SPE Well Decommissioning 2025, 10th June 2025

Zero Leaks. Forever.
Is There A Place For Pragmatism Over Perfection In Well Abandonment?

Ruth Thomas

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Presentation Outline

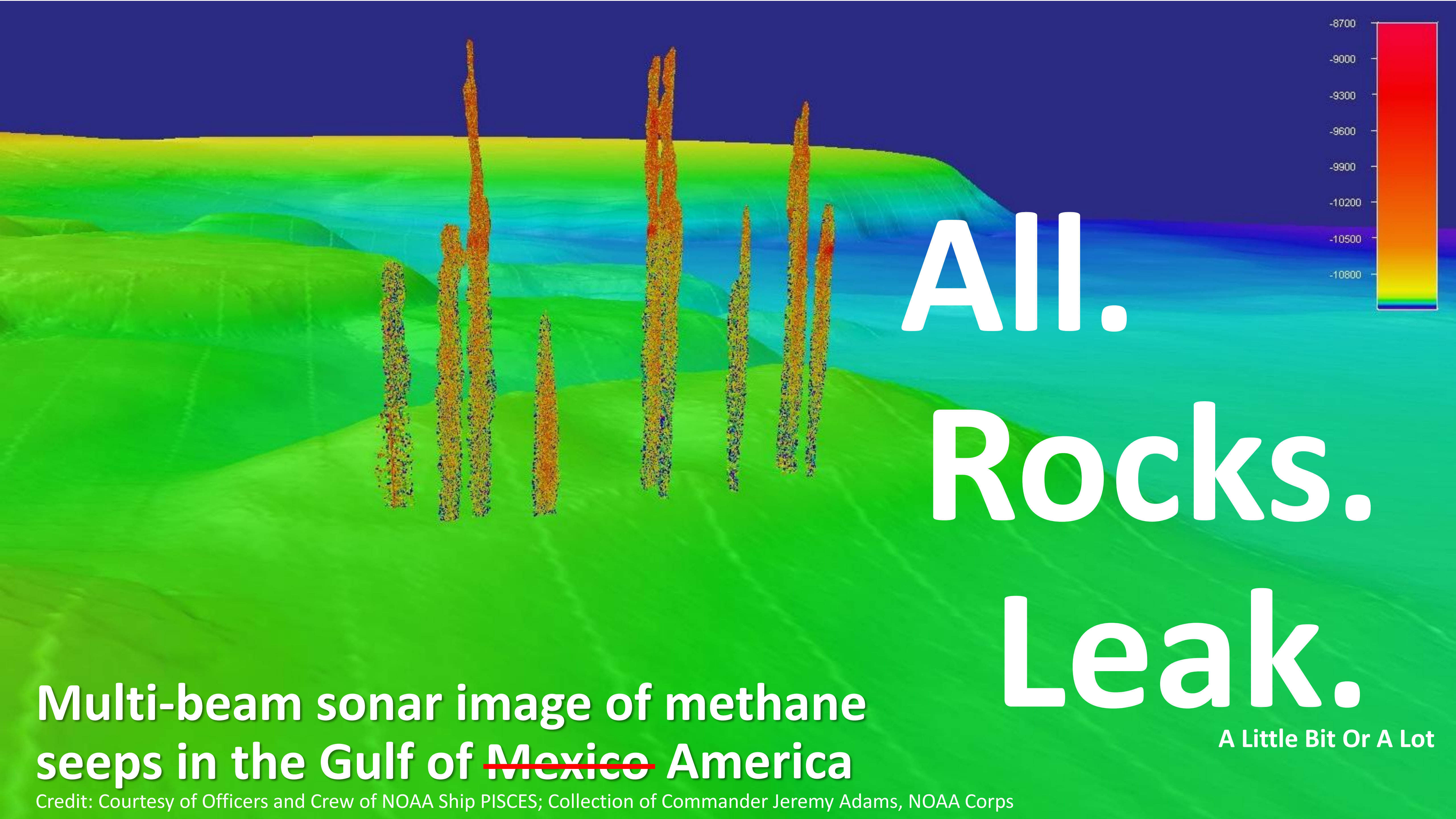
Leaks Around The Globe

Regulatory Expectations

Case Study Example: Options for Isolating Shallow Biogenic Gas Zones

The Role of Leak Characterisation & Societal Cost in Abandonment


Zero Leaks.
Forever.
It’s ok, our plugs
are holding!

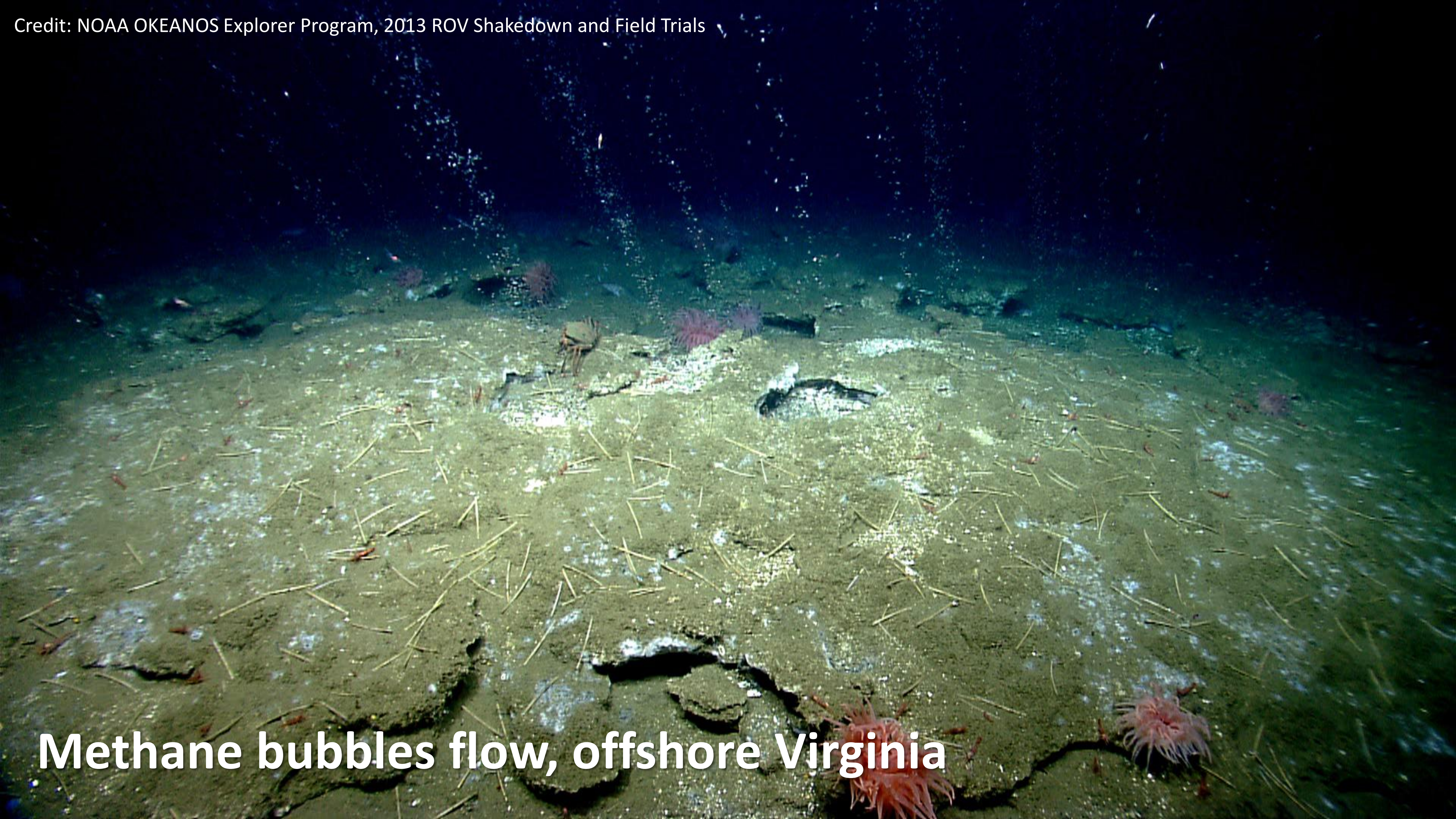


All. Rocks. Leak.

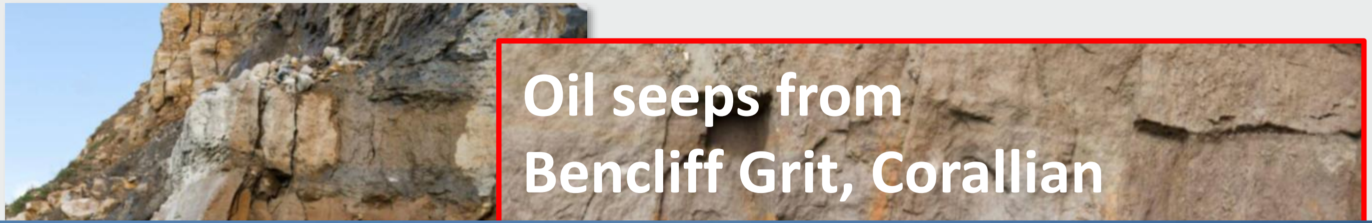
A Little Bit Or A Lot

Multi-beam sonar image of methane seeps in the Gulf of ~~Mexico~~ America

Credit: Courtesy of Officers and Crew of NOAA Ship PISCES; Collection of Commander Jeremy Adams, NOAA Corps


Credit: NOAA OKEANOS Explorer Program, 2013 ROV Shakedown and Field Trials
Methane bubbles flow, offshore Virginia

Somewhere a little closer to home…



Global "Seeps & Weeps"

Offshore seeps

• Onshore seeps

Source: Global distribution of petroleum seeps (G. Etiope, 2009)


Darn, it's cold this time!
Very good reasons to be conscious of the impact of leaking hydrocarbons
(and in particular, methane)

Regulatory Context

Carbon Capture & Storage (CCS)

Cumulative Benefit Mindset for CCS

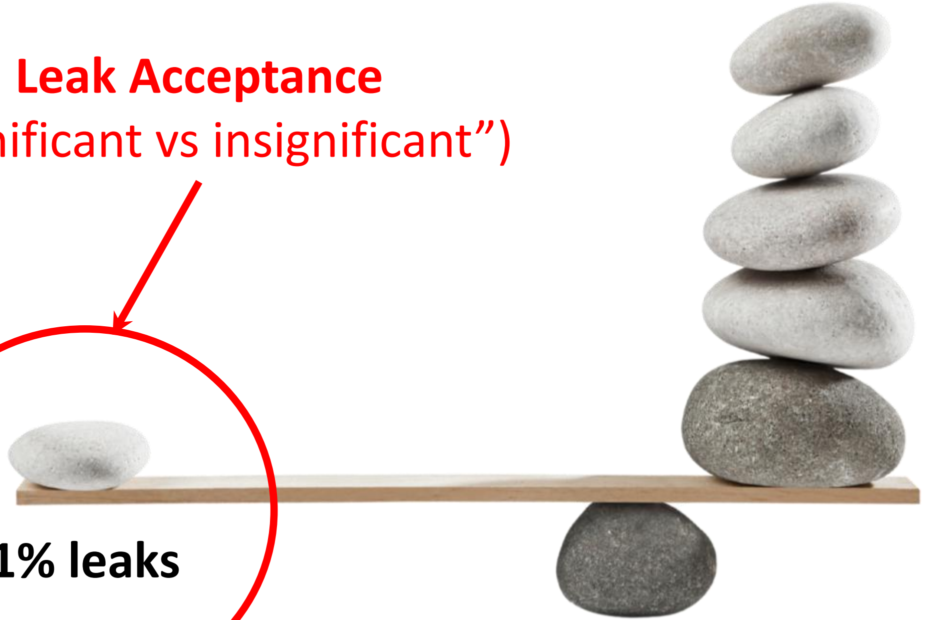
Success is measured by the global total amount of CO_2 removed from the atmosphere and stored underground

Directive 2009/31/EC
("CCS Directive")
Chapter 2
Article 4: Selection of Storage Sites

Guidance Document 1
CO_2 Storage Lifecycle and Risk Management Framework

99% of injected CO_2 is permanently stored

Leak Acceptance
("significant vs insignificant")



1% leaks

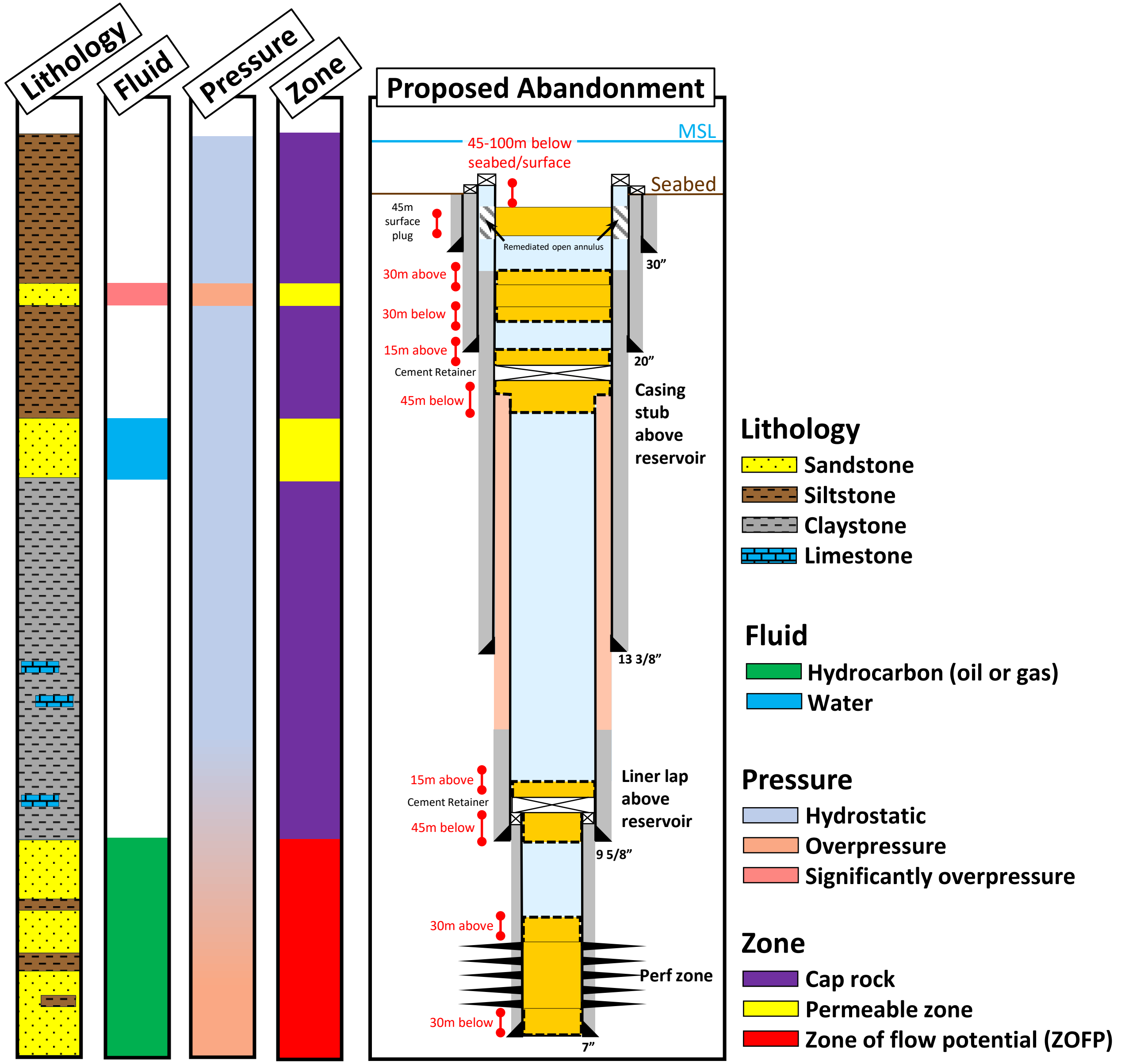
Cumulative benefit outweighs the cumulative negative impacts

Regulatory Context

Well Permanent Plugging & Abandonment (PP&A)

Zero Leaks Forever Mindset

Conservative, multi-level plugging strategy driving cost-escalation and project deferment



Regulatory Context

Well Permanent Plugging & Abandonment (PP&A)

Risk-Based Mindset

Can there ever be an "acceptable leak rate/risk" for hydrocarbons?

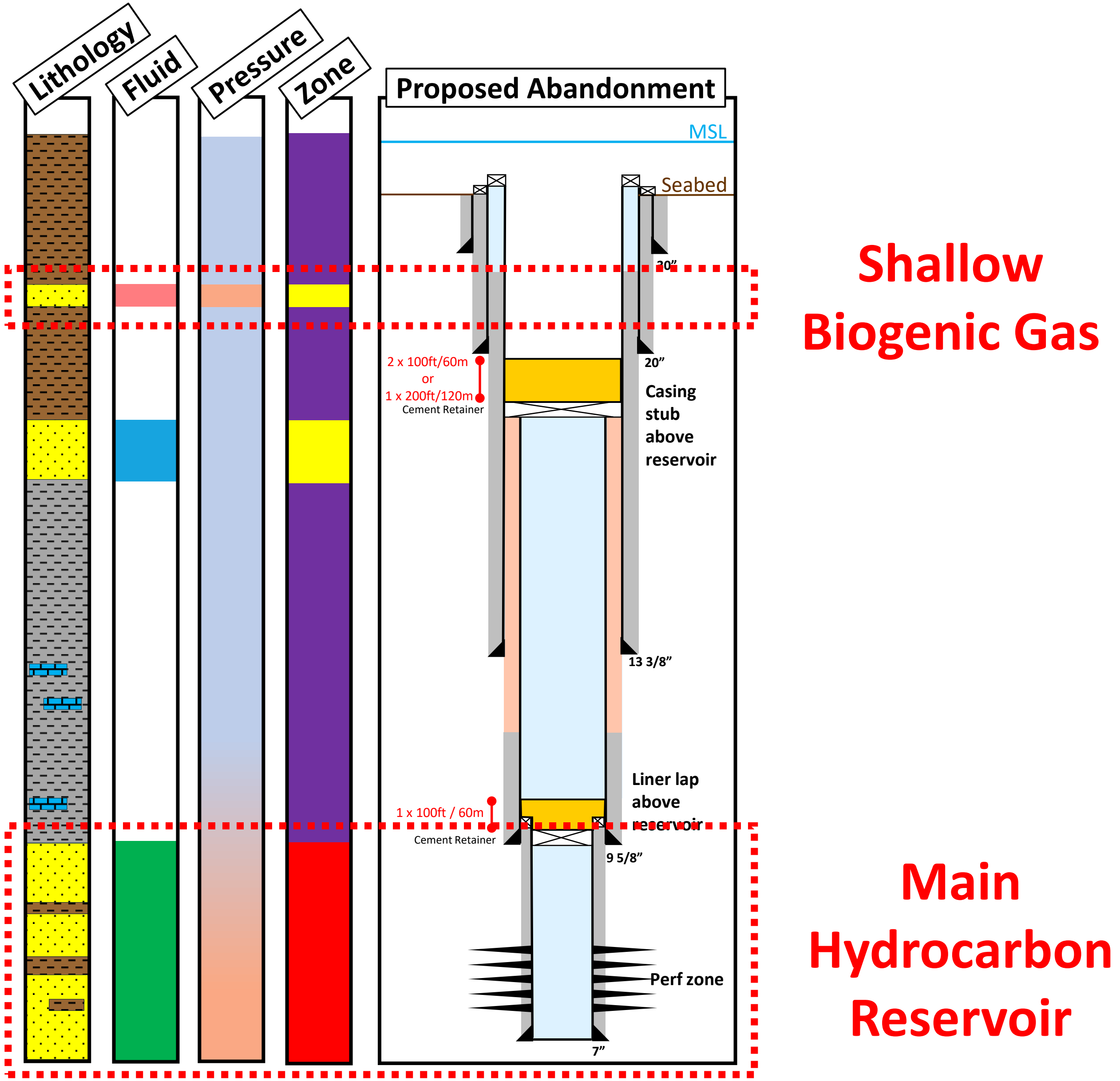
1996 No. 913 HEALTH AND SAFETY statutory instrument

