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A Practical Approach to Identifying and Assessing CO_2 Injection Well Leakage Potential for Application to Carbon Storage Risk Analysis

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Why focus on the injection well?

Risk of CO_2 Release

- Heavier than air
- Asphyxiant
- Odorless and colorless
- Joule-Tompson Cooling
- Could impact plant operations and local infrastructure (highways, residences, etc.)

Well Design Needs

- 50+ year lifetime
- Corrosive environments
- High pressure handling

Existing Methods for Estimating Leakage Rates

- ✓ Pipeline rupture (standard pipe flow calculations)
- ✓ Natural features (fault analysis, subsurface flow modeling, etc.)
- ✓ Abandoned Wellbores (subsurface flow modeling)
- ✓ Subsurface leakage to USDW (subsurface flow modeling)
- ✓ Injection Well [Physics based coupled transient flow models (not commercially available)]
- ✗ **A simple readily accessible method for the injection well**

Sheep Mountain Unit, Colorado USA. 1982

- New CO_2 production well blowout during drilling
- Release Cause: Unintentional underbalanced drilling
- **Release Rate Estimates: 200-250 MMscf/d (10.5k-13.2k tonnes/d)**
- Estimated through temperature log informed heat-transfer calculations
- Release Path: Annular space → naturally fractured zone at the shoe →surface through fissures and offset well's annular wing valves
- Remediation method: Dynamic kill operations at initial release point
- Published by Lynch et al. (1985)

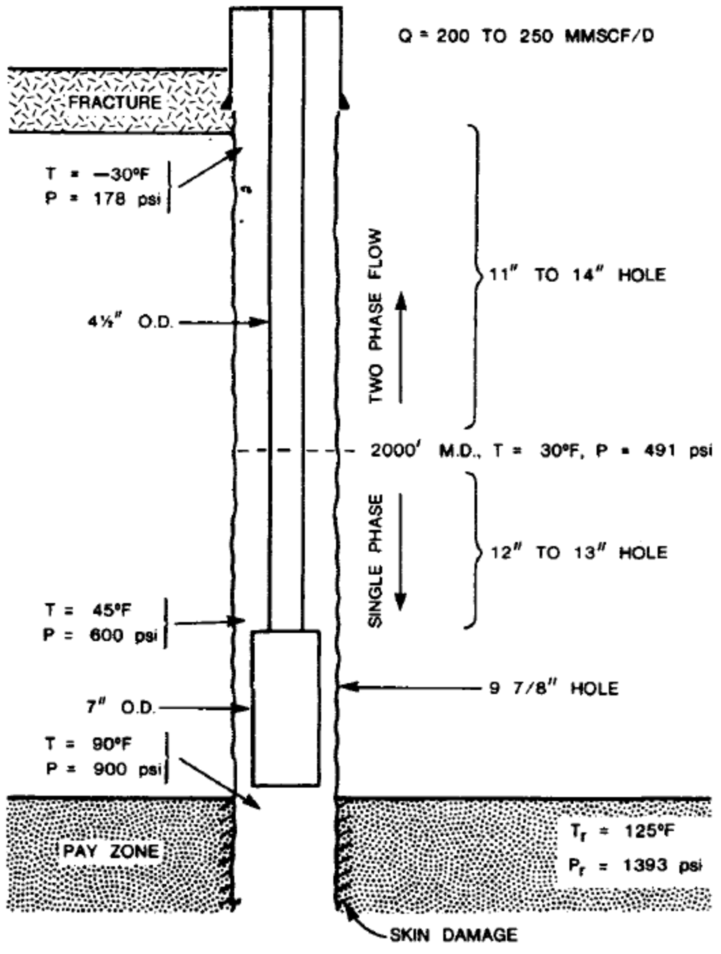

Fig. A-3—Characteristics of freely flowing Sheep Mountain Unit well.

