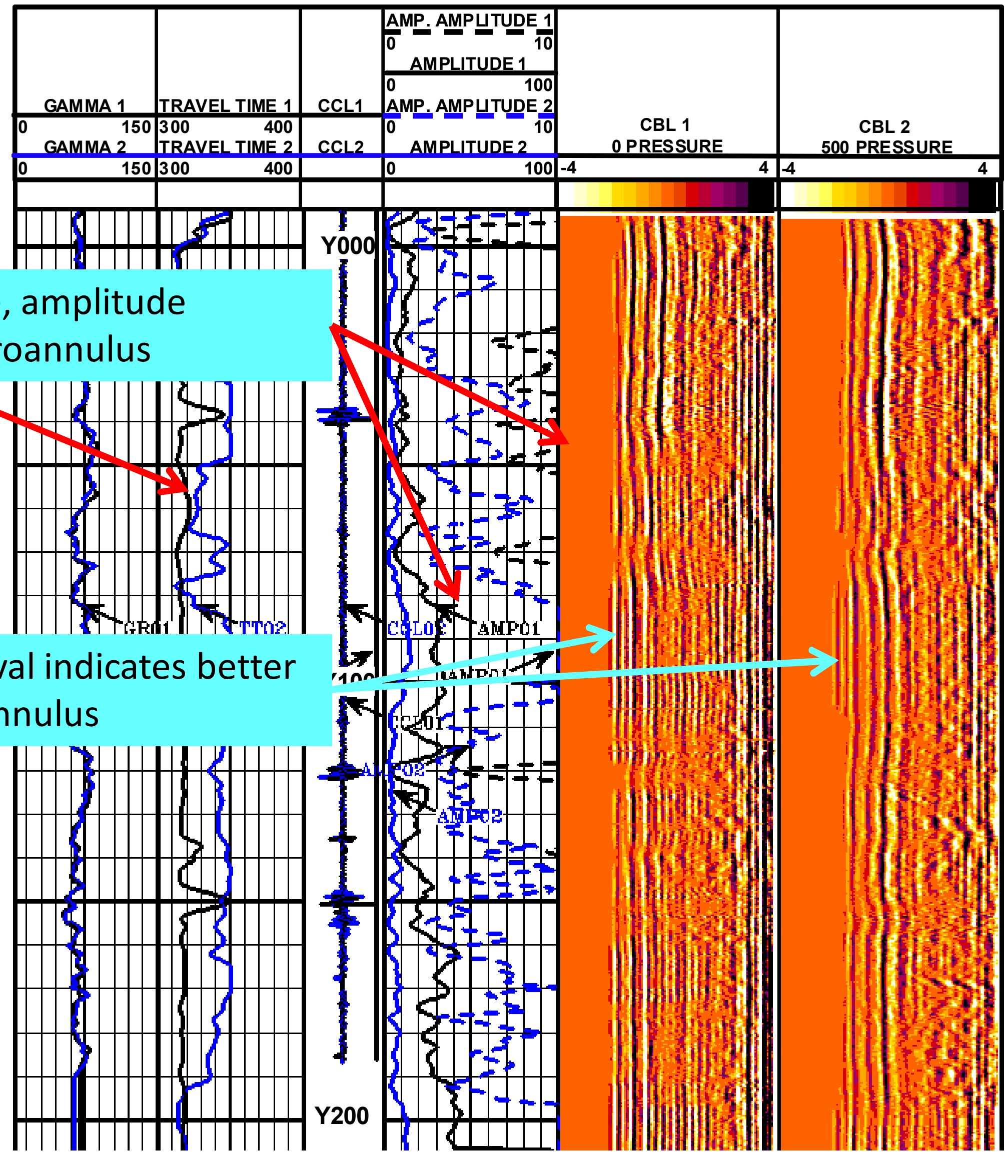
Changes in wmsg, amplitude image, amplitude, with pressure increase = microannulus



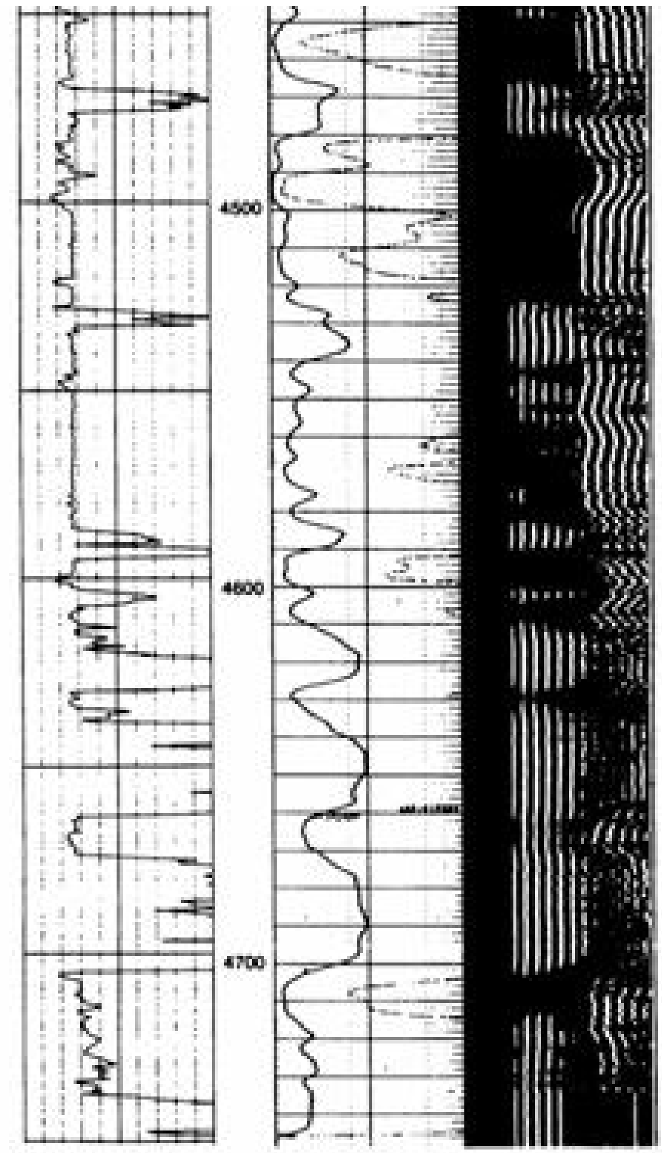
Microannulus 0 and 500 psi

Changes in wmsg, travel time, amplitude with pressure increase = microannulus

Large change in the pipe arrival indicates better bonding suggesting a microannulus



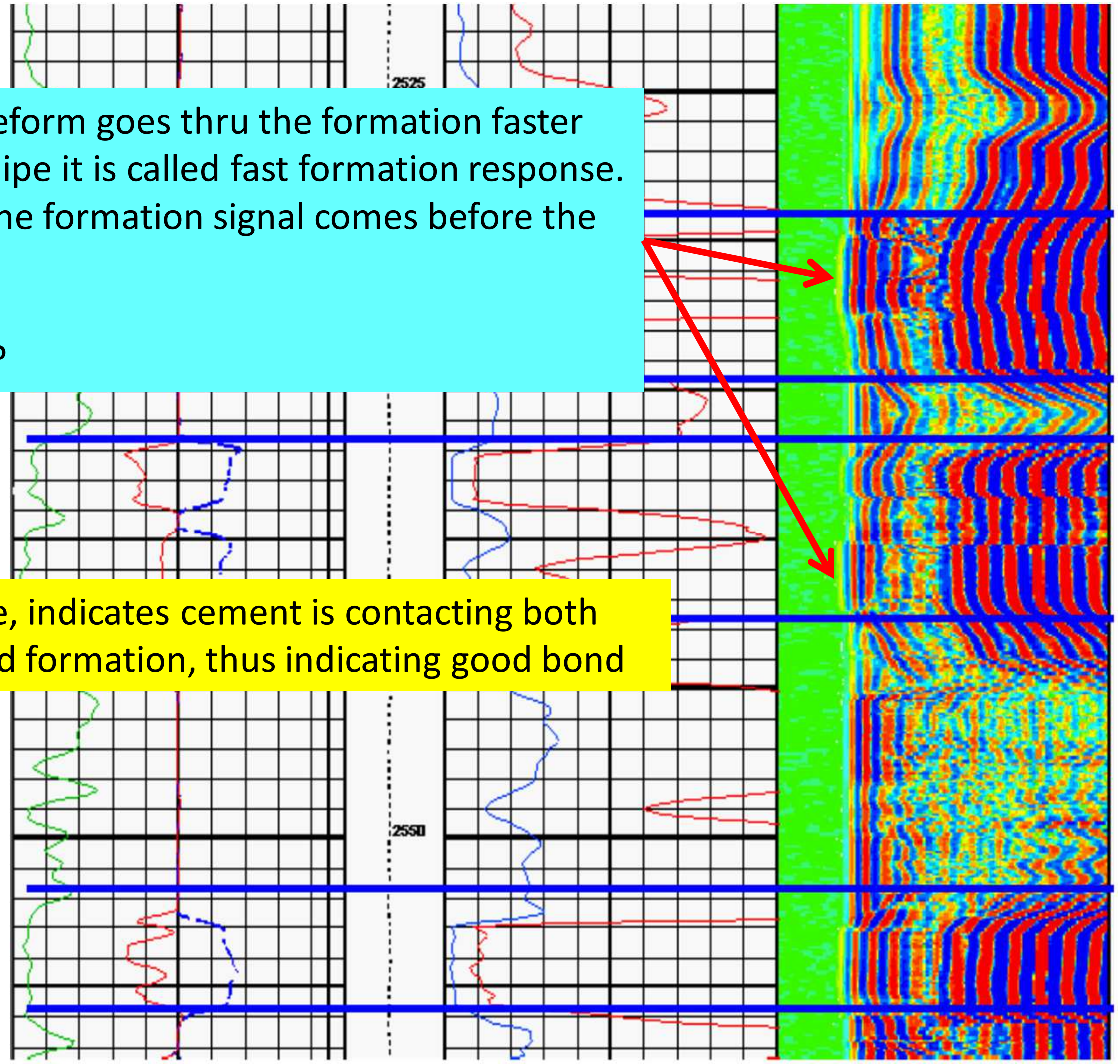
Caliper and Bonding



Fast Formations

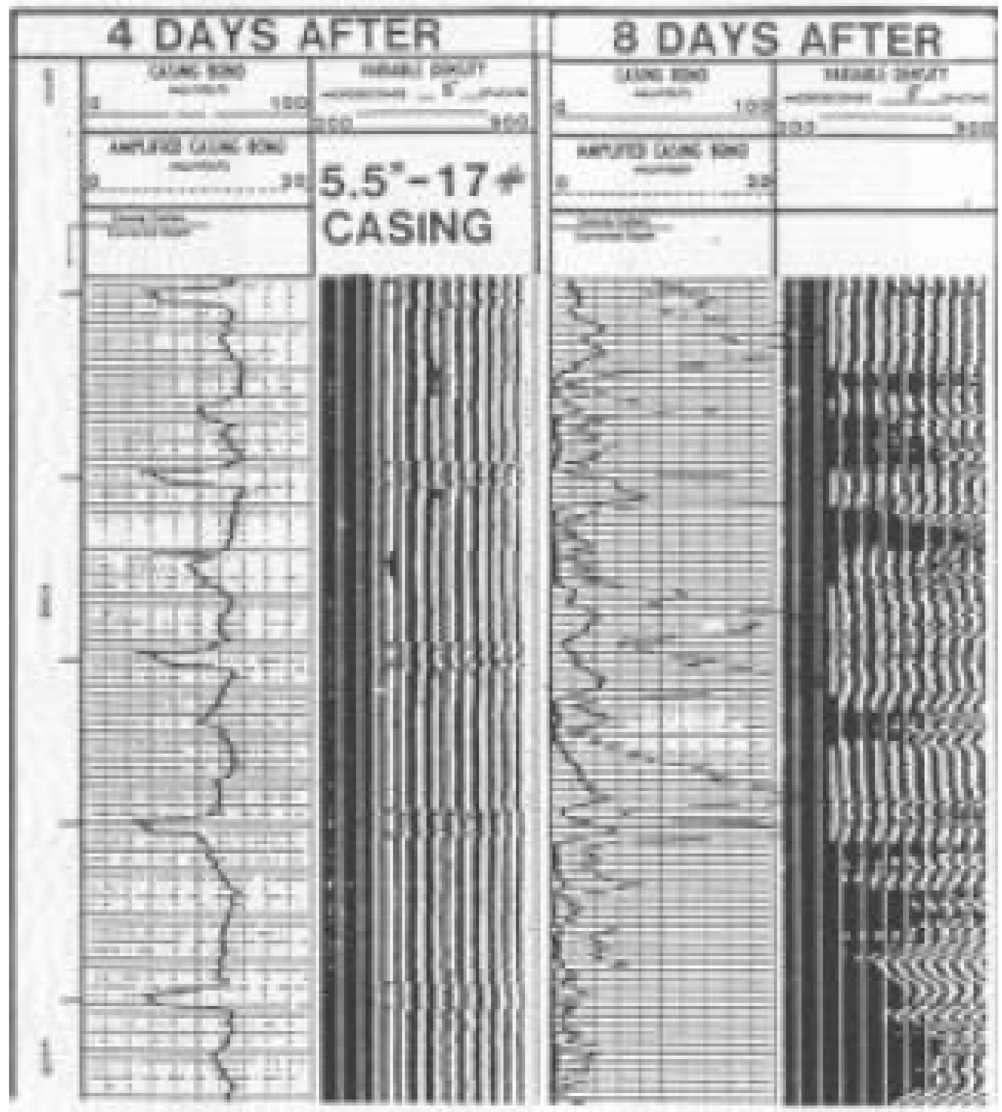
When the waveform goes thru the formation faster than thru the pipe it is called fast formation response. On the wmsg the formation signal comes before the casing signal.

Is it a problem?

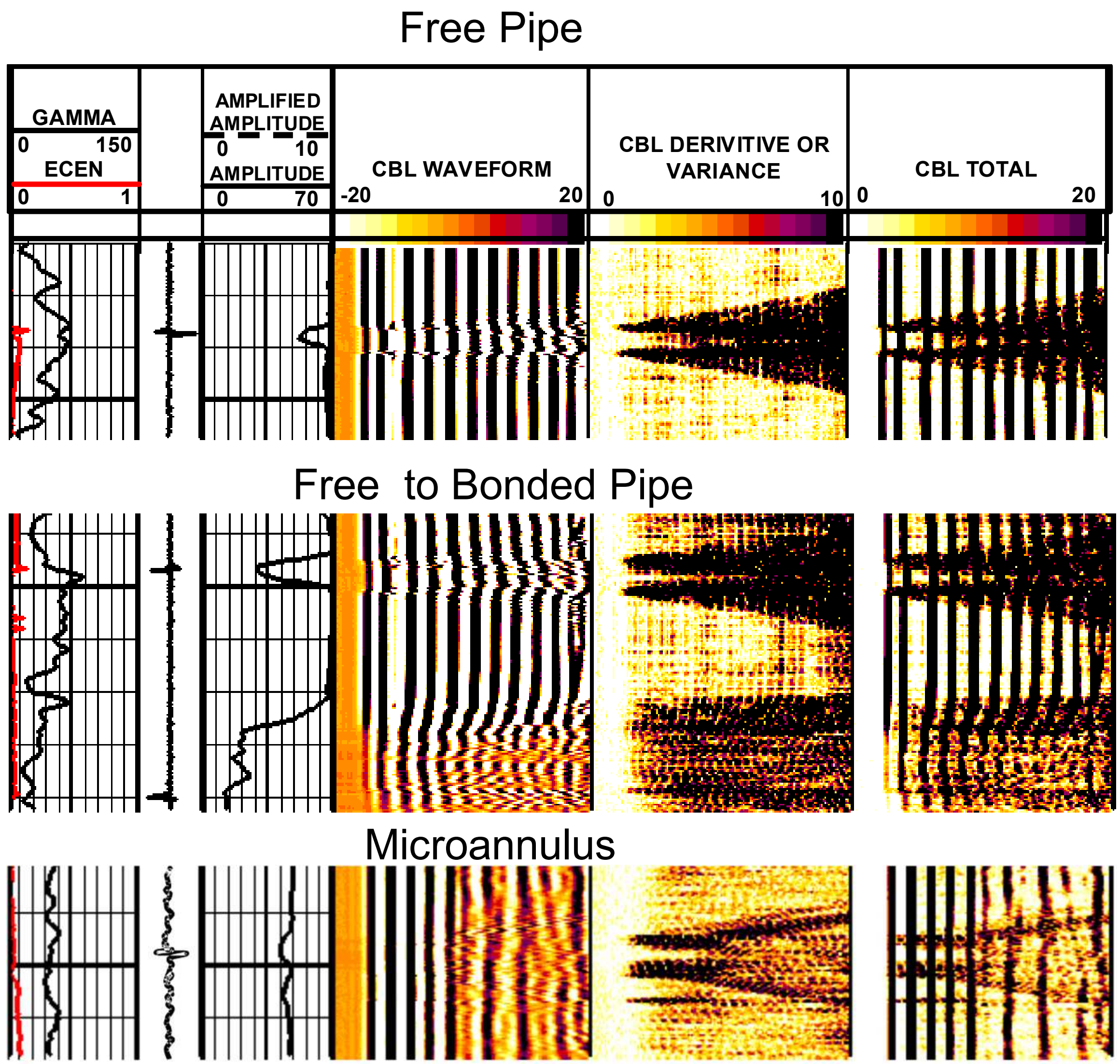


Should not be, indicates cement is contacting both the casing and formation, thus indicating good bond

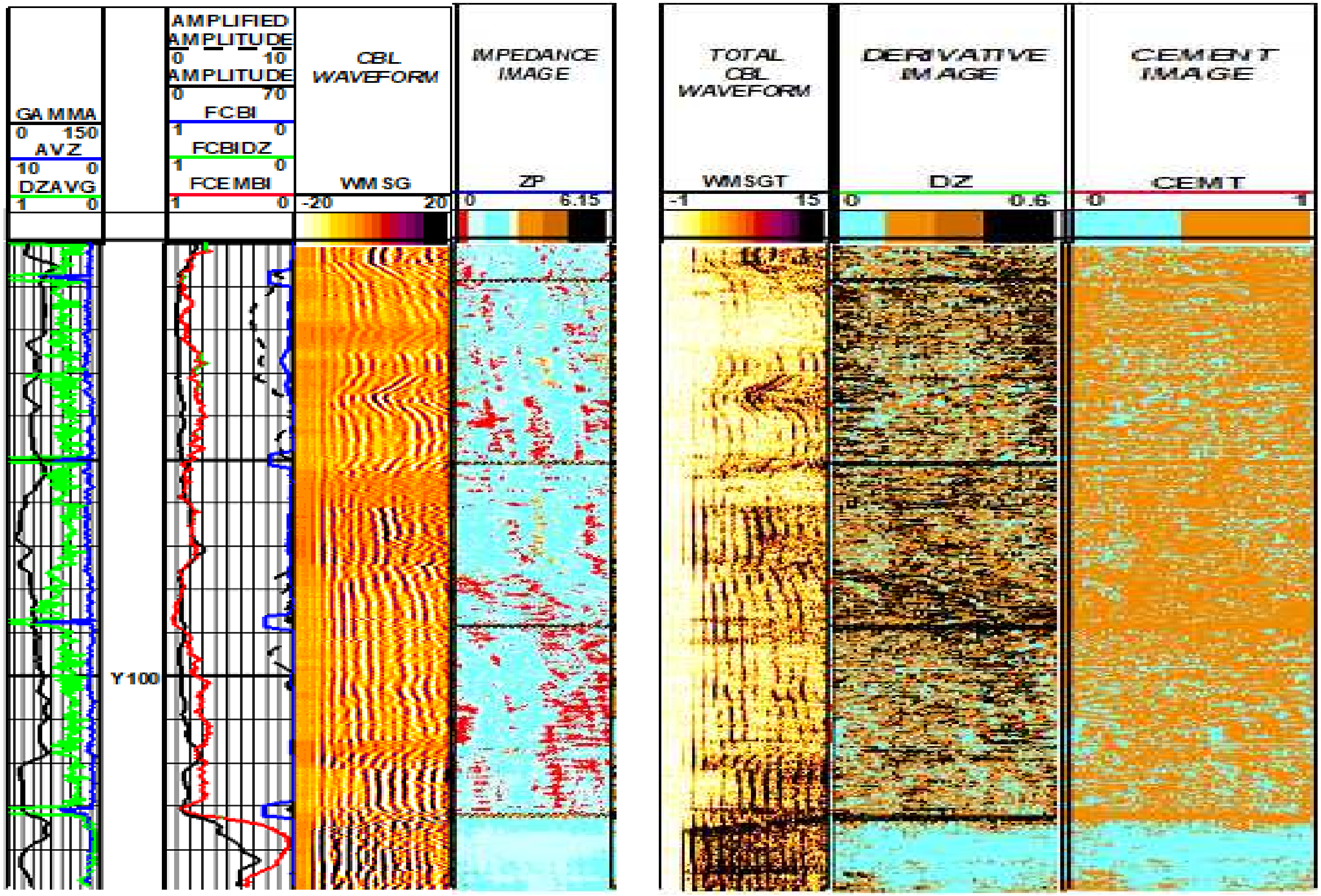
Cement Curing



Collar Responses

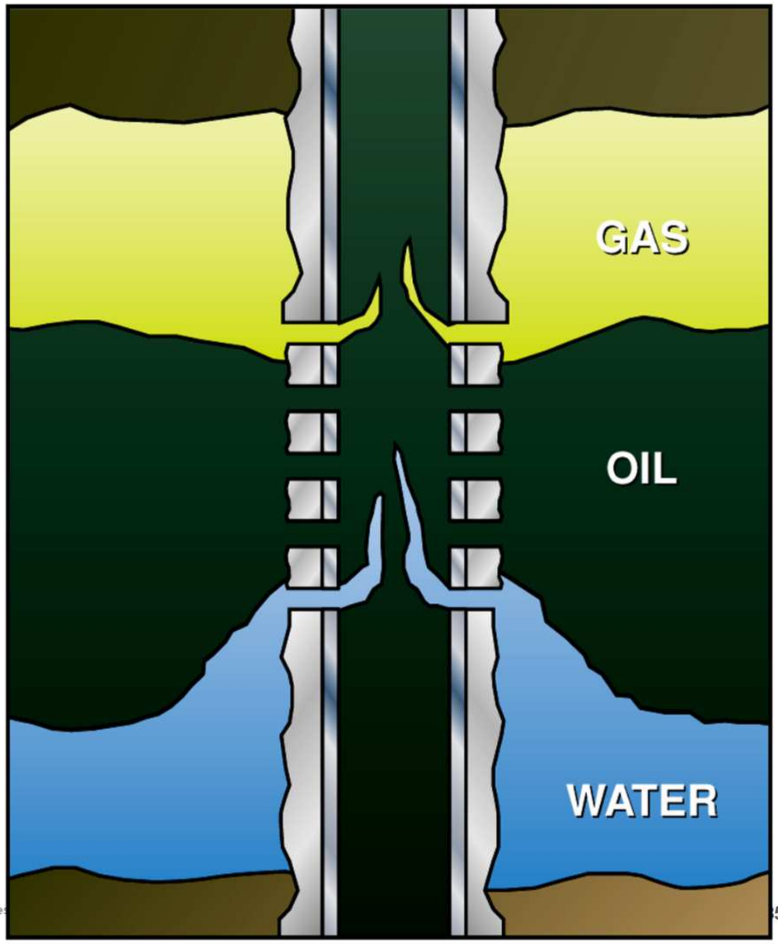


Foamed Cement 8lb/gal



Remedial 101

Problem Determination



- Why are we squeezing
- Shut off water or gas
- Abandon zone
- Temporarily seal off zone
- Injection Profile Modification

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Problem Determination

- Why are we Squeezing
- Repair channel
- Isolate prior to perforating
- Insufficient top of cement
- Repair casing leak

Problem Determination

- Do we need to squeeze now or wait?
- Cost Considerations
- Equipment
- Time Delays
- Well Construction Plans
- Cost

Problem Determination

- What criteria should we use for determining the need to do a squeeze job?
- Sonic evaluation logs
- Primary cement job design
- Primary cement job performance
  - Flow rate
  - Centralization
  - Mud Properties
  - Lost returns during job
- Experience
- Offset well data

Problem Determination

- Will a squeeze job do what we want it to do?
- All channels will be filled with some fluid or mud cake
- Mud must be displaced from channels for squeeze to be effective
- Most channels can not receive cement under squeeze pressure

Squeeze Cementing Myths

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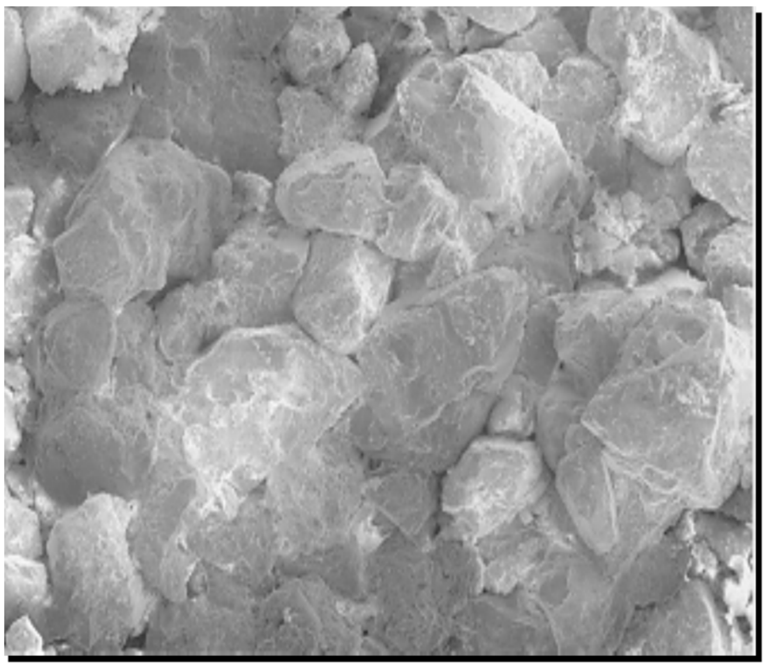
Myth – Cement Slurry Enters the Formation Matrix



