SS-25 Root Cause Analysis

Webinar

CPUC Proceeding: I.19-06-016

November 1, 2019

ACKNOWLEDGEMENTS

- CPUC
- DOGGR
- SoCalGas
- Service Companies

Webinar Logistics

- This Webinar is scheduled from 9 AM to 12 PM PDT.
- Presentation should last less than an hour
- Parties to the CPUC Proceedings will email the questions during or after the presentation.
- We will take a 15 minute break after the presentation, collate and then answer the questions.

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Main Report

- Released May 16, 2019
  - SS-25 Well Failure Causes
    - Cause of the Failure (Metallurgical/Water)
    - Sequence/Timing of the Failure Events
  - SS-25 Post Leak Events
    - Well Deliverability
    - Well Kill Attempts
    - Pathway of the Gas
  - Aliso Canyon Casing Integrity
    - Casing Failure History
    - Shallow Corrosion in the Field
    - Gas Storage Regulations
  - Root Cause
    - Methodology
    - Causes/Solutions

Presentation Outline

- Approach & Timeline
- SS-25 Failure
- Post SS-25 Leak Events
- Aliso Canyon Casing Integrity
- Root Causes

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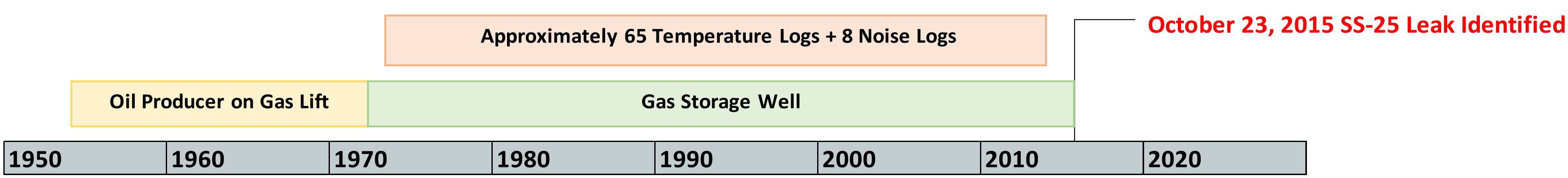
SS-25 Well History

- Drilled and completed Oct 1953 – Apr 1954
- Oil and gas well 1954 – 1973
- Converted to gas storage May 1973 – Jun 1973
- Workover Jun 1976 – Jul 1976, ran annular flow safety system
- Workover Feb 1979, replaced annular flow safety system
- Well service Jan 1980, removed annular flow safety system valve and packoff
- Ran numerous temperature and noise logs 1974 – 2014
- Casing leak Oct 23, 2015; successfully controlled well Feb 11, 2016
- Plugged and abandoned Sep 13, 2018



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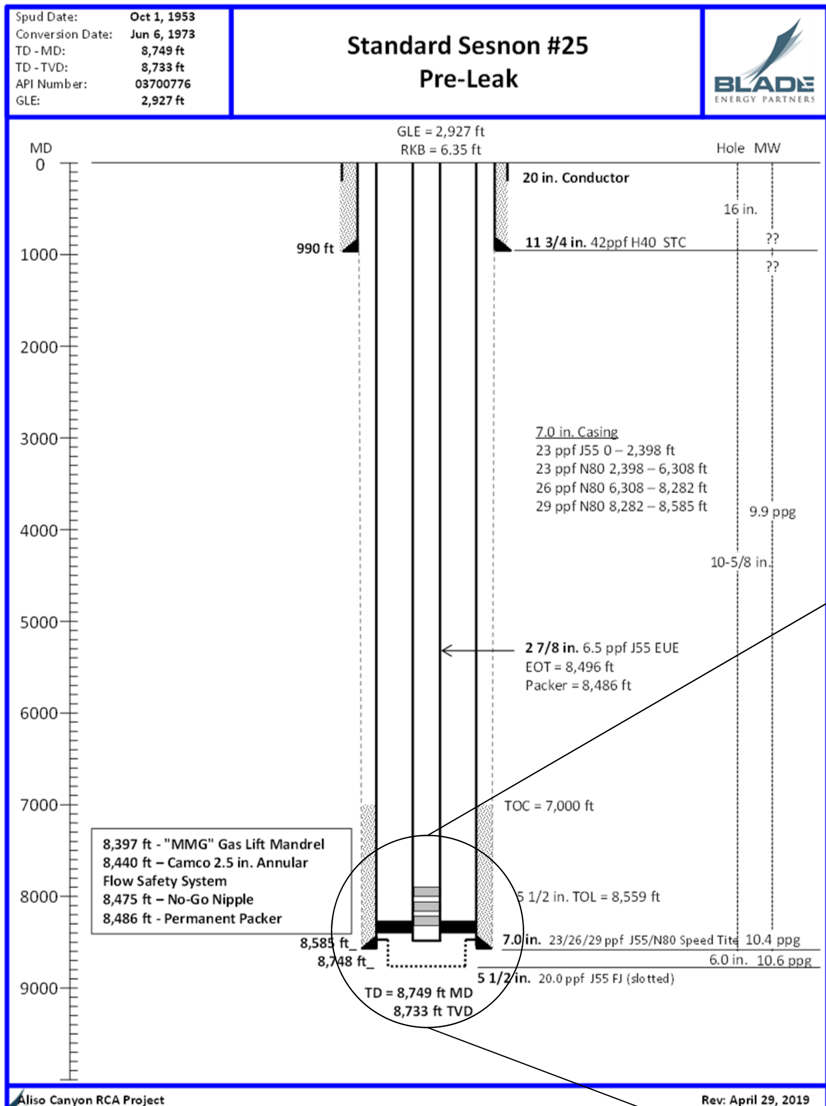
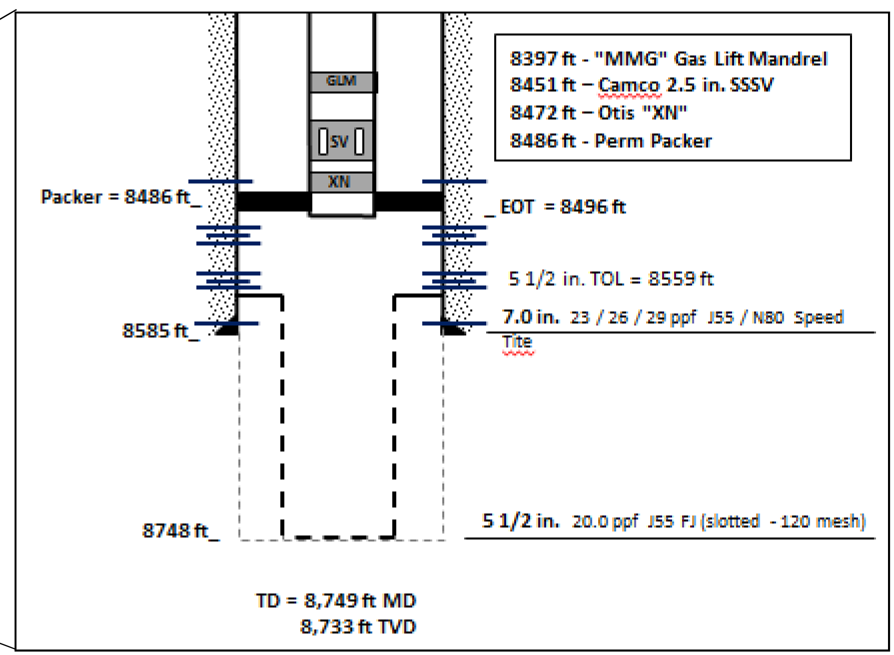
SS-25 Wellbore for Gas Storage



- Injection and withdrawal through the tubing and casing
- Casing flow was through open ports in the annular flow safety system above the packer
- 11 ¾ in. cementing problems
- No leaks or failures in SS-25 until October 23, 2015

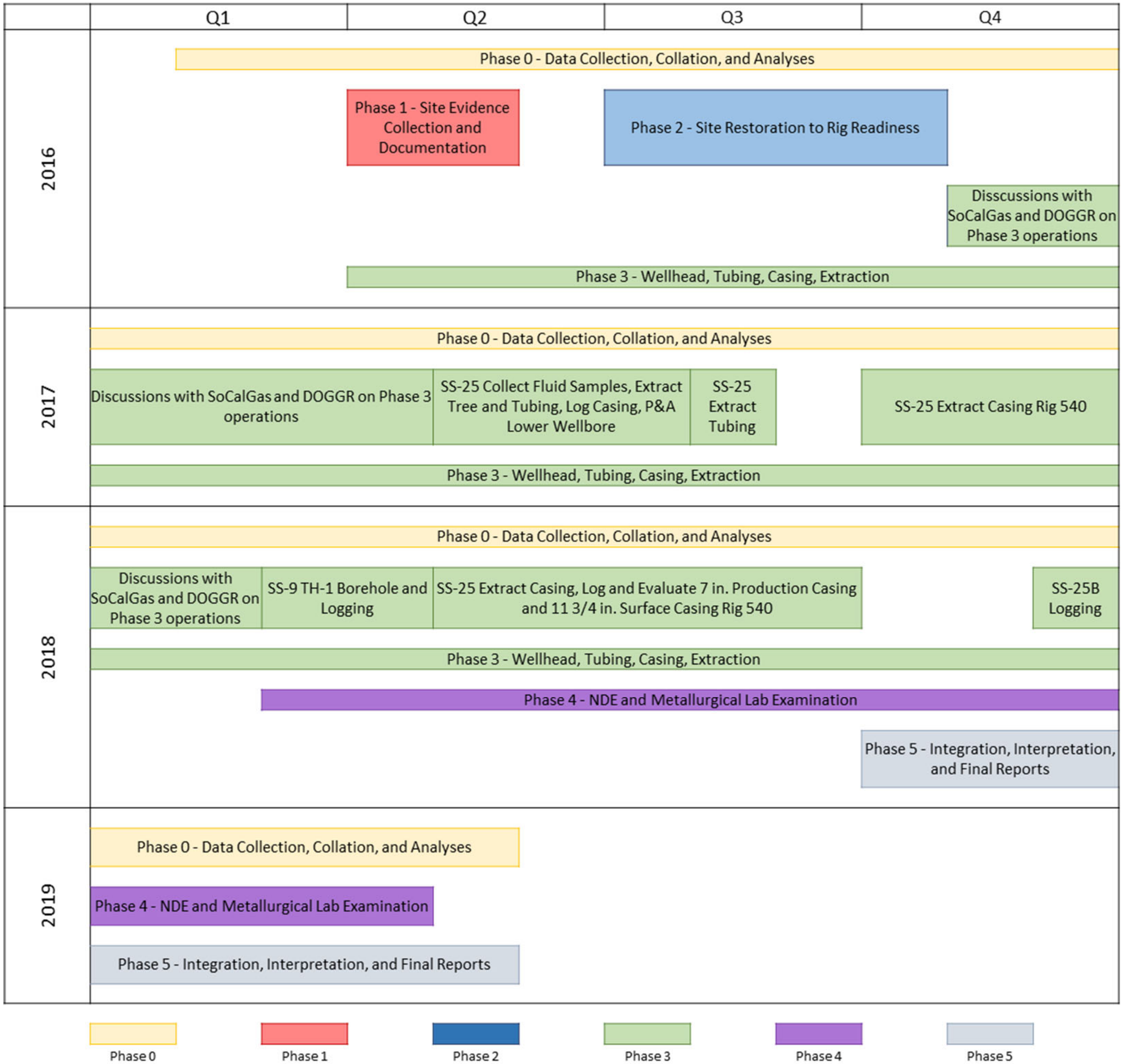


Phases

- An RCA is a systematic process for identifying the root causes of problems or events and defining methods for responding to and preventing them.

- Phase 0: Data collection, collation and analyses
- Phase 1: Site Evidence collection and documentation
- Phase 2: Site restoration to rig readiness
- Phase 3: Tubing, casing, and wellhead extraction
- Phase 4: Non-destructive evaluation and metallurgical examination
- Phase 5: Integration, interpretation, and final report

SS-25 RCA Timeline 2016 – 2019



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Phase 0: Data Collection, Collation and Analysis

- Written records for the Aliso Canyon field and the SS-25 well
- Correspondence; internal and external to the field and company
- Field Operations
- Data requests
- Over 57,000 files collected and reviewed
- To understand the history of the well and field, model field processes, injection and withdrawal, etc.

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SS-25 Failure

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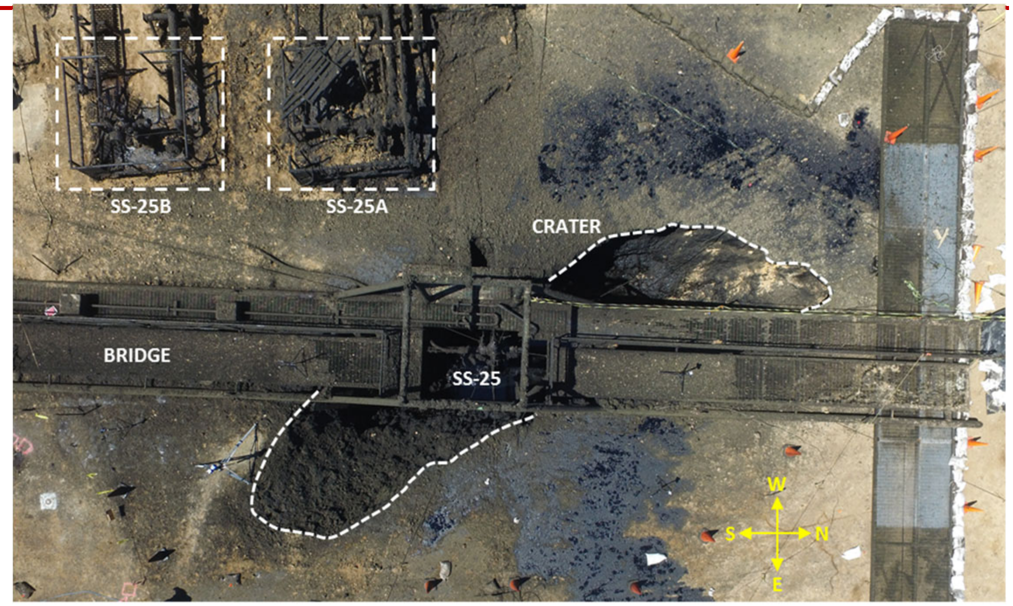
Phase 1: Site Evidence Collection and Analysis

- Locate, document, and collect any physical evidence at the site surface that may be related to the leak event
- Assess condition of the wellbore and casing using through tubing logs



Log	Log Name	Measures or detects
MID	Magnetic Image Defectoscope	Metal loss and other anomalies in multiple strings
HPT	High precision temperature	Temperature and temperature changes in the wellbore
SNL	Spectral noise log	Sound caused by fluid movement in the annuli or the formation
MVRT	Micro Vertilog	Magnetic flux leakage inspection for internal and external metal loss
ICAL	Caliper	Mechanical measurement of internal diameter
GR	Gamma ray	Natural formation gamma rays
Camera	Video camera	Down and side-view video images
DTS	Distributed temperature sensing	Temperature vs. depth using fiber optics technology

