Well Integrity: The Foundation of Everything We Do.

a. Design Best Practices
b. Well Failures and Learnings
c. Well Integrity Testing

International Petroleum Environmental Conference

October 7-9, 2019

Sand Antonio, TX.

George E. King, P.E., GEK Engineering PLLC

My first Engineering boss passed this on to me…

- You cannot build a skyscraper on the foundation of an outhouse.

- The foundation we build upon is well integrity.

Well Integrity Management

- Well Integrity is the application of technical, operational and organizational solutions to reduce the risk of uncontrolled release of formation fluids throughout the life cycle of the well; and the preservation of the formation from outside influences that would have an adverse effect on its capacity to produce. (Well Integrity Management – GOM Dave Porter)

Introduction – what will we cover?

- **Design – We can only improve when we learn from the mistakes:**
  - **Best Practices – Do it right the first time => less problems later.**
  - **Critical Injection Points – What are typical failure points?**
  - **Warning Flags – For some failures, you can see them coming!**
- **<u>Well Failures and how we learn from them:</u>**
  - **Sources of leaks – are 95% of leaks coming from <5% of places?**
  - **Age vs. Era – Old doesn't mean bad if it was done the right way first!**
  - **Barrier failure vs. Integrity Failure – A tremendous difference!**
- ***<u>Testing and (The Culture of Maintenance):</u>***
  - **Everyone wants to build, but nobody wants to maintain.**
  - **A culture of maintenance can only exist in a top=>down driven program.**
  - **This is where Key Performance Indicators (KPIs) can help**

General Well Design Observations

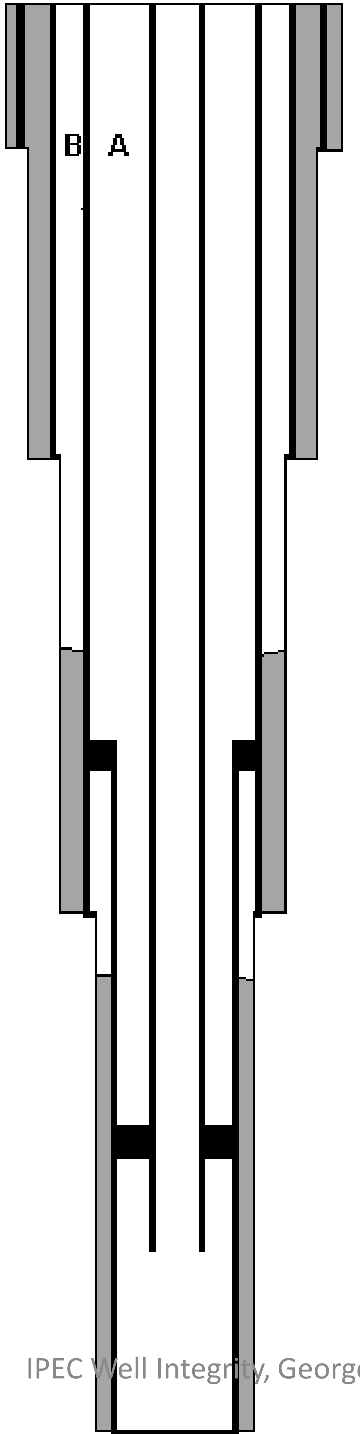
- Wells are designed from inside out & bottom to top.
- Wells are built from outside in and from top to bottom.
- The formation and produced fluids have the final word in what works & doesn’t.
- Wells are built with multiple barriers to provide isolation between well fluids and environment.
- When a barrier fails, a leak can only form when 1.) a movable fluid exists, 2.) a flow path is created and 3.) a differential pressure exists toward the outside.

Multiple Barriers? Unusual?

- Barriers in a modern car in a front-end crash:
    1. Sacrificial crush zones ahead of the passengers.
    2. Collapsible steering wheel.
    3. Air-bags
    4. Seat belt/shoulder harness
- Avoidance
    - Road design – shoulders and dividers
    - Anti-lock disk brakes
    - Fast response power steering
    - Drivers training/experience
    - Warning systems – approach
    - Autobraking

Well Design:

1. Tubing
2. Production Liner
3. Production Casing
4. Surface Casing
5. Conductor Pipe

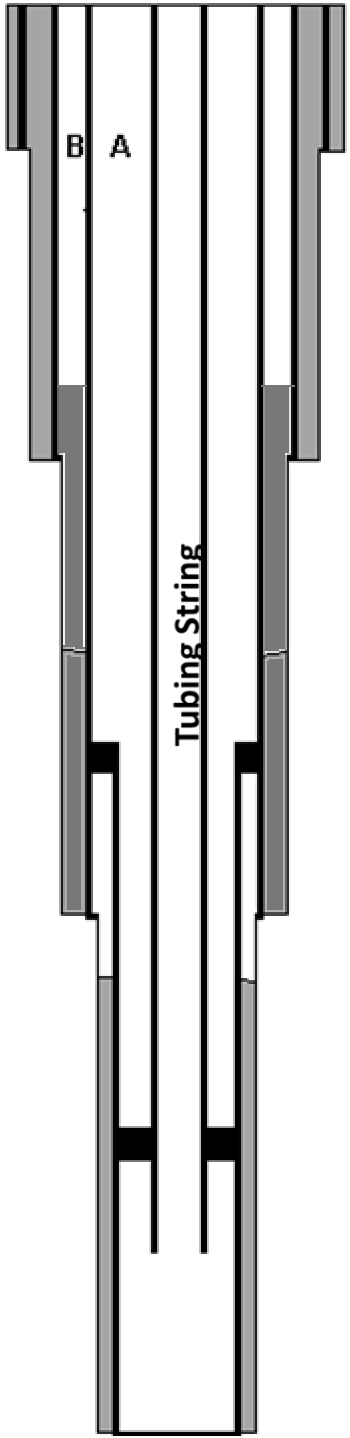


Details and Considerations:

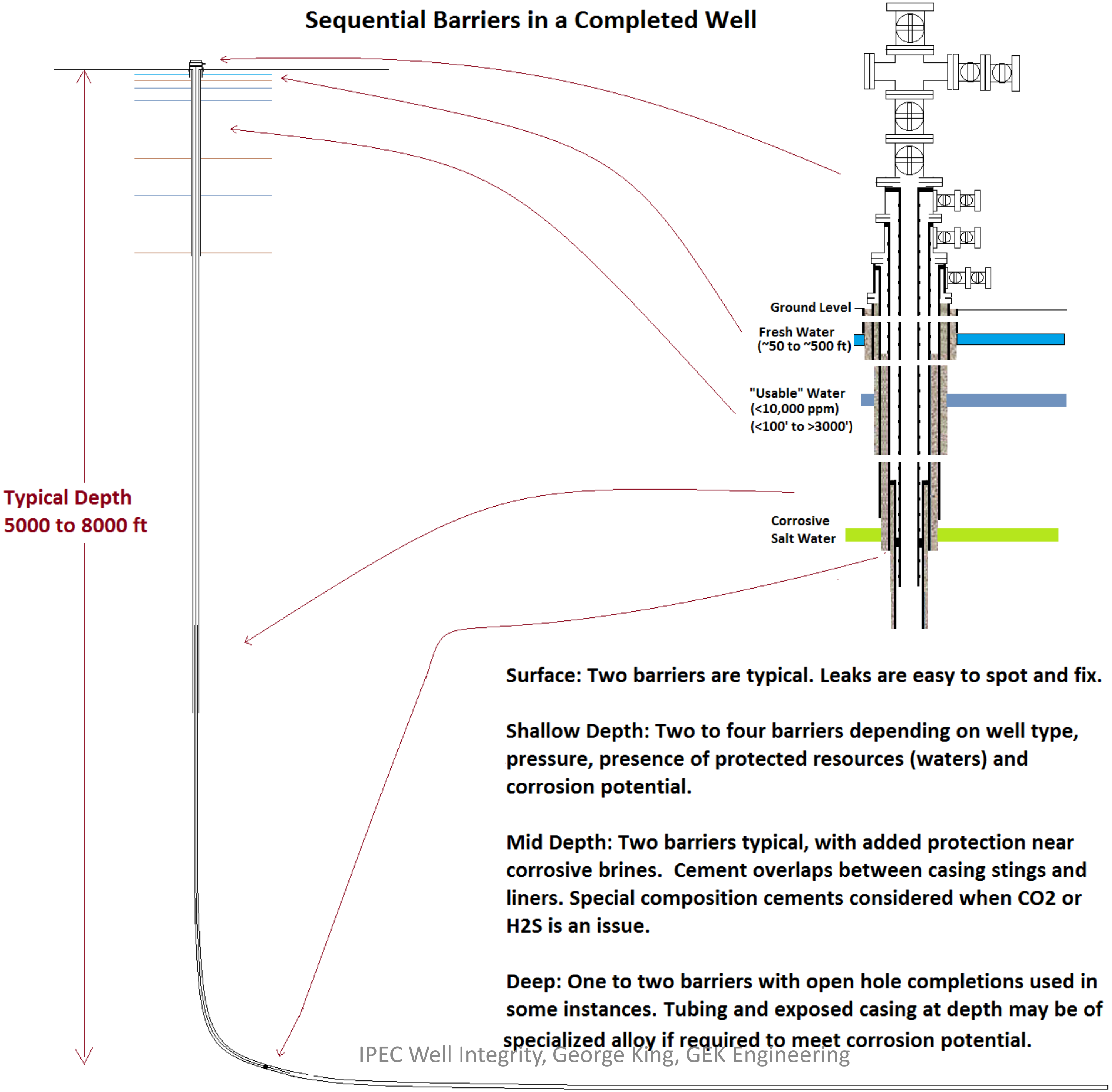
1. Max press during production.
2. Max pressure during shut-in.
3. Max pressure during frac.
4. Packer fluid density & height.
5. Changes in well use? Gas lift source in the “A” annulus instead of packer fluid?
6. Effect of leaks
7. Annular pressure at start-up

Casing Design Intent

- A well is actually designed from the inside out and from the bottom to the top.
- "A" annulus - tubing will collapse before casing bursts (designed to fail internally and prevent leaks or spills).
- "B" annulus – production casing will collapse before surface casing will burst (same leak protection intent).
- "C" annulus – usually cemented up, but watch any sealed area.



Sequential Barriers in a Completed Well



Surface: Two barriers are typical. Leaks are easy to spot and fix.

Shallow Depth: Two to four barriers depending on well type, pressure, presence of protected resources (waters) and corrosion potential.

Mid Depth: Two barriers typical, with added protection near corrosive brines. Cement overlaps between casing stings and liners. Special composition cements considered when CO2 or H2S is an issue.

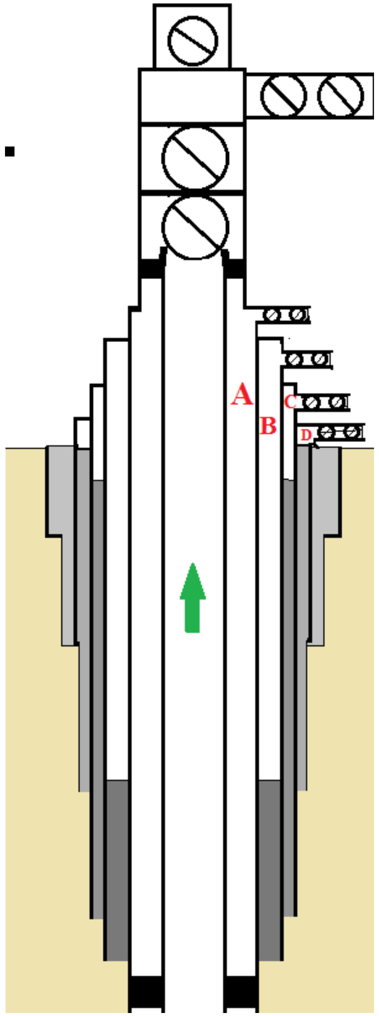
Deep: One to two barriers with open hole completions used in some instances. Tubing and exposed casing at depth may be of specialized alloy if required to meet corrosion potential.

Barrier Failure or Well Integrity Failure

- <u>**Single Barrier Failure => No Leak Path? => No Well Integrity Failure**</u>
- <u>**Unless All Barriers Fail, A Leak Will Not Happen**</u>

Wells are Designed with Multiple Barriers.
Number of Barriers Depends on the Hazard Level.

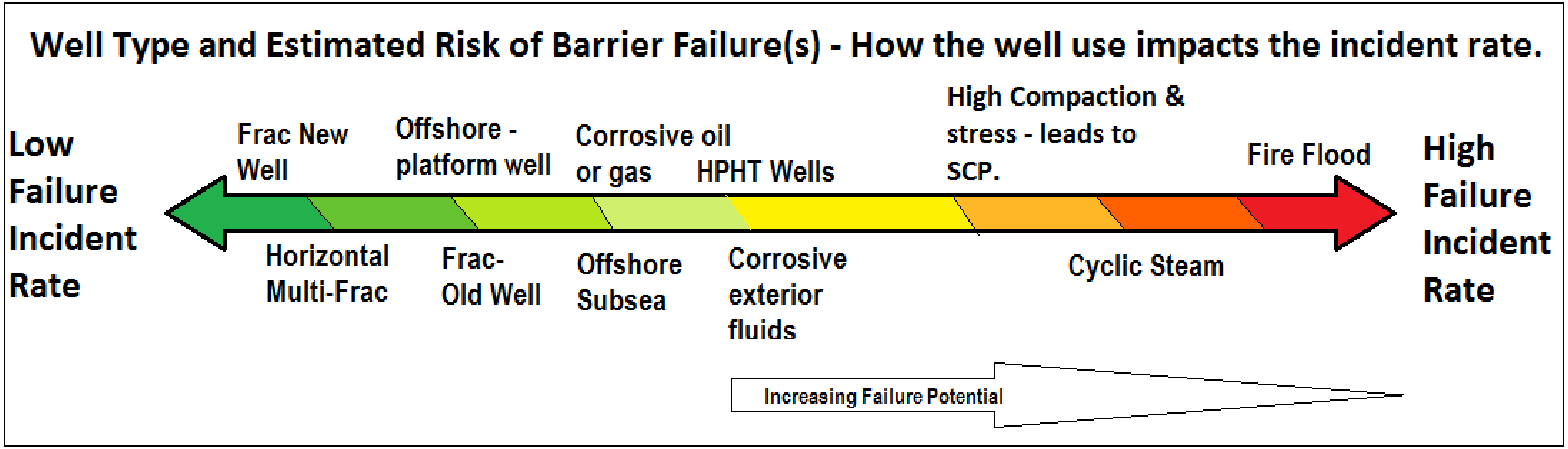
ZONE	Hazard to Ground Water If Well Integrity Is Lost	Typical Number of Barriers
Above Surface	Low	1 to 2
Fresh Water	Low to Moderate	2 to 4
Mid Depth	Very Low	1 to 2
Deep	Lowest	1



Well Types

- Vertical or Horizontal
- Oil
- Gas
- HPHT
- Injection
- Disposal
- Acid Gas and other corrosive producers
- Impact of repurposing a well type

Well Use Influence



Barrier type, Number and Construction Method Vary with Well Type.

Well Construction – well integrity is the thread that stitches these activities together.

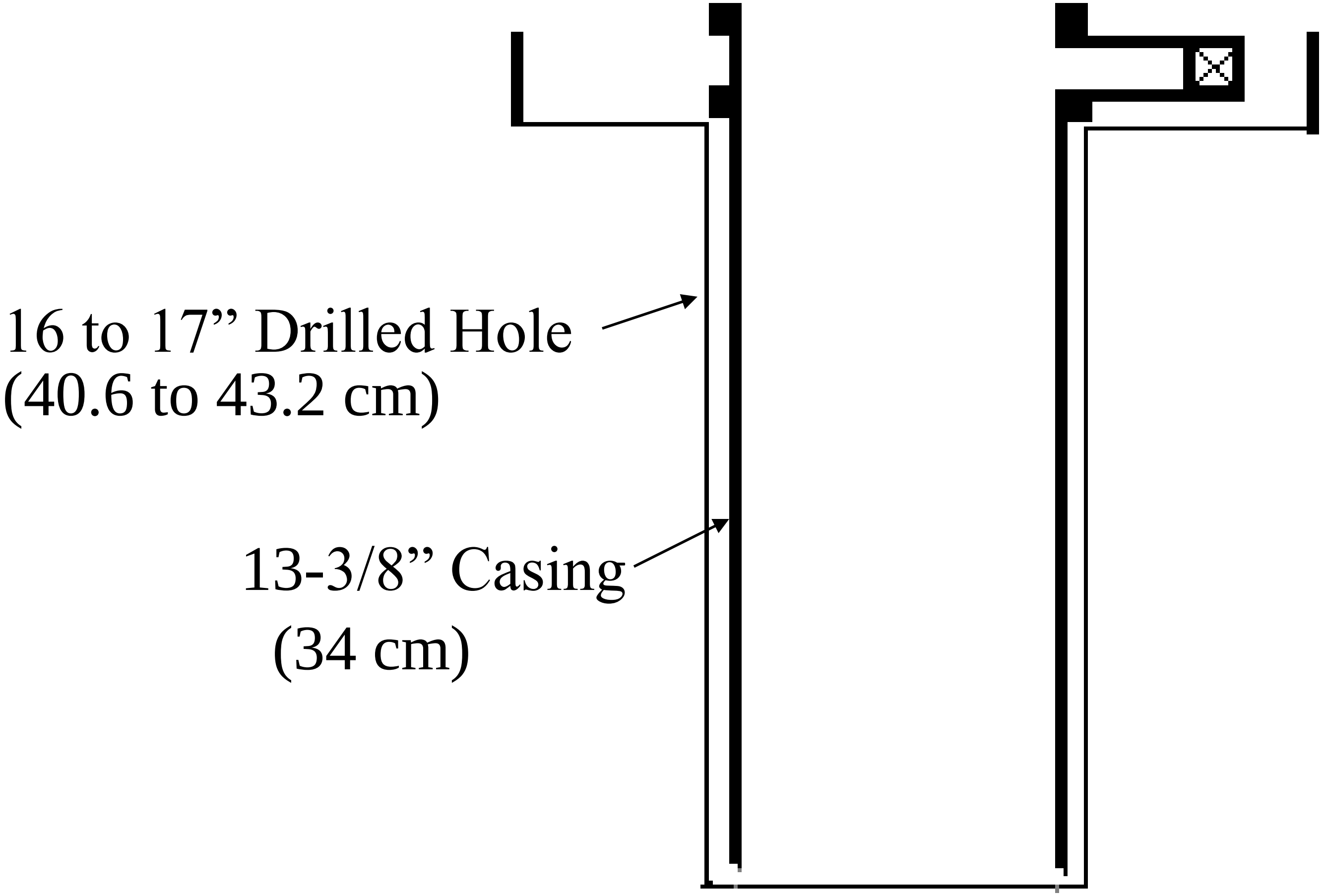
- Drilling
- Casing
- Cementing
- Downhole (DH) equipment
- Operations Outline
- Abandonment

To Begin – The Ideal Well…

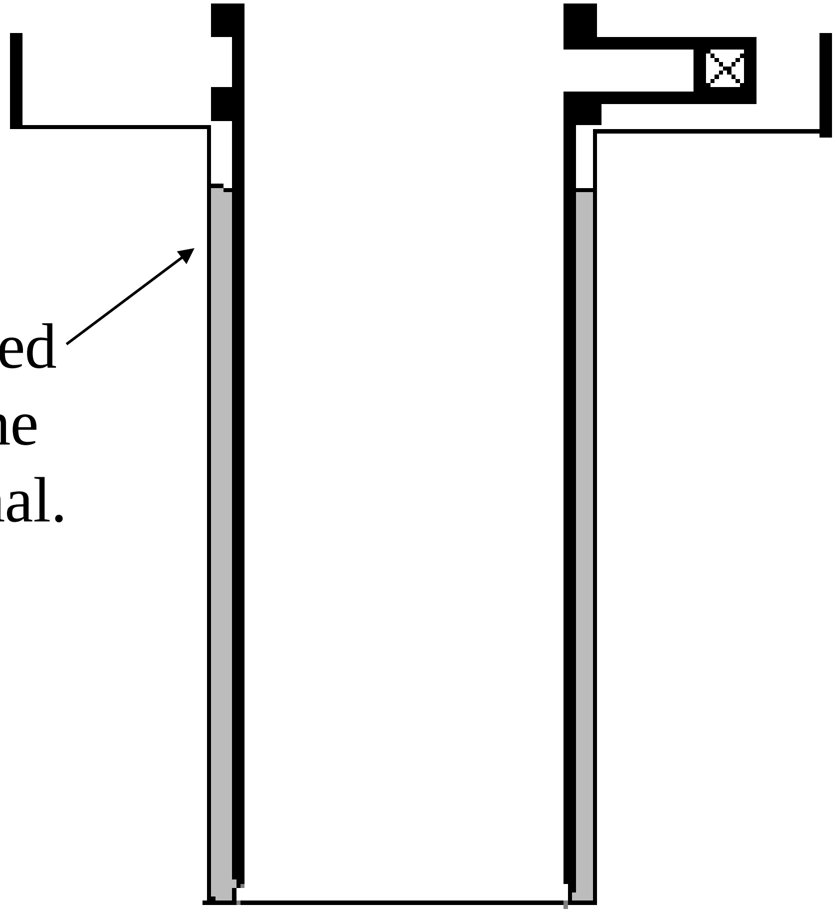
- Doesn't Exist.
- Why?

- All wells should be designed to meet the safety, environmental, and economic goals of a project whose purpose is to produce oil and gas from miles away.
- Mother Nature is anything but consistent.

Wells are drilled in stages with casing strings run and cemented to control formation pressures, to seal off unwanted fluids and to isolate sections of the formation.

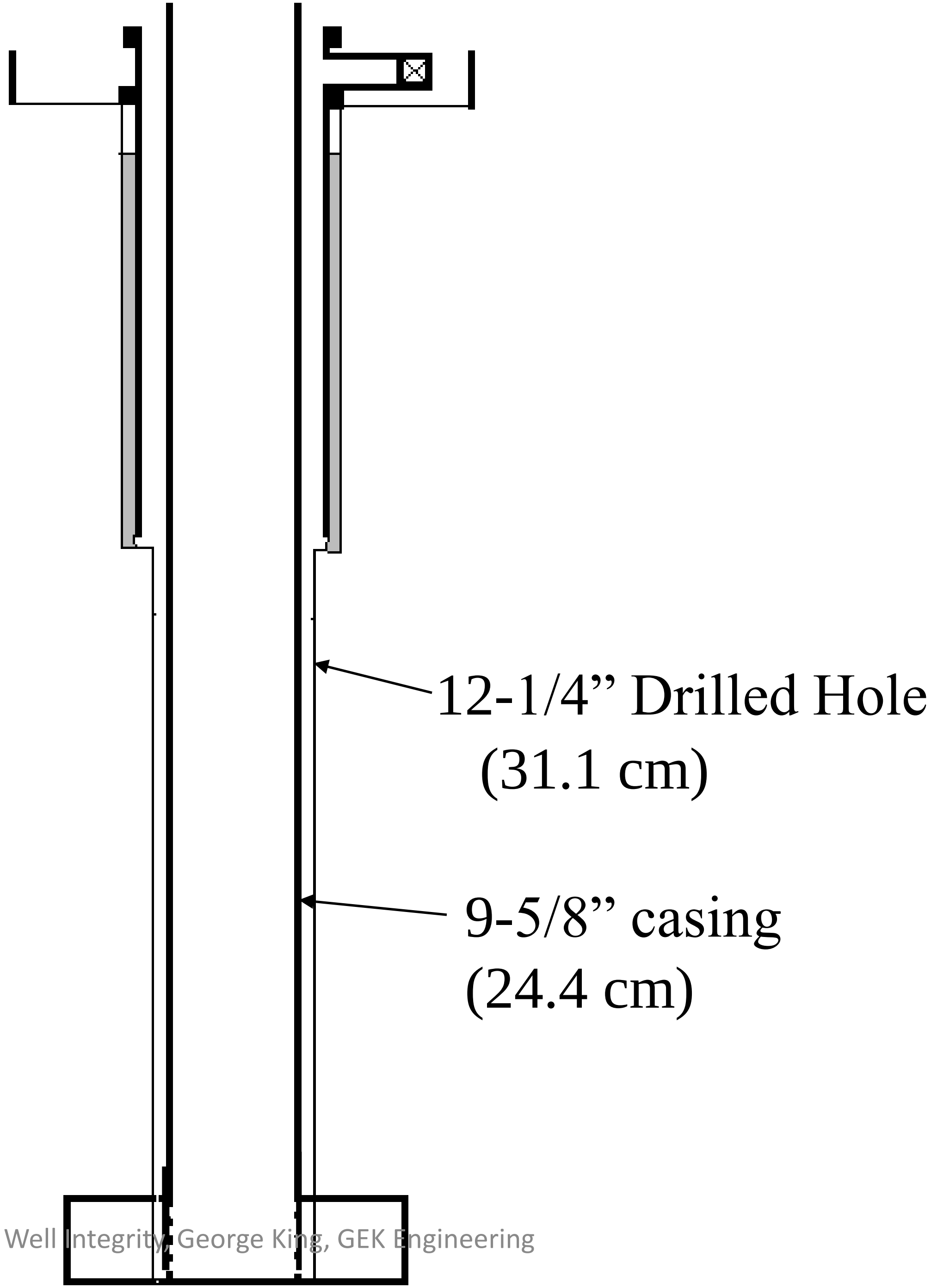


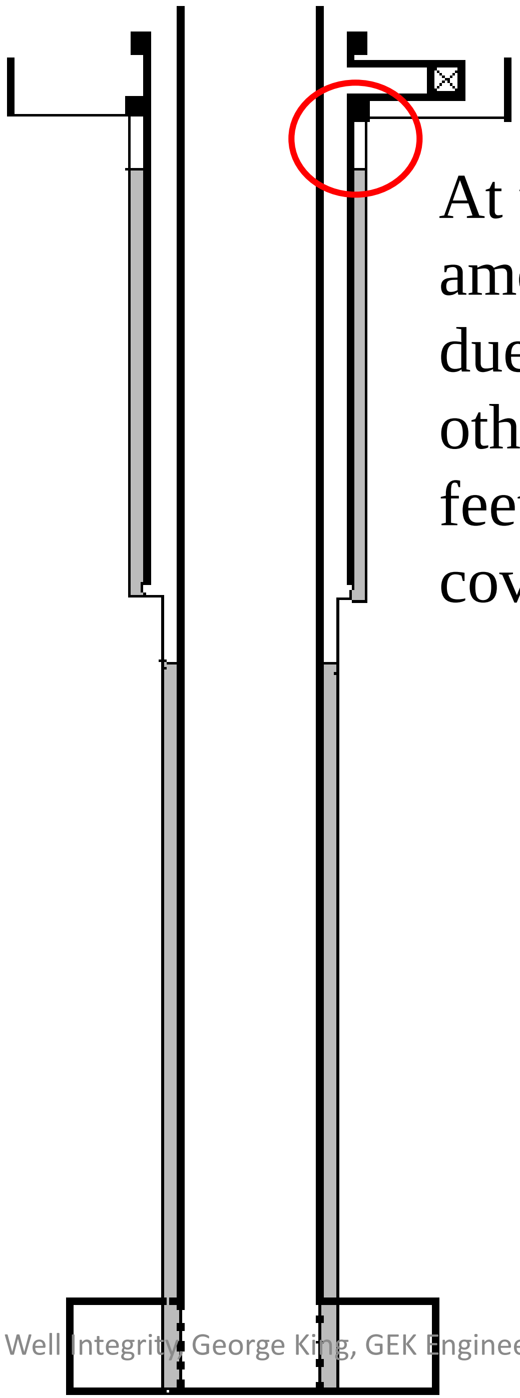
While the steel casing provides the initial strength, the cement provides the seal between zones. It also supports and protects the casing.



Cement circulated to surface – some fallback is normal.