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Alfina 1, Latium Italy, 1973

- Geothermal exploration uncovered a water bearing reservoir with a natural CO2 gas cap
- Release Cause: Not reported
- **Release Rate Estimates: 136 MMscf/d (7,200 tonnes/d)**
- Initial Release Path: Uncased wellbore→ Atmosphere
  - Subsequently shut-in at surface
- Secondary Release path: Uncased wellbore → high vertical permeability pathways → surface through fissures
- Remediation method: Cement plugs and relief wells (minimal success)
- Published by Ferrara et al. (1978)

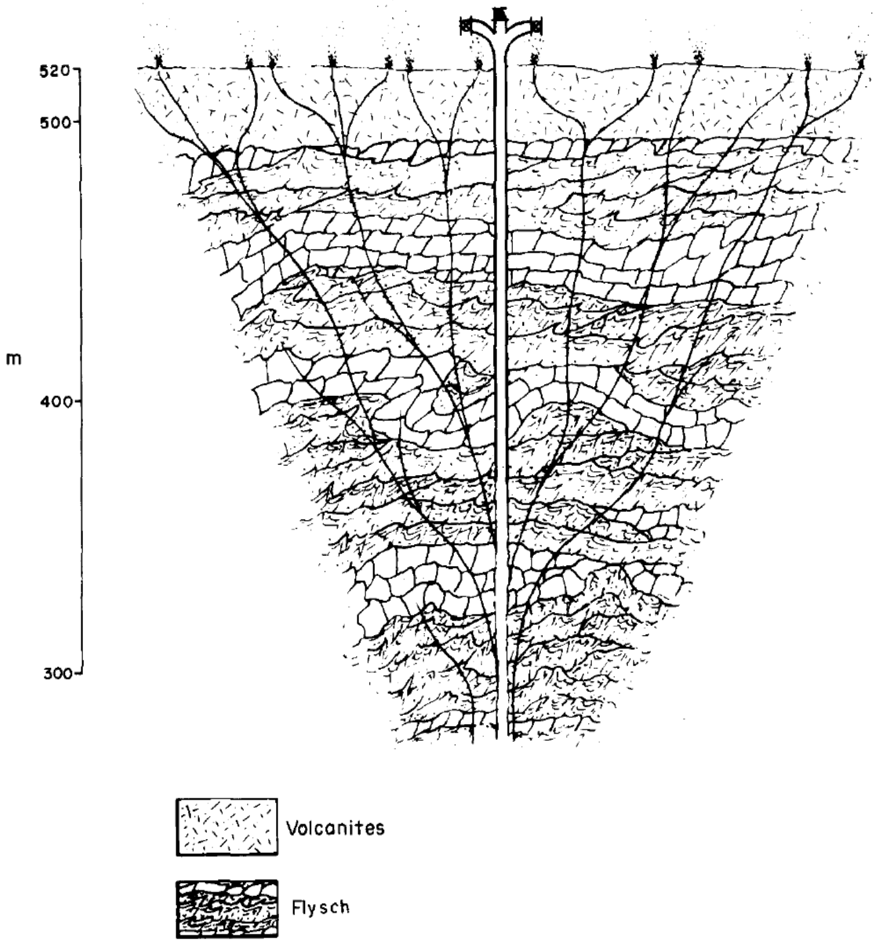


Fig. 2. Sketch of gas blowing-up around the Alfina 1 well.