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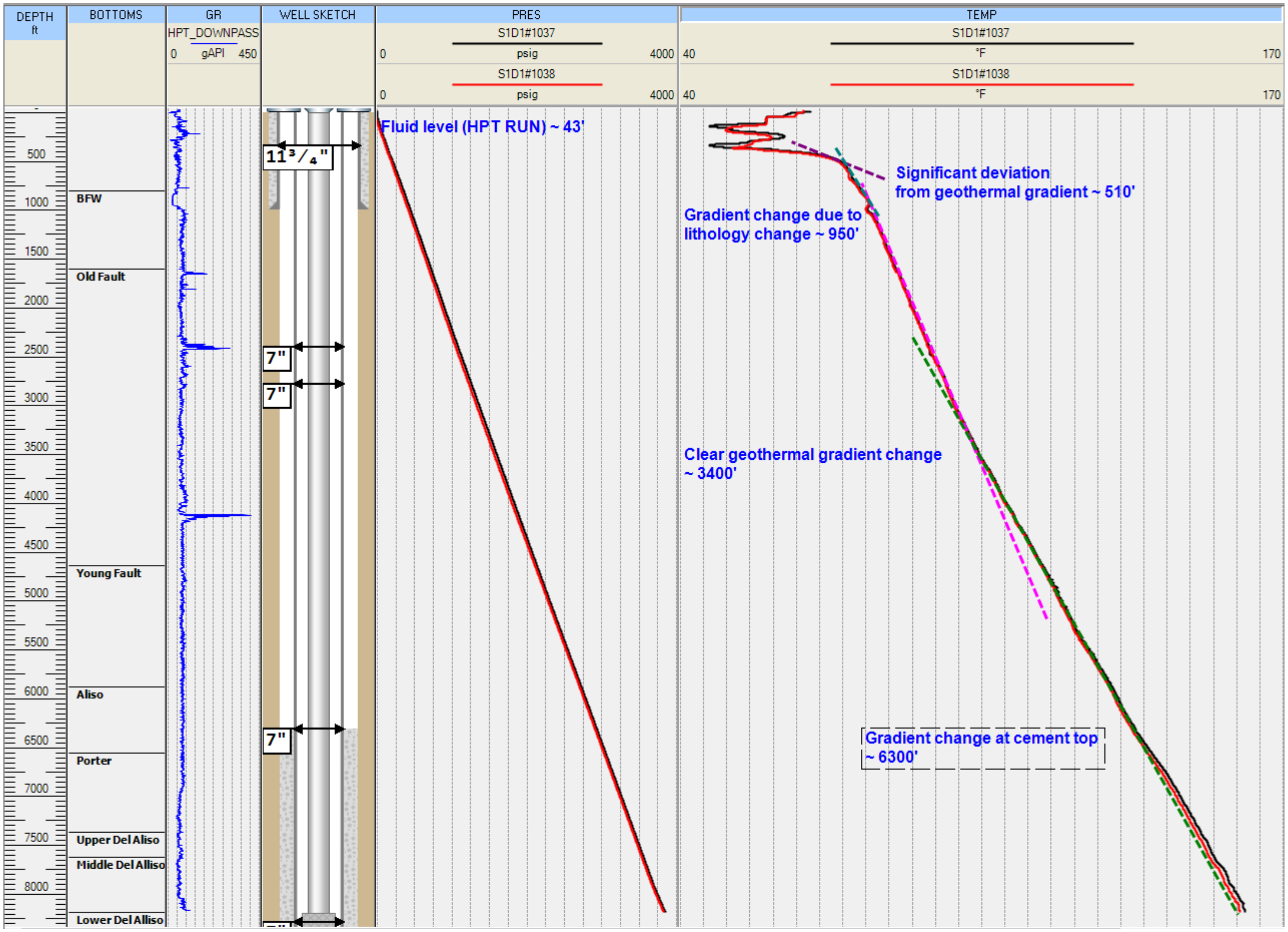
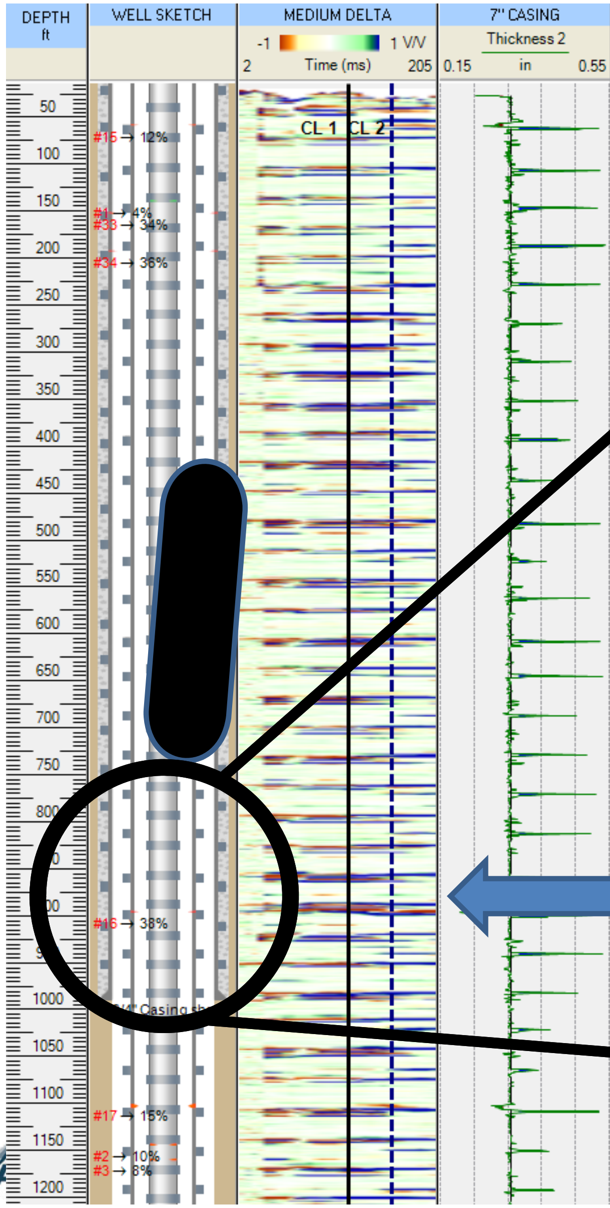
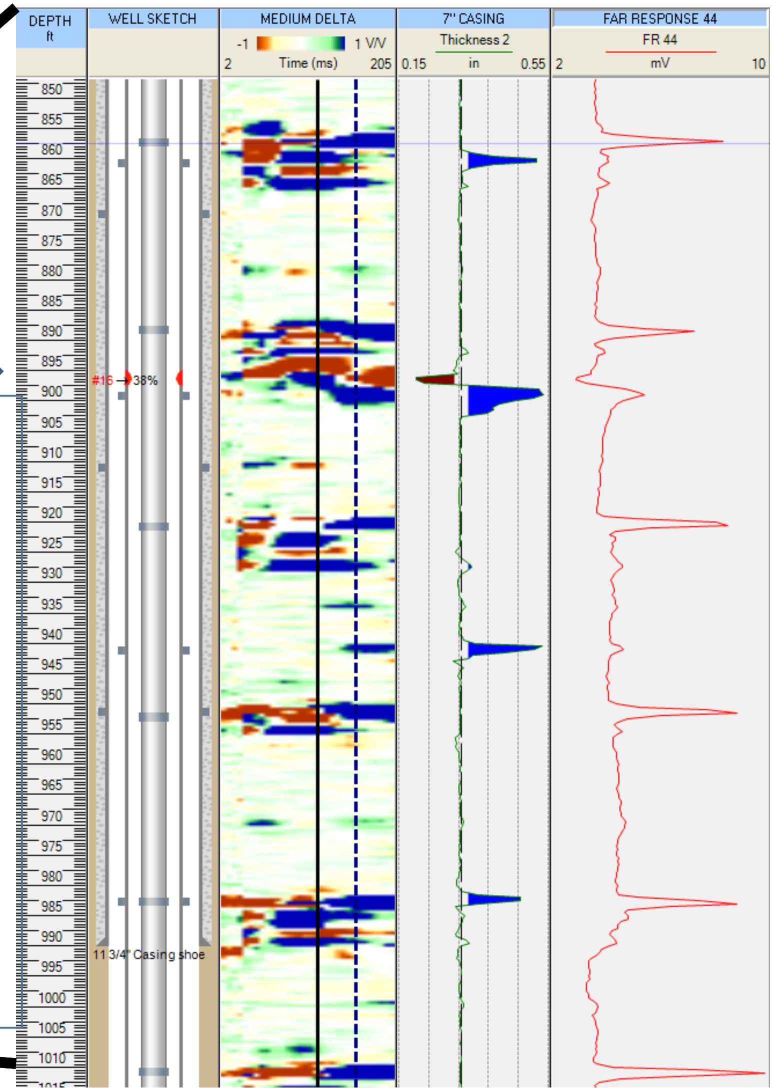
SS-25 HPT Logging Results April 2016



SS-25 MID 7 in. Casing Inspection Results April 2016





Deep significant metal loss adjacent to a connection at 895 ft

Verified by Micro Vertilog

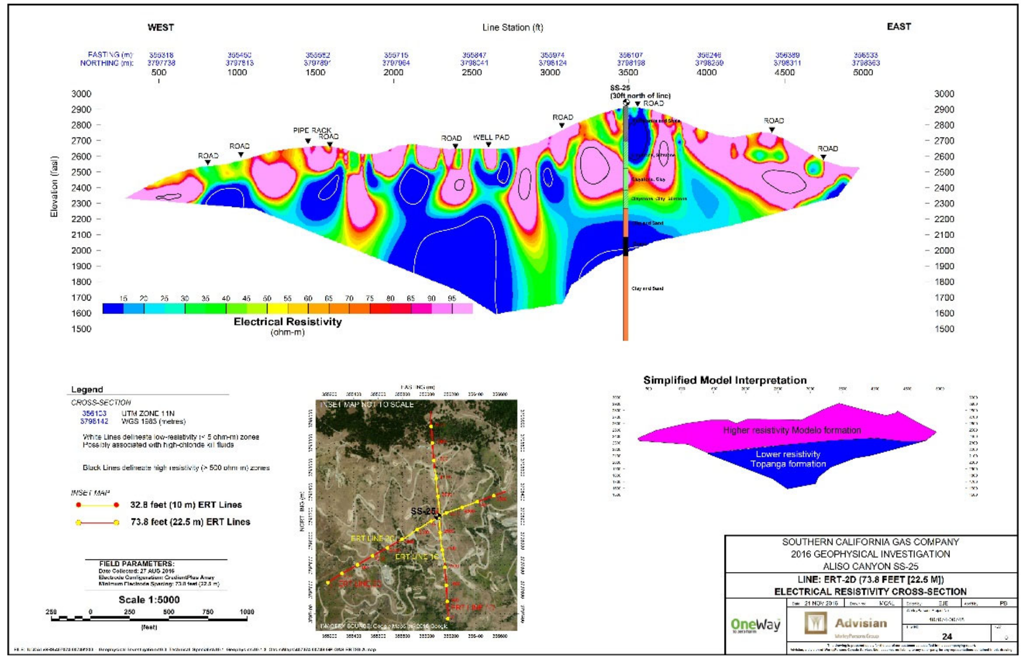
Probable failure location

Phase 2: Rig Readiness

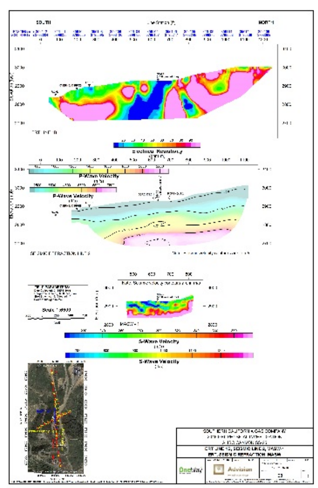
Wellhead Inspection
Crater Repair

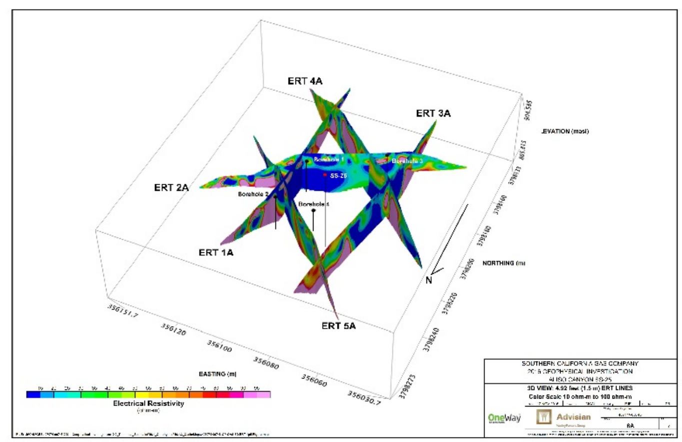
Phase 2: Shallow Geology

- Geophysical data acquired at the SS-25 wellsite from:
  - Electrical Resistivity Tomography (ERT), 15 lines
  - Seismic, 4 lines
  - Nuclear magnetic resonance (NMR) survey
  - 4 shallow boreholes (cuttings/core analysis and wireline logging)



Physical properties of the geological layers, location of water, and to look for shallow faults





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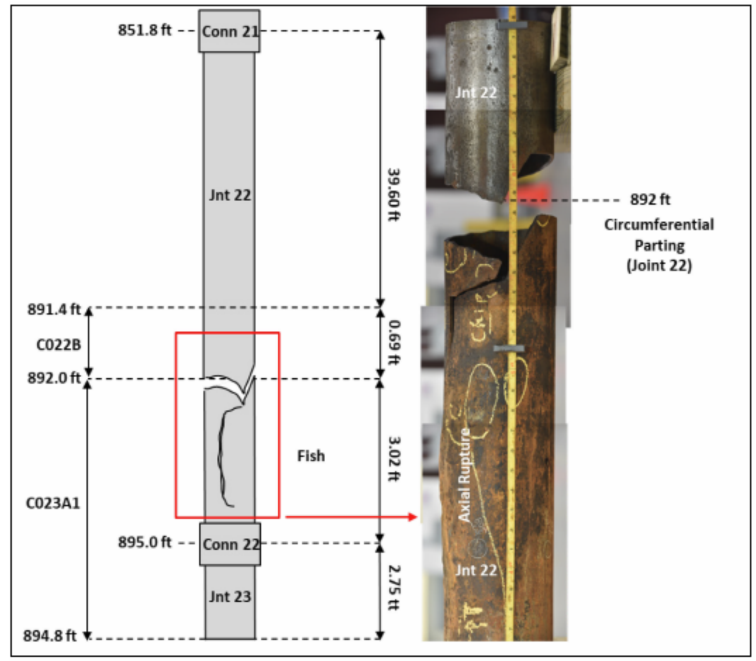
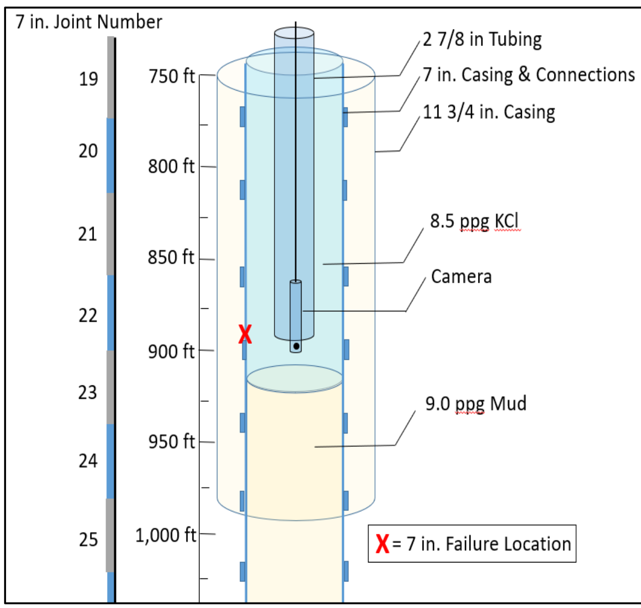
Phase 3: Tubulars Extraction