Berea Sandstone - 350 md

- Cement average particle size 20-50 microns
- > 2000 md formation permeability required

Fact –

Cement particles are too large to enter the matrix of most formations

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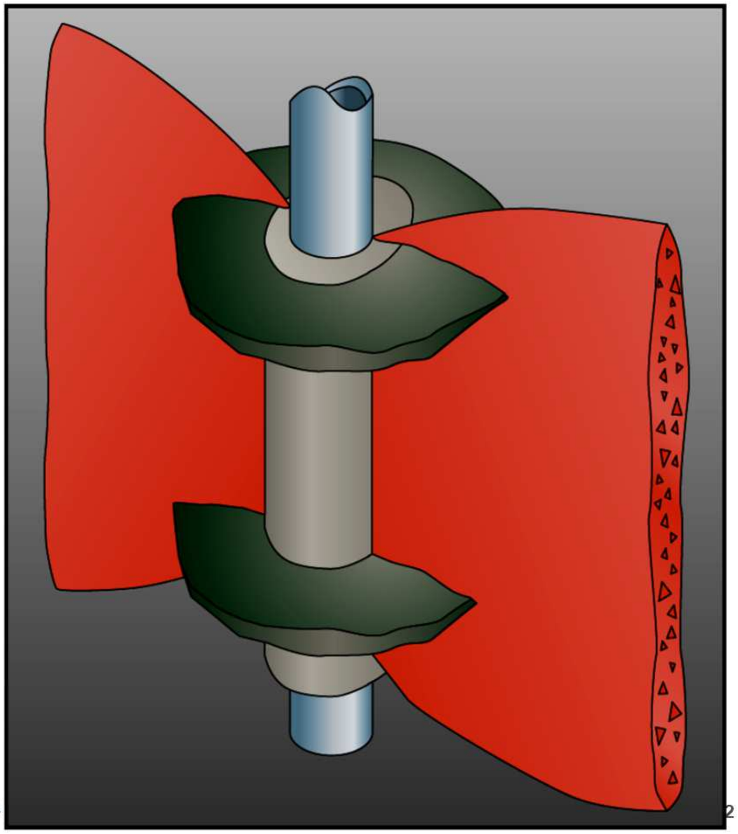
Myth – Squeeze Cementing Produces a Horizontal Pancake of Cement



Fact

- Fracture orientation is normally vertical rather than horizontal
- Fracture may be an angle to the wellbore in deviated wells

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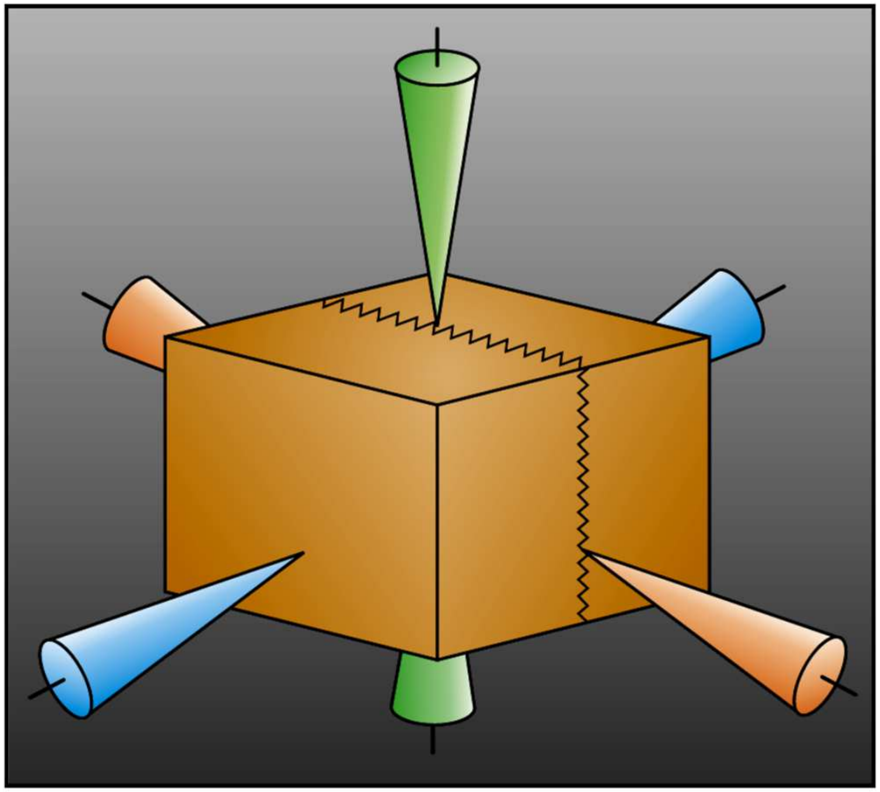
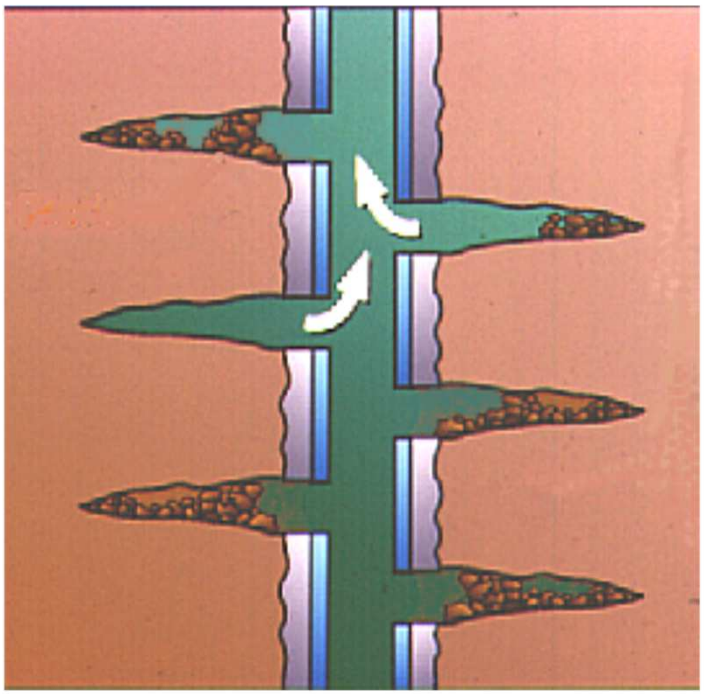
Tri-Axial Loading of Rocks



- Fracture orientation is perpendicular to the least principle stress
- Least principle stress is normally horizontal
- Most induced fractures are vertical

Myth – All Perforations are Open During Injection



Fact

- Perforations may be partially plugged
- Injection pressure of perforations varies
- Cement will take the path of least resistance

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Myth – High Final Squeeze Pressure is Necessary

Fact

- Final Squeeze Pressure Does not Need to Equal Future Working Pressure (Why?)
- Squeeze Pressure is Applied Across Node Before Cement Develops Compressive Strength
- Fracture May be Created
- Productivity May Be Damaged
- High Pressure Does not Insure Placement in Desired Location

SQUEEZE TECHNIQUES

Squeeze Techniques

- Pressure to Squeeze
  - High Pressure Squeeze
  - Low Pressure Squeeze
- Pumping Techniques
  - Hesitation Squeeze
  - Running or Walking Squeeze
- Placement Techniques
  - Squeeze Packer
  - Bradenhead (Including Coiled Tubing)

High Pressure Squeeze

Surface Pressure

+

Displacement Fluid Hydrostatic

+

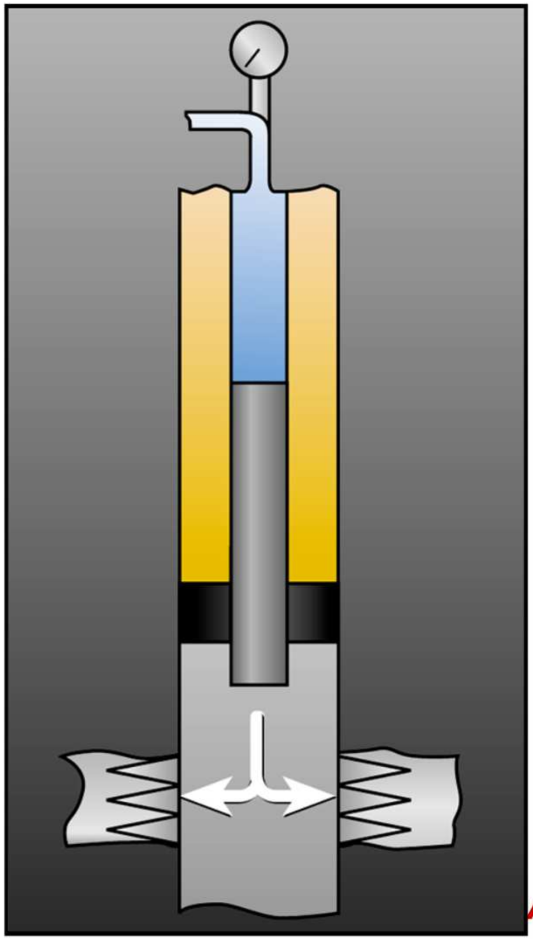
Cement Slurry Hydrostatic

=

Total Bottom Hole Pressure

<u>Greater Than</u>

Formation Fracture Pressure



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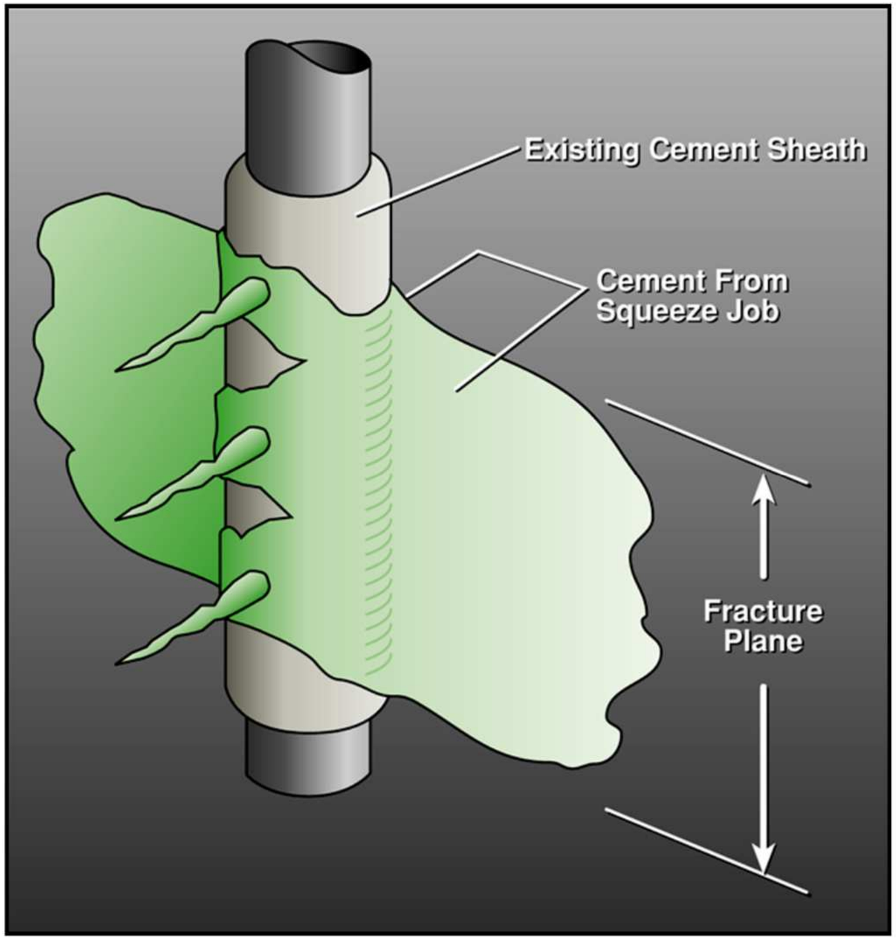

Existing Cement Sheath
Cement From
Squeeze Job
Fracture
Plane

Low Pressure Squeeze

Surface Pressure

+

Displacement Fluid Hydrostatic

+

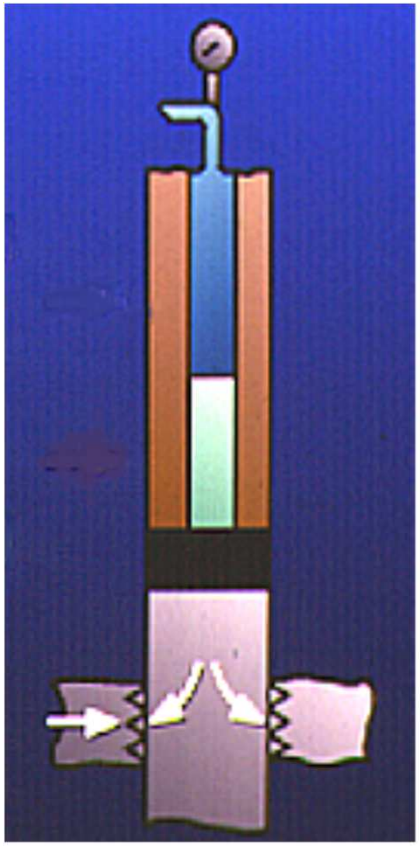
Cement Slurry Hydrostatic

=

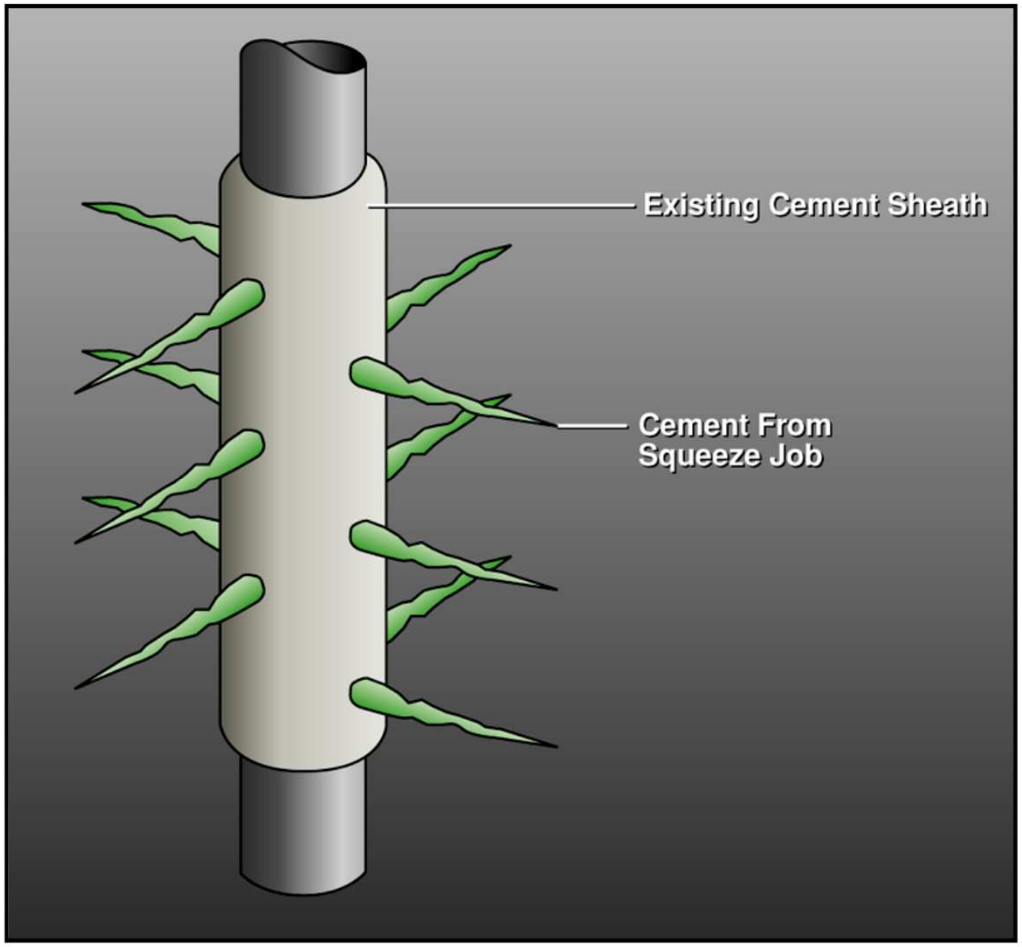
Total Bottom Hole Pressure

<u>Less Than</u>

Formation Fracture Pressure



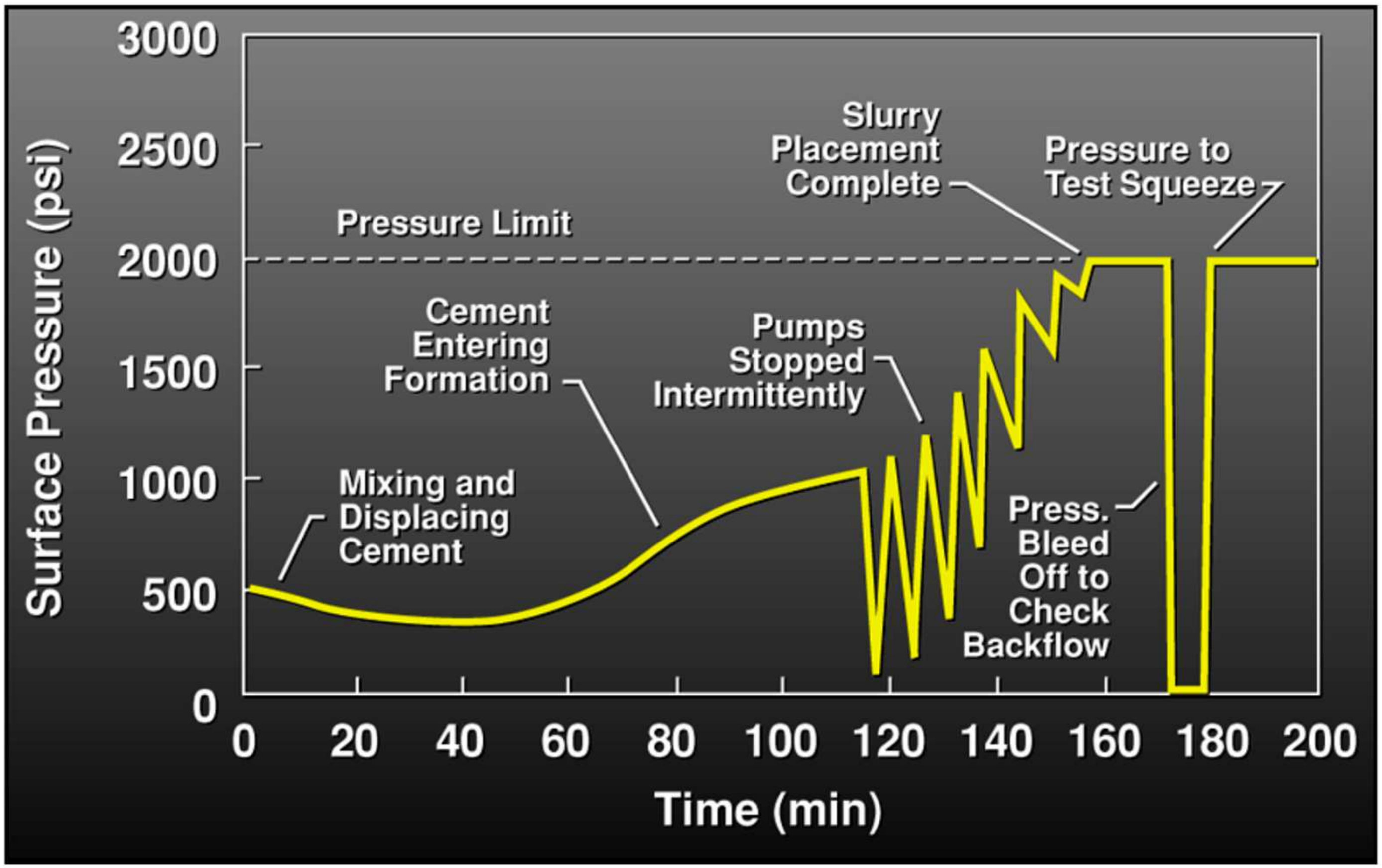
HALLIBURTON


Existing Cement Sheath
Cement From
Squeeze Job

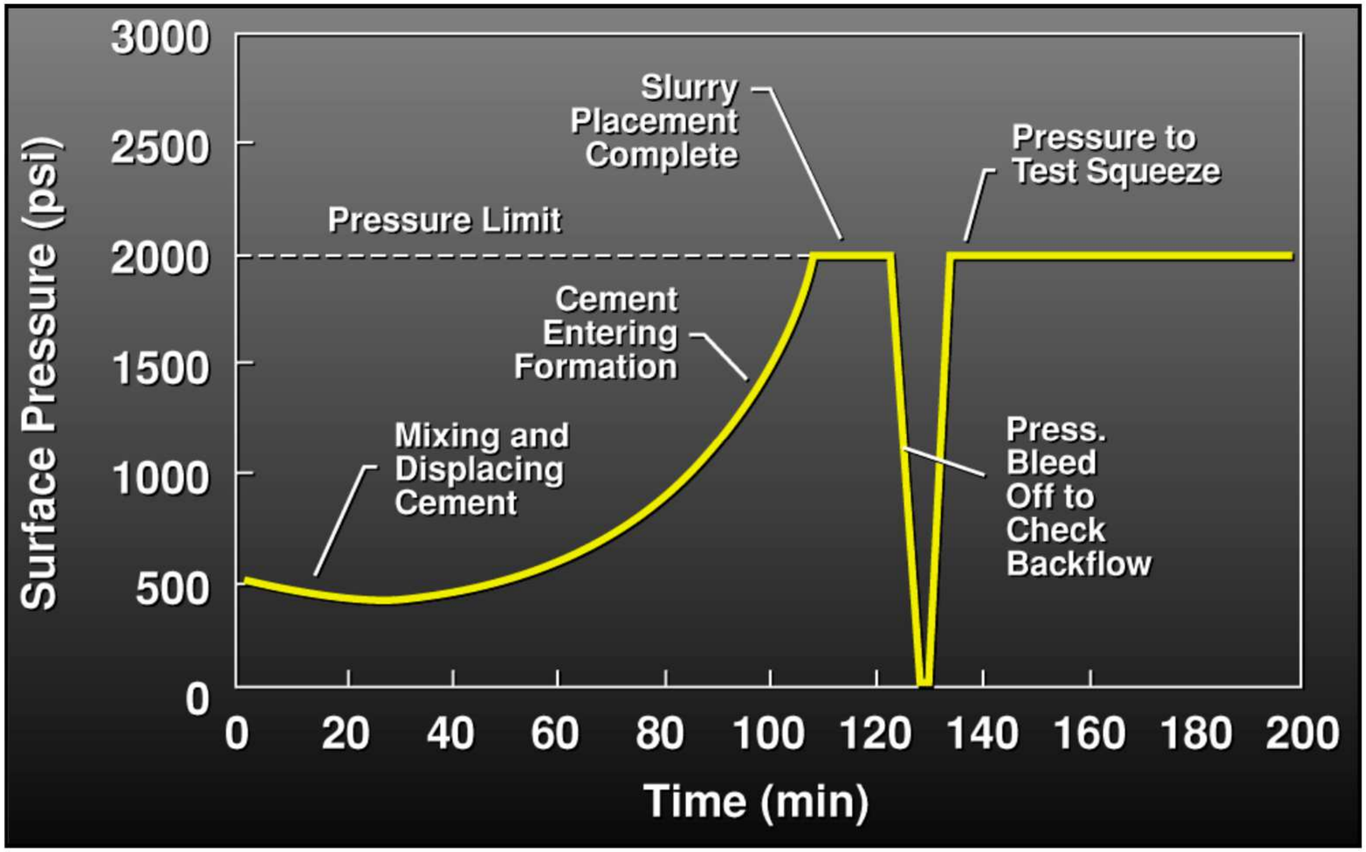
Squeeze Techniques

- Pressure to Squeeze
  - High Pressure Squeeze
  - Low Pressure Squeeze
- Pumping Techniques
  - Hesitation Squeeze
  - Running or Walking Squeeze
- Placement Techniques
  - Squeeze Packer
  - Bradenhead (Including Coiled Tubing)

