SPE DISTINGUISHED LECTURER

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A Fatal Clean-out…An Engineer's Role in Safety

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Outline

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- Background on a fatal accident
- Learn about foam-air
- Describe what happened
- Explore why this accident occurred (best estimate)
- Operational Approach vs Engineered Approach
- Why Engineers matter
- The Engineer's Role in Safety

Background - Operator

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- Excellent safety record
- Professional Environmental, Health & Safety (E,H&S) team (ops focused)
- Experienced operations staff & well work supervisors

Yet…

- Surprising accident killed a young man and injured others
- He (and others) paid the price for this lesson
- You can learn from this lesson at virtually no cost to you or your company

Background - Well

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- Typical Permian Basin horizontal well
- Disappointing production
- Decision to clean out with *foam air*
- During job, a downhole explosion occurred
- Cause - *still not known with certainty*

What is Foam Air?

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- Mixture of water, surfactant (foamer), and air
- High viscosity/low density fluid
- Can circulate debris out of low-pressure wells
- Typically created with air
- Routine – thousands of jobs/year in Permian Basin alone
- *Expect more when currently new laterals age*

Foam Air Unit

- Foam Air Unit (FAU) field unit comprised of water pump, surfactant/chemical pump, and air compressor

Pumping *air* into an oil & gas well!

Is that *safe*?

- Thousands of jobs without incident suggests: “Yes”
- Water film surrounds bubbles of air
- Foam prevents natural gas (fuel) and air (oxygen source) from forming an explosive mixture
- Used to *extinguish* fires

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Foam air is used to extinguish fires, especially aviation fuel.

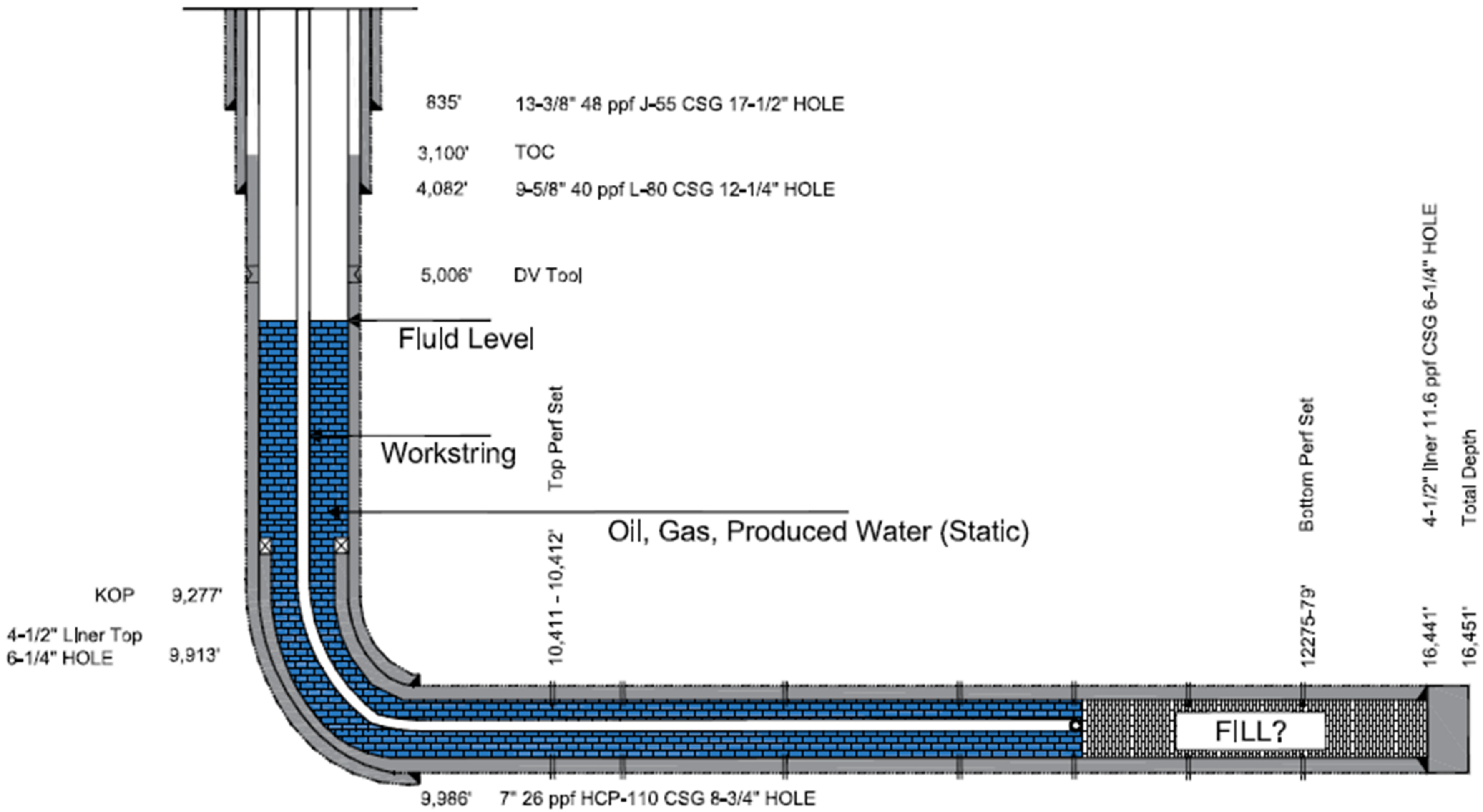
What Happened?
Summary Work Sequence

- Step 1) Killed well – Rigged Up – Pulled pump
- Step 2) Ran workstring & checked for fill (2,609’ short of Total Depth)

Wellbore Diagram

Check for Fill in Lateral

Killed well – Pulled pump – Checked for fill



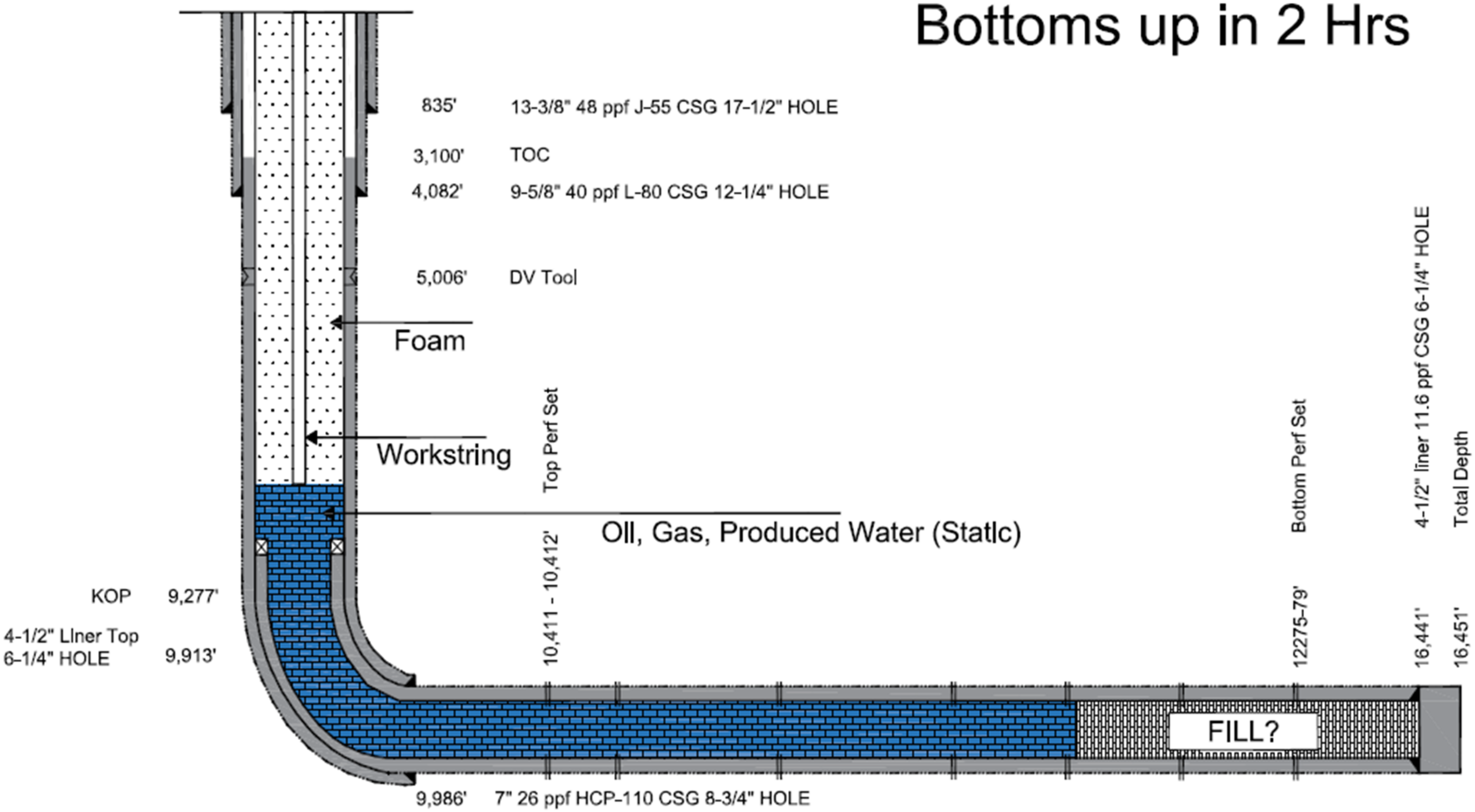
What Happened?
Summary Work Sequence

- Step 3) Ran In Hole with ***new*** workstring to just above kick-off point (KOP)
- Step 4) Established circulation with foam air +/- 1600 psig on tbg 600 psig on annulus with a stripper head (torus) - circulated 2 hours for bottoms up

Wellbore Diagram

Circulate Foam at KOP (Planned)

New workstring to KOP- Establish circulation- Bottoms up in 2 Hrs



What Happened?

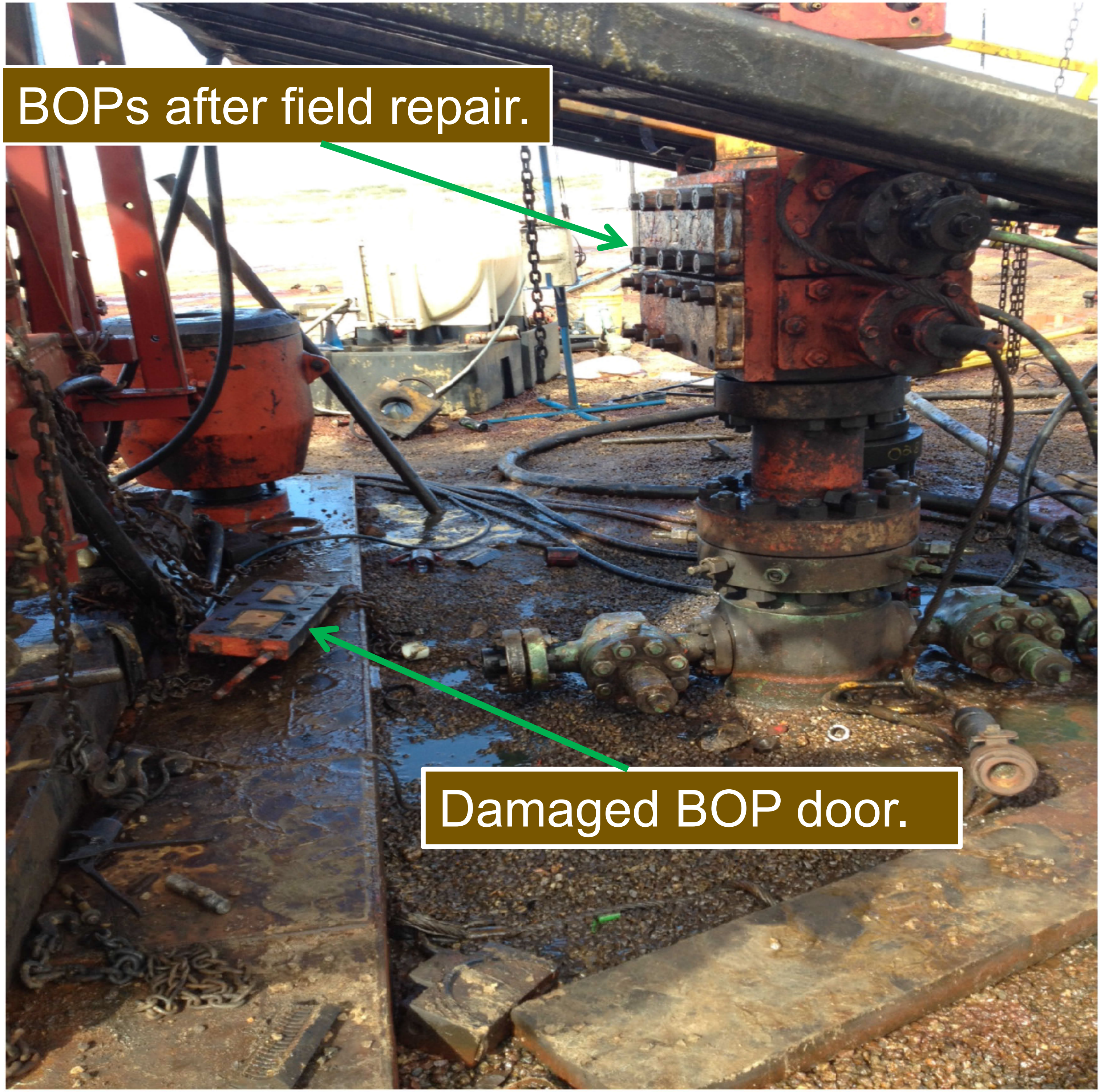
Summary Work Sequence

- Step 5) Shut down. Watched annular pressure *rise* and then stablize. Foam operator declared well ready to strip in to next circulation point. Blew down/disconnected injection line from tubing.