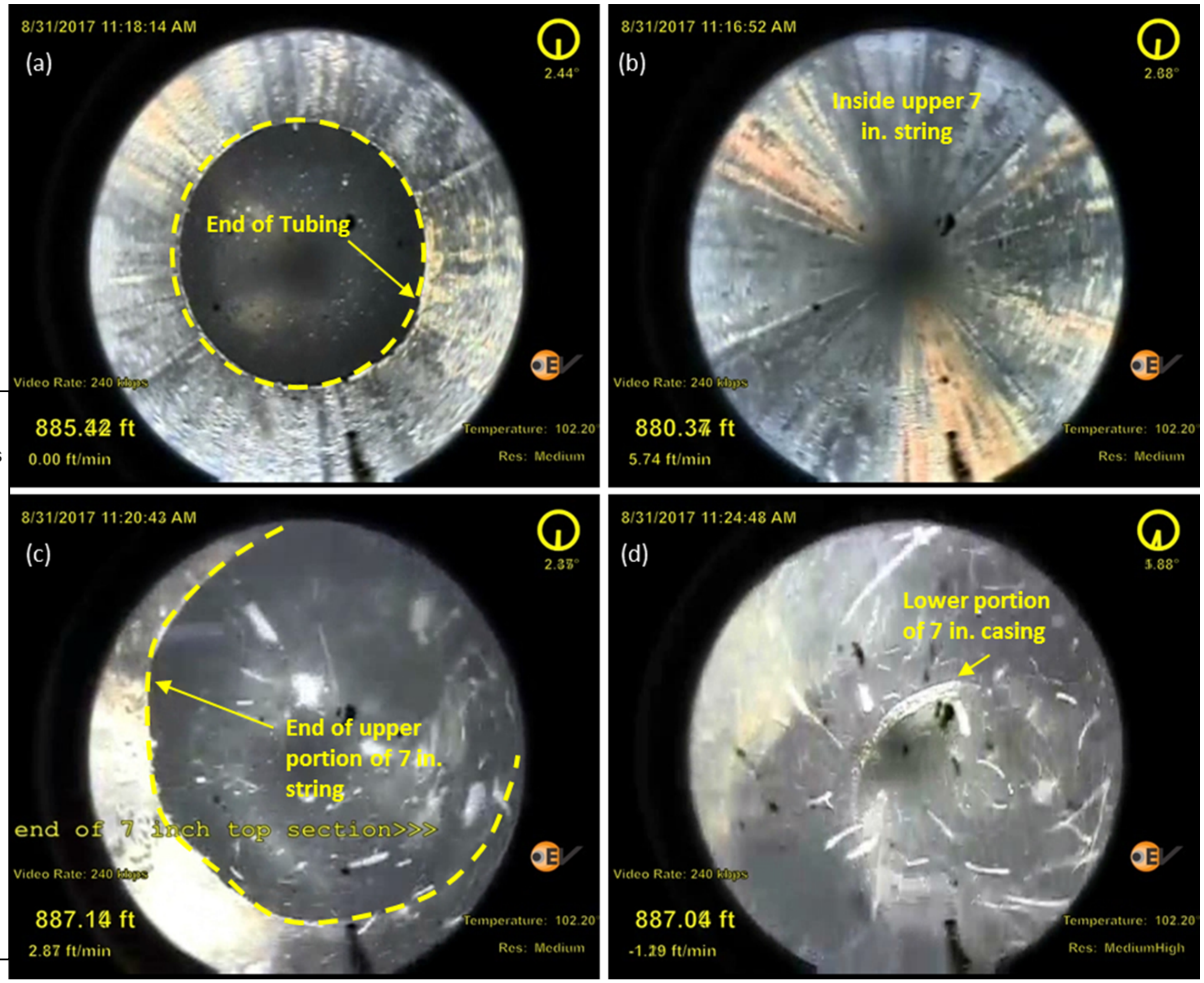
- Documents, protocols, permitting, and procedures
  - Work plans, HAZID and ETOP
  - Tubing, casing, wellhead extraction protocol
  - Tubular handling protocol and procedures to prevent damage to evidence
  - Evidence security protocol
  - Fluid and solids sampling procedures
  - Tubing and casing logistics protocols
  - Meetings and draft documents for regulatory permitting
  - SS-25A and SS-25B
  - P-35, P-34, SS-12, P-45, SS-44A casing and fluid samples
- Protocols reviewed by CPUC, DOGGR, PHMSA, National Labs, and SoCalGas



Tubing Extraction and Video Camera Results August 2017

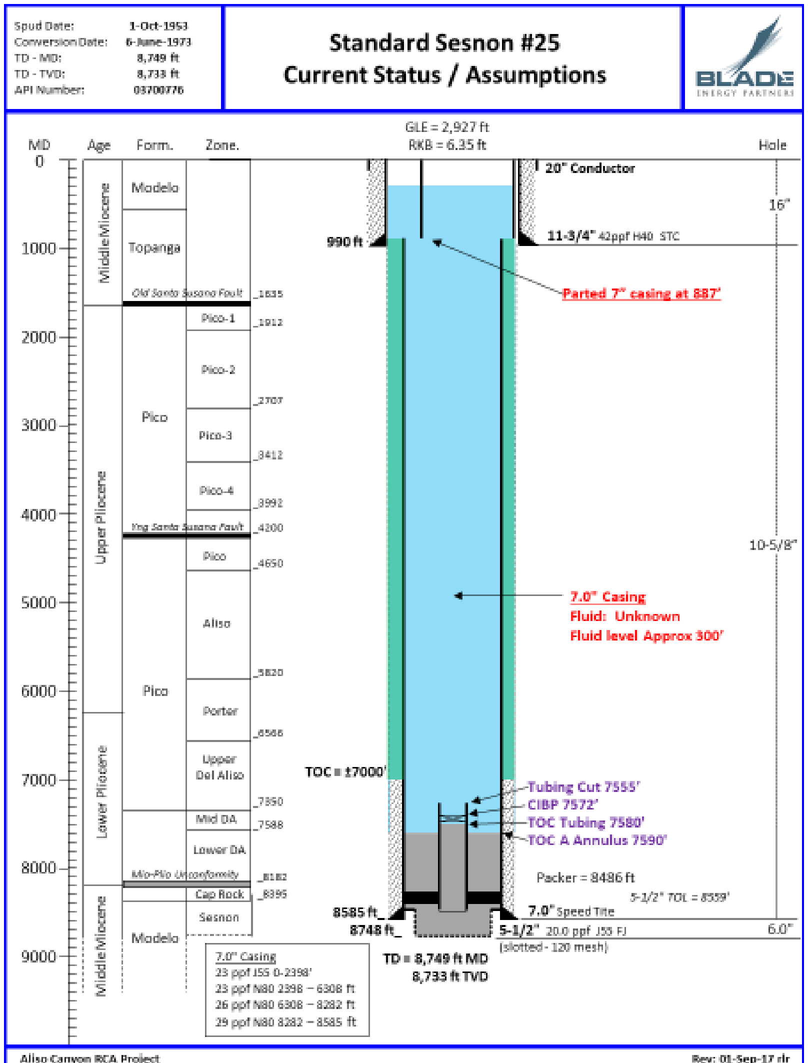
- Logs indicated 7 in. casing metal loss at approximately 895 ft
- Downhole Camera run below end of tubing to determine location of parted 7 in. casing





Upper parted casing pulled out of the well

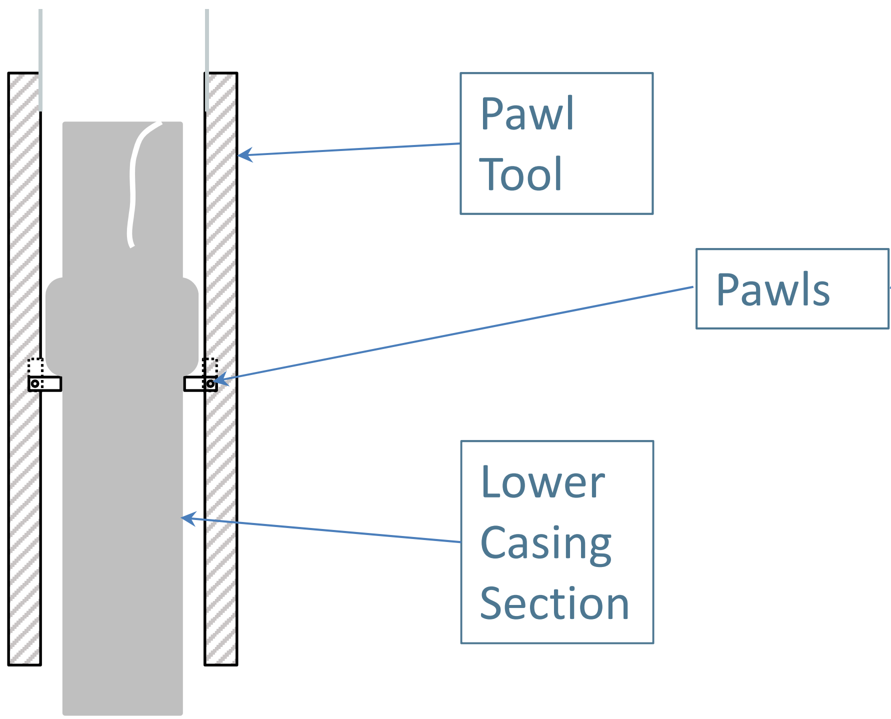
Phase 3: 7 in. Casing Extraction



- Extraction of the upper 7 in. casing was accomplished without difficulty
- Essential for the RCA to extract the lower parted casing with minimal or no damage
- Lower parted casing was essential to establishing the sequence of the failures
- 1025 feet of 7 in. casing was extracted

Pawl Tool to Recover Lower 7 in. Casing Section without Damage

- Tool custom designed for this application
- Tool passes over the top of the casing stub
- Spring-loaded pawls catch on the connection OD upset to recover the casing section after the casing is cut
- Camera used to guide the tool over the casing



7 in. and 11 ¾ in. Casing Evaluation Tools

Objective was to gather as much information as possible on the condition of the casing and the wellbore before extracting the casing

Log	Log Name	Measures or detects
Camera	**Video camera**	**Down and side-view video images**
ICAL	Caliper	Mechanical measurement of internal diameter
GR	Gamma ray	Natural formation gamma rays
HRVRT	**High resolution Vertilog**	**Magnetic flux leakage inspection for internal and external metal loss**
MID	Magnetic Image Defectoscope	Metal loss and other anomalies in multiple strings
PNX	Pulsed neutron	Water saturation, carbon oxygen ratio, presence of gas
IBC	**Isolation scanner**	**Solid-liquid-gas map of annulus material, hydraulic communication map, acoustic impedance, flexural attenuation, casing thickness image, internal radius image**
SSCAN	Sonic scanner	Cement bond quality, formation characterization, identification of fractures
UCI-NEXT	**Ultrasonic corrosion imager, LithoScanner**	**High resolution ultrasonic casing ID and OD imaging, lithology type, water and hydrocarbon identification**
CPET	Corrosion and protection evaluation tool	Identifies anodic/cathodic cells indicating active corrosion
CHDT	Cased hole dynamics tester	Drills a hole through the casing, measures pressure, collects fluid sample, plugs the hole

Phase 4: NDE and Metallurgical

- Examined casing and tubing joints from SS-25 using automated UT
- Conducted internal and external laser assessments on the extracted casing
- Connection testing and documenting flow rates on all casing connections extracted from SS-25
- Mechanical Testing including tensile, Charpy, chemistry and fracture mechanics
- Fractographic work using Scanning Electron Microscope and Focused Ion Bean (FIB).
- Energy dispersive spectroscopy, Raman spectroscopy, Inductively couple plasma (ICP)
- Microbiological analyses including MPN, qPCR and Amplicon Metagonics

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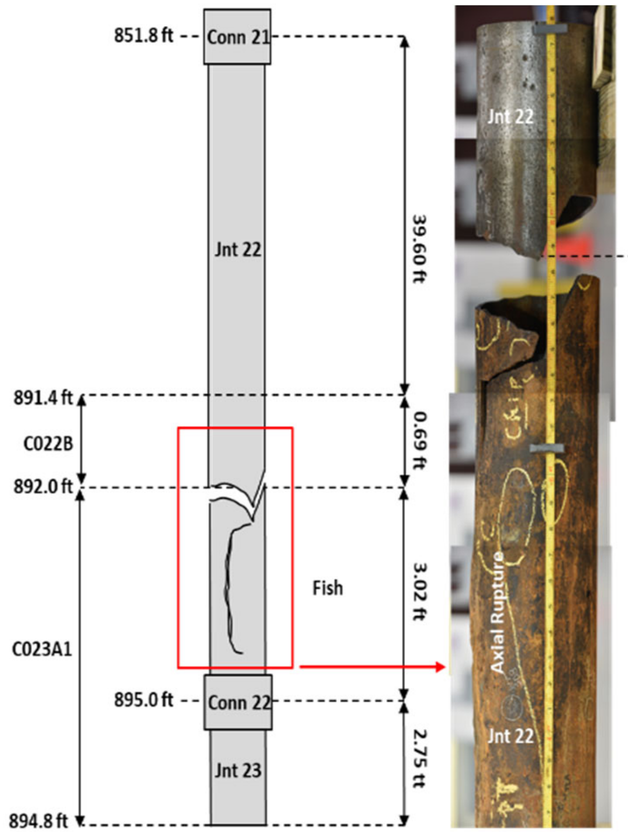
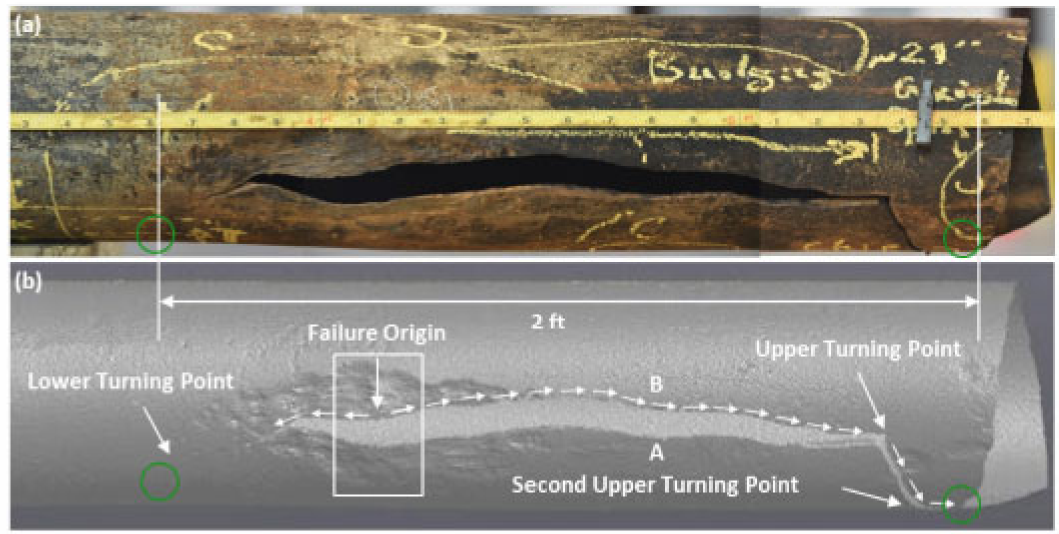
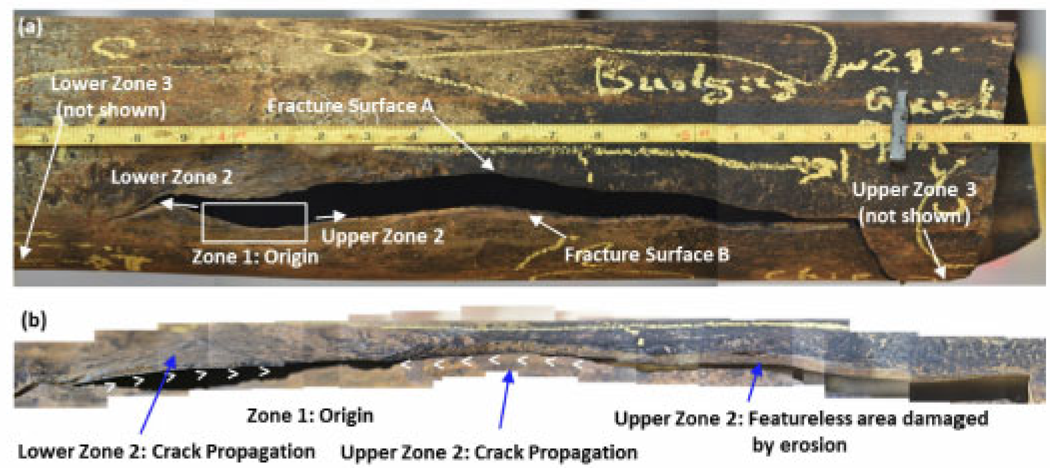
7 in. Casing Rupture