Reg. 13 of Offshore Installations and Wells (Design and Construction, etc) Regulations 1996 (SI 1996/913) [DCR]

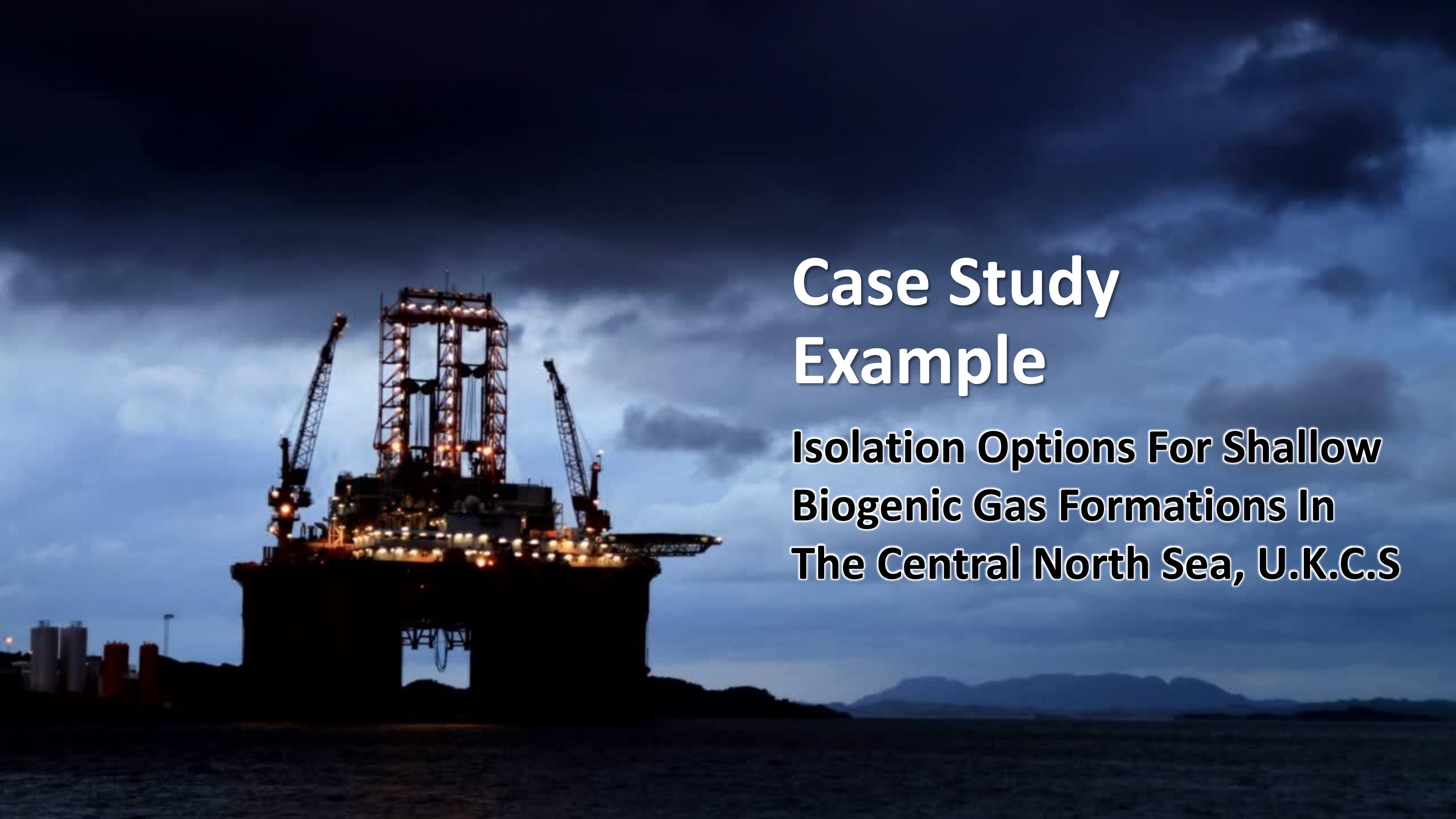
oeUK

OEUK Well Decommissioning Guidelines

Issue 7, "Section 2, Evaluation of Formations with Flow Potential"



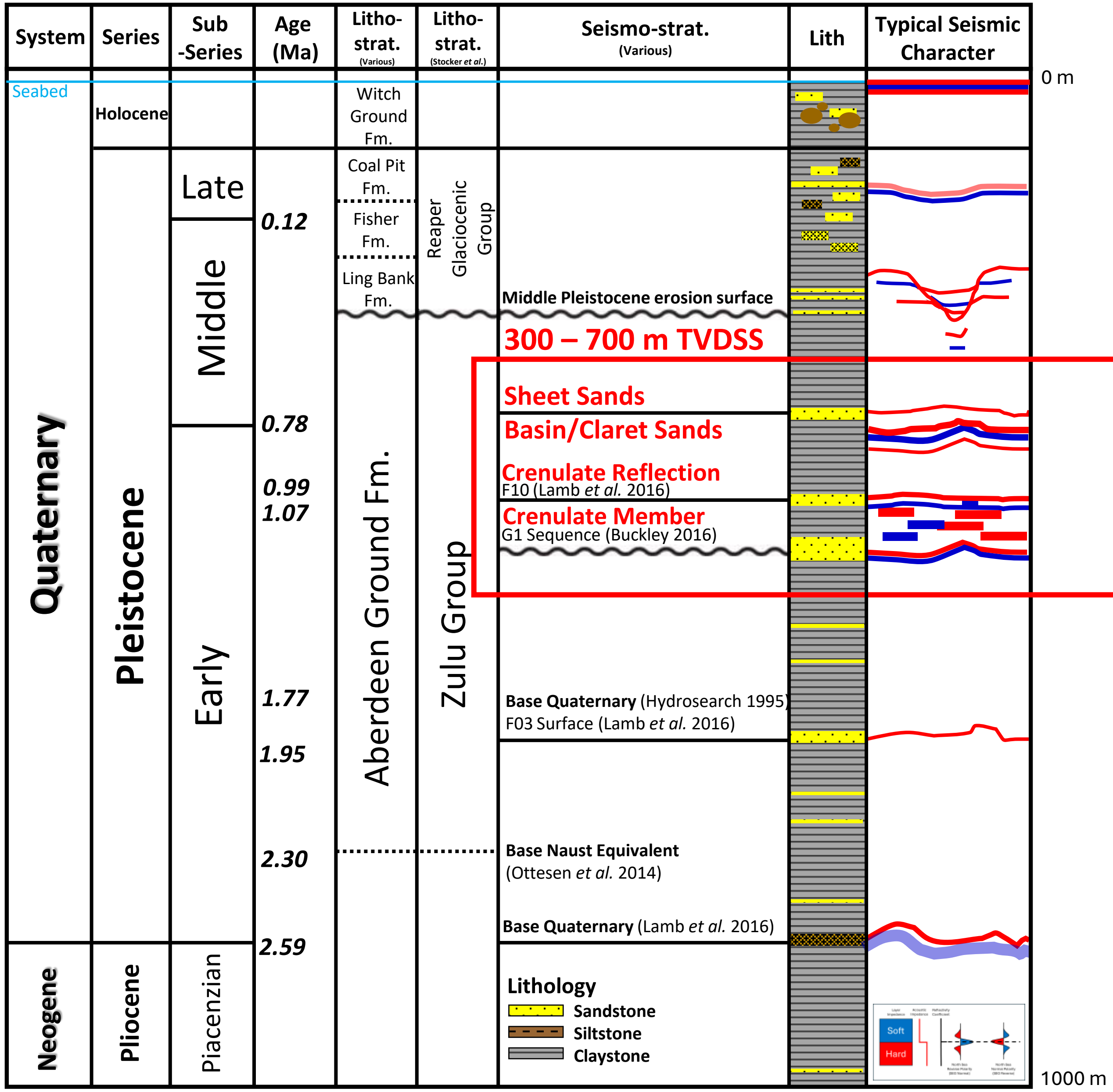
*as low as reasonably practicable



Case Study Example

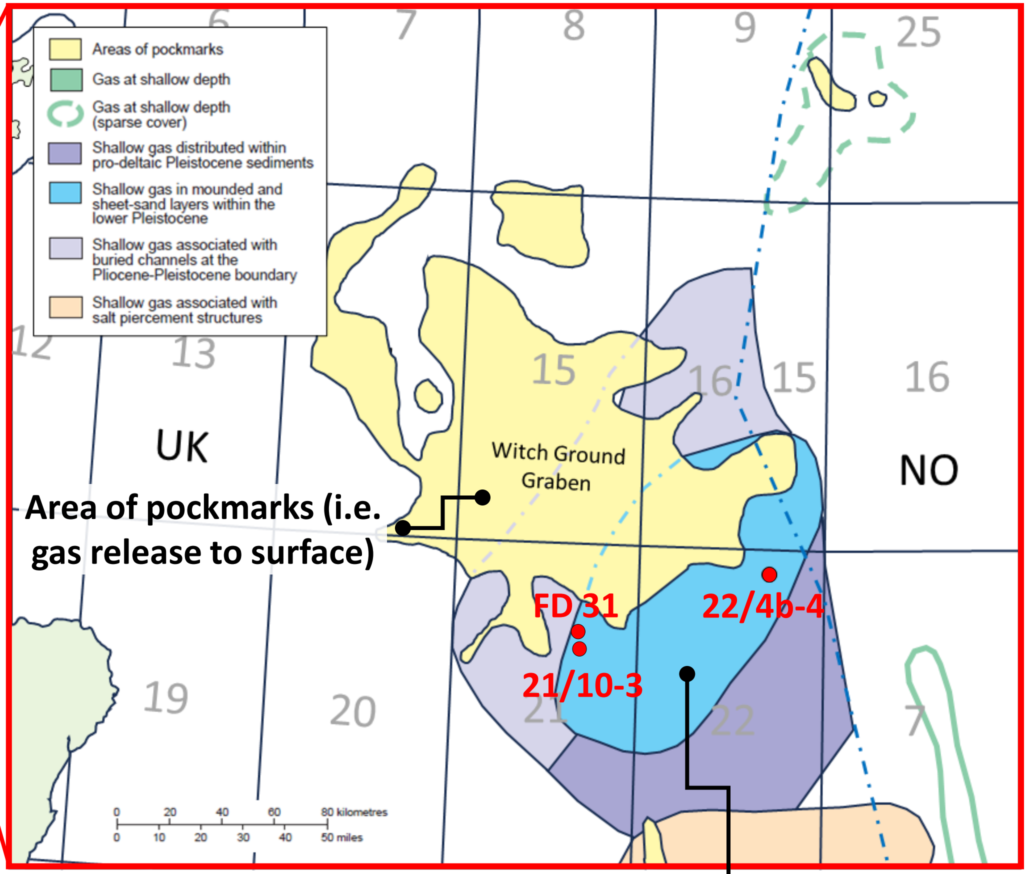
Isolation Options For Shallow Biogenic Gas Formations In The Central North Sea, U.K.C.S

Where Is Biogenic Gas Present?



Re-drafted from "Has anyone seen the Crenulate?" Francis Buckley, OSIG 2017

- Early Pleistocene interval comprising sandstones and siltstones of mixed glacio-marine origin



Re-drafted from Millenium Atlas, 2000

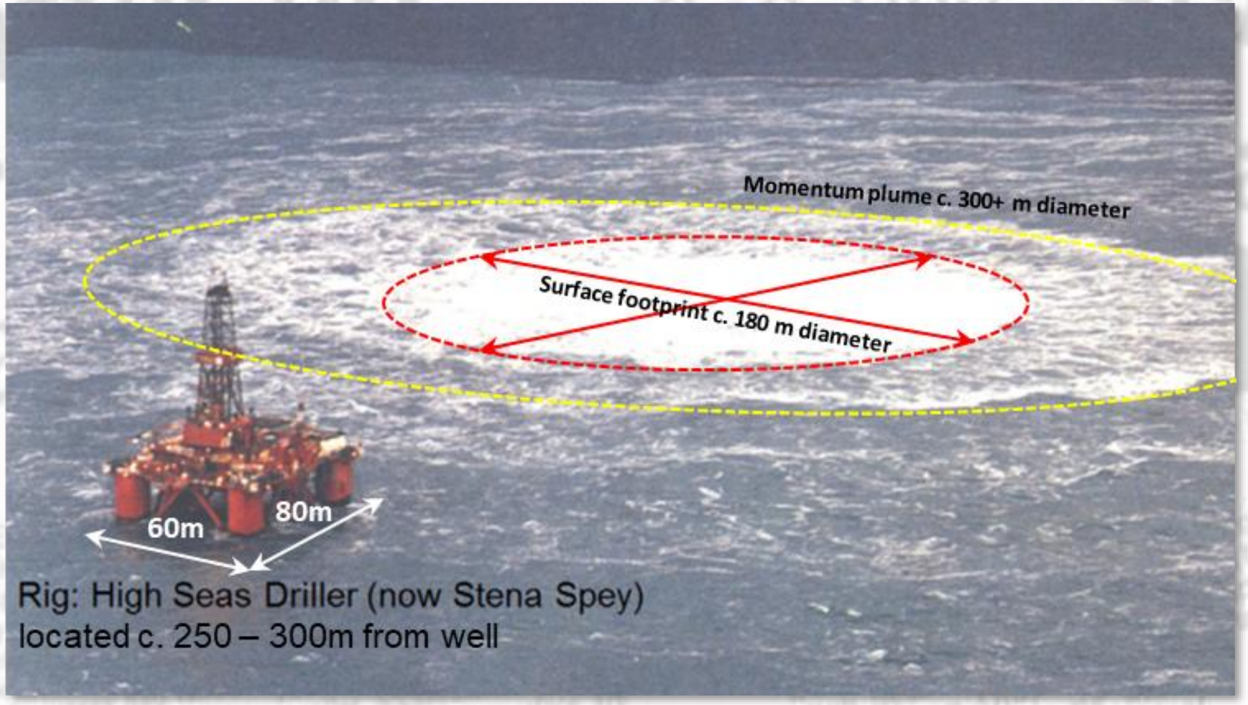
- Blow-out wells

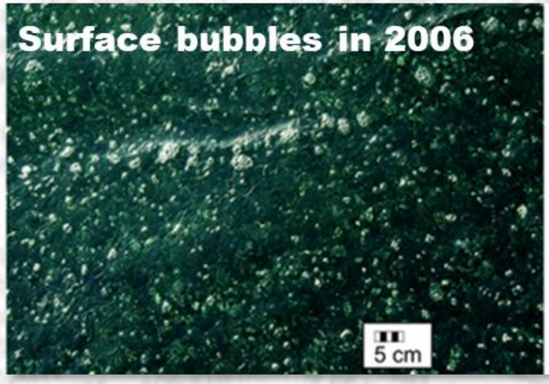
Shallow gas in mounded and sheet-sand layers

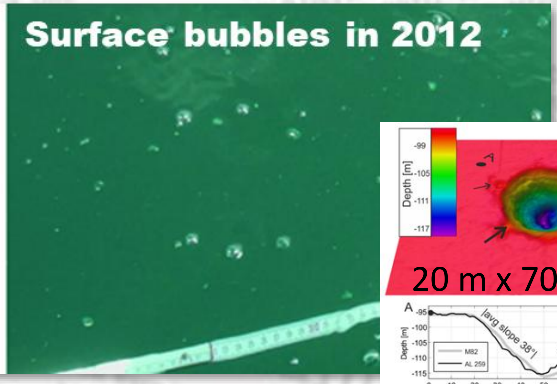
Historical Blow Out

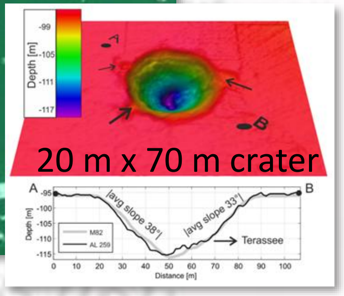
Well 22/4b-4

Source: von Deimling *et al*. 2015

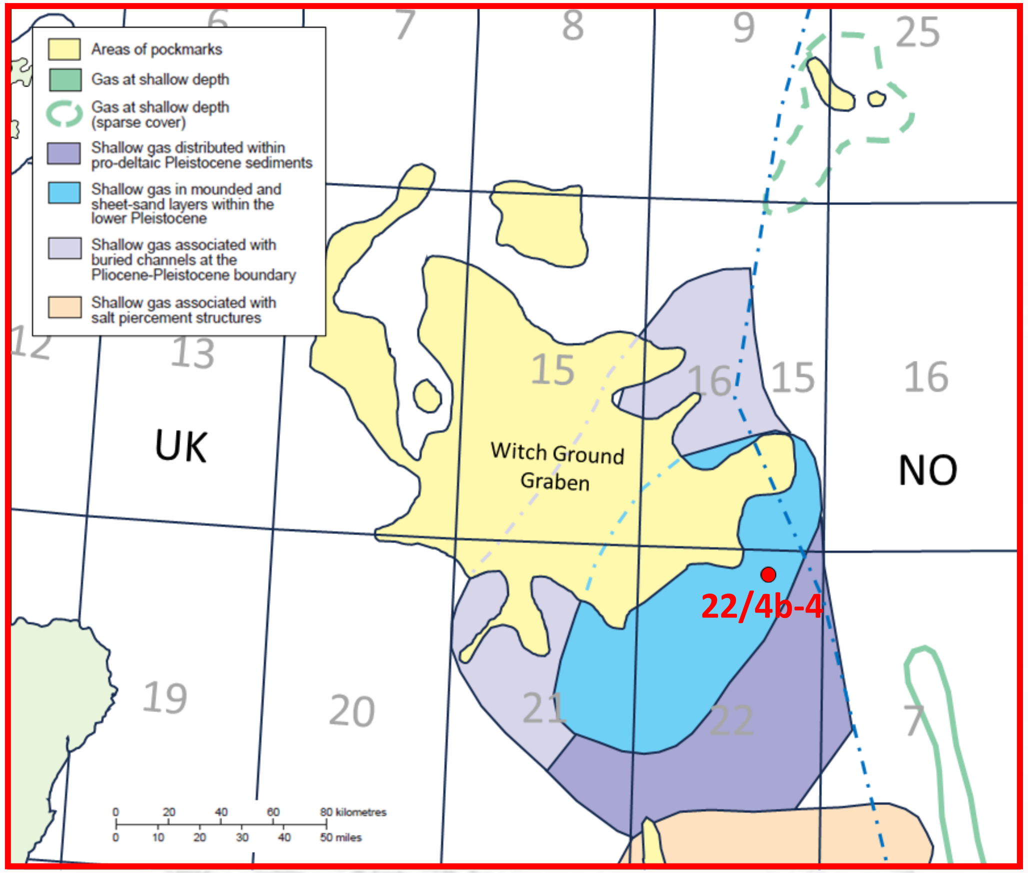








- 22/4b-4 blowout in November 1990
- The well had encountered a 31 - 46m thick, 67 psia over-pressured gas sand at c. 360m below seabed