Methodology

- Determine critical failure points
- Model reservoir production rates
- Generate IPR curves
- Conduct nodal analysis to estimate leakage rate
- Apply to risk analysis

Critical Failure Point Analysis

Purpose

- Identify all possible failure points and modes

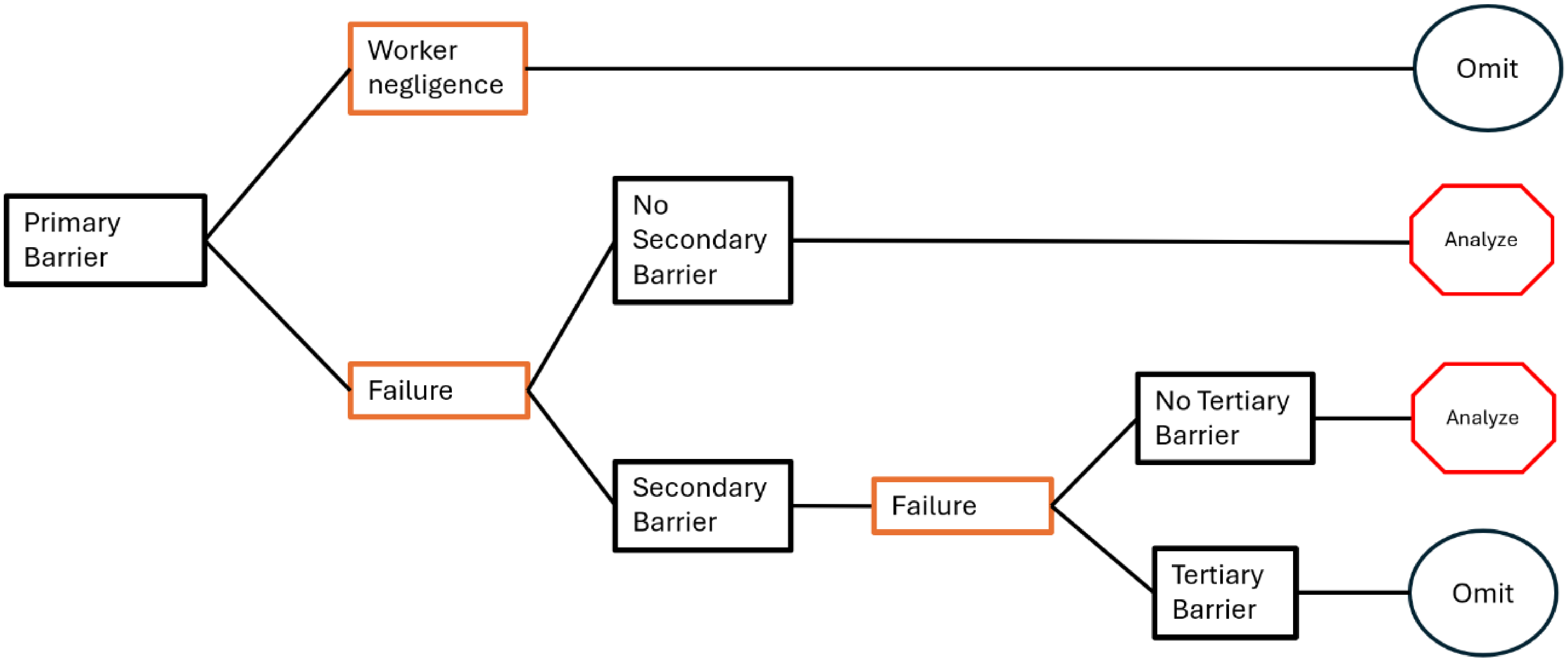
Assumptions

- 2+ failures were omitted (double-jeopardy).
- Worker's negligence is omitted
- Acts of Terror is neglected
- The well is constructed to Class VI standards