- Axial rupture region
  - Bulged
  - Wall Loss maximum at Origin
  - Chevron Marks towards origin

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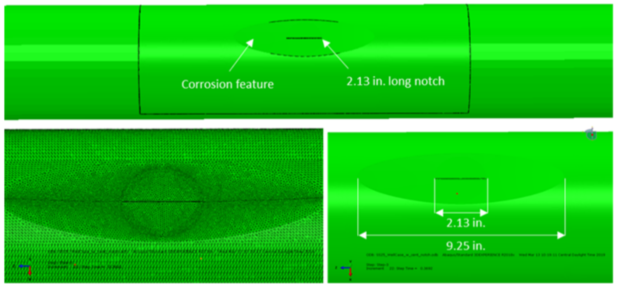
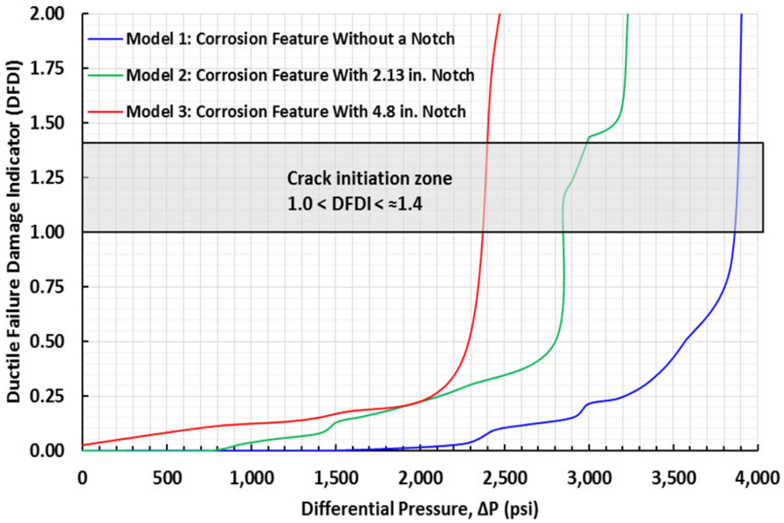
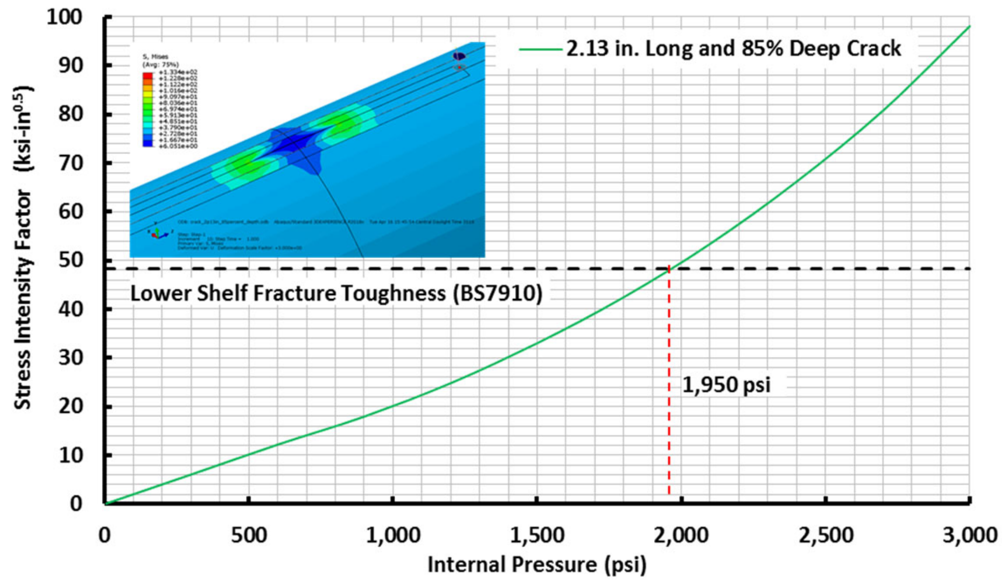
7 in. Axial Rupture Origin Verified







Crack initiated within the groove.
Cracked region unstably grew and the axial rupture resulted

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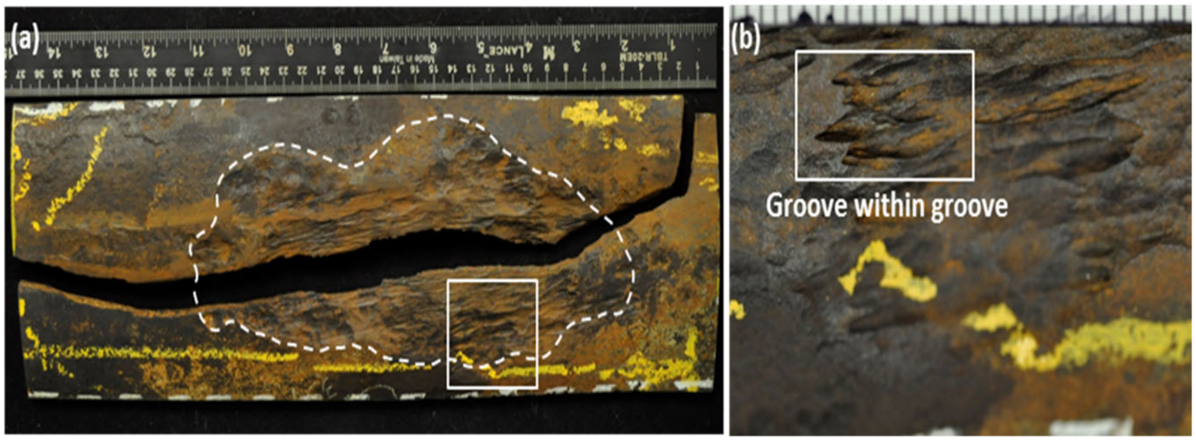
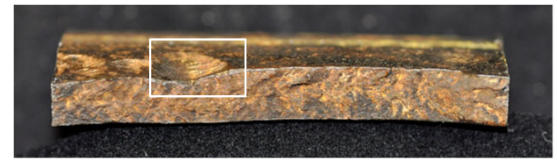
7 in. Casing Corrosion at Failure Location





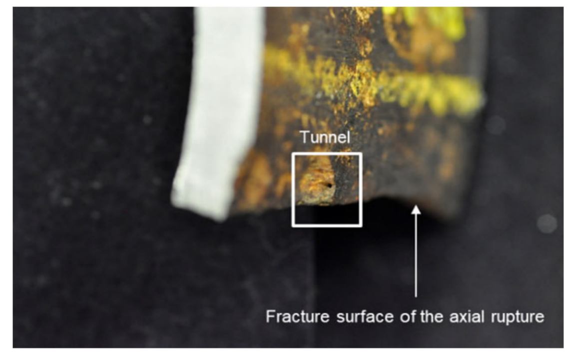


Table 13: Predominant Species Composition of Individual Casing Scale Samples

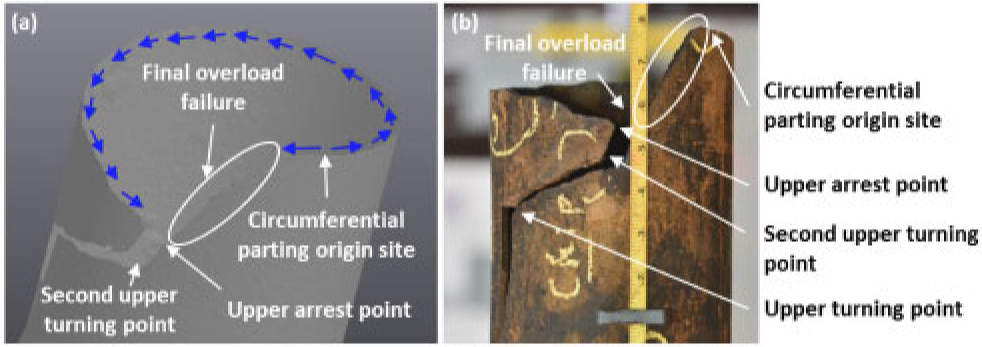
Predominant Species Composition of Individual Casing C025 and C026 Samples, % of Microbial Population									
Individual Species	CO25-S07	CO25-S08	CO25-S17	CO25-S21	CO26-S01	CO26-S04	CO26-S06	CO26-S12	CO26-S16
Methanobacterium aarhusense	0.4	0.004	0.06	1.0	0.1	7.6	0.9	42.5	24.9
Methanobacterium sp.	23.7	22.4	37.9	26.5	26.6	48.0	42.3	34.1	22.6
Methanocalculus sp.	0	0	1.3	4.4	23.5	2.9	0.5	0.02	0.04
Methanocorpusculum sinense	0	0	2.9	0	0.01	0.6	0	0.01	0
Alkalibacter sp.	5.8	20.4	0.1	0	0.04	0.1	0.5	0.5	0.09
Alkalibacterium sp.	24.0	31.8	24.1	17.2	19.7	6.4	2.8	8.3	0.2
Alkaliflexus sp.	12.6	0.6	0.2	0.4	0.01	0.1	0.3	0.02	0.013
Halolactibacillus halophilus	1.1	0.2	3.0	2.6	7.6	11.08	2.4	1.1	1.3
Ercella succinigenes	6.8	0.8	0.02	0.1	0.01	0.02	0.05	0	0

Select traits and list of organisms found to be present in greater than 1% of the total population of well SS-25 casing joints C025 and C026. Values are the percent abundance, color-coded as such: Yellow are >10%, Blue are 1% - 10%, Gray are 0%.

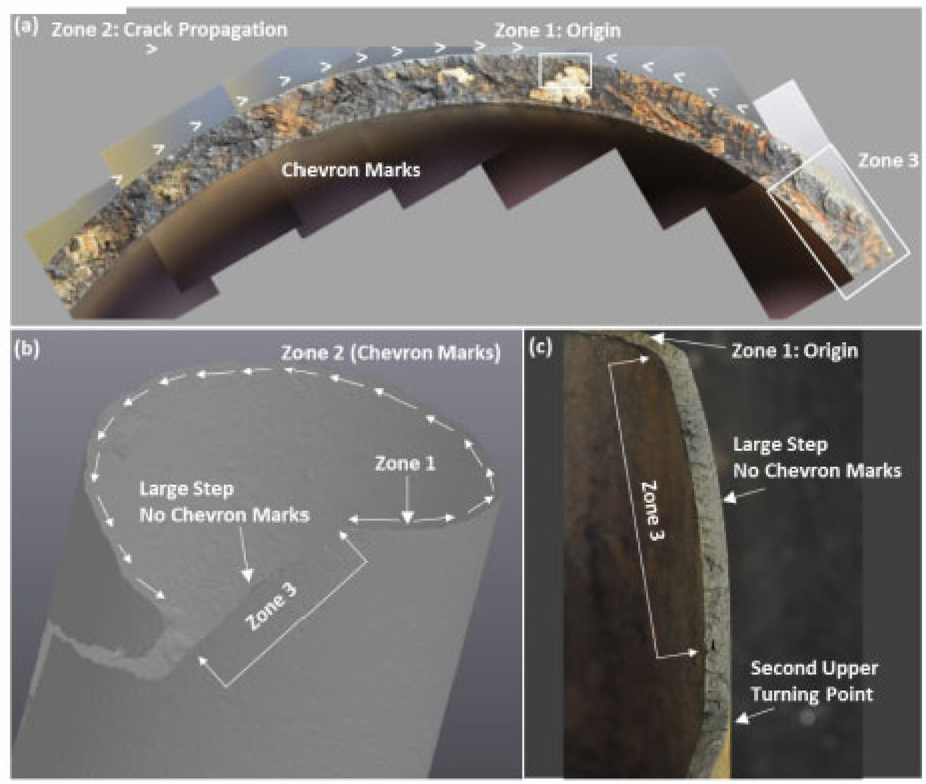
- Metal Loss with striated grooves
- Grooves off axial around 10 to 15 degrees and not associated with any microstructural feature
- Numerous tunnels parallel to the axial rupture fracture surface
- Organic matter within tunnels
- Anerobic environment
- Amplicon Metagenomics- Predominantly Methanogens a form of Archaea that have been known to cause corrosion

Microbial Corrosion at Failure Location

7 in. Casing Parting



- Circumferential Parting a separate event
- Indications of a brittle fracture confirmed with fractographic work
- Separate initiation
- Temperature estimated based on fracture toughness measurements to range from -76ºF to -38ºF