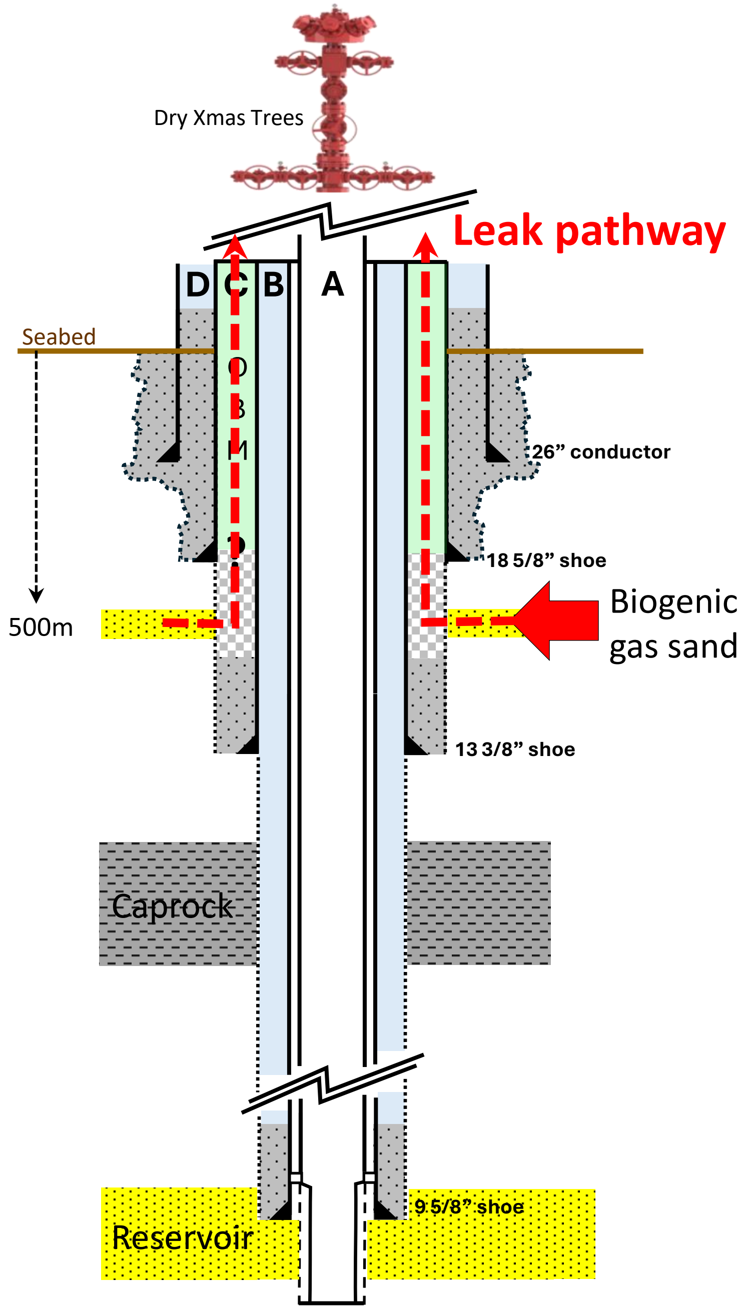
Re-drafted from Millenium Atlas, 2000

- **"1.7k to 25k t/CH₄/year"** (Leifer *et al.* 2015)

Nearby Platform Abandonment

Well Architecture & Current Status

- Platform with 12 wells
- **Sustained annular pressure (SAP)** of up to **150 psi** present in C-annulus



Operational pressures and gas must be managed safely

The necessity for long-term isolation remains a subject of ongoing debate

What are the options for isolating "chronic low-level biogenic gas leakage"

Option 1: Conventional Barrier
- Milled window approach
- Fully verified
- "Pressure containing"

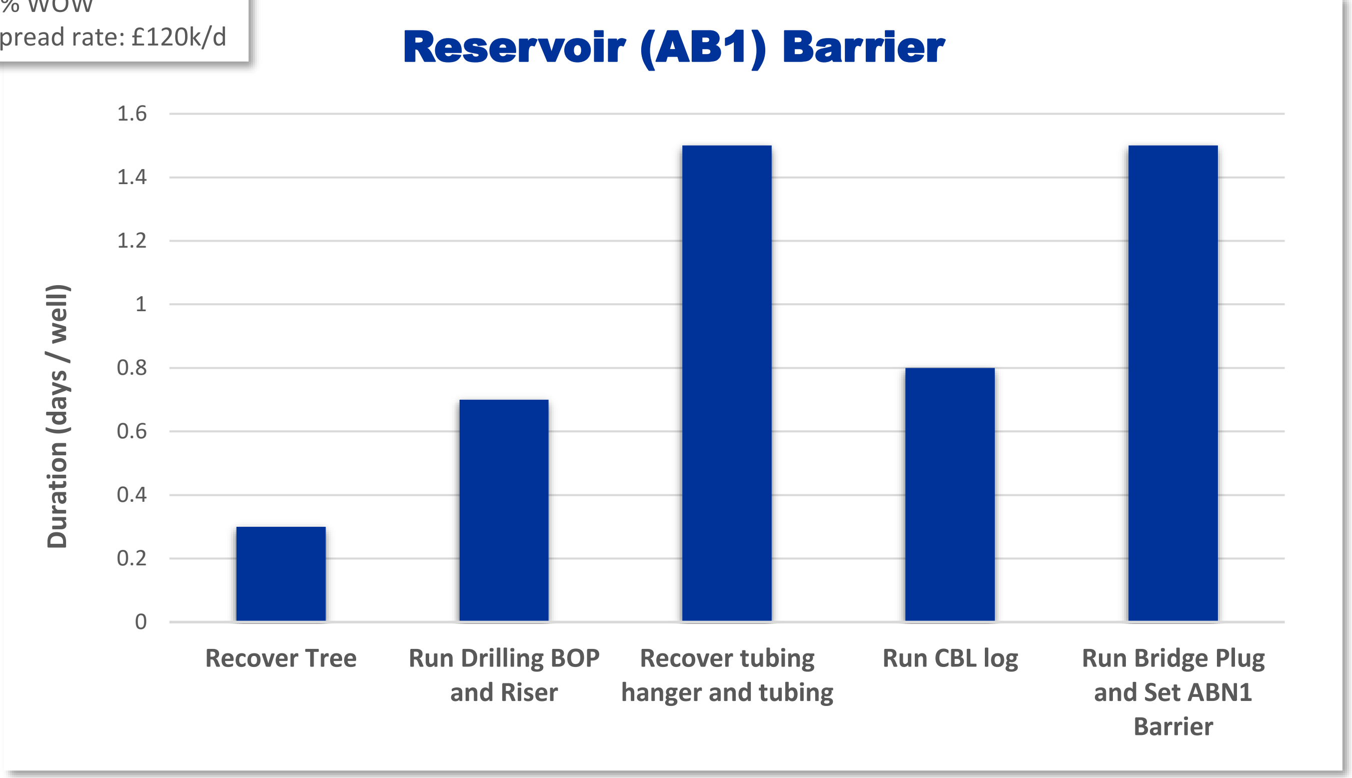
Option 2: Perforate & Squeeze Barrier
- "Best Endeavours"
- Annuli may remain unverified

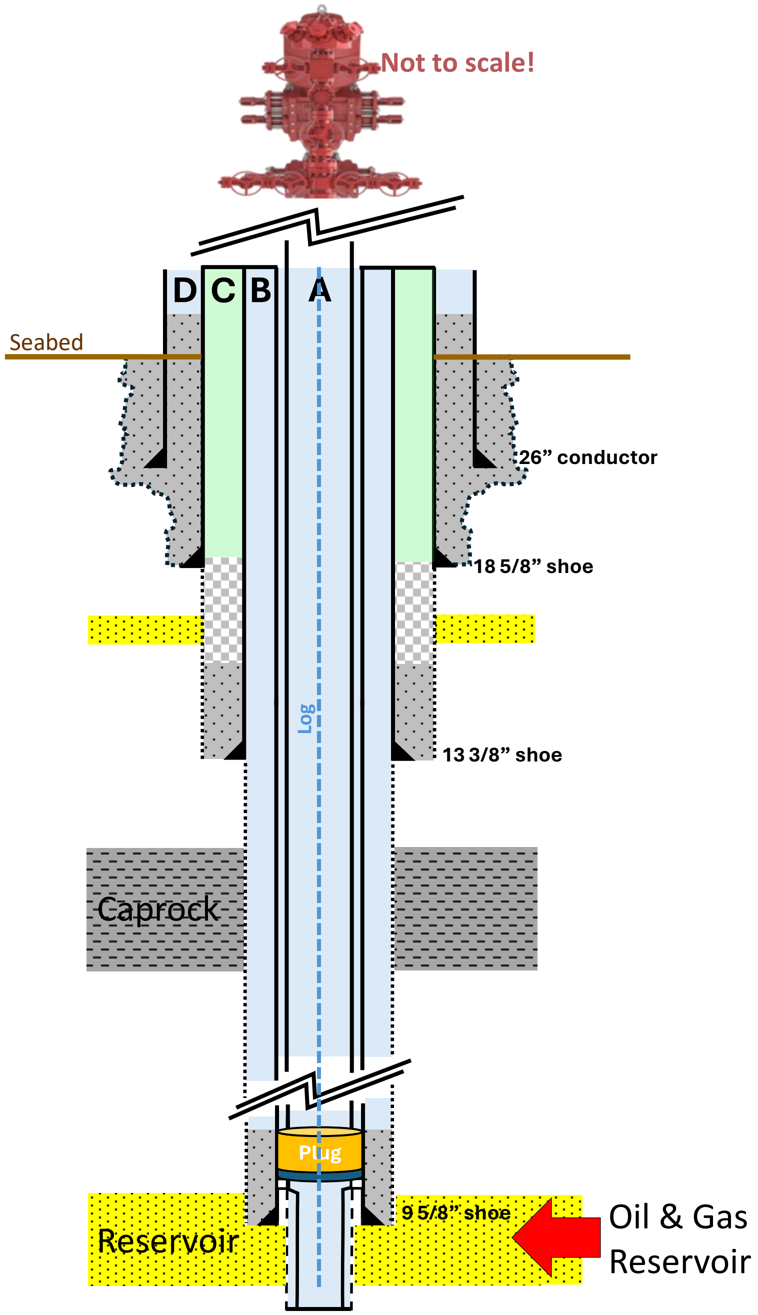
Option 3: Environmental Barrier
- Isolation of annular contaminants only

Reservoir Abandonment

Simplified Operational Steps

Assumptions:
Level 4 cost estimate
9% NPT
5% WOW
Spread rate: £120k/d



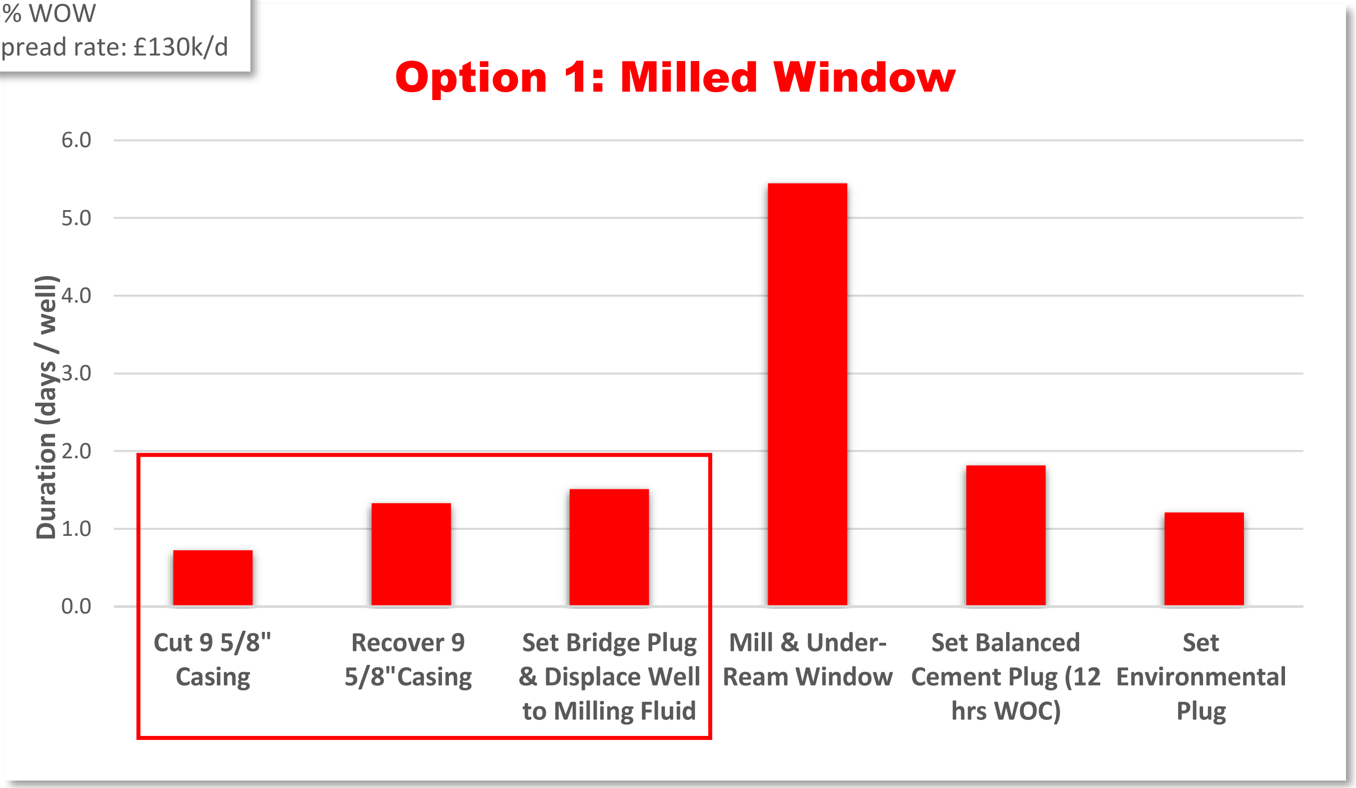


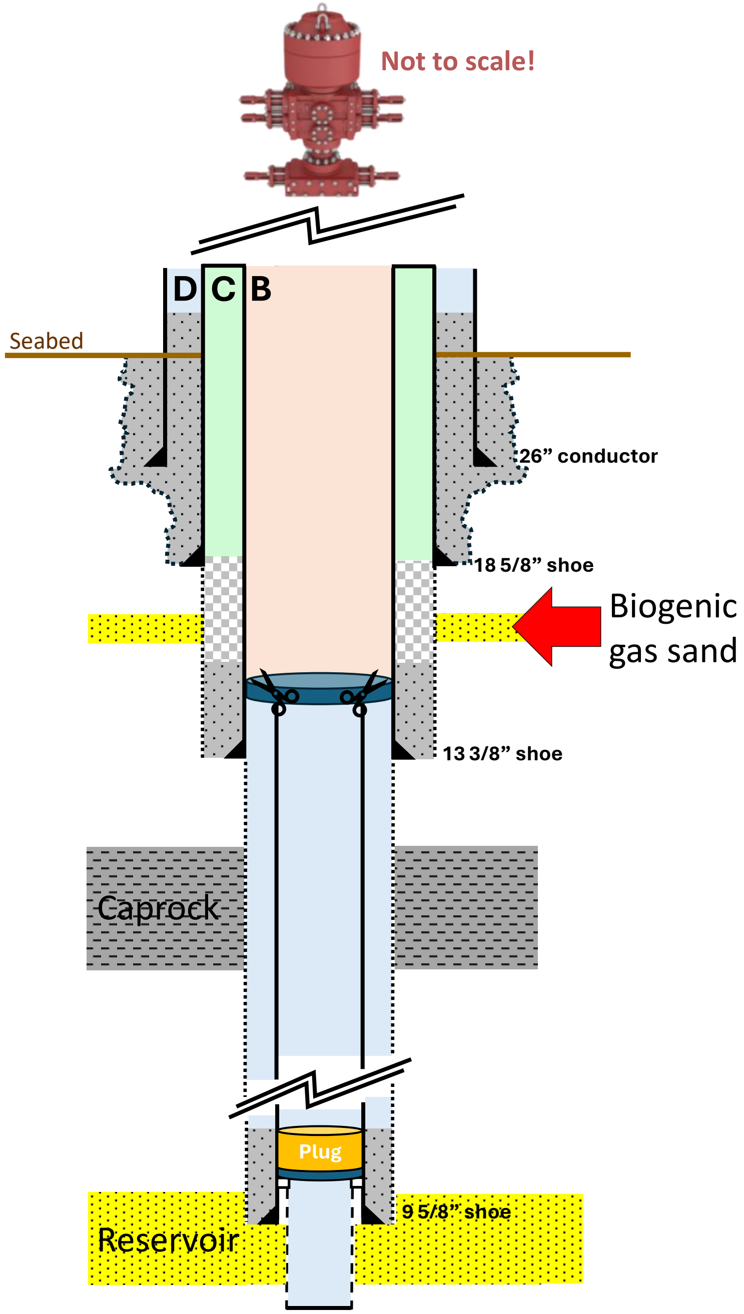
Total time per well: 6 days
Total cost per well: £0.72 mm
Total cost across all wells (n=12): £8.61 mm

Option 1: Conventional Barrier

Simplified Operational Steps

Assumptions:
Level 4 cost estimate
9% NPT
5% WOW
Spread rate: £130k/d





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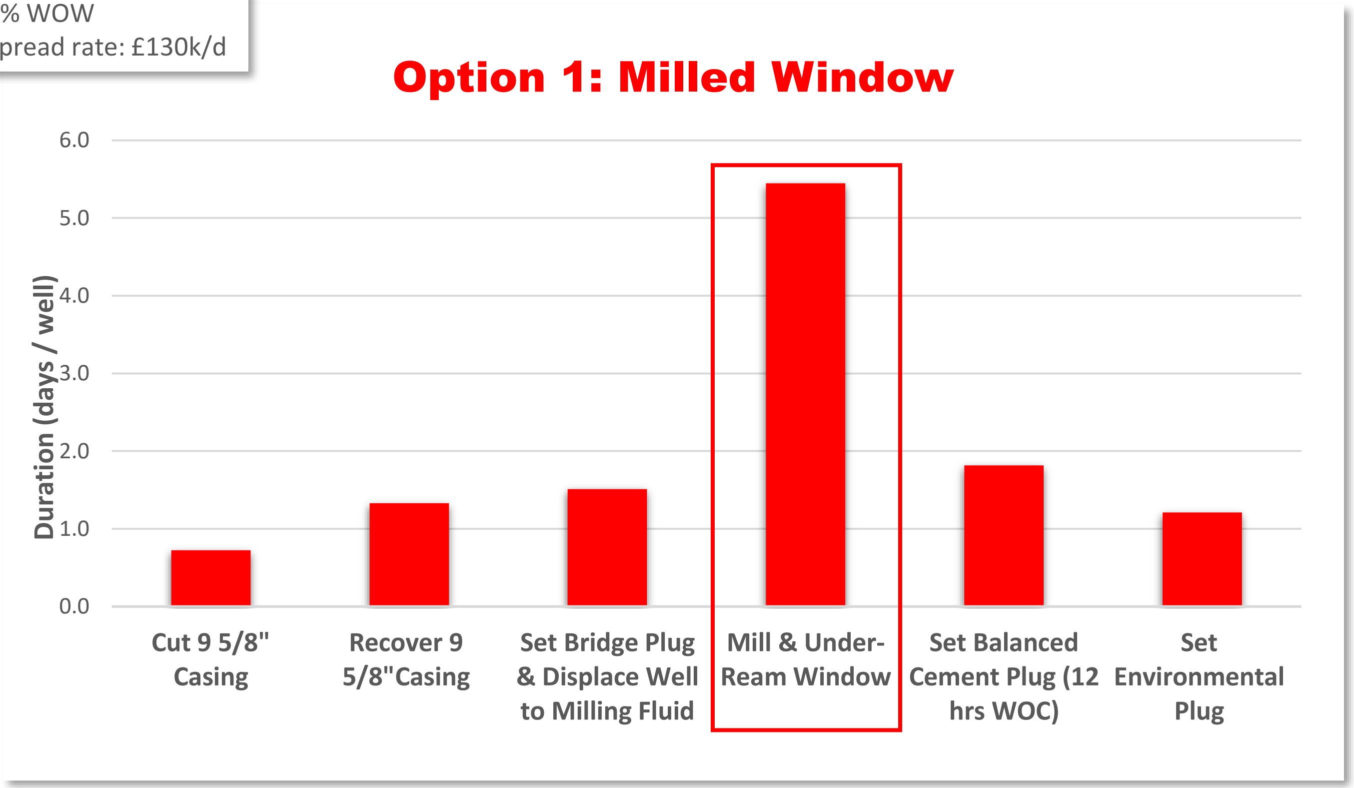