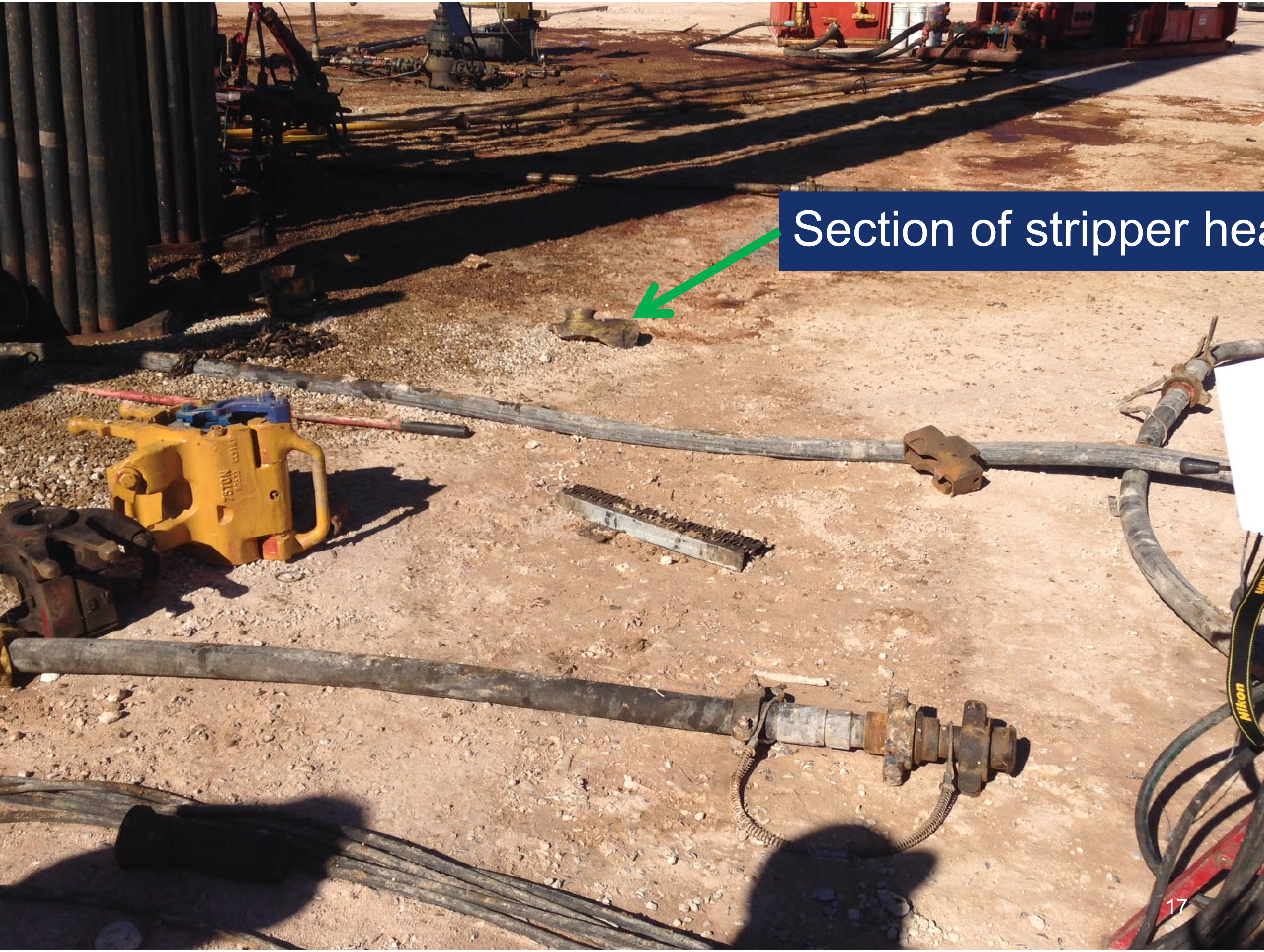
- Step 6) Ran in hole with 12 more joints of ***new*** workstring.

Explosion occurred. “Ash” & foam released with oil on ground.


5,000 psi BOP
Door Blown Off

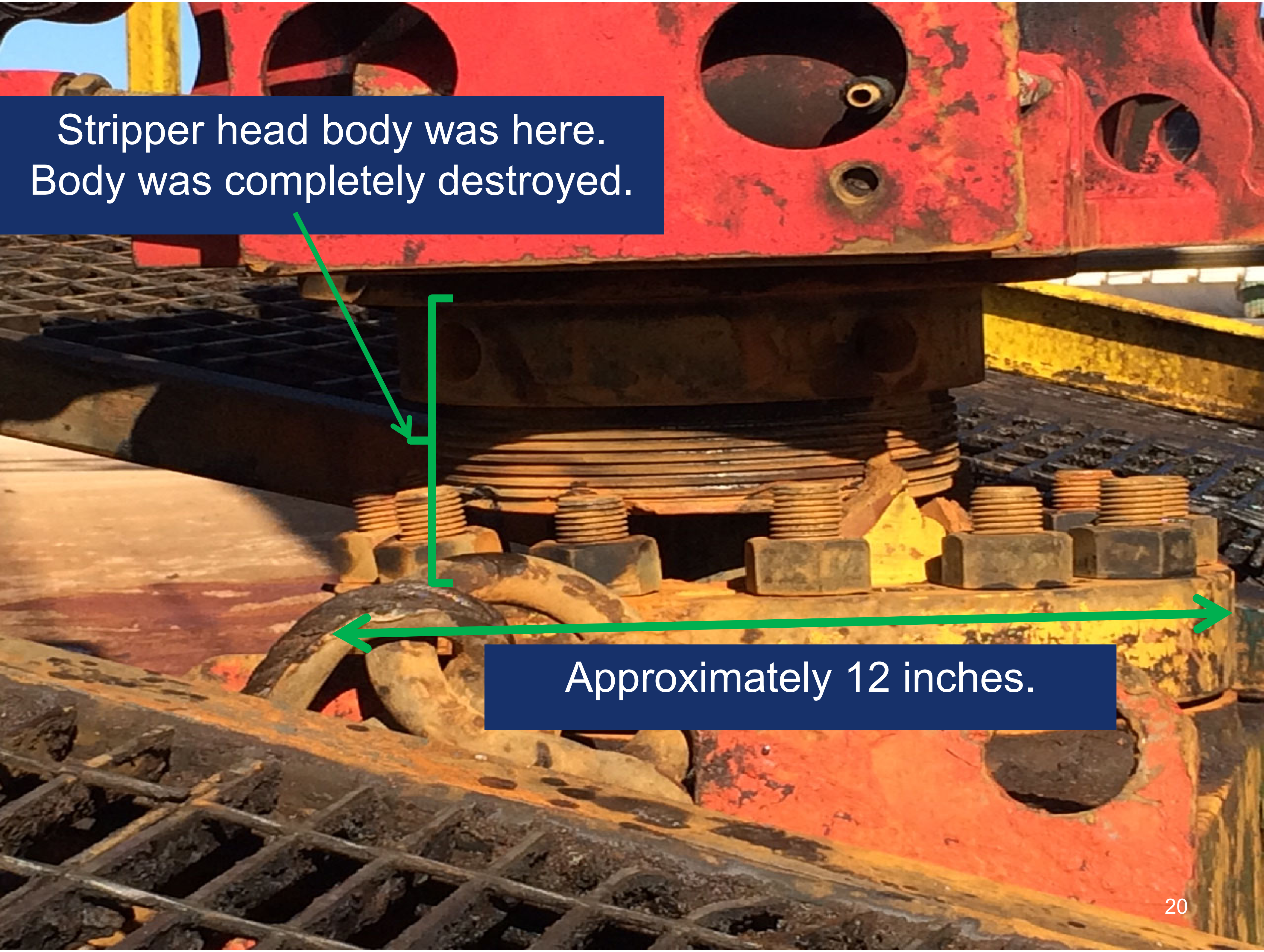


SPE DISTINGUISHED LECTURER


Section of stripper hea


Section of stripper head


Approximately 12 inches


Stripper head body was here.
Body was completely destroyed.
Approximately 12 inches.

Stripper head rubber element blown through the keeper and the slips.

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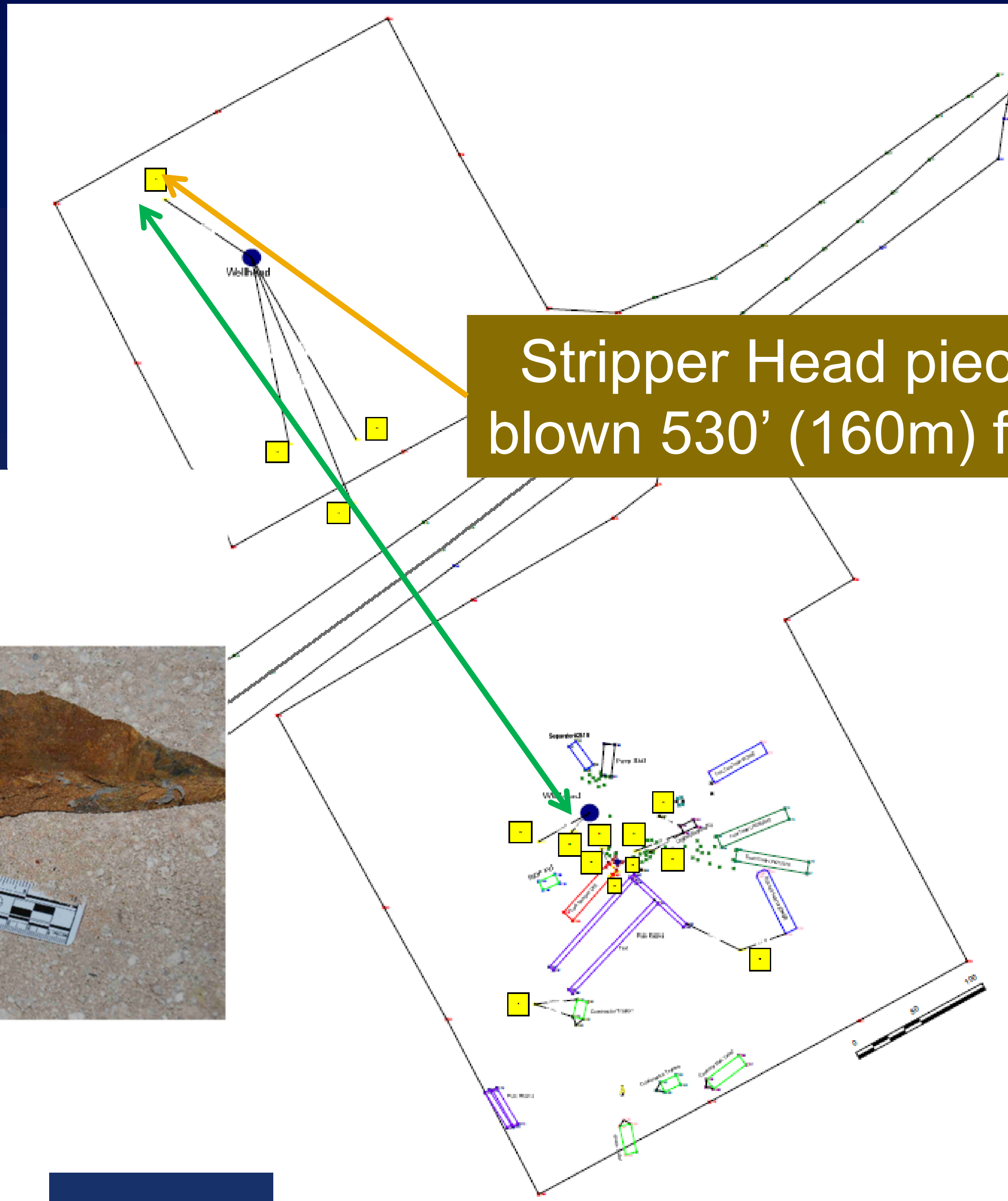
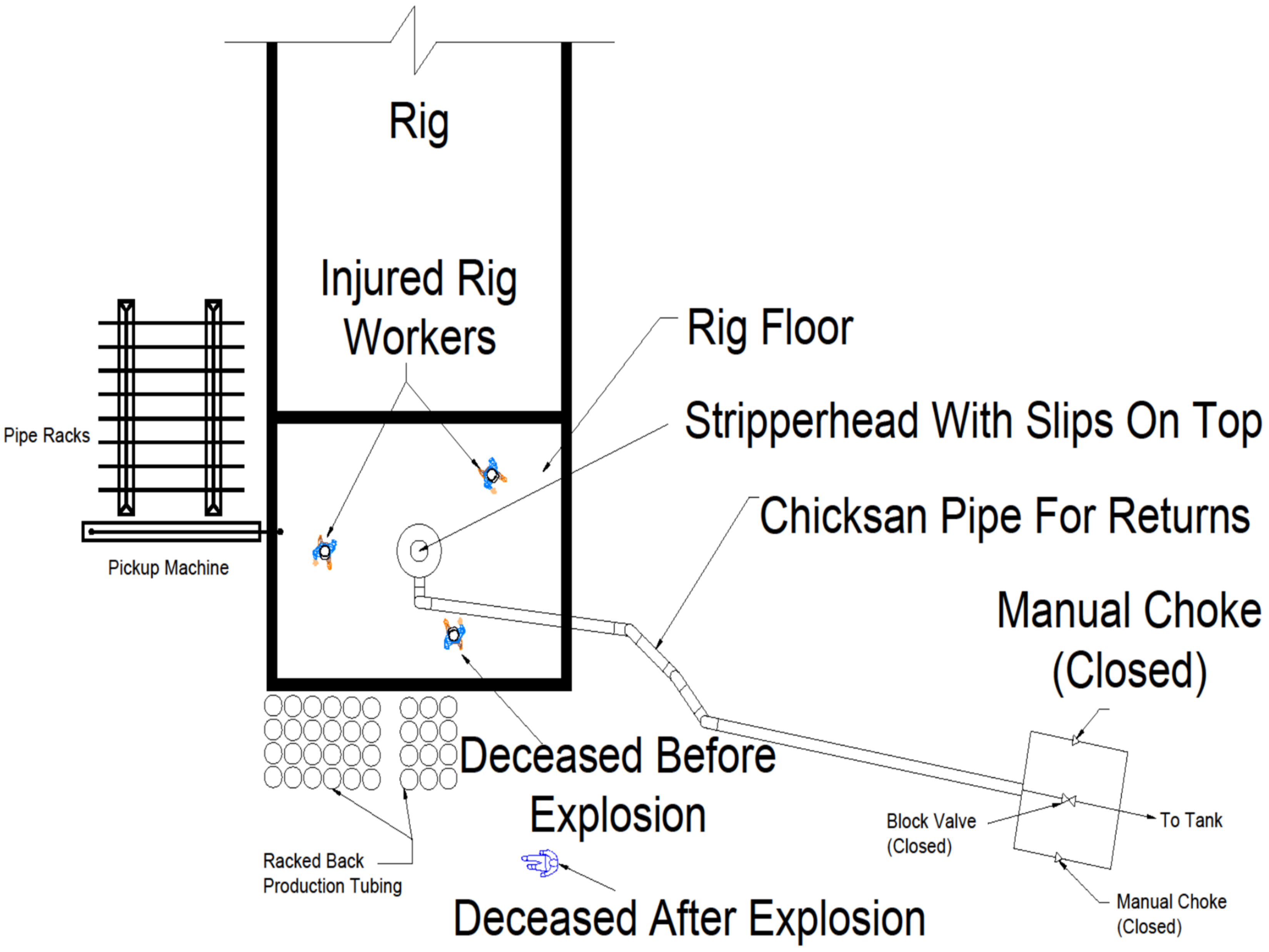