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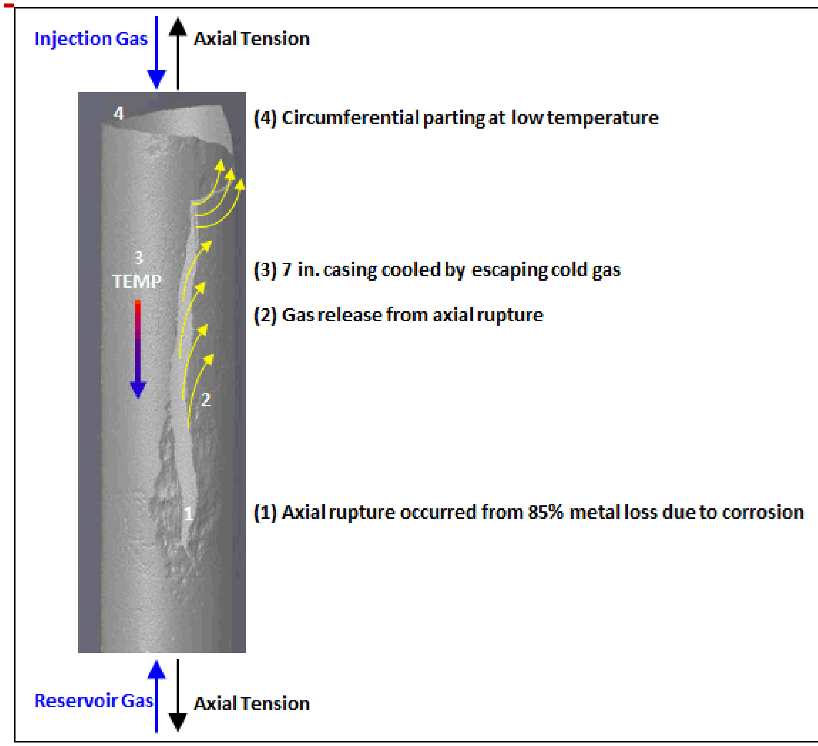
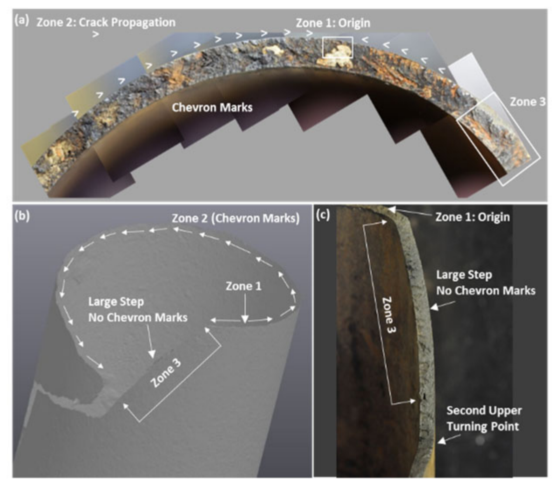
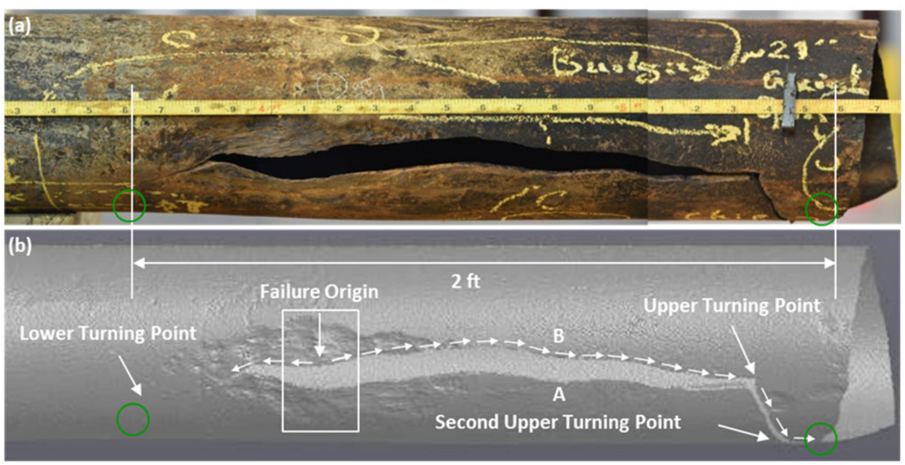
7 in. Casing Failure Sequence



- External corrosion with 85% wall reduction
- Corrosion caused by microbes resulting in grooves
- Notch acted like a stress concentrator
- Large patch of corrosion
- Axial rupture
- Cooled (-60°C to -39°C) and then circumferential parting





Two separate events-failure sequence

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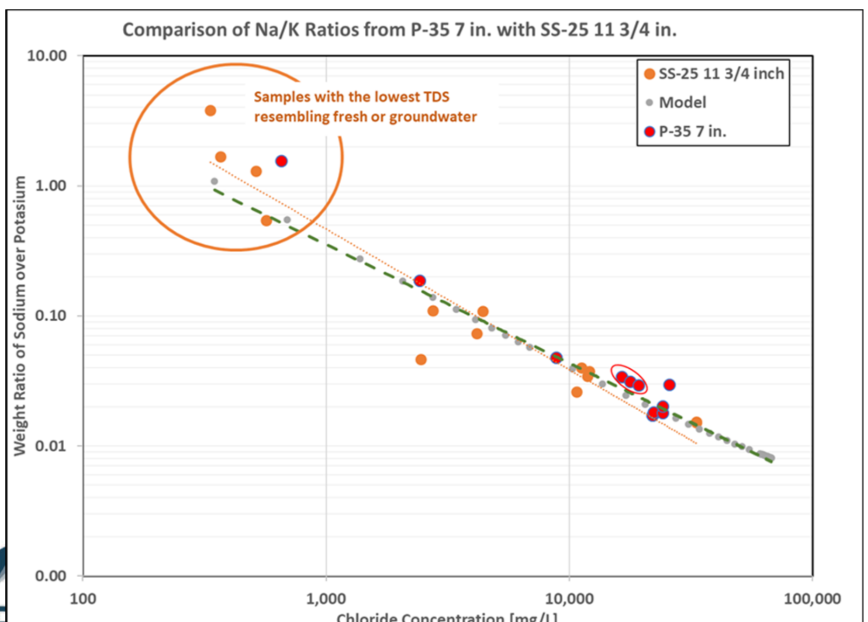
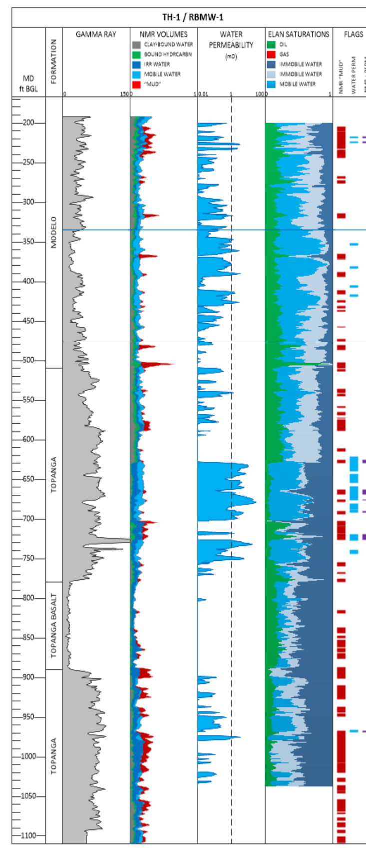
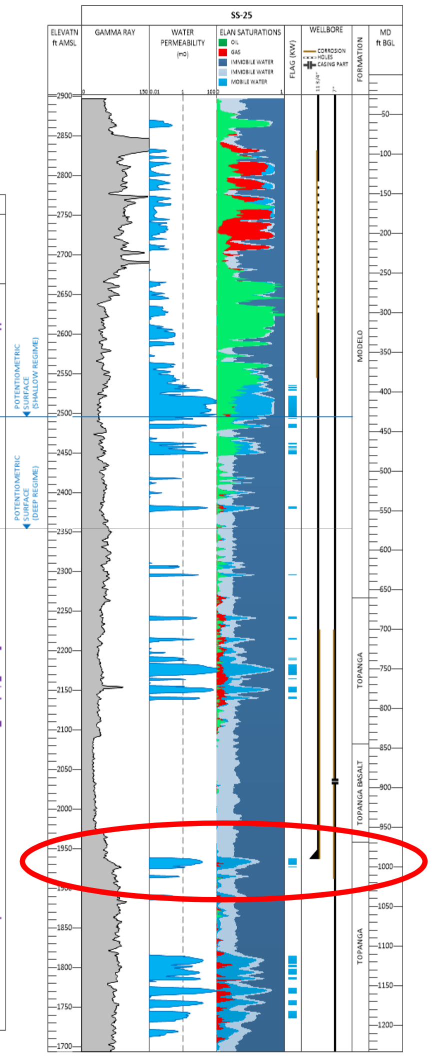
Water and Corrosive Media

- Two boreholes were drilled at SS-9 to assess location of ground water. Two distinct sources of ground water were identified.
  - Shallow (340 to 440 ft)
  - Deeper (900 to 1000 ft)
- Logged to assess the water layers
- Cased hole dynamics tester
  - Low salinity ground water clearly identified in certain samples







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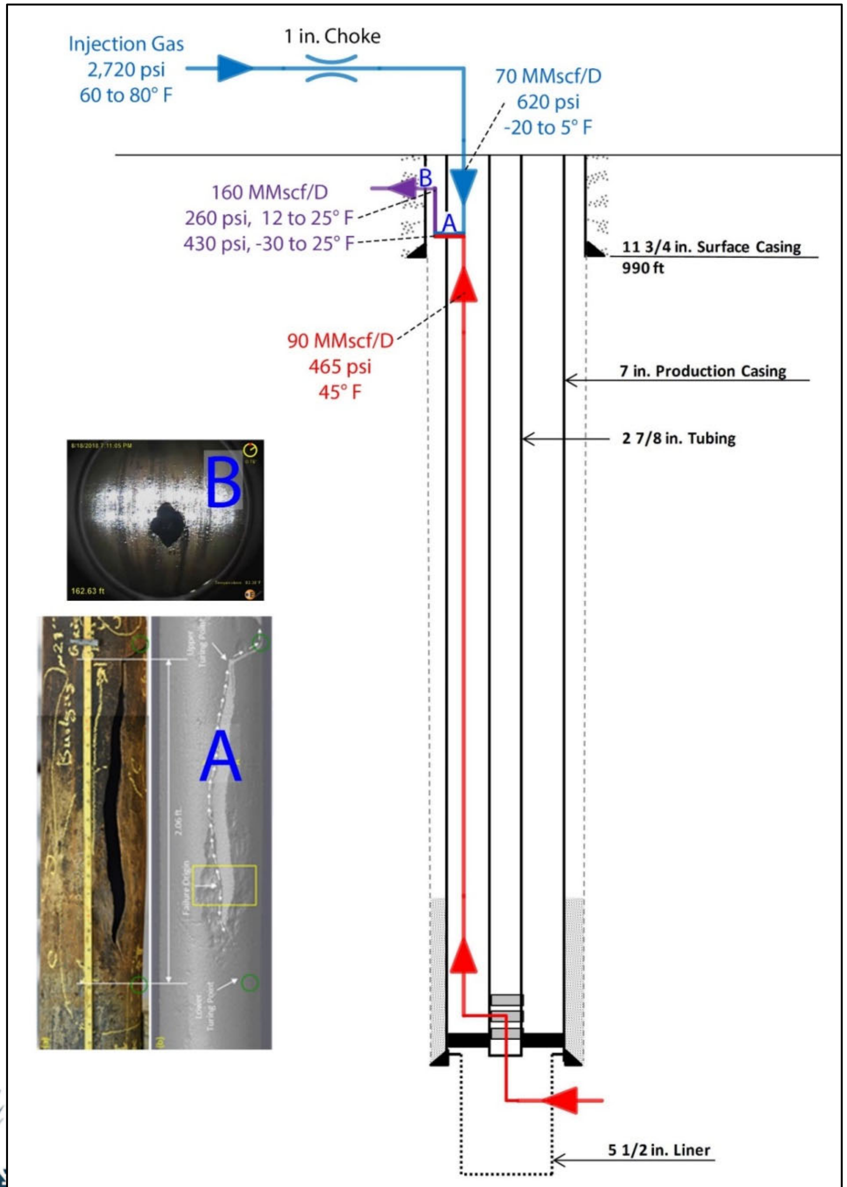
7 in. Casing Failure Sequence



October 23, 2015

- Well opened for injection between 3 and 4 AM
- Axial Rupture happened first
- Gas flow increased to a total of 160 mmscf/D
- Metal cooling resulted in brittleness and circumferential parting within hours of axial rupture
- All failures same day

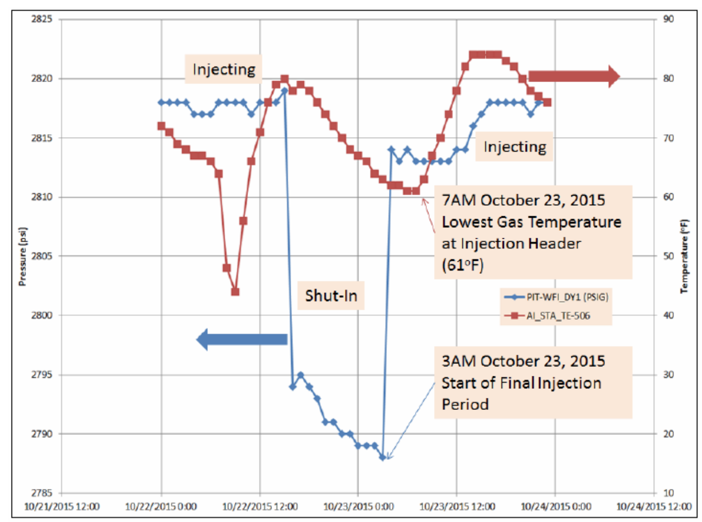


Figure 118: PIT-WFI_DY1 Hourly Pressure and AI_STA_TE-506 Hourly Temperature Measurements