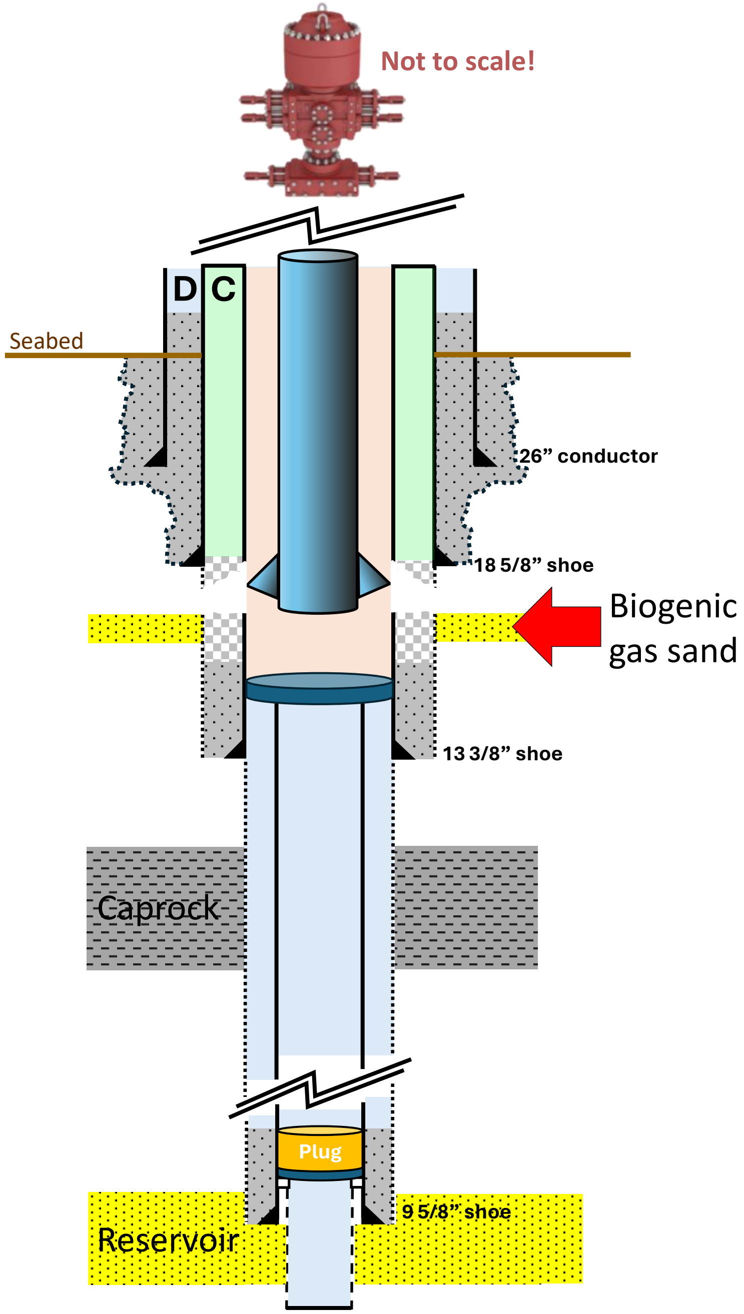

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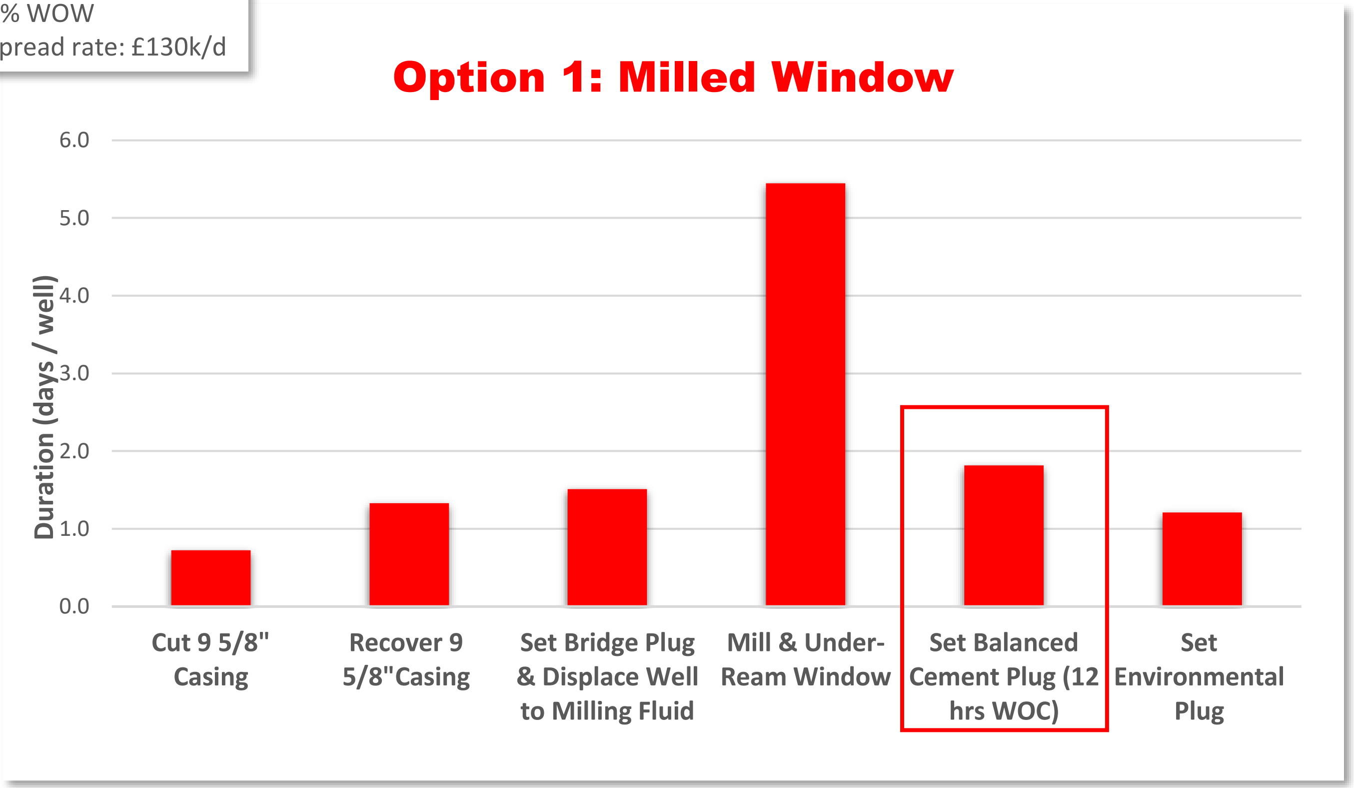

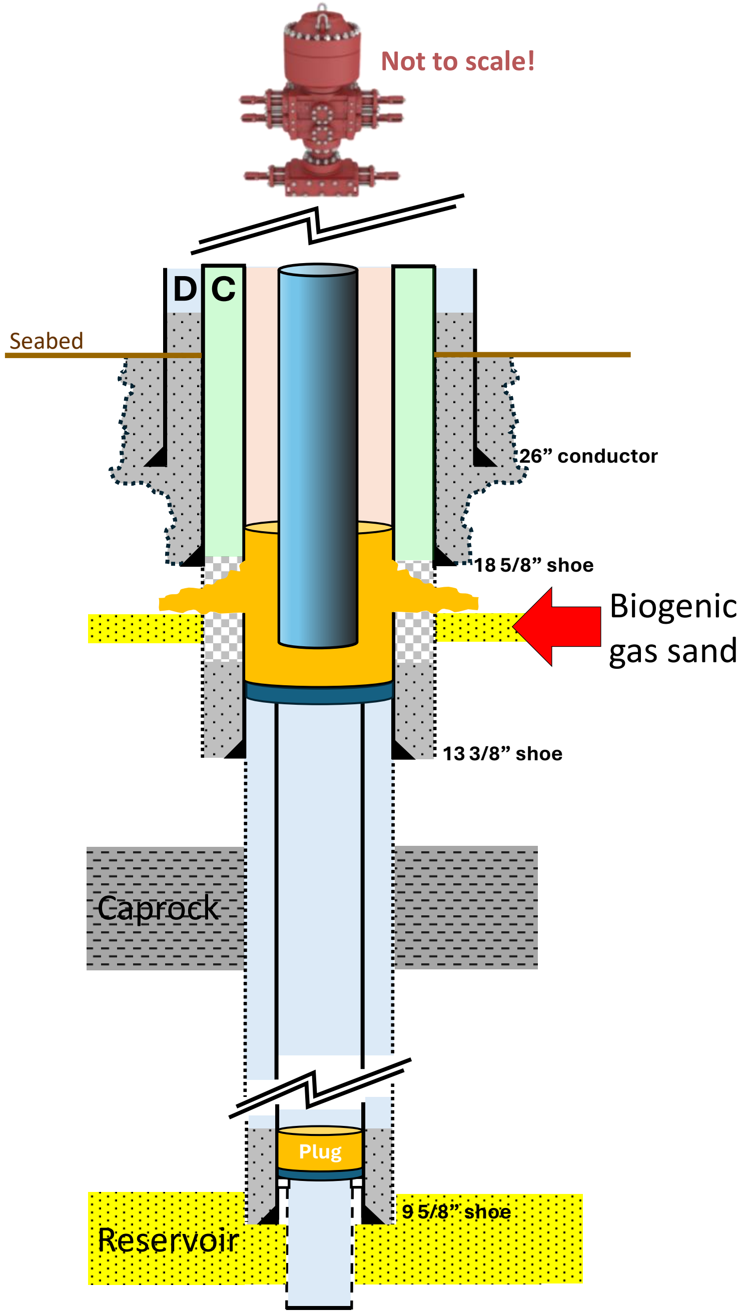

➢ Verified, fully rock-to-rock barrier

Option 1: Conventional Barrier

Simplified Operational Steps

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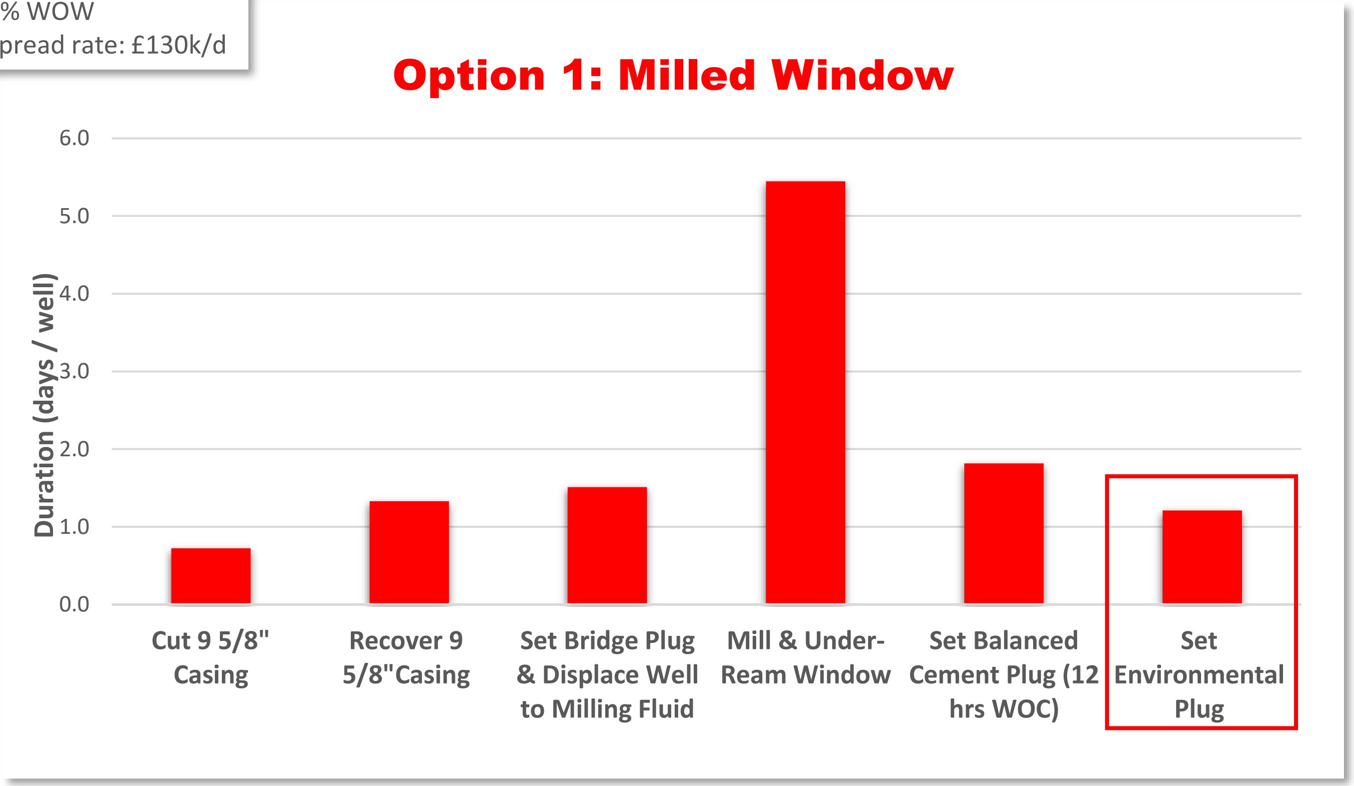
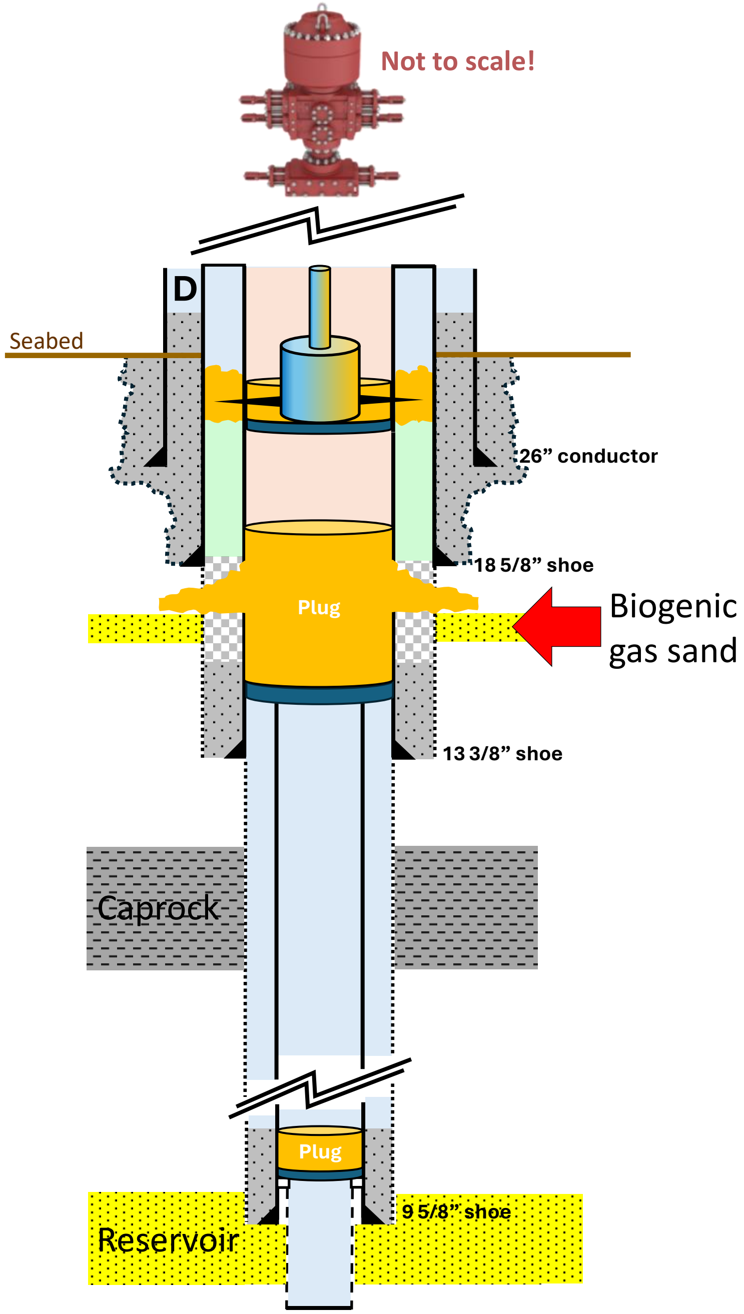
Spread rate: £130k/d