Stripper Head piece 4” x 8” x 1” blown 530’ (160m) from wellhead!

Rig Floor Detail



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What Happened?

Aftermath

- Tended to injured. Secured the scene. Immediately investigated by Occupational Safety & Health Administration (OSHA) accident inspector, operator, other service providers.
- Captured relevant samples.
- Engaged expert accident investigators.
- Engaged outside engineering firm for analysis.
- Engaged foam expert.
- Tested casing…*no leaks*. Ran casing log.
- Gathered additional information through legal discovery process (legal proceedings made for slow data acquisition).

What Happened?
Analysis

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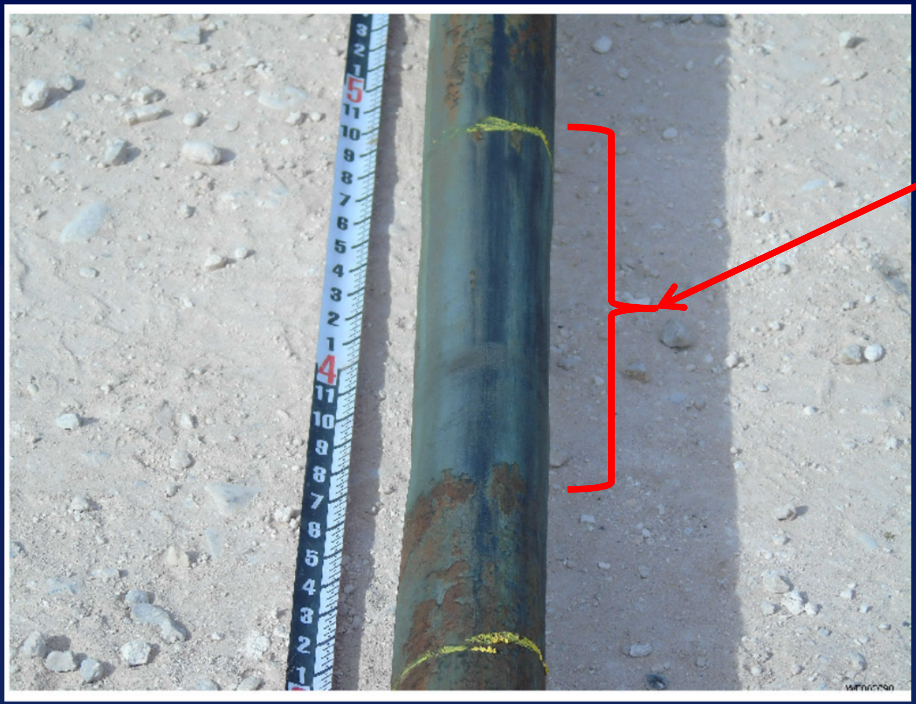
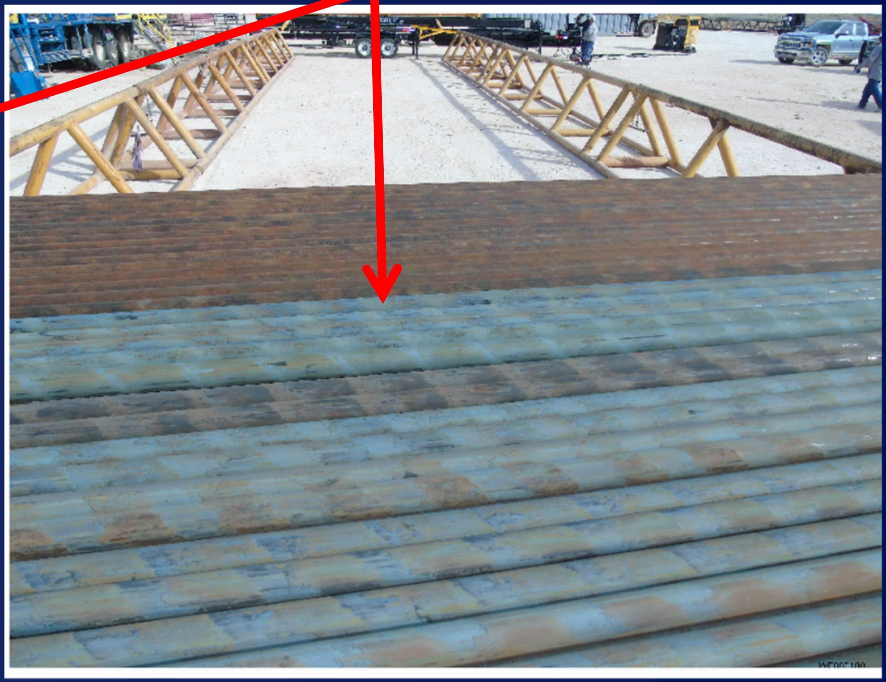
- Initial downhole explosions (detonations or deflagrations) occurred at approximately 606’ and 698’ from surface in annulus.
- Shockwave and combustion travelled up the annulus until it struck the top of the closed annulus (stripper head/BOPs), destroying both.
- How do we know?



New work string "compressed" – reduced diameter.

New mill scale on new work string "burned". Had the look of copper green from +/- 700' to surface.



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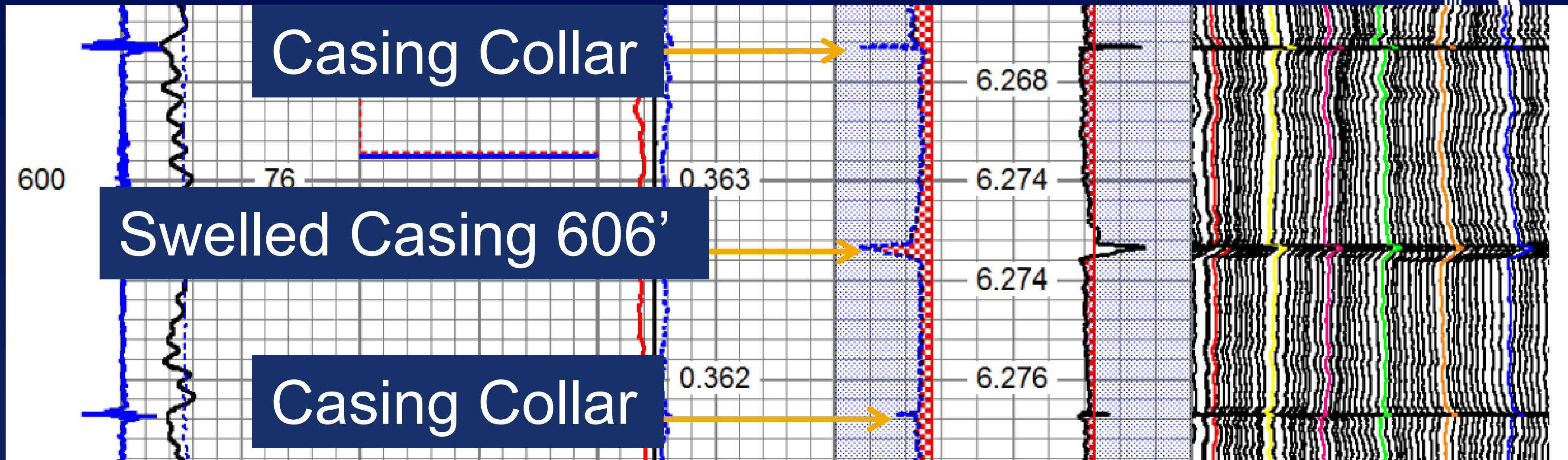

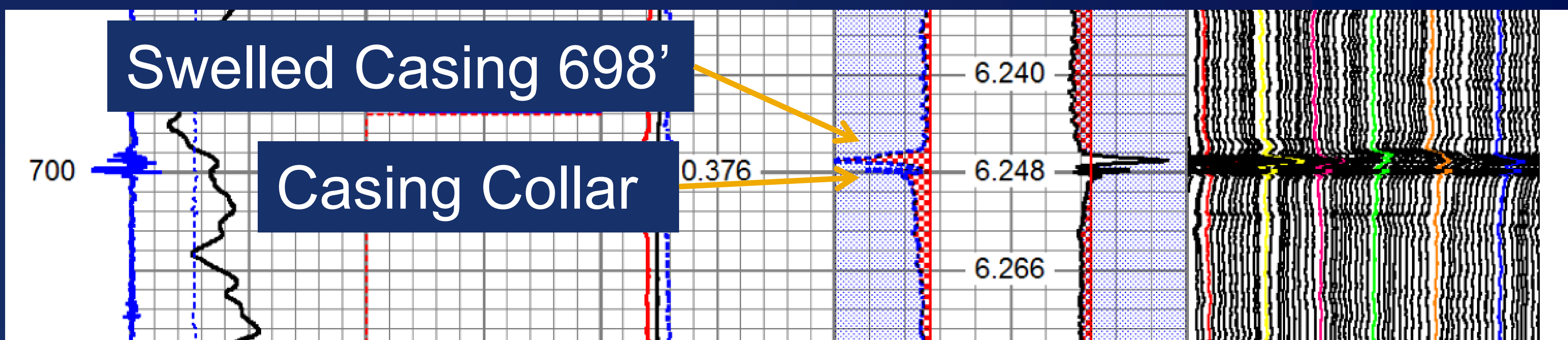

Casing swelled at depths of tubing deformations.
Casing passed a pressure test after the incident.

What Happened?
Questions

- Explosive mixture formed in the annulus and was ignited.
  - Where did hydrocarbons come from? (Fuel)
    - Only source was downhole.
  - How was the explosive mixture formed? (Oxygen)
  - Ignited how? (Ignition)
    - Heat of friction? Static electricity? Auto-detonate? Catalytic reaction?

- Let's learn a little about foam.

Foam “challenges”

- Even “stable” foams break down with time.
- Foams break down with temperature.
- Certain foams break down due to *contact with crude oil*.
- What happens to the air when foams break down?
- Can an explosive mixture be created? Yes. If methane is present (oxygen already present).

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An Operational Approach

VS

An Engineered Approach

An Operational Approach

- Considered a "Routine Field Operation".
- *No real engineering involvement*.
  - Design
  - Execution
- Depended on well work supervisor's and service providers' experience and *"what worked last time"*.

An Operational Approach

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- FAU crew used a standard "operational" procedure: Circulated bottoms up using rules of thumb, shut well in, and watched for a modest *pressure <u>rise</u> on annulus before stabilizing*.
- Based on observations and Operational Experience, crew determined that is was safe to proceed (with tragic results).