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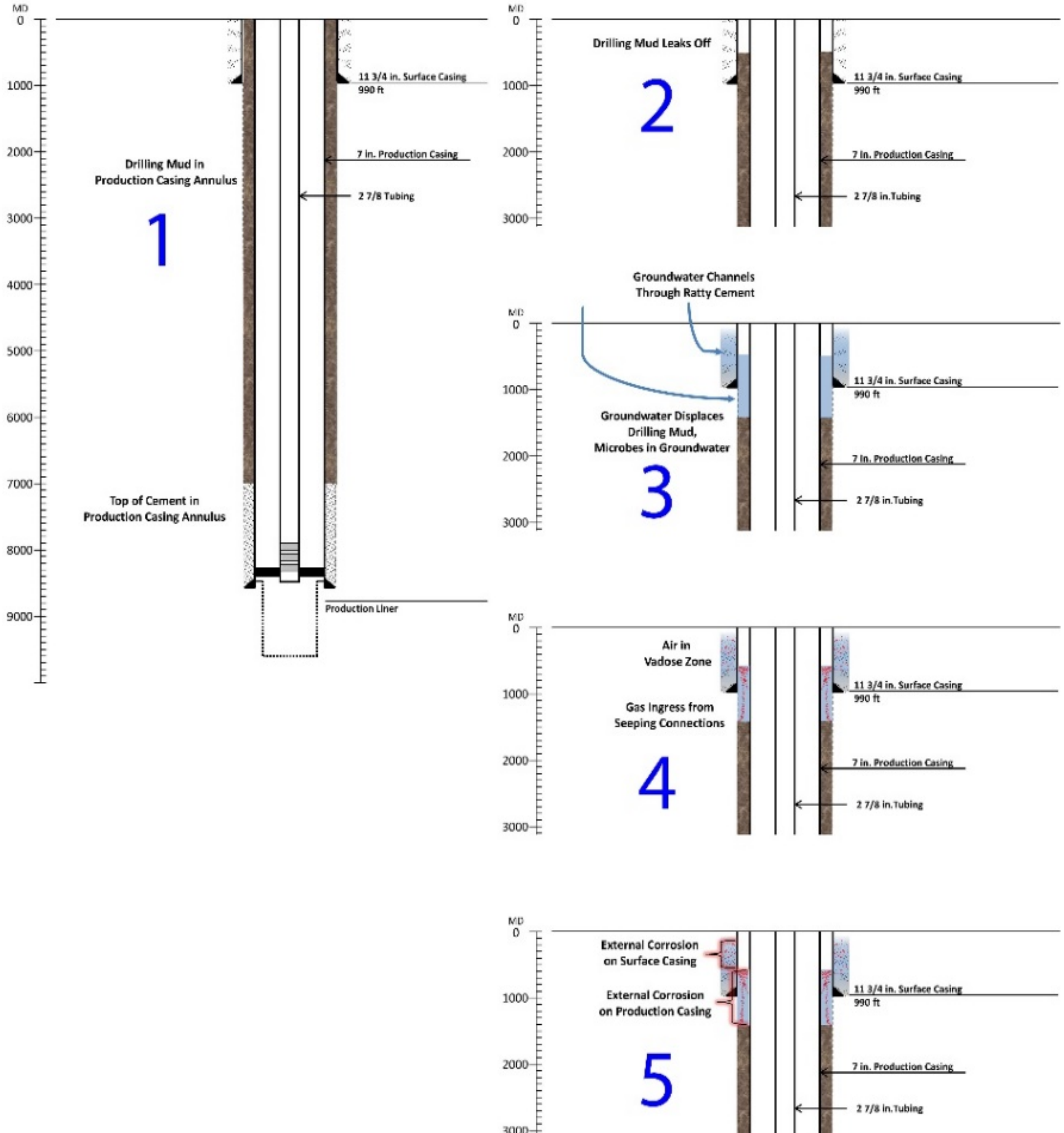
7 in. Corrosion

- Annulus groundwater ingress and egress
- Dry and wet seasons
- External corrosion due to microbes



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Summary

- Failure Sequence established
- Leak Sequence was identified
- Corrosion mechanism that caused the axial rupture was microbial
- Groundwater was the corrosive media

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SS-25 Root Cause Analysis

Post Leak Events

Post Leak Events

- Blade's objectives in analyzing these events were to answer the following questions:
  - When did the failure occur?
  - What was the initial leak rate? How did this leak rate change over time?
  - What phenomenon caused the low temperatures that facilitated the brittle circumferential parting identified by the metallurgical analysis?
  - What was the leak path? How did the leak path change over time?
  - How did the injection network respond to the failure? Could the failure have been detected in real time by a surveillance system?
  - Why did each of the kill attempts fail?
  - How much gas leaked from the reservoir during the incident?

SS-25 Blowout Timeline

Date	Day	Event(s)
October 23, 2015	1	SS-25 leak was discovered at 3:15 PM and injection header valve was closed at 3:30 PM.
October 24, 2015	2	Wellhead seals were tested and repaired without any effect on the SS-25 leak. **Kill attempt #1. Failed. Tubing plugged.**
October 25, 2016	3	Field injection was stopped.
November 6, 2015	15	Tubing ice plug was cleaned out using coiled tubing.
November 8, 2015	17	Production logs (temperature, noise, spinner, pressure) were run in SS-25.
November 12, 2015	21	Field depressurization was started.
November 13, 2015	22	**Kill attempt #2. Failed.** Blowout vent opened 20 ft from the wellhead and shot “debris 75 ft into the air.” SS-25 “blew out in the conventional sense “ Relief well was planning started.
November 15, 2015	24	**Kill attempt #3. Failed.**
November 17, 2015	26	Notice of Intention to Drill New Well for P-39A relief well was filed with Division of Oil, Gas and Geothermal Resources (DOGGR).
November 18, 2015	27	**Kill attempt #4. Failed.**
November 20, 2015	29	SoCalGas decided to drill P-39A relief well.
November 23, 2015	32	Permit to drill P-39A relief well was issued by DOGGR.
November 24, 2015	33	**Kill attempt #5. Failed.** 30 ft × 10 ft crater was created at well site by fluids from kill job.
November 25, 2015	34	**Kill attempt #6. Failed.**
December 4, 2015	43	P-39A relief well was spudded (started drilling).
December 22, 2015	61	**Kill attempt #7. Failed.**
February 11, 2016	112	Relief well intersected with SS-25 and brought it under control. Leak was stopped.
February 14–17, 2016	115–118	SS-25 was permanently isolated from the gas storage reservoir with cement.

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Well Deliverability

- Nodal-analysis well (inflow/outflow) model was built using available SS-25 data over its history and from an adjacent monitoring well SS-5 data
  - Well flow occurrences just prior and after the failure
  - Well flow following failure after shut in
- Well Outflow-Inflow model was developed using PROSPER
  - Estimated reservoir pressure in SS-25 and compared to adjacent monitoring SS-5 BHP
- Well Deliverability (or Gas Flow rate) was estimated the model developed

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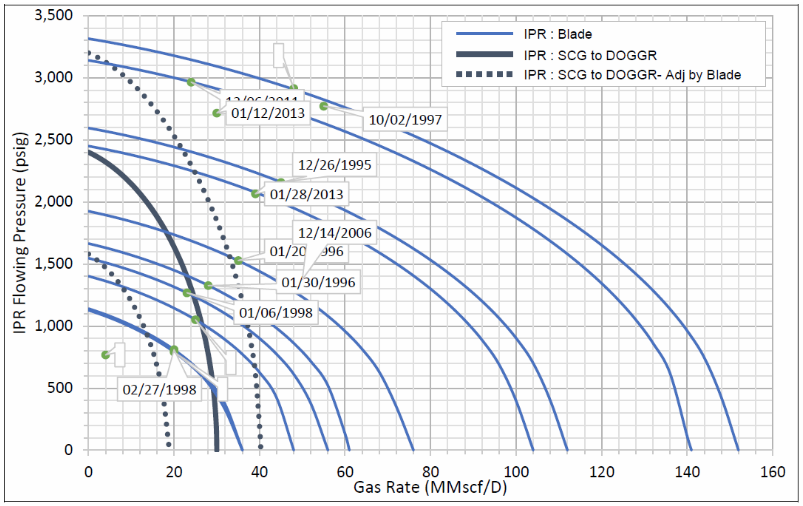
Inflow Performance Relationship (IPR)



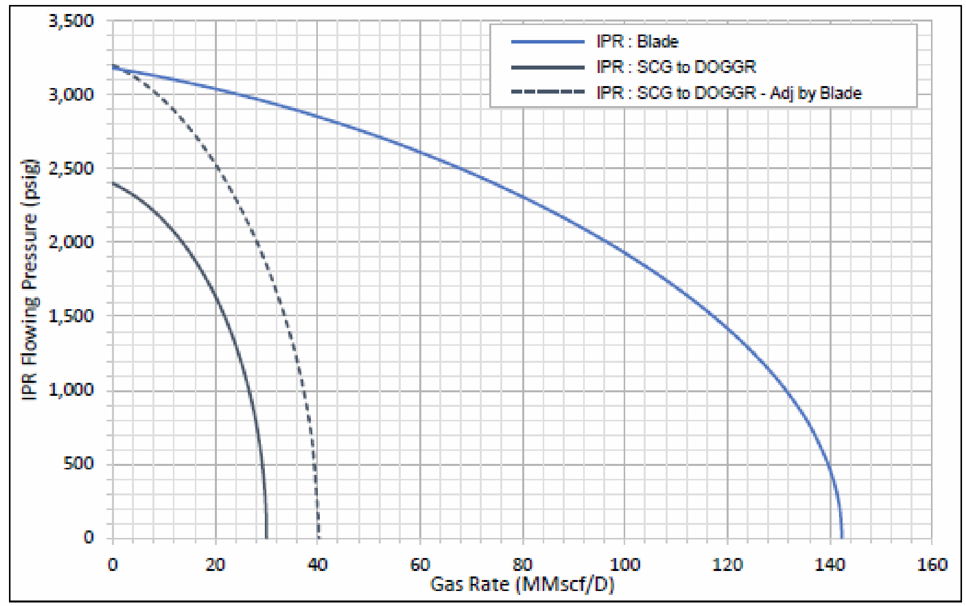


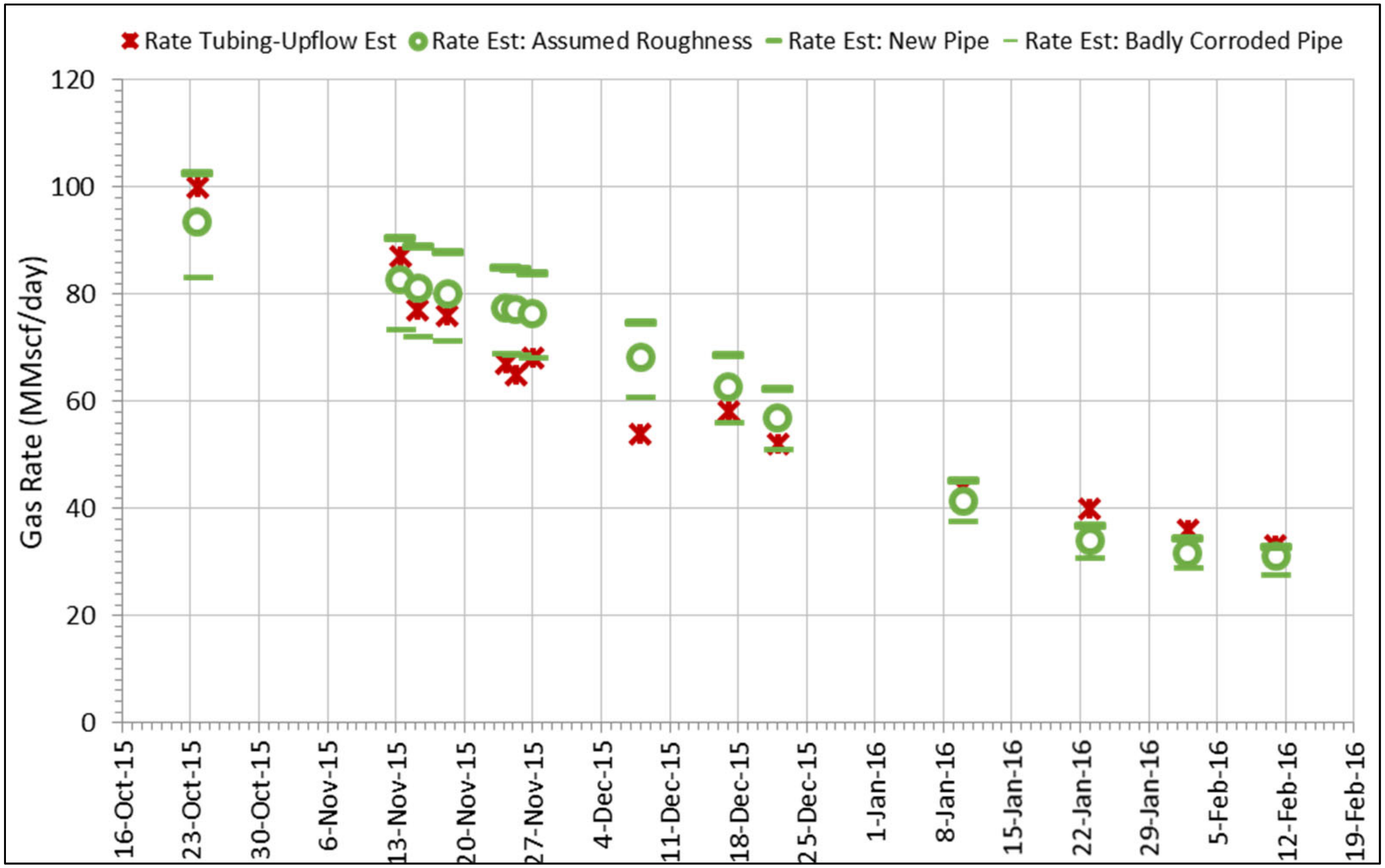
Table 16: Reservoir Properties at SS-25 Calculated from Well Tests

Reservoir Pressure	3,200 psi
Permeability	80 md
Reservoir Thickness	45 ft
Reservoir Porosity (net)	0.20
Connate Water Saturation	0.20
Perforation Interval (net)	45 ft
Wellbore Radius	5 in.
Wellbore Skin	0
Non-Darcy Flow Factor	0.0844 $(MMscf/D)^{-1}$
Tubing / Casing Roughness	0.0072 in.

- IPR – Bottom hole Pressure as a function of production rate
- IPR estimates that were matched to the 9 good well tests.
- Best estimate properties were established (80 md and 0 skin)
- Initial flow rates using the detailed PROSPER model was matched with two other methods of estimation

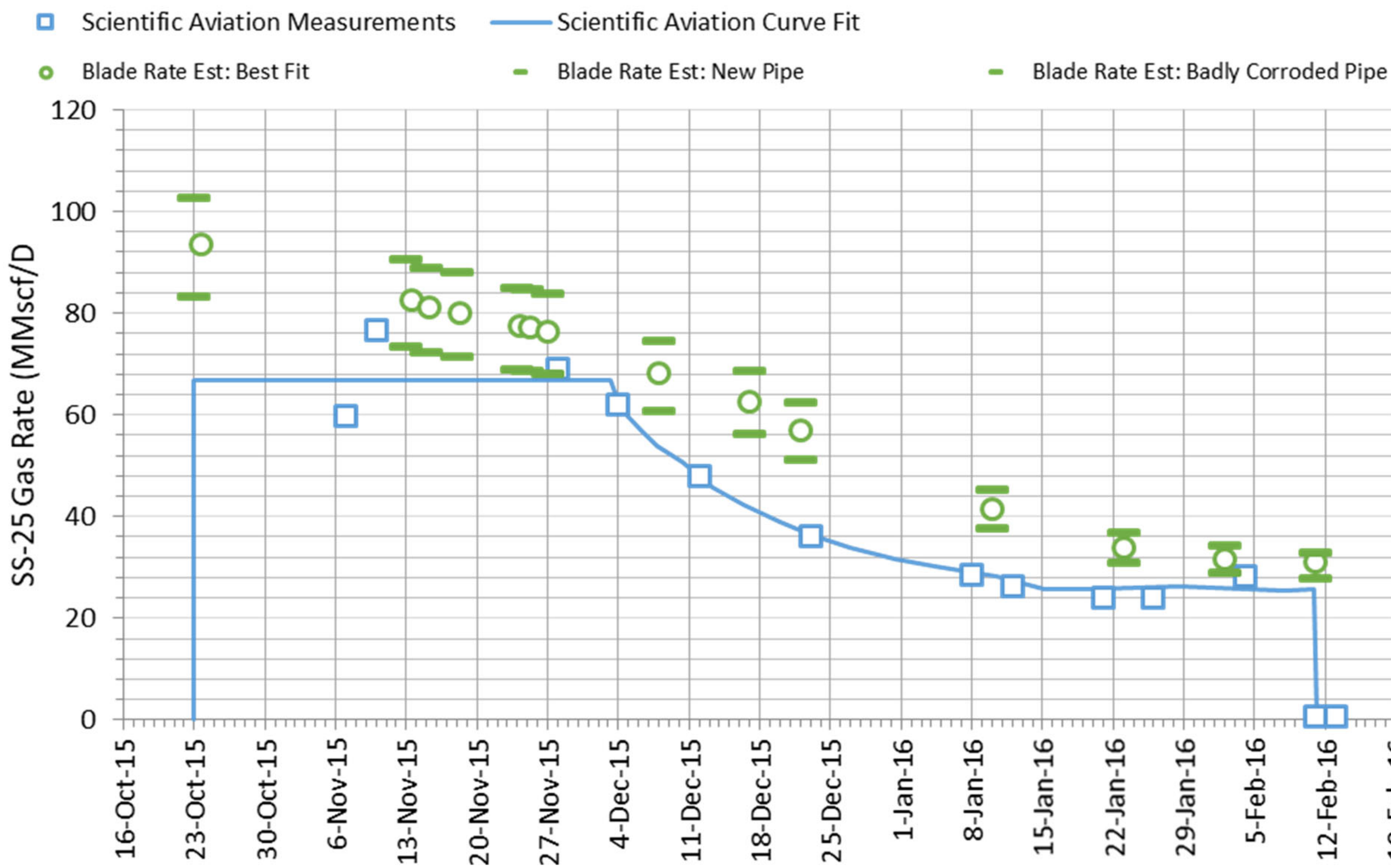
Estimated Leak Rate vs. Time Modeling

- Using flowing wellhead pressure, Shut in tubing to estimate bottom hole pressure and annulus dimensions to estimate flow rate -Upflow
- Matches the more detail Upflow-Inflow PROSPER models.