Total time per well: 12 days

- Environmental barrier for annuli containment

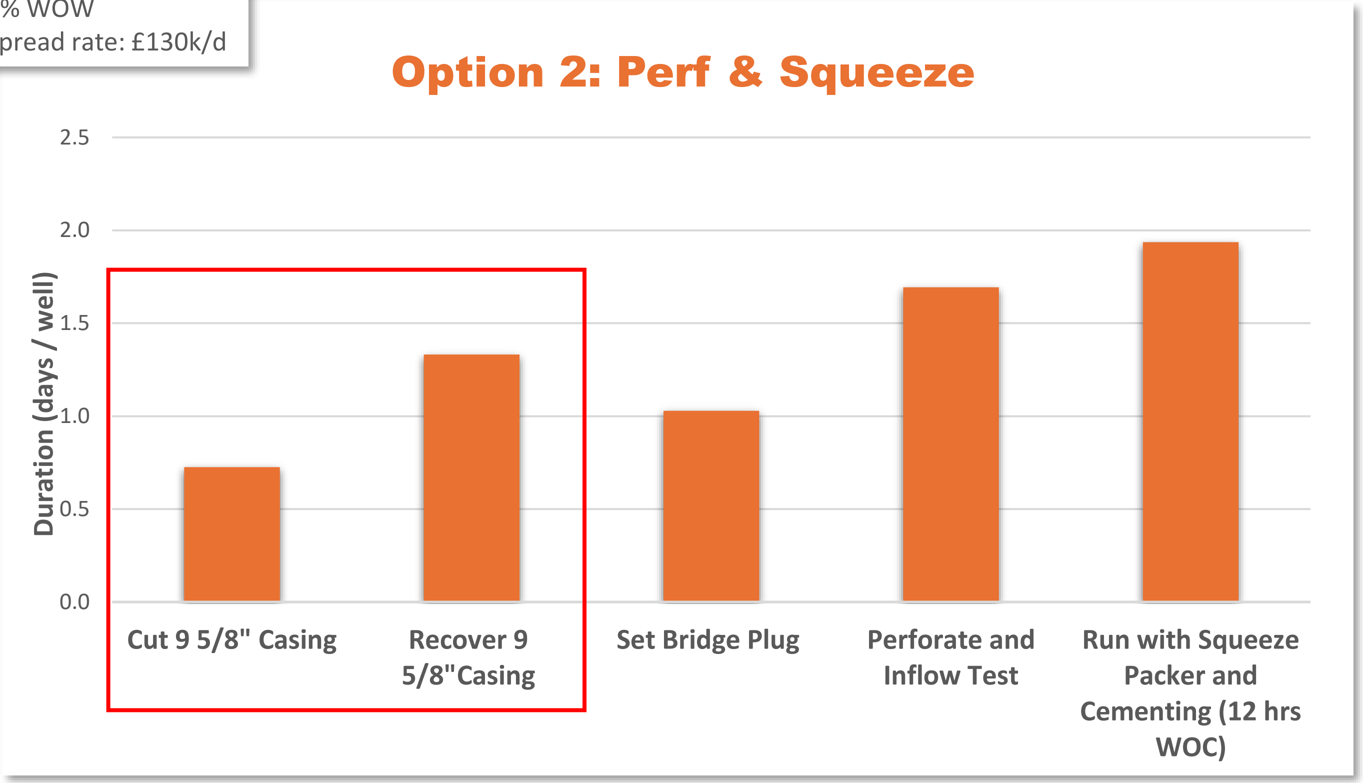
Total cost per well: £1.68 mm

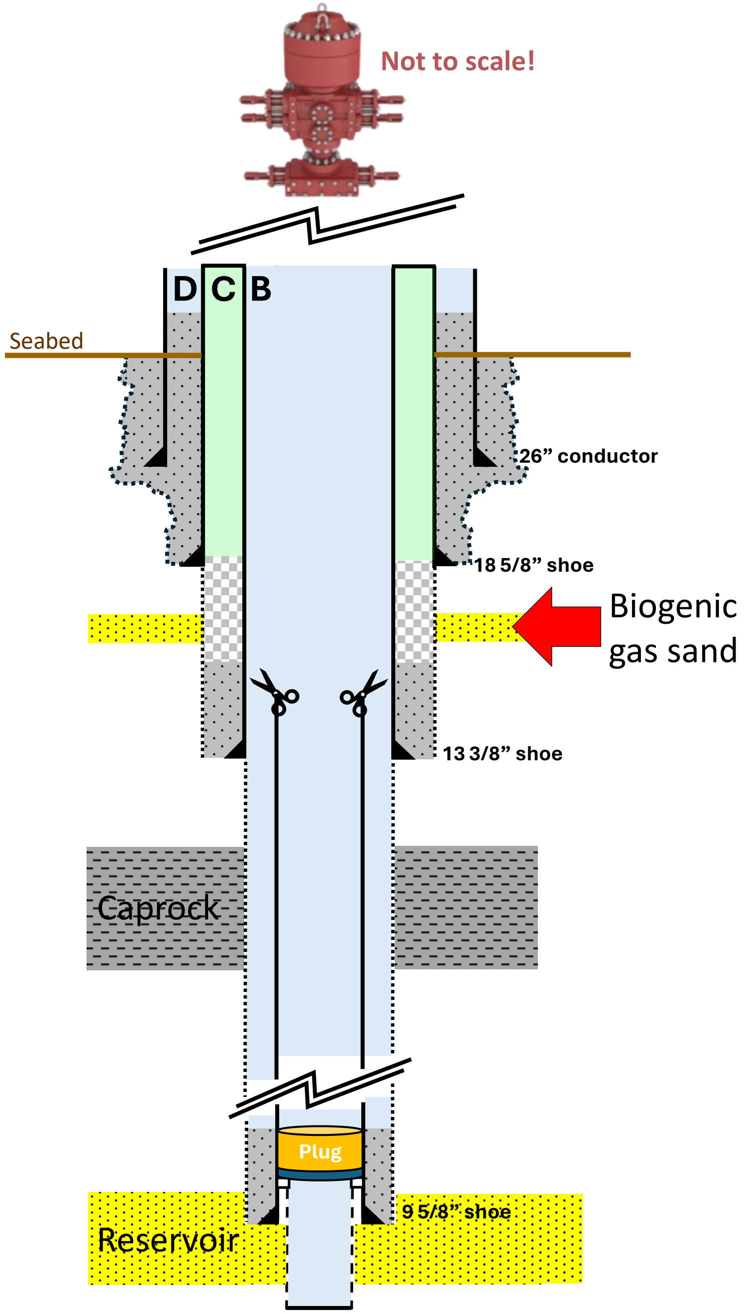
Total cost across all wells (n=12): £20.13 mm

Option 2: Perforate & Squeeze Barrier

Simplified Operational Steps

Assumptions:
Level 4 cost estimate
9% NPT
5% WOW
Spread rate: £130k/d





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Simplified Operational Steps

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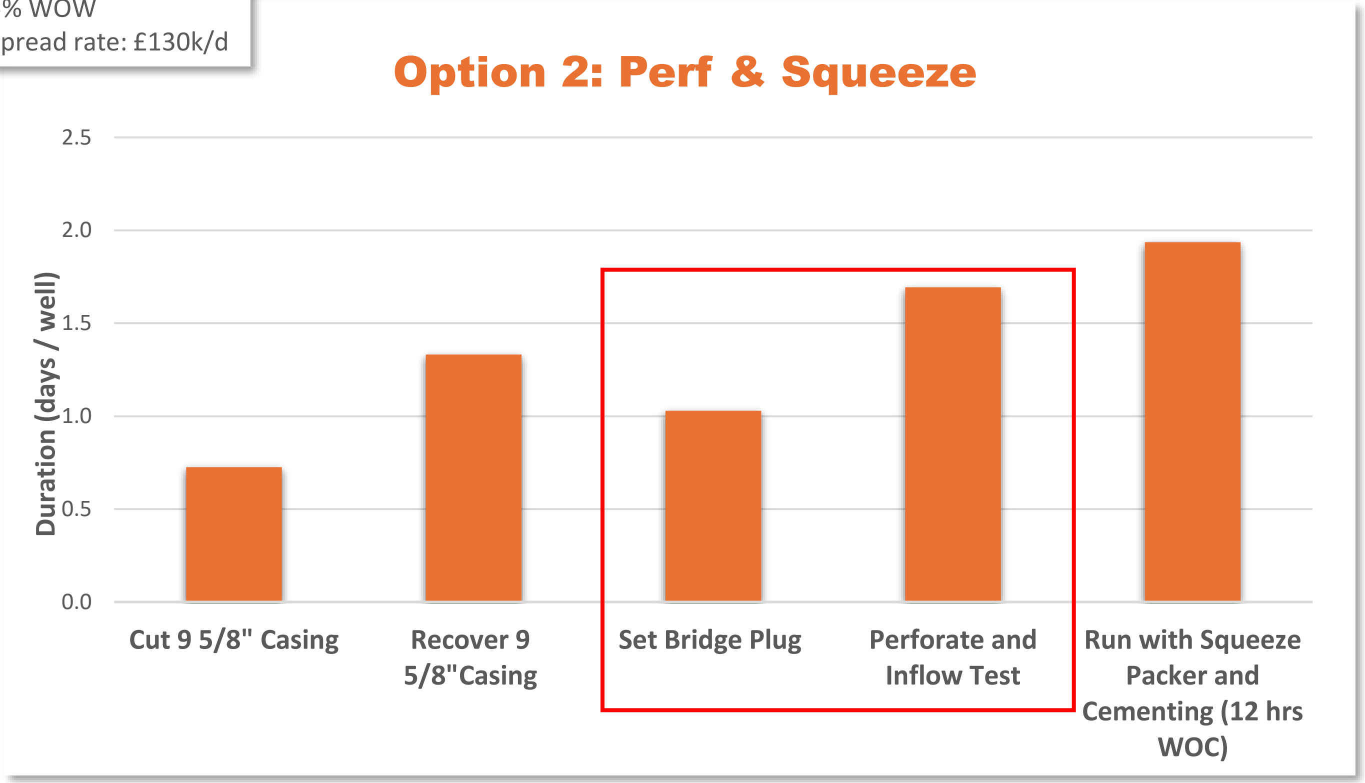
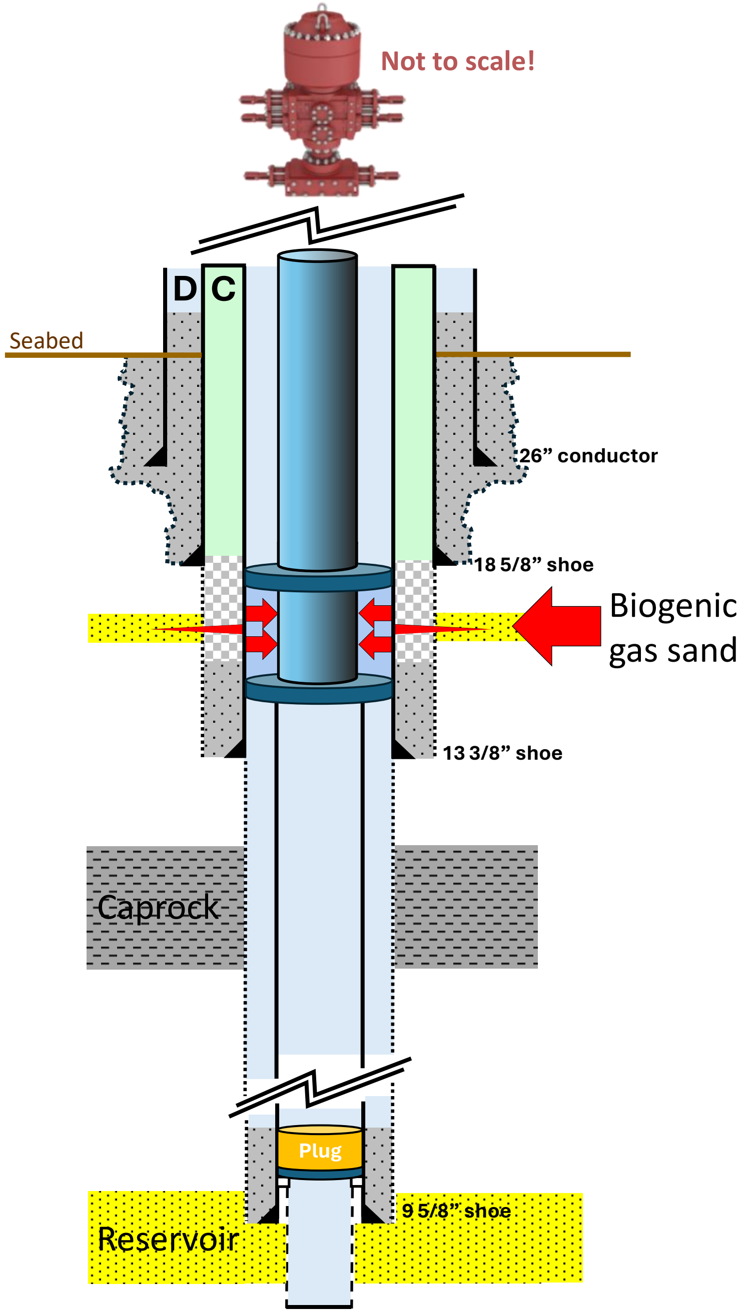


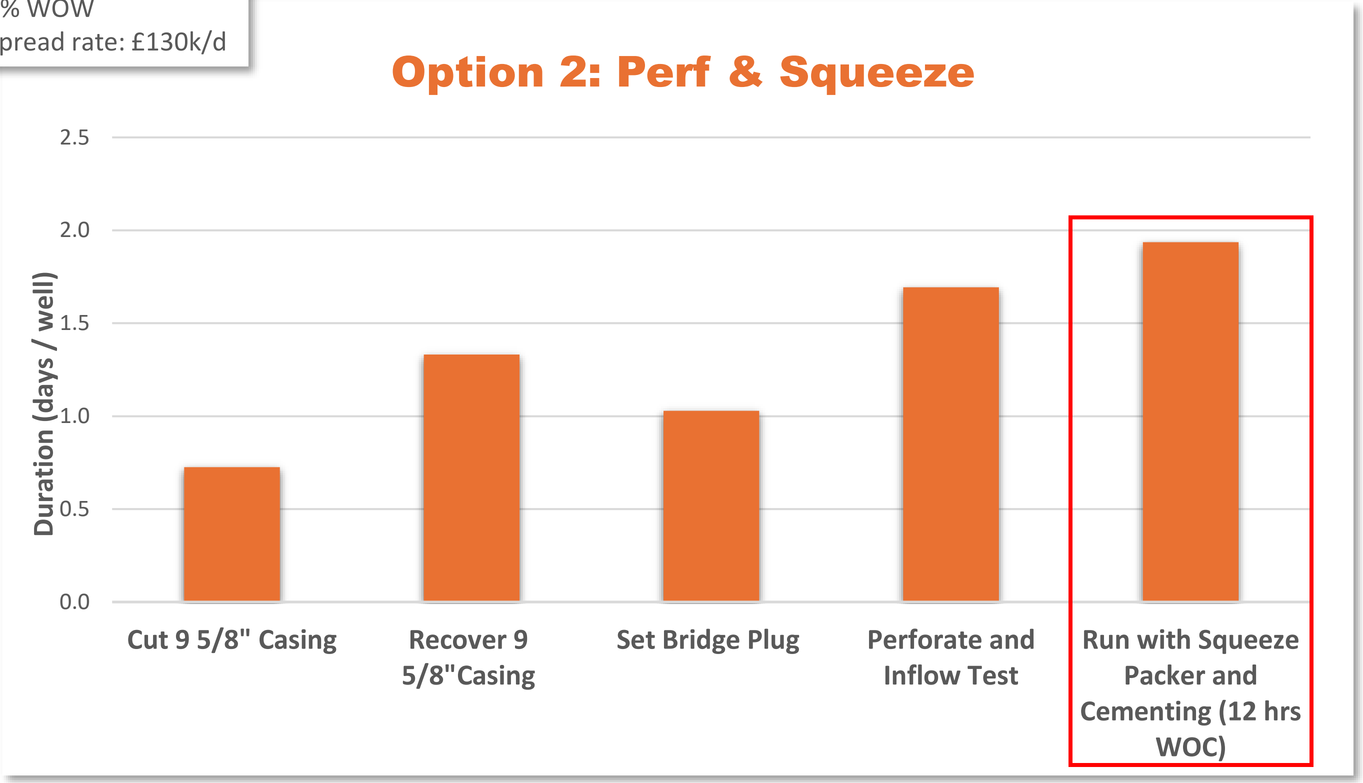


- "Knowledge is Power" - inflow test is an opportunity to collect a pressure data point to de-risk operations – only required on first well

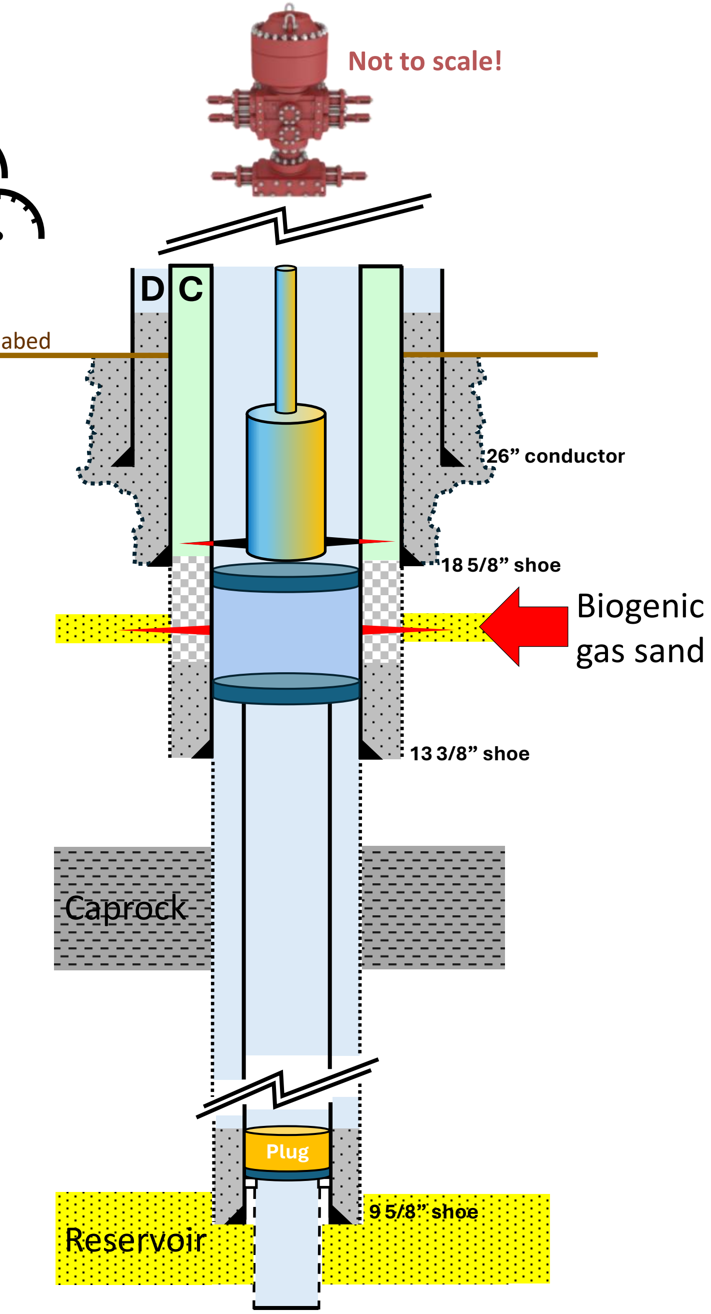
Option 2: Perforate & Squeeze Barrier

Simplified Operational Steps

Assumptions:
Level 4 cost estimate
9% NPT
5% WOW
Spread rate: £130k/d



Gator Perforating System

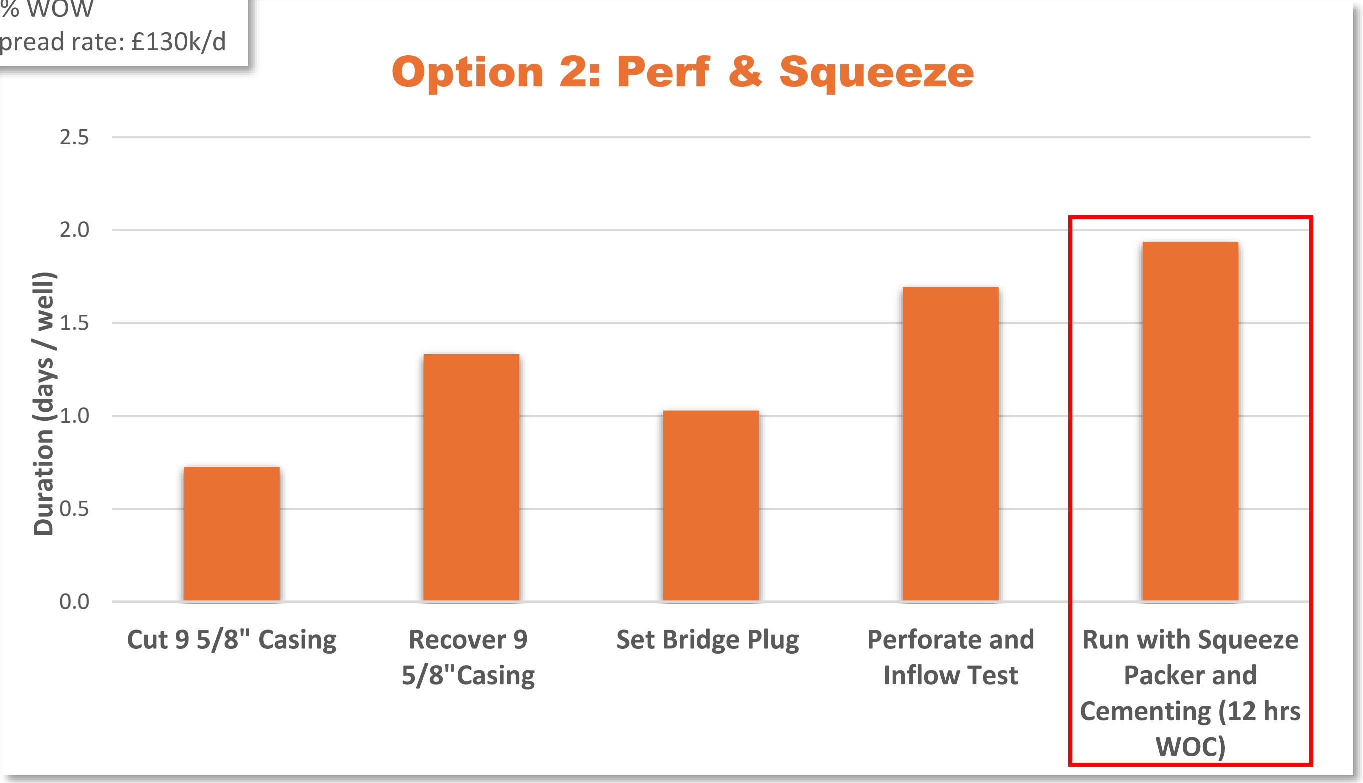


- Obtaining circulation pathway might be challenging due to strung out cement – may have to repeat - shallower