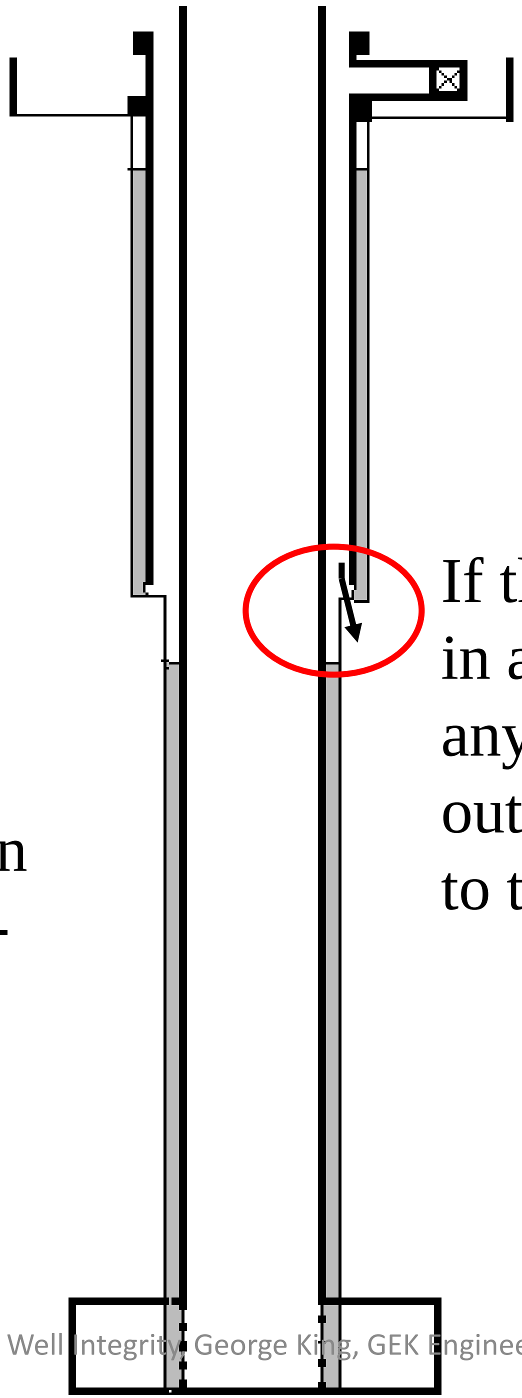
The deeper parts of the well are drilled and the deeper casing string (the production casing in this example) is run through the upper strings (the surface casing) after the upper casing is cemented and tested to the maximum pressures expected in drilling the lower sections.





At the surface the small amount of cement fallback due to gravity, leakoff and other factors may leave a few feet with poor cement coverage.

Regardless of intent – cement is never perfect. And – it only extends to ground level.

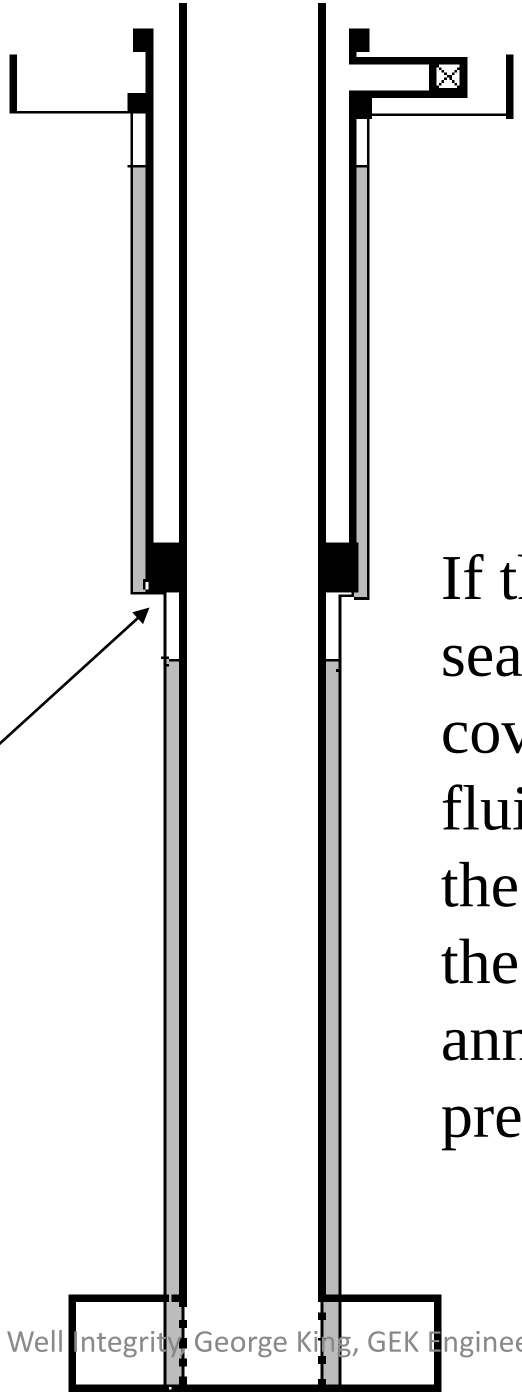


9-5/8" (24.4 cm) cemented, but open area left below 13-3/8" (34.0 cm) overlap.

If the uncemented section is in a permeable formation, any annular pressure in the outside annulus can bleed off to the formation.

Consequences of sealing the annulus at the bottom.

Packer or cement seal



If the open lap is cemented sealed with cement or covered with mud or other fluid loss control material, the ability is lost to bleed off the pressure and the outside annulus becomes a sealed pressure chamber.

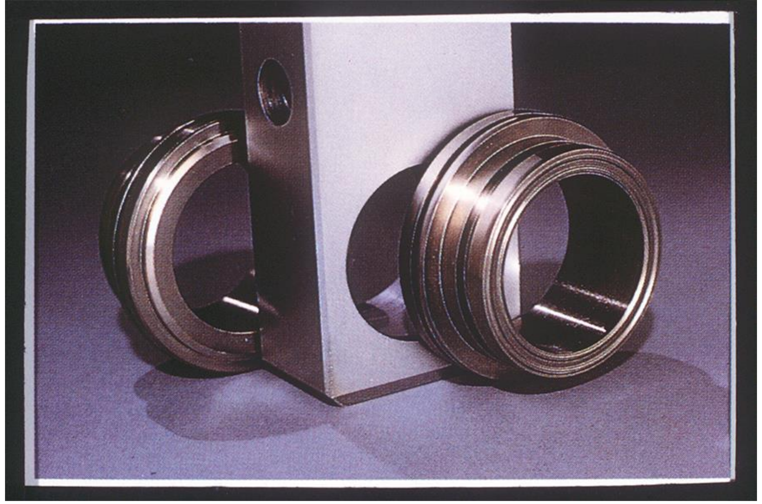
The Two Barrier Rule

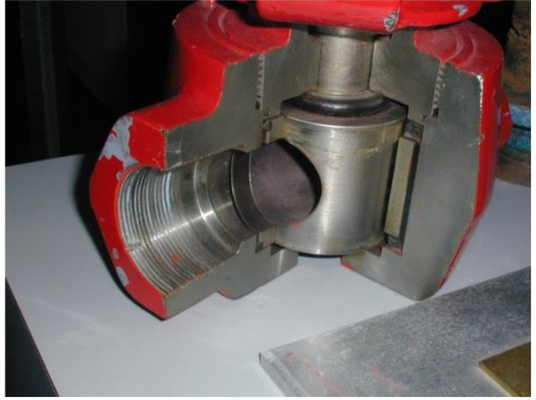
- Barriers may be the same in some instances.
- Both must be capable of controlling the full well pressure.
- Many barriers are conditional – may need back-up.

Wellhead Cutaway

Multiple barriers and methods of creating other barriers.

Valves

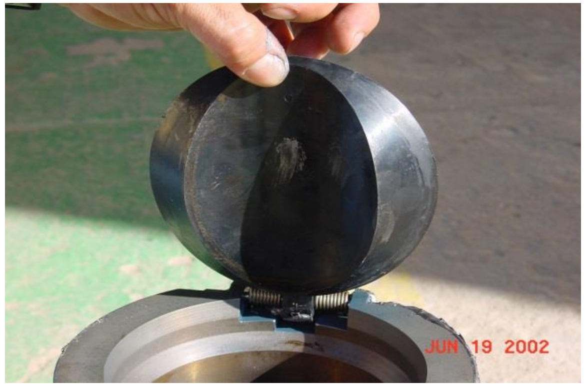




Above and Below: Gate valve seals and bar – common in wellheads.

If a valve requires greasing to pass a pressure test, does the maintenance schedule rigid?

Right top: plug valve – common in surface treating “iron”



Right center: dowhole flapper valve.

Right lower: butterfly valve common on tanks.

Note: open a valve fully (count the turns) and close it fully (also count turns) – throttling flow with a valve will lead to erosion.

Some Considerations on Horizontal Multi-Fractured Completion Methods

	Plug & Perf - Cemented	O.H. - Packer & Sleeve	Csg Sleeve - Cemented	CT Op. Sleeve-Cemented
Comparison Considerations	Less expensive, slower Unlimited stages Refrac easier Csg landing not critical Frac screenouts rare High entry pts /frac stage Csg-to-frac time short Frac points decided later High frac rate possible Cleanout easy (w/ CT) Prop placement ? Gauge hole not critical	Higher cost, faster Stage # usually limited Refrac more difficult Landing depth critical Screenouts less rare Low entry pt/frac stage Packer set days to weeks Frac points dtm csg set pt. Frac rates limited Cleanout difficult Prop placement controlled Gauge hole critical	Moderate cost, faster Stage # limit w/o PNP Refrac easier (PNP) Landing depth critical Screenouts less rare Low entry pt/frac stage Csg-to-frac time short Frac points dtm csg set pt. High frac rate possible Cleanout easy (W/CT) Prop placement better Gauge hole not critical	Higher cost, mod. speed Stage # limit w/o PNP Refrac easier (PNP) Landing depth critical Screeouts more common One entry pt / frac stage Csg-to-frac time short Frac points dtm csg set pt. Frac rate limit per stage Cleanout circ. (CT in place) Prop placement best Gauge hole not critical
Advantage	Most common horizontal multi-frac completion in U.S. Offers high degree of reliability at low cost.	Offers near-continuous fracturing. Ball drop systems most common HMF in Canada	Offers speed of ball drop systems, with higher rate and refrac potential.	Best placement of proppant. Offers closable frac sleeves.
Disadvantage	Multiple entry points, but cannot control prop placement.	Higher cost. Gauge hole required. Landing position critical. Isolation is packer seal dependent.	Higher cost. Critical to get sleeves positioned at frac points.	Higher cost for CT. Critical to get sleeves position at frac points.

Potential For Pollution is Reduced by Application of Technology. We learn from our failures…………

Time Era	Operation Norms - Level of Technology	Era Potential For Pollution
1830 to 1916	Cable Tool drilling, no cement, wells vented	High
1916 to 1970	Cementing isolation steadily improving.	Moderate
1930's	Rotary drilling replace cable tool, BOPs	Moderate & Lower
1952	Fracs reduce # wells. Better pipe & cement	Lower from Frac aspects
1960	Gas tight couplings and joint make up	Moderate
1970	Cement improving, Horizontal Wells introduced	Lower
1988	Multi-frac, horizontal wells, pad drilling reducing environmental land footprint 90%	Lower
2005	Well integrity assessment, premium couplings, adding barriers & cementing full strings.	Lower after 2008 to 2010 (STRONGER Reg Review)
2008	Chemical toxicity & endocrine disruptors sharply reduced. Real time well integrity needs studied - early warning & avoidance.	Lowest yet, most states caught up with design and inspection requirements.

Cement was first used to isolate wells in 1903. Over 100,000 wells drilled before 1903, most in Northeast US.

What is the value of technology?

Comparison to the Airlines
Causes of Fatal Air Crashes (%) by Decade
Why did weather crashes drop over time?

Cause	1950's	1960's	1970's	1980's	1990's	2000's
Total Pilot Error	57%	56%	43%	46%	51%	54%
Other Human Error	2%	9%	9%	6%	9%	5%
Weather	16%	9%	9%	6%	9%	5%
Mechanical Failure	21%	19%	20%	20%	18%	24%
Sabotage	5%	5%	13%	13%	11%	9%
Other Cause	0	2%	1%	1%	1%	0

Why?

- Weather crashes decline because measurement and prediction methods improved.
- The culture of inspection and maintenance is also important:
  Odds of being killed on a single scheduled airline flight:
  - 1 in 29 million for the top 30 airlines,
  - 1 in 1.7 million for the 25 worst airlines;

So, <u>some operators just do a much better job</u>

One indicator of a Culture of Maintenance is production performance => minimum breakdowns, minimum spills, short cycle time to return to production, safe operation performance, and well-trained people .

Metrics, Alarms, Failures & Improvements

- Key Performance Indicators or KPI’s – a quick view......
- Star ★ - areas of importance for inspection
- “Red Flags” – early signs that something is amiss.
- Risk - always present – how to manage it.
- Failure tolerance - ? – why it is needed.

LINK INSPECTION & KPI'S TO FAILURE CAUSES

General Well & Integrity Failure Causes & Estimated Qualitative Failure Frequency by Well Types				
Well Type	Typical Failure	Common Cause	Failure Rank Expected	Mitigation Methods
Fireflood	Pipe burn-off, collapse, breaks, severe corrosion	Extremely hot gasses	High rate of pipe failure but low incidence of fire flood use.	Few
Steam Flood	Connection failure, cement bond failure	Pipe expansion and coupling load cycling	High rate of failure but only localized steam flood use	Designs that allow for cyclic expansion and contraction.
HPHT (high Press & Temp)	High pressure related pipe failures	Collapse & burst common, erosion failures possible	Moderate to low	HPHT design philosophy, controlled drawdown, fit-for-purpose equipment
High Compaction Stress	Pipe collapse and shear failure	Subsidence, formation flow (salt)	Moderate in a few geographical locations, rare overall.	Very heavy wall pipe, concentric strings with cement fill.
Producer in Corrosive Environments	Interior or exterior corrosion	O_2 leaks, CO_2, H_2S, Low pH waters, MIC, microbial induced corrosion hydrogen embrittlement	Moderate - Depends on maintenance – can be the most common damage in industry & and most expensive	Eliminate O_2 entry, Corrosion resistant alloys (CRA), corrosion inhibitors – problems sharply reduced with regular maintenance
High Pressure Injection (disposal and re-injection wells)	Leaks & corrosion, some seismic disturbance potential	Thread leaks, Continuous HP operation & large flow volumes of saline water	Low - Small saltwater leaks. Seismic noted in about 0.01% of UIC Class II wells	Lower if wells properly designed, sighted & operated. Routine pressure testing required.
Fracturing Old Well	Pipe burst or collapse	Low side corrosion in casing, loss of pipe strength, seep leaks	Moderate risk but infrequent fracturing of old wells lowers threat potential.	Pressure testing required and drift test recommended before running tools or equipment.
Fracturing New Well	Pipe burst or fracture height growth.	Short duration pressure surge	Very low risk. Frequency of burst failures in new pipe at/or below rated pressure about 0.0005%	Pipe and coupling inspection, adequate cement fill and limit max surface pressure.
Producing Wells	Leaks & Corrosion	Well pressure drops steadily in producing wells due to depletion and thus the risk is low.	Very low risk	Wider use of gas-tight threaded connections and metal-to-metal would lower risks further

Quality and Inspections…….

Two Quotes to Remember:

- “Inspection does not improve the quality, nor guarantee quality. Inspection is too late. The quality, good or bad, is already in the product. As Harold F. Dodge said, “You can not inspect quality into a product.” - W. Edwards Deeming

- Quality Is not an act, it is a habit. - Aristotle

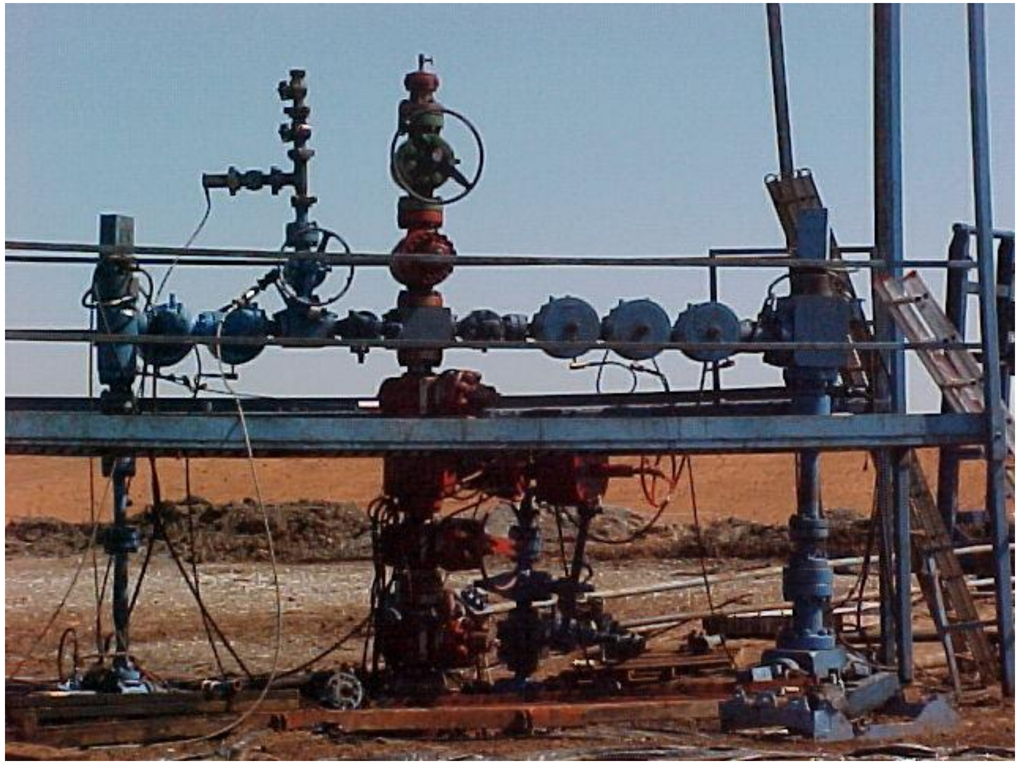
Visual Inspections

- You see less than 1% of the well from surface.

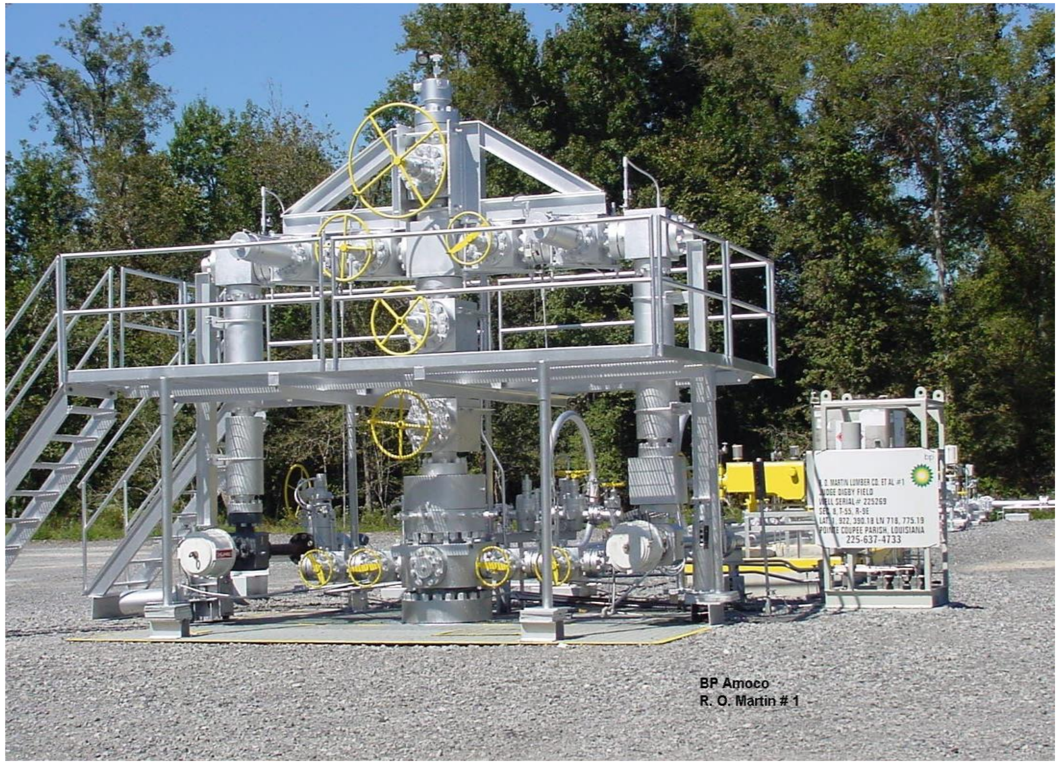
- What you can see can suggest a lot about the 99% you cannot see.

- But, to confirm it requires testing……..

Do not go just by appearances……



OR



Both were good, solid wells.

Can we afford to fail?

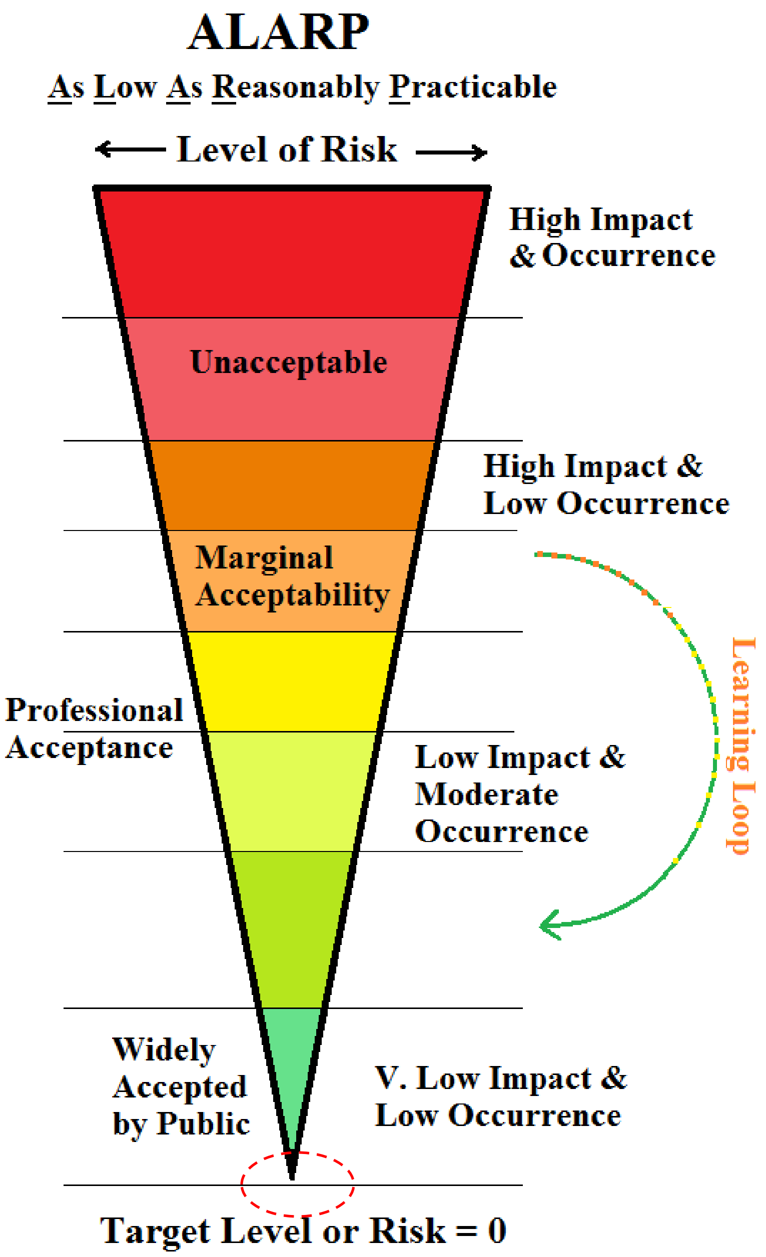
> "Failure is central to engineering. Every single calculation that an engineer makes is a failure calculation. Successful engineering is all about understanding how things break or fail"
>
> – Henry Petroski

Risk = Frequency of Occurrence vs. Impact

Risk exists in every action.

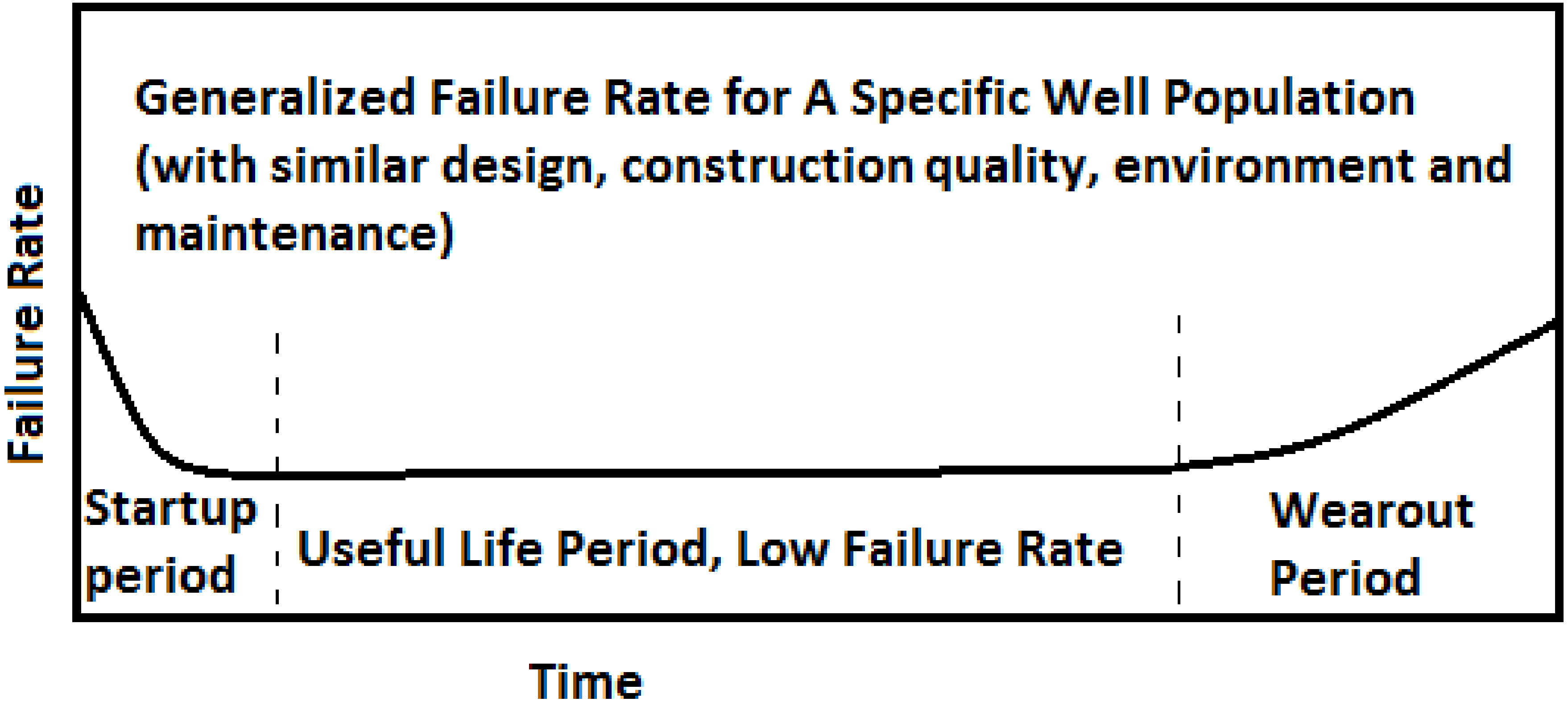
What is operationally safe?

Occurrence & impact create a threat level that we can understand & accept or reject based on what we believe: hopefully on assessment of facts.