An Engineered Approach

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- First: Understand the Objective
- By default, we <u>perceived</u> the objective as:
  - Establish circulation to clean out debris
- Never actually defined the objective
- We <u>assumed</u> that field personnel would maintain a safe work environment during the clean-out

<u>Never assume when safety's at stake</u>

An Engineered Approach

SPE DISTINGUISHED LECTURER

- Our objective *should have been*:
  - Establish circulation to *safely* clean out debris *while maintaining a bottom hole pressure sufficient to prevent influx of reservoir fluids*

An Engineered Approach

SPE DISTINGUISHED LECTURER

- FAU crew looked for and reported a *rise* in annular pressure after shut-in. What are possible sources of this pressure rise?

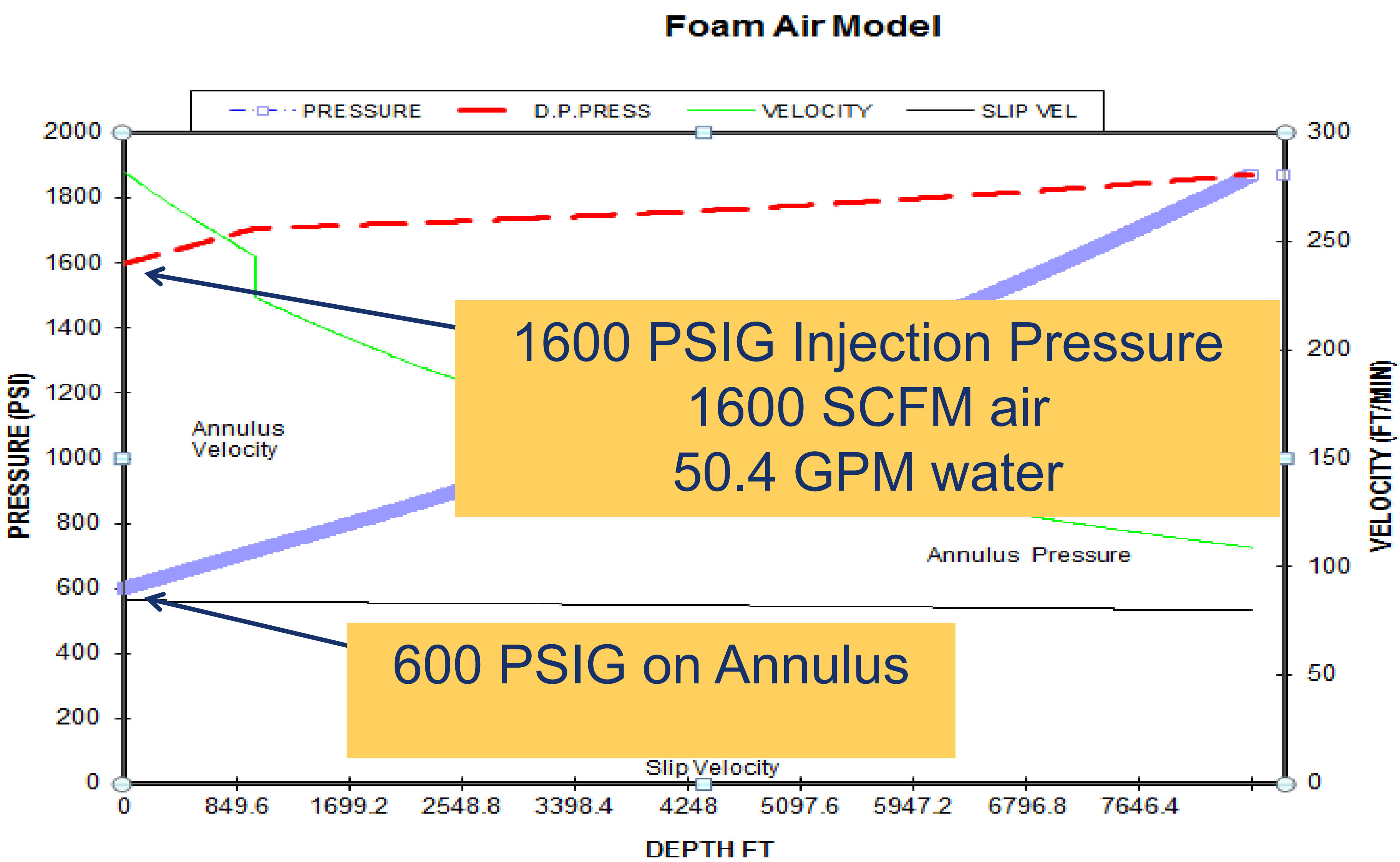
  1) Elimination of circulating friction (instant). Similar to reducing equivalent circulating density (ECD). How much?

  2) Feed-in from reservoir to a closed system until BHP balanced reservoir pressure. Well flowing.

If friction loss was less than pressure rise, *well was feeding in the entire time.*

An Engineered Approach

- Let's look at some engineering details…



Matches known parameters (pressure and rates).

Calculated annular friction = 132 psi

Credit: Reuben Graham

An Engineered Approach

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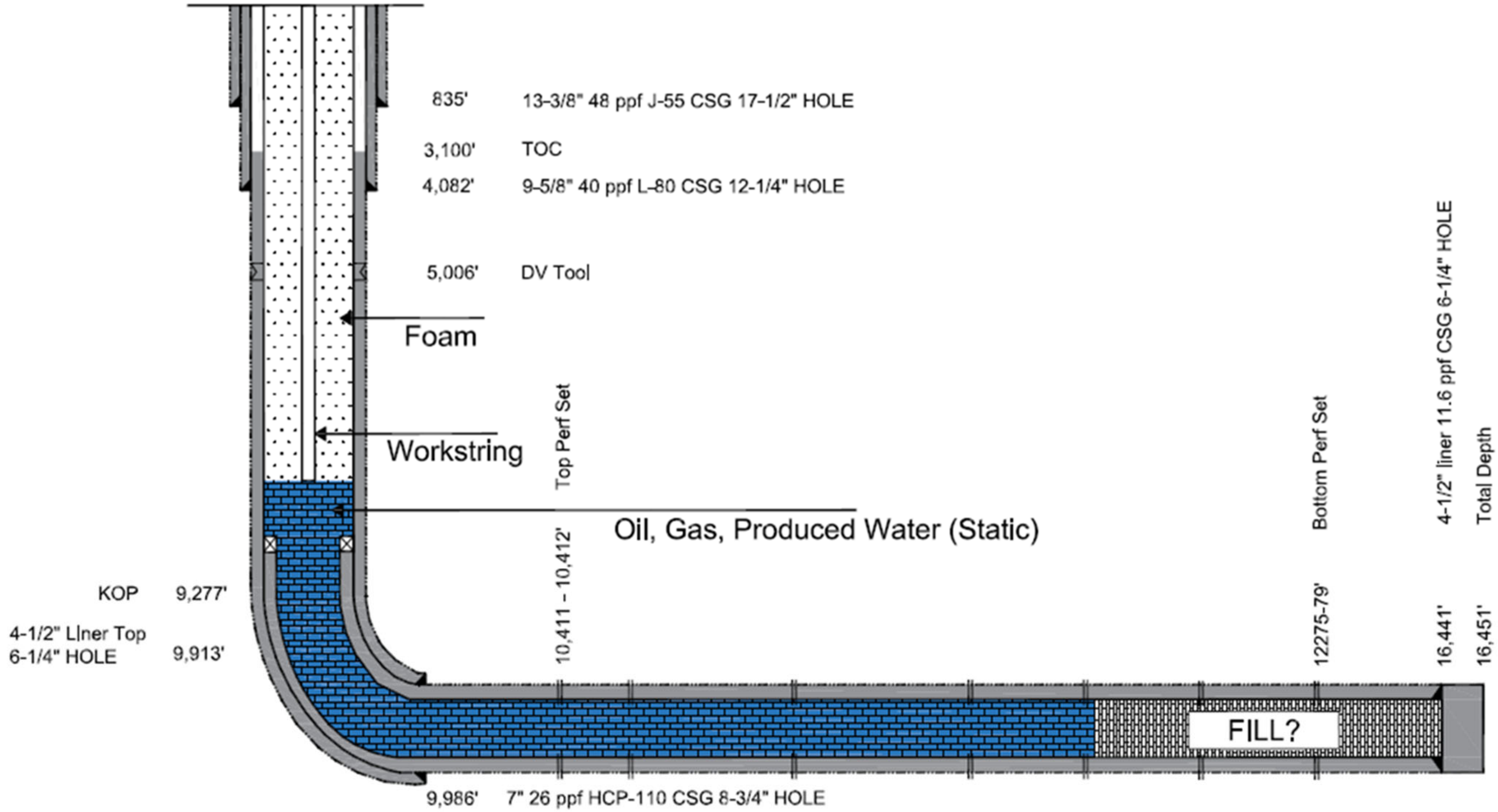
- Annular friction pressure 132 psi (+/-).
- Exact pressure rise after shut-in not known.
- Pressure rise reported later was "around 200 psi". Could have been higher.
- *Surface pressure rise was likely greater than annular friction loss.* Bottom hole circulating pressure (BHCP) was too low. That would explain hydrocarbons in the annulus.

Well was flowing the entire time and Operational Procedure was <u>*inadequate*</u>.

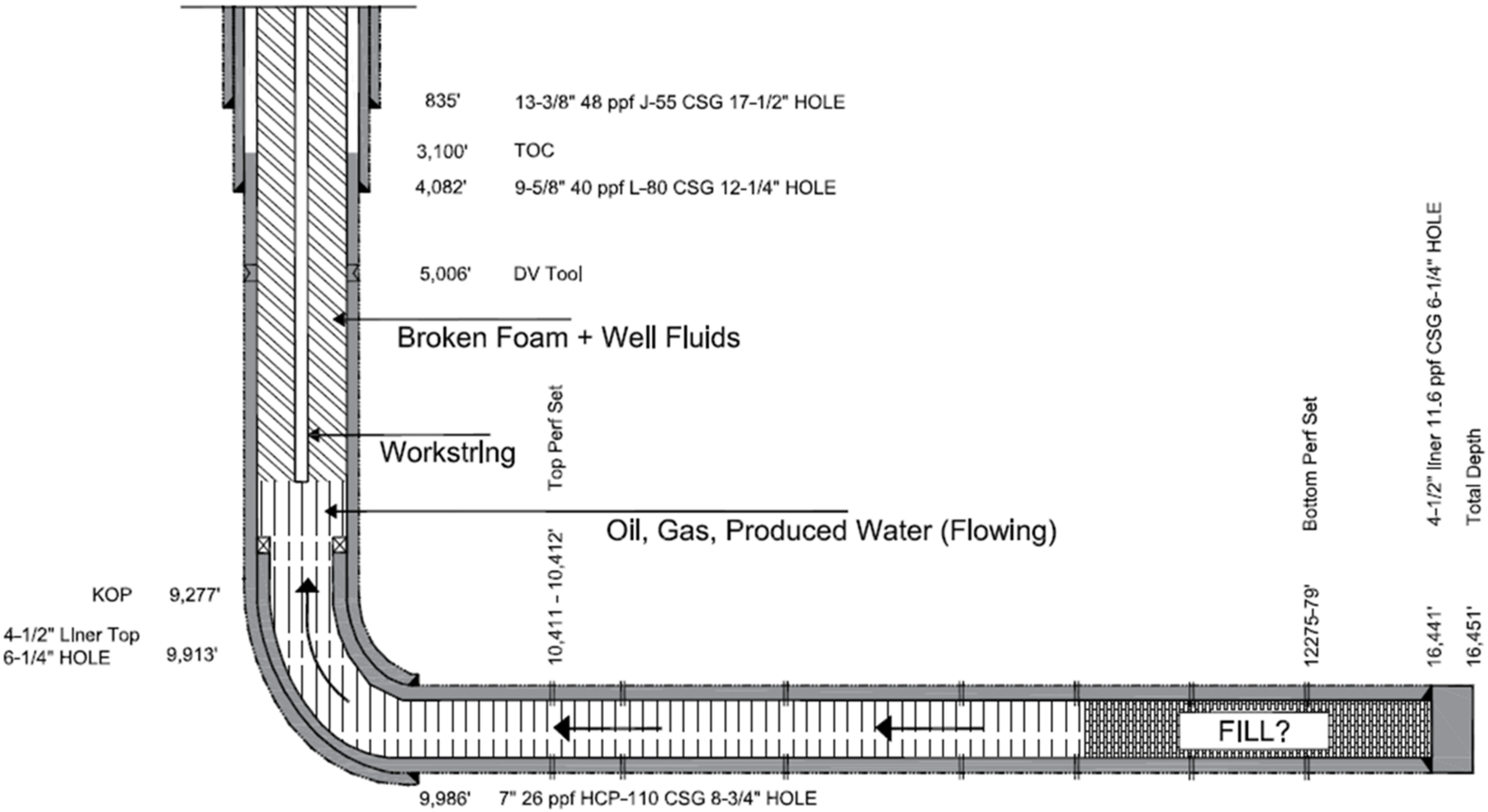
Wellbore Diagram

Circulate Foam at KOP (Planned)