Corrective Action

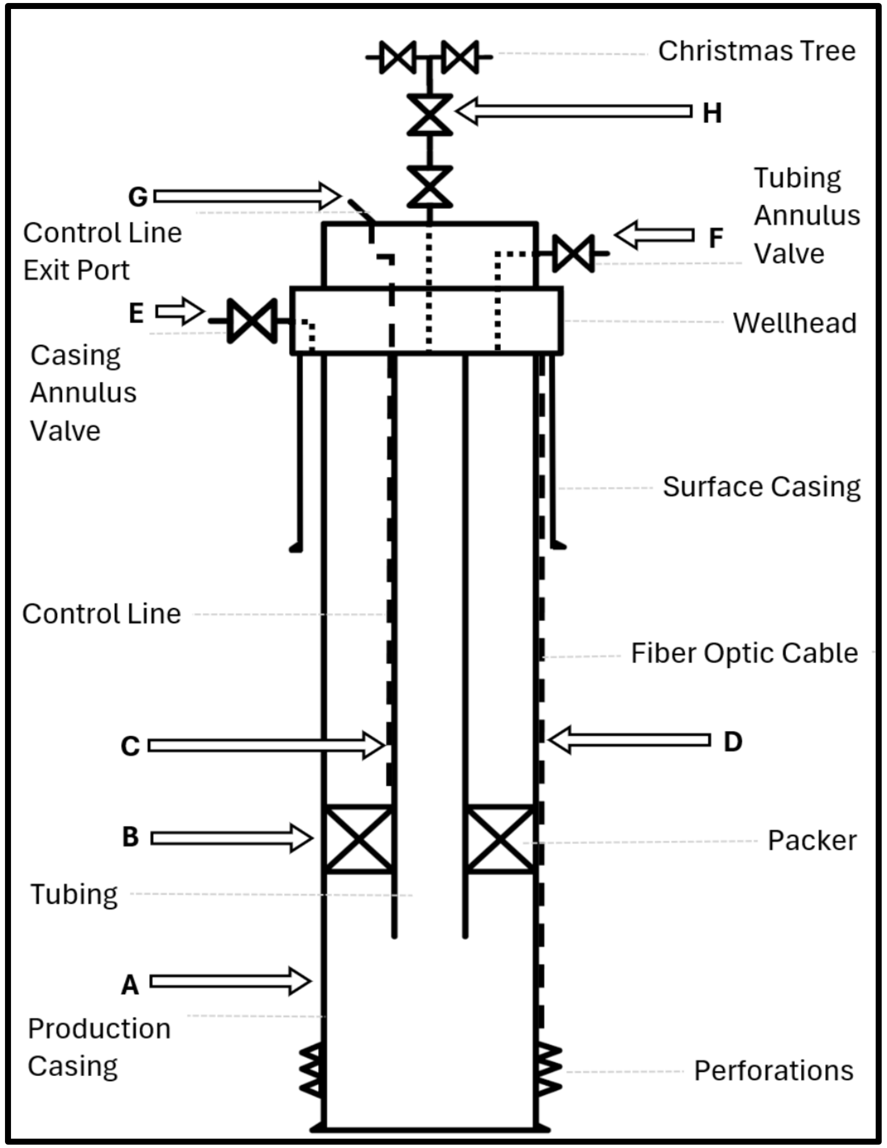
- How is the leak addressed?
- How long will it take?

Critical Failure Point Analysis Workflow



Potential Class VI Well Failures

#	Primary Barrier	Estimated Leakage Timeframe	Reason
A	Casing	Omitted	Multiple barriers to surface
B	Packer	Omitted	Multiple barriers to surface
C	Casing Annulus	Omitted	Multiple barriers to surface
D	External Control Lines	Omitted	Multiple barriers to surface
E	Casing Annulus Valve	Omitted	Multiple barriers to surface
F	Tubing Annulus Valve	8-12 hours	Two barrier failure
G	Control Line Exit Port	3-4 days	Two barrier failure
H	Master Valve	7-days	Single barrier (worst case failure)