Hesitation Squeeze



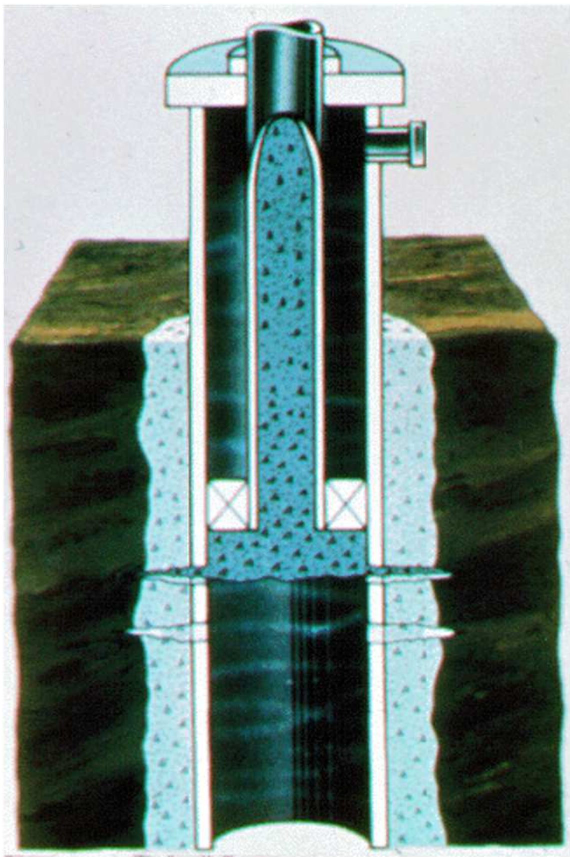
“Running/Walking” Squeeze



Squeeze Techniques

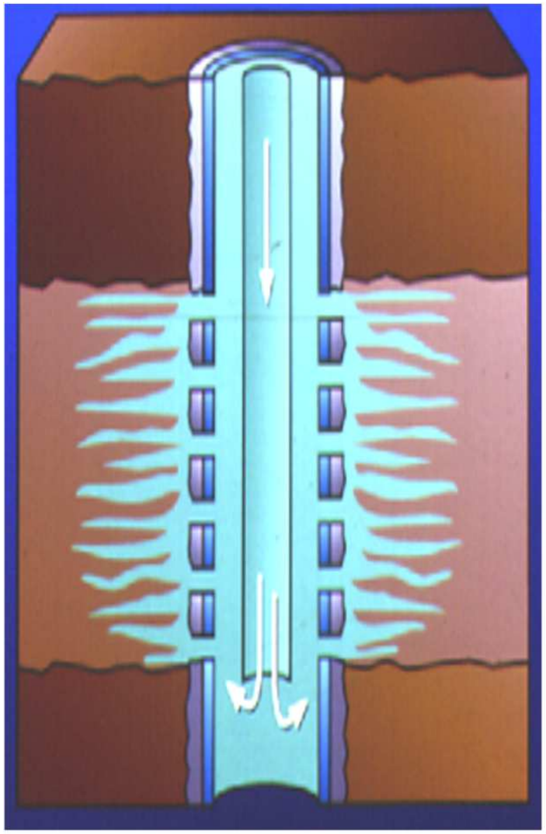
- Pressure to Squeeze
  - High Pressure Squeeze
  - Low Pressure Squeeze
- Pumping Techniques
  - Hesitation Squeeze
  - Running or Walking Squeeze
- Placement Techniques
  - Squeeze Packer
  - Bradenhead (Including Coiled Tubing)

Squeeze Packer Method



- Retrievable or drillable squeeze packer set above injection point
- Isolates casing above packer from squeeze pressure
- Higher squeeze pressure possible
- Annular pressure can be applied

Bradenhead Method



- Spot cement across squeeze interval
- Pull workstring above cement top
- Close BOP/Bradenhead & reverse tubing clean
- Apply squeeze pressure

Disadvantages

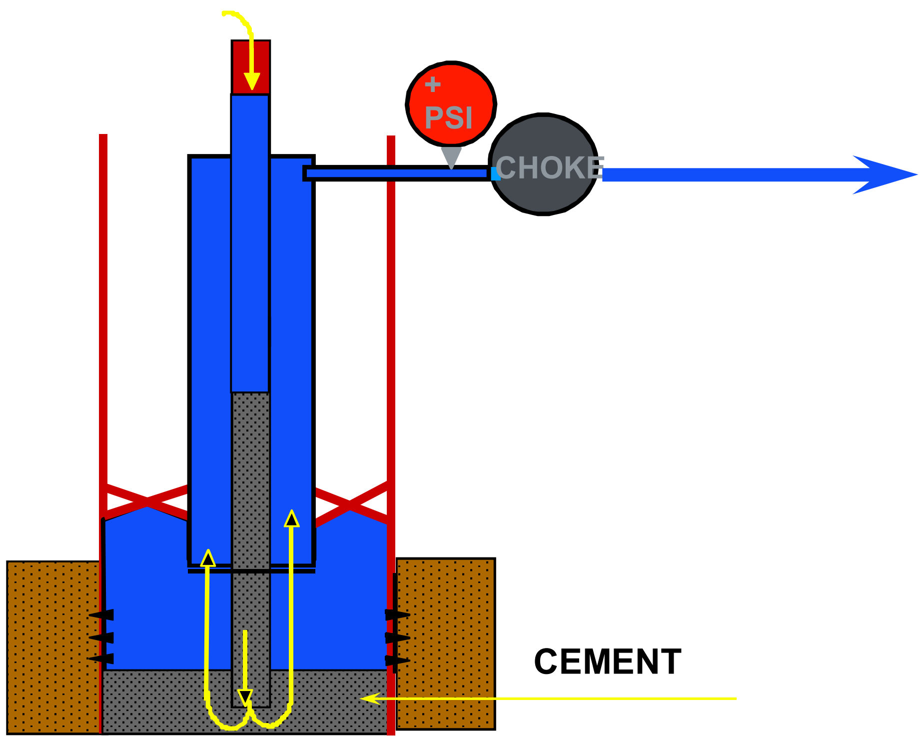
- Casing exposed to squeeze pressure
- Limited squeeze pressure

Advantages

- Cost reduction
- Wash cement out of casing

Coiled Tubing Method

- Form of Bradenhead
- Inside Production Tubing
- Higher Pressure Possible
- Improved control of slurry placement



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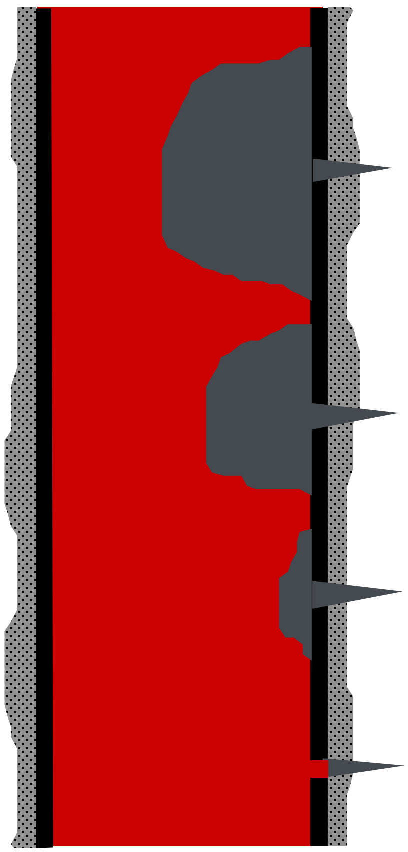
Squeeze Slurry Design

Squeeze Slurry Design Considerations

- Application Temperature
  - API Squeeze BHCT
  - Other factors
- Thickening Time
- Fluid Loss Control
  - HP vs. LP Squeeze applications
  - Multiple perforations
- Static Gel Strength
- Spacers

Fluid Loss Control vs. Filter Cake



1000 cc - Neat Cement Slurry

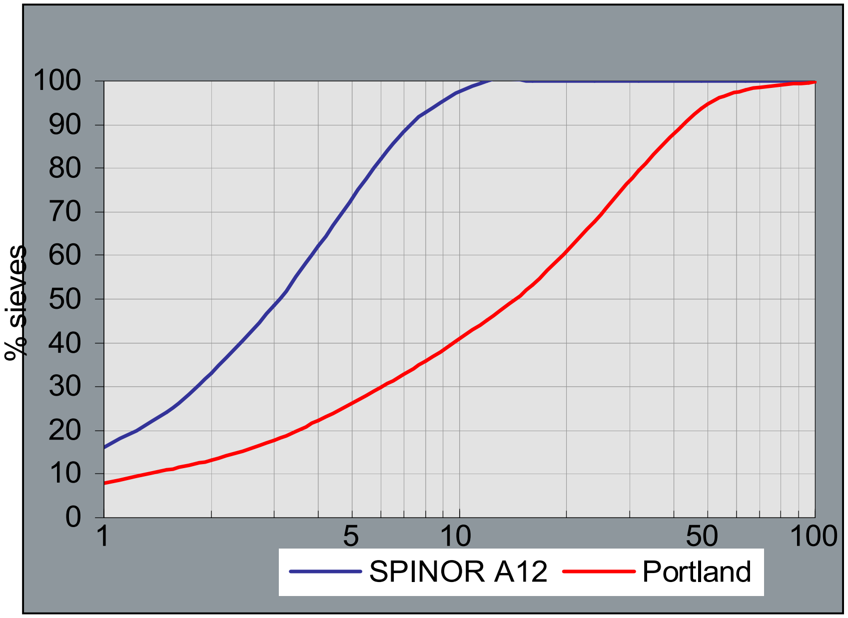
300 cc Fluid Loss Slurry

75 cc Fluid loss Slurry

25 cc Fluid Loss Slurry

Ultra-Fine Cement

- Penetration into small leaks, gravel packs, etc.
- Casing Leaks where there is low injection rate
- Behaves like Portland cement
- Average particle size around 10 micron



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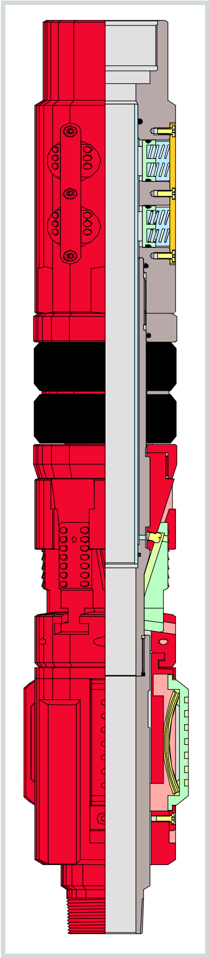
Tool Selection



- Squeeze Packers
  - Drillable
    - » Cast Iron
    - » Composite
  - Retrievable

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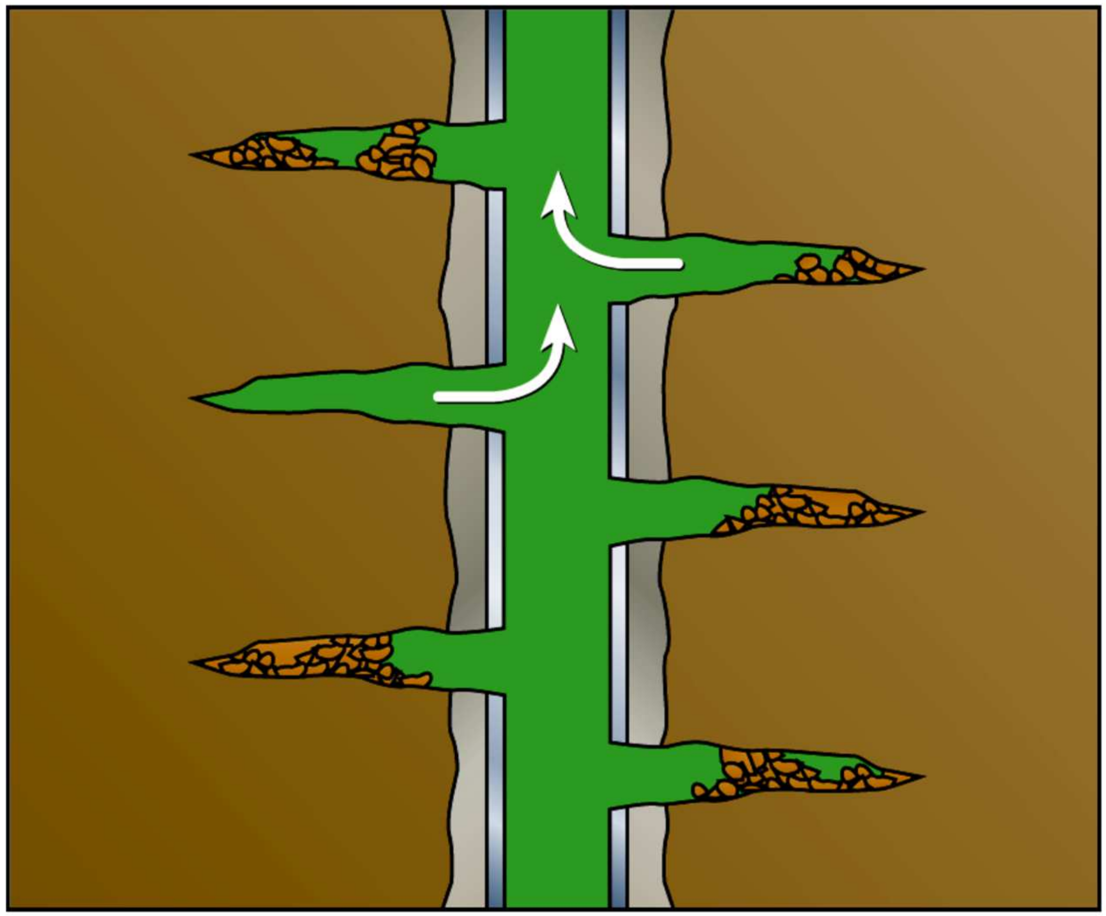
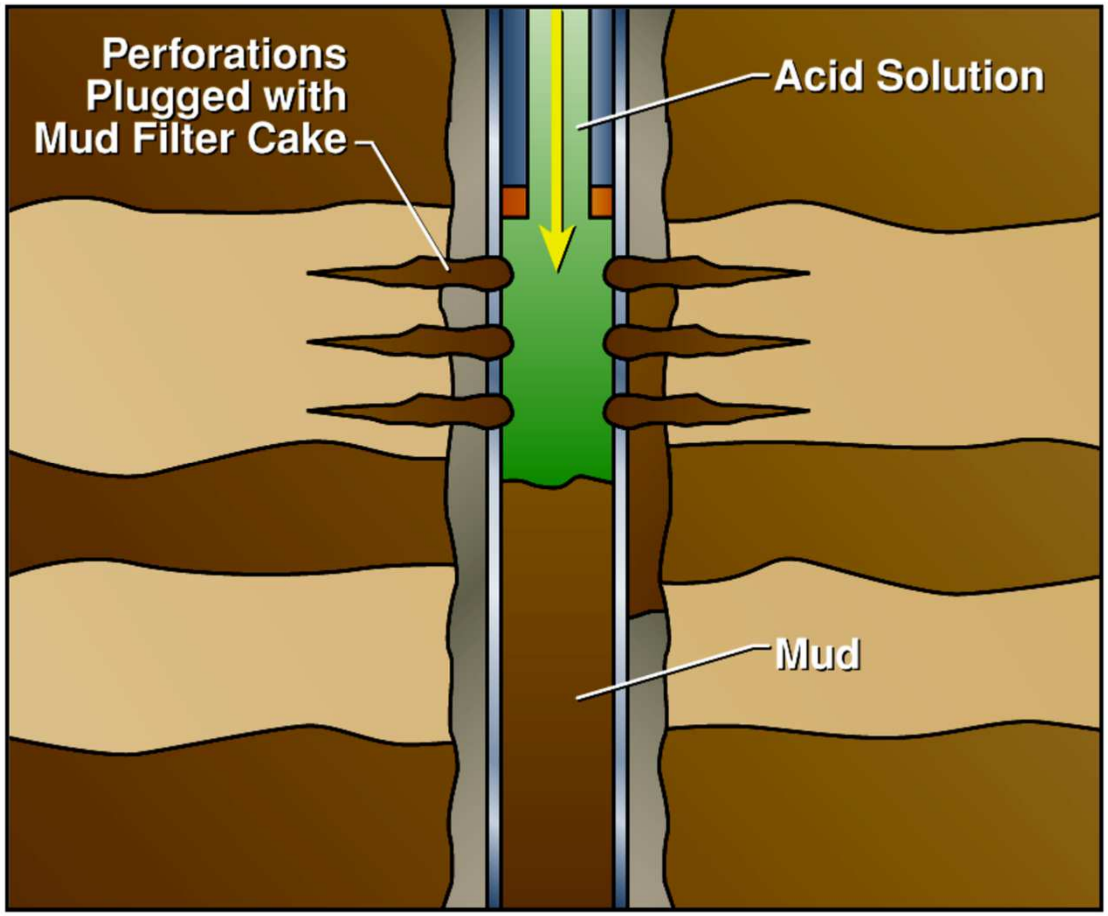
Tool Location

- Set in cemented casing when possible
- Close to interval to minimize cement drill-out
- Adequate distance from perfs for staging volume
- Displace tubing volume before staging
- Safe distance from perfs to prevent casing collapse

Job Execution

- Well preparation
  - Well fluid circulated and balanced
  - Perforations open
- Pressure test surface treating lines, work-string, and tools to maximum expected pressure
- Use clean workover fluids for injection




Perforations Plugged with Mud Filter Cake
Acid Solution
Mud

Squeeze Applications

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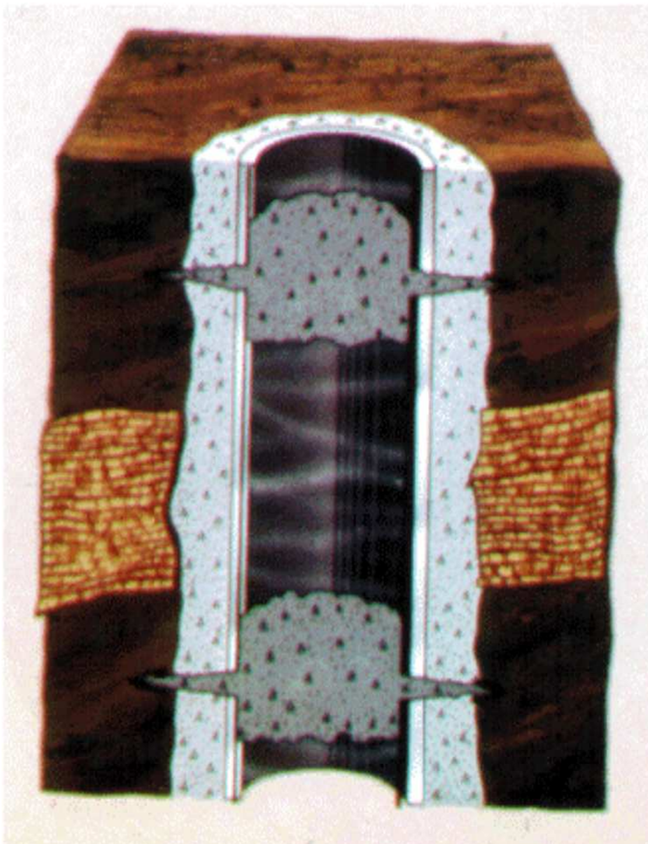
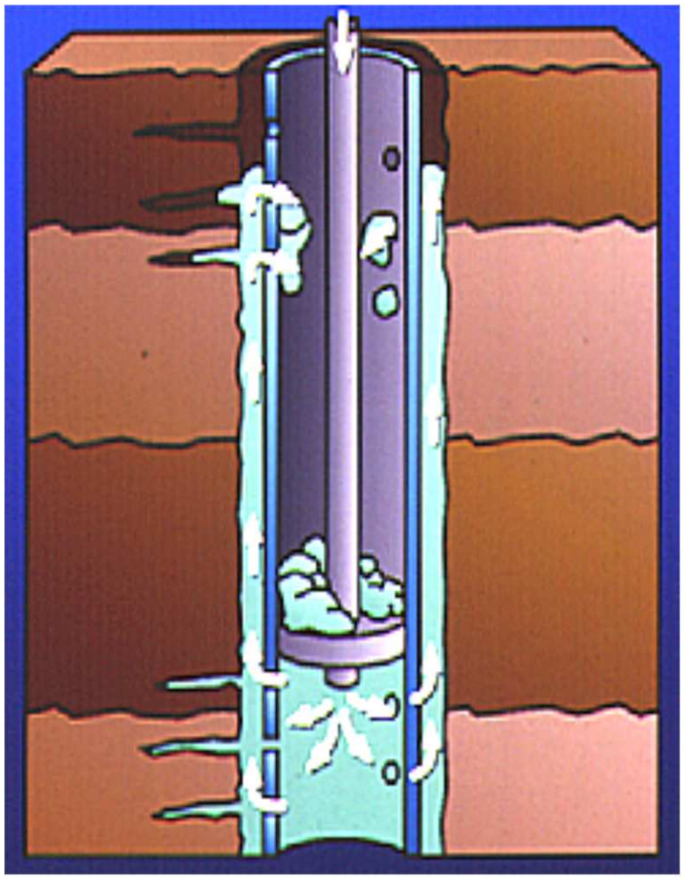
Block Squeeze



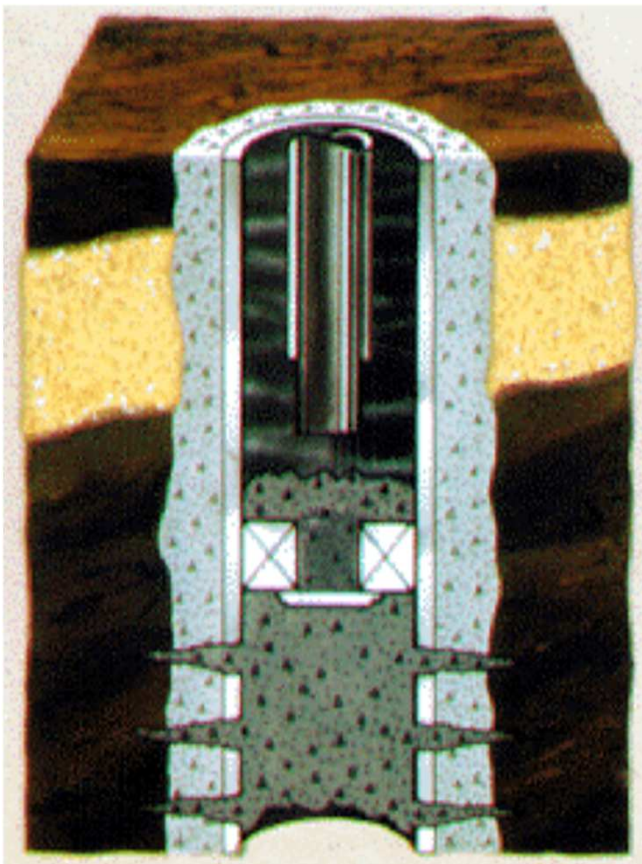
- Performed to isolate zone
- Perforate & squeeze below zone
- Perforate & squeeze above zone
- Drill out & test
- Difficult to remove trapped fluid/mud
- Avoid Fracturing
- Questionable practice

Circulation Squeeze



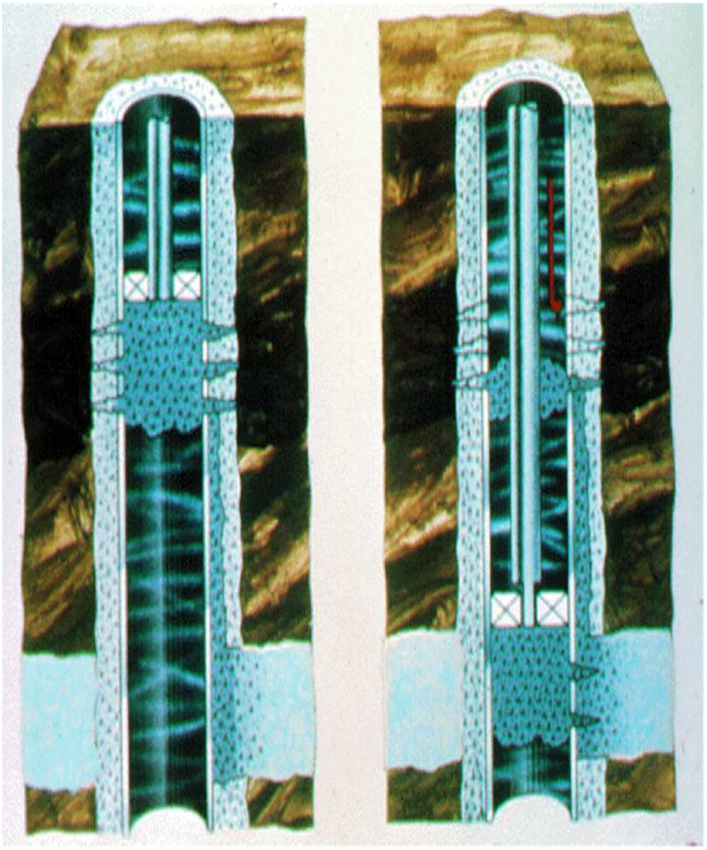
- “Suicide Squeeze”
- Drillable tool set between perforations
- Circulation path back into casing above
- Improved channel cleaning
- Possibility of sticking
- Possibility of casing collapse

Abandonment Squeeze



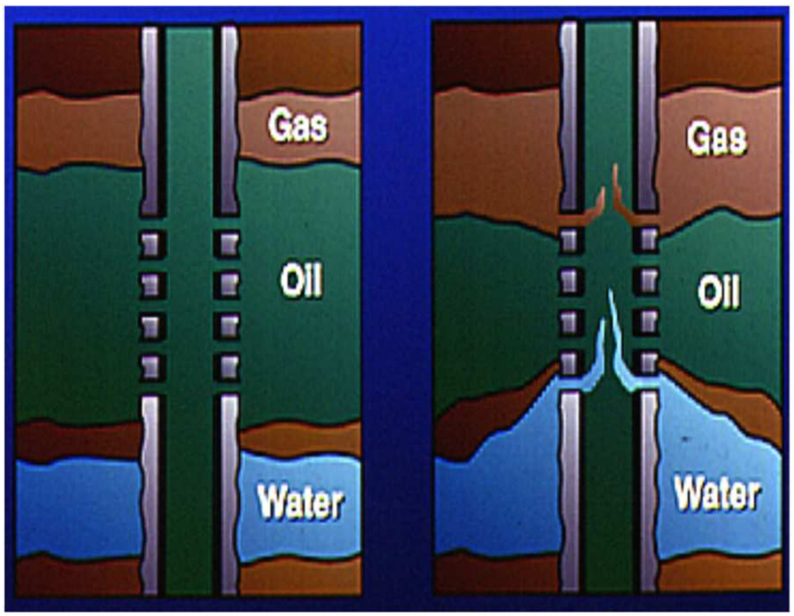
- Retainer set high to meet regulatory plugging requirements
- Perform low pressure squeeze through retainer
- Sting out & dump cement on top of retainer

Channels



- Channel must be clear of mud
- Allow production to clean channel if possible
- Clean channel with acid or chemical wash
- Perform low pressure squeeze
- Inject into production perfs or adjacent to problem zone

Unwanted Production



Initial   Current

- Water coning from below
- Gas cap production due to depletion
- Channels
- Vertical fractures
  - Natural
  - Created
  - High vertical permeability