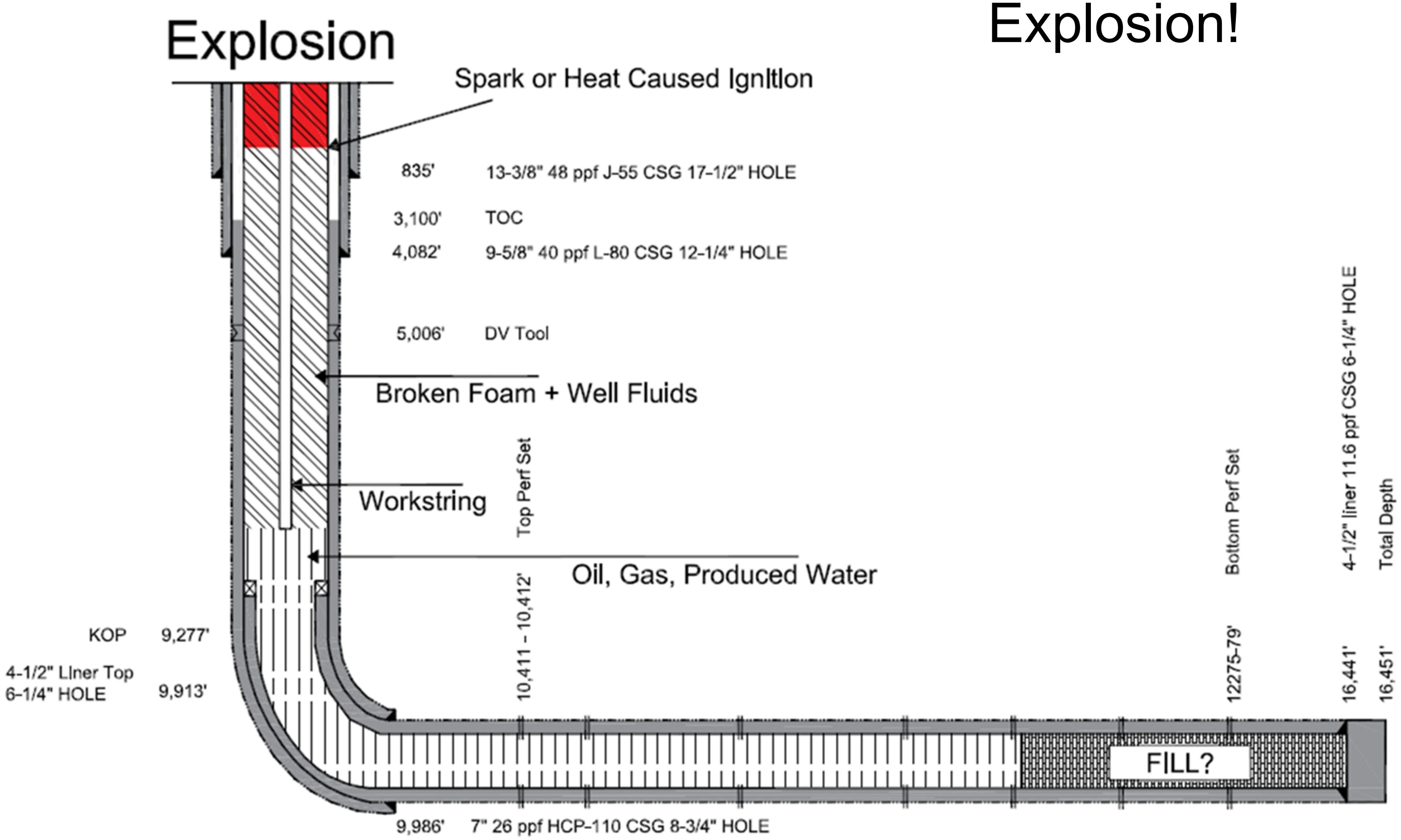
Wellbore Diagram

Circulate Foam at KOP (Actual)



Wellbore Diagram

Ran in hole with 12 joints.
Explosion!



An Engineered Approach

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- With the proper OBJECTIVE:
  - Annular friction loss would have been understood
  - Proper downhole pressures would have been maintained
  - Proper field test would have been established
  - Result: No hydrocarbon feed-in/Safe operation

Another Engineered Option

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- Just described a safe process established through engineering
  - Complicated
  - Many unknowns
  - Requires modelling for insight on each job

Foam "challenges"

- The field is not a laboratory:
  - Air, water, foamer rates not known precisely
  - Downhole temperature not known precisely
  - Elements can change while circulating
  - Annular pressure can also change
  - Downhole pressure may not be stable
- Therefore (especially without a model):
  - Downhole pressure is not known precisely
  - Neither is BHP target precisely known

An Engineered Approach

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- Our objective *should have been*:
  - Establish circulation to *safely* clean out debris *while maintaining a bottom hole pressure sufficient to prevent influx of reservoir fluids*
- Maybe that was not reasonably achieved.
- With the insight gained through inquiry, is there a better idea?

Another Engineered Option

- Better idea: ***Eliminate Oxygen*** by using nitrogen instead of air
  - Membrane units reject (most) O2 on site
  - Modestly more expensive
  - *Justified by proper engineering understanding of the risks.*
- **Eliminating Oxygen is another Engineered Approach to achieving a safe procedure**
- **End here to prevent a similar accident?**

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The Real Lesson:
Engineers have a role in creating a safe workplace

When engineers *delegate* potentially dangerous processes, **including facility design,** to our field staff (or safety staff) without thorough inquiry, we *abdicate* our responsibility as individuals with specialized knowledge and skills to those ***without a similar background*.**

The Real Lesson:
Engineers have a role in creating a safe workplace

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- This procedure, and many others, required a deep understanding of the physics of the job to make it safe 100% of the time.

That task requires Professional Engineering Judgement.

The Real Lesson: ***Engineers have a role in creating a safe workplace***

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- This accident opened my eyes to a danger.
- Author Trevor Kletz' series on industrial accidents opened my eyes to a new way of thinking about engineering and safety
- Kletz' message:
  - The engineer needs to engage and adopt a mentality of *actively searching out and eliminating danger* to protect valuable equipment and precious lives (Job Hazard Analysis ID/OP)

The Real Lesson:
Engineers have a role in creating a safe workplace

- Professional safety guidance (RP 75, SEMP, STAMP, etc.) creates a "structured" way to think about and implement these safety identification and mitigation concepts
- Field personnel deserve engineered, safe procedures and facilities - they trust us

Please don't let them down!

The life you save might be yours!

Safety Begins <u>Here</u> Also!

Questions?

Your Feedback is Important

Enter your section in the DL Evaluation Contest by completing the evaluation form for this presentation

Visit SPE.org/dl

Appendix

AUTO IGNITION

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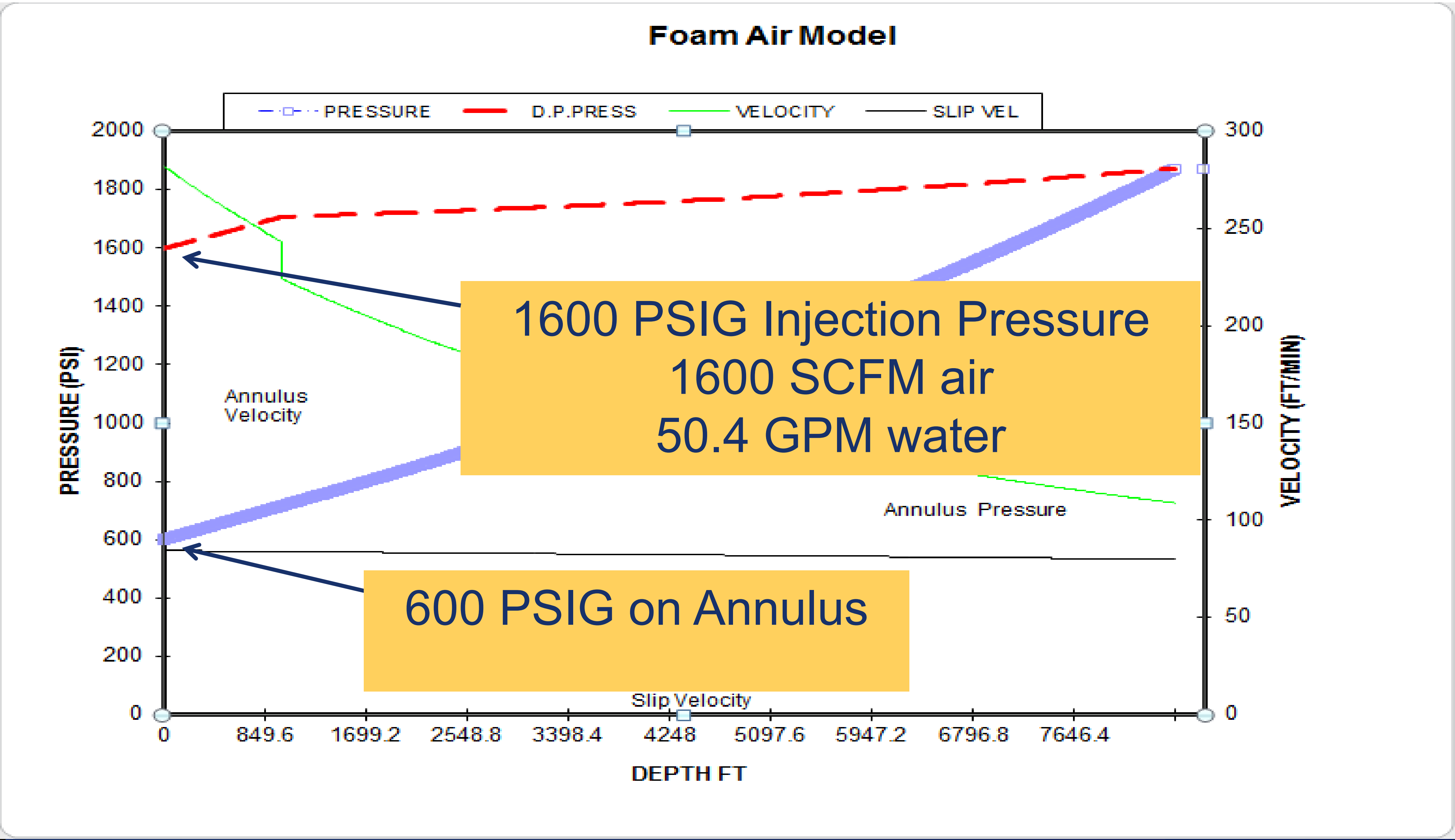
Auto Ignition?

Diesel/air mixture in an engine auto-detonates at roughly 14:1 compression ratio from the heat of adiabatic compression.

Could the explosive mixture have auto ignited? On this job, air is compressed from 0 psig (14.7 psia) to 1600 psig (110:1) but in several stages using interstage coolers with no hydrocarbons present. Compressed air with foam travels down tubing (gaining pressure) and up the annulus (losing pressure).



Matches known parameters (pressure and rates).

Calculated annular friction = 132 psi

Credit: Reuben Graham

Auto Ignition?

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Annular pressure was approximately 600 psig. 600 psig * 14 = 8,400 psi. Where could that kind of pressure come from? Could pipe to pipe friction cause ignition (deflagration) and the resulting sudden, adiabatic compression of explosive mixture in annulus create detonation of the remaining explosive mixture? Not sure that mattered at that point.

FOAM CHALLENGES

Foam air unit control panel

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The field is not a laboratory!

DETAILS

Foam “challenges”

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- Math to calculate foam “properties”
  - Quality (% Air)
  - Density
  - Circulating (bottoms up) time
  - Annular pressure profile
- Complex/Iterative
- Takes an Engineer - Foam air operators focus on *Operations, not Thermodynamics* (*Math + Physics + Chemistry)*.

Plausible Theory of this Explosion

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- Field Operational Procedure yielded improper BHCP
- Allowed feed-in of oil & gas *during* circulation
- Oil and gas moved down lateral to the vertical, moved uphole, oil evolved more gas, oil killed foam – “released” air (oxygen) from foam, explosive mixture was created
- Pipe on Pipe friction caused ignition

An Engineered Approach

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- Operational approach yielded a lack of information:
  - What Circulating BHP we did achieve?
  - What Circulating BHP needed to be achieved?
  - What was annular friction during circulation?
- With an Engineered approach (with a foam model), a proper field procedure could have been used to find a *safe* downhole circulating pressure.
- Key - Knowing annular friction

An Engineered Approach

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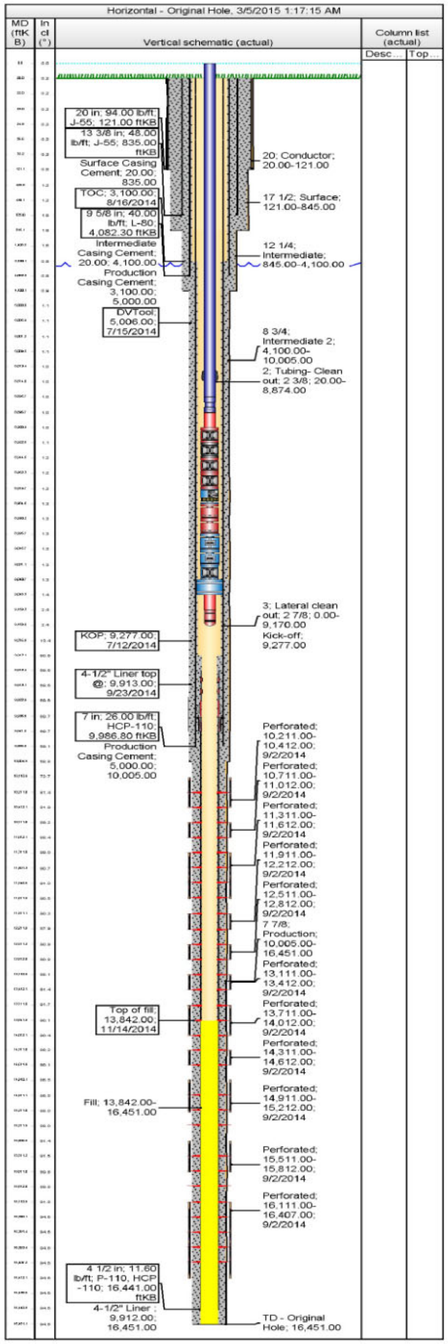
- Estimate circulating friction through foam models to gain insight to set proper field guidance.
- Establish circulation pressure *above* reservoir feed-in pressure & *confirm* by a properly designed field test.
- Employ foam tests to check for compatibility with well fluids & check foam quality periodically during the job (in & out).
- With no feed-in and good foam, the annulus is fuel-free and safe.
- Result: Safe operation.