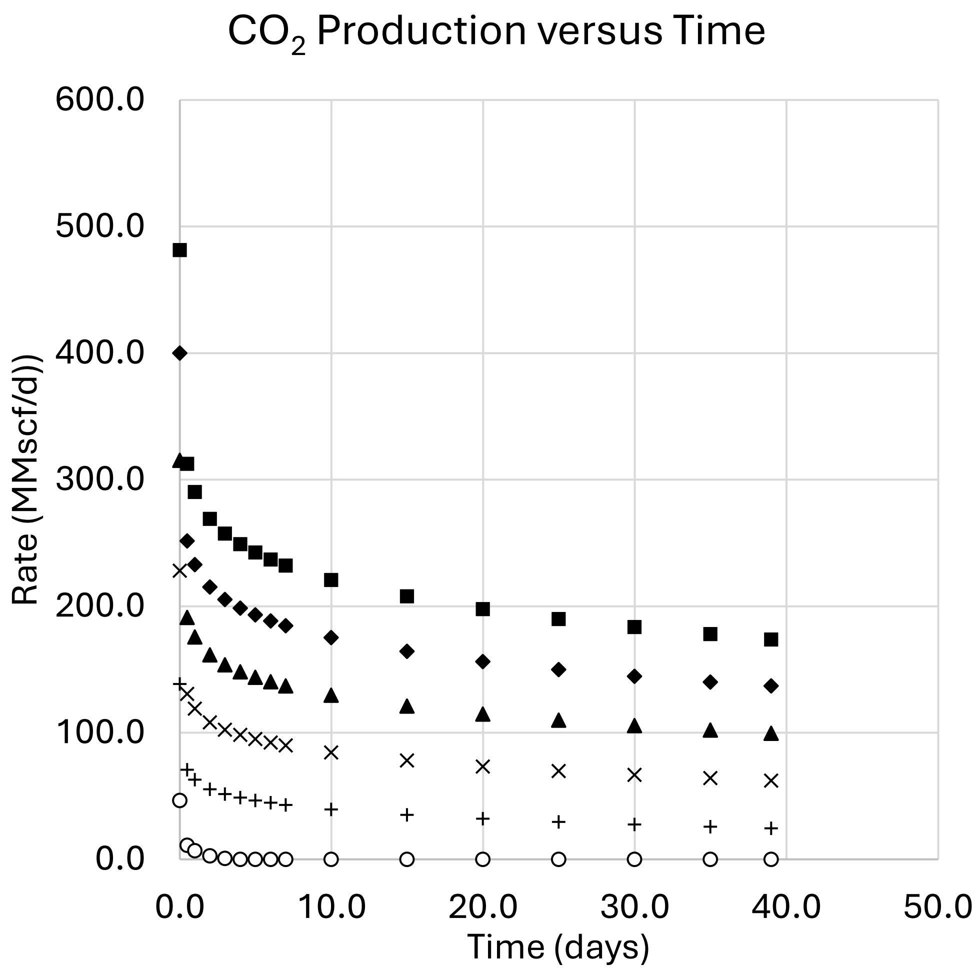


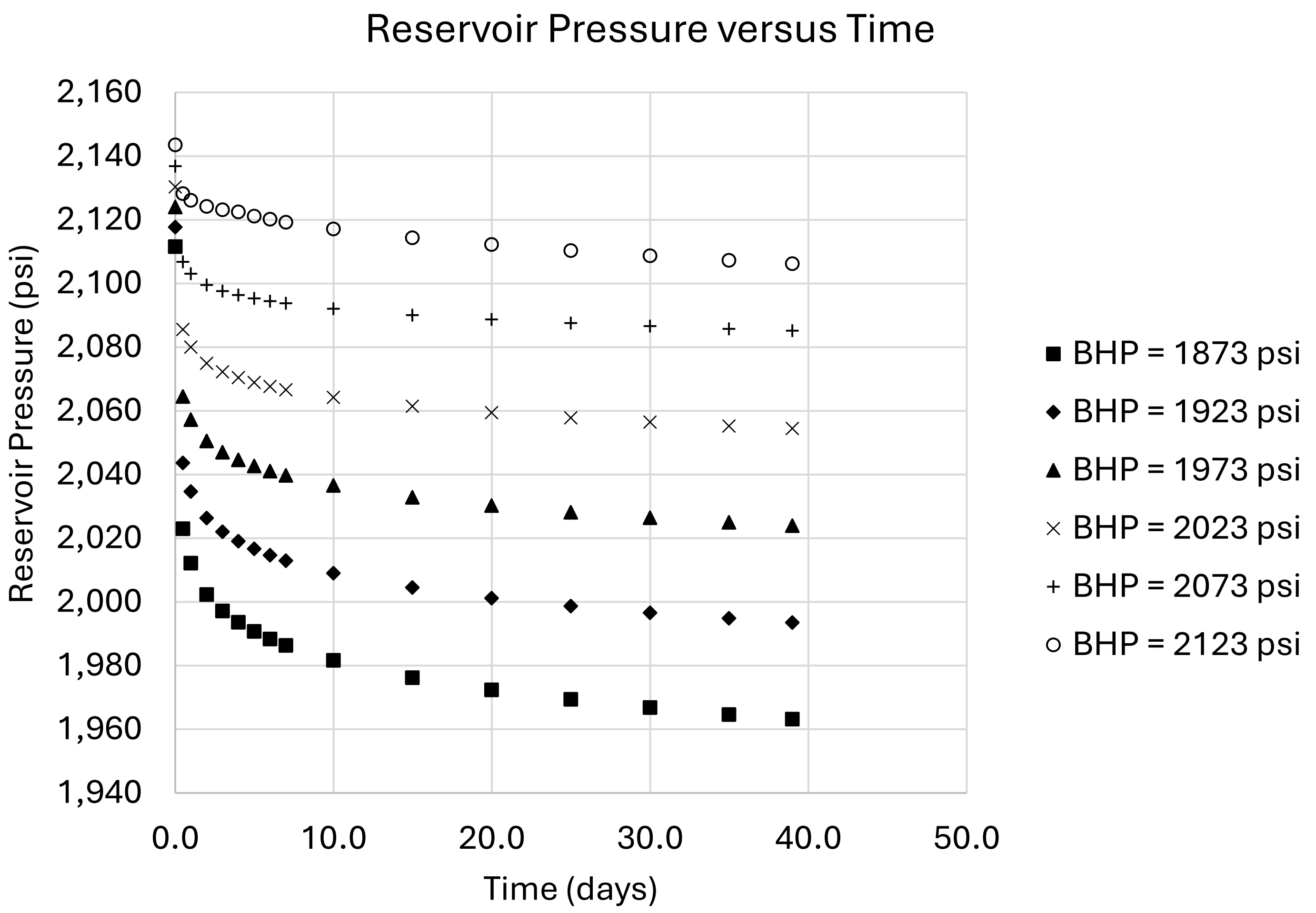
Model Setup

- Built on a potential Class VI project modeled with data from nearby wells
- 30-years injection @ 290 MMscf (5.6 Mmtpa) through 3 wells.
  - 97 MMscf/d (1.9MMtpa) per well
- CO_2 production (reservoir → well) modeled at the end of injection
  - highest reservoir pressure → highest leakage risk
  - CO_2 production was modeled at 50 psi decreasing BHP increments

Model Parameters	Value
Depth	4,500-5,000 ft
Average Permeability	250-300 mD
Average Porosity	30-40%
Net Thickness	200-300 ft
Temperature	120-125 ^oF
Initial Reservoir Pressure	~2,000 psi
Post-injection Pressure	~2,200 psi (Δ = 150-200 psi)