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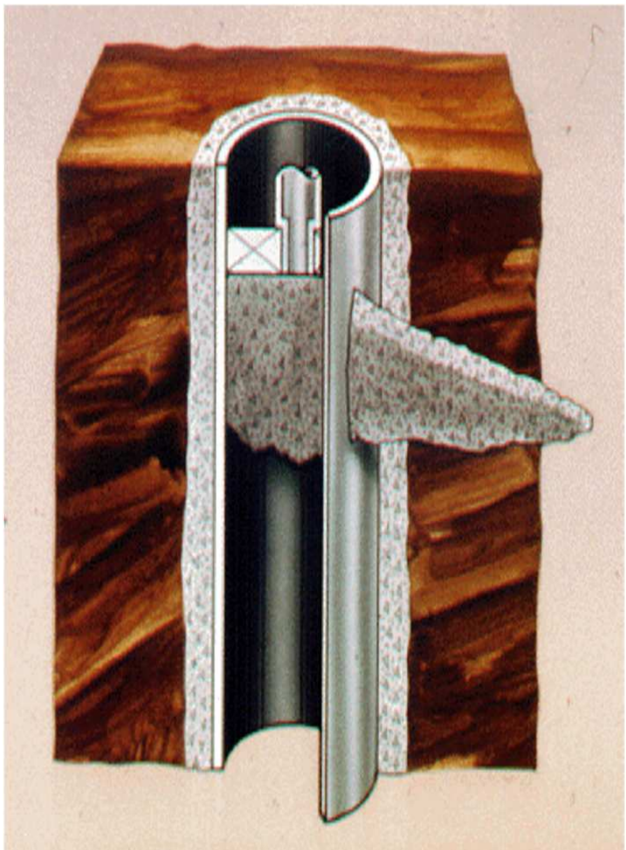
Corrosion Holes

- Often occur above cement top
- May require multiple stages
- Caution with tools due to weak or enlarged casing
- New holes can be created during squeeze
- Use low pressure squeeze

Casing Split



- Often occurs above cement top
- May require multiple stages
- Caution with tools due to restrictions or enlarged casing
- Split length may increase during squeeze
- Use low pressure squeeze

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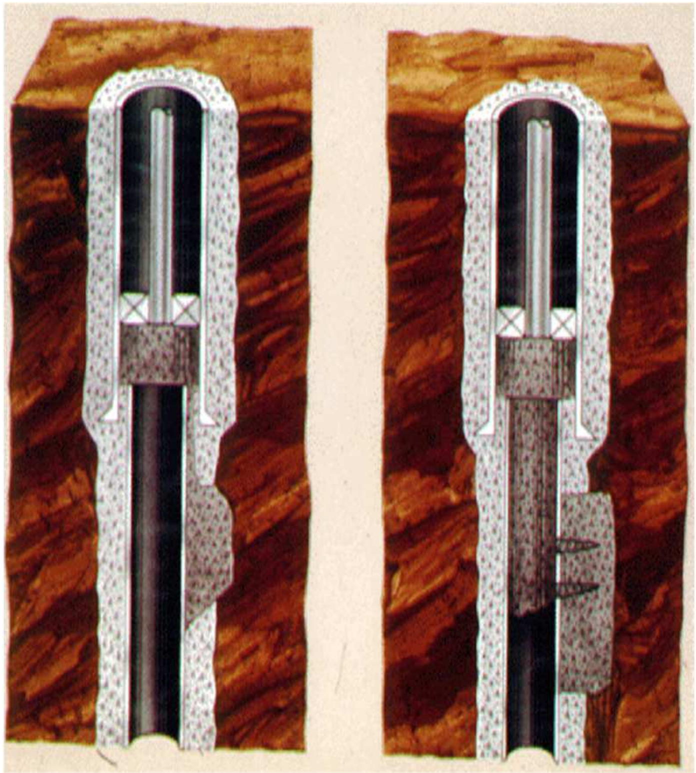
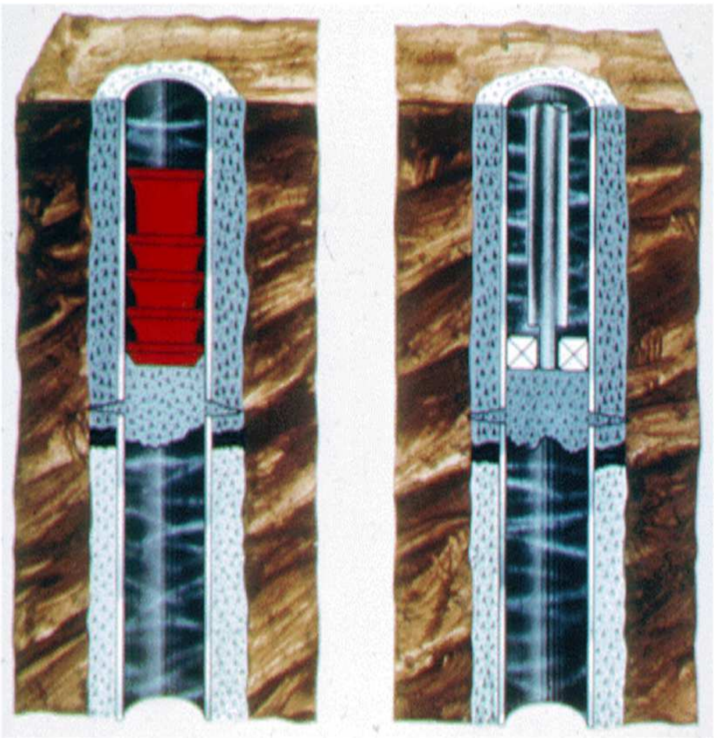
Liner Top



- Poor mud displacement during primary cement job
- No cement returns to liner top
  - Solids bridging
  - Losses due to high ECD
  - Planned Tack & Squeeze

Re-Cementing



Displacement Plug **Packer**

- Raise the top of cement
- Displacement plug method
- Packer method (drillable)
- Circulate to surface to condition/clean annlus
- Use large volumes of flush/spacer
- Mod/Low fluid loss cement
- Casing collapse possible with packer method

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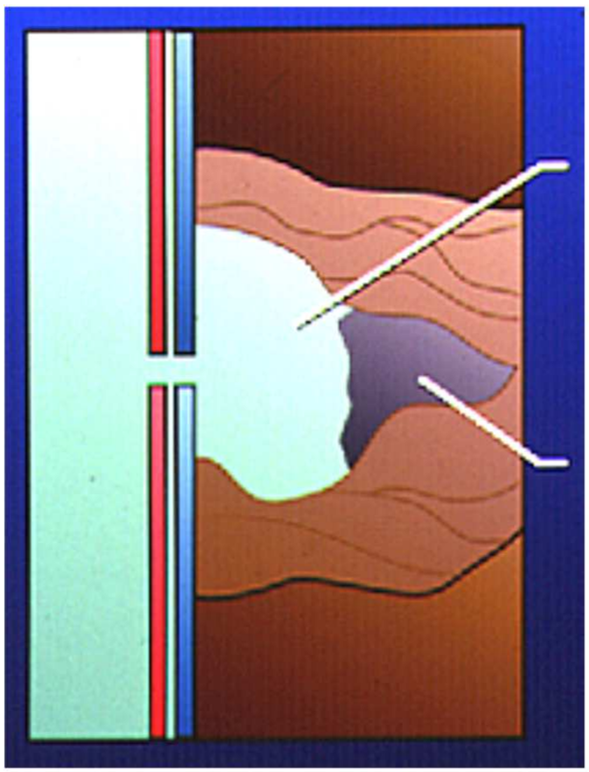
Fractured or Vugular Zones



- Multiple stages likely
- Lead or first stage
  - Lost circulation material
  - High fluid loss cement
  - Thixotropic cement
  - Foam cement
  - Quick setting cement
  - Reactive pre-flushes
- Second stage
  - Low fluid loss cement

Long Perforated Interval

- Difficult to inject into all perforations at once
  - Acid wash optional
- As perforations are squeezed others will take fluid
- Low pressure squeeze
- Low fluid loss, extended TTT, low/slow SGS
- Ball sealers optional
- Spot cement across entire interval with Coiled Tubing or tailpipe

Collar Leaks

- Often extremely low injection rate
- Treatment systems
  - Internally catalyzed treatments
  - Microfine cement
  - Resin

Casing Inspection 101

Multi-Finger Caliper TOOLS

24 finger MFC – 1.75” to 4.5” range
Finger Spacing 0.229” to 0.589”

40 finger MFC – 3.0” to 7.5” range
Finger Spacing 0.236” to 0.589”

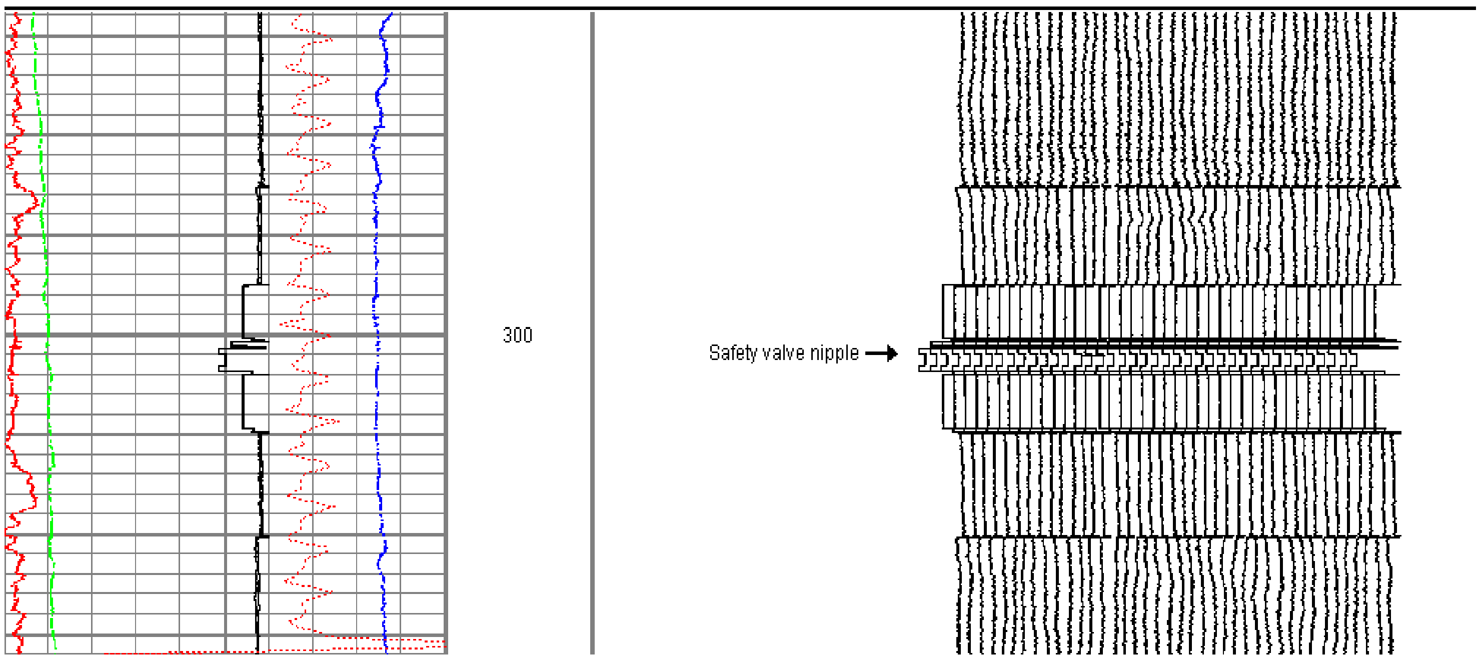
60 finger MFC – 4.5” to 9 5/8” range
Finger Spacing 0.236” to 0.504”

80 finger MFC – 8.5” to 16” range
Finger Spacing 0.334” to 0.628”

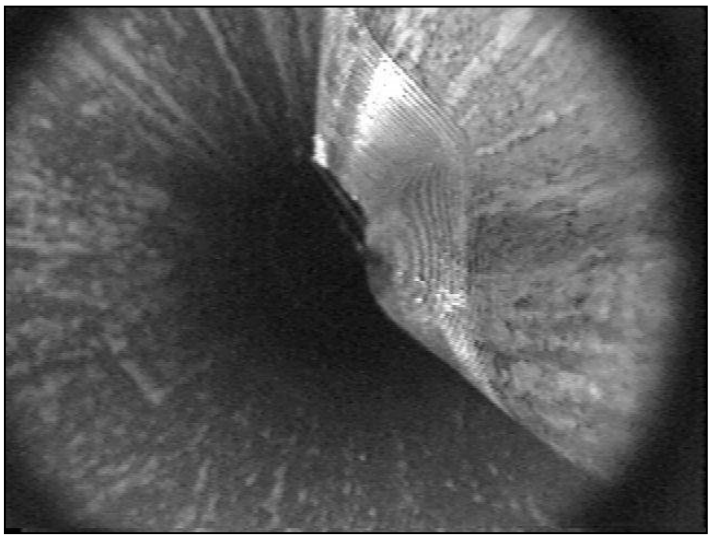
MFC EXAMPLE

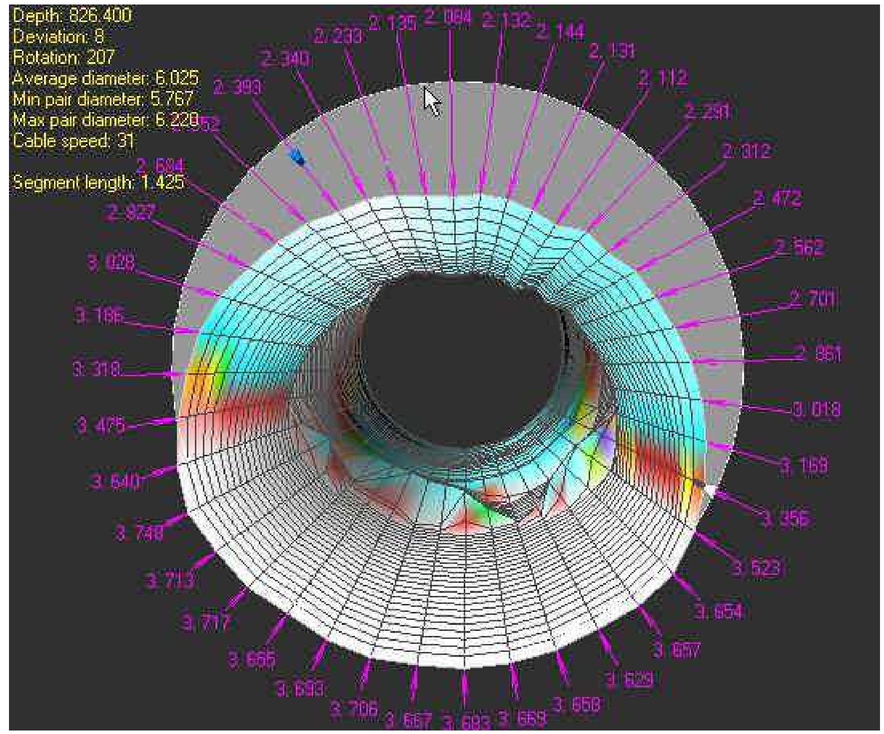
4	MAXDIA (in)	8
4	MINDIA (in)	8
4	AVEDIA (in)	8
0	MITDEV (°)	20
-40	MITROT (°)	360
0	LSPD (ft/min)	-50
0	CENTOFF (in)	1

1.5	FING01 (in)	5.5
1.45	FING02 (in)	5.45
-0.4	FING39 (in)	3.6
-0.45	FING40 (in)	3.55



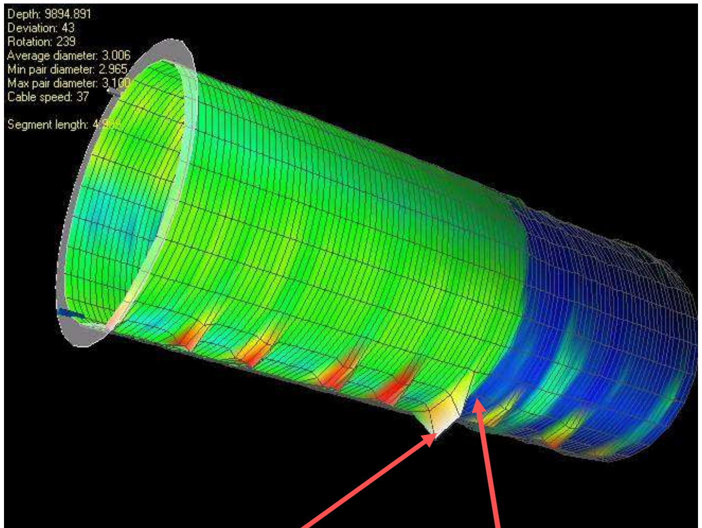
COMPARING VIDEO & MFC DATA





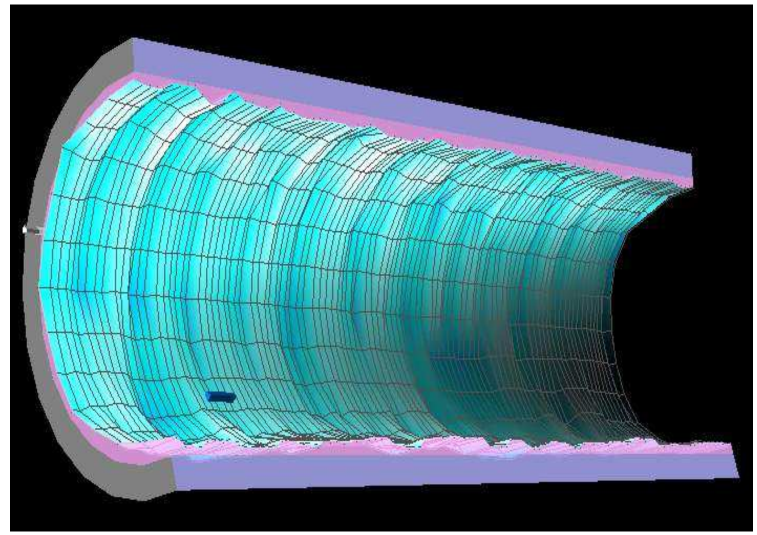
Crushed Casing (not the same well)