Downhole Profile - Vertical Wells

Well Name: POKER LAKE UNIT CVX JV BS #028H (23-24-30)

Field: Sect: 23 Town: 24S Rng: 30E County: Eddy State: New Mexico

Surface Location: 590' FNL & 1060 FEL, Sec 23, T24S-R30E



Well Information

Orig KB Elev (ft)	Gr Elev (ft)	KB-Grd (ft)	Spud Date	On Production Date	PBTD (All) (ftKB)
3,453.00	3,433.00	20.00	6/12/2014	10/11/2014	

Wellbores

Wellbore Name: Original Hole **Kick Off Depth (ftKB):** 9,277.0

Size (in)	Act Top (ftKB)	Act Btm (ftKB)
20	20.0	121.0
17 1/2	121.0	845.0
12 1/4	845.0	4,100.0
8 3/4	4,100.0	10,005.0
7 7/8	10,005.0	16,451.0

Schematic Annotations

Type	Depth (ftKB)	Annotation

Casing Strings

Csg Des	Wellbore	OD (in)	Wt (lb/ft)	Grade	Top Thread	Set @ (ftKB)	Top (ftKB)
Conductor	Original Hole	20	94.00	J-55		121.00	20.0
Surface	Original Hole	13 3/8	48.00	J-55	ST&C	835.00	20.0
Intermediate 1	Original Hole	9 5/8	40.00	L-80	LT&C	4,082.30	20.0
Production	Original Hole	7	26.00	HCP-110	BT&C	9,986.80	20.0
Liner	Original Hole	4 1/2	11.60	P-110	BT&C	16,441.00	9,912.4

Perforations

Perf Date	Top (ftKB)	Btm (ftKB)	Zone	Current Status
9/2/2014	10,211.0	10,412.0	2nd Bone Spring Sand, Original Hole	Active (10,111.0 - 10,112.0)
9/2/2014	10,711.0	11,012.0	2nd Bone Spring Sand, Original Hole	Active (10,711.0 - 10,712.0)
9/2/2014	11,311.0	11,612.0	2nd Bone Spring Sand, Original Hole	Active (11,611.0 - 11,612.0)
9/2/2014	11,911.0	12,212.0	2nd Bone Spring Sand, Original Hole	Active (12,211.0 - 12,212.0)
9/2/2014	12,511.0	12,812.0	2nd Bone Spring Sand, Original Hole	Active (12,811.0 - 12,812.0)
9/2/2014	13,111.0	13,412.0	2nd Bone Spring Sand, Original Hole	Active (13,111.0 - 13,112.0)
9/2/2014	13,711.0	14,012.0	2nd Bone Spring Sand, Original Hole	Active (13,711.0 - 13,712.0)
9/2/2014	14,311.0	14,612.0	2nd Bone Spring Sand, Original Hole	Active (14,311.0 - 14,312.0)
9/2/2014	14,911.0	15,212.0	2nd Bone Spring Sand, Original Hole	Active (14,911.0 - 14,912.0)
9/2/2014	15,511.0	15,812.0	2nd Bone Spring Sand, Original Hole	Active (15,511.0 - 15,512.0)
9/2/2014	16,111.0	16,407.0	2nd Bone Spring Sand, Original Hole	Active (16,111.0 - 16,112.0)

Tubing Strings

Tubing Description	Run Date	String Length (ft)	Set Depth (ftKB)
Tubing- Clean out	11/15/2014	8,854.00	8,874.00

No.	Item Des	Jts	OD (in)	Wt (lb/ft)	Grade	Top (ftKB)
2-1	2-7/8" PH-6	13	2 7/8	6.50	L-80	20.0
2-2	2-7/8" Check Valve	1	2 7/8			429.5
2-3	2-7/8" PH-6	31	2 7/8			430.0
2-4	2-3/8" PH-6	240	2 3/8			1,406.5
2-5	mill tooth bit 3 5/8	1	3 5/8			8,873.2

Tubing Description	Run Date	String Length (ft)	Set Depth (ftKB)
Lateral clean out	12/23/2014	9,170.00	9,170.00

No.	Item Des	Jts	OD (in)	Wt (lb/ft)	Grade	Top (ftKB)
3-1	2-7/8" 6.5 ppf L-80 8RD Tubing	273	2 7/8	6.50	L-80	0.0
3-2	2-7/8" Standard Seating Nipple	1	2 7/8			8,895.5
3-3	2-7/8" x 4' EUE 8rd 6.5 ppf N-80 Tbg Sub	1	2 7/8		N-80	8,896.6
3-4	GE TD1750 AR-MDLR PUMP 124 stgs	1	4			8,900.8
3-5	GE TD1750 AR-MDLR PUMP 124 stgs	1	4			8,922.6
3-6	GE TD1750 AR-MDLR PUMP 99 stgs	1	4			8,944.5
3-7	GE TD1750 AR-MDLR PUMP 99 stgs	1	4			8,962.1
3-8	TR4 MAG-2-GE INTAKE	1	4			8,979.7
3-9	TR4 DBG-GE SEAL	1	4			8,984.6
3-10	TR4 98L-GE SEAL	1	4			8,990.2
3-11	E45 UT GE 80 HP MTR	1	4.56			8,995.8
3-12	E45 UT GE 80 HP MTR	1	4.56			9,016.8
3-13	BHP Sensor - OSIRIS 6 GE	1	4			9,037.1
3-14	Cavins Desander	1	6 1/4			9,040.7
3-15	2-7/8" EUE 8rd 6.5 ppf L-80 Tbg	4	2 7/8	6.50	L-80	9,045.3
3-16	Bull Plug	1	2 7/8			9,169.3

Other Downhole Equipment

Run Date	Des	OD (in)	Top (ftKB)	Btm (ftKB)
10/8/2014	Fill	4	13,842.00	16,451.00

Cement

Surface Casing Cement , 6/13/2014

String: Surface, 835.00ftKB **Cement Evaluation Results:**

Stage Number	Stage Top (ftKB)	Stage Bottom (ftKB)	Vol Cement Ret (bbl)	Top Measurement Method
1	20.0	835.0	62.0	Volume Calculations

Fluid	Amount (sacks)	Class	Dens (lb/gal)	Yield (ft³/sack)
Lead	400	C	13.50	1.76
Tail	300	C	14.80	1.33

Intermediate Casing Cement , 6/24/2014

String: Intermediate 1, 4,082.30ftKB **Cement Evaluation Results:**

Stage Number	Stage Top (ftKB)	Stage Bottom (ftKB)	Vol Cement Ret (bbl)	Top Measurement Method
1	20.0	4,100.0	70.0	Circulated

Fluid	Amount (sacks)	Class	Dens (lb/gal)	Yield (ft³/sack)
Lead	1,000	C	12.90	1.91
Tail	150	C	14.80	1.32

Production Casing Cement , 7/14/2014

String: Production, 9,986.80ftKB **Cement Evaluation Results:**

Stage Number	Stage Top (ftKB)	Stage Bottom (ftKB)	Vol Cement Ret (bbl)	Top Measurement Method
1	5,000.0	10,005.0	0.0	Volume Calculations

Fluid	Amount (sacks)	Class	Dens (lb/gal)	Yield (ft³/sack)
Lead	963	C	12.60	1.62
Tail	230	C	13.00	1.48

Stage Number	Stage Top (ftKB)	Stage Bottom (ftKB)	Vol Cement Ret (bbl)	Top Measurement Method
2	3,100.0	5,000.0	0.0	Volume Calculations

Fluid	Amount (sacks)	Class	Dens (lb/gal)	Yield (ft³/sack)
Lead	264	c	12.60	1.62

Liner Cement , 8/8/2014

String: Liner, 16,441.00ftKB **Cement Evaluation Results:**

Stage Number	Stage Top (ftKB)	Stage Bottom (ftKB)	Vol Cement Ret (bbl)	Top Measurement Method
1	9,912.0	16,451.0	14.0	Circulated

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Detailed Work Sequence (1)

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- Killed well - Shut off Electric Submersible Pump (ESP)
- Rigged Up rig – Nippled Up Blow Out Preventors
- Pulled and laid down ESP (sand in pump).
- Picked up workstring – Ran in hole into lateral to 13,842' and set down on "fill" (Total Measured Depth=16,451').
- Pulled out of hole. Picked up new workstring & ran in hole to 8,496 (above Kick off point of 9,277').
- Rigged up Foam Air Units (FAUs).
- Established circulation with foam air – 1,600 scfpm (air), 1.2 bpm (water and foamer), 1,600 psi Tubing Pressure, 600 psi Casing Pressure on return flow manifold.
- Circulated 2 hours for *estimated* bottoms up.

Detailed Work Sequence (2)

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- Shut down FAUs and shut in annulus. Watch annular pressure *rise* ???
- Foam operator declared well ready to strip in to next circulation point. Blew down/disconnected injection line from tubing.
- Ran in hole through the stripper head with 12 joints of new workstring (+/-360’) to 8,856’.
- Explosion.
- Damage to BOPS, stripper head, tubing, and casing.
- Injuries to rig personnel.
- Company man near edge of pad saw “ash” flow out of well followed by foam. Well stopped flowing naturally. What was “ash”? Found oily film but no solids on the ground!

KLETZ AND SAFETY

Trevor Kletz Books
(Partial List)