Modeled CO_2 Production – Constant BHP



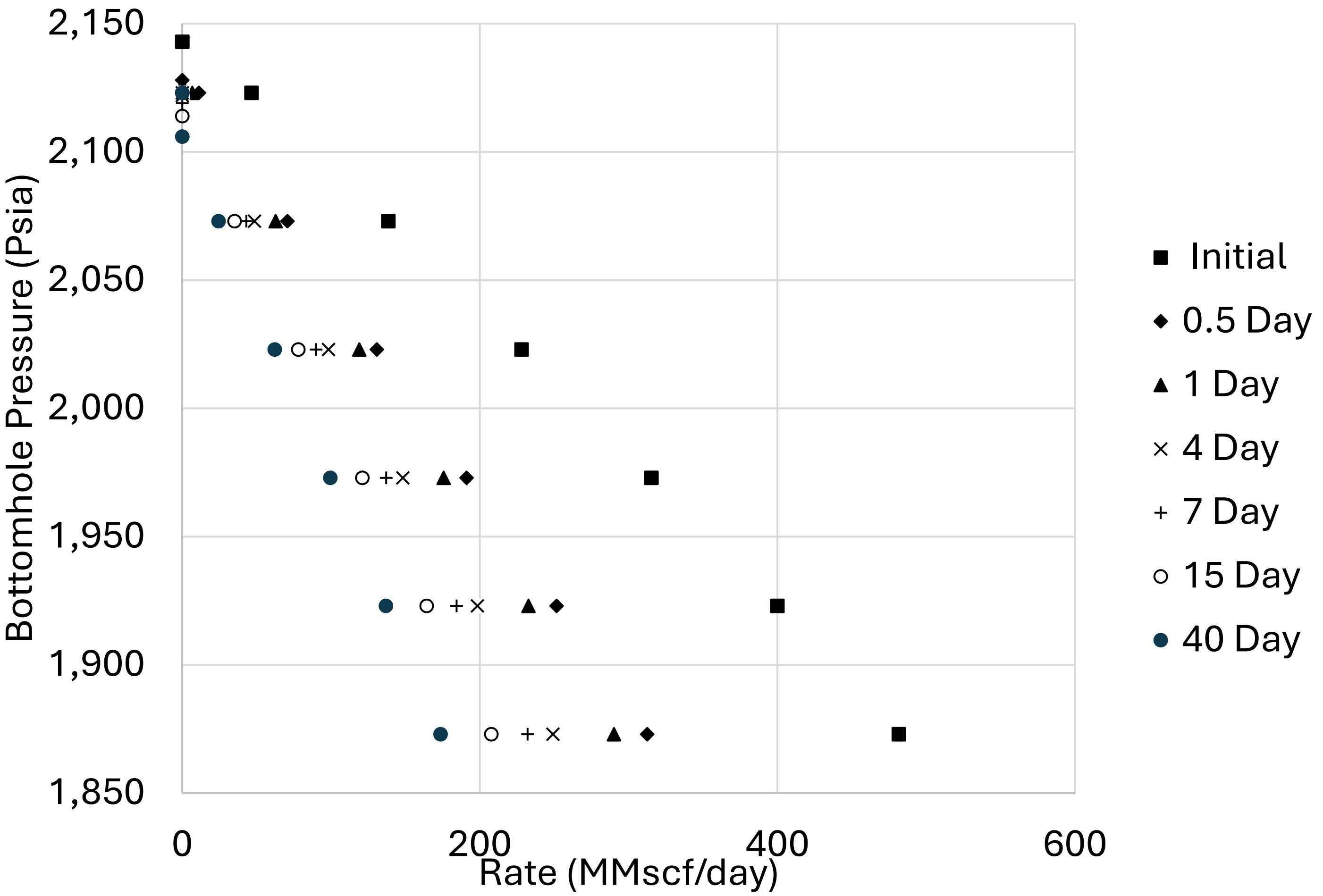


Creating Pseudo Well Deliverability Tests (PWDT)

- CO_2 production rates at each BHP were plotted at various timestamps of the leak and remediation process identified during critical failure point analysis

- Initial bottomhole pressure was matched with average reservoir pressure at the early timestep of the IPR