SCALE DEPOSITION & REMEDIAL WORK



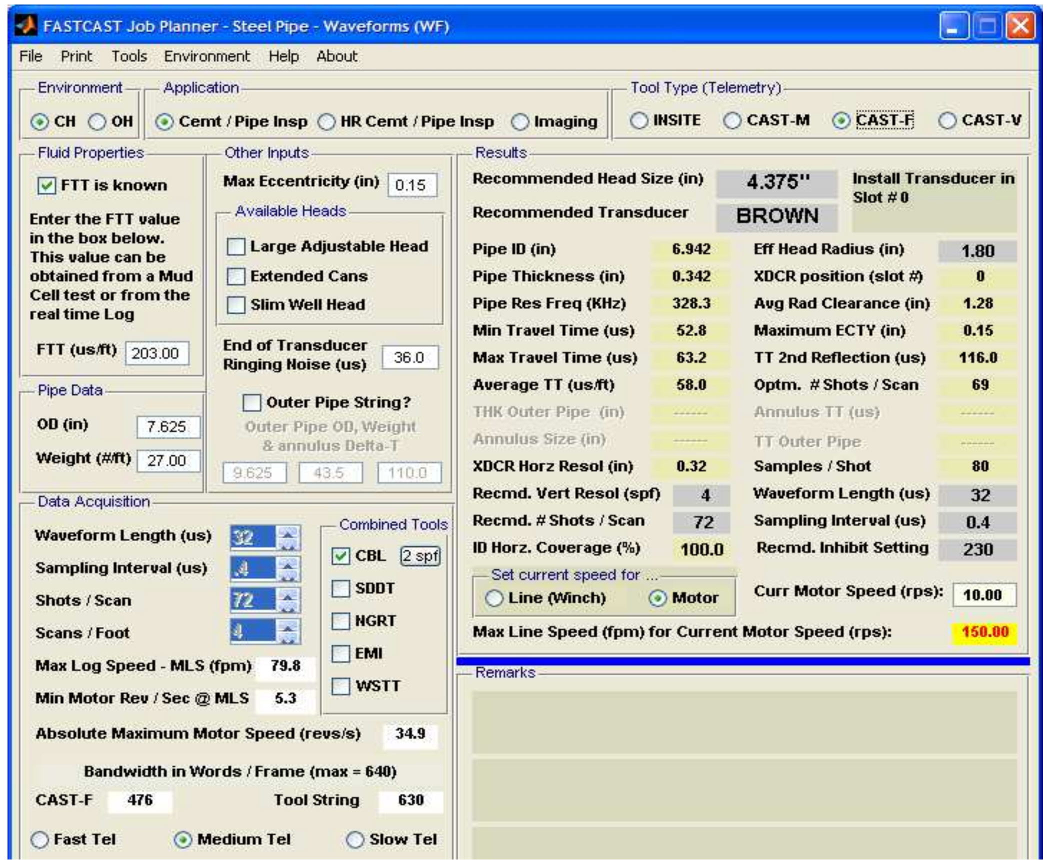
Hole in tubing

Lower Limit of
scale cleanup job



Section view of
scale precipitation

Casing Inspection Ultrasonic Scanners



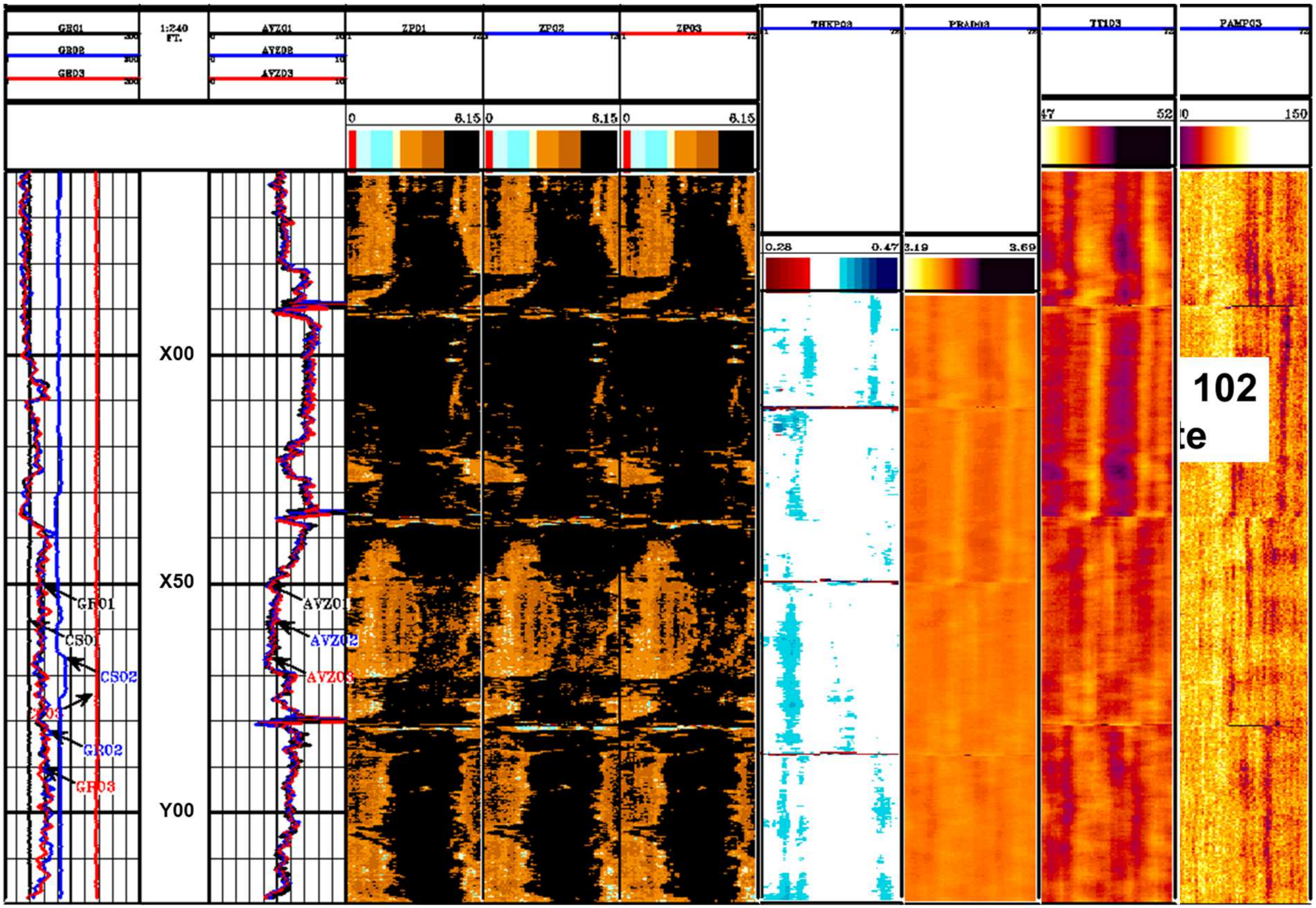
Pipe Amplitude

Travel Time

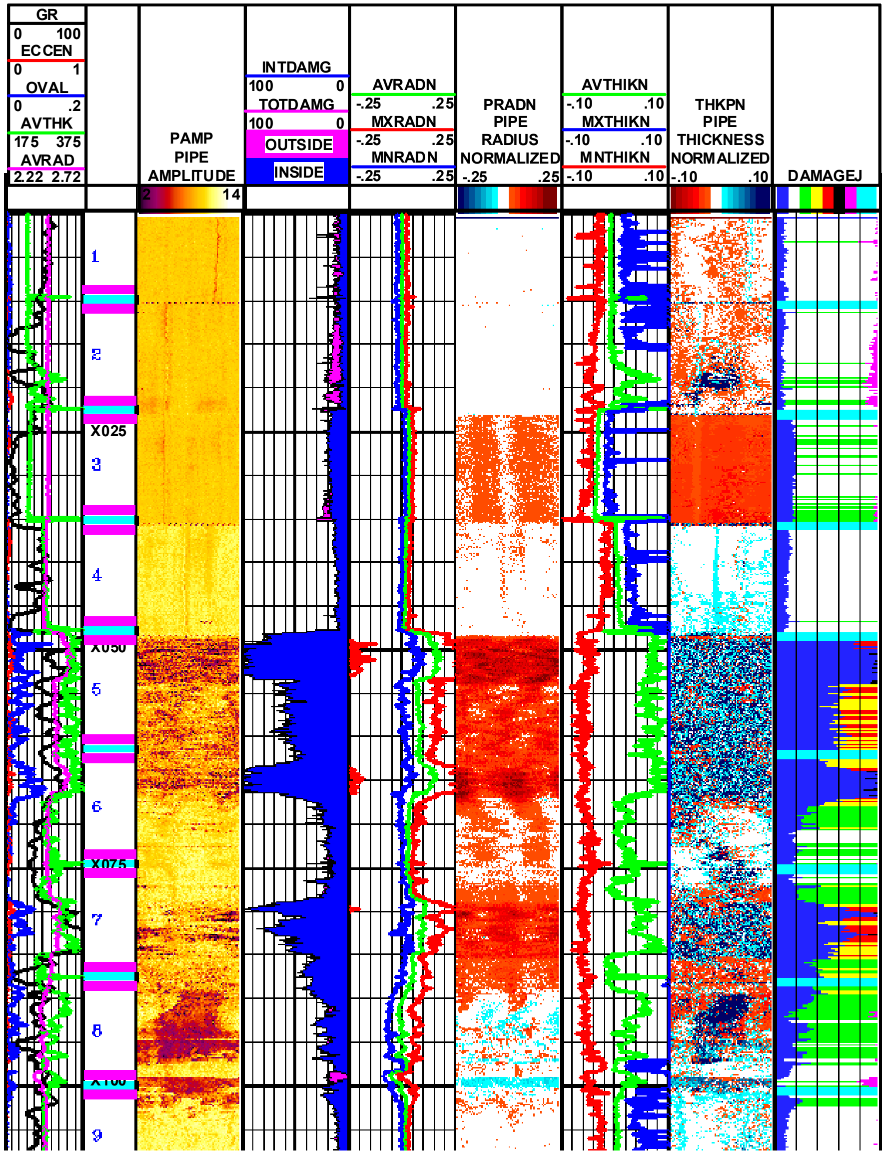
Pipe Radius

Pipe Thickness

Impedance

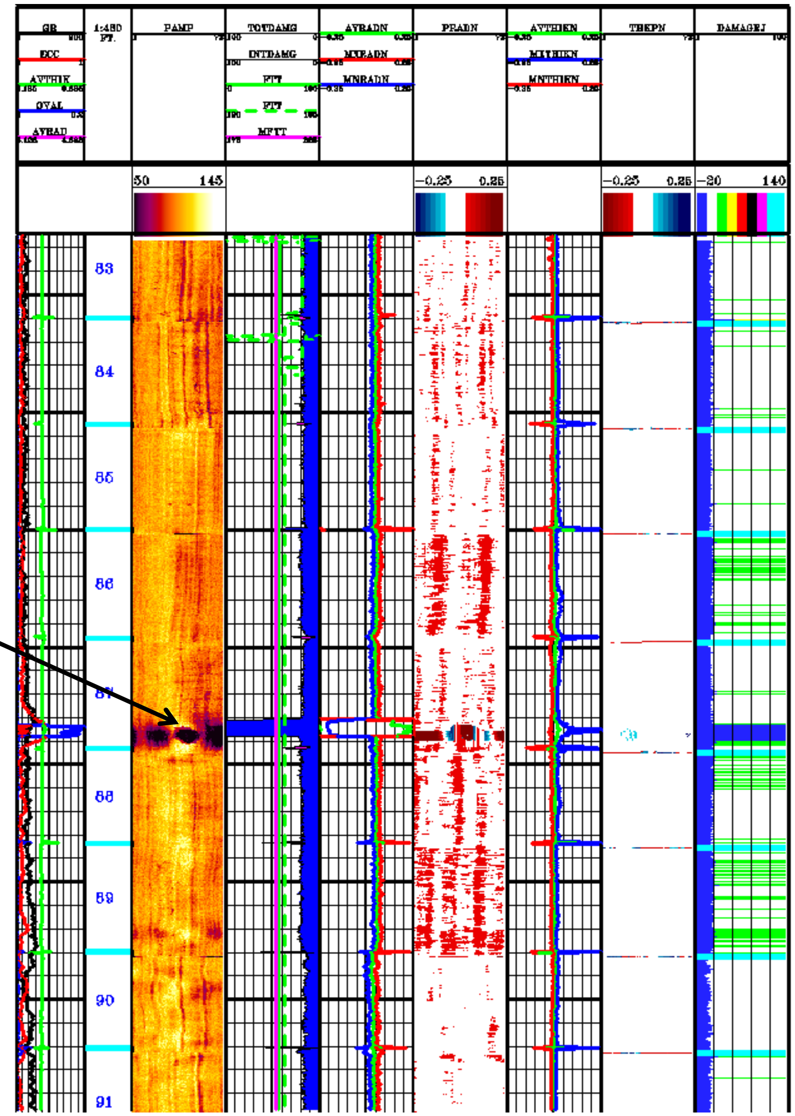


CASE Post Processing



FASTCASE
7 inch liner

There is a single (large) hole with thin wall areas adjacent to the hole

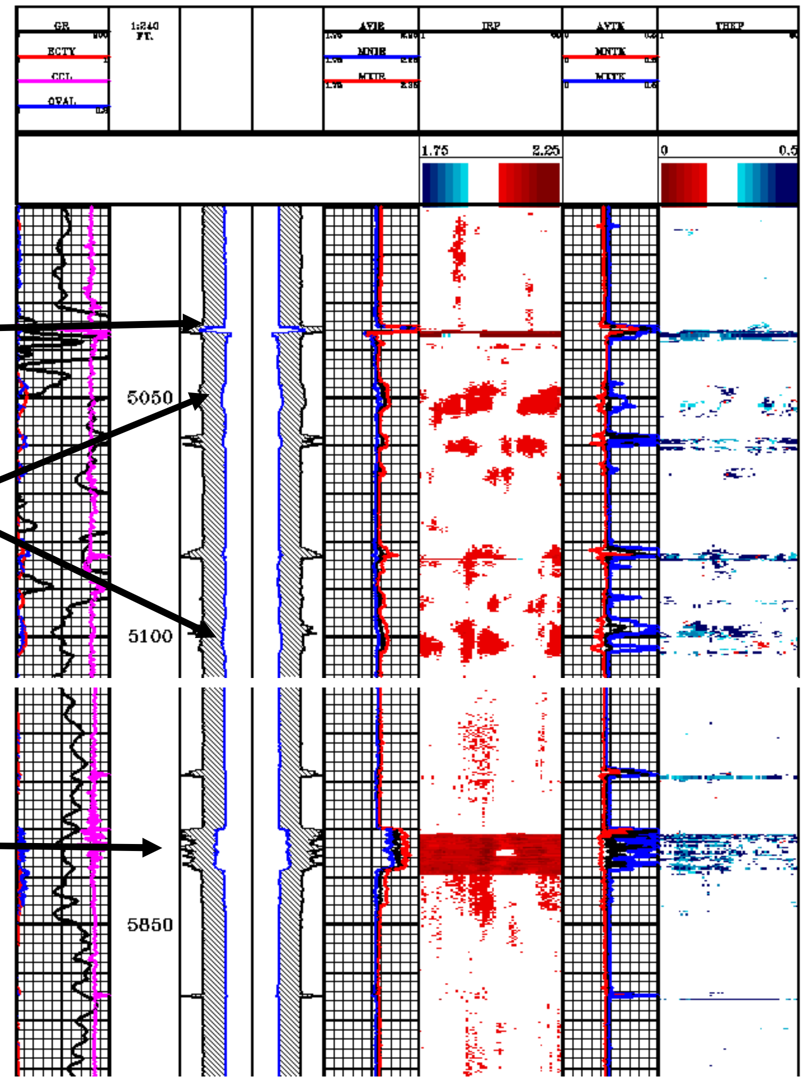


CAST-M 4 ½” Casing Inspection

Collar leak

Casing Swelling from Capsule Perforating Guns

Damage from Milling Packer



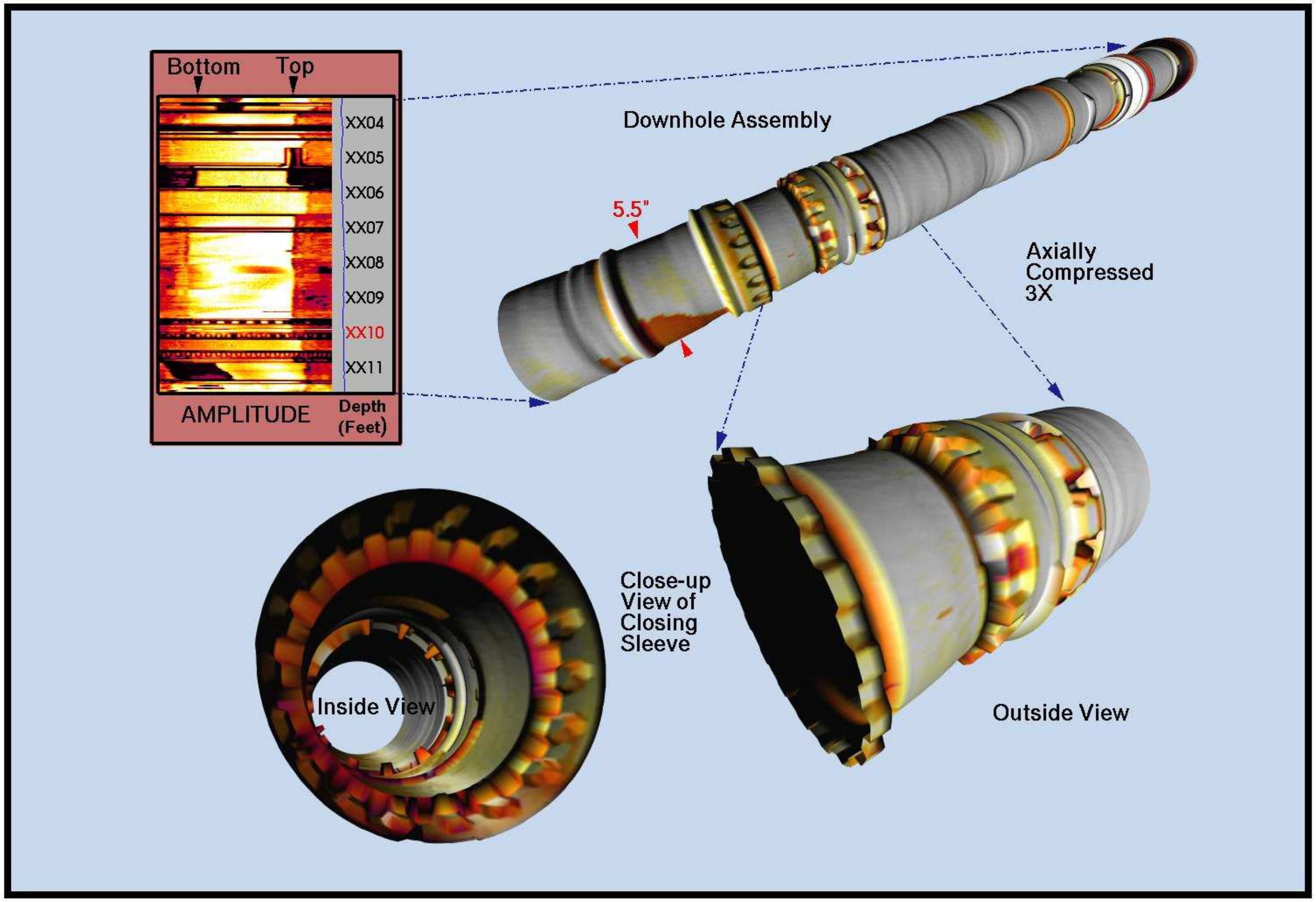
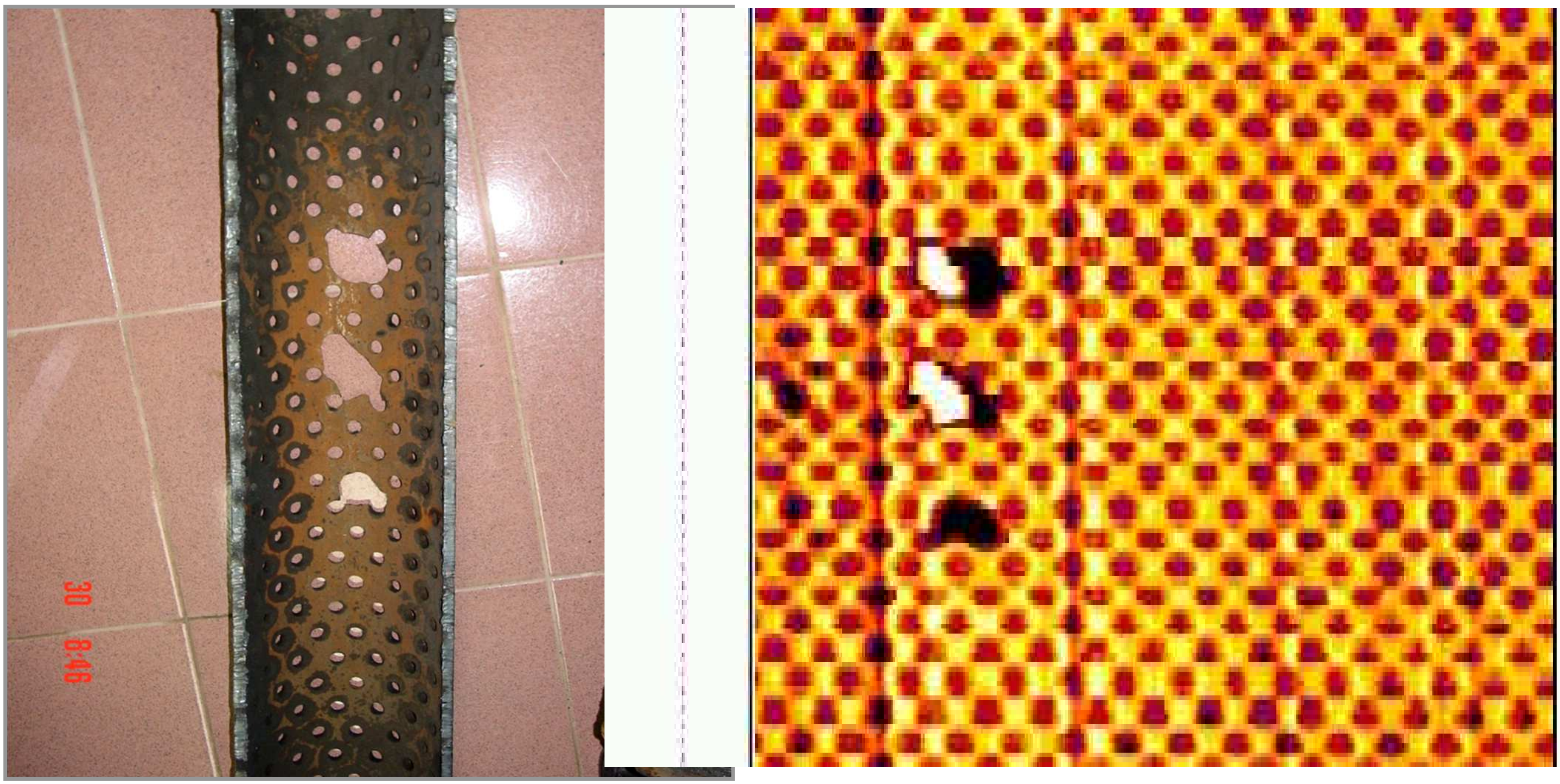


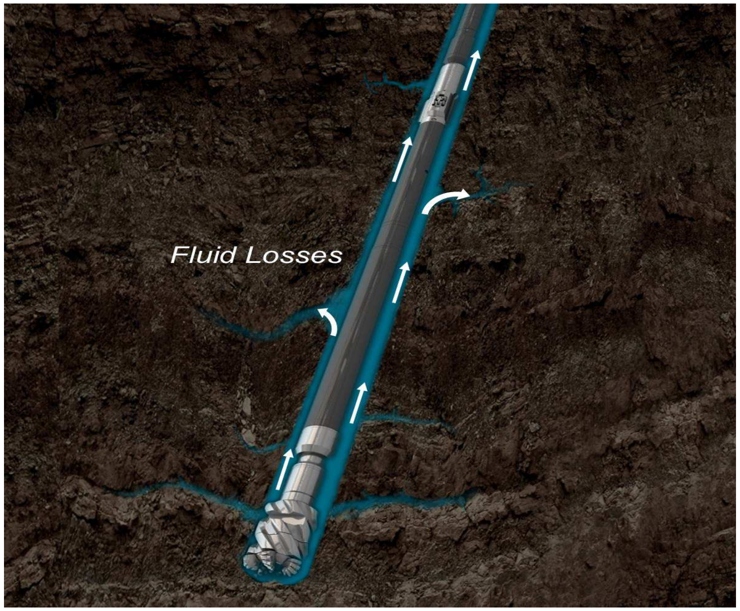
FIGURE 10. A CAST 3-D reconstuction of a cased hole downhole assembly in a horizontal well with a close up of a sliding sleeve seen in the closed position.

Slotted liner damage as seen by CAST™ in casing inspection mode



Lost Circulation Challenges

- Lost circulation is the biggest non-productive cost in the industry today
  - 10-30% of all drilling NPT attributable to losses and wellbore instability
- Lost circulation occurs from:
  - Highly permeable formations
  - Naturally fractured formations
  - Cavernous formations
  - Induced fractures
- Resulting in:
  - Anything from seepage to total losses



BridgeMaker^{TM} II Lost Circulation Material

HALLIBURTON

What is BridgeMaker™ II Lost Circulation Material?

- A special pre-blended LCM designed for use in spacers, but works equally well in cement
- Bridges across a broad range of fracture widths
- Carefully composed for optimum performance and suspension for spacer and cementing fluids
- Tested for problem-free pumping though float equipment
- Environmentally Friendly - North Sea compliant

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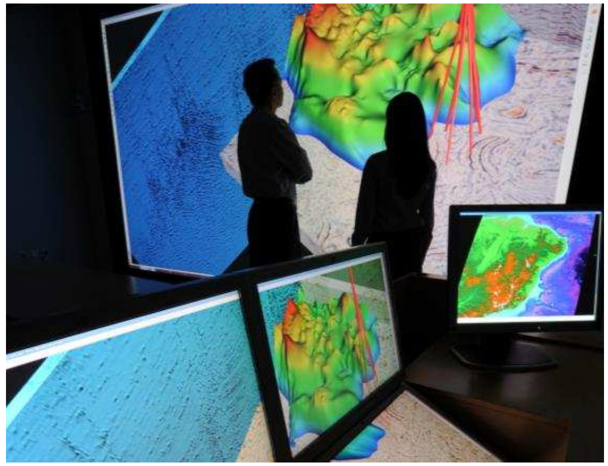

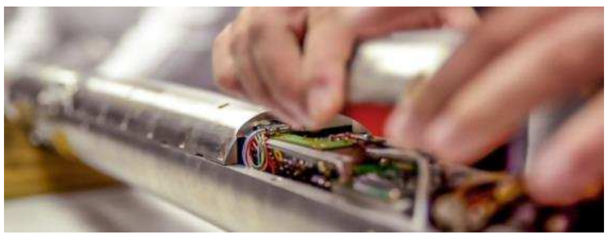


Cementing New Technology

BridgeMaker™ II Lost Ciruclation Material – Properties

- Physical Properties
  - Blend SG = 1.71
  - Bulk Density 0.49-0.65 SG (31-40 lb/ft3)
- Temperature Limits
  - Upper limit 347°F (175°C) **short term** (4 – 6 hours)
  - Upper limit 302°F (150°C) **medium term**
- Recommended Loading
  - Add 30-80 kg/m3 or 10-28 lb/bbl for primary cementing operations
- Bridging Capabilities
  - Easily plugs fracture widths up to 1000μ at 1000 psi ΔP deposit pressure
  - At higher concentration plugs 1500μ at 1000 psi ΔP deposit pressure
  - Lower deposit pressure allows better plugging
  - Can withstand at least 1500 psi ΔP once deposited
- Secondary Effects
  - Moderate effect on fluid viscosity – can establish correction factor
  - No impact on wettability

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BridgeMaker™ II Lost Circulation Material– Performance – LCM Test Cell

- Performance tested in LCM test cell (modified to handle coarse materials)
  - Slotted disks
  - Instant pressure application (N2 over floating piston)
  - Room temperature
  - Record spurt loss and time

Disks used for the testing:

500μ flat disk

1000μ flat disk

1500μ flat disk

1000μ -1500μ V-slot disk

BridgeMaker™ II Lost Circulation Material – Other Applications

- What if I want to use as LCM for stopping losses?
- When mixed in 1.60 SG TSE+ maximum concentration is
  - ±260 kg/m3
  - ±91 lb/bbl
- Suspends well in fluids with viscosity
  - Econolite™ Additive – liquid
  - Unweighted spacers
  - Needs filler material to plug properly

Example – use with no filler:
80 kg/m3 in TSE+ 1.06 SG
➔Spurt loss 268 ml
Flow 1.45 SG lead slurry after, no fluid loss control
➔ Spurt loss 8 ml

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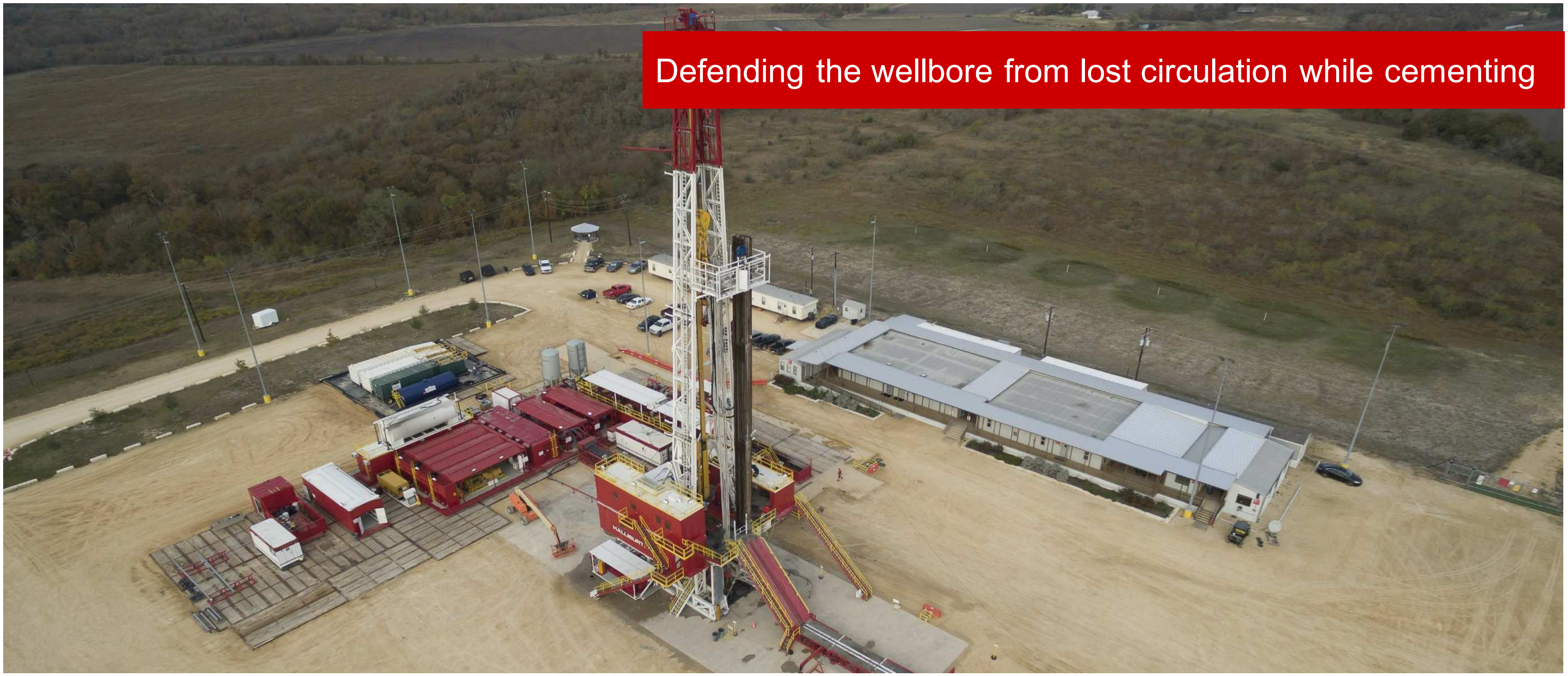
Tuned Defense Cement Spacer

HALLIBURTON

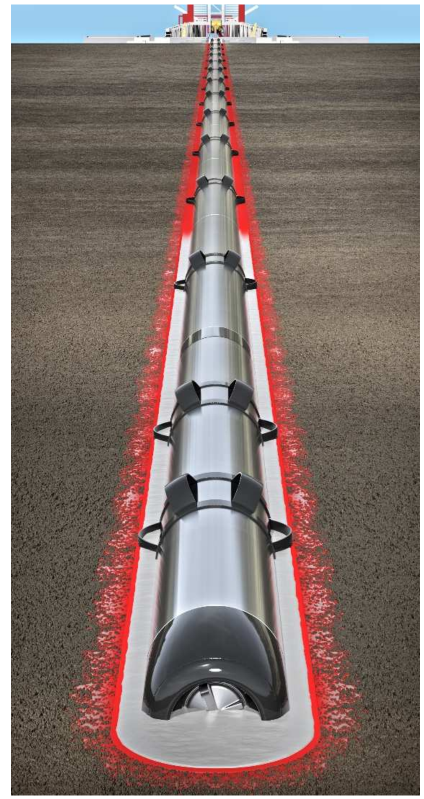
CUSTOMER CHALLENGE



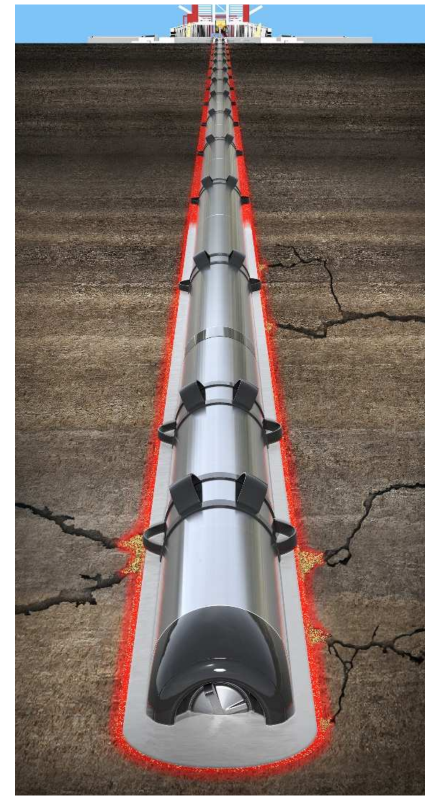
HALLIBURTON SOLUTION – Tuned® Defense™ Cement Spacer