Option 2: Perforate & Squeeze Barrier

Simplified Operational Steps

Assumptions:
Level 4 cost estimate
9% NPT
5% WOW
Spread rate: £130k/d

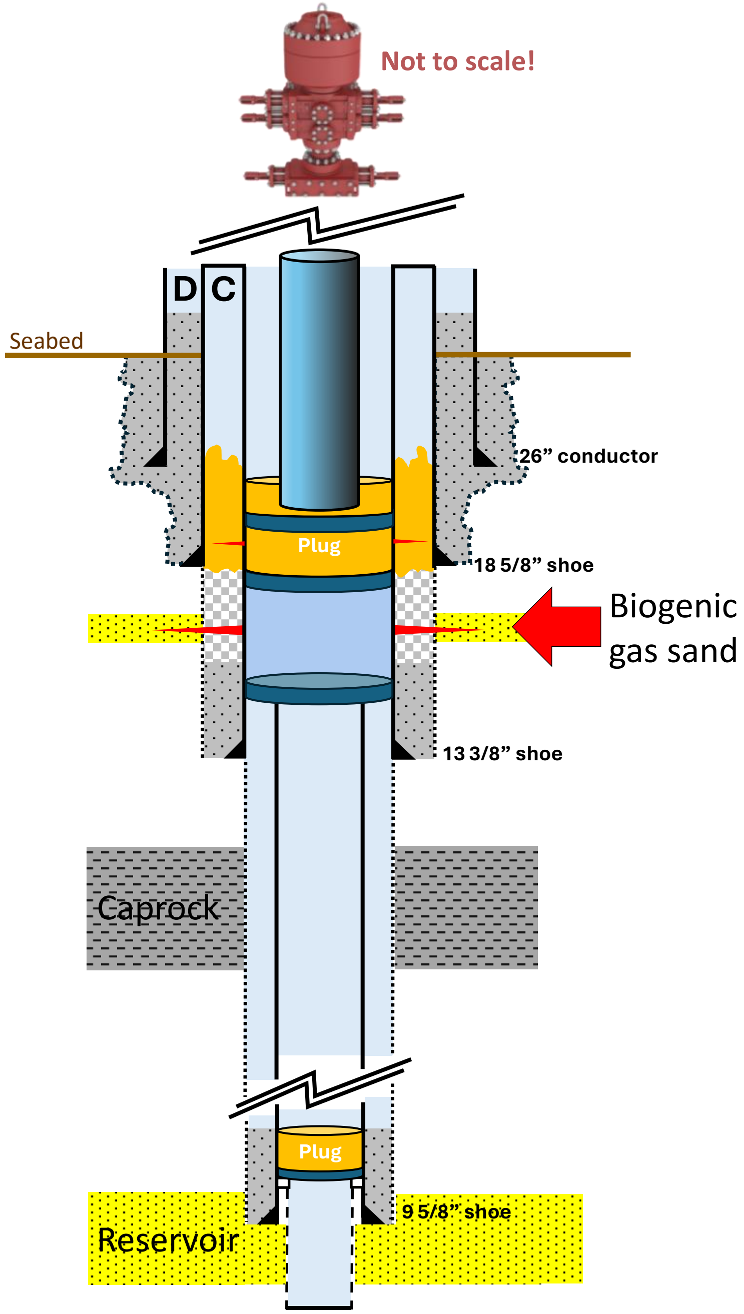


Total time per well: 6.7 days

- Unable to verify base of annular cement / quality

Total cost per well: £0.928 mm

Total cost across all wells (n=12): £11.14 mm



Option 3: Environmental Barrier Only

Simplified Operational Steps

Assumptions:
Level 4 cost estimate
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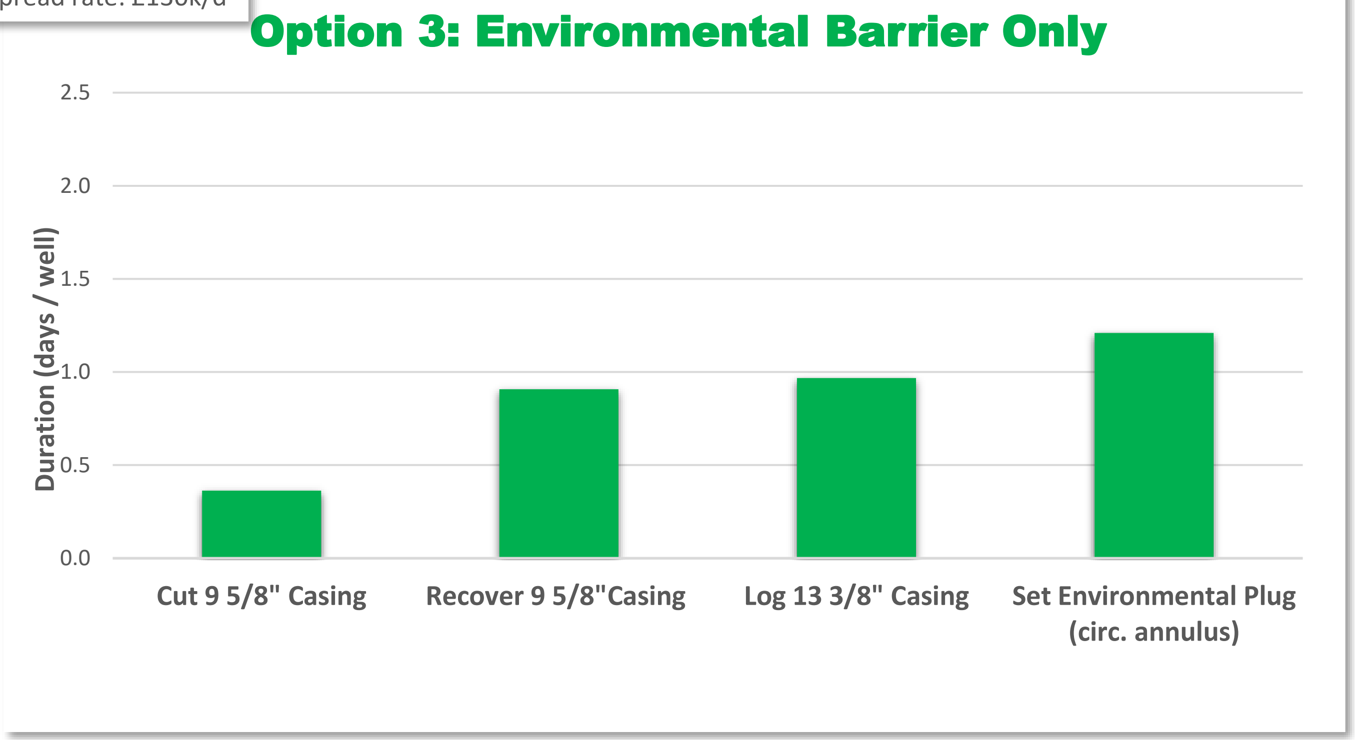
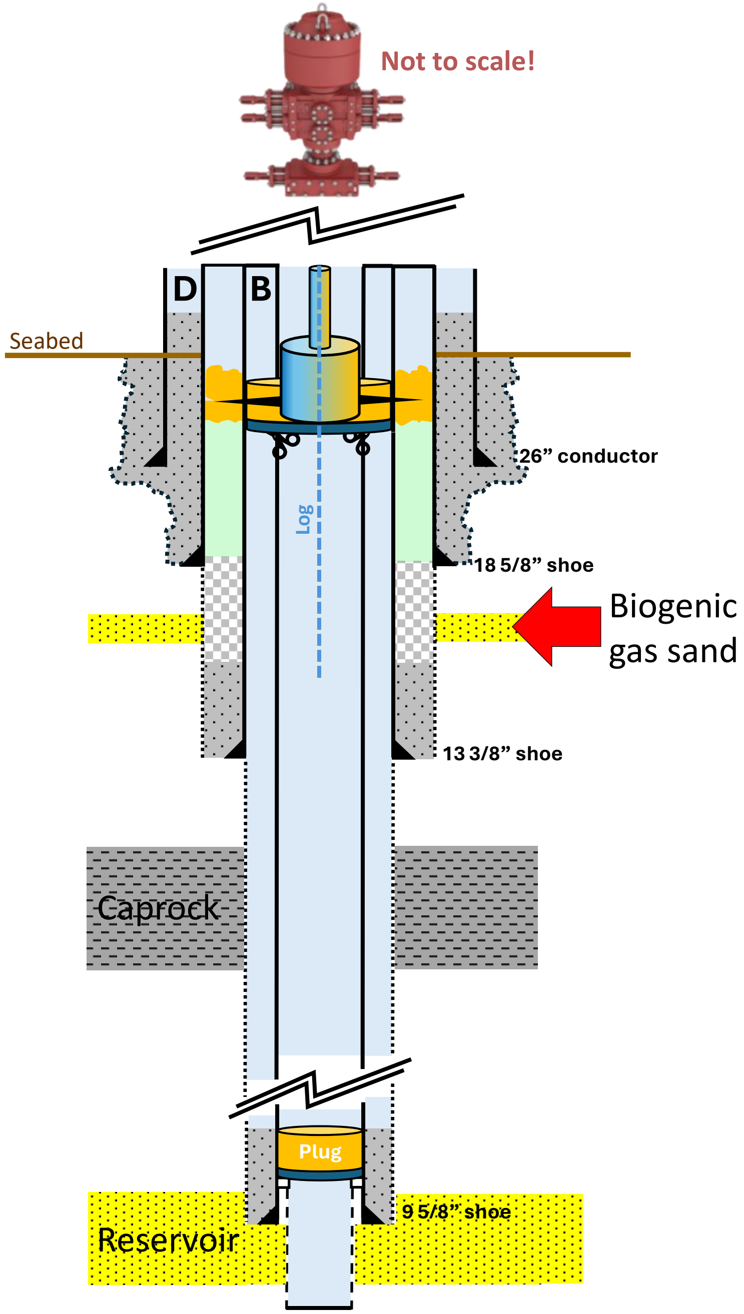
5% WOW
Spread rate: £130k/d





- Isolation of annular contaminants only

Total time per well: 3.4 days

Total cost per well: £0.517 mm

Total cost across all wells (n=12): £6.21 mm

How Do Options 1 – 2 – 3 Compare?

Comparative Assessment Criteria

Three options assessed against criteria for:

Legislation	Technical	Environment	Cost
Does option comply?	How complex is the option & what is the chance of success?	What is the resource burden and is there a residual leak risk?	What is the overall cost of option?

According to:

Negative – **Positive**

This assessment assumes all options are technically possible and can be executed safely

How Do Options 1 – 2 – 3 Compare?

Comparative Assessment Results

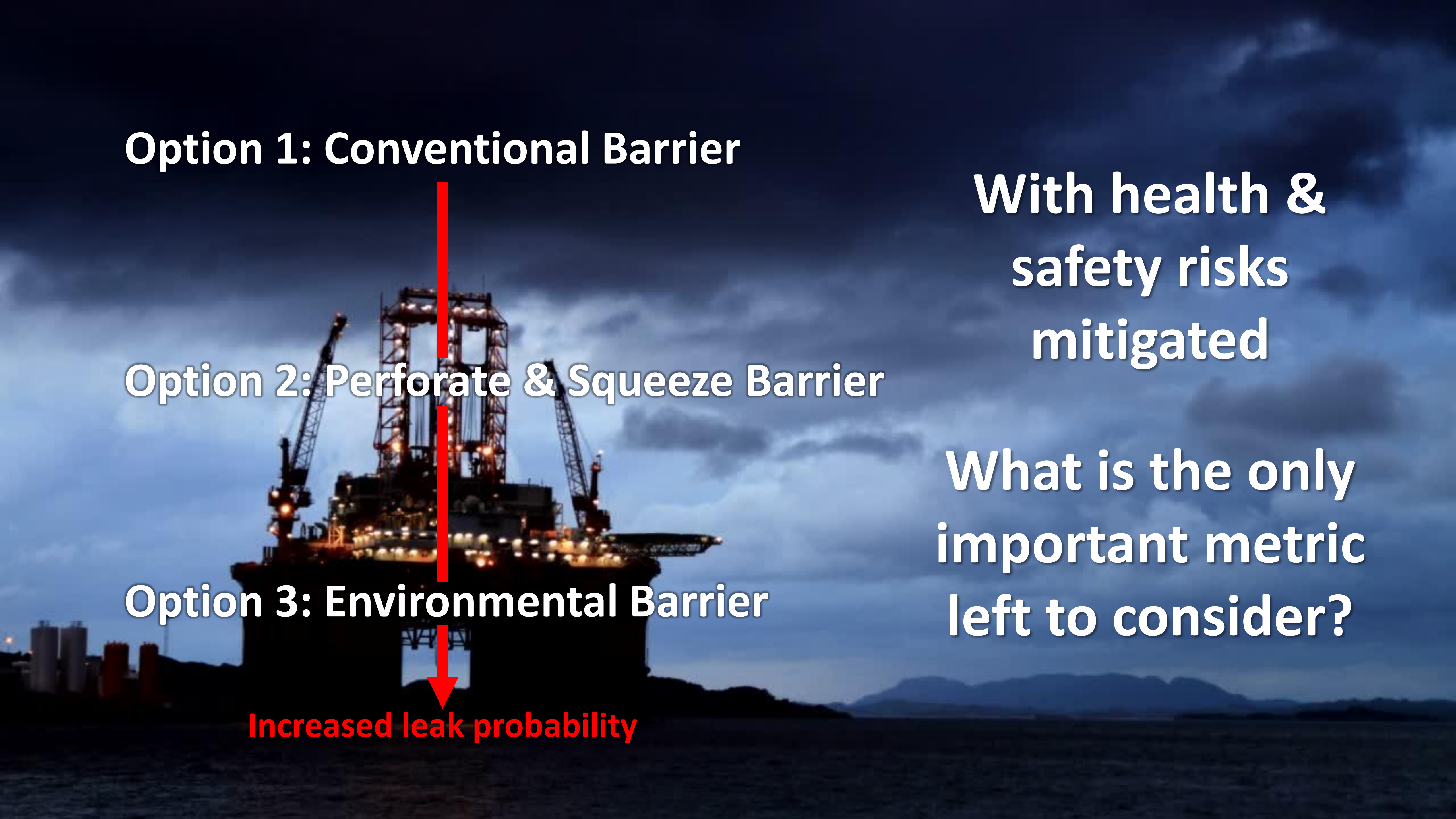
Negative → Positive

Criteria / Option	Legislation	Technical	Environment	(Days) Cost £
Option 1: Conventional Barrier	Fully-lateral barrier Complies with Regulation / Guidance	Lower chance of success. Need sufficient weight and torque to mill, SWARF, pack-offs, determines P&A unit, short response time	Extended operational time uses more resources If successful = gas-tight, pressure containing	(144.5 days) £20.13 mm
Option 2: Perforate & Squeeze Barrier	Not a fully-verified barrier Complies with spirit of ALARP	Good chance of success Establishing circulation pathway may impact quality of annular barrier	Simpler operations uses less resource than Optio Increased likelihood of future leakage	(80.6 days) £11.14 mm (£8.9 mm less than Option 1)
Option 3: Environmental Barrier only	Annular OBM containment only	Excellent chance of success Simple operations, proven technology	Simpler operations uses less resource than Options 1 and 2 Much increased likelihood of leakage	(41.4 days) £6.21 mm (£4.9 mm less than Option 2)

Trade Off

Risk of Future Leakage

i.e. Leak Acceptance

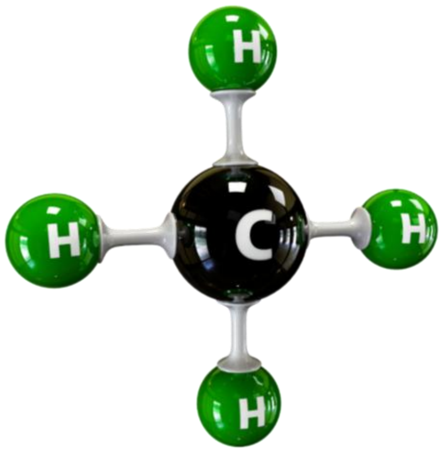

Option 1: Conventional Barrier
Option 2: Perforate & Squeeze Barrier
Option 3: Environmental Barrier
Increased leak probability
With health & safety risks mitigated
What is the only important metric left to consider?

Key Consideration

"Cost to Society" of releasing methane into the atmosphere

Climate Impact of Methane (CH_4)

Calculating "Cost to Society"?