Different methods provided similar flow rates

Scientific Aviation Leak Rate vs. Time Modeling



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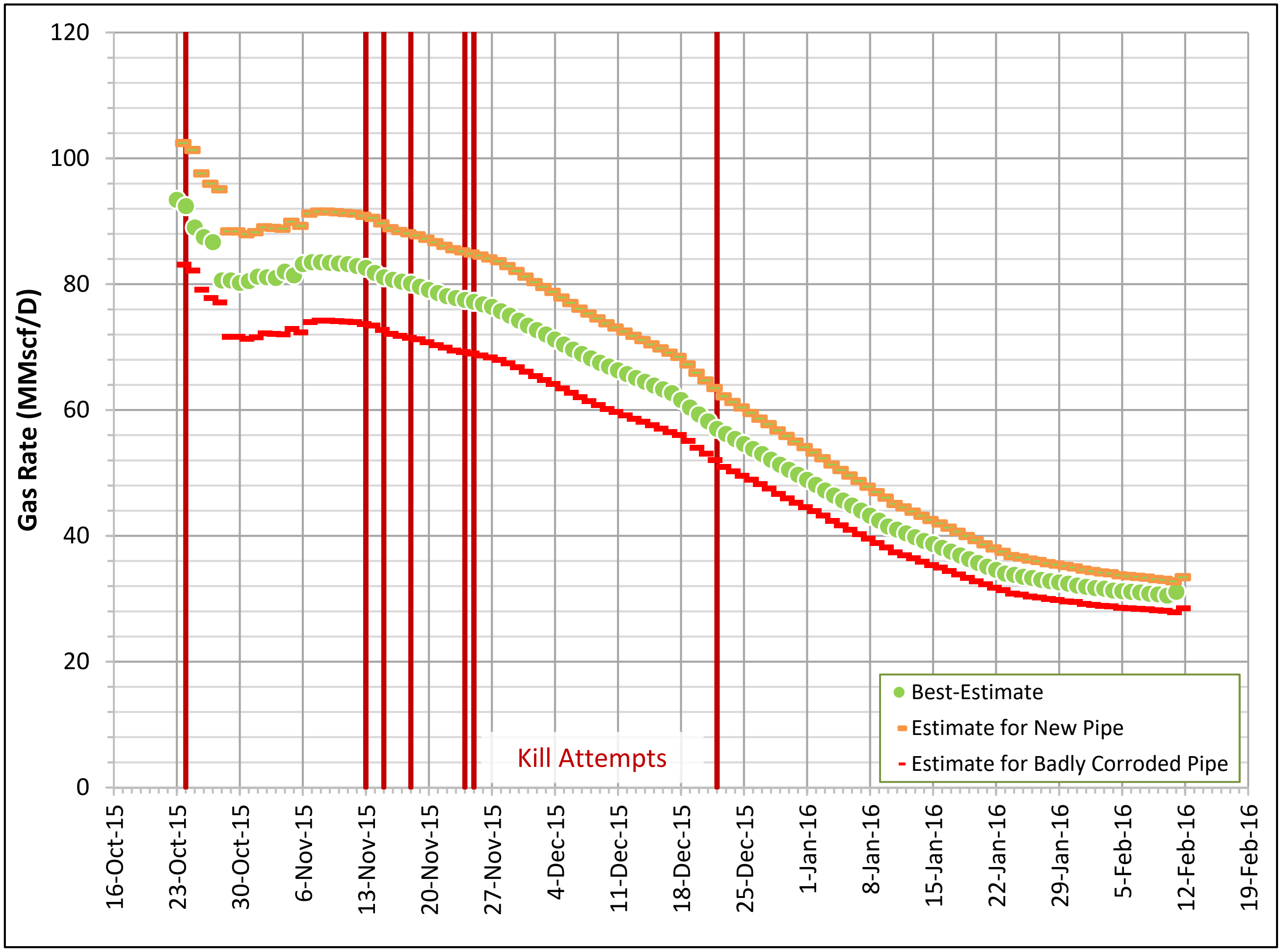
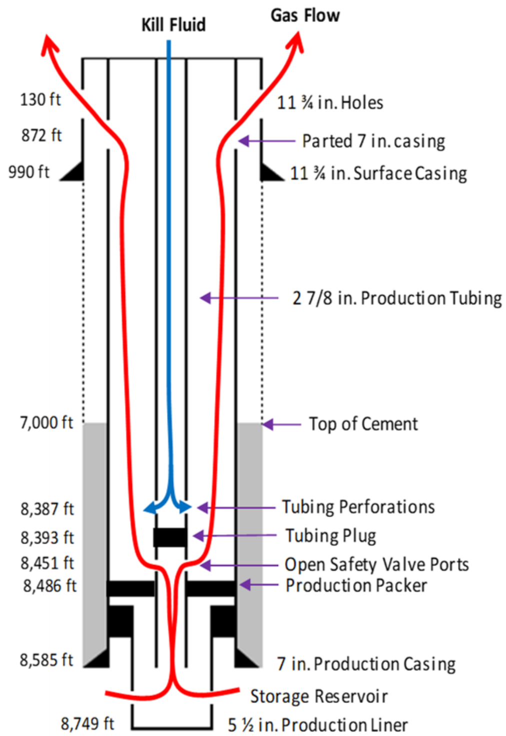
Well Flow Nodal Analysis Leak Rate vs. Time Modeling



Flow rates during each kill attempts essential for appropriate Kill Modeling

SS-25 Kill Attempts



- Drillbench Blowout Software was used for the modeling
- Kill attempt 1 – 6 used low density fluid, 8.3 – 10 ppg at 5 – 13 bpm
- Kill modeling predicts a kill was possible with 12 – 15 ppg fluid at 6 – 8 bpm
- No evidence of kill modeling through Kill attempt 6
- Kill attempt 7 was distinctly different and nearly successful; however conditions had deteriorated on location and was not safe to continue

Table 21: Kill Attempt #3 Alternatives

Gas Rate (MMscf/D)	Kill Fluid	Kill Rate (bpm)	Gas Flow Stopped? Yes/No	Time to Stop Gas Flow (min.)	Time for One Circulation (min.)	Time Less than One Circulation Yes/No	Surface Pressure when Influx Ceased (psia)	Maximum Pump Pressure (psi)	Successful Kill? Yes/No
81	12 ppg	8	Yes	35	35	Yes	2,416	2,431	Yes
	15 ppg	6	Yes	43	46	Yes	0	1,521	Yes

Modeling and Assessment demonstrate that Kill could have been successful with heaver fluids at a higher pump rate

SS-25 Root Cause Analysis

Aliso Canyon Casing Integrity

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Rationale

- Assess casing Integrity issues on a field wide basis
- Similarities or differences in mechanisms between SS-25 and other wells
- Assess the trend of casing leaks with age or other factors

Casing Failure Analysis Process

- Reviewed well files for Aliso Canyon gas storage wells
  - Drilling and completion reports
  - Workover and well servicing reports
  - Well log data
  - Well design
    - Casing size, wall thickness, grade, connection, setting depth, cementing
    - Tubing size, wall thickness, grade, connection, packer depth, completion equipment
  - Dates
    - Spud, completion, workover, well servicing, P&A (if applicable)
- Conformation of casing failures reported in the well file data
- Indications of casing failures leading to a workover
    - Anomalies from temperature, noise, or inspection logs
    - Annulus or anomalous pressure data
    - Visual, smell, sound, etc.

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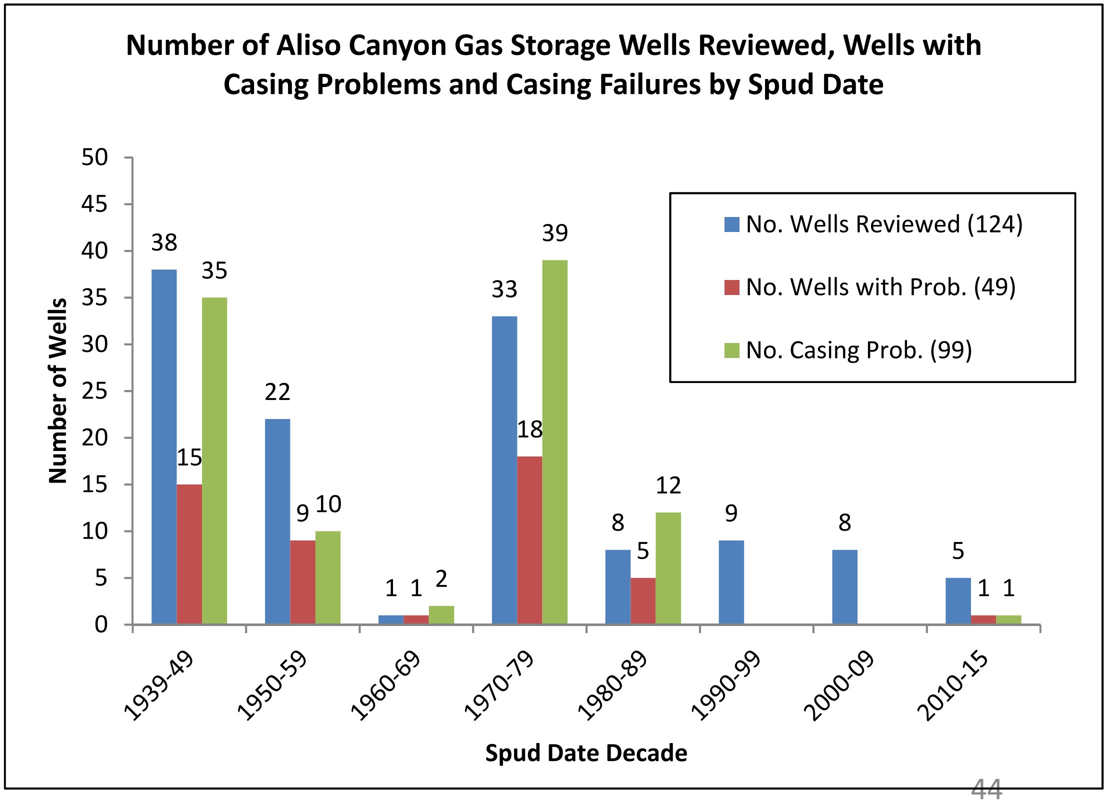
Aliso Canyon Historical Casing Failures

- 124 gas storage wells were evaluated for casing integrity
- 49 wells had casing failures
- 99 failures (63 casing leaks, 29 tight spots, 4 parted casing, 3 other)
- Repairs executed
  - Squeeze cementing
  - Inner casings
  - Scab liners
  - Casing patches
  - P&A
- No failure analysis reported
- No patterns of failures
  - Wide range of depths
  - Field wide failures



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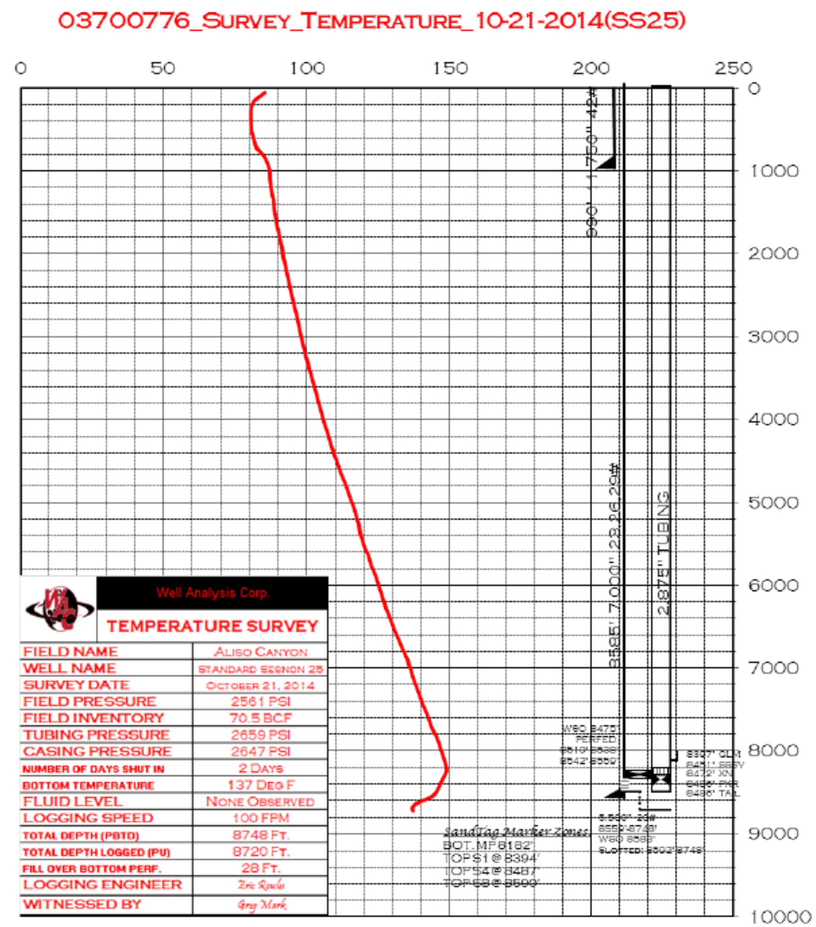
SS-25 Temperature Survey October 21, 2014

- Regulations required annual temperature surveys
- SS-25 complied with the requirements.
- No temperature anomalies--similar to previous surveys