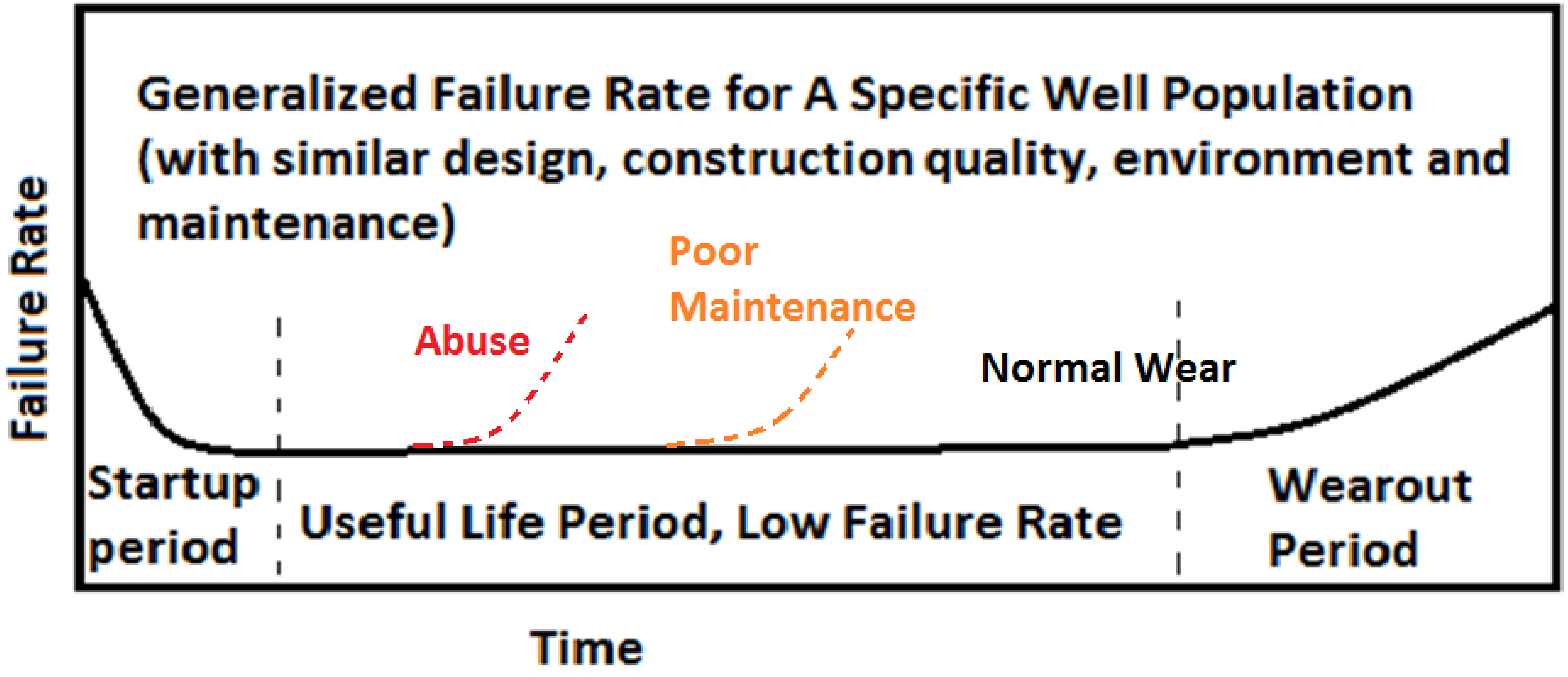
SPE 166142, Barrier vs. Well Failure, King

The Element of Time – always a factor. When does the warranty run out…..?



Curves such as this describe continuous load / constant use assumptions.

But all operators are not the same.



The difference that a Culture of Maintenance can make is staggering.

What is a Culture of Maintenance?

- Maintenance - the set of actions that minimize deterioration of an asset, and, in some cases, the infrastructure of a development.
- Maintenance extends an asset’s working life, ensuring that it can continue to operate to a design level.
- Culture is acceptance of the need to exercise the required maintenance. It must be firmly rooted in the business plan of the company.

Failures in Age and Era

- Era of construction, the type of well, the location and the practices of that era are often more important than just age.
- The target of exploration is another factor
  - HPHT Wells,
  - Coal bed methane,
  - Tight Gas,
  - Sand Control wells,
  - Deep Water,
  - Shales.

For every new oil and gas source, the technology of well construction and stimulation must be adapted to fit the specifics of the formation.

Era of Construction – Technology in Practice

Pollution potential & risk are functions of technology & maintenance in practice <u>over</u> time.

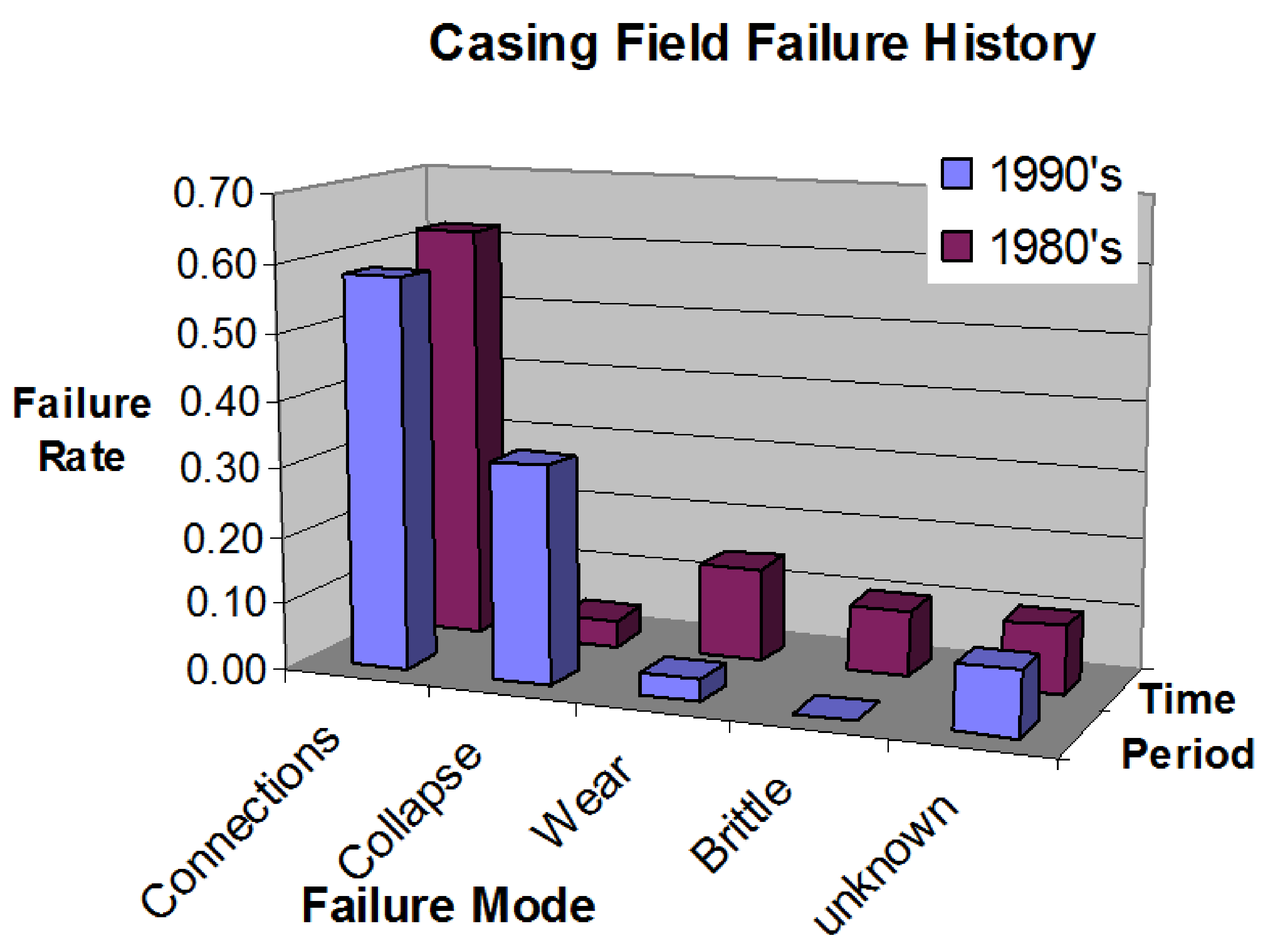
=> Old well behavior doesn't necessarily describe new well behavior.

1905 **vs.** **2015**

9 hp., 25 mph and every practical safety device known to man in 1905.

640 hp., 200 mph and every practical safety device known to man in 2015.

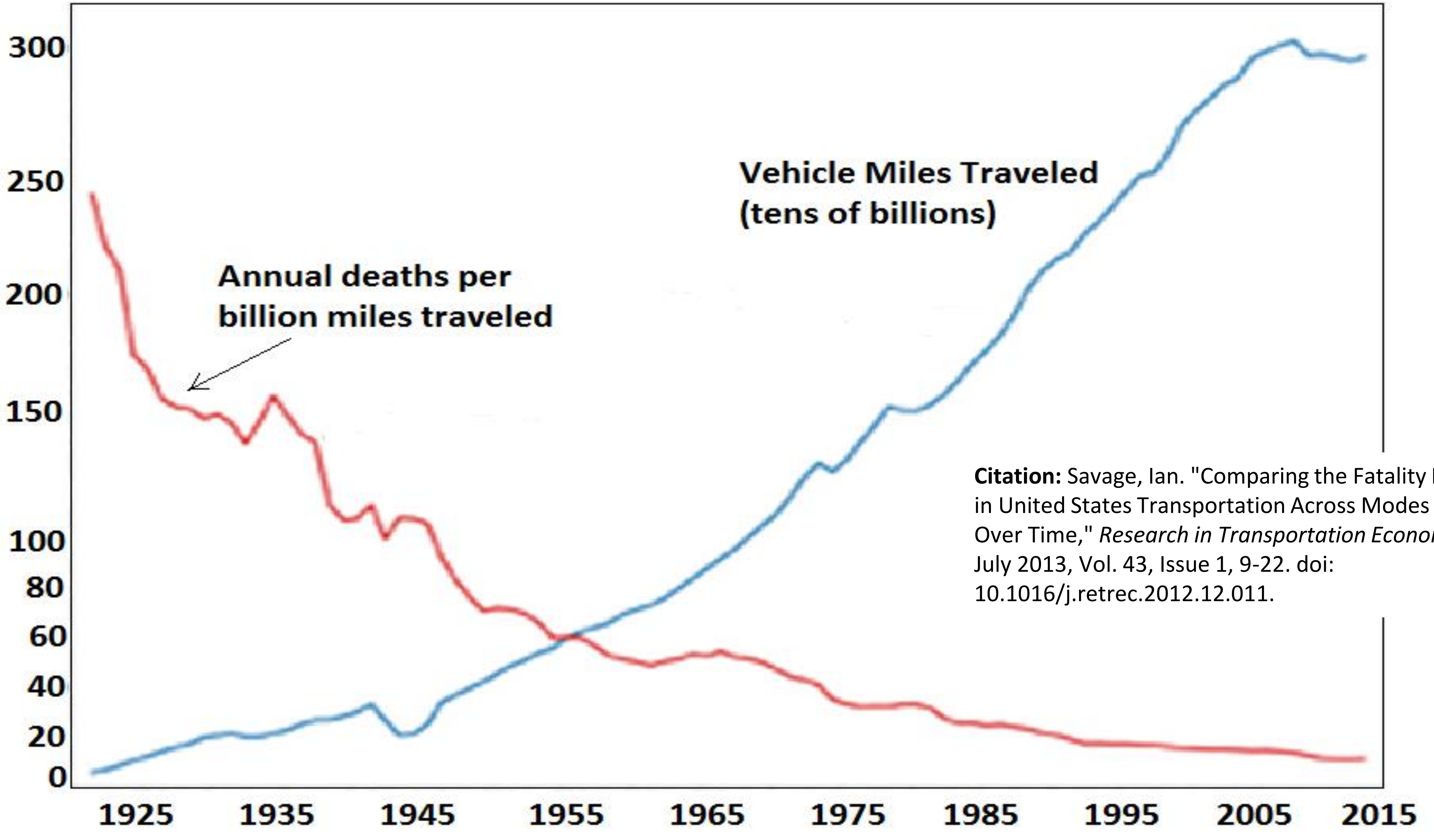
Example Failures in an Era - Casing



Bian Schwind, PPI

The increase in casing collapses in 1990’s, is probably due to increased drilling, more deep drilling, and more deep-water operations.

Cars (and drivers?) getting safer.

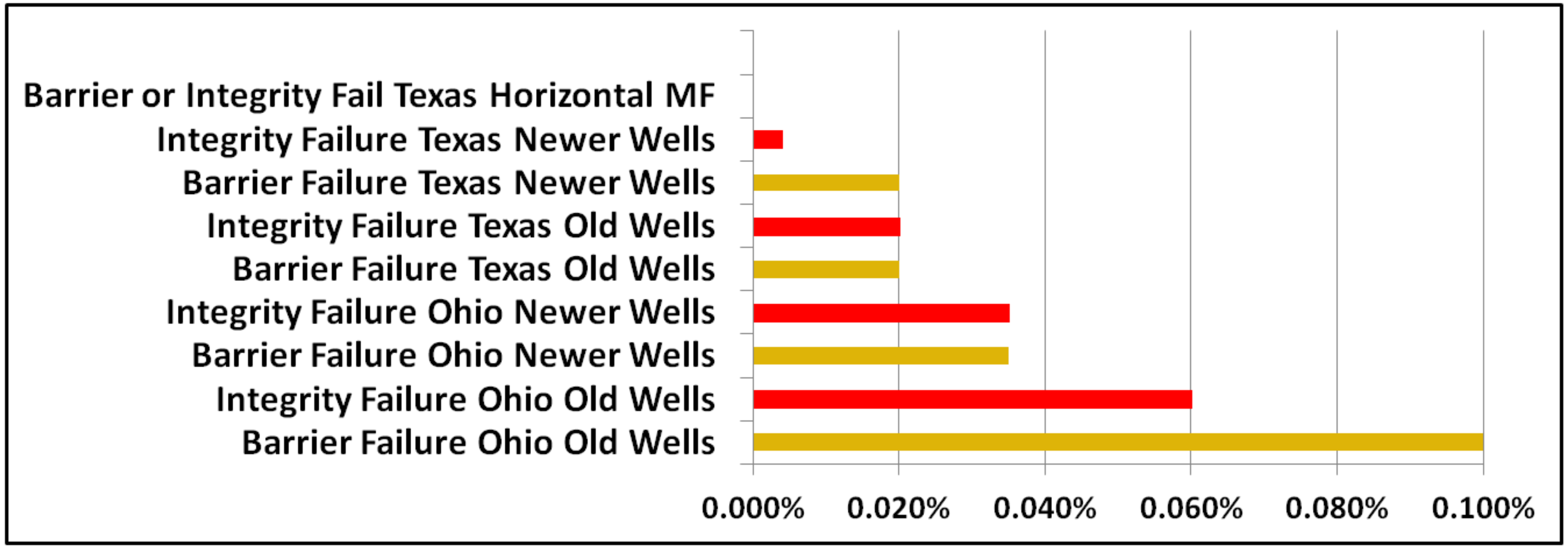


Citation: Savage, Ian. "Comparing the Fatality Risks in United States Transportation Across Modes and Over Time," *Research in Transportation Economics*, July 2013, Vol. 43, Issue 1, 9-22. doi: 10.1016/j.retrec.2012.12.011.

Do Oil & Gas Wells Leak?

- Although it is a common accusation, the great majority of wells do not leak.
- If enough protection barriers fail, a most common subsurface leak type is for liquids (overwhelmingly salt water) to leak into the well.
- There are sharp differences between a barrier failure in a multiple barrier well design and an outright well integrity failure that could lead to pollution of water or air.

Barrier and Integrity Failures Study from a population of 330,000 US wells



Kell, S. 2012. State Oil and Gas Agency Groundwater Investigations and Their Role in Advancing Regulatory Reforms, A Two State Review: Ohio and Texas. Ground Water Protection Council, Oklahoma City, Oklahoma (August 2011), http://fracfocus.org/sites/default/files/publications/state_oil__gas_agency_groundwater_investigations_optimized. pdf.

Things That Keep actual Well Integrity Failures Very Low

1. Pressure inside the wells is lower than outside in hydrostatic of water table.
2. Modern wells are built with multiple barriers.
3. Cement reinforces and protects the casing.
4. Regulations are tighter now than a few years ago.
5. Multi-Fractured horizontal wells replace 5 to 10 vertical wells in many developments. Less pollution potential with fewer water table penetrations.

Older well data often skewed by lack of barrier & integrity differentiation.

What Proves it? – rankings of proven groundwater pollutants.

Proven Another Way - % of Produced Fluids Leaked

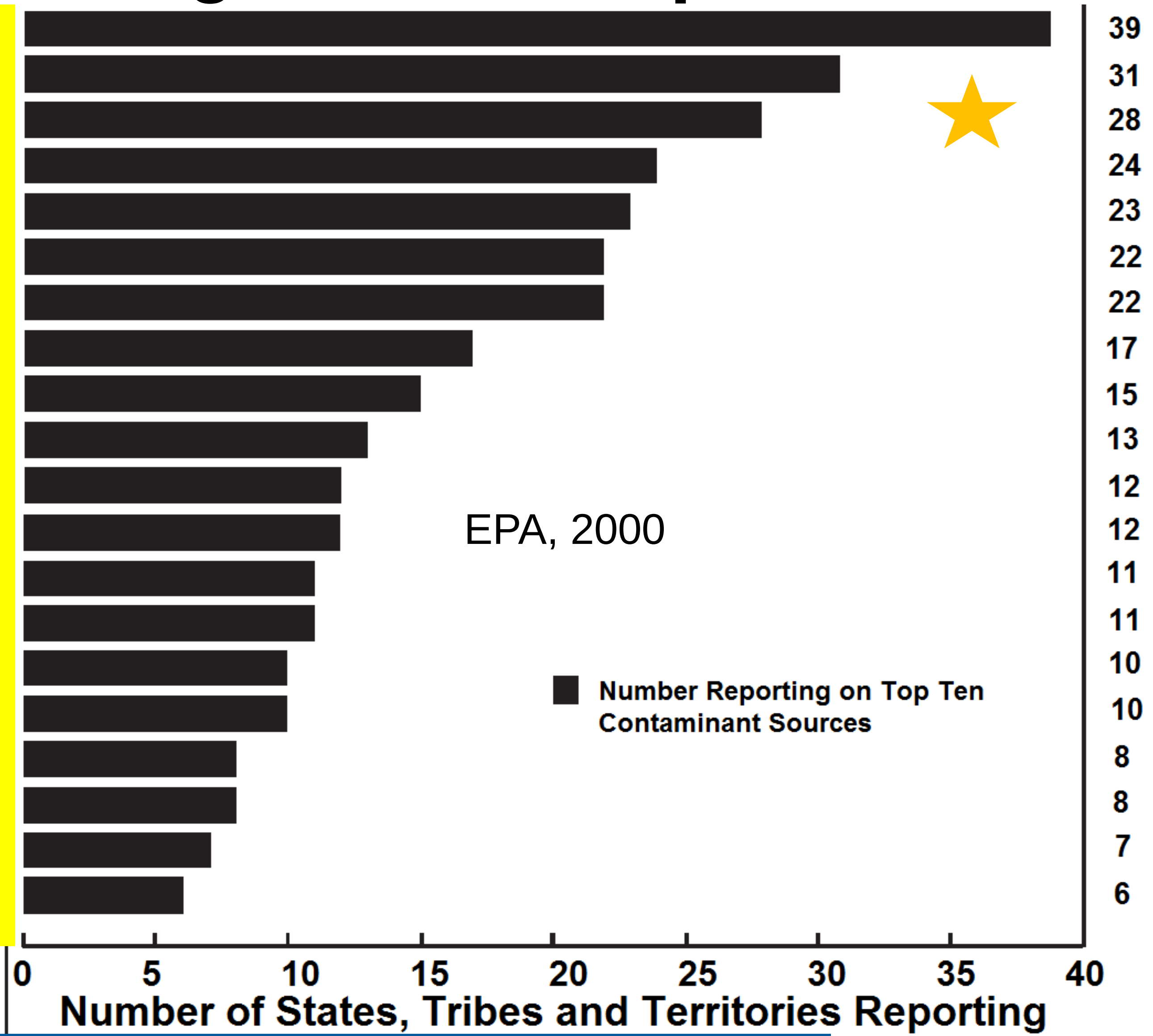
Area	Number of Wells	Type of Wells	Barrier Failure Freq. Range (w/ containment)	Integrity Failure (leak path – in or out)
US Gulf of Mexico	11,498 (3542 active	Platform based wells	30% overall first annulus SCP 50% of cases. 90% of strings w/ SCP have less than 1000 psi. 10% are more serious form of SCP (Wojtanowicz, 2012)	0.01% to 0.05% of wells leaked ---------- 0.00005% to 0.0003% of prod oil spilled 1980 thru 2009.
US Gulf of Mexico	4,099	Shoe test failures required repair	12% to 18% require cement repair to continue drilling	0 (all repaired before resuming drilling)
Norway	406	offshore	18%	0
GOM /Trinidad	2,120	Sand Control	0.5 to 1%	0% subterranean ~0.0001% via surface erosion potential
Matagorda Island 623	17	Compaction failures; casing shear & sand fail	80% to 100% - the high number is due to high pressure and formation compaction.	Wells routinely shut-in and repaired prior to restart.
Sumatera	175	without maintenance	43%	1 to 4%

SPE 166142, Barrier vs. Well Failure, King

What are some more common groundwater pollutants?

Underground storage tanks (UST) in neighborhood filling stations and convenience stores were made of steel until the mid 1980s. These shallow buried steel tanks corroded in groundwater and are one of the most common sources of pollution.

UST – Gas & Diesel
Septic Systems
Landfills
Spills
Fertilizer
Large Industrial Facilities
Hazardous Waste Sites
Animal Feedlots
Pesticides
Surface Impoundments
Storage Tanks – surface
Urban Runoff
Salt Water Intrusion
Mine Drainage
Agriculture Chem. Facilities
Pipelines & Sewer
Shallow Inj. Wells (Class V)
Salt Storage & Road Salting
Land application of Waste
Irrigation Practices



Oil and Gas Wells Didn't Make the List.

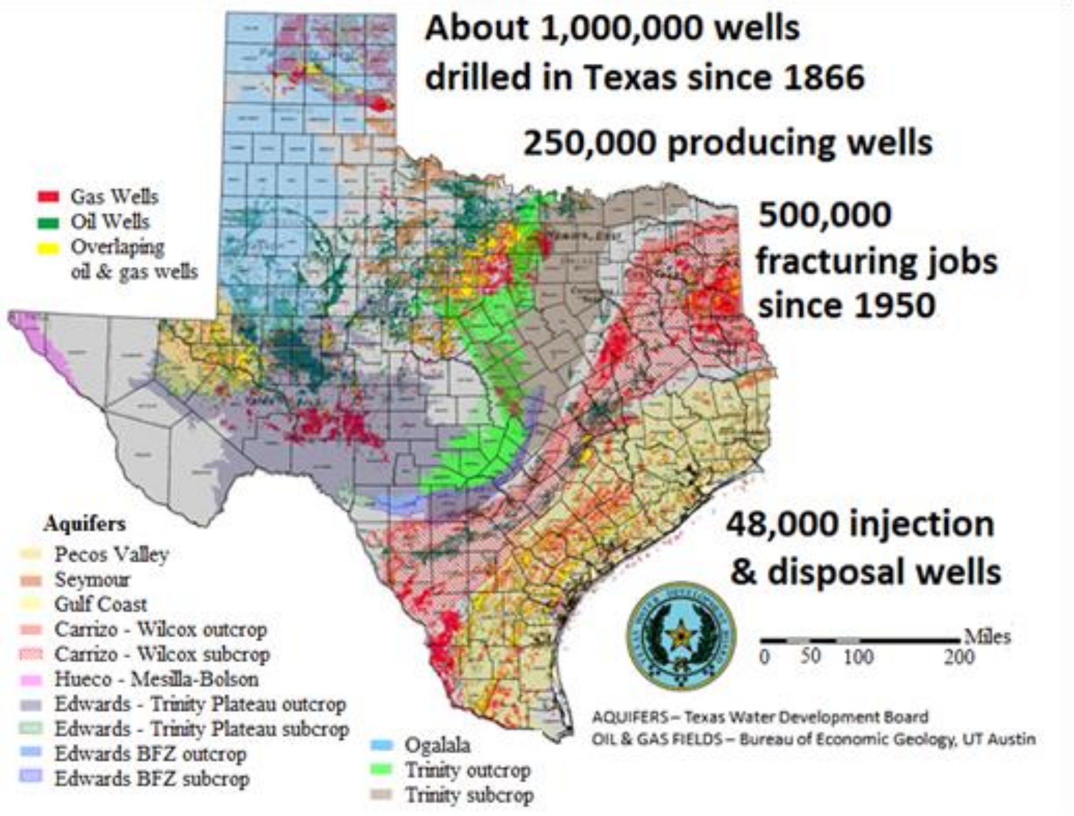
What are Groundwater Pollutants Today & Where do Oil & Gas Wells Rank?

Used Texas as a Study Case.

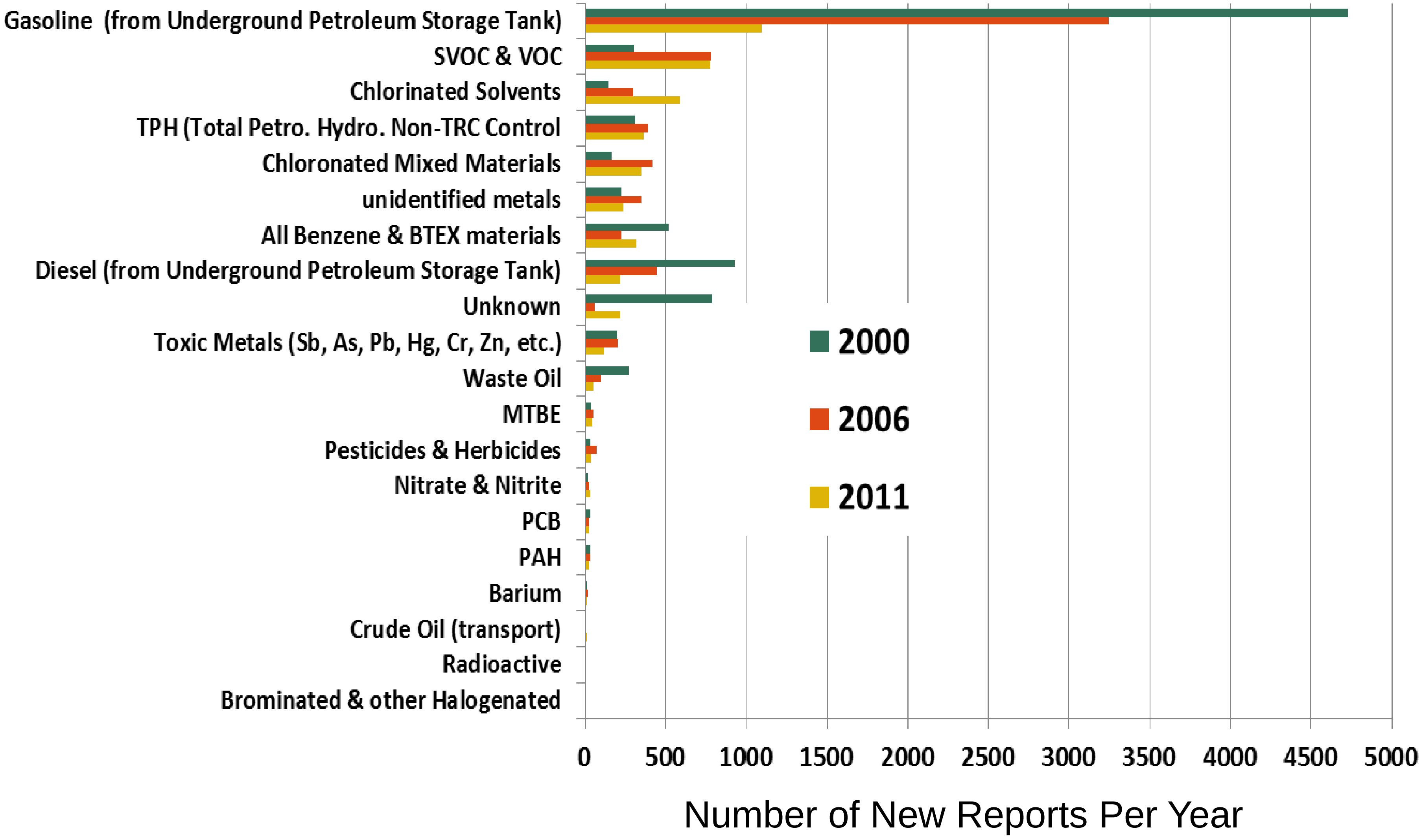
Over a million penetrations through the 29 major & minor aquifers in Texas.

Texas is #2 in total Groundwater withdrawals with ~ 80% going to Agriculture & Municipalities.