Next-generation adjustable rheology cement spacer with lost circulation capabilities to maintain wellbore stability

- Achieve planned top of cement
- Effective mud displacement
- Enable a dependable barrier to maximize production



Eliminate Seepage



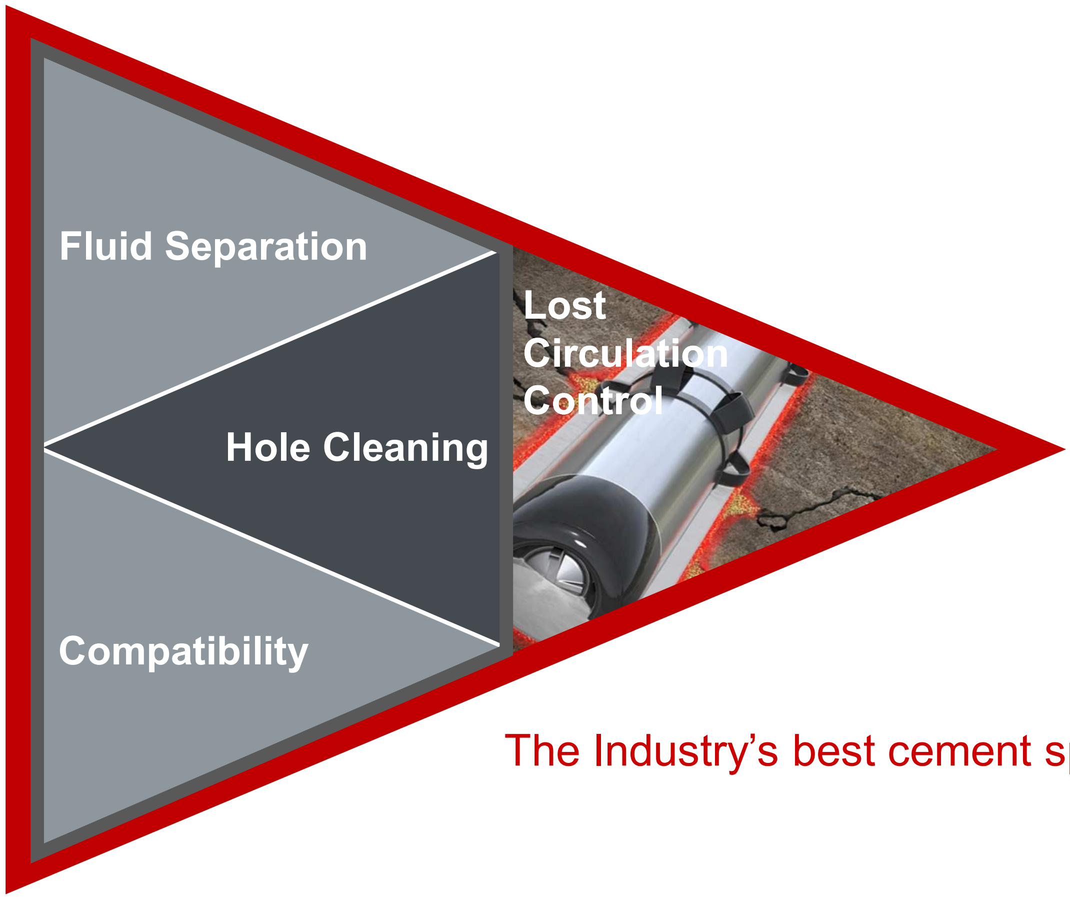
Prevent severe losses

HALLIBURTON

What do you want from a cement spacer?

Tuned® Spacer Portfolio

- Industry leading spacer systems system for over 22 years
- Used in over 11,000 cement jobs per year



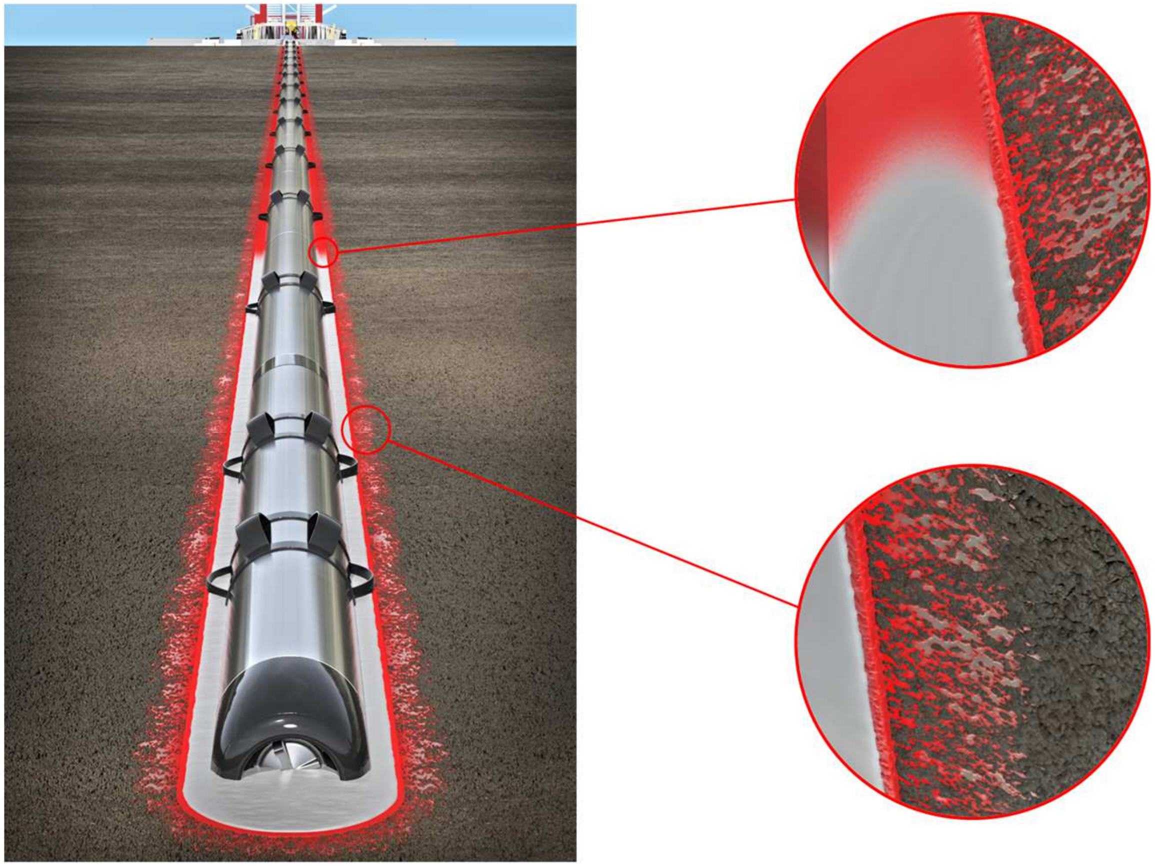
Tuned® Defense™ Cement Spacer

The Industry's best cement spacer just got better.

HALLIBURTON

What Makes Tuned® Defense™ Cement Spacer Unique?

Seepage to partial loss control



Optimized fluid rheology helps improve mud displacement

Ability to reduce seepage and achieve top of cement

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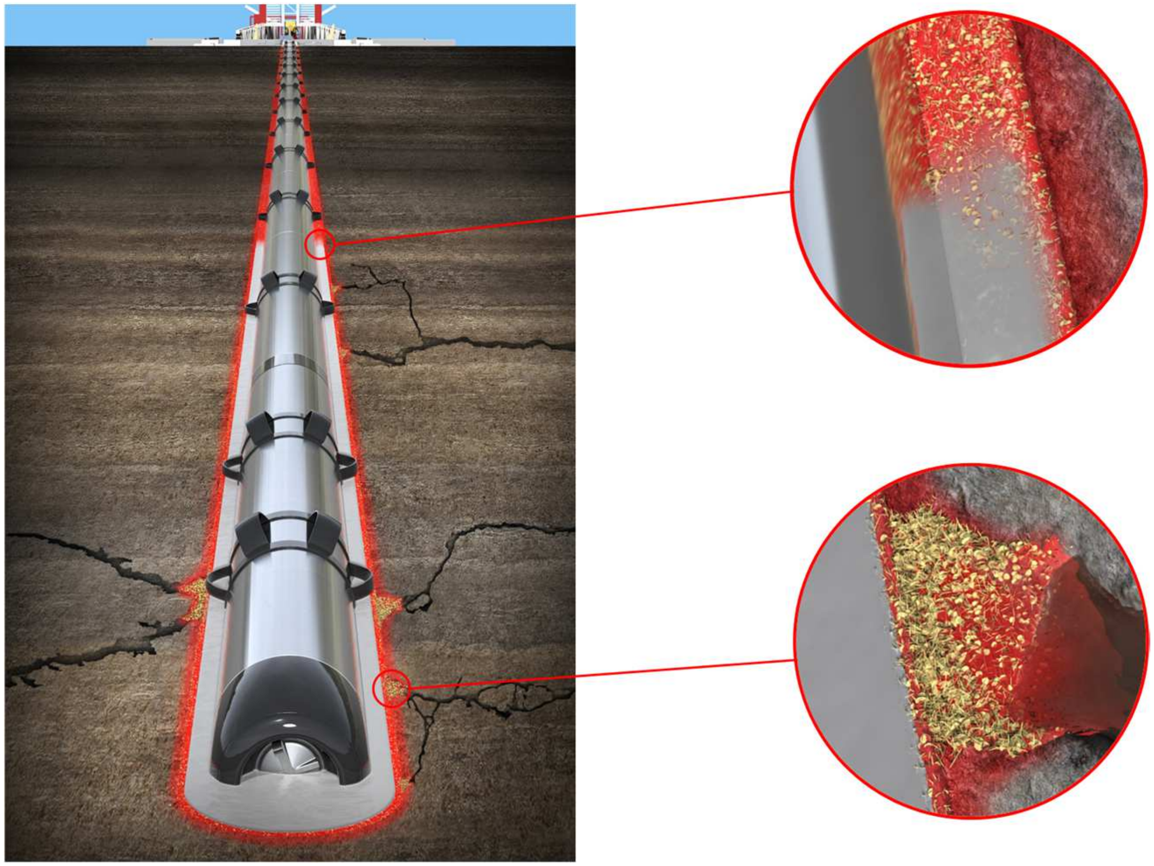
What Makes Tuned® Defense™ Cement Spacer Unique?
Up to Severe Loss Control



Optimized fluid rheology helps improve mud displacement

Ability to plug fractures and prevent losses when tailored with BridgeMaker™ II LCM

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Tuned® Defense™ Cement Spacer Technical Capabilities

- Up to 325°F*
- Up to 19 ppg density
- Non-damaging to the formation
- Able to seal pores up to 500 microns
- Combines with BridgeMaker™ II LCM to plug fractures up to 3000 microns

* DefenseMod™ 325 Additive may be used above 300°F

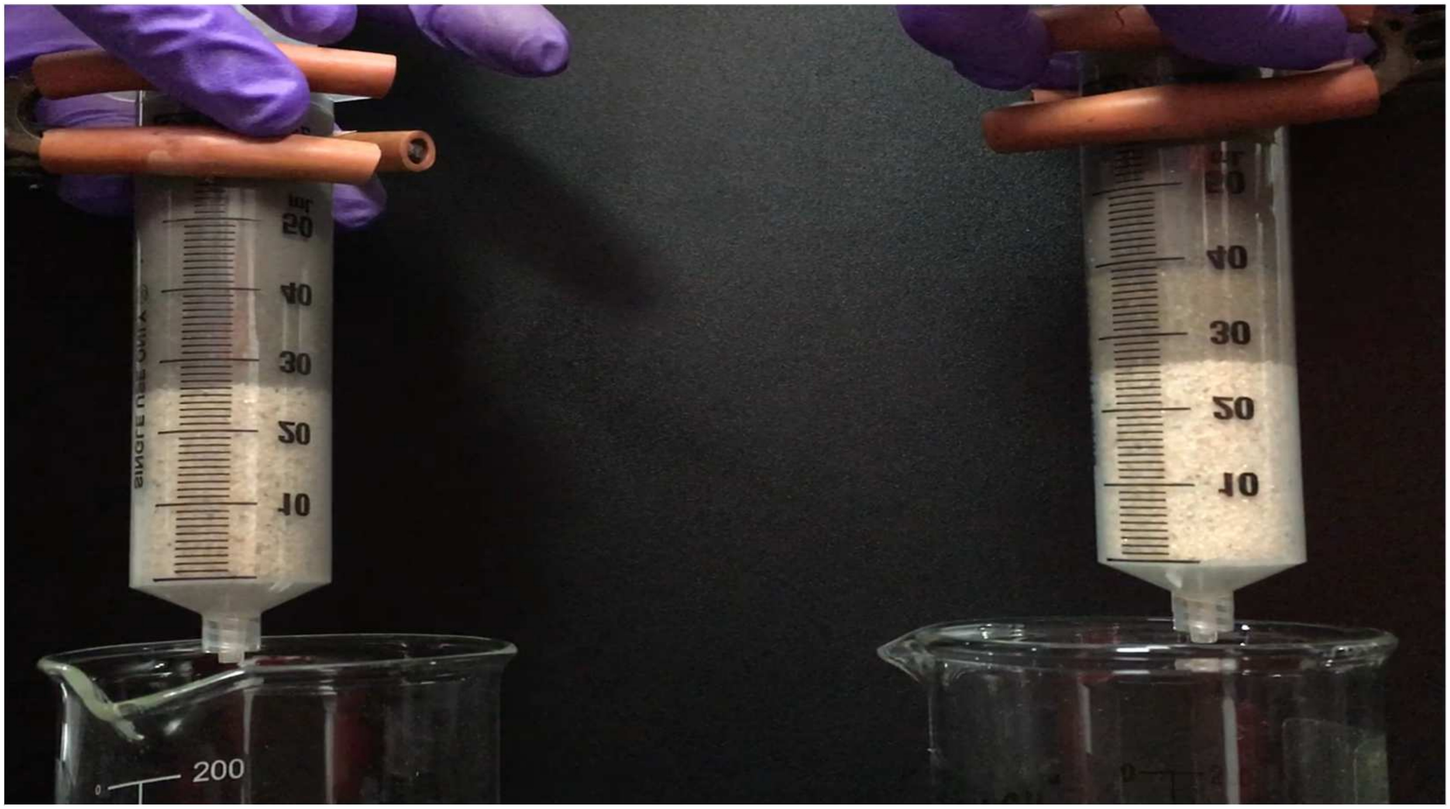
Tuned® Defense™ Cement Spacer Test Procedures

A spacer's ability to control losses can be tested and verified.

- Fluid Loss Cell
  - Same apparatus used for API Fluid Loss testing
  - 250 micron screen (60 mesh)
  - 1000 psi pressure

- Particle Plugging Apparatus (PPA)
  - Common apparatus in drilling fluid labs
  - 500 to 3000 micron slots
  - 1000 psi pressure

Tuned® Defense™ Cement Spacer Demonstration



Conventional Spacer
without loss control

Tuned® Defense™ Cement Spacer
with loss control

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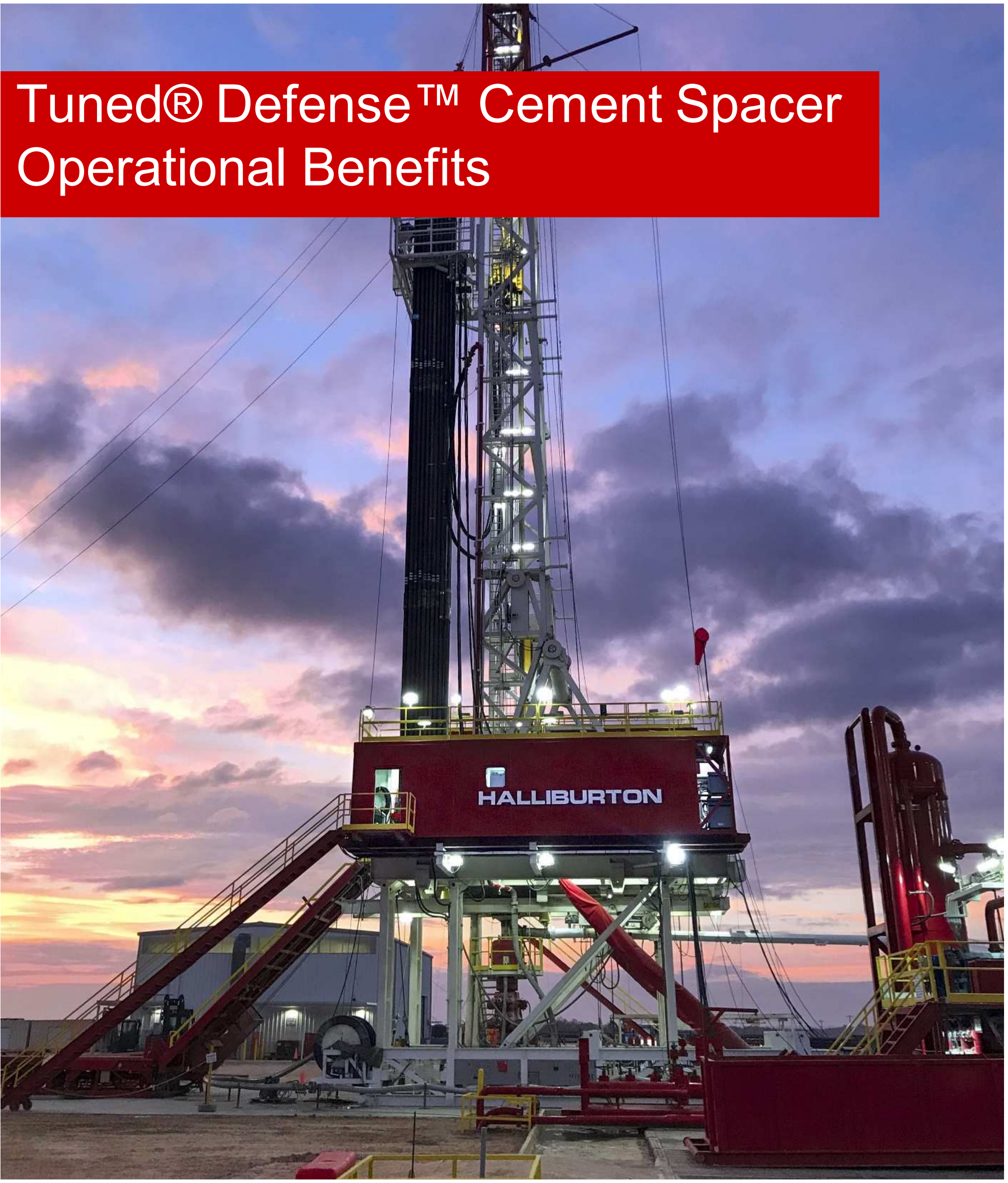
Tuned® Defense™ Cement Spacer Operational Benefits



Increase confidence in achieving top of cement

Avoid remediation

Minimize non-productive time

Lower overall operating costs

Tuned® Defense™ Cement Spacer Potential Applications

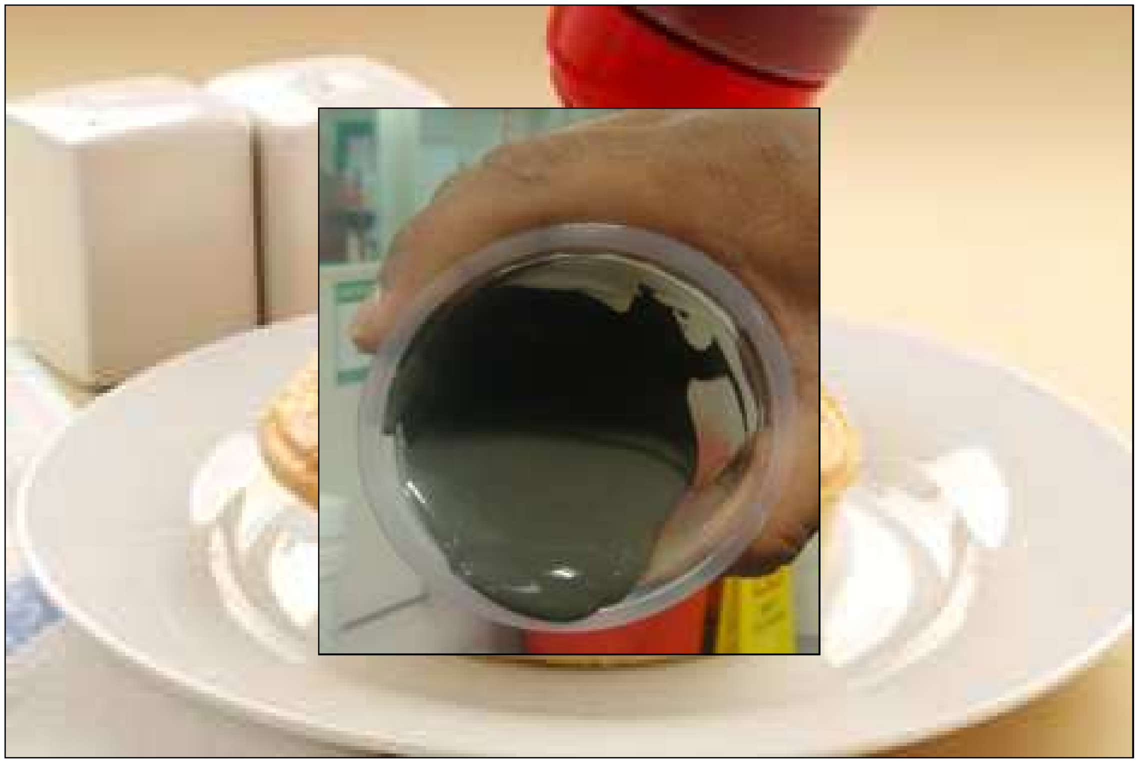
Permeable or fractured formations

Narrow pore pressure/frac gradient margins

Fields with history of losses

Areas with strict top of cement requirements

SentinelCem™ Cement



What is SentinelCem™ Cement?

- **What It Is:**
  - A Dependable Barrier for Losses that uses Chemistry rather than Physical Mechanisms (LCM)
  - A highly-thixotropic cement slurry with Low Solids Content and High Yield
  - Acid Soluble System
- **What It Does:**
  - Can cure Total Lost Circulation
  - Can be pumped through the drilling BHA
  - Enables deeper formation penetration
- **What It Means:**
  - Minimizes risks of cost overruns and NPT
  - Allows Operator to continue drilling ahead
  - Enables access to deeper reservoirs previously inaccessible

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Why SentinelCem™ Cement?

Features

- Lightweight slurry density 10 ppg
- Low percentage of solids ~10% by volume, ~20% by weight
- Rapidly gels when pumping is stopped, yet becomes pumpable again when shear is returned.
- Acid soluble

Benefits

- Reduced hydrostatic on weak formations
- Allows for pumping through the Drilling BHA
- Maximum penetration into the loss zone maximizes the chance of success to cure the losses
- Can be used in production reservoirs

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Case Study:
SentinelCem™ Cement Placed Using the BHA Solves Total Lost Circulation

Operator Challenge

- Over 500 bbls/hour of Total Losses were experienced during drilling in the Llanos Basin in Colombia.

Solution

- SentinelCem™ cement due to the shear-rate dependent rheology.
- Low viscosity during pumping enabled placement via drilling BHA.
- Rig-time was reduced by avoiding additional trips.