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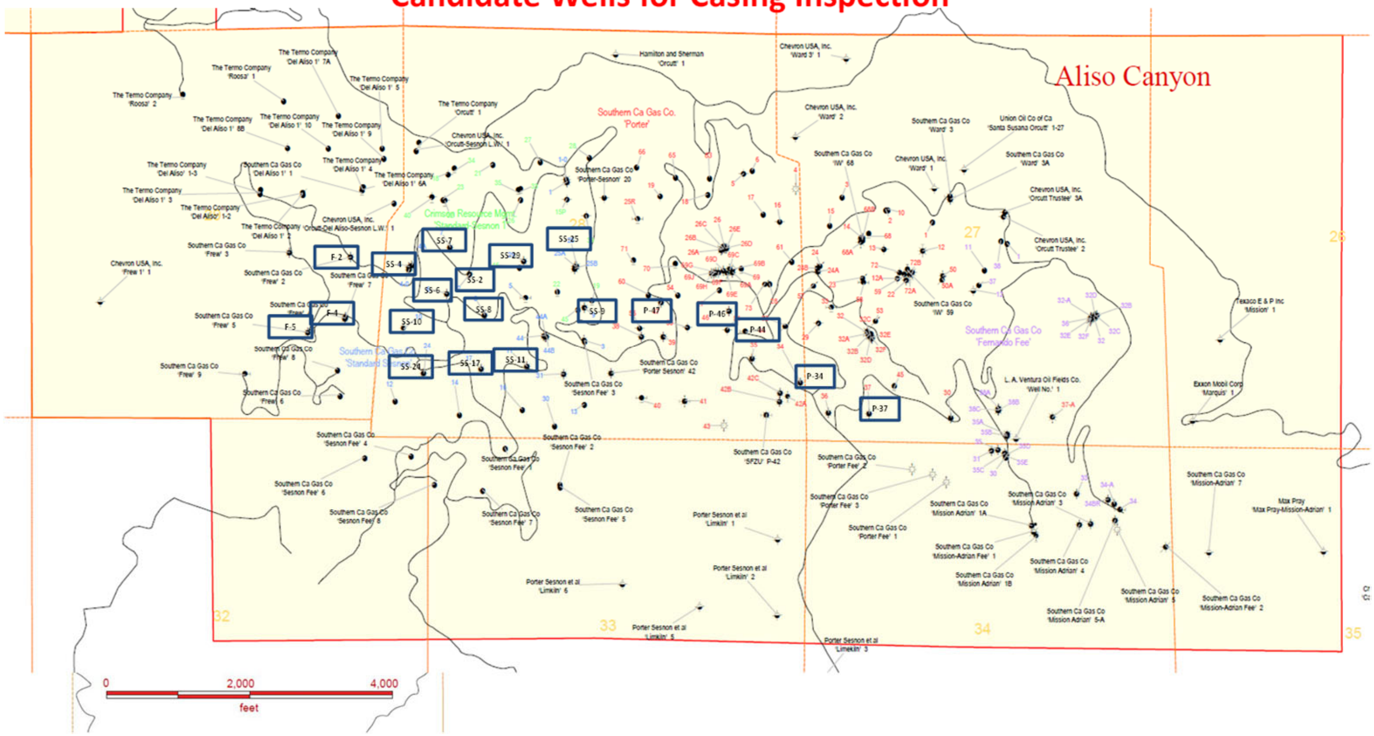
1988 Memo for Casing Inspection of 20 Wells

Candidate Wells for Casing Inspection



- Plan to log 20 wells (SS-25 was on the list as low priority)
- 7 wells were logged within 2 years; 5 wells showed external wall loss from 20 – 60%
- Inspection logs were not run in SS-25

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General Rate Case Submission

- GRC 2016 (testimony in 2014)
  - Historically, most of the well work was reactive in response to corrosion or other problems identified by routine surveillance. Well integrity issues were becoming more frequent.
  - Recognized the possibility of undetected hazards that could lead to major failures. Half of the 229 storage wells (4 fields) were more than 57 years old.
  - New funding requested for SIMP: a detailed assessment on underground assets—a proactive system to minimize risk

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SS-25 Root Cause Analysis

Root Cause Analysis

Root Cause Analysis

- The final step was to integrate all of the data, analyzes, reviews and conclusions to understand the root causes.
- A systematic process, supported by data, evidence and technical analysis is necessary to identify the true underlying problems that contributed to the event.
- Blade selected a structured, evidenced based RCA process that makes no preconceived or predefined assumptions about possible causes
- The process first defines a <u>primary effect</u> followed by identification of causes.

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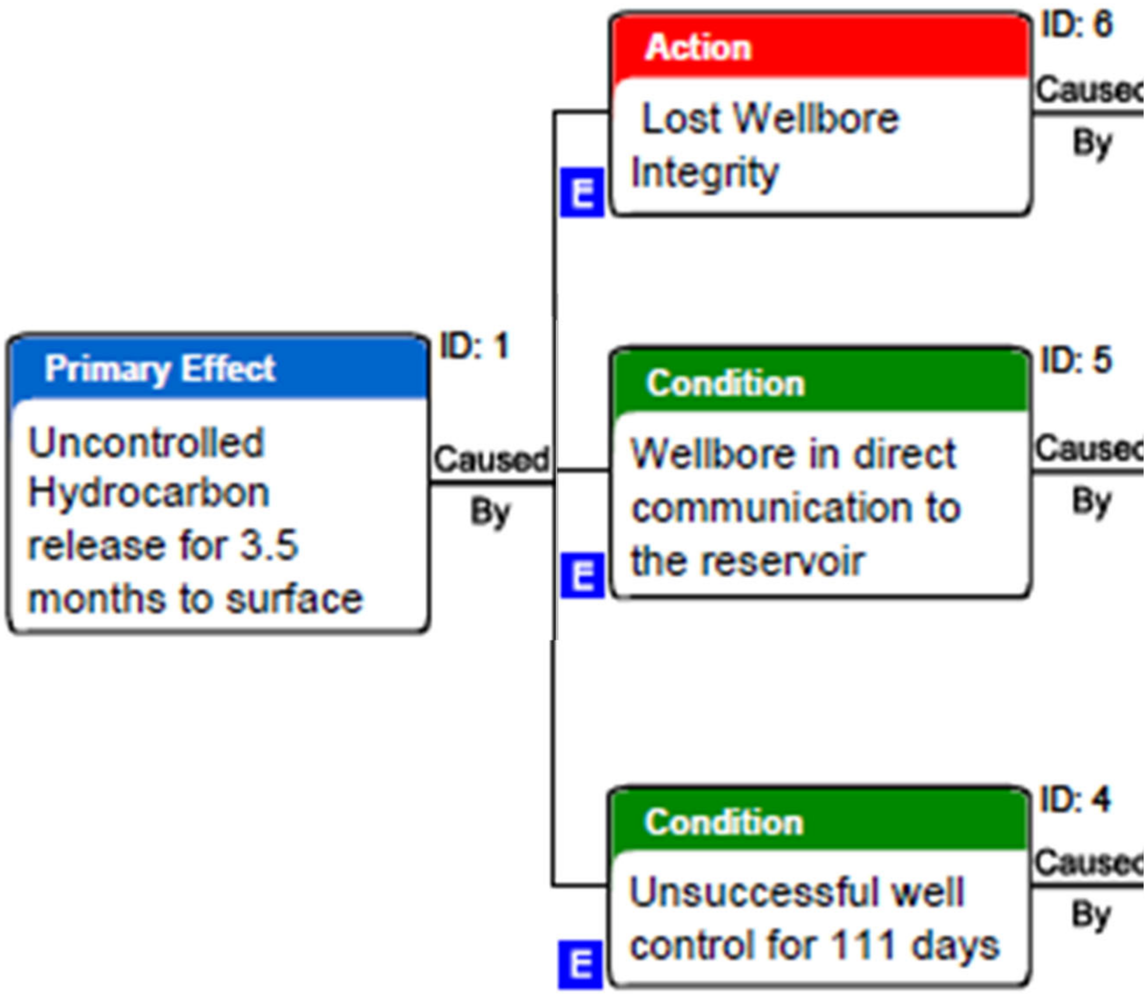
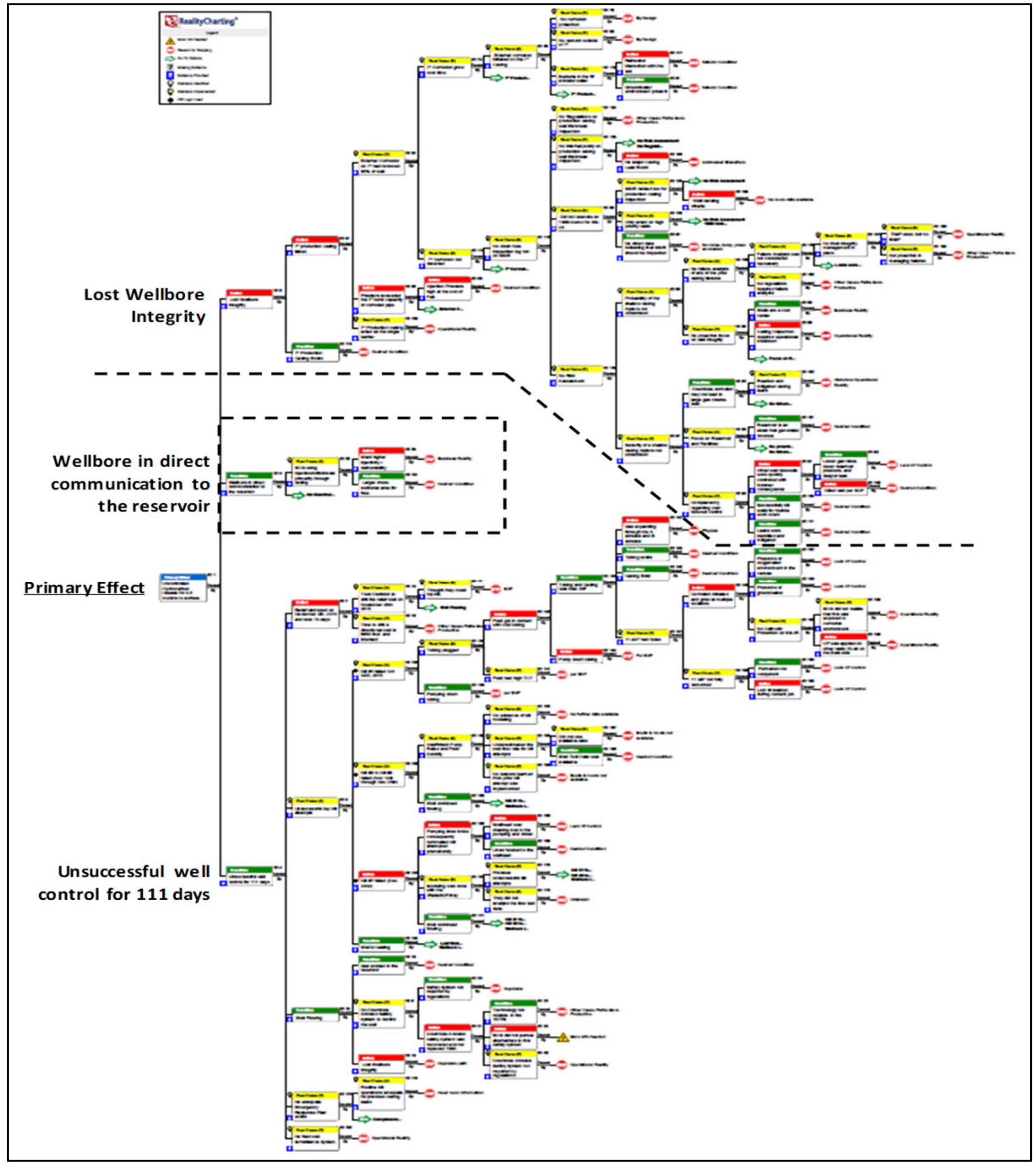
Root Cause Analysis-Primary Effect



Root Cause Analysis

- The next step was to explore the causes for each of the three effects to determine what had caused them and why.
- This process continued until identification of causes was no longer possible



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Root Cause Analysis

The investigation into the SS-25 incident revealed two types of causes: Direct causes and Root causes.

- Direct Causes are those that if identified and mitigated, would have prevented the SS-25 incident and would also prevent similar incidents.
- Root Causes are those that if identified and mitigated, would have prevented SS-25 type incidents and other well integrity incidents through the use of procedures, best practices, design, management system, standards, and regulations.

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Causes

- Direct
  - Axial rupture due to microbial corrosion on the OD of the 7 in. casing
  - Unsuccessful top kills because of insufficient fluid density and pump rates
- Root
  - Lack of follow-up investigation
  - Lack of risk assessments for well integrity
  - Lack of dual barriers
  - Lack of wall thickness inspections (regulations or internal policy)
  - Lack of well specific well control plans
  - Lack of real-time continuous well surveillance
  - Lack of knowledge on the locations of ground water
  - Lack of systematic practices of external corrosion protection for surface casing strings

Solutions

- SoCalGas Current Practices and DOGGR Regulations implement the following:
  - A Risk Based Well Integrity Management System Should be Implemented
  - Casing Wall thickness inspection
  - Tubing Packer Completion – Dual Barrier System
  - Implement Cathodic Protection when appropriate
  - Well Surveillance Through Surface Pressure (Tubing and Annuli)
  - Well Specific Detailed Well Control Plan
  - Conduct a Casing Corrosion Study
- Additional Possible Solutions
  - Conduct a Casing Failure Analysis
  - Ensure Surface Casings Are Cemented to Surface for New Wells

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Main Report

- Detail Summary and Root Causes
- Supplementary Reports
  - Four Volumes

Supplementary Report – Volume 1

- Approach:
  - Phase 0 Summary Report
  - Phase 1 Summary Report
  - Phase 2 Summary Report
  - Phase 3 Summary Report
  - Phase 4 Summary Report

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Supplementary Report – Volume 2

- SS-25 Well Failure Causes
  - SS-25 Casing Failure Analysis
  - SS-25 7 in. Speedtite Connection Testing and 11 3/4 in. STC Assessment
  - SS-25 Analysis of Microbial Organisms on 7 in. Production Casing
  - SS-25 7 in. Casing Internal Corrosion Assessment
  - SS-25 Inspection Log Analyses
  - SS-25 Temperature, Pressure, and Noise Log Analysis
  - Aliso Canyon Field: Hydrology
  - SS-25 Geology Summary
  - SS-25 7 in. Casing Load Analysis
  - SS-25 Tubulars NDE Analyses
  - SS-25 Annular Flow Safety System Review

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Supplementary Report – Volume 3

- Post SS-25 Leak Events
  - SS-25 Nodal Analysis with Uncontrolled Leak Estimation
  - Aliso Canyon Injection Network Deliverability Analysis Prior to Uncontrolled Leak
  - Analysis of the Post-Failure Gas Pathway and Temperature Anomalies at the SS-25 Site
  - SS-25 Transient Well Kill Analysis

Supplementary Report – Volume 4

- Aliso Canyon Casing Integrity
  - Analysis of Aliso Canyon Wells with Casing Failures
  - Aliso Canyon Shallow Corrosion Analysis
  - Aliso Canyon Surface Casing Evaluation
  - Review of the 1988 Candidate Wells for Casing Inspection
  - Gas Storage Well Regulations Review
  - Aliso Canyon Field Withdrawal/Injection Analysis
  - Aliso Canyon: Regional and Local Seismic Events Analysis

Questions and Answers

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