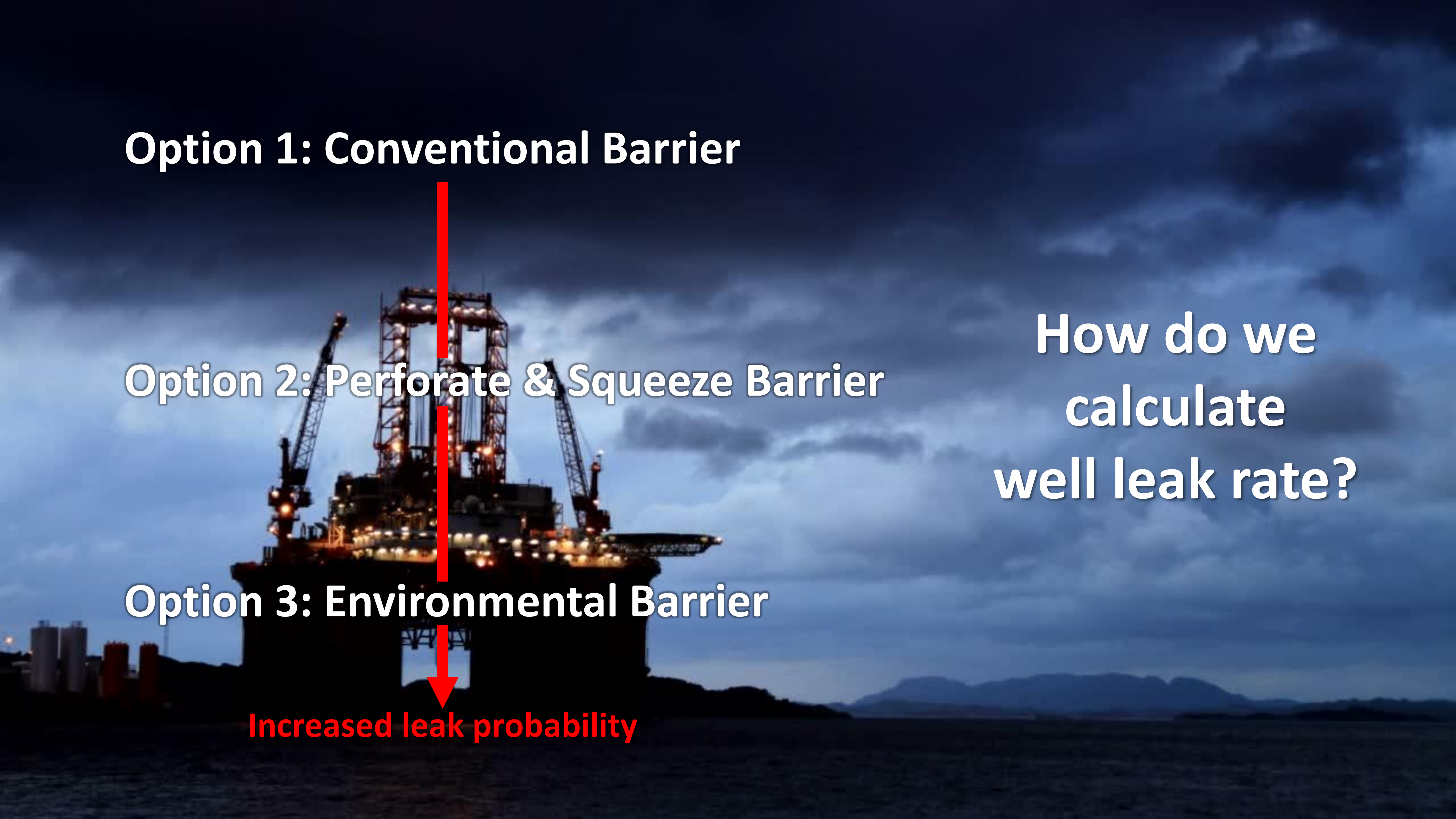


- Methane is a **more potent** greenhouse gas (GHG) than CO_2 in the short-term
- **Global Warming Potential** (GWP) **84-87** times that of CO_2 over **20 years***
- Methane emissions are standardised to **CO_2 equivalent** (CO_2e)
- **Carbon Value** is determined by UK Government as the "**cost of reducing emissions to meet the UK's climate goals**" – applied to all CO_2e metrics

	Assumed leak rate / volume over 20 years	tCH_4 to tCO_2e using GWP20 (87)	2025 Carbon Value**	Societal Cost (£)
Unmitigated Leak Rate Example	Leak rate 10 tCH_4 /yr = **200 tCH_4**	200 tCH_4 * 87 = **17,400 tCO_2e**	**£287/tCO_2e**	17,400 tCO_2e * £287 **£ 5 mm**

*per IPCC AR6, updated Aug 2024

**2025 value from Department for Energy Security and Net Zero (DESNZ)



Option 1: Conventional Barrier

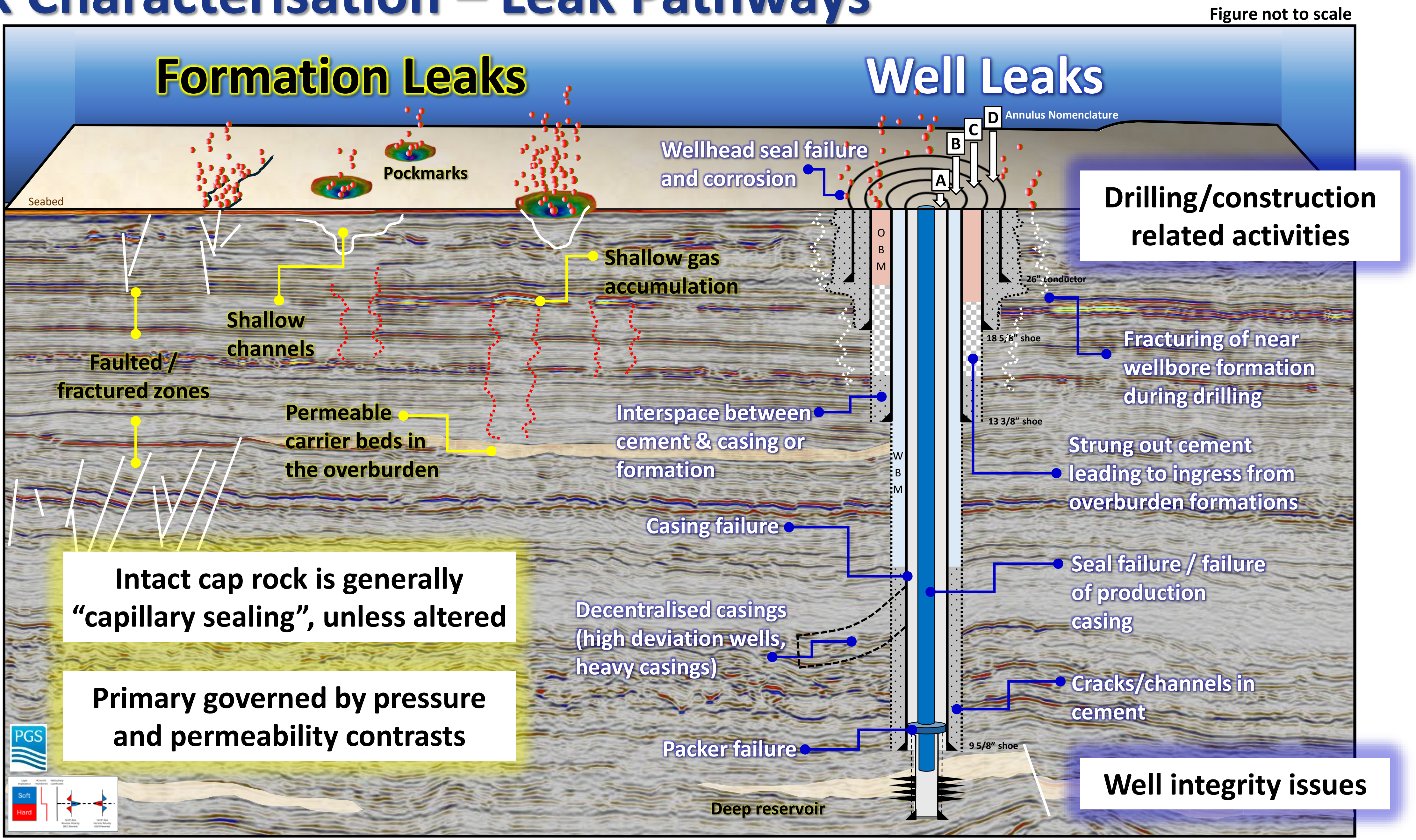
Option 2: Perforate & Squeeze Barrier

Option 3: Environmental Barrier

Increased leak probability

How do we calculate well leak rate?

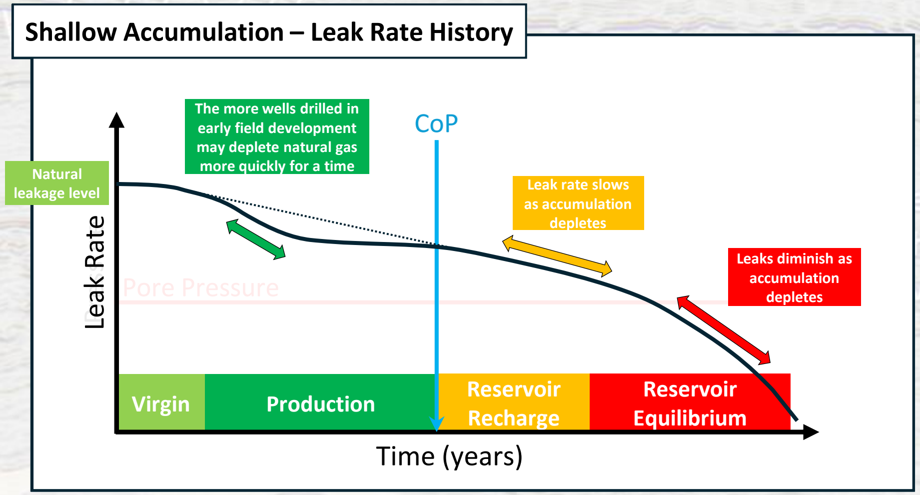
Leak Characterisation – Leak Pathways



Leak Characterisation – Leak Evolution

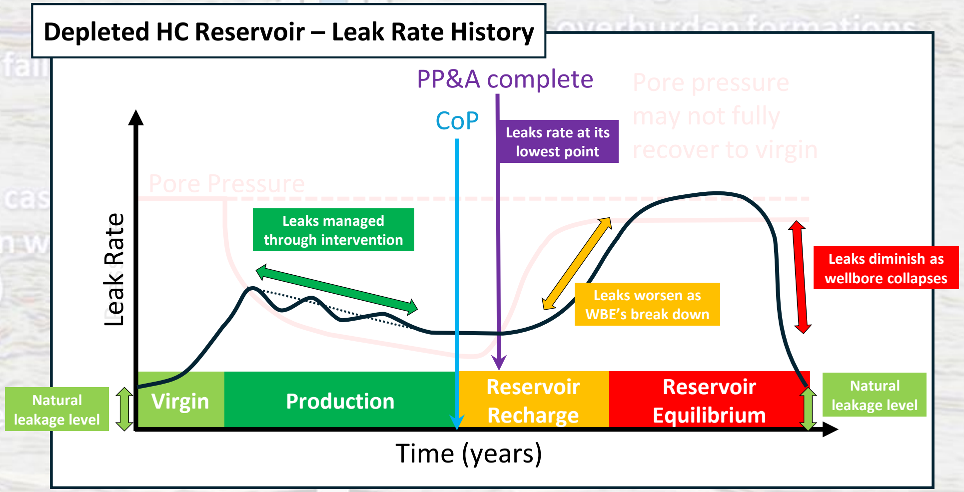
Formation Leaks

- More frequent, **multiple bubble streams** across **wide areal extent**
- However, as accumulation depletes, **bubble diameter and leak rate** both **decreases** (evidence from surveys)



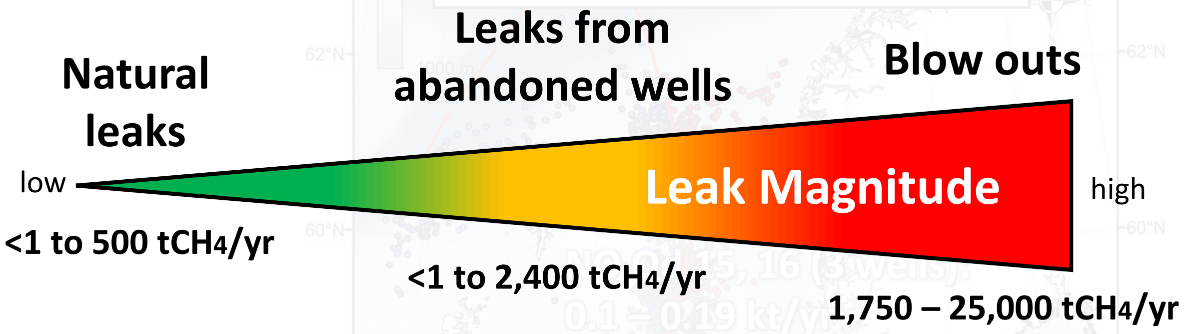
Well Leaks

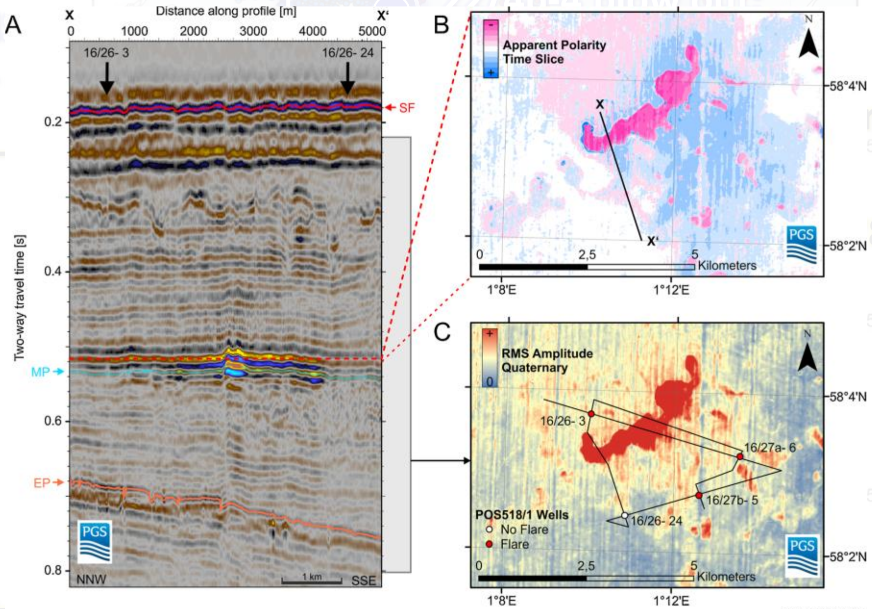
- **Less frequent bubbles** / bubble streams, **sourced more locally**
- However, **as well barriers degrade**, or **pressure recharge** occurs, **leak rate may increase** until eventual wellbore collapse



Leak Characterisation – Leak Rate

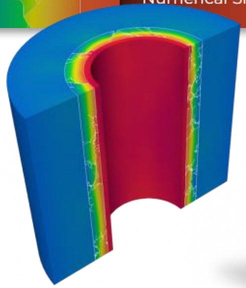
- **Leakage rates are highly variable**
- **Geological setting**
- **Well design, construction & abandonment history**
- **Proximity to shallow gas (< 1000 m)**
  (Böttner *et al.* (2020)
- **Wells spud before 2010 more likely to leak**
  (Böttner *et al.* (2020)

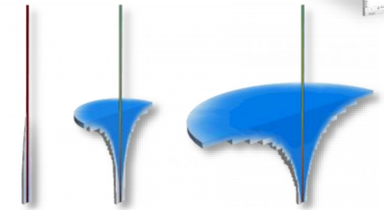


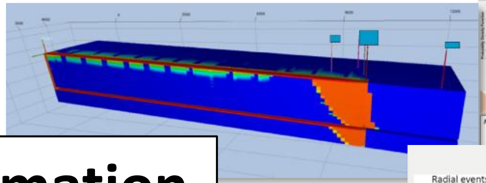


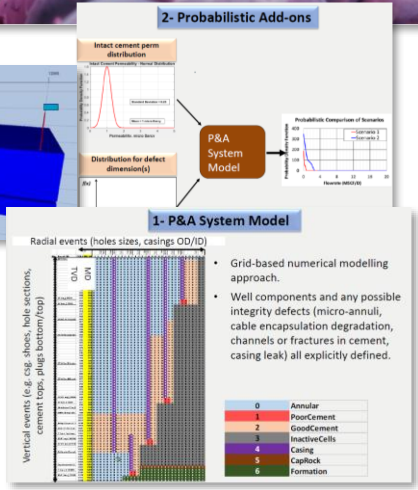
Böttner *et al.* (2020) Seismic Anomaly Indicating Shallow Gas Presence

Leak Characterisation – Modelling









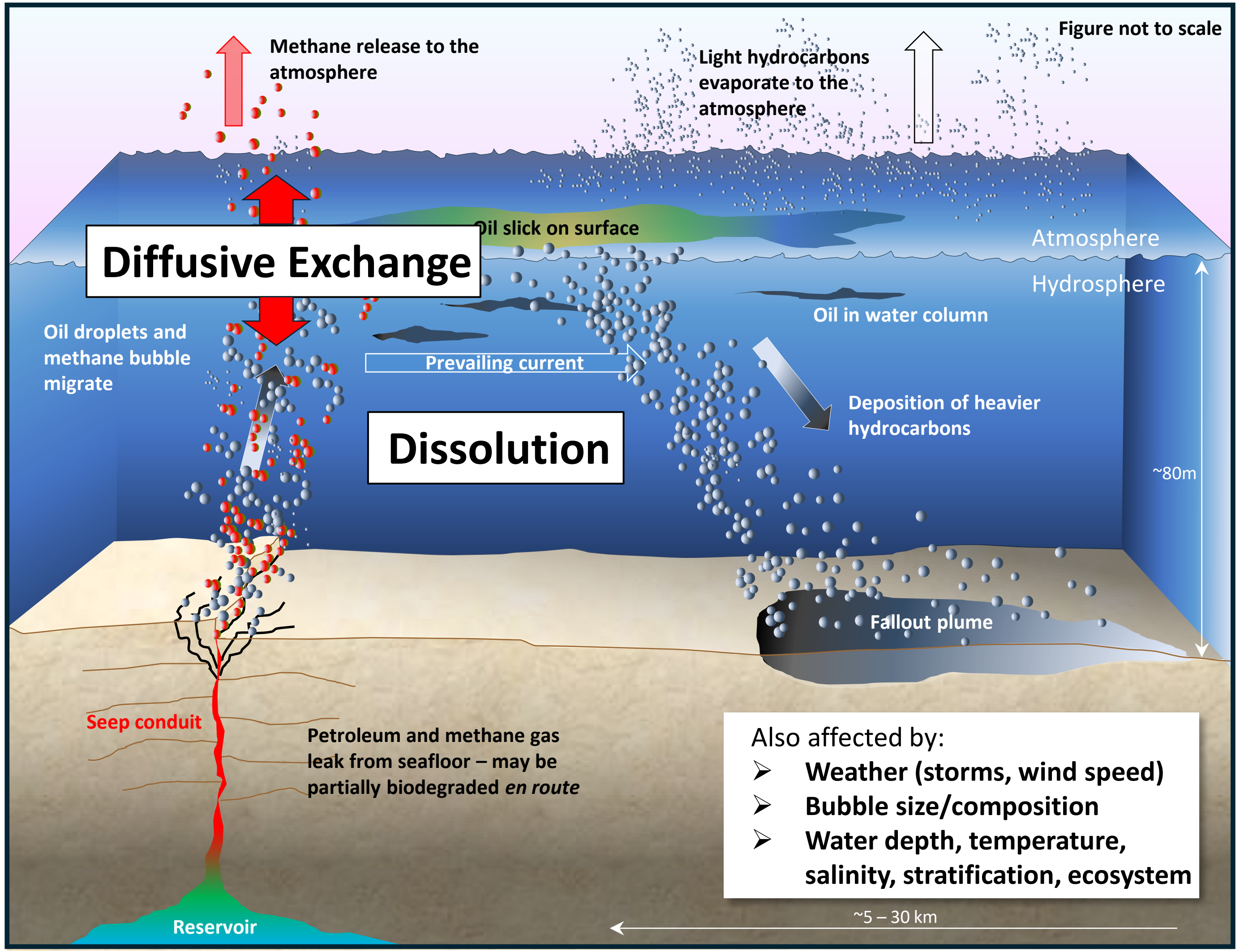
Probabilistic analysis of well / formation failure mechanism(s), leakage pathways, crossflow volumes and testing of chosen P&A strategy on leak characteristics

Key Metric

How much methane is released into the atmosphere?