If the water was really polluted by O&G wells, we'd see it quickly in Municipal & Ag.

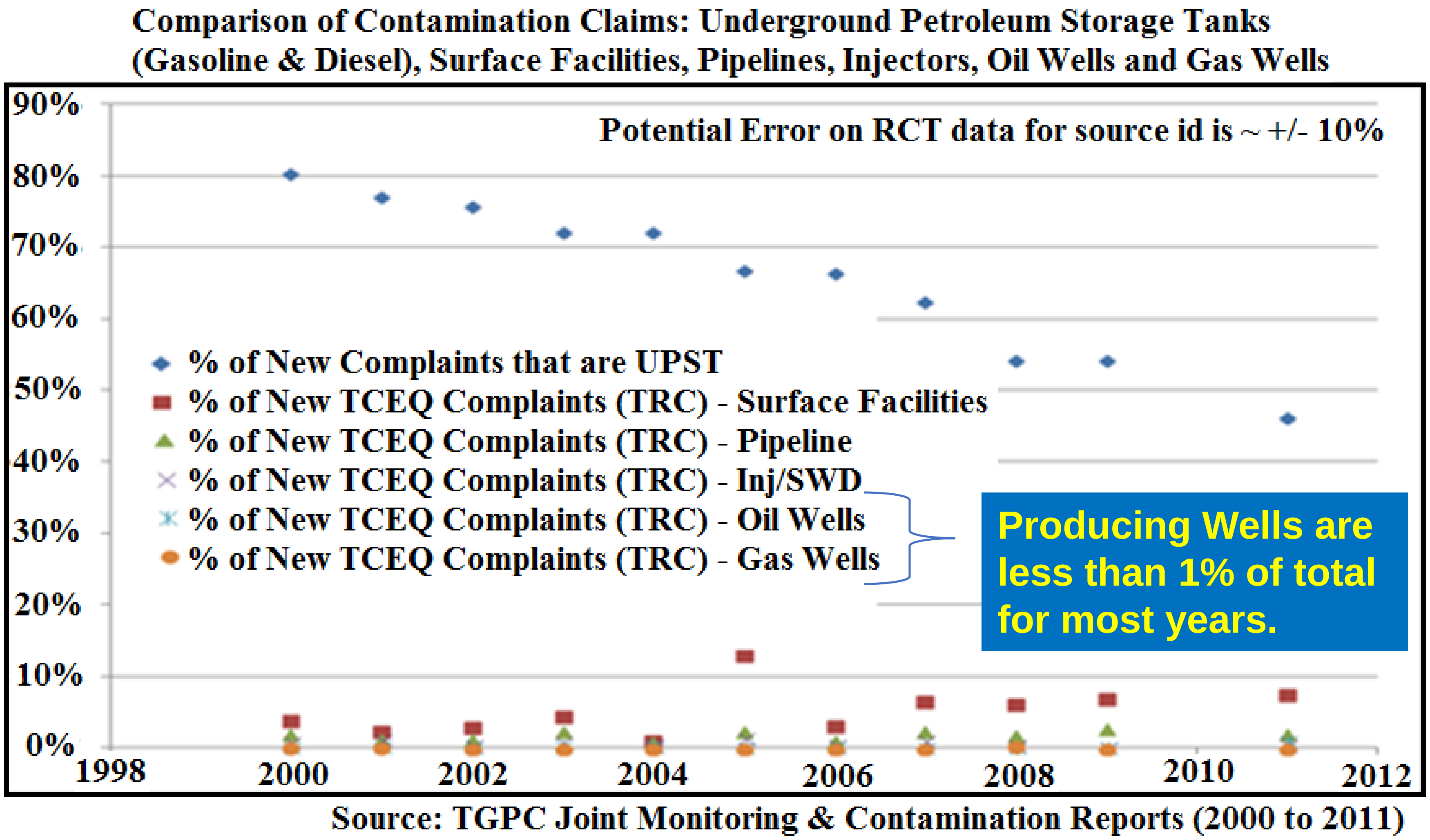


Last 12 years of Pollution Reports in Texas – Top 20 Listed - TCEQ & TGPC Database

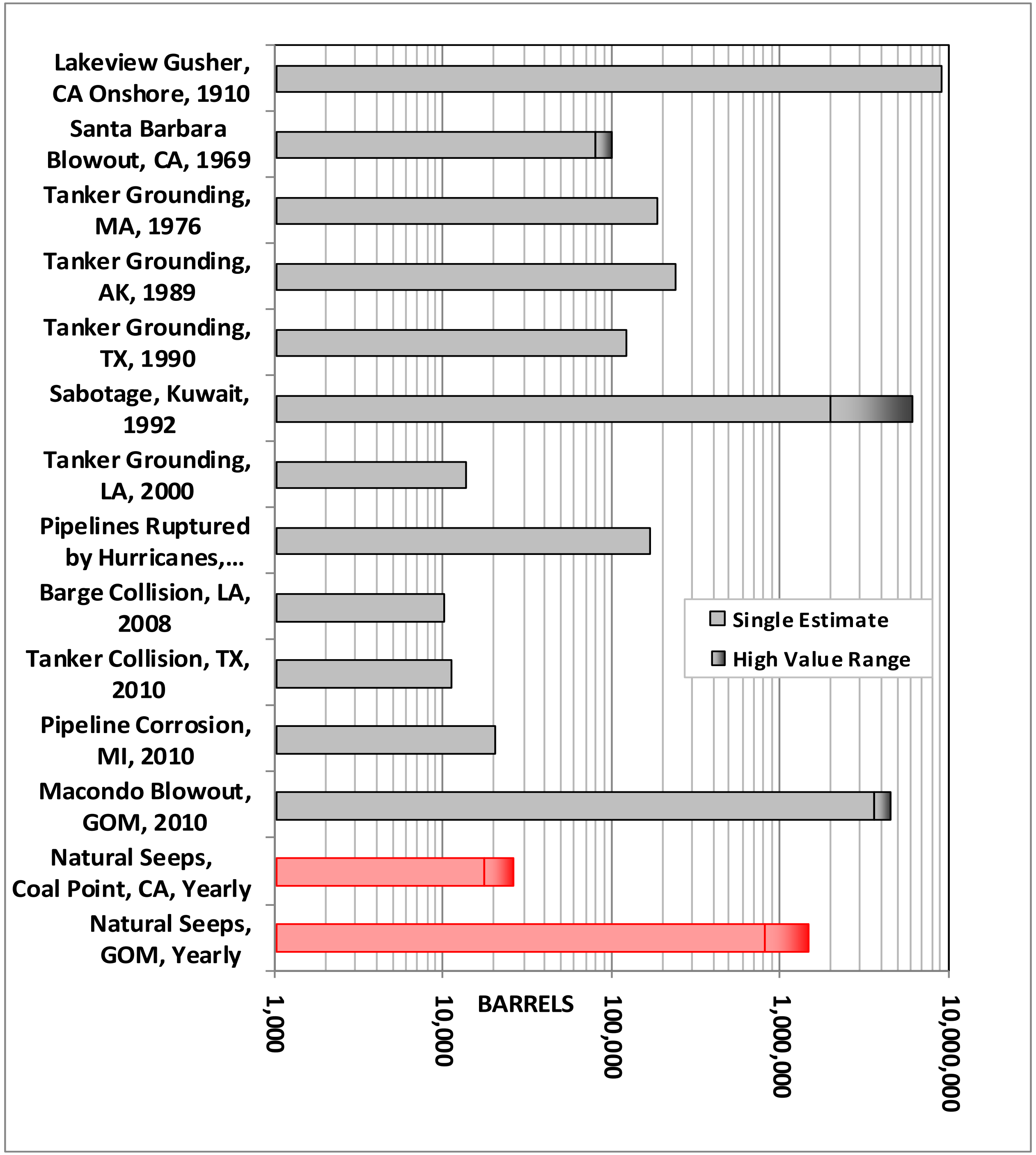


SPE 166142, Barrier vs. Well Failure, King

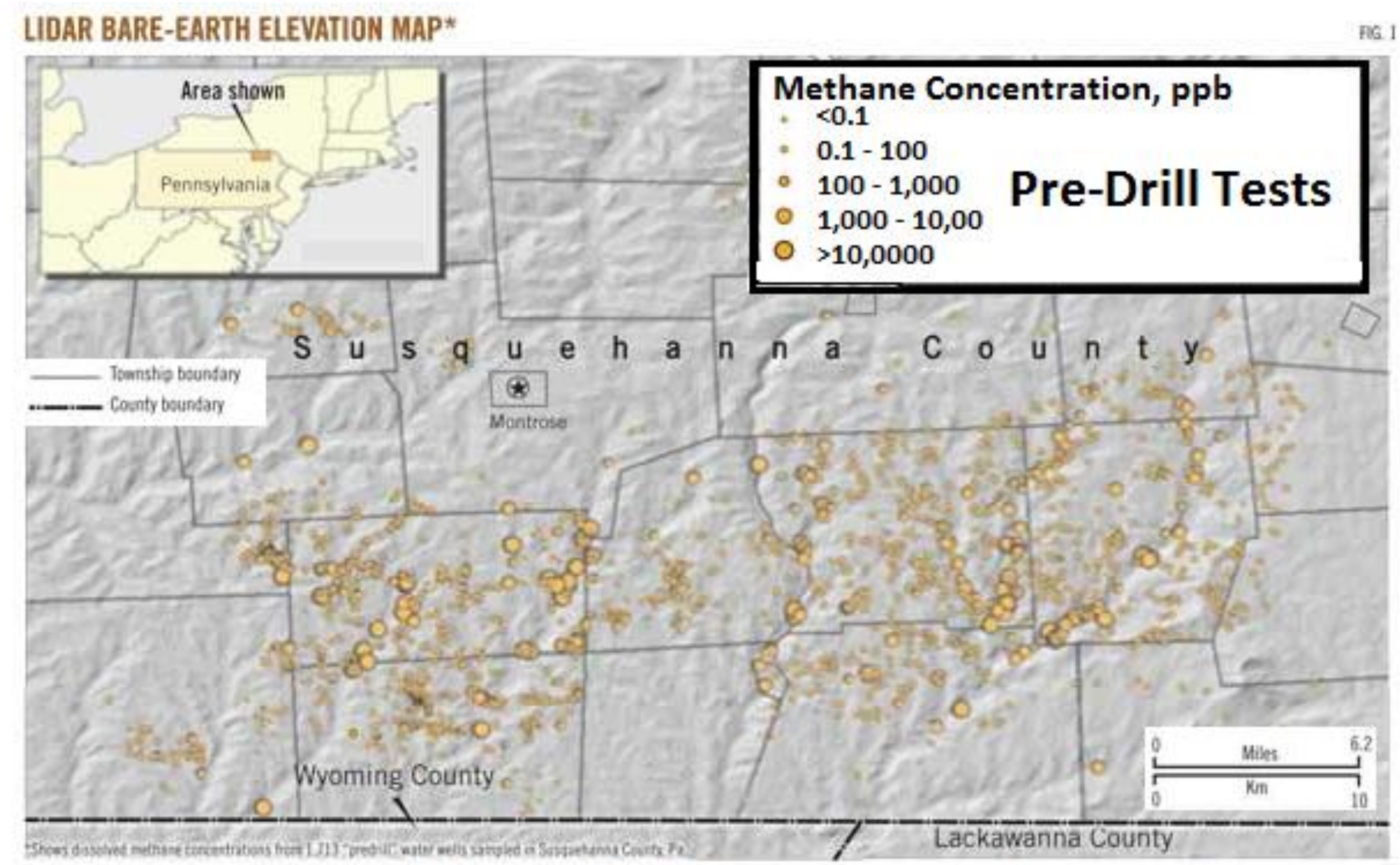
Allocation of Texas TCEQ Pollution Claim Frequency



Comparing Spills and Seeps



Various sources – data in SPE 166142



Pre-Drill water well sampling & background survey show methane to be nearly ubiquitous in water wells in this region - over 78% of water wells exhibit detectable methane.

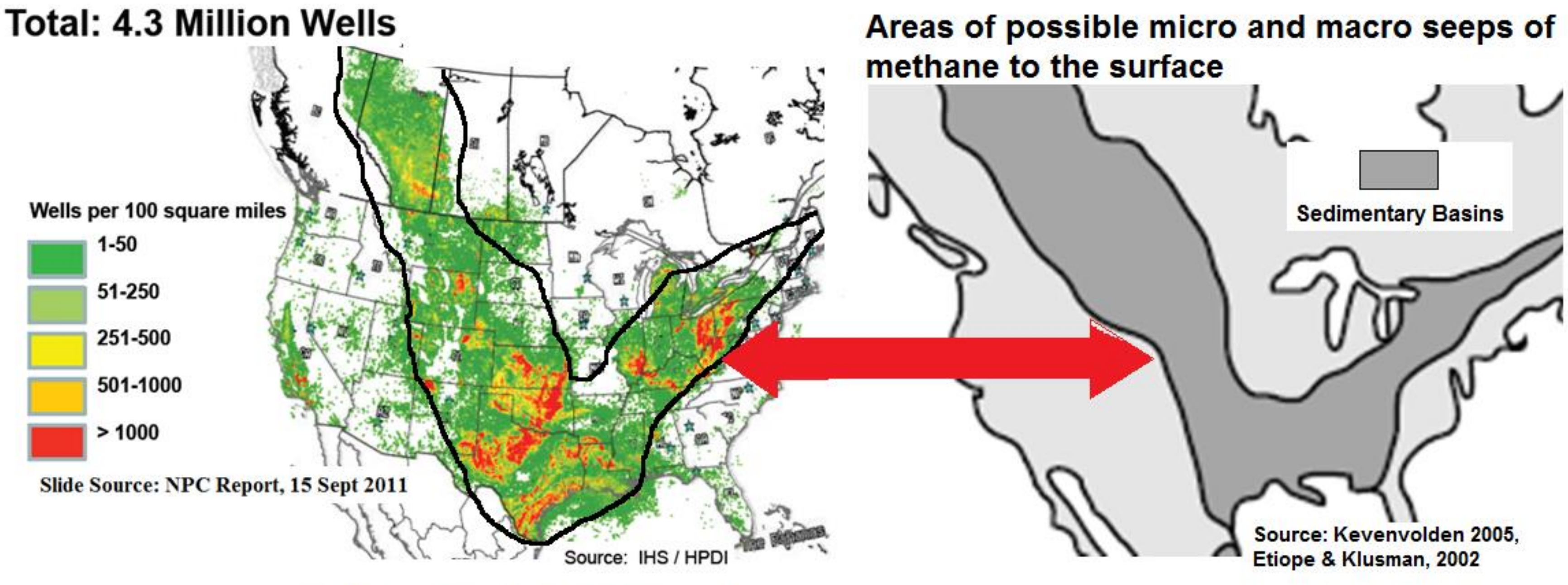
1700 well study.

Source: **Lisa J. Molofsky, John A. Connor, Shahla K. Farhat,** GSI Environmental Inc.

Methane Seepage from Soils

Oil & Gas Seeps are indicators of oil & gas beneath the surface

Many natural seep flows diminished as wells were drilled & produced.



Well Density in US & Canada

Sedimentary Basins in US & Canada

ELSEVIER

Marine and Petroleum Geology 22 (2005) 579–590

Marine and Petroleum Geology

www.elsevier.com/locate/marpetgeo

Gaia's breath—global methane exhalations

Keith A. Kvenvolden*, Bruce W. Rogers

US Geological Survey, 345 Middlefield Road, MS 999, Menlo Park, CA 94025, USA

Received 29 April 2004; accepted 31 August 2004

Abstract

Methane (CH_4) is the most abundant organic compound in the Earth's atmosphere, where it acts as a greenhouse gas and thus has implications for global climate change. The current atmospheric CH_4 budget, however, does not take into account geologically-sourced CH_4 seepage. Geological sources of CH_4 include natural macro- and micro-seeps, mud volcanoes, and other miscellaneous sources such as gas hydrates, magmatic volcanoes, geothermal regions, and mid-ocean ridges. Macro-seeps contribute ~25 Tg (teragrams) CH_4/yr to the atmosphere, whereas, micro-seepage contributes perhaps 7 Tg CH_4/yr. Mud volcanoes emit ~5 Tg CH_4/yr, and miscellaneous sources emit ~8 Tg CH_4/yr to the atmosphere. Thus, the total contribution to the atmosphere from geological sources is estimated to be 45 Tg CH_4/yr, which is significant to the atmospheric organic carbon cycle and should be included in any global inventory of atmospheric CH_4. We argue that the atmospheric CH_4 global inventory of the Interplanetary Panel on Climate Change must be adjusted in order to incorporate geologically-sourced CH_4 from naturally occurring seepage.

Published by Elsevier Ltd.

Keywords: Methane; Seeps; Global inventory; Carbon cycle

1. Introduction

The surface of the Earth is the site of fundamental biogeochemical processes involving the release and exchange of various gaseous compounds, such as carbon dioxide (CO_2) and oxygen (O_2). Well known is the biological exchange of CO_2 for O_2 by heterotrophic organisms and the counterpart exchange of CO_2 by autotrophic consumption to produce O_2 during photosynthesis in a life-sustaining cycle. Carbon dioxide is also generated by geological processes. It is released at the Earth's surface through volcanism and is the product of O_2-utilizing combustion of biomass and fossil fuels.

Also present in the atmosphere near the Earth's surface (i.e. in the troposphere) are other gases, including N_2, H_2, He, Ar, Rn, CO, SO_2, H_2O (vapor), H_2S, HCl, DMS, CH_3SH, $(CH_3)_3N$, CH_4 and higher molecular-weight hydrocarbons, all of which are part of the gaseous exhalations from the Earth. In Greek mythology, the Goddess of Earth is named Gaia; thus, one could refer to the rich mixture of atmospheric gases exhaling at the Earth's surface as Gaia's breath. This analogy might be favored by Lovelock (1995), who formulated the Gaia hypothesis (later called Gaia theory) to explain the workings of the living Earth.

Besides CO_2, the other principal carbon-containing gas in Gaia's breath is CH_4 (methane), the most abundant organic compound in the Earth's atmosphere. Its total abundance, which is generally increasing slowly (Dlugokencky et al., 1998), is currently approaching 5000 Tg (1 Tg $= 10^{12}$ g CH_4), according to IPCC (2001). This organic component of Gaia's breath is the subject of this paper.

The CH_4 atmospheric budget and the sources of CH_4 for this budget have been subjects of increasing interest starting with Ehhalt and Schmidt (1978), and followed by Cicerone and Oremland (1988), Fung et al. (1991), IPCC (1996), Lelieveld et al. (1998), Houweling et al. (1999), and IPCC (2001), and reviewed by Reeburgh (2003). CH_4 plays an important role in the Earth's radiative and chemical balance and thus is a factor in considerations of global climate change (IPCC, 2001). In the estimates of the global CH_4 budget referenced above, the sources can be organized under two main categories, natural (wetlands, termites, oceans, fresh water, wild ruminants, natural forest fires, and gas hydrates)

* Corresponding author. Tel.: +1 650 329 4196; fax: +1 650 329 5441.
E-mail address: kkvenvolden@usgs.gov (K.A. Kvenvolden).

0264-8172/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.marpetgeo.2004.08.004

Source of methane gas from seeps?

How much? 5 to 10 bcf/day From Natural Seeps.

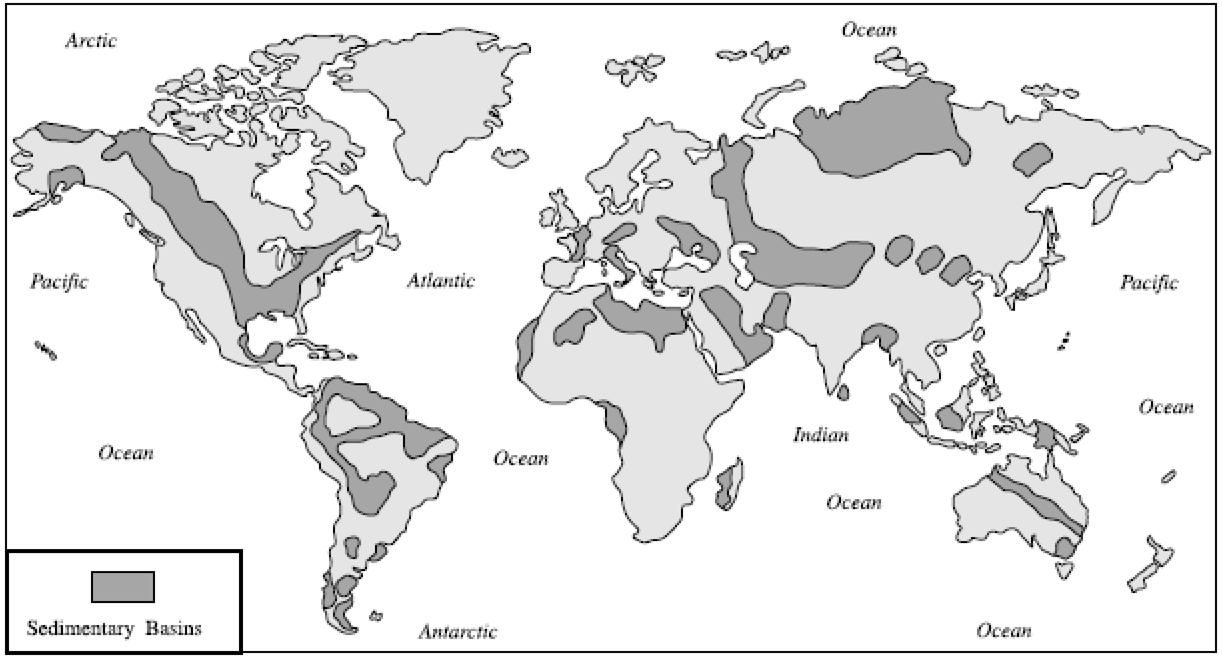


Fig. 6. Map showing location of sedimentary basins throughout the world where micro-seepage of CH_4 may occur. Adapted from Etiope and Klusman (2002).

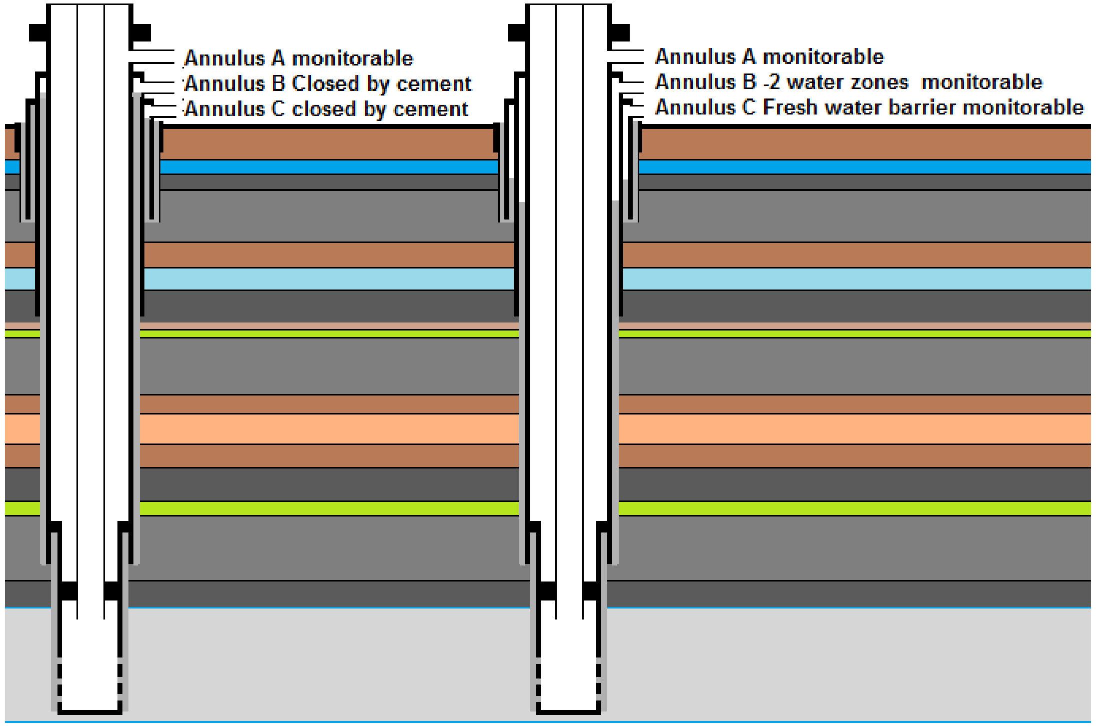
Methane Emissions – From Oil & Gas

- Super Emitters, ~80 to 90+% of emissions in an O&G Producing Area
  - A small number of potential offenders:
    - Gas Plants
    - Pipelines
    - Compressors
- Macro Emitters, ~5 to 10+% of emissions
  - A moderate number of potential emitters
    - Maintenance Operations
    - Valves
    - High bleed controllers
- Micro Emitters, ~<5 to 10% of emissions
  - A small number of potential emitters
    - Thread leaks
    - Low bleed controllers

Cement Every Annulus to Surface?
May NOT be the best plan. – SURPRISE!

Full Annulus Cementing?

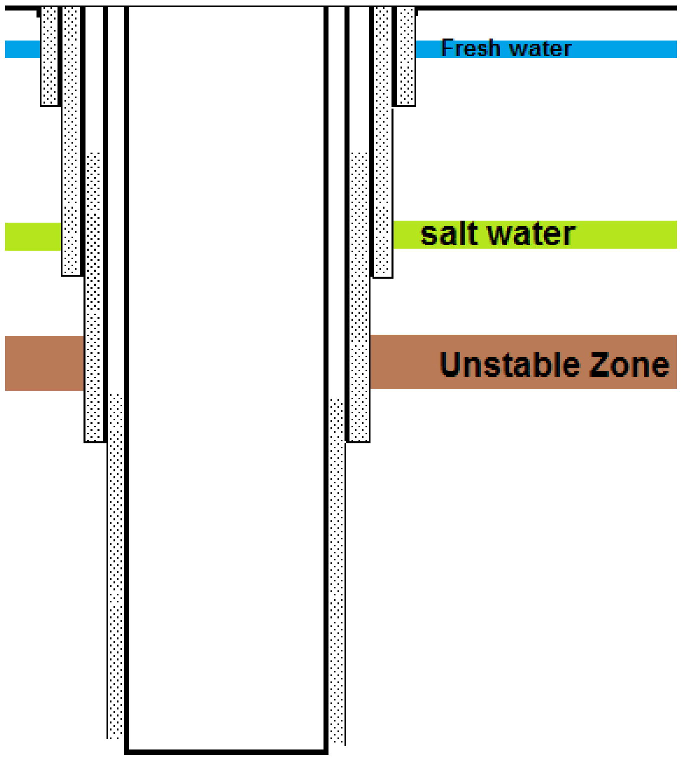
- **Most full cement columns require a two-stage cement job – requires perforating or DV tool – may decrease well integrity.**
- **Careful positioning of cement top in inner annulus allows monitoring of pressure build-up or monitoring type of fluid flow if leaks are seen.**
- **Repair options increase when open annulus exists including down-squeezes & inner pipe removal.**



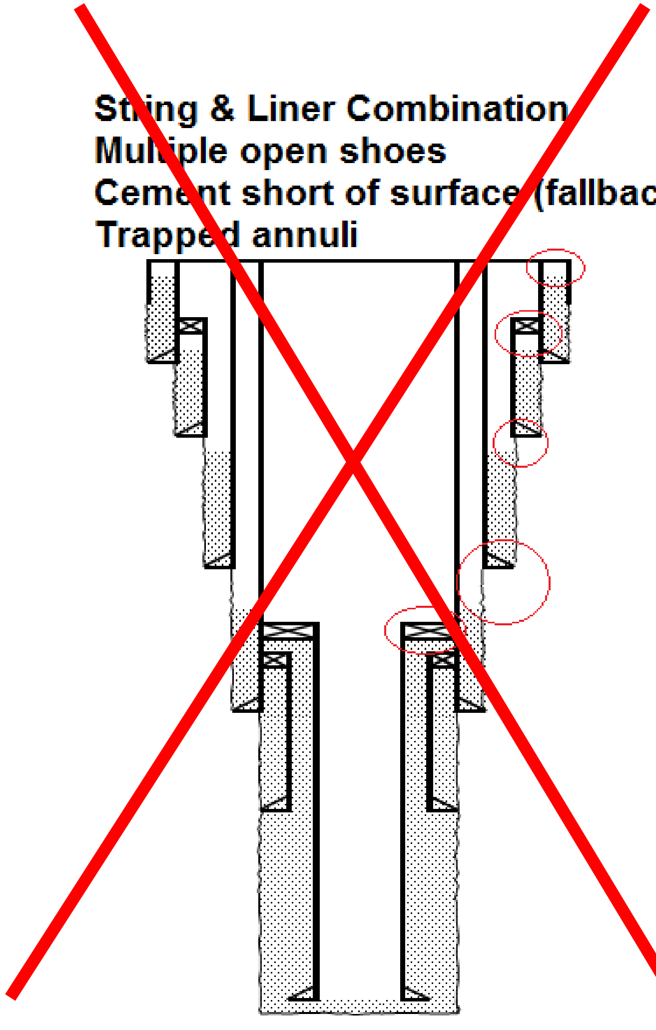
- **Placing end of casing in strong, low permeability formations increases isolation success.**
- **Placing salt water and fresh water zones behind different casing strings nearly eliminates potential for salt water intrusions behind the pipe.**

Open Annulus and Open Shoe. Still a viable completion?