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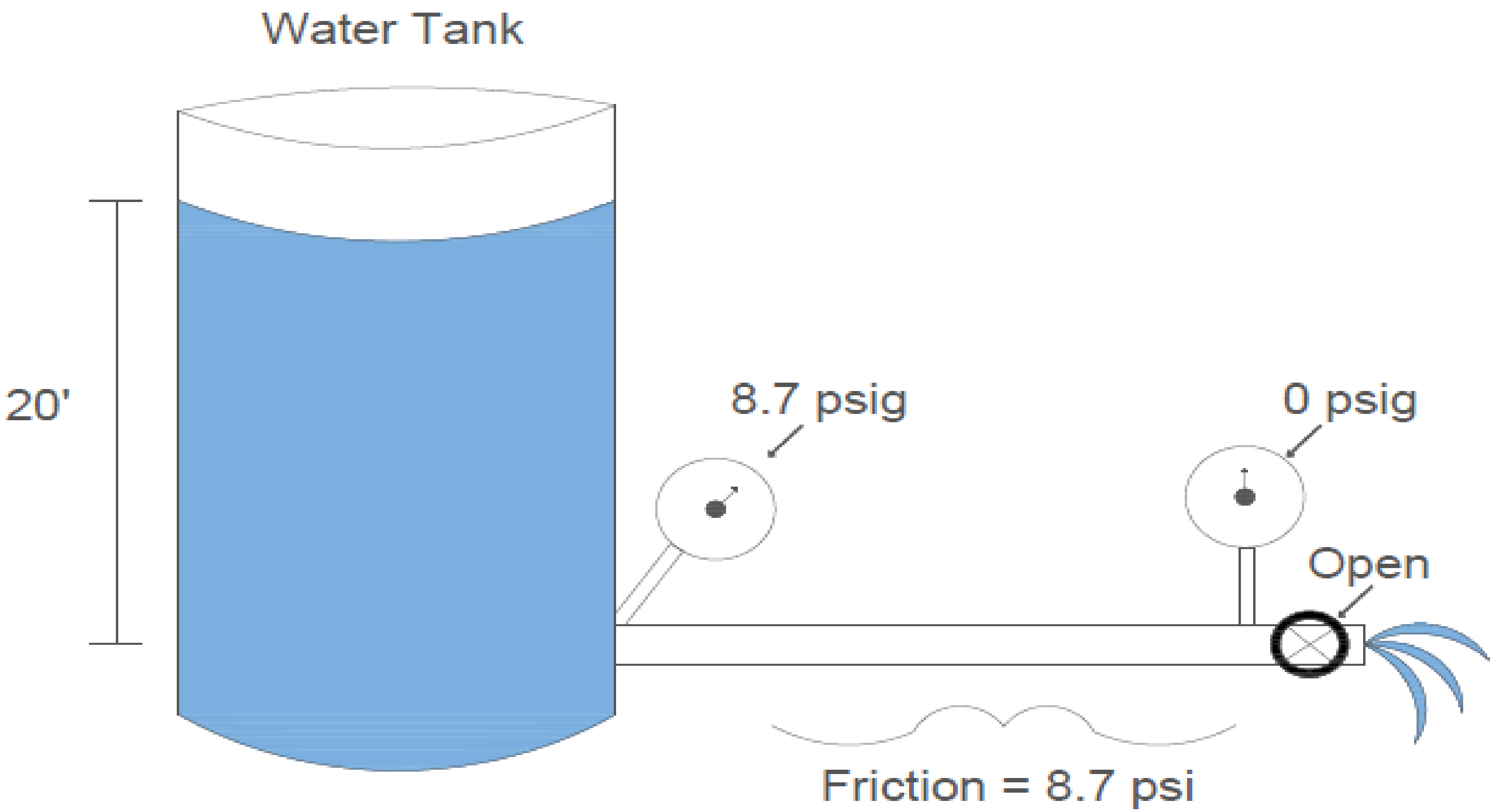
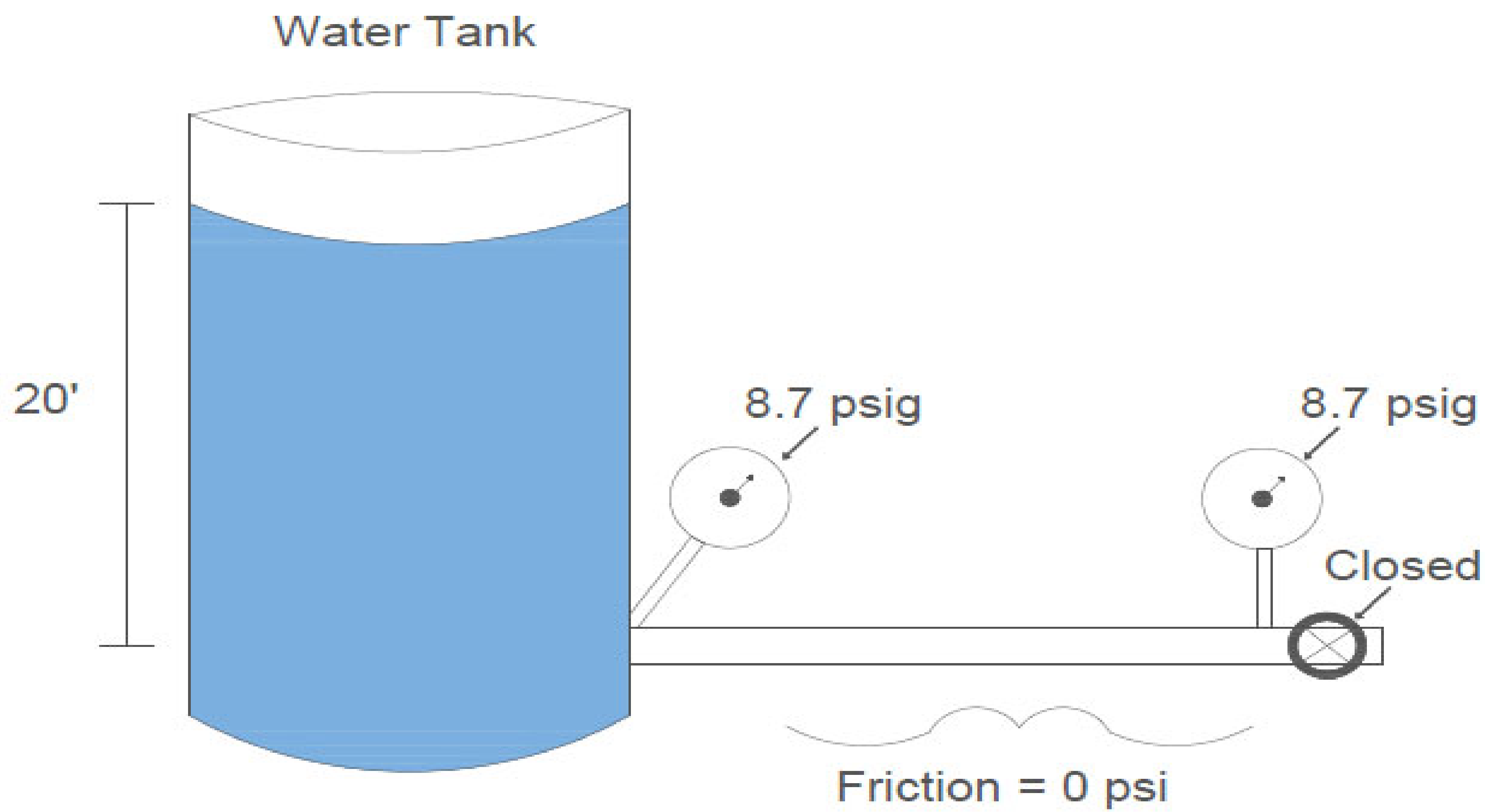
- What Went Wrong?: Case Studies of Process Plant Disasters
- Still Going Wrong
- Learning from Accidents
- An Engineer's View of Human Error
- Lessons From Disaster
- Process Plants…A Handbook for Inherently Safer Design
- Computer Control and Human Error
- Plant Design For Safety: A User-Friendly Approach
- By Accident...a Life Preventing Them in Industry

Safety Standards

- API RP 75 (RP for Development of a Safety and Environmental Management Program (SEMP) for Offshore Operations and Facilities, April 2013)
- STAMP – Systems-Theoretic Accident Model and Processes
- IOGP, IADC, IRF, HSE-UK
- ISO 45001 and 31000

CIRCULATING FRICTION


Water Tank
20'
8.7 psig
0 psig
Open
Friction = 8.7 psi


Water Tank
20'
8.7 psig
8.7 psig
Closed
Friction = 0 psi

FIRE AND EXPLOSION BASICS

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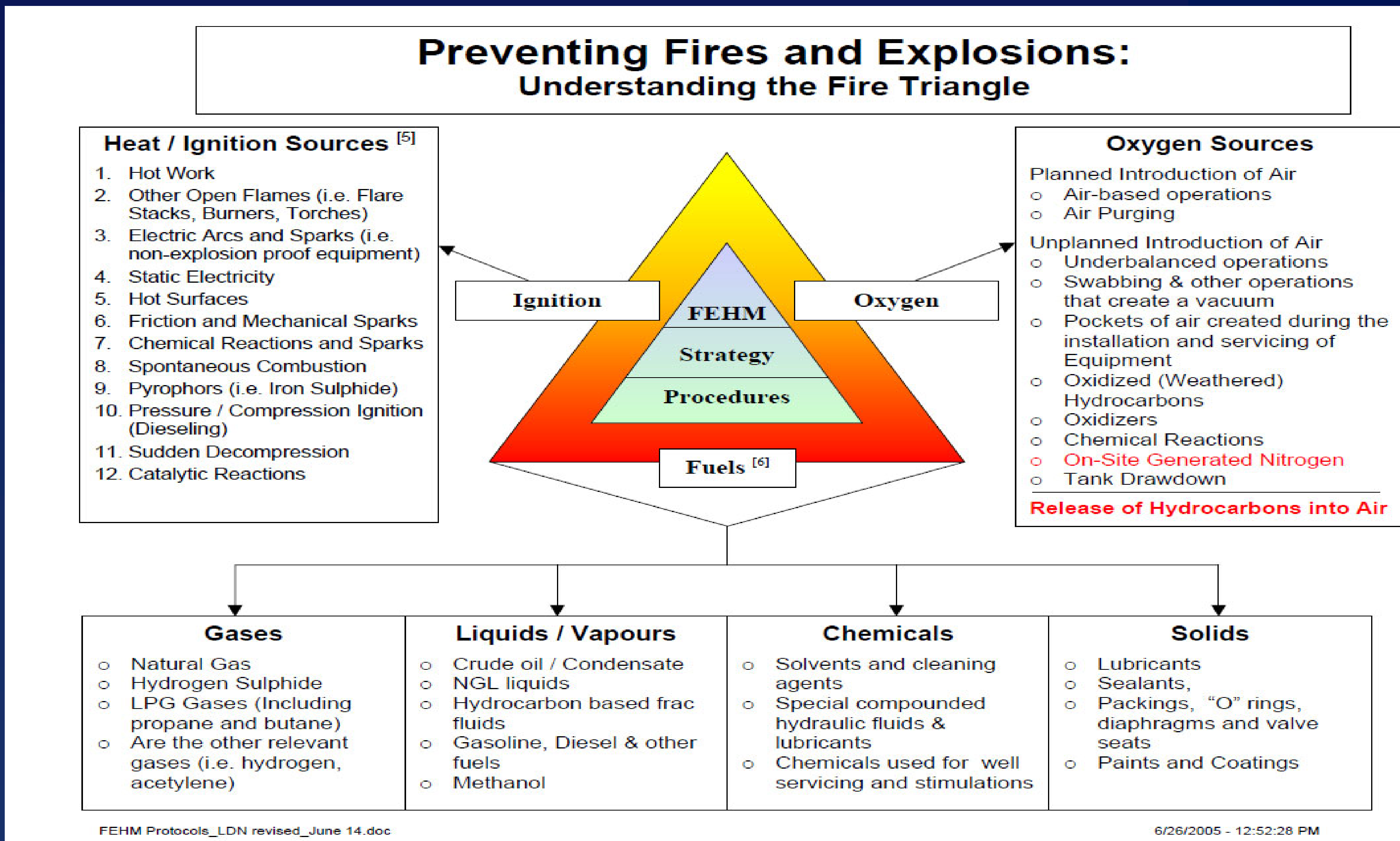
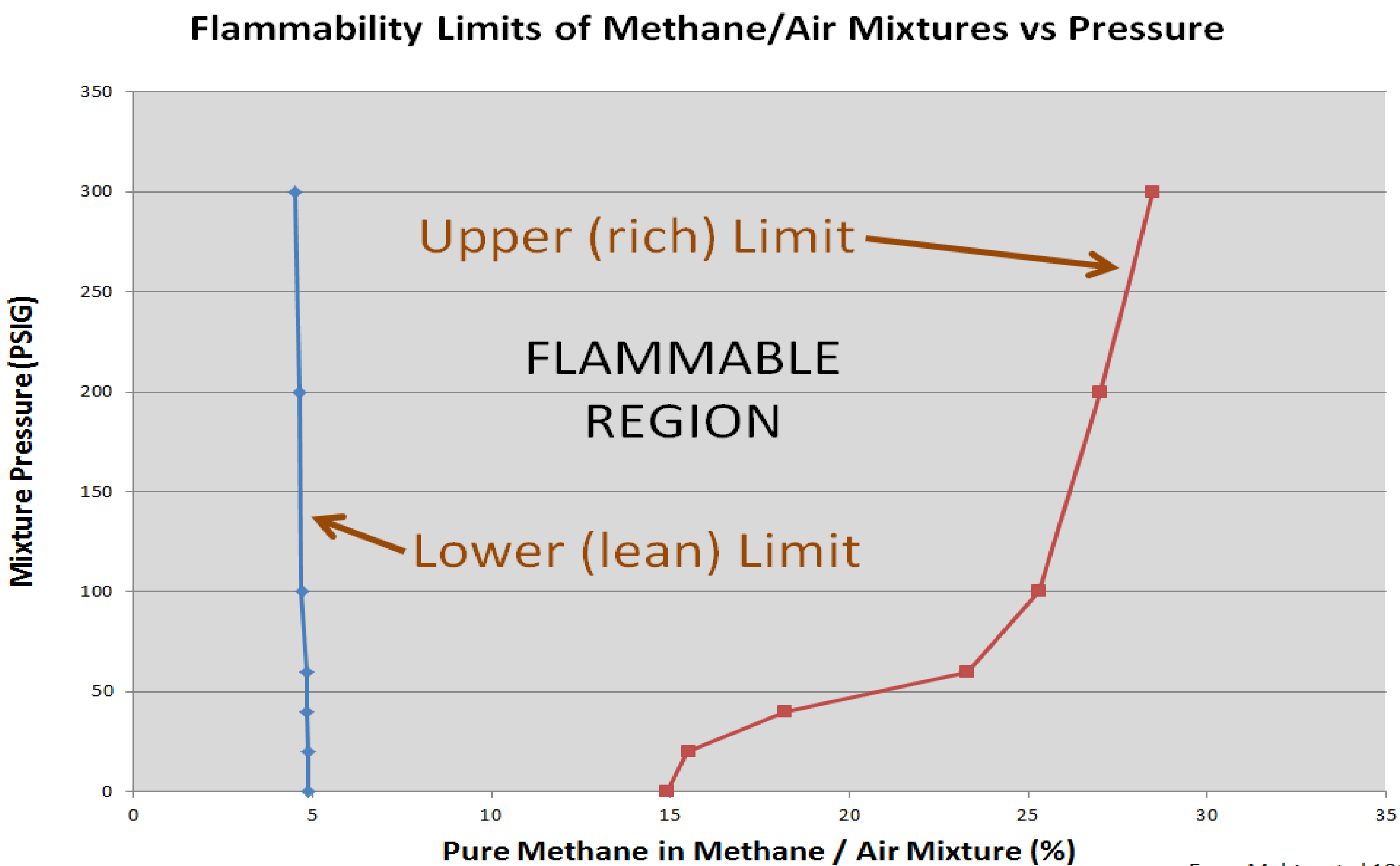
Fire & Explosion Basics