Results

- Circulation was re-established on three different wells with total losses.
- Avoided the need for remediation.
- Operator saved $250,000 (USD) per well in rig time and mud recovery

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Tailoring SentinelCem™ Cement Designs

- SentinelCem™ cement is a low complexity slurry
- Low sensitivity to mild changes in BHCT
- All standard API lab testing applies
- Additional Considerations
  - Use FYSA to measure rheology
  - Always perform On-Off-On Thickening Time tests

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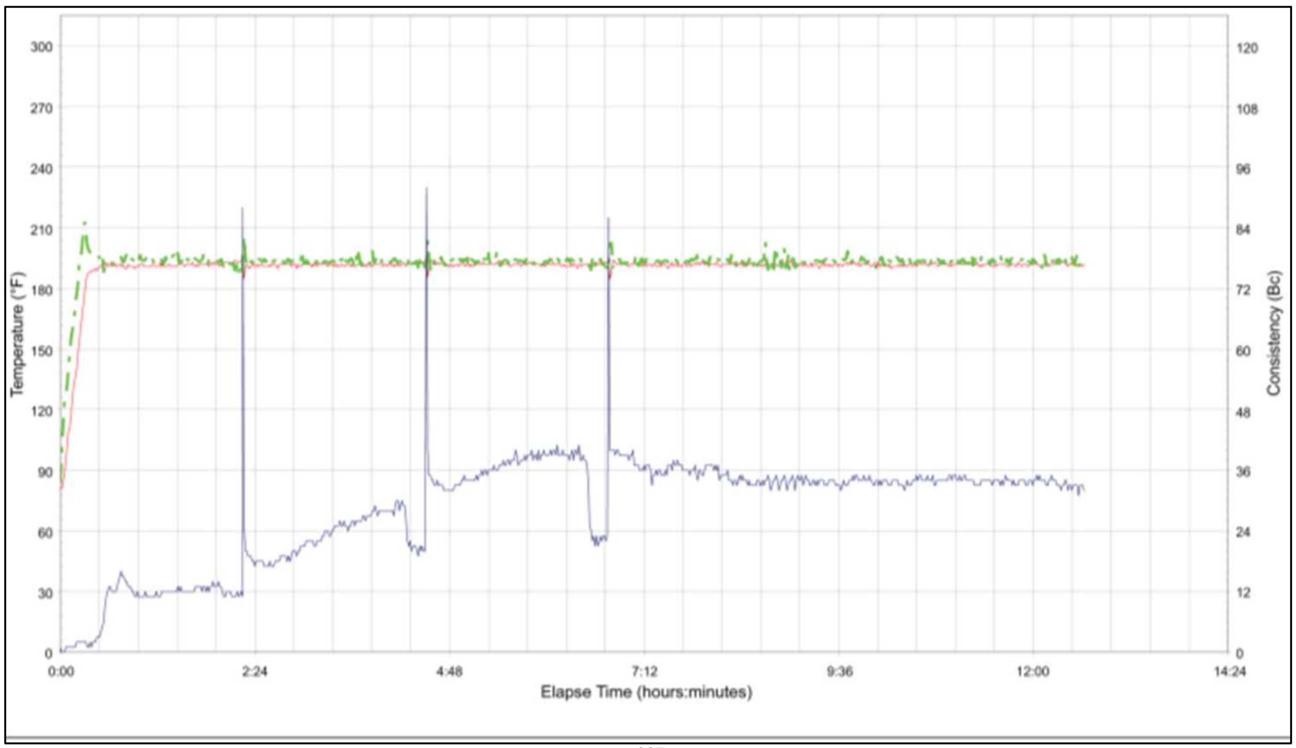
SentinelCem™ Cement – Highly Thixotropic Behaviour

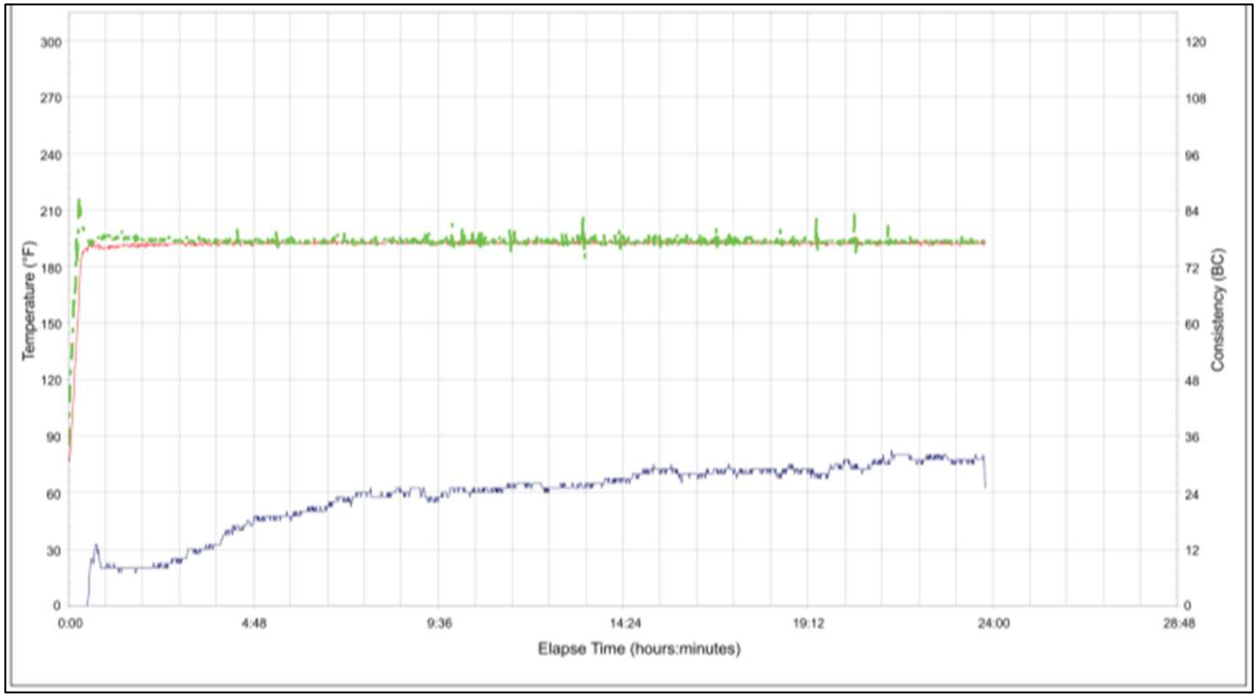
- When pumping stops, slurry gels rapidly.
- When pumping continues, the slurry re-establishes liquid form



HALLIBURTON

SentinelCem™ Cement – Highly Thixotropic Behaviour

- When kept under continuous shear, SentinelCem™ cement can be pumpable for >24 hours



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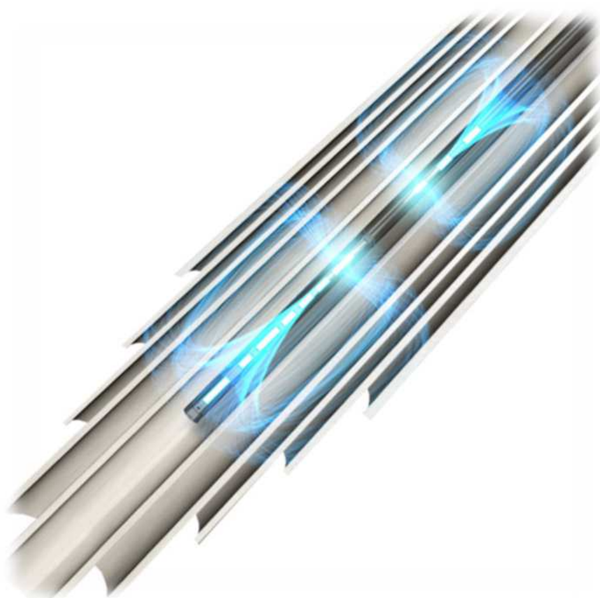
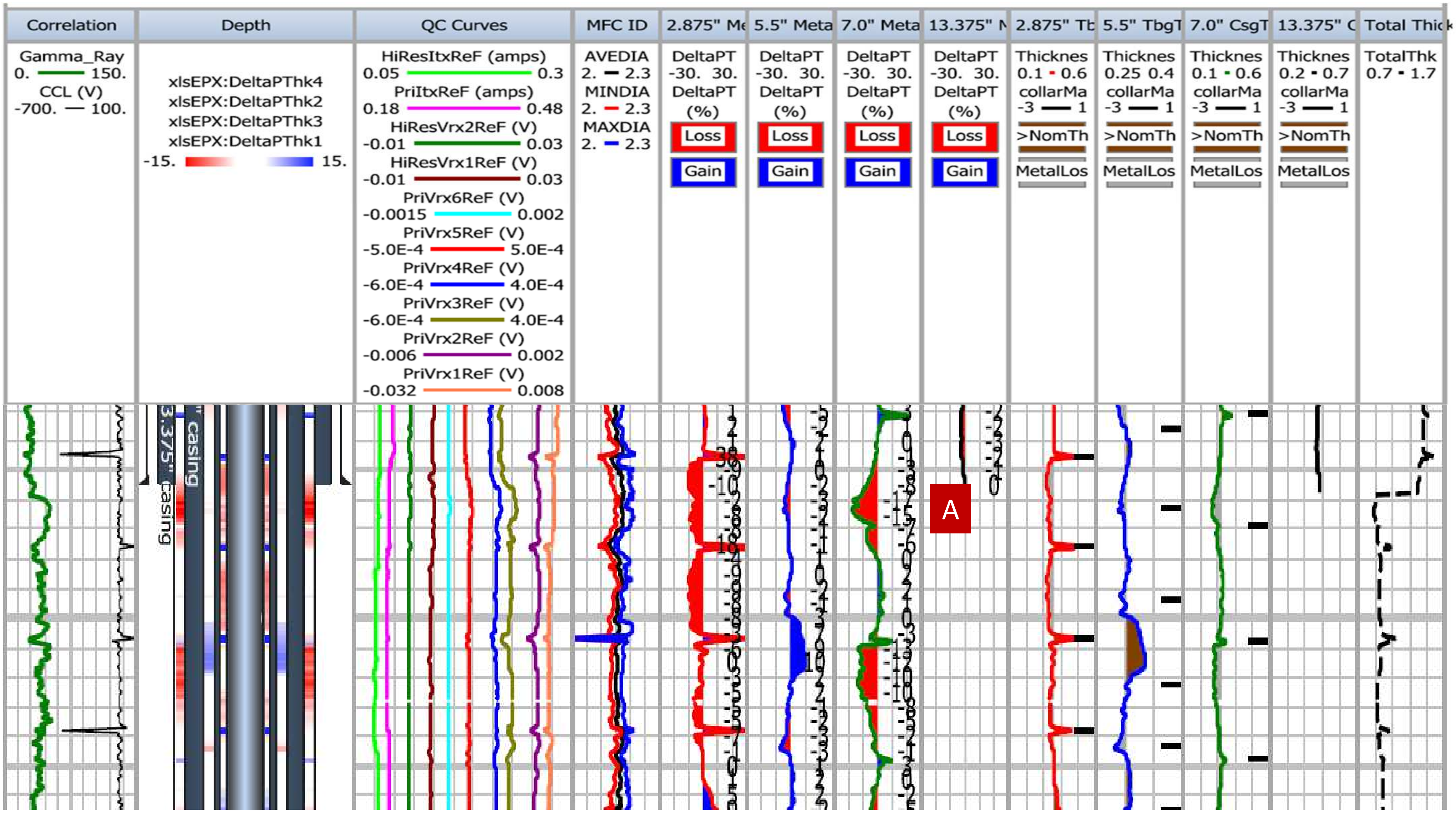
Electromagnetic Pipe Xaminer

Electromagnetic Pipe Xaminer® V (EPX™ V) Performance Specifications



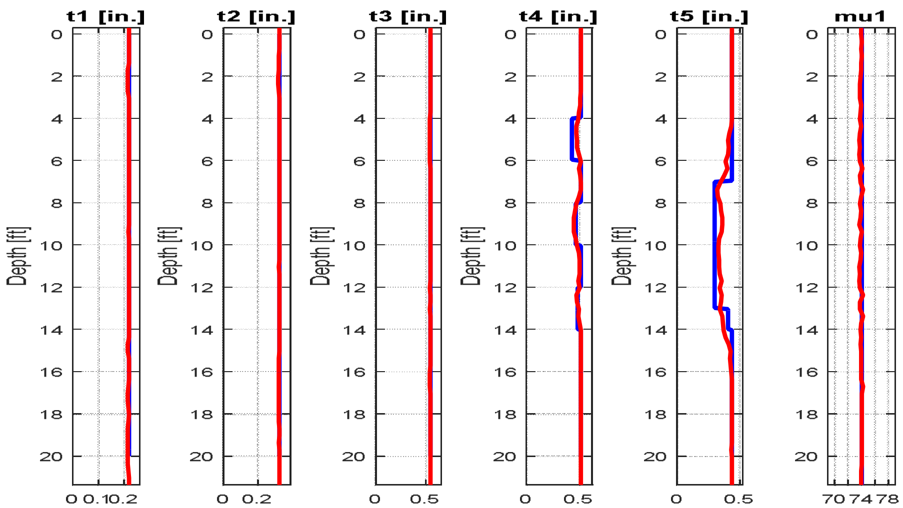
General Tool Specifications	English	Metric
Tool Length	17.34 ft	5.28 m
Tool OD	1.69 in.	42.93 mm
Tool Weight	87.00 lb	39.46 kg
Maximum Pressure	15,000 psi	103 MPa
Maximum Temperature	350°F	176°C
Measurement Range		
Minimum Tubular OD	2.38 in.	60.45 mm
Maximum First Tubular OD for Maximum Resolution	7.00 in.	177.8 mm
Maximum First Tubular OD	24.00 in.	609.6 mm
Maximum Casing Size	24.00 in.	609.6 mm
Maximum Total Metal Thickness (current)	2.5 in.	63.5 mm
Thickness Measurement Accuracy and Detection		
1st Pipe Defect Detection	1%	
1st Pipe (2 strings) Accuracy	2% or 0.015 in.	2% or .38 mm
Total Metal Thickness 1.2” (3cs)	7%	
Total Metal Thickness 1.8” (4cs)	10%	

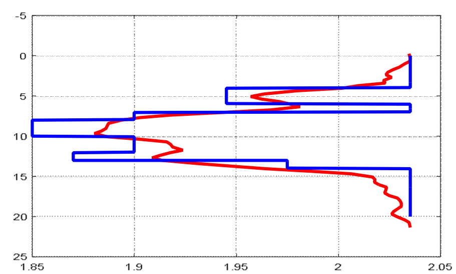


Correlation
Depth
QC Curves
MFC ID
Gamma_Ray
0. 150.
CCL (V)
-700. 100.
xlsEPX:DeltaPThk4
xlsEPX:DeltaPThk2
xlsEPX:DeltaPThk3
xlsEPX:DeltaPThk1
-15. 15.
HiResItxReF (amps)
0.05 0.3
PriItxReF (amps)
0.18 0.48
HiResVrx2ReF (V)
-0.01 0.03
HiResVrx1ReF (V)
-0.01 0.03
PriVrx6ReF (V)
-0.0015 0.002
PriVrx5ReF (V)
-5.0E-4 5.0E-4
PriVrx4ReF (V)
-6.0E-4 4.0E-4
PriVrx3ReF (V)
-6.0E-4 4.0E-4
PriVrx2ReF (V)
-0.006 0.002
PriVrx1ReF (V)
-0.032 0.008
AVEDIA
2. 2.3
MINDIA
2. 2.3
MAXDIA
2. 2.3
DeltaPT
-30. 30.
DeltaPT
(%)
Loss
Gain
Thicknes
collarMa
-3 1
>NomTh
MetalLos
TotalThk
0.7 1.7
13.375" casing
A

Full-Resolution Array Optimization for Overlapping Defects

- Overlapping defects in pipes 4 and 5

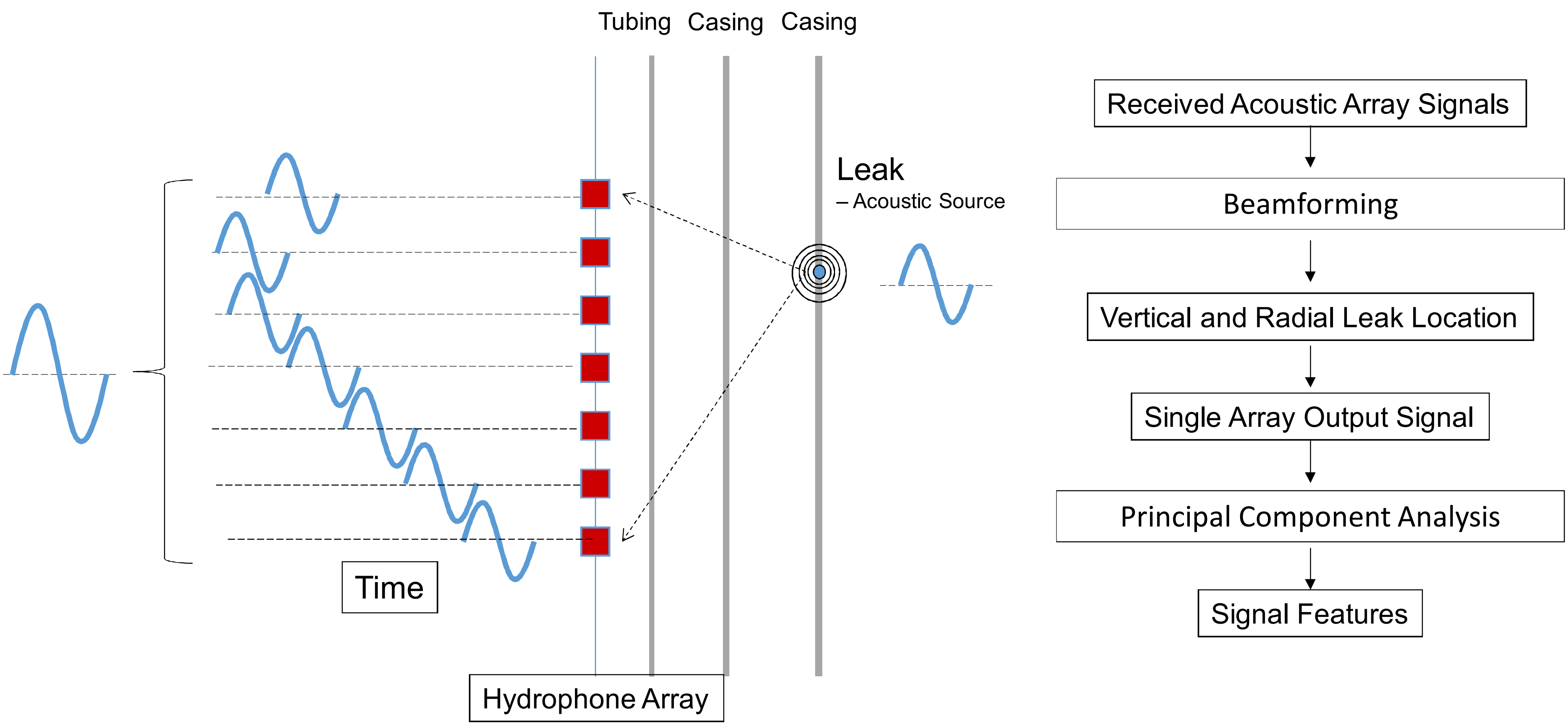


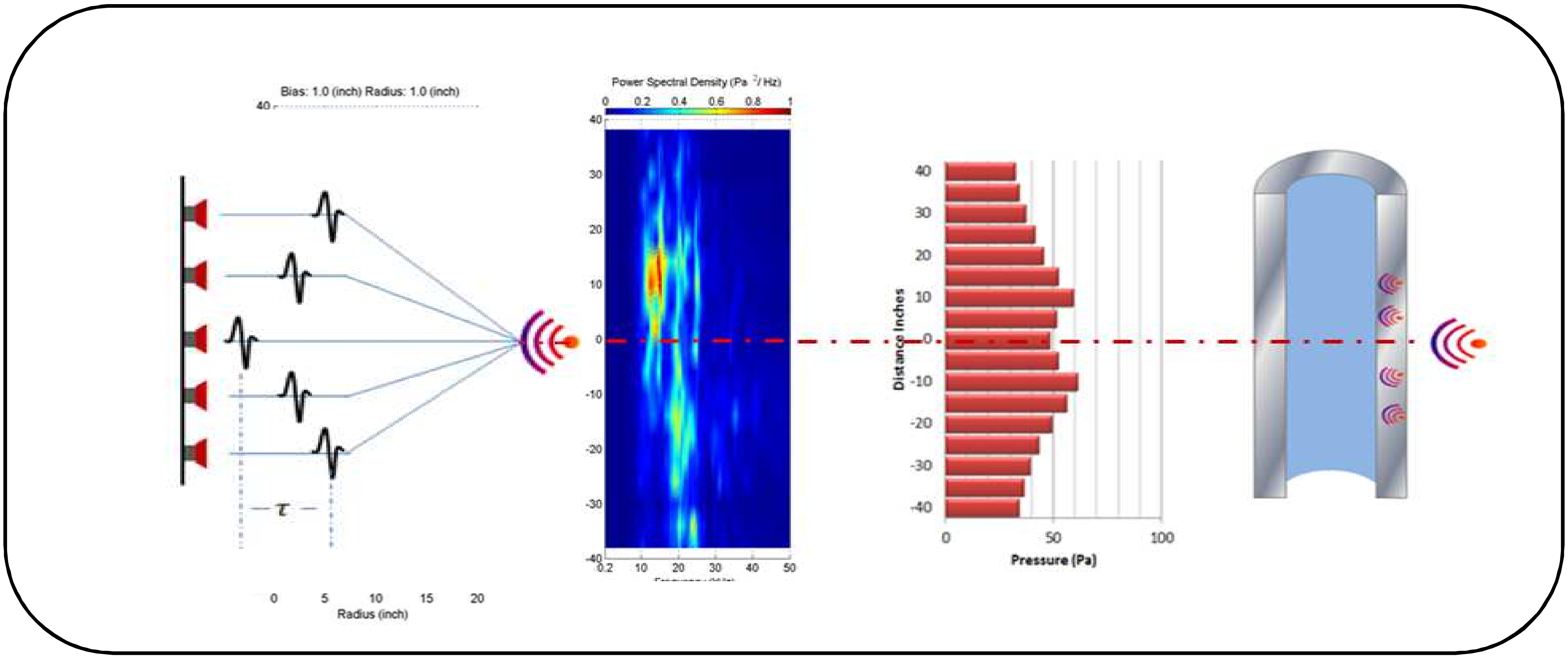


blue: actual
red: inverted

ACX (Array Noise Tool)

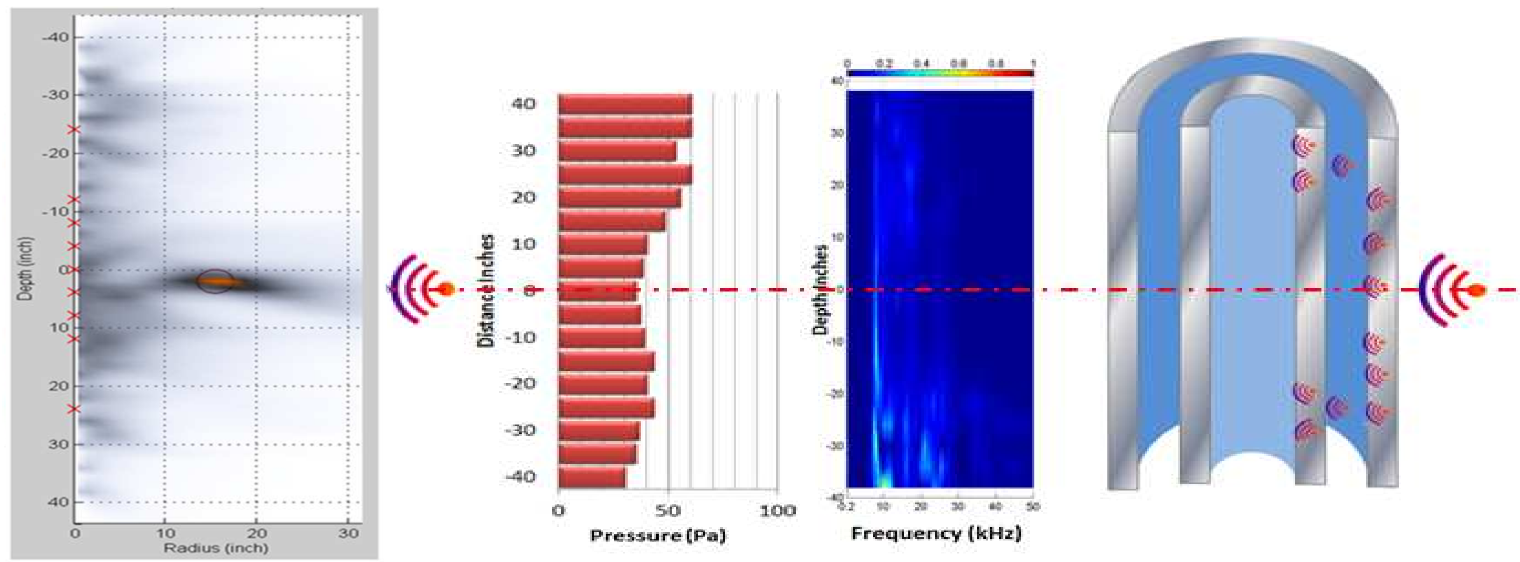
Beamforming





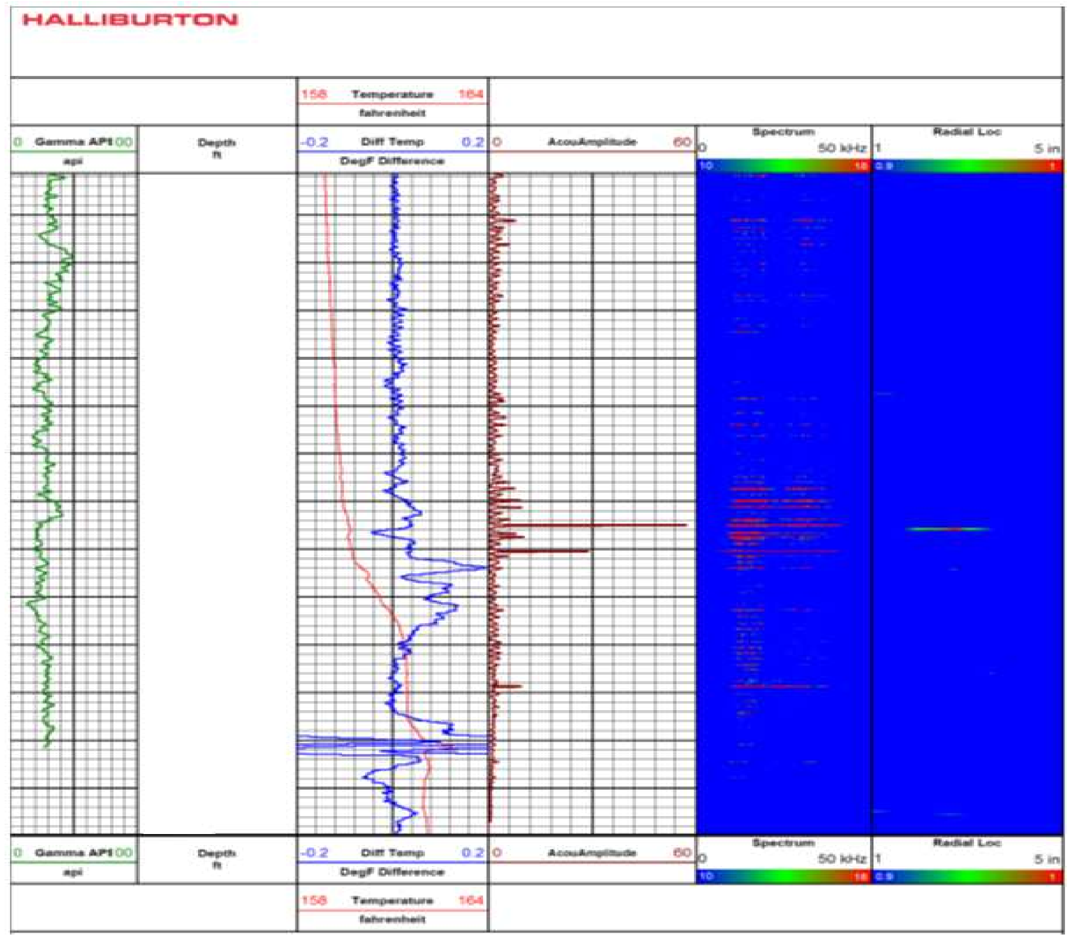
Bias: 1.0 (inch) Radius: 1.0 (inch)
τ
0 5 10 15 20
Radius (inch)
Power Spectral Density (Pa ²/ Hz)
0 0.2 0.4 0.6 0.8 1
Distance Inches
Pressure (Pa)
0 50 100