Full length casing strings
No open shoes
Cement to surface on 2 outer strings
Open annulus preserved on inner csg

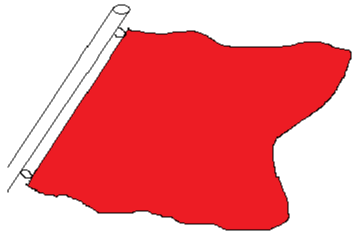


String & Liner Combination
Multiple open shoes
Cement short of surface (fallback)
Trapped annuli



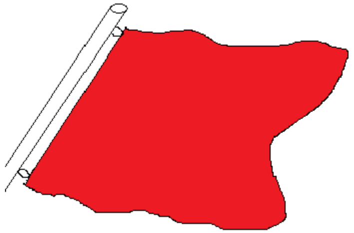
Can accidentally pressure up shallow zones.

Early Warning Signs? - Design



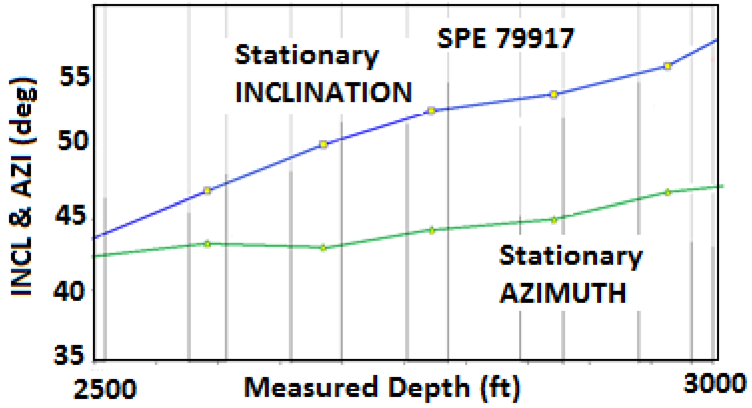
- Extremely long casing strings (especially with very little cement).
- Short overlaps (<200 ft)
- Open shoe wells.
- Limited cement
  - <200 ft. in overlaps
  - Gas charged formations (coal, shale, etc.) that are not covered by cement.
- Poor alloy selection.
- Connections that are not suitable for the well purpose.
- Well designs that lack flexibility to recomplete or repair.
- “Cookie-Cutter” designs in non similar environments.
- High risk well types.

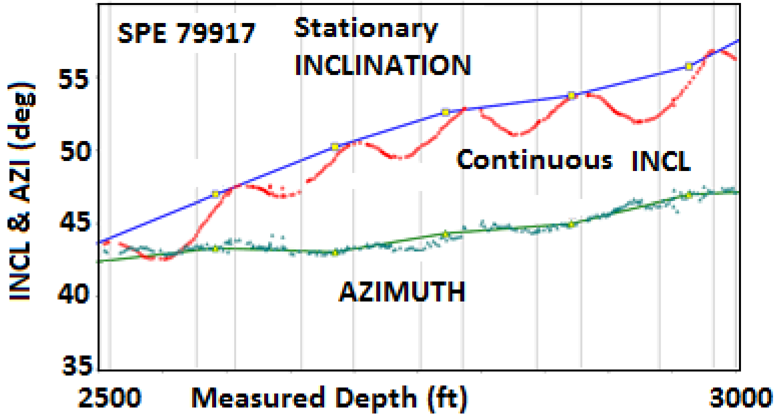
Early Warning Signs? – Re-Design



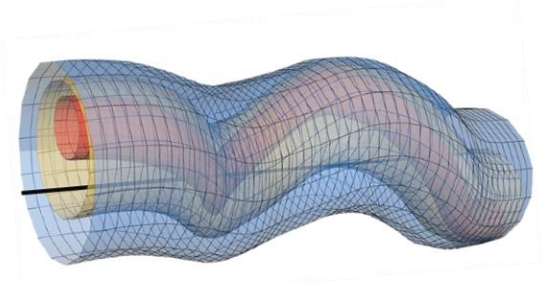
- Repurposed wells.
  - Producer-to-injector – check alloys and cement
  - Conversion of primary flow wells to high pressure gas lift.
  - Deepened wells – wear in pipe and higher pressures
  - Recompleted to soft sand or soft chalks – subsidence?

Buckling Failure Points (symptoms & causes)





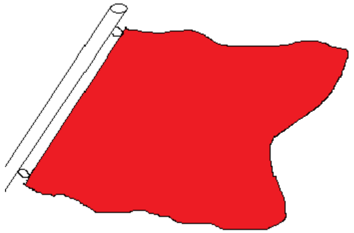
Causes?
Too much dog leg severity (DLS) – drilling too rapidly, Subsidence, etc.



(Graphic courtesy of Gyrodata – SPE Dec 2015)

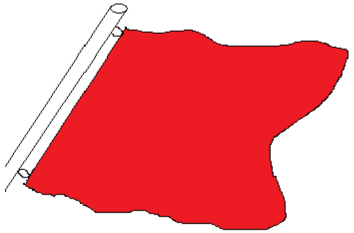
Source: Rassenfoss, S., "Drilling Wells Ever Faster May Not Be the Measure of Success," SPE JPT

Early Warning Signs? - Drilling



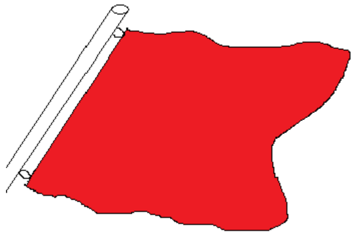
- Record time drilling
- Make-up problems
- High makeup RPM (over 20 rpm)
- No gradual torque shows
- Early leak issues at the threads
- Fast casing running (<3 sec/ft where clearances are close => Surge pressure rises sharply.)
- Casing-to-hole clearances less than ¾” (18 mm) or clearances > ~3” for smaller casing.

Early Warning Signs? - Completion



- Wells that had drilling problems.
- Non centralized wells
- Long periods of rotating drill string
- Poor cement practices.
  - Radial clearances (casing O.D. to hole diameter less than ¾” or more than ~2”)
  - Poor chemical dispersion/flush prior to cement pumping.
  - Poor cement density control (loss of circulation)
  - Poor returns
- Wells that repeatedly failed pressure testing

Cement Specifics – Isolation Critical



Cement Application & Design Failure Issues

- Poor Design Information
- Lack of Centralization
- Low Cement Top
- Poor Cement Blending
- Poor Preflush Design
- Lack of Fluid Loss Control
- Fracture Breakout (Cement)
- Excess Water
- Lack of Pipe Movement

Post-Pumping Issues

- Gas Cut Cement
- Cement Shrinkage & Fallback
- Deterioration by SO_4 or CO_2
- Very High Temperatures

Cementing Statistics

- Primary cementing cost about <u>5% </u>of well cost.
- About 15% of primary cement jobs require squeezing because a shoe test failed.
- Total cost of cementing when squeezing is required is about <u>17%</u> of well cost. (12% savings in a five million dollar well is $600,000)
- Typical number of squeezes required to fix a problem in a primary cement job = 3.
- Perforating holes in pipe and squeezing can weaken the pipe and some squeeze operations are suspected of collapsing the pipe.

How Much Cement is Needed for Isolation? Every inch of cement is NOT required to be perfect.

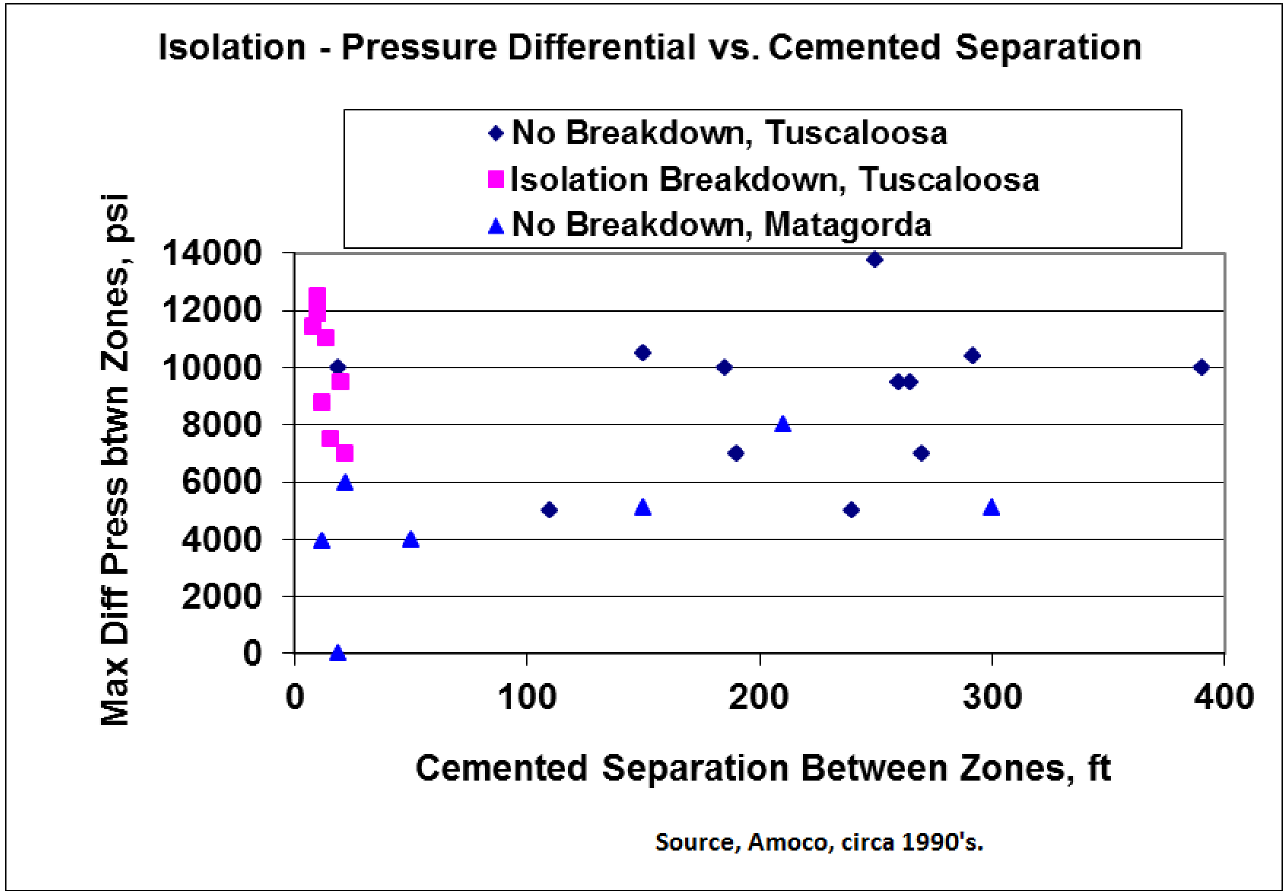
Quality of cement is more important than the volume.

Isolation can only be measured with a pressure test.

Bond logs are not always best tool

- ~10% channels missed.
- Instances of false negatives & positives.

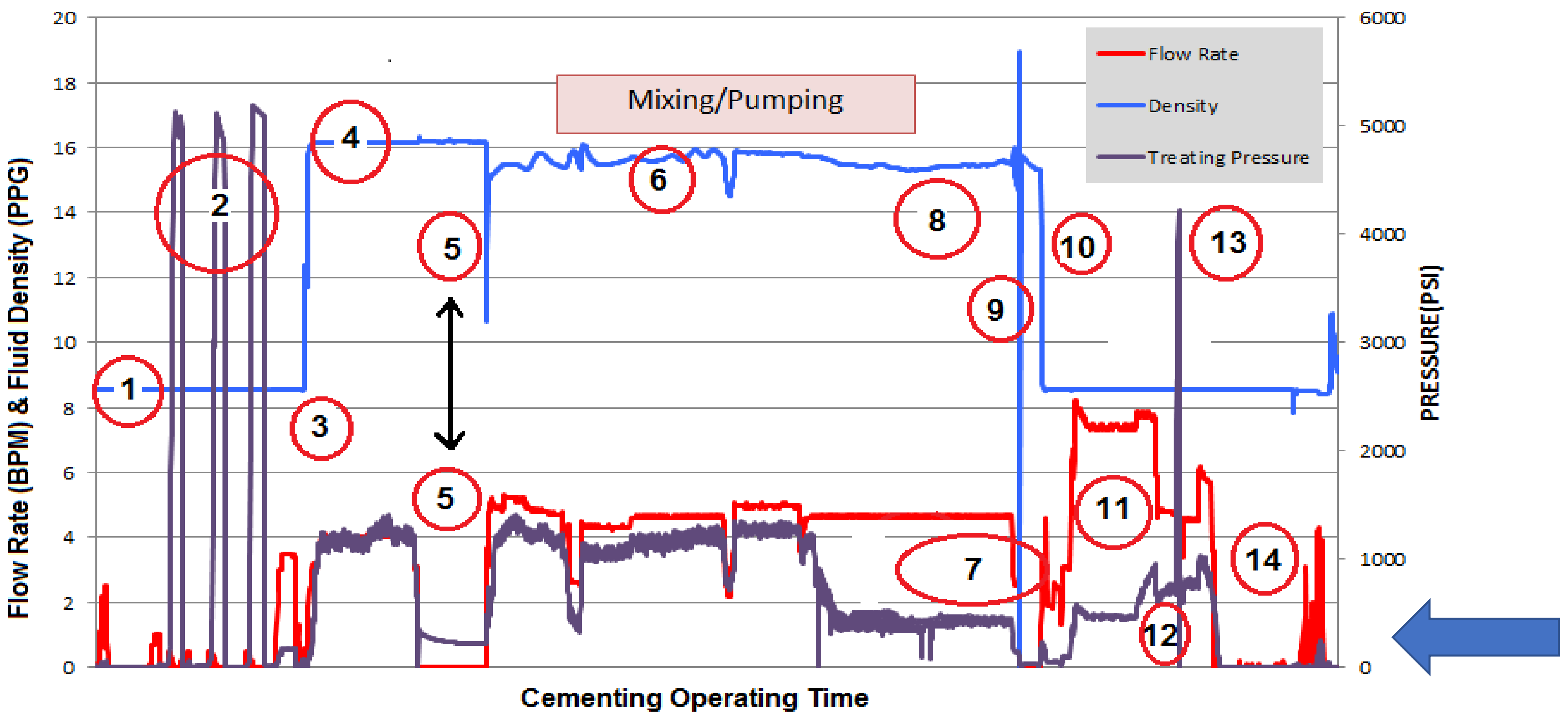
Over 10,000 psi can be held with less than 50 ft of cement, but 200 to 300 ft is routinely used.



SPE 166142, Barrier vs. Well Failure, King

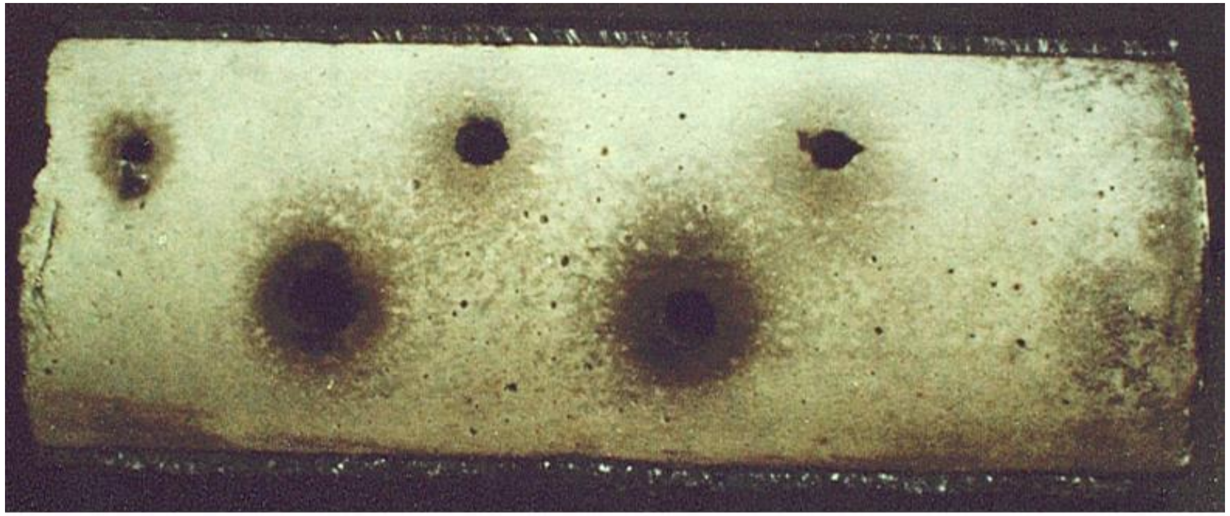
The Best "Tool" for Evaluating Cement Quality is the Pump Chart

1	**Filling surface equipment w/ fresh water**	**8**	**Cement density variance – was a special tail-in slurry used?**
2	Pressure test – two leaks in surface connection & a successful test	9	Shut-down to flush surface lines and drop the solid top plug.
3	Pump spacer to separate mud from cement	10	Bottom plug lands, diaphragm ruptures & cement into annulus.
4	Constant density spacer and early batch mixed cement	11	Free-fall make up – more flow in than out - pressures equalizing
5	Shut down to drop bottom plug & switch to on-the-fly cement	12	Cement lift pressure too low – check return volumes and timing.
6	Pumping cement – within density guidelines, but barely.	13	Top plug "bumps" (lands in the shoe track) – placement complete.
7	Cement free-fall – heavier cement pushes mud faster than pump in.	14	Hold back pressure on casing if float valve fails. (not in this case).



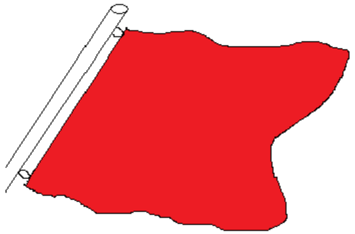
Does Perforating Shatter Cement?

- Unconfined Cement? – Yes
- Confined Cement? – Probably Not.



Multiple perforating (3 gun runs, 12 total shots) using 20 g & 23 g. DP charges, 5-1/2” casing cemented inside 8-5/8” casing. Outer 8-5/8” casing cut away for photograph.

Early Warning Signs? - Fracturing

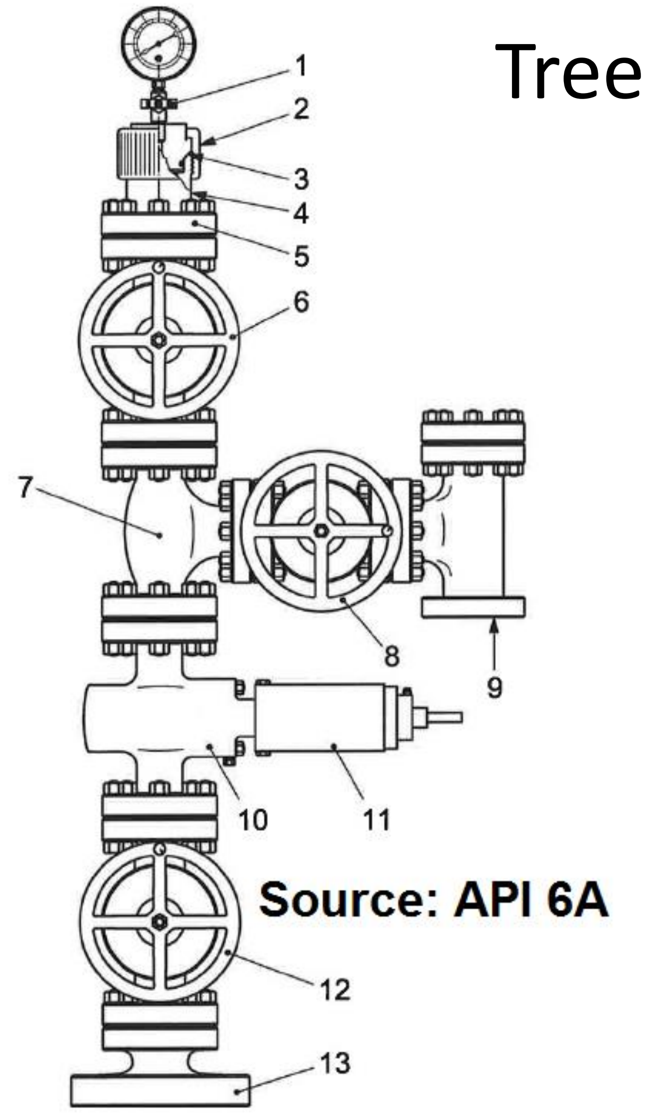


- Fracture jobs that sharply applied frac pressure repeatedly.
- Over-pressured fracturing (above ECD adjusted frac gradient).
- 30 or more frac stages (30 is very approximate)
- Single very long casing strings (depends on geology)

Statistics

- Primary cementing cost about 5% of well cost.
- About 15% of primary cement jobs require squeezing
- Total cost of cementing when squeezing is required is about 17% of well cost.
- Typical number of squeezes required to fix a problem in a primary cement job = 3.

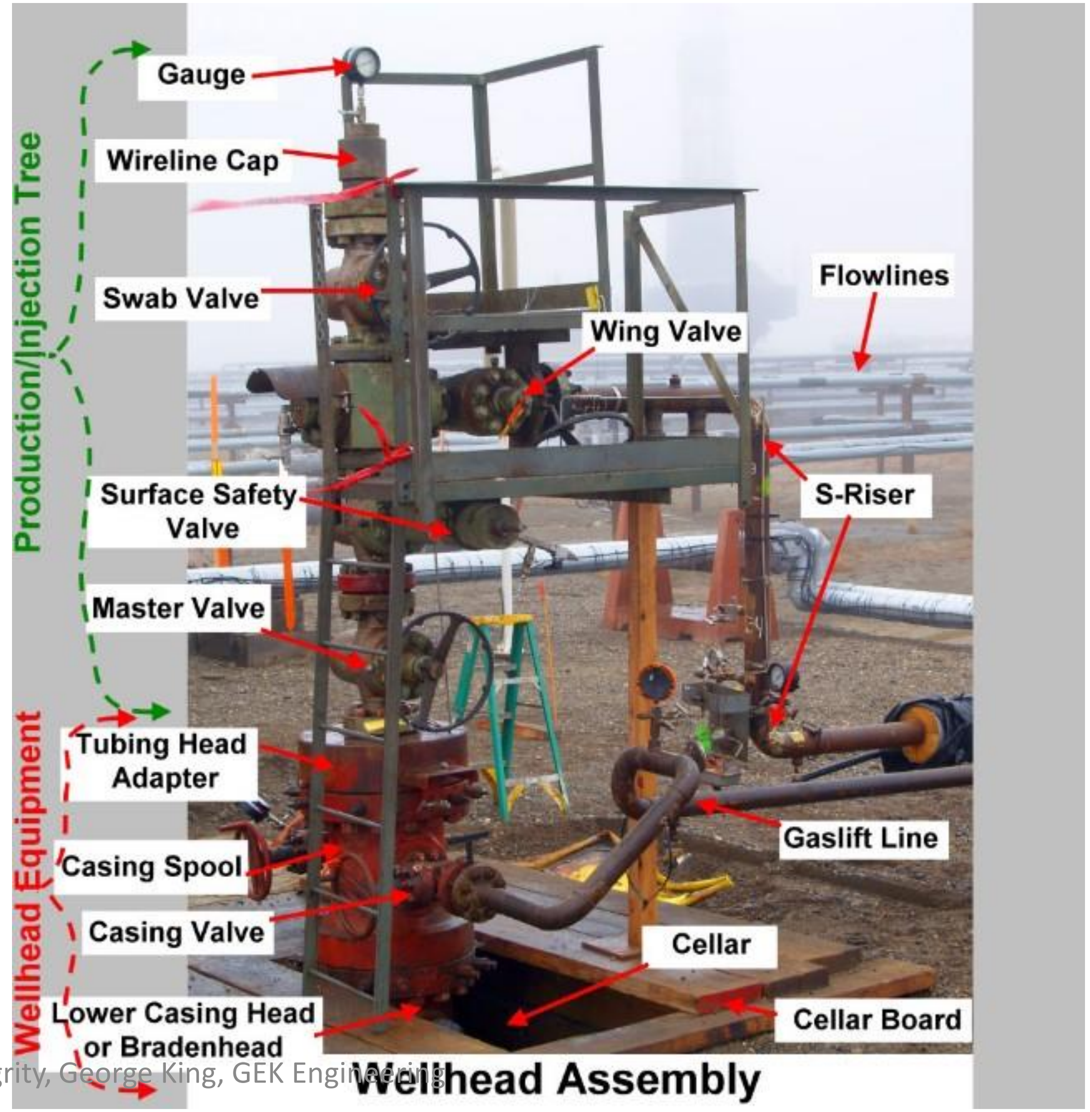
Trees – Surface Control Point



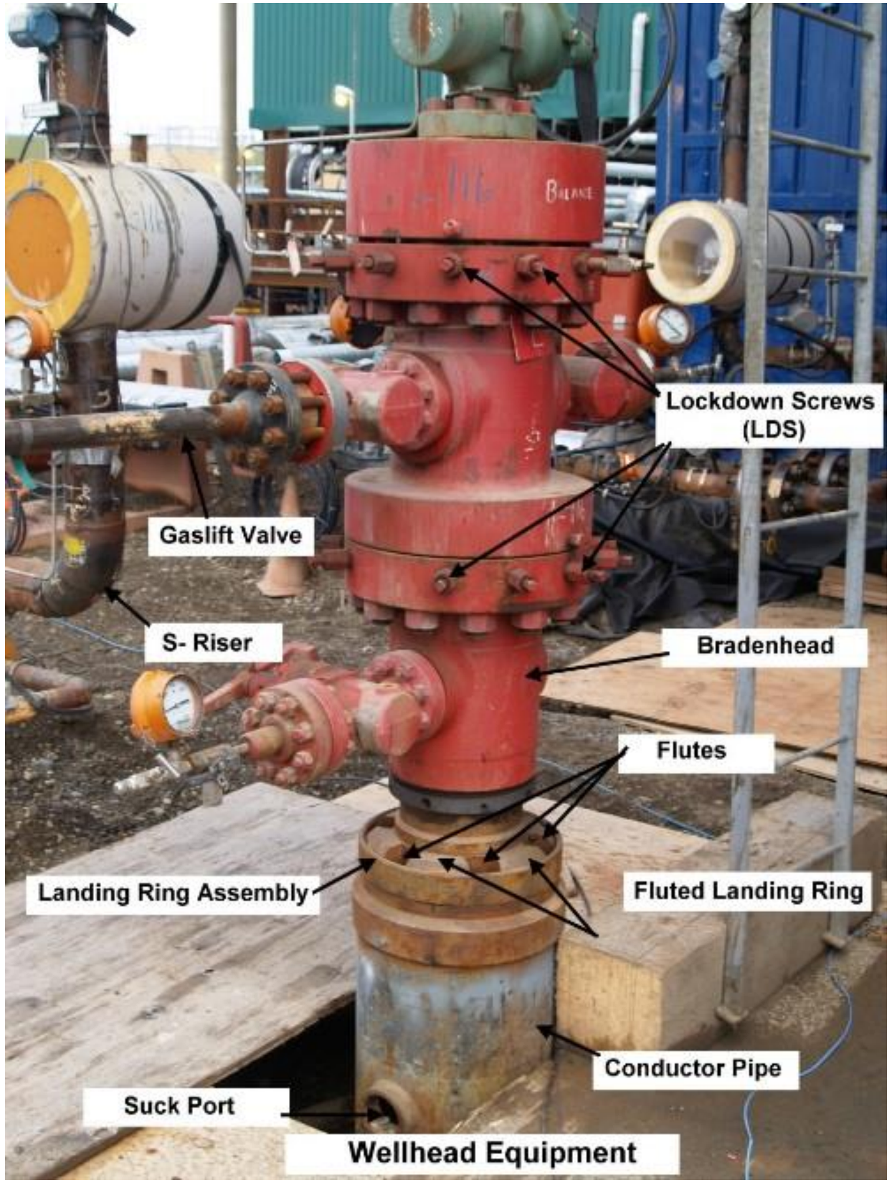
Key

1 gauge valve	8 wing valve (manual or actuated)
2 bonnet nut	9 choke
3 blanking plug	10 surface safety valve
4 body	11 actuator
5 top connector	12 master valve
6 swab or crown valve	13 tubing-head adapter
7 tee	