Atmospheric Emissions

Not All Leaks Are Delivered To The Atmosphere



Reproduced from Woods Hole Oceanographic Institution, J. Cook (2014)

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ELSEVIER

The fate of hydrocarbon leaks from plugged and abandoned wells by means of natural seepages

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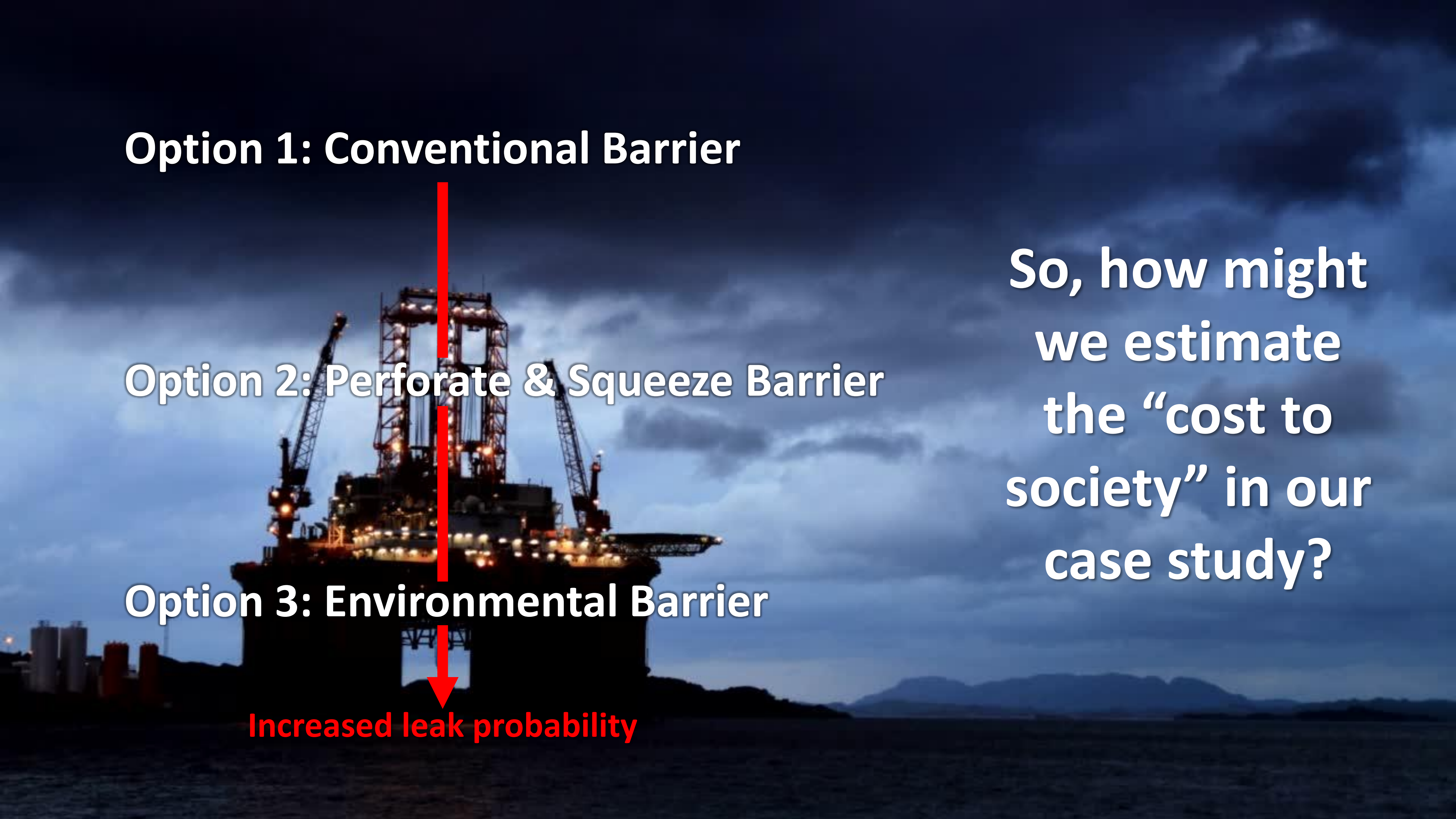
SINTEF

Oil Spill Contingency And Response (OSCAR)

Characterising the receiving environment is also important



Option 1: Conventional Barrier

Option 2: Perforate & Squeeze Barrier

Option 3: Environmental Barrier

Increased leak probability

So, how might we estimate the "cost to society" in our case study?

Case Study: Estimating Societal Cost

Unmitigated Well Leak Rate Assumptions

- All wells drilled before 2010 (1992 – 2008)
- Wells are within 200 m of a seismic anomaly at Early Pleistocene level
- Leak flowrate estimated via Radial Flow Equation (non-compressible)

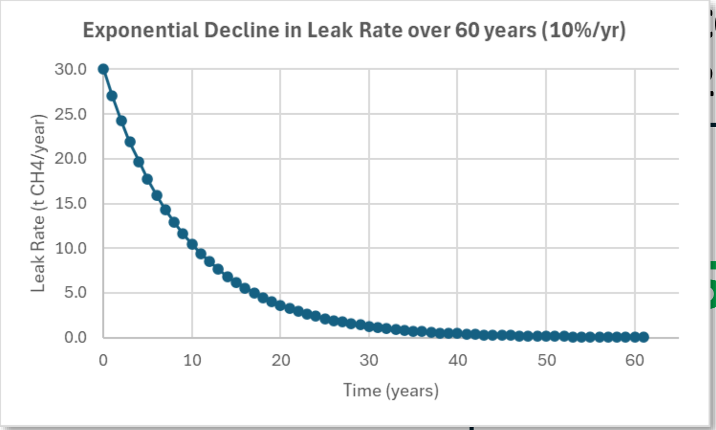
Assumptions:
10 m thick formation @ 500 m TVDSS
1 mD permeability of strung-out cement in C-annulus
Negligible pressure loss through annular flow
Annular fluid is density of base oil
Temperature increase minimal 5.4 K
Dynamic Viscosity (gas) RPT for methane 11.1 µPa·s

$$q = \frac{2\pi k h (p_e - p_{wf})}{\mu \ln(r_e/r_w)}$$

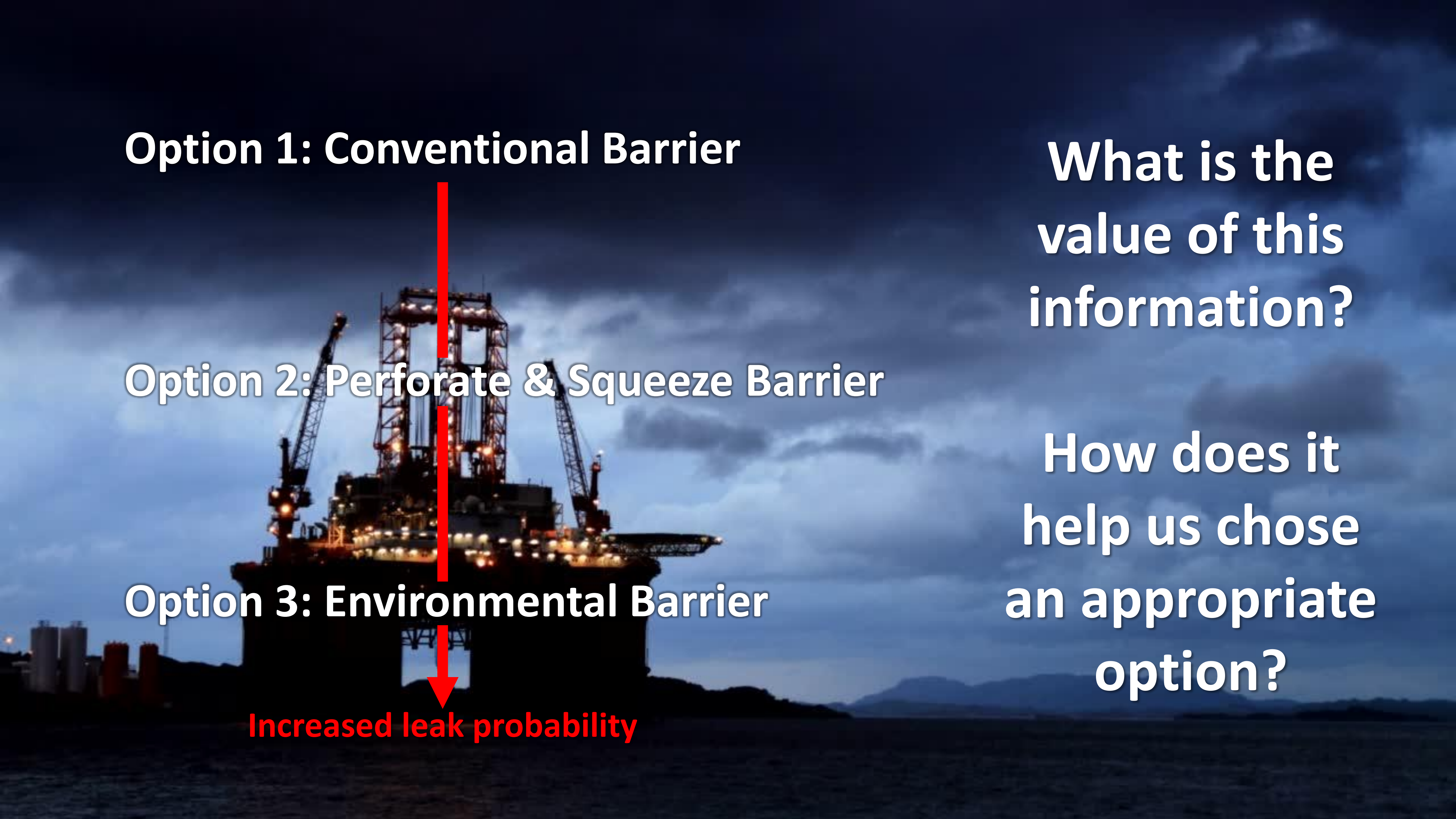
Where:
q = volumetric flow rate
k = permeability of porous medium
h = thickness of flow zone
pe = pressure at the external boundary (radius re)
pwf = pressure at the wellbore (radius rw)
μ = dynamic viscosity of the fluid
Ln(re/rw) = natural logarithm of the ratio of the external radius to the wellbore radius

Thanks Dave Roberts (Well-Safe Wells TA) for your help!

	Assumed leak rate / volume over 60 years		O2e using 0 (87)	Societal Cost (£) (CV) £287 * tCO_2e
Unmitigated Potential Leak Rate from Wells (n=12)	30 tCH_4/well/yr EXP decline 10%/yr = 3,235 tCH_4		5 tCO_2e	£8.08 mm



* estimate from literature (95-99%), but with more wells leaking, dissolution power of water column will decrease



Option 1: Conventional Barrier

Option 2: Perforate & Squeeze Barrier

Option 3: Environmental Barrier

Increased leak probability

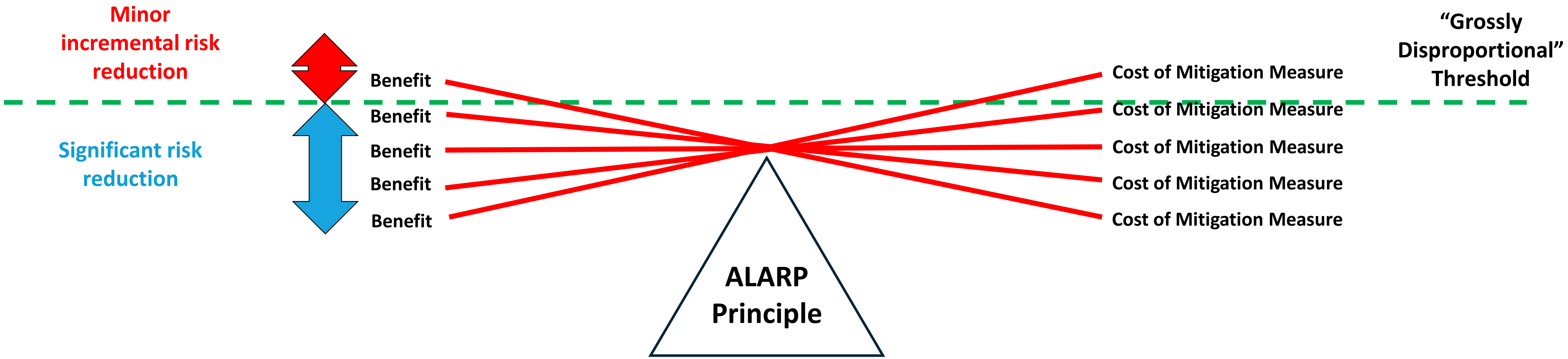
What is the value of this information?

How does it help us chose an appropriate option?

Case Study: Cost-Benefit Analysis

Is The Proposed Solution Proportional To The Problem?

Societal Cost £8.08 mm

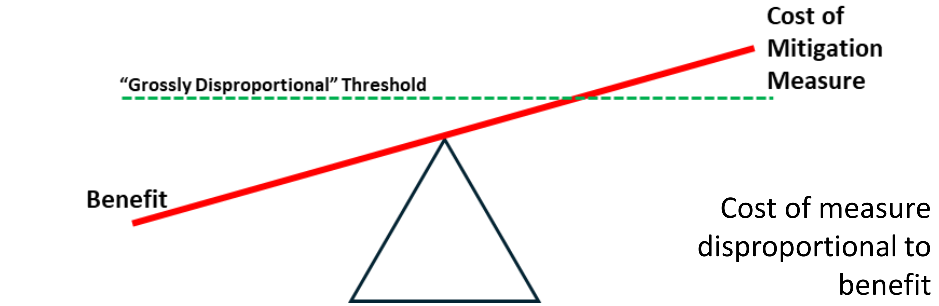
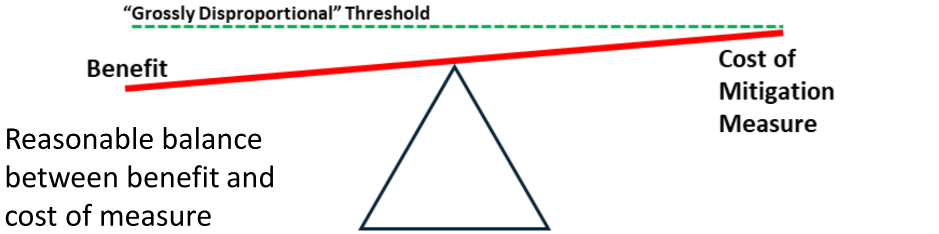
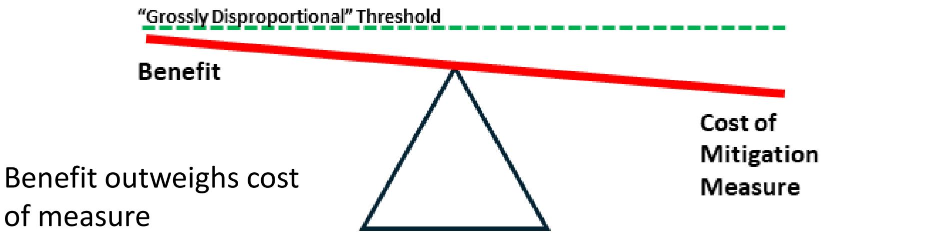


Does the cost of the isolation option for biogenic gas leakage remain beneath a "grossly disproportional" threshold?

Case Study: Cost-Benefit Analysis

Is The Proposed Solution Proportional To The Problem?

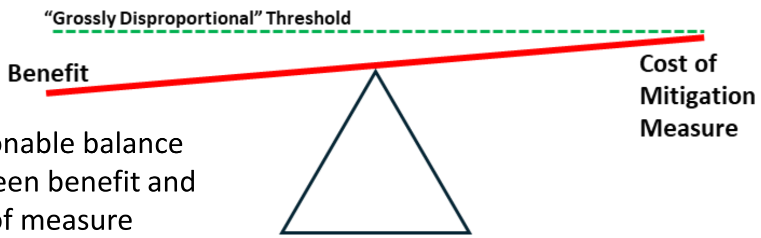
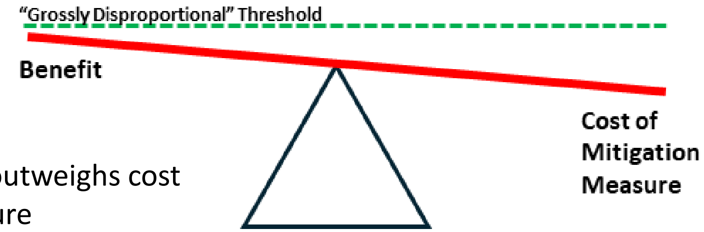
Societal Cost £8.08 mm

	Operational Cost (£)	Operational Cost (£) vs. Societal Cost (£)	Cost Difference (£)
Option 1: Conventional Barrier	£20.13 mm		+ £12.05 mm
Option 2: Perforate & Squeeze Barrier	£11.14 mm		+ £3.06 mm
Option 3: Environmental Barrier only	£6.21 mm		- £1.87 mm

Case Study: Cost-Benefit Analysis

Is The Proposed Solution Proportional To The Problem?

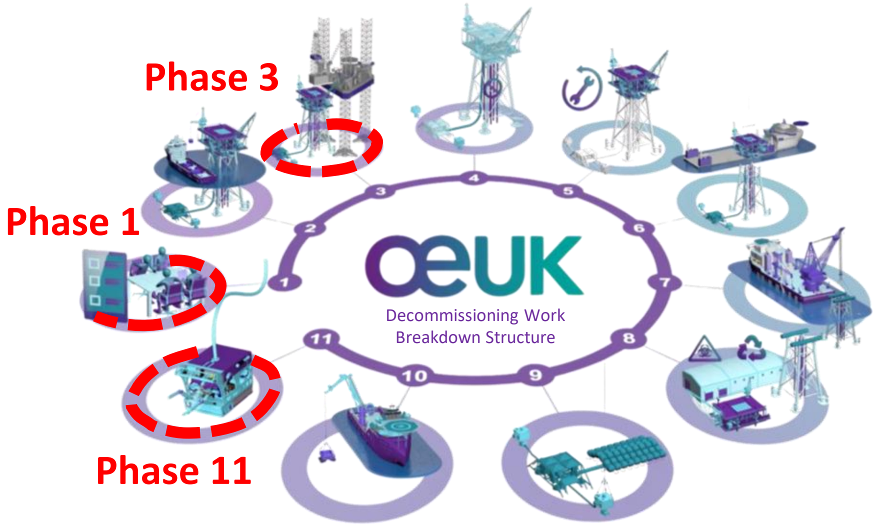
Societal Cost £8.08 mm

	Operational Cost (£)	Operational Cost (£) – Societal Cost (£)	Cost Difference (£)
Option 2: Perforate & Squeeze Barrier	£11.14 mm	 Reasonable balance between benefit and cost of measure	+ £3.06 mm
Option 3: Environmental Barrier only	£6.21 mm	 Benefit outweighs cost of measure	- £1.87 mm


Should leak rate modelling form part of the decommissioning planning process?
(As a means to deliver cost-effective well abandonment)

Proactive Abandonment Planning

Suggested Workflow & Data Gathering Opportunities



Typical Evolution of a Decommissioning Project

Characterise

- Leak characteristics and rate
- Natural leaks? Does it impact isolation strategy?

Compile regional frameworks

Model

- Model realistic leakage scenarios from well
- What % of emission reaches the atmosphere?

- **Phase 1: Project Management**
- **Environmental Impact Assessment (EIA)**

Cost-Benefit Analysis

- Determine “cost to society” of a leak
- Use it to provide a decision-making framework for risk mitigation which is proportional to the problem

- **Phase 3: Well Abandonment**
- **Acquire data to support continued use of ALARP**

Monitor

- Monitoring plan (were the assumptions correct?)
- Intervention plan, if required

- **Phase 11: Post-Decom Monitoring**
- **Conduct further monitoring beyond 3 years**

Conclusions

All. Rocks. Leak. — Leak characteristics vary – key metric is the volume reaching the atmosphere and impacting society

Opportunities — Leaks can be modelled and sites monitored – we should leverage existing opportunities to gather data

Cost-Benefit Analysis — Calculating the "cost to society" is a valuable metric for justifying a solution which is proportional to the problem in terms of cost/risk reduction

Mindset — This method requires a change of mindset and an acceptance that there is a place for pragmatism

WELL-SAFE SOLUTIONS

OUR VISION

To be the trusted full well life-cycle partner of choice

Thank you!

Any Questions?

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