Tubing and Casing

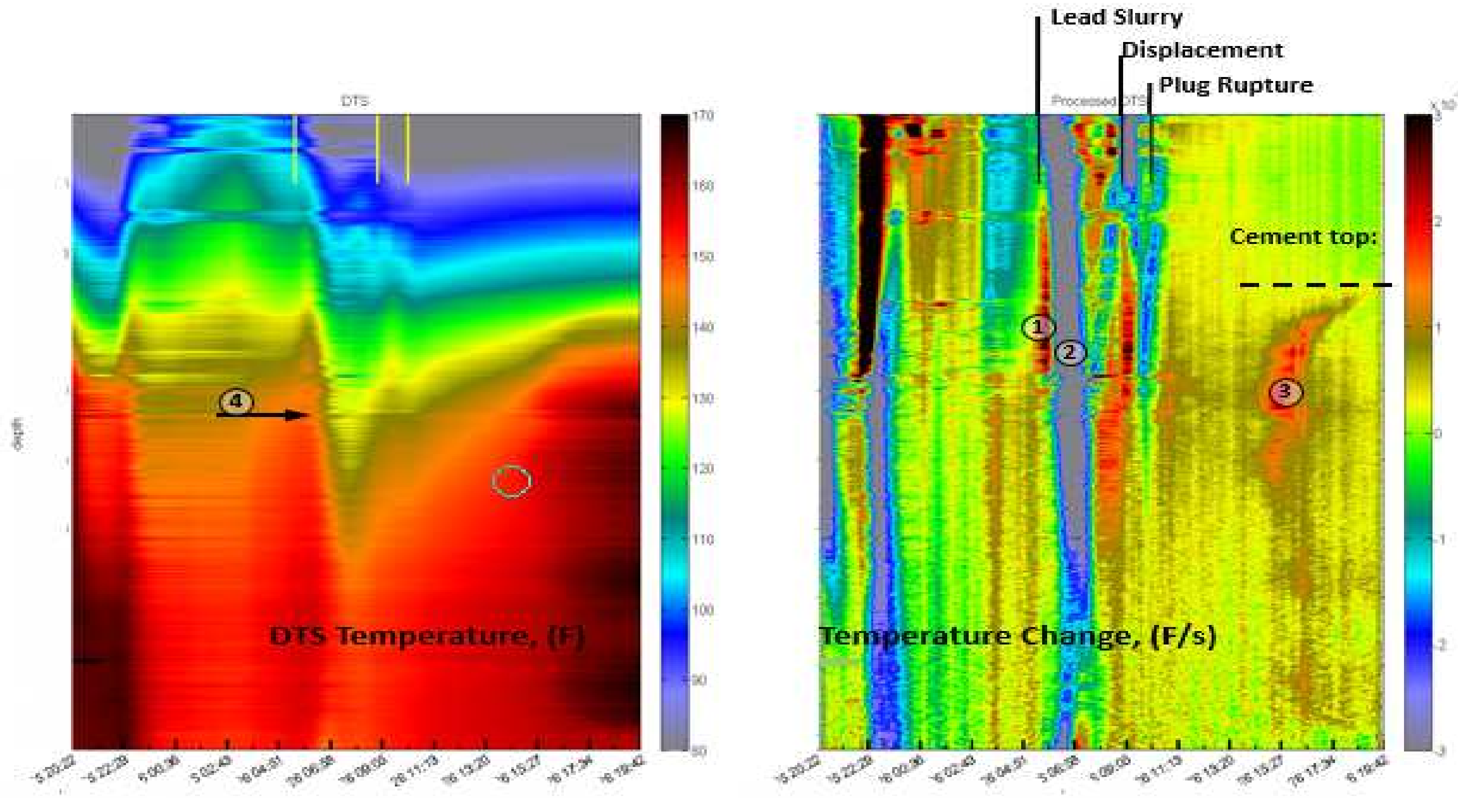


Gas-Lift Mandrel Leak

- Radial Pick
  - » Clear indication
  - » Maximum deviation at depth of leak is 70°

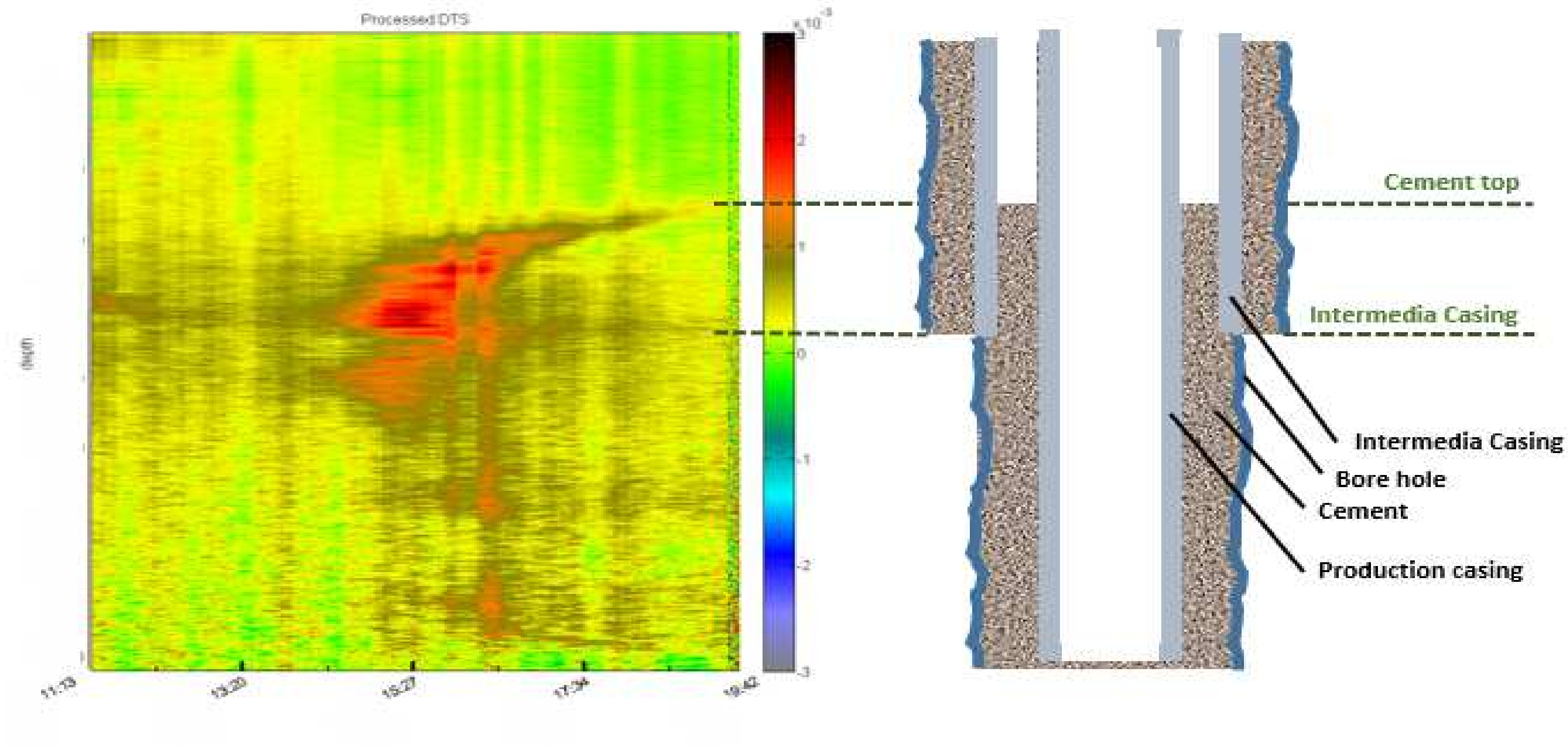


Fiber Optics use for Cement Evaluation



① Warm drilling Fluid in annulus was pushed upward
② Cool cement flowed downward in casing
③ Heat effect by cement curing
④ End of Intermedia casing

Temperature Increase from Cement Curing



Temperature Increase between TOC and Intermediate casing is enhanced because the exothermic heat released by cement curing dissipated slower in this zone

PACERS
Peak Analysis of CBL Waveform
Radial Segmented

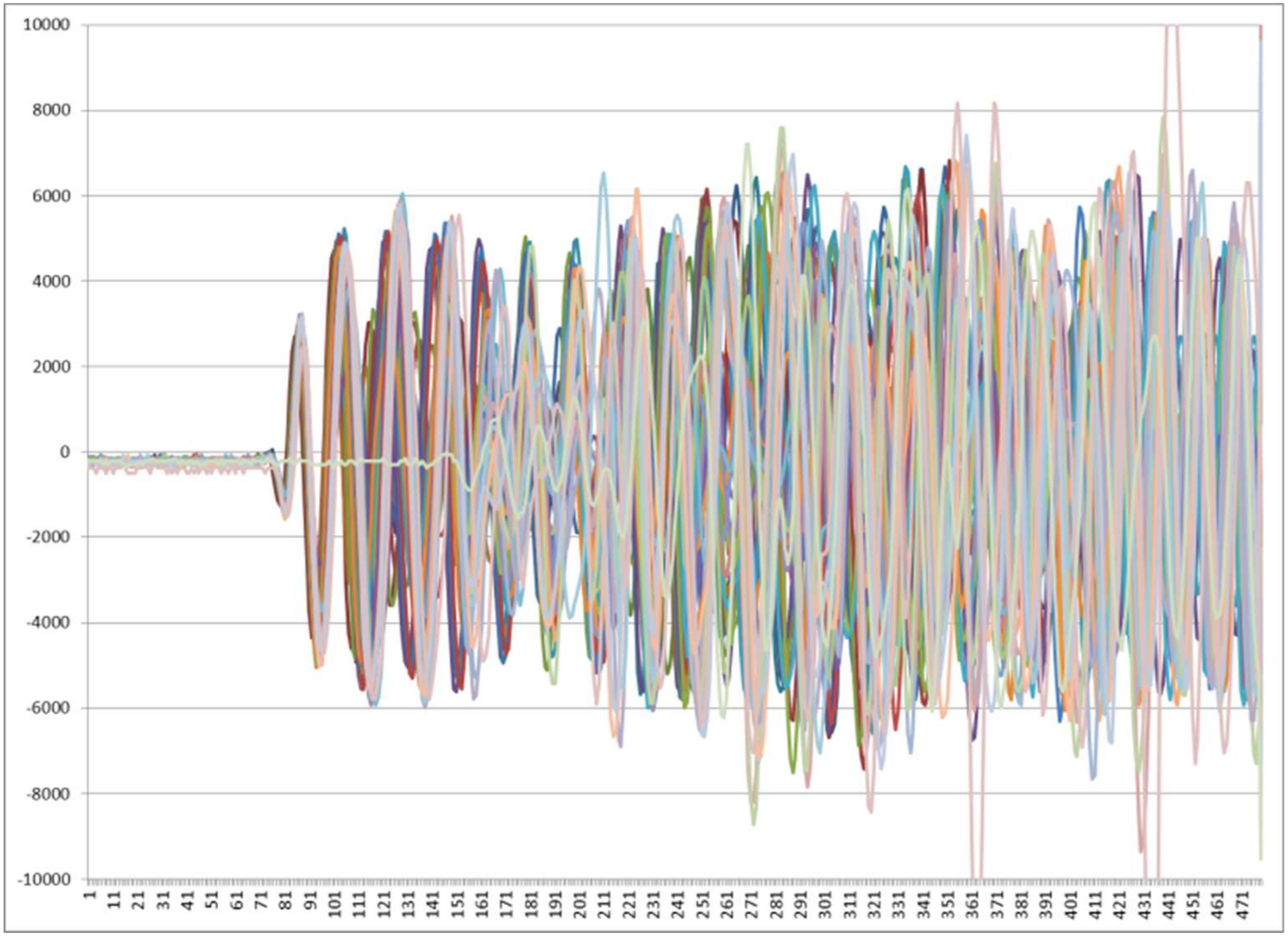
PACE (Peak Analysis for Cement Evaluation)

- The new technique uses the peaks and troughs of the waveform for analysis and a derivative process is used to determine the peaks and troughs.

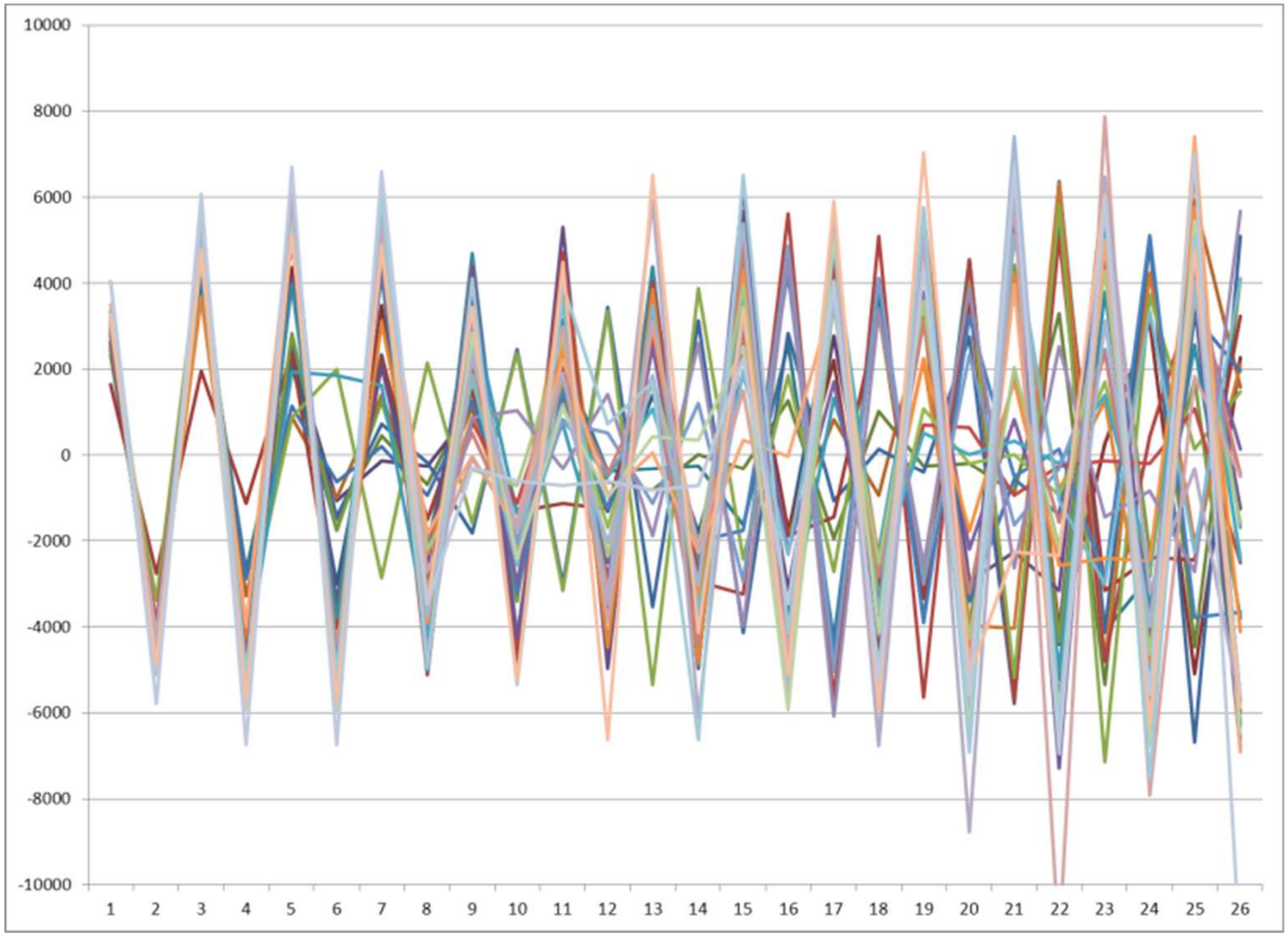
- When the derivative changes sign is the peak or trough of that waveform, and the value of the waveform will be called a peak.

- This provides an automatic method of picking both the positive and negative peaks of the entire waveform.

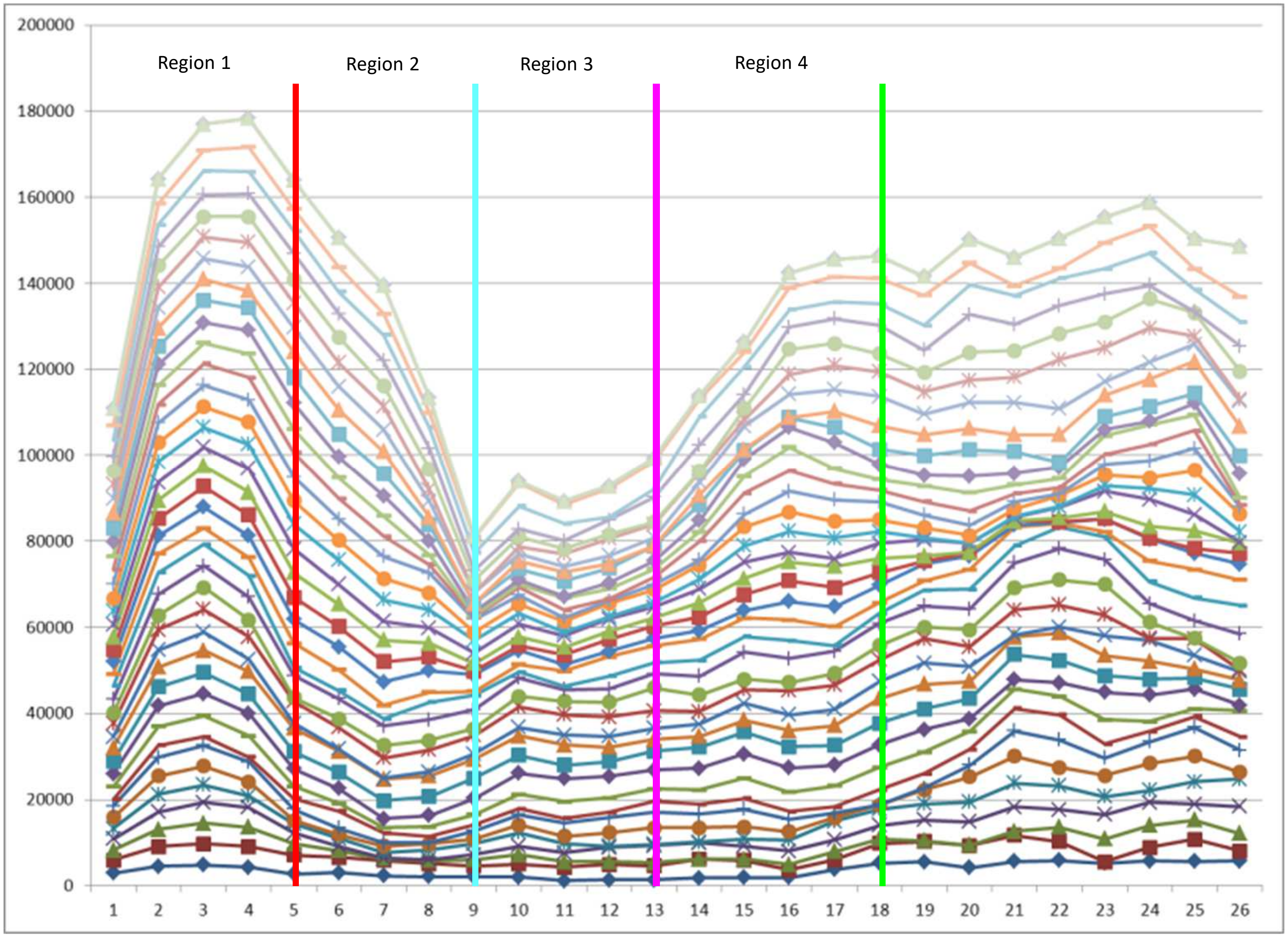
CBL Waveforms



CBL Peaks

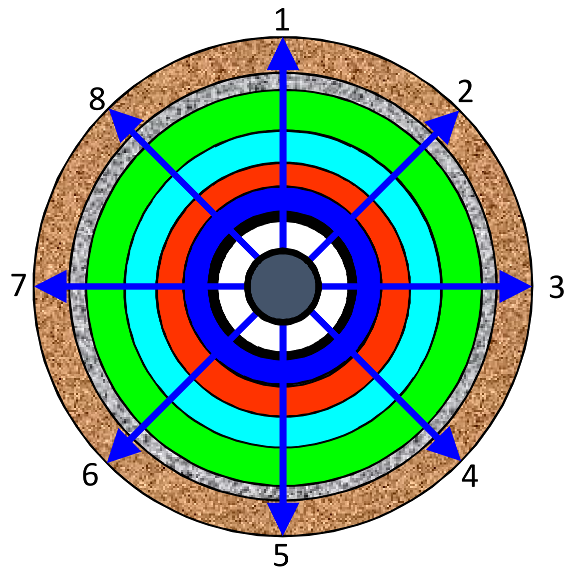

10000
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
-10000
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26

Stacked Absolute Value of the CBL Peaks



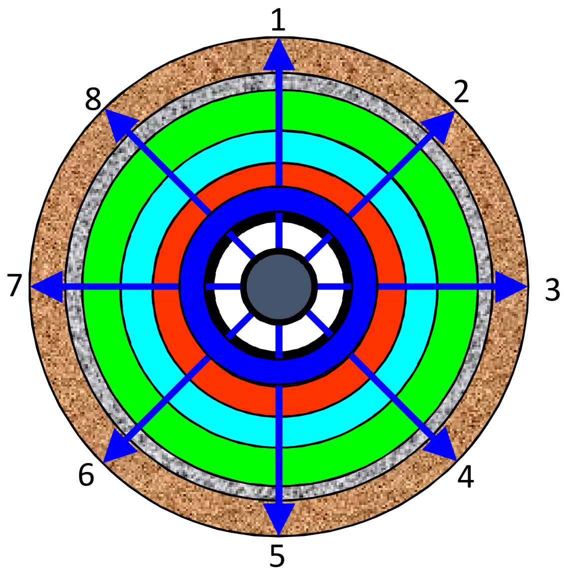
PACE (Peak Analysis for Cement Evaluation) Segmented Radial Shells

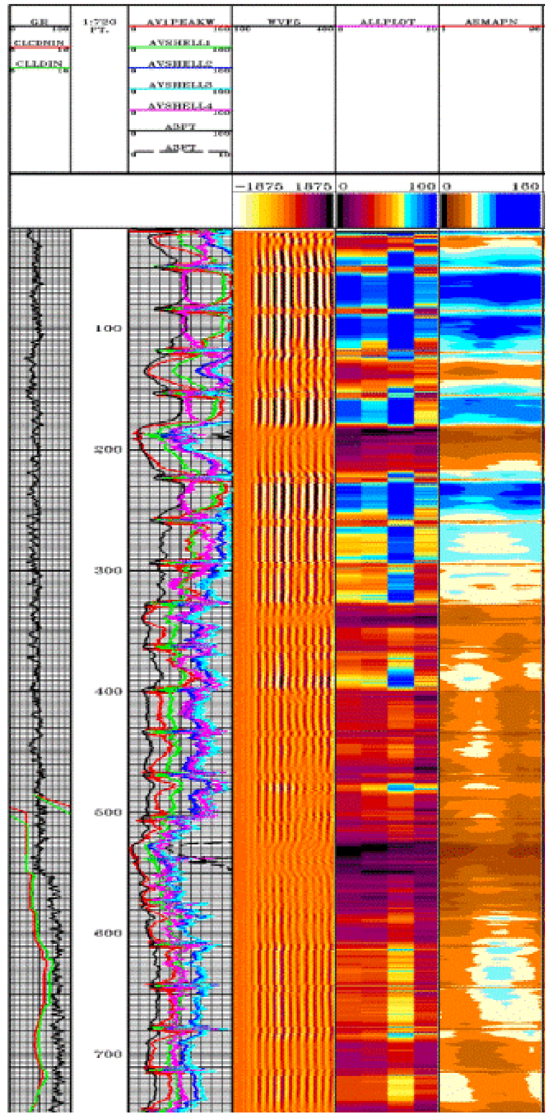
- Taking each region from each segmented PACE it is possible to create Shells1 – Shells 4
- The average amplitude reading from each Segmented PACE is used and interpolated to the next reading allowing an image to be created
  - If a RB curve is available all regions will be corrected
- Shell 1 is nearest to the wellbore while Shell 4 is further away



PACER Shell

Peak Analysis of CBL Waveform
Radial Segmented





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