Typical Christmas Tree Nomenclature

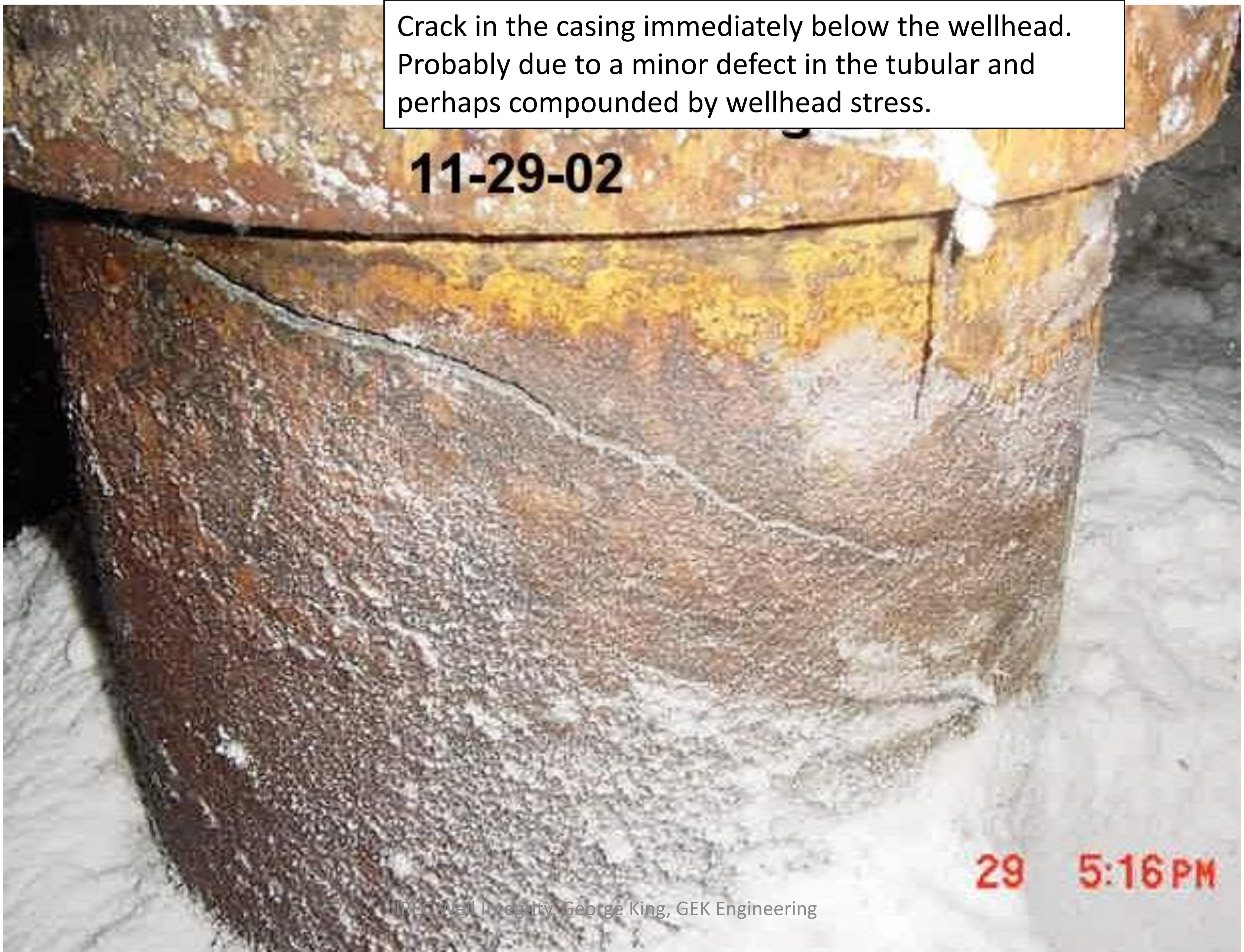


Wellheads


Lockdown Screws (LDS)
Gaslift Valve
S- Riser
Bradenhead
Flutes
Landing Ring Assembly
Fluted Landing Ring
Conductor Pipe
Suck Port
Wellhead Equipment


P2-42 Leaking Bradenhead
08-14-02

Crack in the casing immediately below the wellhead. Probably due to a minor defect in the tubular and perhaps compounded by wellhead stress.



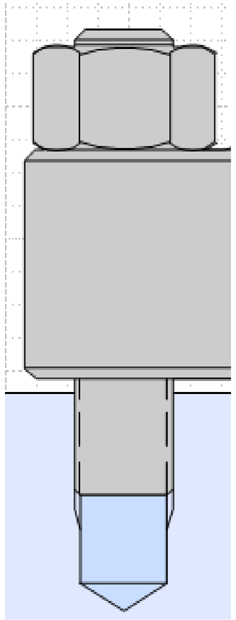
Flanges – look closely

Information Sources: Woodco, Joe Anders (BP-Alaska), Danny Pitts (Stress Engineering)

Stud Makeup Requirements

API specifies stud thread engagement should equal the stud diameter.

A good workmanship standard is to have a minimum of 2 threads but no more than 10 threads extending past the nut.

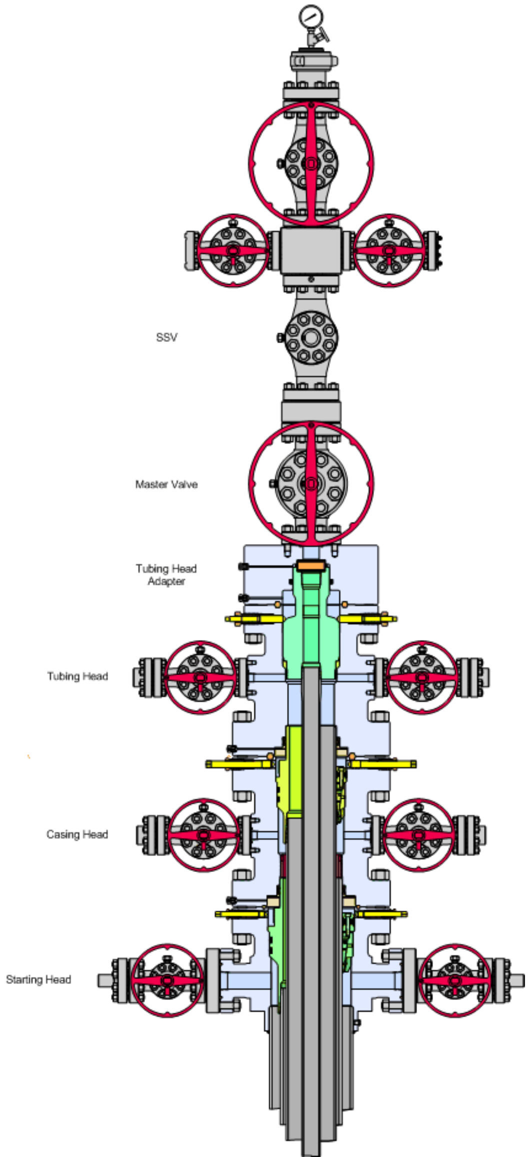


What do you do when the studs are short?

Before

After

Importance of a single bolt in a flange?



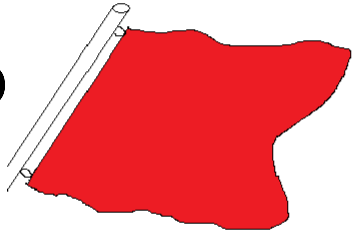
The wellhead is the surface pressure control point.

A leak cannot be accepted.

Because of the pressure differential from inside the well to the atmosphere, any leak will likely become a “washout” due to erosion.

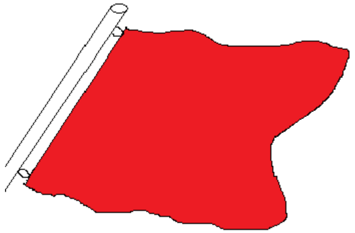
There is a safety factor built into every flange, but the best approach is do it right the first time.

Early Warning Signs - Inspection?



- Poor construction methods
- Poor maintenance of surface equipment
- Leak stains
- Poor valve performance
- Valve wear – erosion
- Valves that must be repeatedly greased to pass a pressure test (most are in this group)

Not all of the problems are in the well and few are visible.



Slow flow unable to sweep sludge and biomass out of pipes

SPE Presentation: Microbial Corrosion (MIC) in the Eagle Ford Shale (Patrick J. Breen – Marathon)

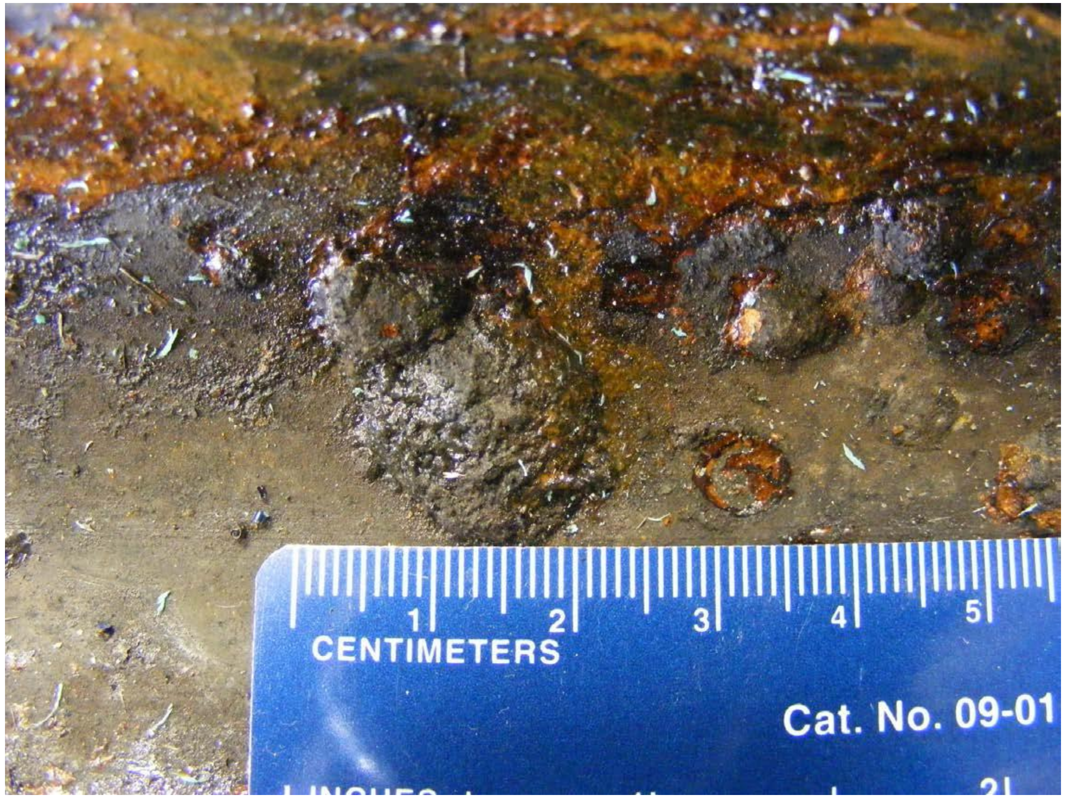
Eagle Ford MIC

Slow flow unable to sweep sludge and biomass out of pipes

SPE Presentation: Microbial Corrosion (MIC) in the Eagle Ford Shale (Patrick J. Breen – Marathon)

Eagle Ford MIC

The blister is a combination of the covering and other debris from MIC attack.

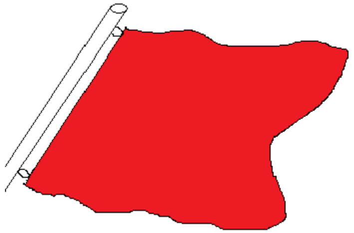


SPE Presentation: Microbial Corrosion (MIC) in the Eagle Ford Shale (Patrick J. Breen – Marathon)

Eagle Ford MIC

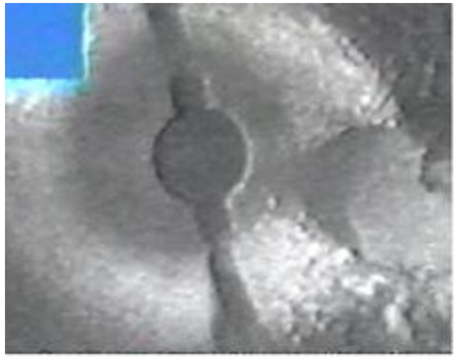
Underneath, there is a characteristic, "stair step" pit.

Corrosion Failures



- Higher than about 5% (mole) CO_2
- H_2S and mixtures of H_2S and CO_2

Failures – Older Wells – Risks increase - Sometimes



Wear?

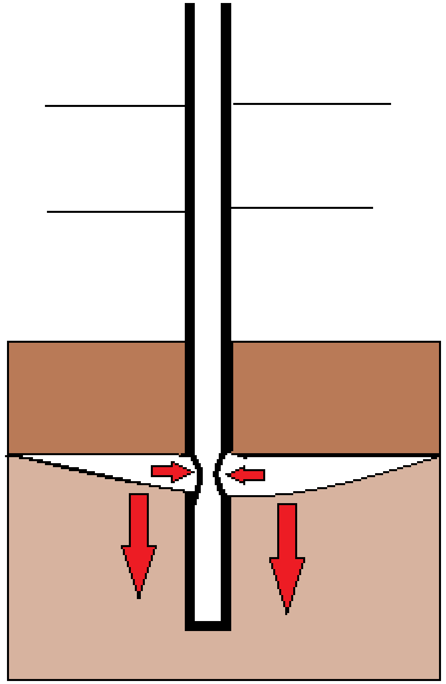
Collapse

Burst – Above
cement support

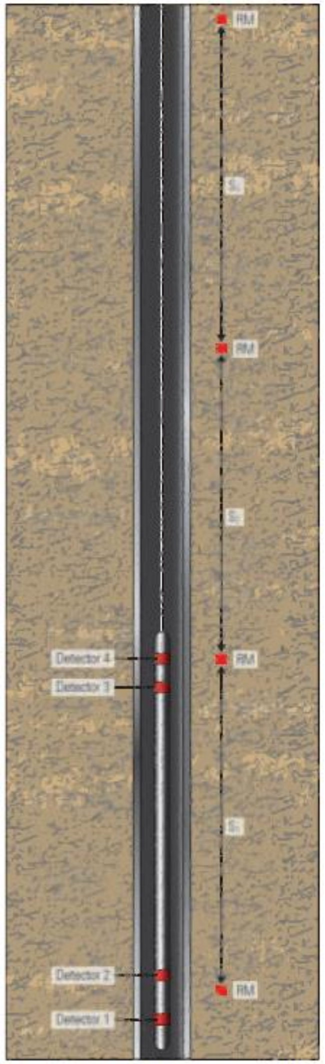
Hydrogen embrittlement – high
strength P-110 Coupling

Compaction, Subsidence & Collapse

- Removal of a load supporting element (gas/oil/water) means the formation matrix must support more load.
- Most severely affected are weak formations UCS (unconfined compressive strength) < ~2000 psi.
- As a formation shrinks – it can increase tension on the cemented casing.



Such events are rare, usually in soft sands and chalks. Particularly rare in onshore wells with hard sandstone or dolomite formations. .



^ Monitoring radioactive bullets. A sonde with four gamma ray detectors minimizes the effect of unintentional tool movement by detecting two radioactive markers (RM) almost simultaneously. The bullet separation, S_1, S_2 and S_3, should be approximately equal to the mean separation between the top and bottom pairs of detectors.

https://www.slb.com/~/media/Files/resources/oilfield_review/ors06/aut06/compaction_and_subsidence.pdf

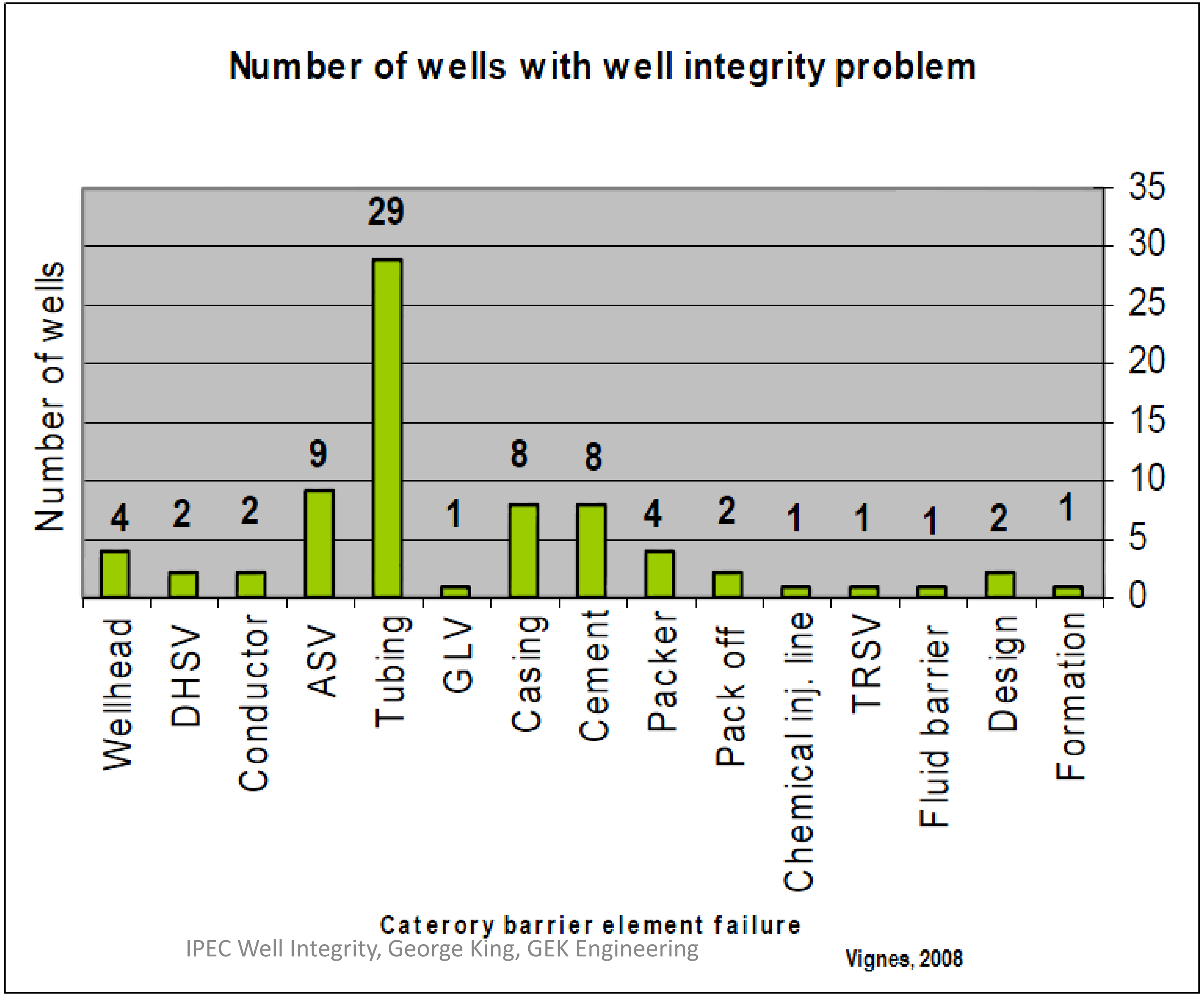
What Fails?

Is it related to a barrier failure or a well failure?

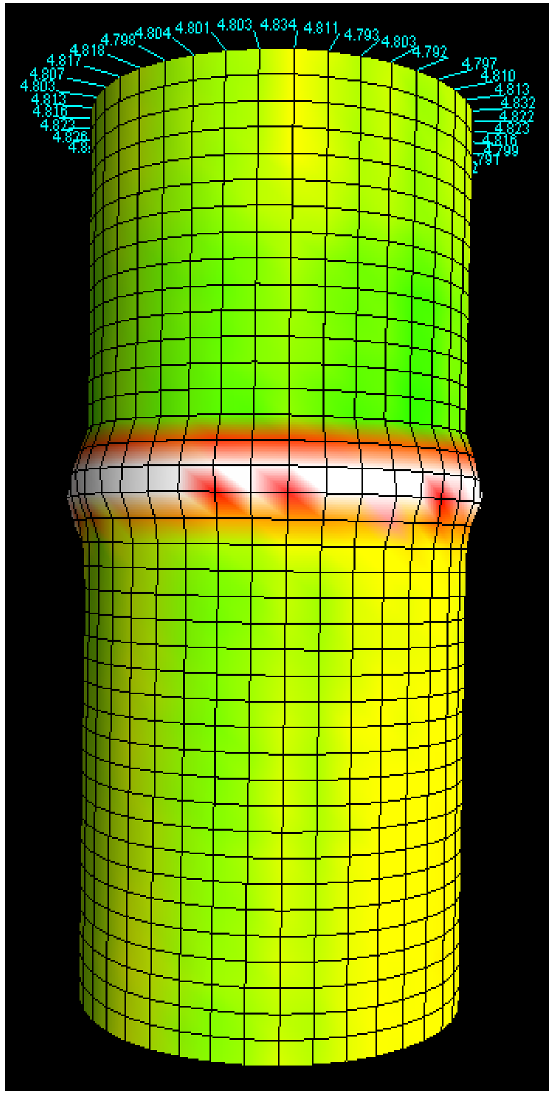
Is it prevented by another step such as cementing?

What should happen in a design to prevent it?

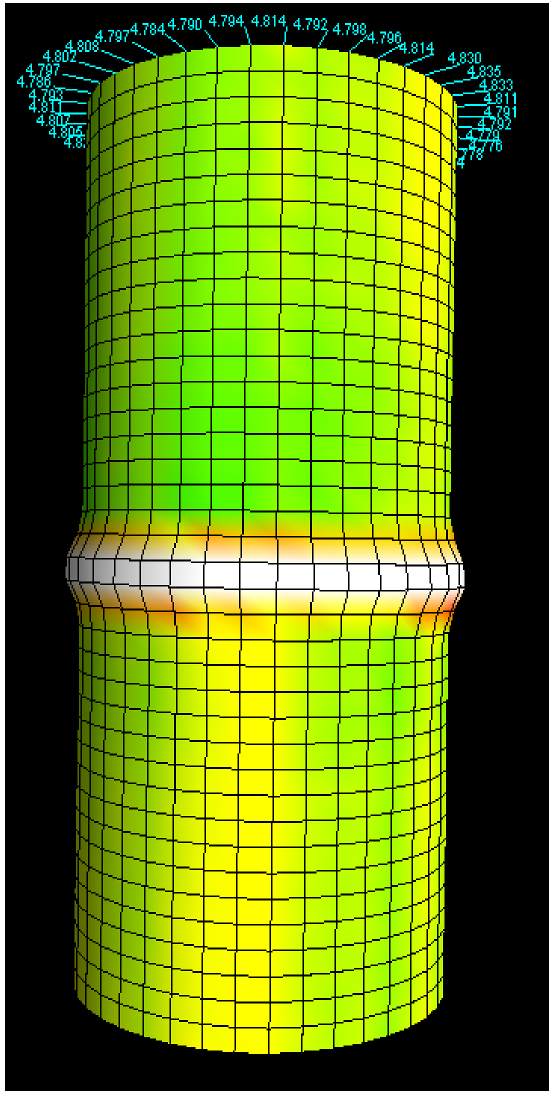
Identity of barrier failures in a Norwegian study of 406 wells with 75 reporting a barrier issue. None of the issues created pollution.



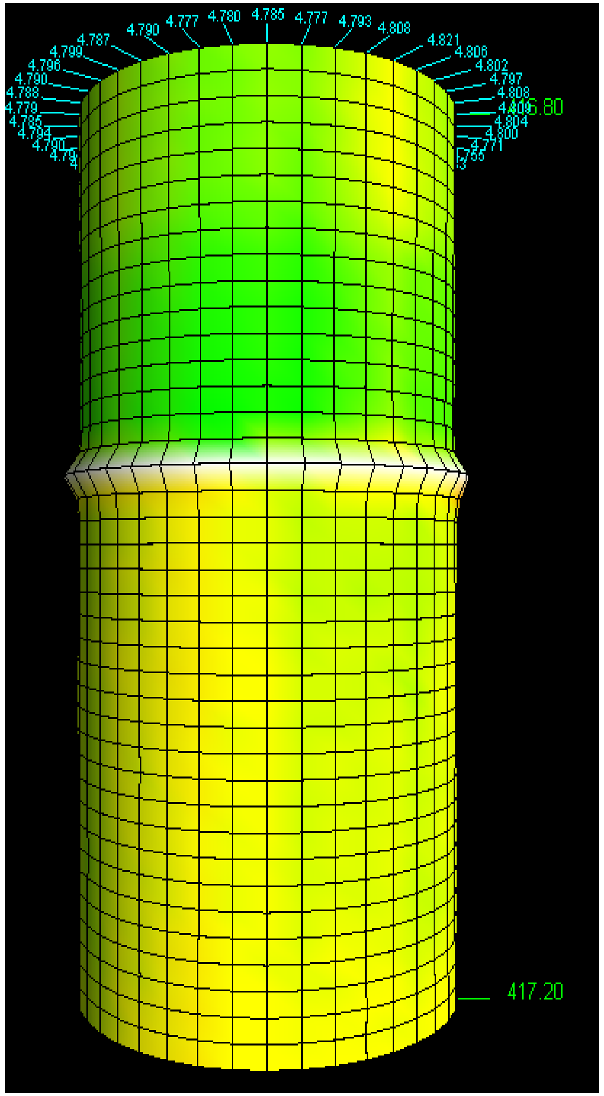
Erosion most serious in the upper couplings – just under the wellhead.