From http://webapps2.ucalgary.ca/~ursenbac/hazards/hydrocarbon_fuels.php



From Mehta, et al 1998

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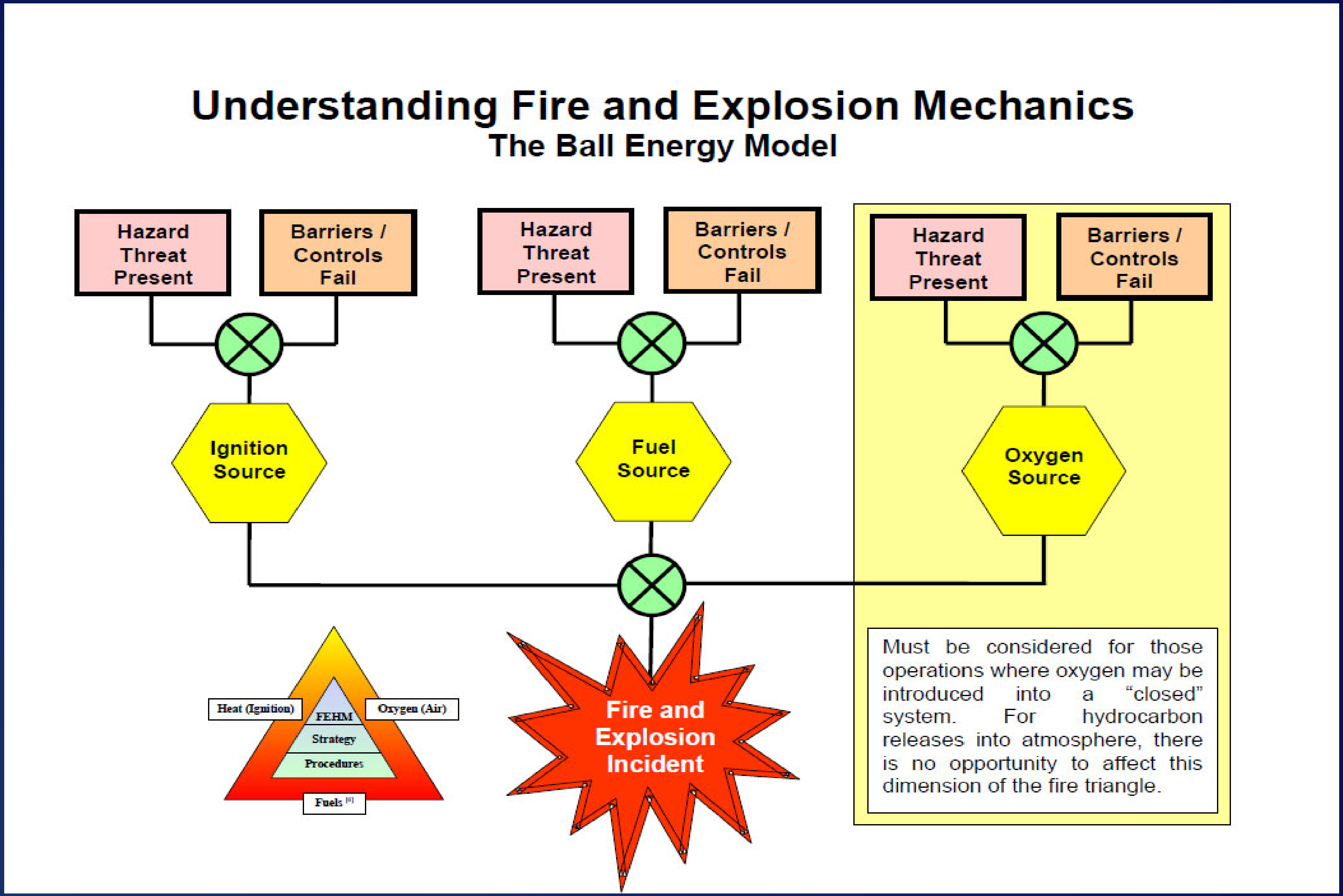
Fire & Explosion Basics



From http://webapps2.ucalgary.ca/~ursenbac/hazards/hydrocarbon_fuels.php

SLUG FORMATION

Slug Formation

- Feed-in is likely not at constant rate
- What can cause flowrate to change?
- What is the likely impact?

Fracture Volume Calculations

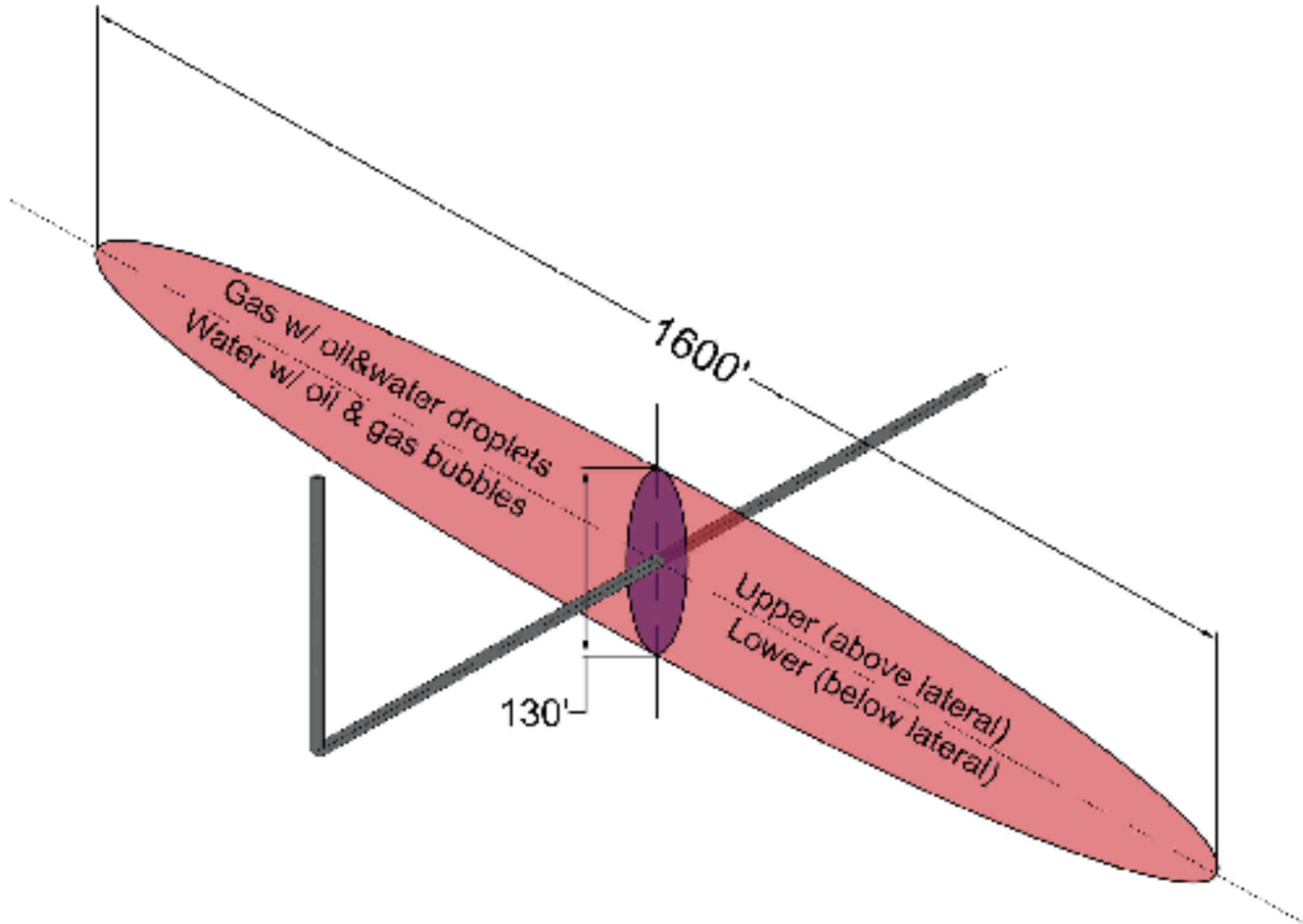
- Assume:
  - Fracture width = 0.01" (after leak-off)
  - Fracture height = 130'
  - Fracture length = 1600' (tip to tip)
  - Lateral centered between upper and lower limits
- Fracture volume:

$$Vol_{frac} = 130' \times ½ \times 1{,}600' \times 0.01" \times (1'/12") = 86.7 \text{ cu ft}$$

If 30 stages (fractures):

$$Vol_{total} = 2600 \text{ cu. ft.}$$

Formation of an Oil "Slug"



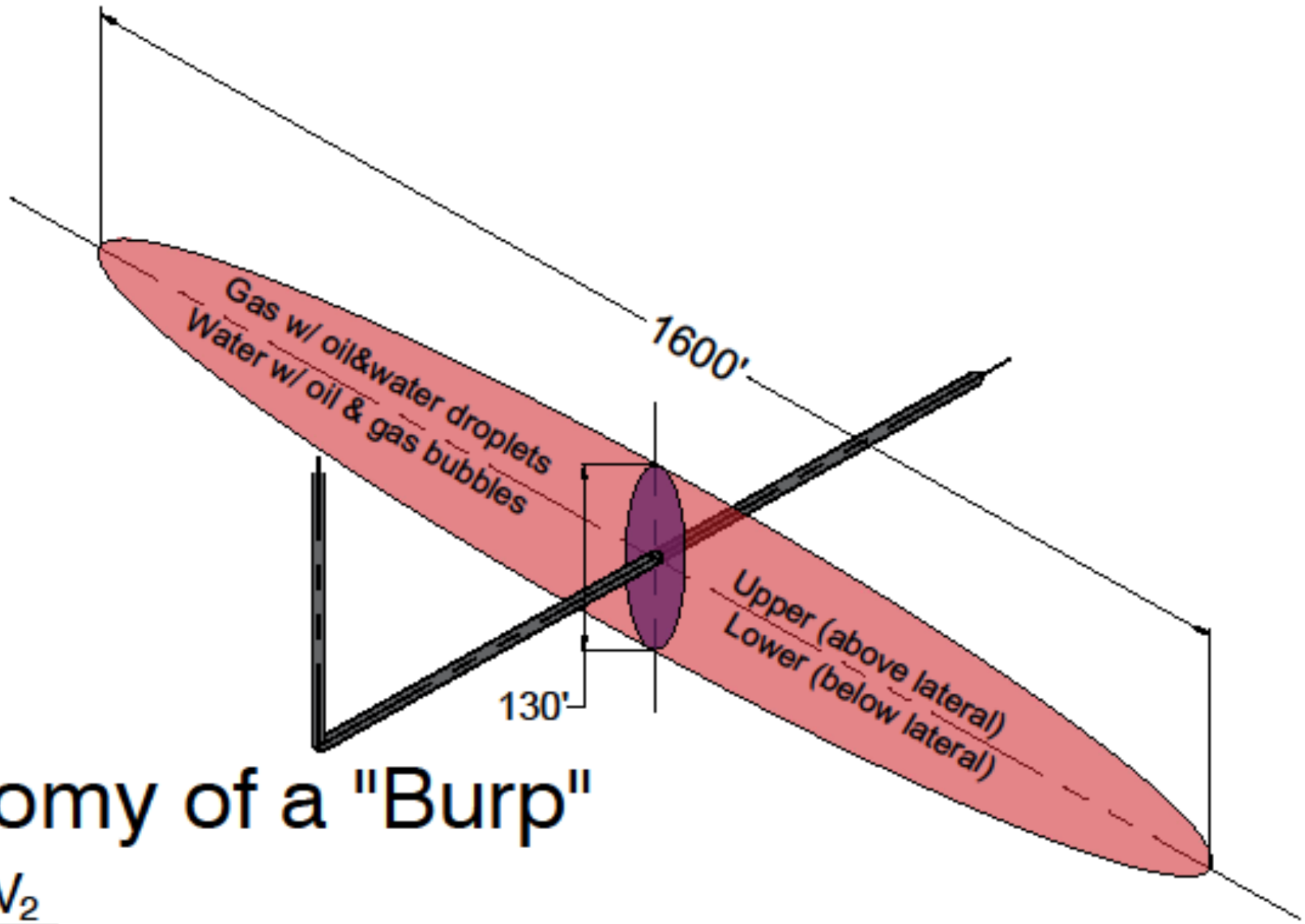
Typical Fracture Geometry

- Assume average width after leak-off = 0.01 inches
- Estimated volume of fracture above lateral = 86.7 ft^3 =15.4 bbls
- Estimated volume of 30 stages above lateral = 2600 ft^3 = 463 bbls

Slug Formation

- What happens if the backpressure held on the annulus drops just by 10 psig?

Formation of an Oil "Slug"



Anatomy of a "Burp"

$$\frac{P_1}{P_2} = \frac{V_2}{V_1}$$

If bottom hole circulating pressure drops by 10 PSI, from 1,900 PSIA to 1,890 PSIA

$$\frac{1900}{1890} = \frac{X}{463 \text{ bbls}} \qquad X = 465.4 \text{ bbls} \longrightarrow \triangle = 2.4 \text{ bbls}$$

2.4 bbls in 2-3/8" tbg x 7" 26#/ft csg ⟶ 74.7 ft of "Slug"

Effect of Pressure Drop on Trapped Gas

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A 10 psi pressure drop while circulating with BHP = 1500 psia yields:

+/- 75 feet of oil in annulus

Even if all of fracture does not react quickly, clearly even a small pressure drop can expel a significant “slug or burp” of oil.