Coupling 1

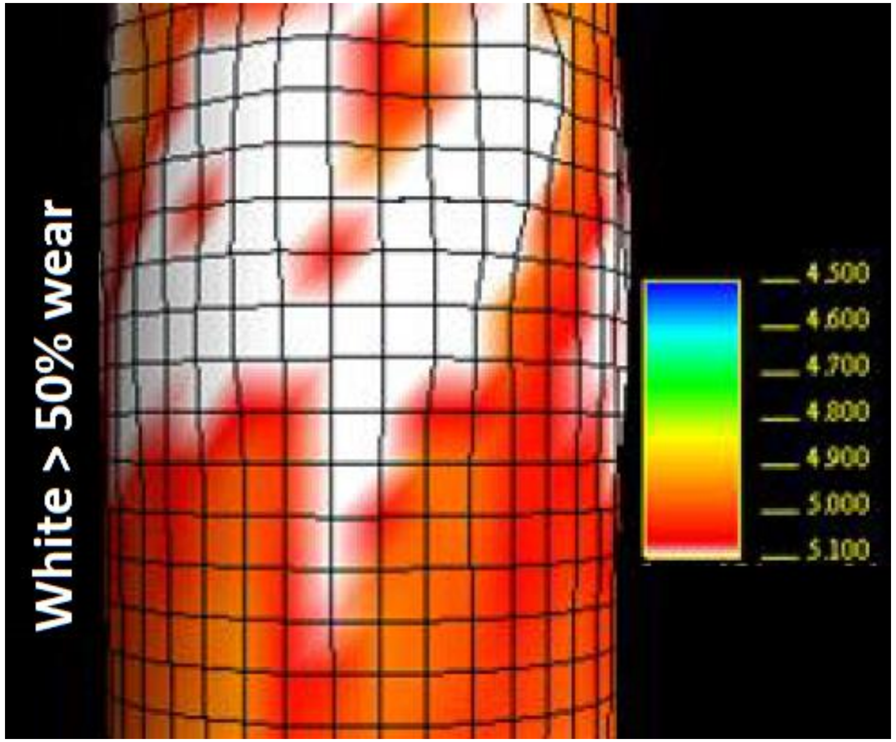


Coupling 2



Coupling 42

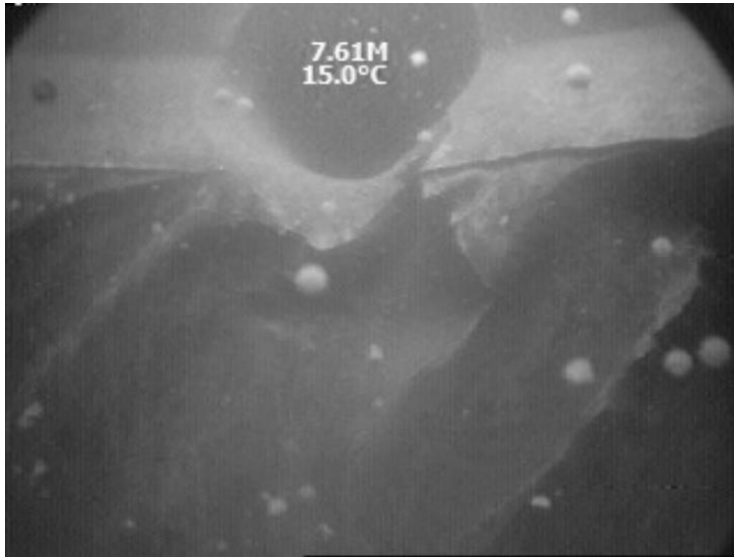
Monitoring Check - Erosional wear after Fracturing

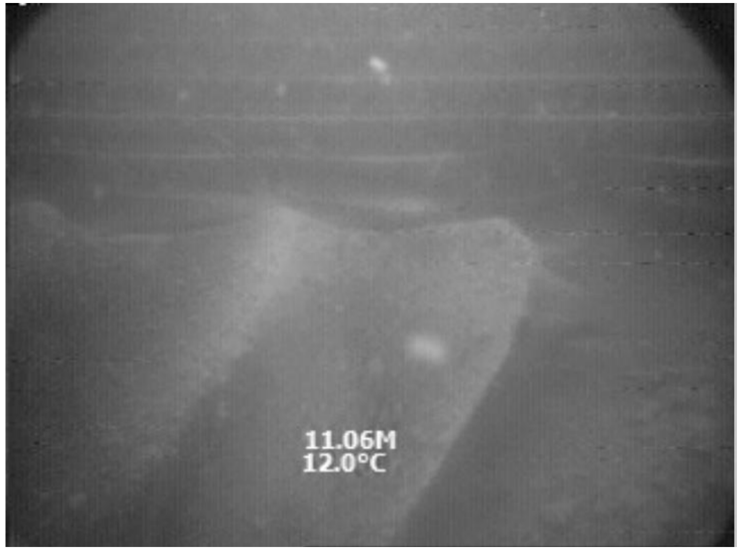


Example of wear (by multi-arm caliper measurement) in a joint of 5-1/2” P-110 casing.

Erosion was less than 15 feet below ground level.

The swirl pattern common in these erosion occurrences indicated a fast flow environment with significant instability in the flow path. Common downstream of annular access ports or other flow interruptions for about 8 to 20 pipe diameters.

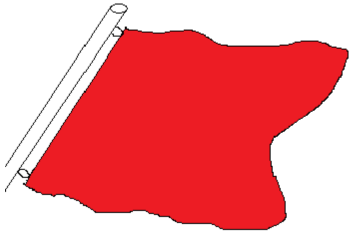




Erosion below ports in tubinghead

Coupling 1

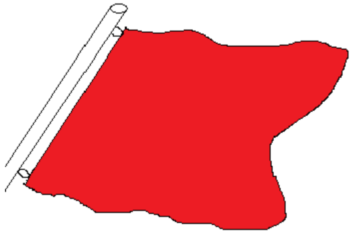
Coupling 2



Early Warning Signs- Potential Casing Damage

- High Dog Leg Severity
- High rate fracturing with numerous stages
- Very large proppant amount used in the frac
- Tubing-to-annuli leaks developing

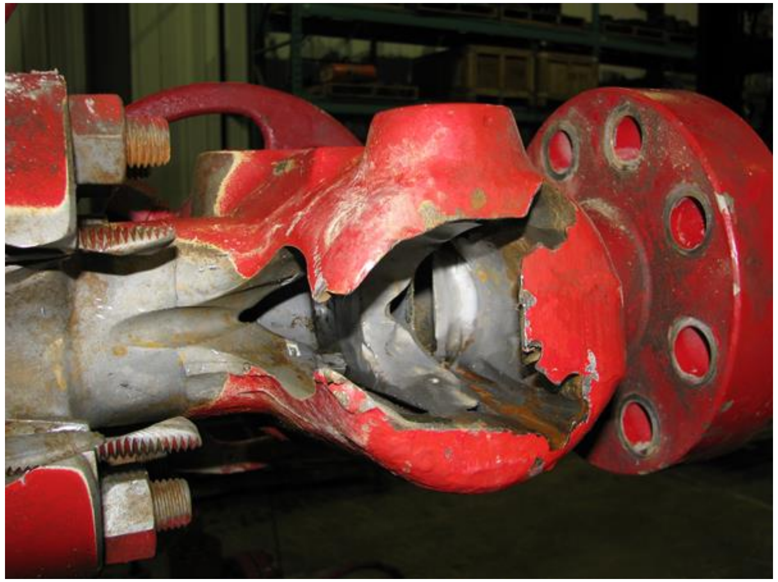
- KPI’s
  - Established company workflows to high-grade or optimize hydraulic fracture placement.



Warnings - Production

- Look for changes in the system due to corrosion, embrittlement, erosion.
- Repurposing wells – producer to injector and adding high pressure lift systems.
- Weather effects.
- fluid changes
- Secondary recovery and refracturing

Surface erosion



Small leaks can become big leaks and even bigger problems if not corrected immediately.

A culture of maintenance stops these problems.

Vertical Fractures – where do they stop?

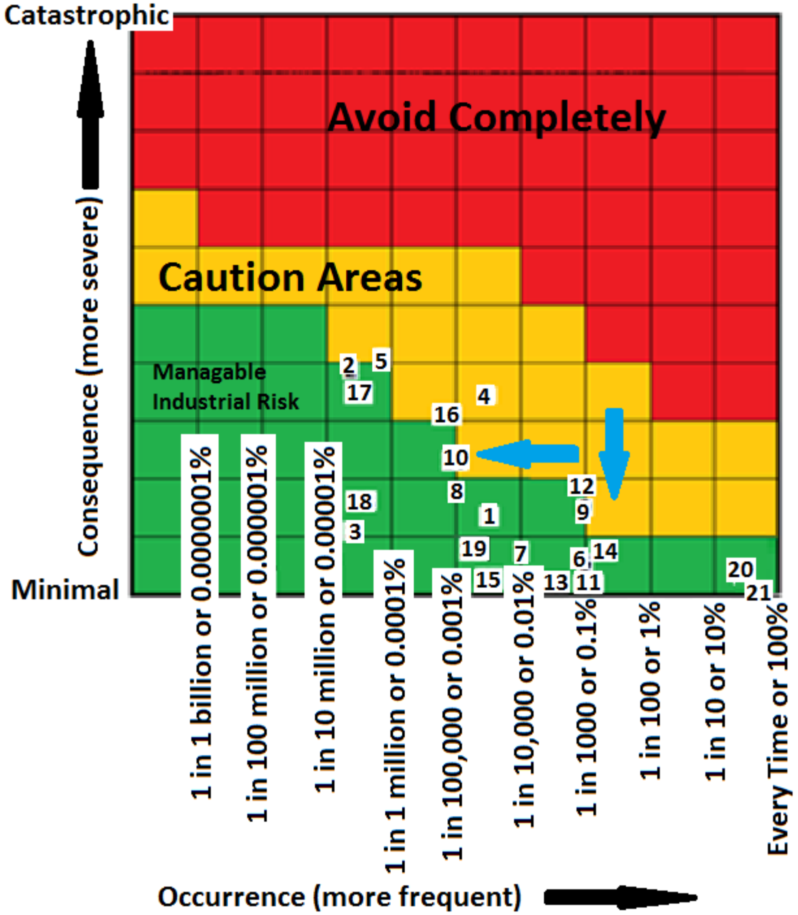
Fracture across shale barri.mpg

Actual hydraulic fracture in a west Texas carbonate formation at a depth of 4579’.

Width of the fracture is approximately 0.09”.

Fracturing: Level of Risk?

Fracturing Risk: Occurrence vs. Impact. Both are sharply reduced by technology application



10: > 1 mile Diam. Subsurface Pollution., Toxic, Not Recoverable. Similar to Acid Mine Drainage.

9: 100 ft to 1 mile Diam. Subsurface Pollution, Toxic, Not Recoverable.

8: > 1 mile Diam. Surface Pollution, Slow Biodegradation.

7: 100 ft to 1 mile Diam. Surface Pollution, Toxic, Slow Biodegradation.

6: <100 ft. Subsurface Pollution. Toxic, but fully biodegradable or recoverable.

5: <100 ft. Diam. Surface Pollution, Toxic but biodegradable or recoverable.

4. Spill or Leak of 50 to 500 bbls, Non Toxic but persistent chemical, Similar to spreading salt on icy roads

3. Large Volume (<5000 gal) Spill of fresh or salt water with polymer and trace of biodegradable biocide (50 ppm), Similar to treated sewage.

2. Large Volume (<25,000 gal) spill of fresh or salt water with biocide in low concentration (150 ppm), Similar draining swimming pool on the lawn.

1. Small spill (< 5 gal) of diluted, non toxic, quickly biodegradable chemical.

Potential Outcomes

__Transport and Storage__
1 Spill of clean water - fresh or low salt
2 Spill of conc. biocide (Glutaraldehyde - 50%)
3 Spill of dry additives - toxic but recoverable
4 Spill of 150 gal diesel - wreck - 20% recoverable
5 Spill of diesel refueler - ~4700 gal, 20% recoverable
6 Spill of frac water - no additives, 5000 gal
7 Spill frac tank, water w/ biodeg biocide (<50 ppm)
8 Spill < 10 gal diesel fuel while refueling
9 Spill frac tank frac flowback, <20,000 gal, no toxics

__Subsurface Well Events__
10 Frac ruptures surf csg, loss of 500 gal frac water
11 Tbg pulls out of pkr - no losses outside well
12 Cement channel - 1/4" diam. Well < 2000 ft deep
13 Cement channel - 1/4" diam. Well > 2000 ft deep
14 Intersects other well in pay, no leak or pollution
15 Intersects properly abandoned well, no leak
16 Intersects improperly abandoned well, 500 gal lost
17 Frac to surface thru rock layers, well depth >2000 ft
18 Earthquake from frac of Mm > 5.0 (Richter)
19 Frac intersects a natural seep & increases seep rate
20 Air Emissions (SOx, NOx, particulates) >> normal

__Desired Outcome (Target is 99%+)__
21 No spills or measurable pollution

Weather Related

Warmer weather – but expanding gas cools things very rapidly, especially at restrictions.

Collapse caused by ice – water inside a near-surface annulus.

Pipe wall deterioration – Multiple causes

Failures like this may have multiple causes.

Even corrosion of the steel wall is rare, more common corrosion attacks are localized pitting, embrittlement, abrasion or erosion-assisted corrosion and corrosion attacks at the 6’oclock position in horizontal lines.

Surface Casing Burst (rare)

This example of a 13-3/8” casing from an Alaska well burst when a gas leak from a gas-lift source in the tubing-by-production casing annulus leaked through a buttress thread connection and pressured up the production casing-by-surface casing annulus, creating a trapped annulus.

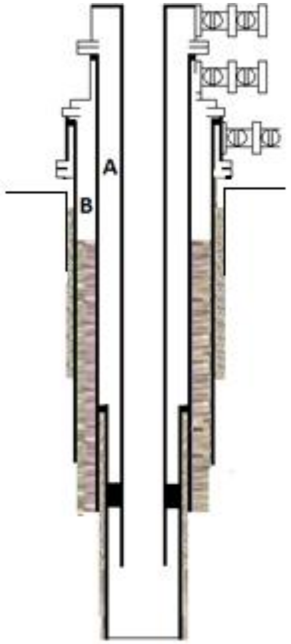
The nearly liquid filled annulus, already pressure up by the leaked gas, was further stressed as the well was brought on, raising pressure rapidly.

The original cement job top (1980’s vintage) was thirteen feet (13’) below the surface.

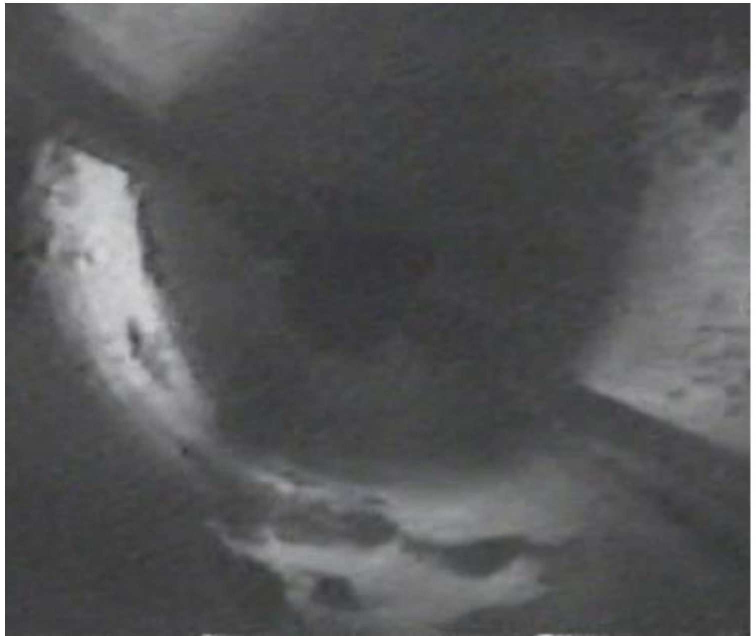
The casing burst just above the cement top and before the inner casing could collapse.

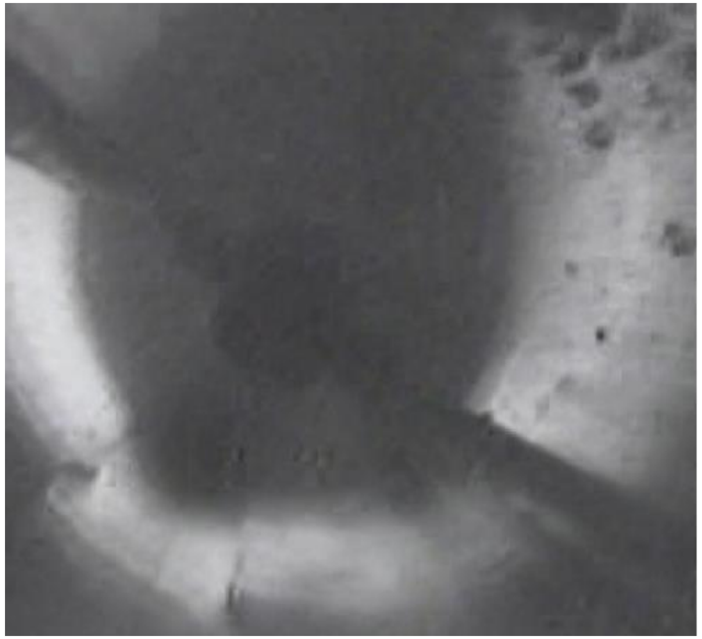
Failure to bring cement to surface on a surface casing:

1. Decreases casing support by the cement.
2. Increases potential for oxygen corrosion or and/or bacterial induced corrosion



Corrosion Trench





The cause is water condensate from the flowing gas stream as temperature and pressure decline during production. The water adsorbs CO_2 can and runs down the low side of the tubing.

Salt – Changes Well Integrity Radically.

Source: Envind L. Kristensen, Stratoil, "Field Experiences and Challenges with Halite Scaling in the Bakken, SPE Flow Assurance Meeting., October 28/29, 2015. Galveston, TX.

1970's Industry Study of Failures

Method	% of Failures
Corrosion (all types)	33%
Fatigue	18%
Brittle Fracture	9%
Mechanical Damage	14%
Fab./Welding Defects	16%
Other	10%

Cause	% of Failures
CO_2 Corrosion	28%
H_2S Corrosion	18%
Corrosion at weld	18%
Pitting	12%
Erosion Corrosion	9%
Galvanic	6%
Crevice	3%
Impingement	3%
Stress Corrosion	3%

In 2019, the problems are the same, but quality control and inspections have reduced fabrication defects.

EAGLE FORD MIC

Slow flow unable to sweep sludge and biomass out of pipes

SPE Presentation: Microbial Corrosion (MIC) in the Eagle Ford Shale (Patrick J. Breen – Marathon)

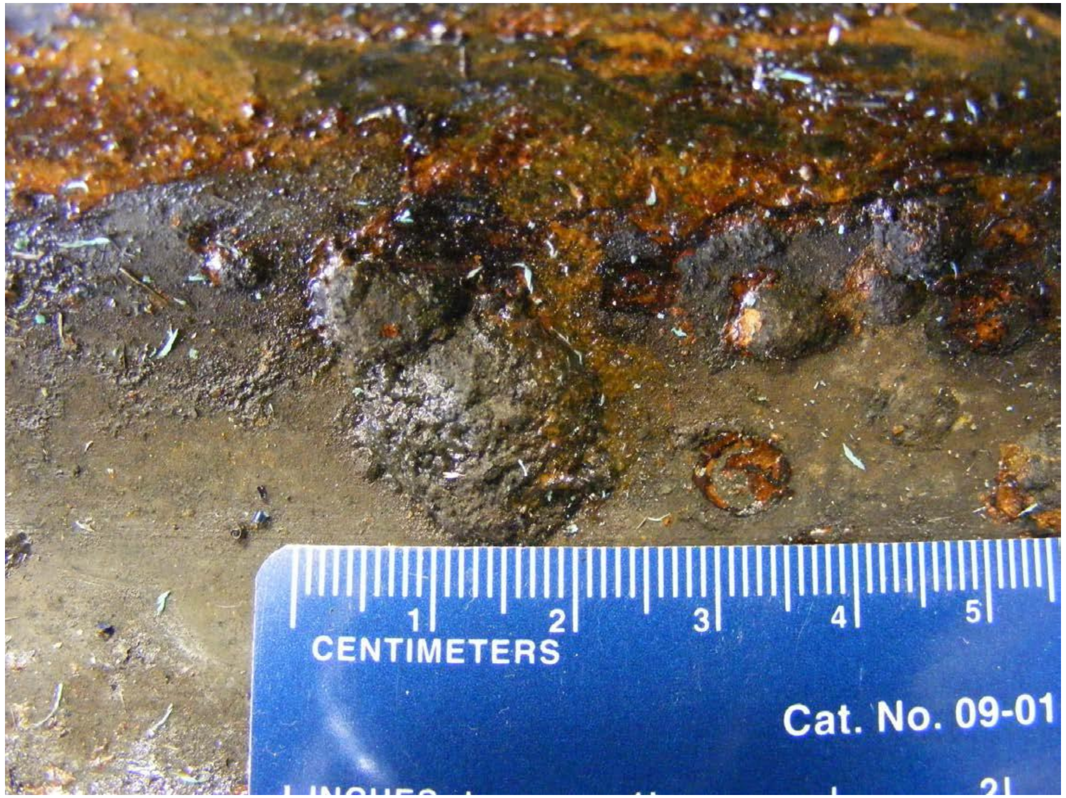
EAGLE FORD MIC

Slow flow unable to sweep sludge and biomass out of pipes

SPE Presentation: Microbial Corrosion (MIC) in the Eagle Ford Shale (Patrick J. Breen – Marathon)

Eagle Ford Gathering Lines

SPE Presentation: Microbial Corrosion (MIC) in the Eagle Ford Shale (Thanks to Patrick J. Breen – Marathon)



Left: a “blister” that is debris covering a bacteria colony.

Center: the pit in the pipe wall under the “blister” – note the “stair-step” sides.

Right: a pit through the gathering line wall.

This type of damage occurred within six months of gathering line construction.

Some Corrosion Control Best Practices

1. Maintain high pH (pH >7 minimizes acid reactions)
2. Control gas breakout (turbulence disturbs protective layers and inhibitor films)
3. Use passive metals (e.g., Carpenter 20, Hasteloy, Monel, etc. – but match alloy to case)
4. Remove Oxygen (Close tank hatches, pump intake leaks and use nitrogen blankets)
5. Control velocities (too low allows bacteria growth, too high disturbs inhibitor films and layers)
6. Lower chlorides (low pH and high salt concentration can be very corrosive)
7. Bacteria control (continuous & batch treating may work, but survey and remove sessile colonies)
8. Acid/brine use considerations and alternatives
9. Control bacteria in waters used for any purpose
10. Inhibitor injection – match inhibitor to the need
11. Coatings may work in initial construction but watch erosion and wireline cuts.

Corrosion – management strategy

- Adopt a corrosion management strategy.
- Be aware of corrosion and erosion causes.
- Completion planning must reflect corrosion potential over well's life.
- Develop maintenance programs, measure corrosion.
- Know the corrosion specialists.
- Ensure inhibitors are compatible with materials and the reservoir!
- If tubing corrosion is suspected, DO NOT bullhead fluids in the perforations or the formation.

REMOVAL OF "PROTECTIVE" FILM

corrosion in tubing exacerbated by abrasion from wireline operators.

Conclusions - Specific Takeaways

- Problem types may be common to an area or technique. Problems in drilling are reliable precursors to problems with well integrity.
  - Dog Leg Severity (DLS)
  - Poor cementing practices
  - Cutting corners on any part of well construction.
- Production issues on older wells (prior to refracturing) must be examined.
  - Corrosion, hydrogen embrittlement, erosion, etc.
- Recurring problems demand a closer look at the what, why, when and how of failures.

Critical Issues – early warnings

1. "Drilling incidents are often leading indicators of well integrity problems".
2. Initial well and completion design are factors in the ability to stimulate or re-stimulate.
3. Critical factors in cementing include:
   - Landing points of critical upper completion casing strings to provide a high strength "shoe",
   - Centralization of the pipe,
   - Pre-cementing preparation of the drilled hole,
   - Quality of cements during mixing and pumping,
   - Minimize gas flow, fluid loss & equivalent circulating density in cement placement.
   - Final cement top position that seals off all annular gas charged formations and protects against leaks,
   - Sufficient cement overlap between nested casing strings,
4. High pressure, high temperature and cyclic applications of high pressures can produce cracks in some single-barrier cement sheaths. This can be offset by cement and additive selection

Gas Storage Well – Recompleted from a producing well. Look at Records…….

- Initial drill 10-5/8” hole from surface to 2767’ – lost circulation twice while drilling. (1953)
- Opened 10-5/8” hole to 16” from surface to 990’.
- Ran and cemented 11-3/4” (42 lb/ft) Youngstown (H-40) T&C casing at 990’ with 600 sx Diamix 1:1 followed by 100 sx of neat cement.
- Lost circulation with 114 ft3 (20 bbls) of cement slurry to displace. TOC 260 ft below surface.
- Cemented twice around top of casing – 75 sx, then 60 sx neat cement.
- Cleaned out to 2567’- drilled 10-5/8” hole to 2925’. Twisted off drill collar – fished 2 days and washed over & recovered drill collar.
- Drilled 10-5/8” hole 2925’ to 3073’ Twisted off 11 joints DP and 2 drill collars – fished and recovered.
- Drilled 10-5/8” hole to 4530
- Drilled 8-5/8” hole to 4948
- Lost 893’ of DP, drill collar and tools – fished for 7 hours – no recovery.
- Plugged back to 3967’ – set cement plug, set whipstock at 3860’
- Drilled off whipstock with 7-7/8” bit to 3929’ at 3.5 degrees deviation.
- Opened hole to 8-1/2”- opened to 10-5/8” to 8585’
- Ran mixed string of 7” casing, (26lb/ft J-55, 23 lb/ft N-80, 26lb/ft N-80, 29 lb/ft N-80) to 8585’
- Cemented with 600 sx cement (came 1724’ up the annulus, creating 6861’ of open hole to the bottom of the 990’ shoe of the 11-3/4” surface string.
- Drilled out with 6” bit to 8749’, reamed, ran 189’ 5-12” flushed joint liner (slotted) (1954)

Sustained Annular Pressure
(SPE 119869 case history – gas storage)

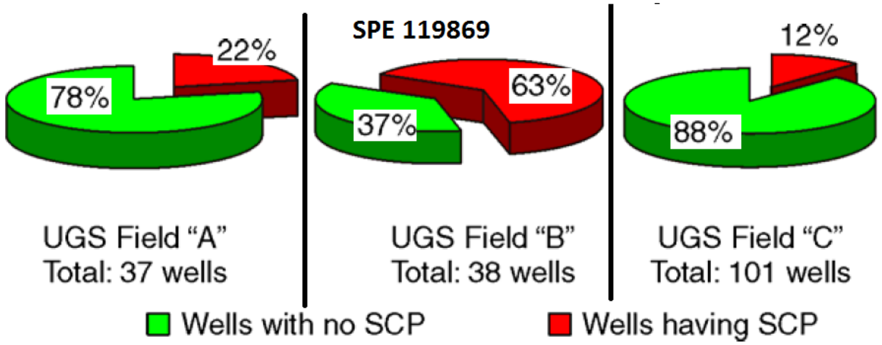
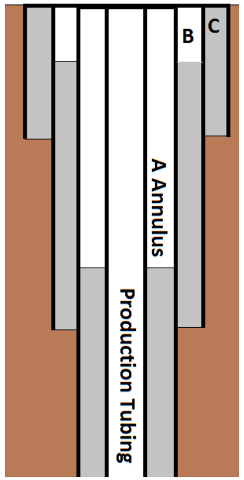


Fig. 1—Sustained casing pressure observed before this study.



Rotation
Thin or Light Mud
Good Centralization
Plugs Ahead & Behind
Optimized Shoe Track Length
Enhanced Modeling & Sensitivities Run
Verification Testing
LCM Fluid Design

Fig. 10—Cement sheath bond log.

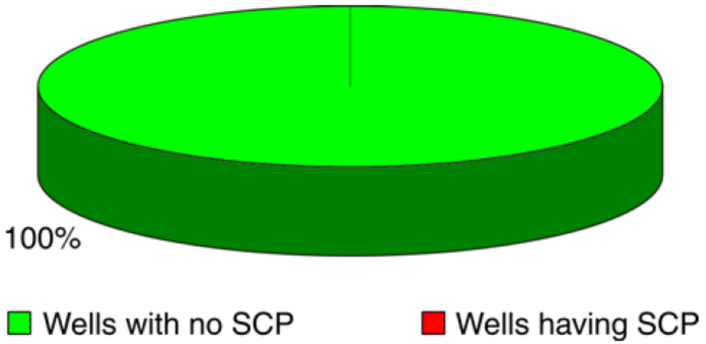
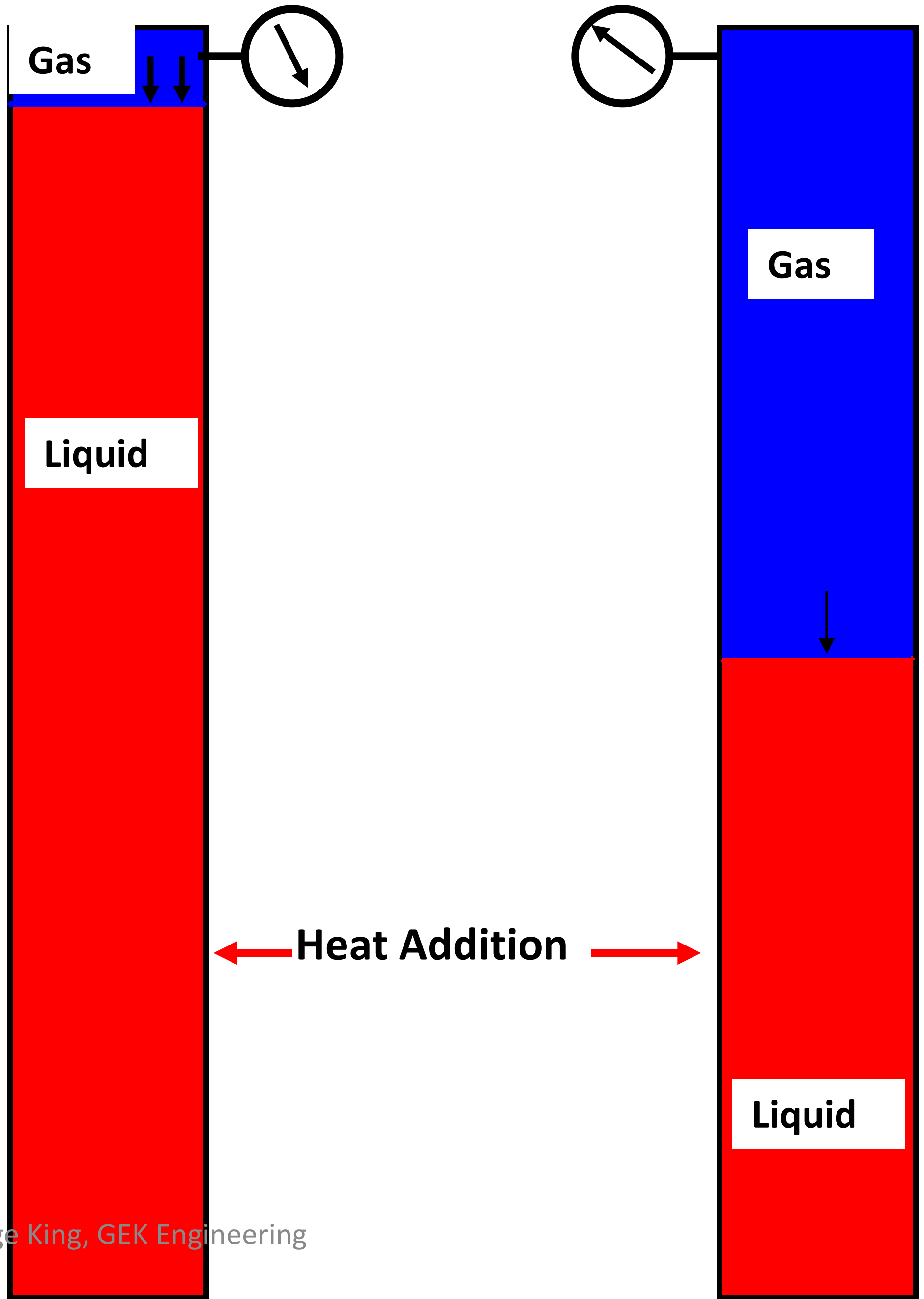


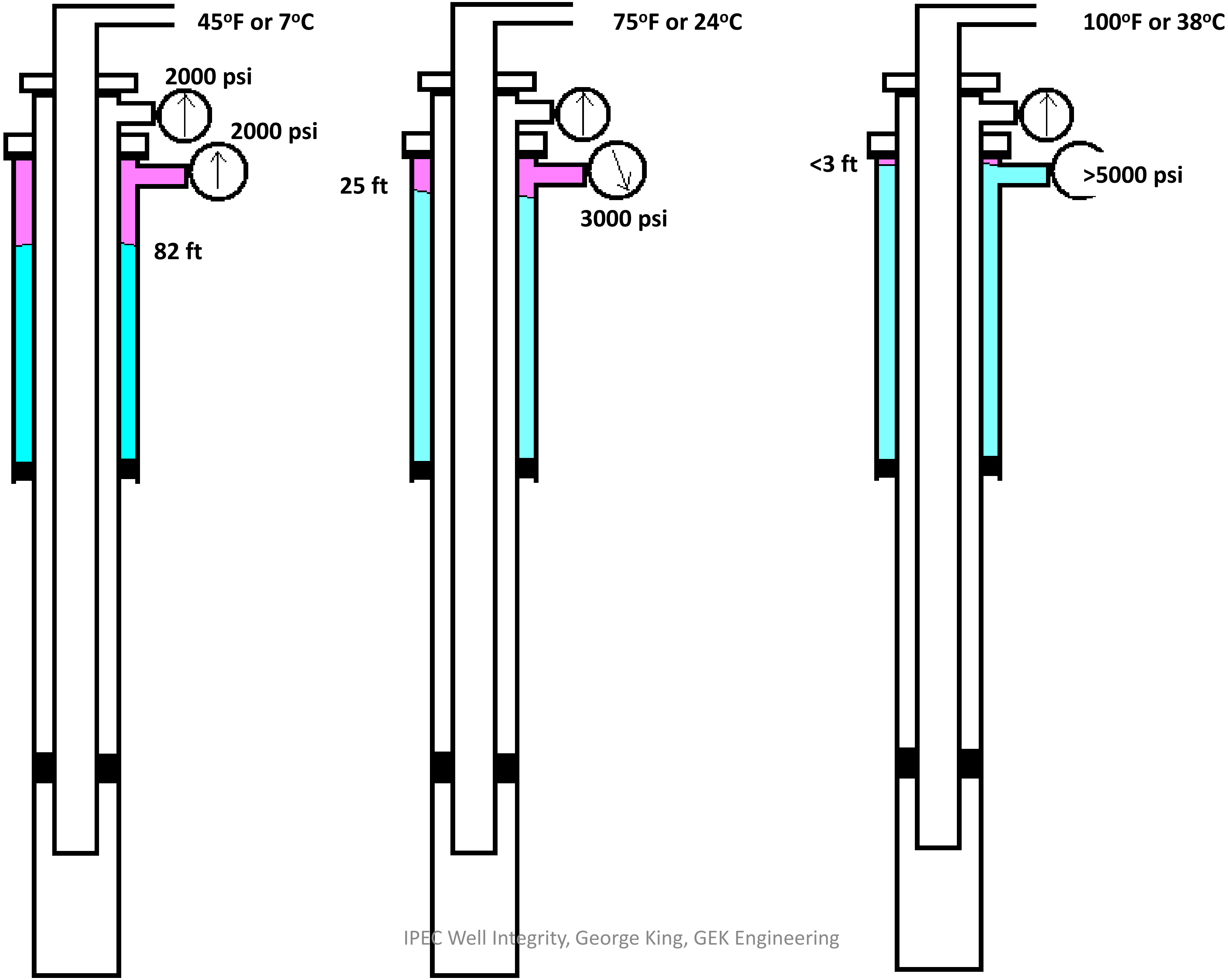
Fig. 11—SCP not observed after implementing solutions from this study.

If you relate the trapped volumes and the initial compression factors back to well operation:

- An annulus with more low pressure gas will compress slower than one with small gas volume

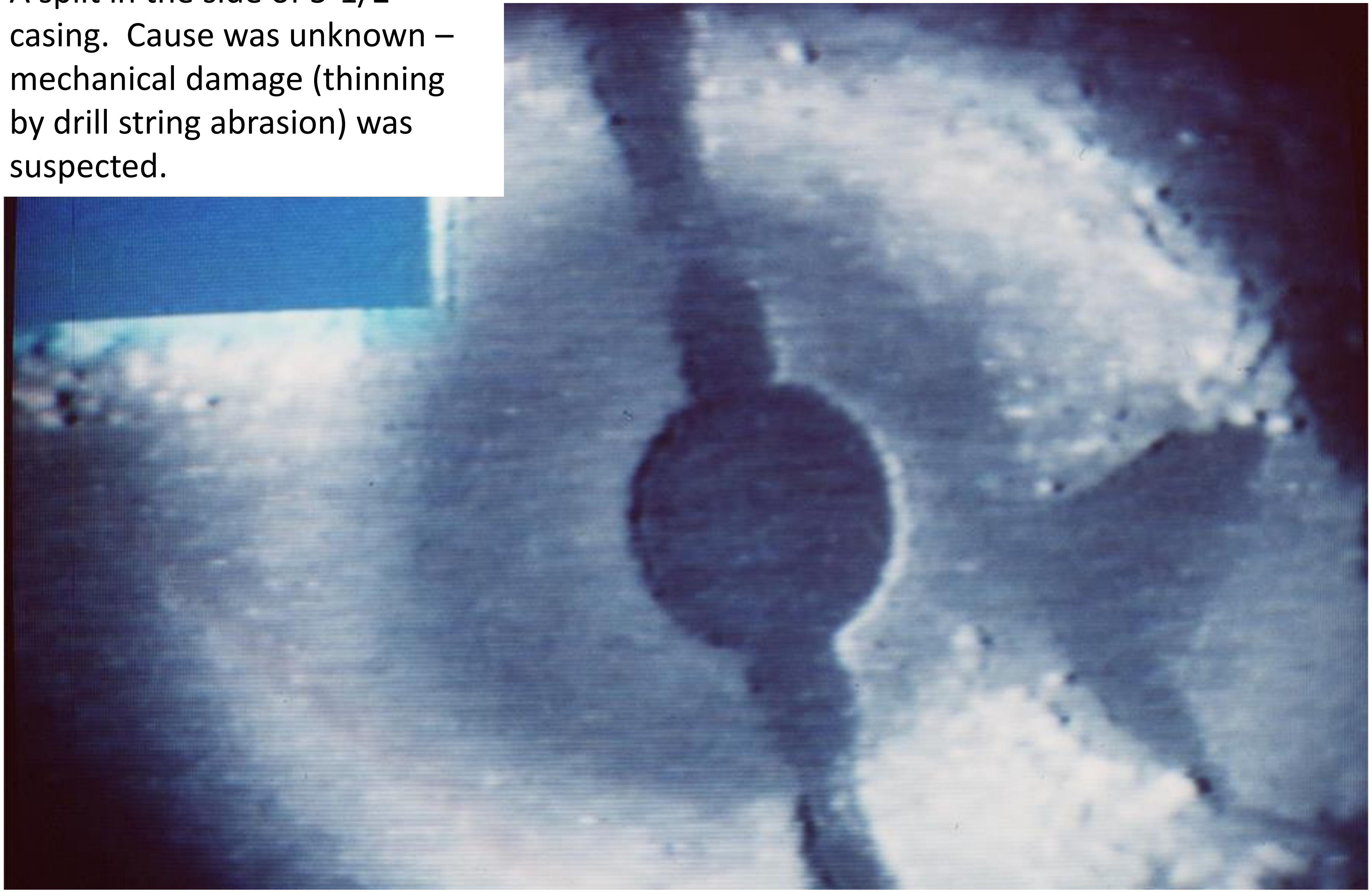
- An annulus with a gas volume that is already highly compressed will experience a faster pressure rise.




45°F or 7°C
2000 psi
2000 psi
82 ft
75°F or 24°C
25 ft
3000 psi
100°F or 38°C
<3 ft
>5000 psi

Wear Damage

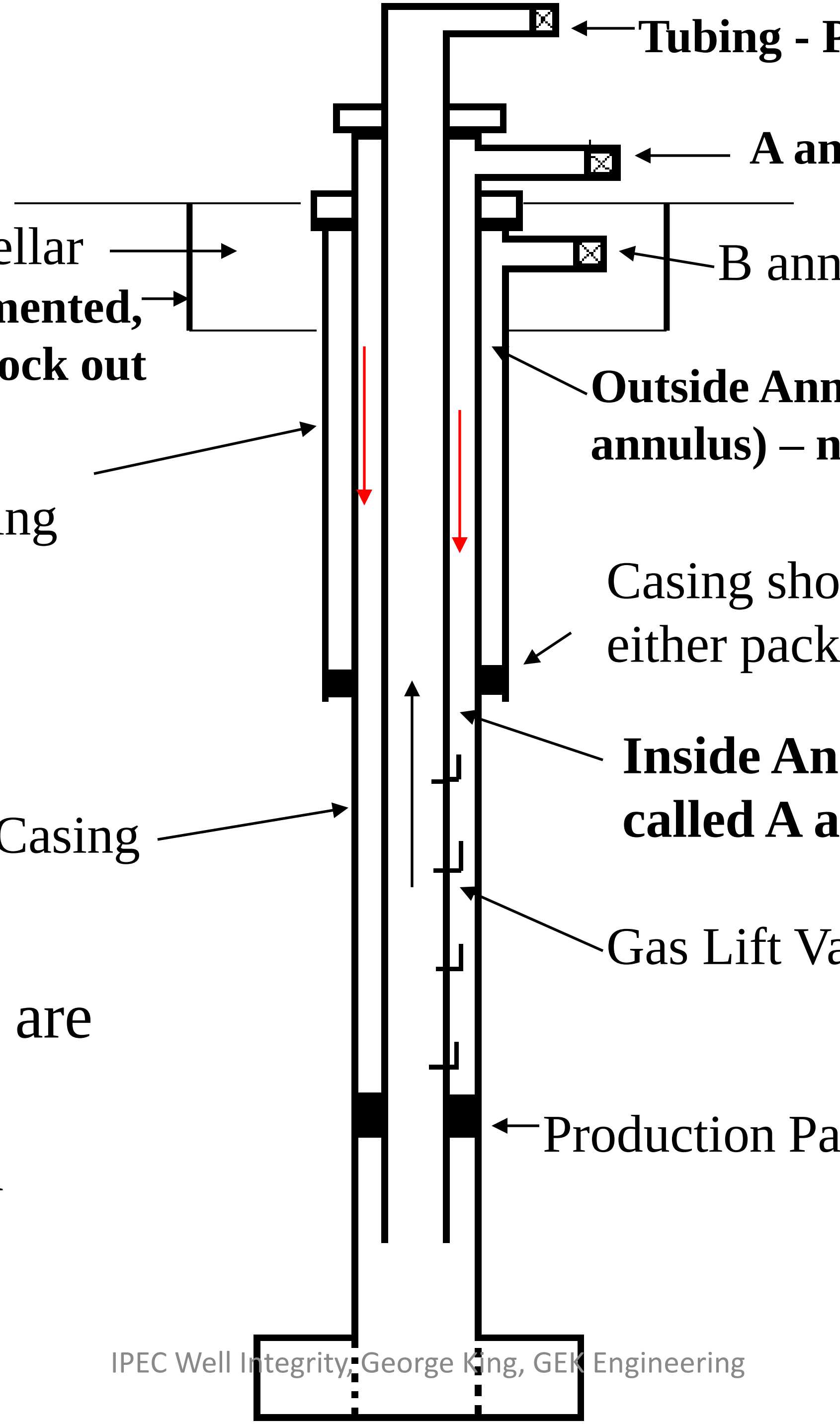
A split in the side of 5-1/2” casing. Cause was unknown – mechanical damage (thinning by drill string abrasion) was suspected.



Annular Pressure and Integrity

- The causes of annular pressure
- What defines well integrity?
- Rate of heat transfer – loss and gain
- Leaks – self equalizing and one-way.
- Remediation,
- Monitoring,
- Prevention.

Parts of a Well



Cement locations are not shown in this drawing although cement is used.

Pressure Integrity Tests

- PIT or leakoff test used to evaluate isolation created by a cement job. The formation immediately below the shoe is open to the test.
- Procedure – BOP is closed and fluid slowly pumped into well. At a set pressure, injection is stopped & pressure is monitored for a time to check for leaks, then pressure is released.
- Drilling can progress is the test shows no leaks that cannot be explained by the permeability of the formation.

Pressure Integrity Tests

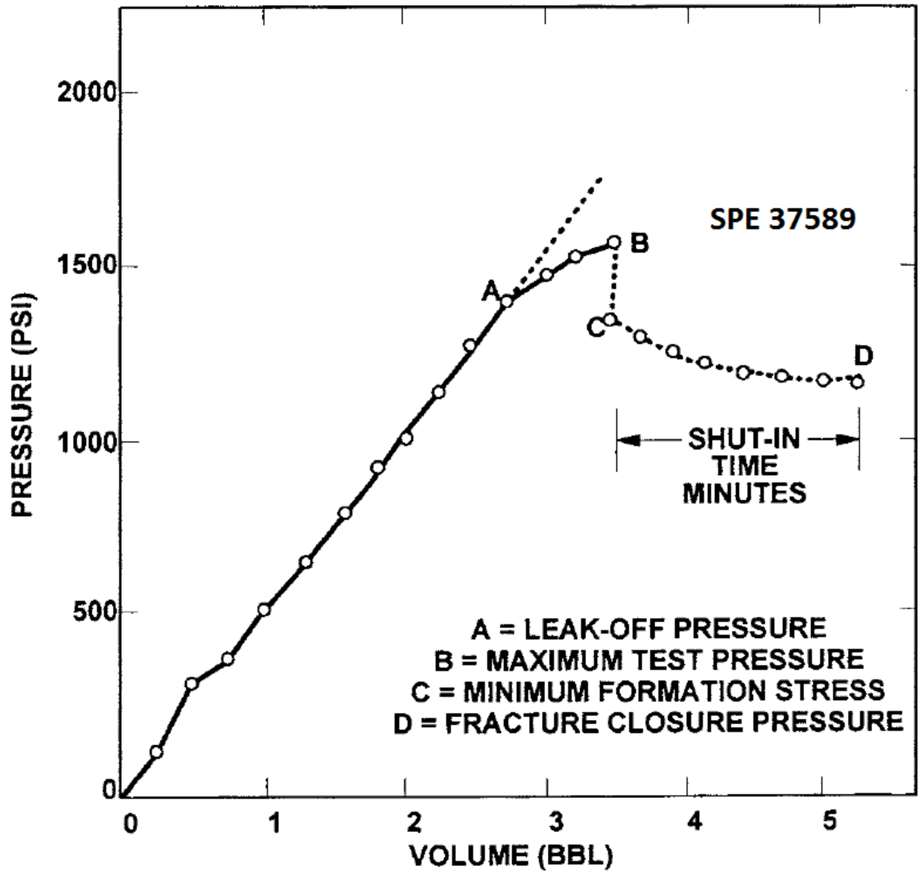
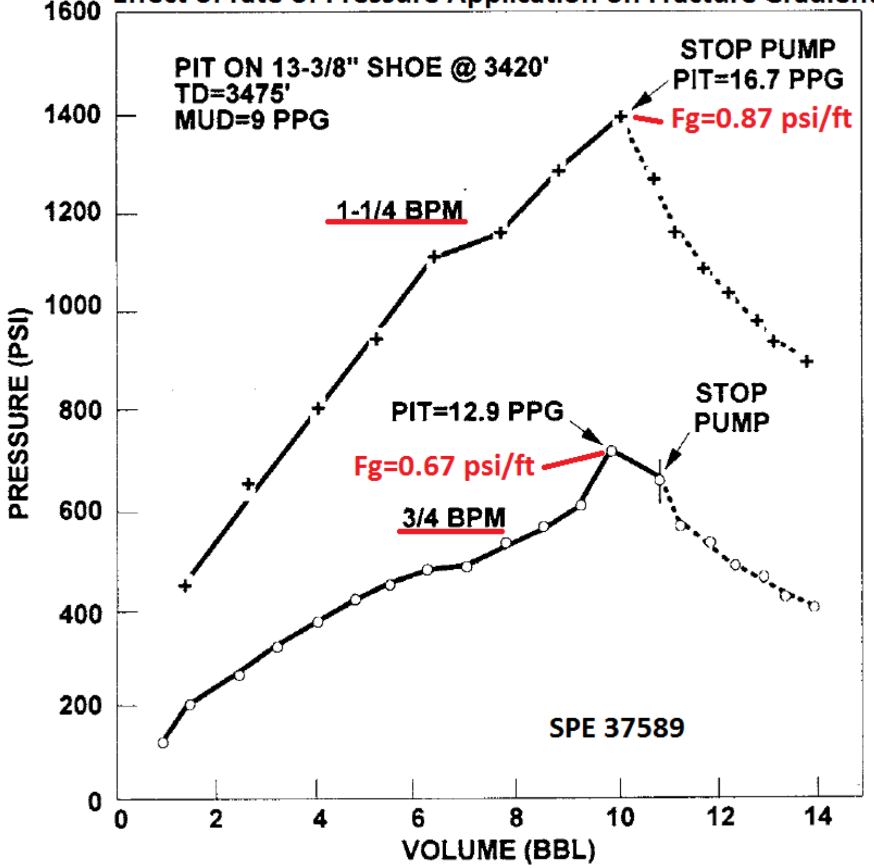


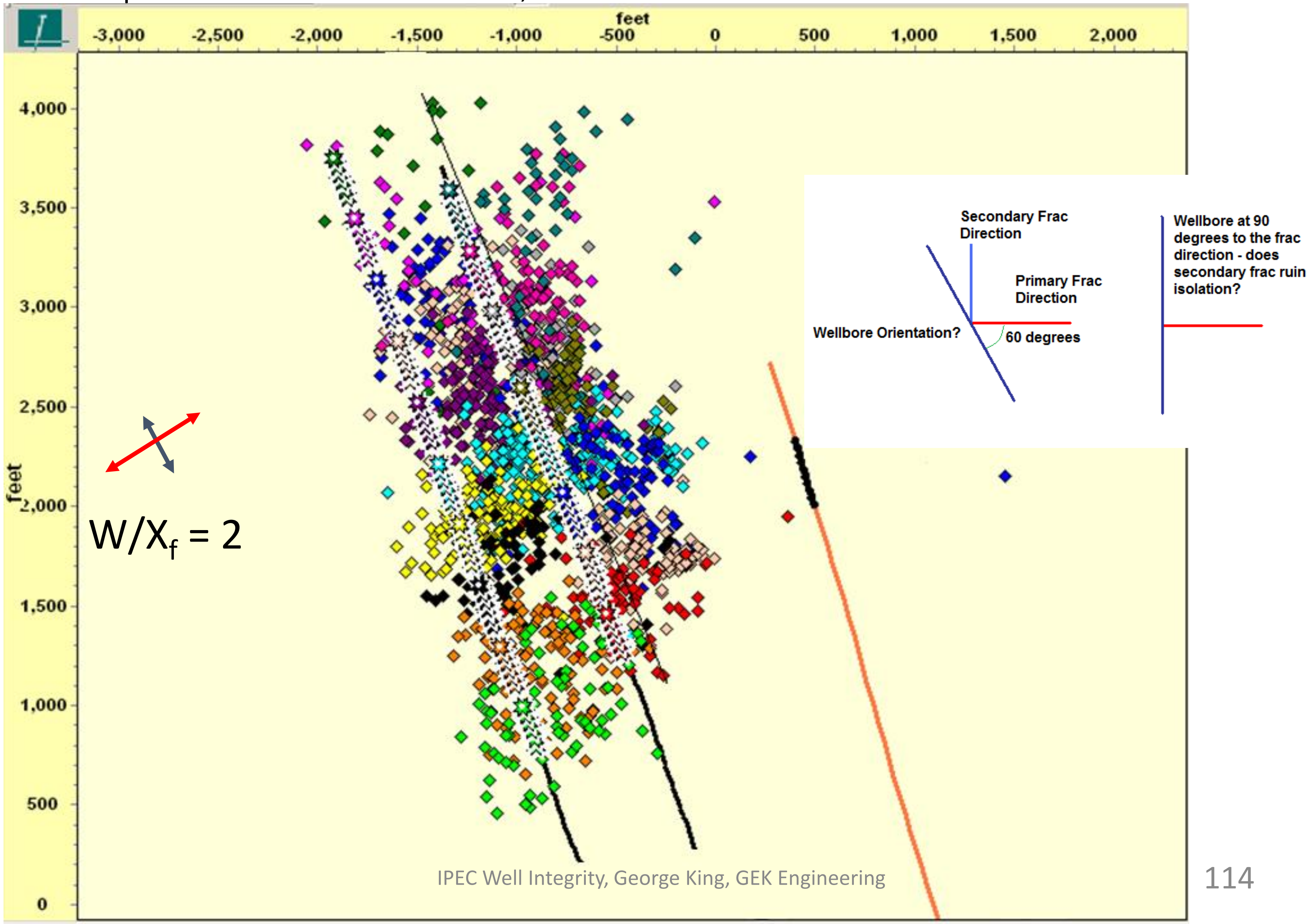
Fig. 2 Typical Open-Hole PIT Plot

Effect of rate of Pressure Application on Fracture Gradient



Too slow a rate will not properly describe the safe pressure.

Sequential Fracs – Barnett, Western Parker Co.



Examining Cement isolation (PNP)

Table 2—Number of stages showing communication with adjacent stages in 9 wells completed using cemented plug and perf systems (CPnP) and instrumented with FO both DAS and DTS. In average 13% of all the stages show lack of isolation from adjacent stages (*re-interpreted data). SPE 173348

Well	Total number of stages	Number of stages showing communication with adjacent stages
A	13	0
B	15	0
C	16	0
D	14	0
E*	9	1
F*	8	7
G	7	1
H	10	2
I	11	2
Totals	103	13

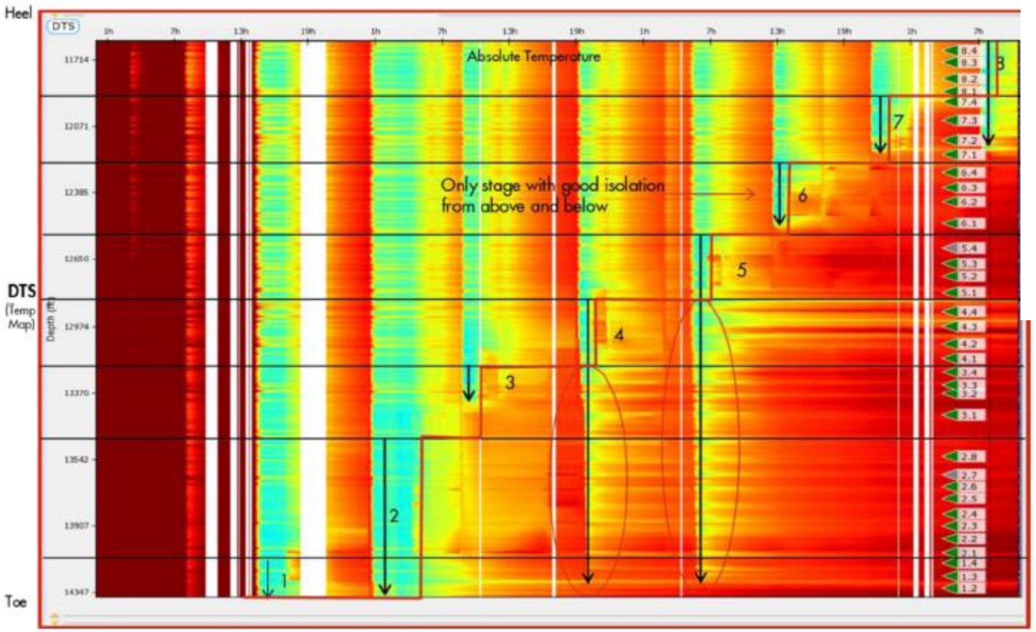


Figure 5—DTS temperature map of multi-stage hydraulic fracture stimulation (8 stages) in a horizontal well completed using cemented plug and perf systems limited entry (CPnP). Warm colors represent high temperature while cooler colors symbolize relatively lower temperatures. In this well the expected "stair-step" pattern is broken in all but one of the stages. The DTS indicates that during the stimulation of stages 4 and 5 communication occurs all the way to stage 1 (red ovals).

Well Integrity is in Every Step

Design	Application	Stimulation	Production	Maintenance	P&A
Information	Knowledge	Design	Economics	Commitment	Intent
Regulations	Experience	Regulations	Optimization	Barriers	Regulations
Economics	Commitment	Transport	Lift	Optimization	Geology
Function	Time	Fluids	Δ Press	Upgrades	Fluids
Flexibility	Metrics	Chemicals	Δ Temp	Corrosion	Pressure
Timing	Inspection	Proppant	Fluid Change	Scale	Steel
Trapped Press	Regulation	Safety equip	Barriers	Deposits	Plugs
Fluids	ΔP Testing	Pressure	Repurpose?	Leak Checks	Set points
Alloys	Requirements	Fluids	Life Extended?	Analysis	Milling?
Cement Blend		Time		Water Control	Leaks
Geology		Erosion		Inspection	Cement
Well Type		Backflow		Expectation	Testing
Design Life		Barriers		Report	Checks?
Repurpose?		Containment		Action	Time
		Fluid Storage			