  - $P_{wf}(t) = P_r(t) \rightarrow Q(t) = 0$ MMscf



Selecting the Correct Inflow Performance Relationship

- Pressure Squared IPR:

$$Q_g = J({P_r}^2 - {P_{wf}}^2)$$

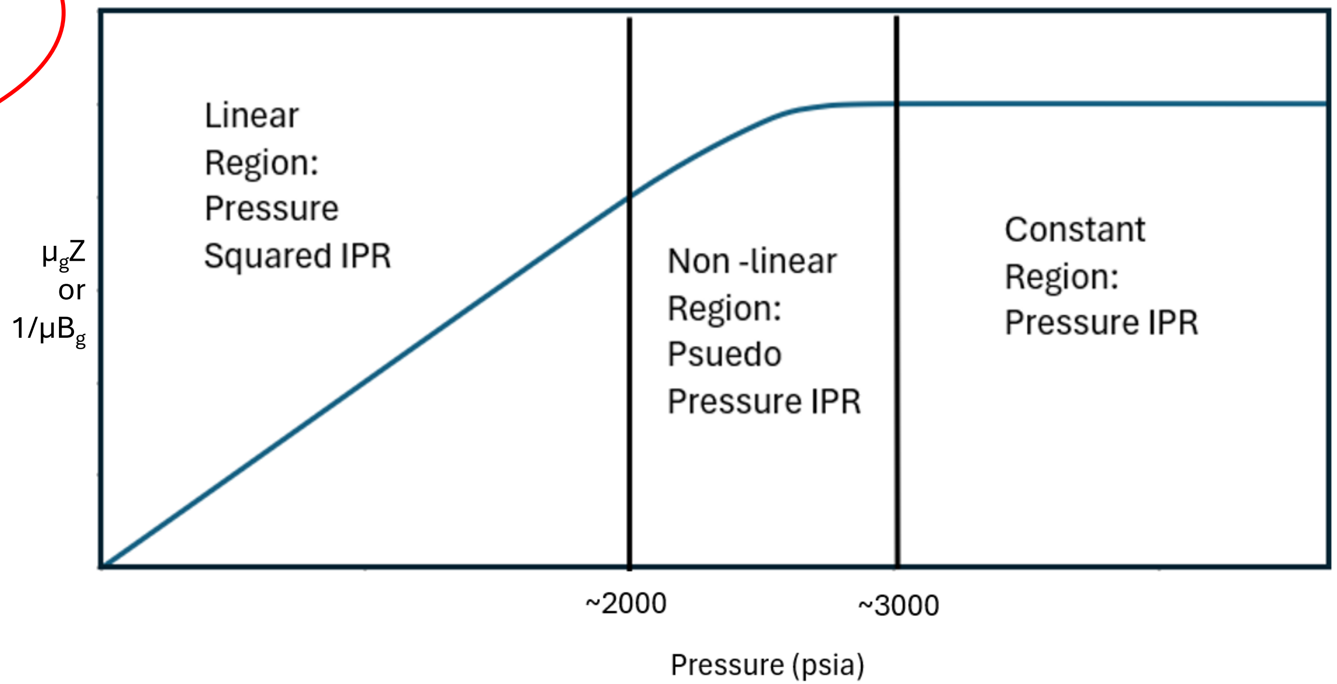
when $$J = \frac{kh}{1422(\mu_g Z)_{avg}[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s]}$$

- Pseudo Pressure IPR:

$$Q_g = \frac{kh[\varphi_r - \varphi_{wf}]}{1422T[\ln(\frac{r_e}{r_w}) - 0.75 + s]}$$

- Pressure IPR

$$Q_g = \frac{7.08(10^{-6})kh(P_r - P_{wf})}{(\mu_g B_g)_{avg}[\ln(\frac{r_e}{r_w}) - 0.75 + s]}$$



The approximate behavior of the gas viscosity relationship.

Adapted from Ahmed and Meehan (2012)

Generating the IPR Curve

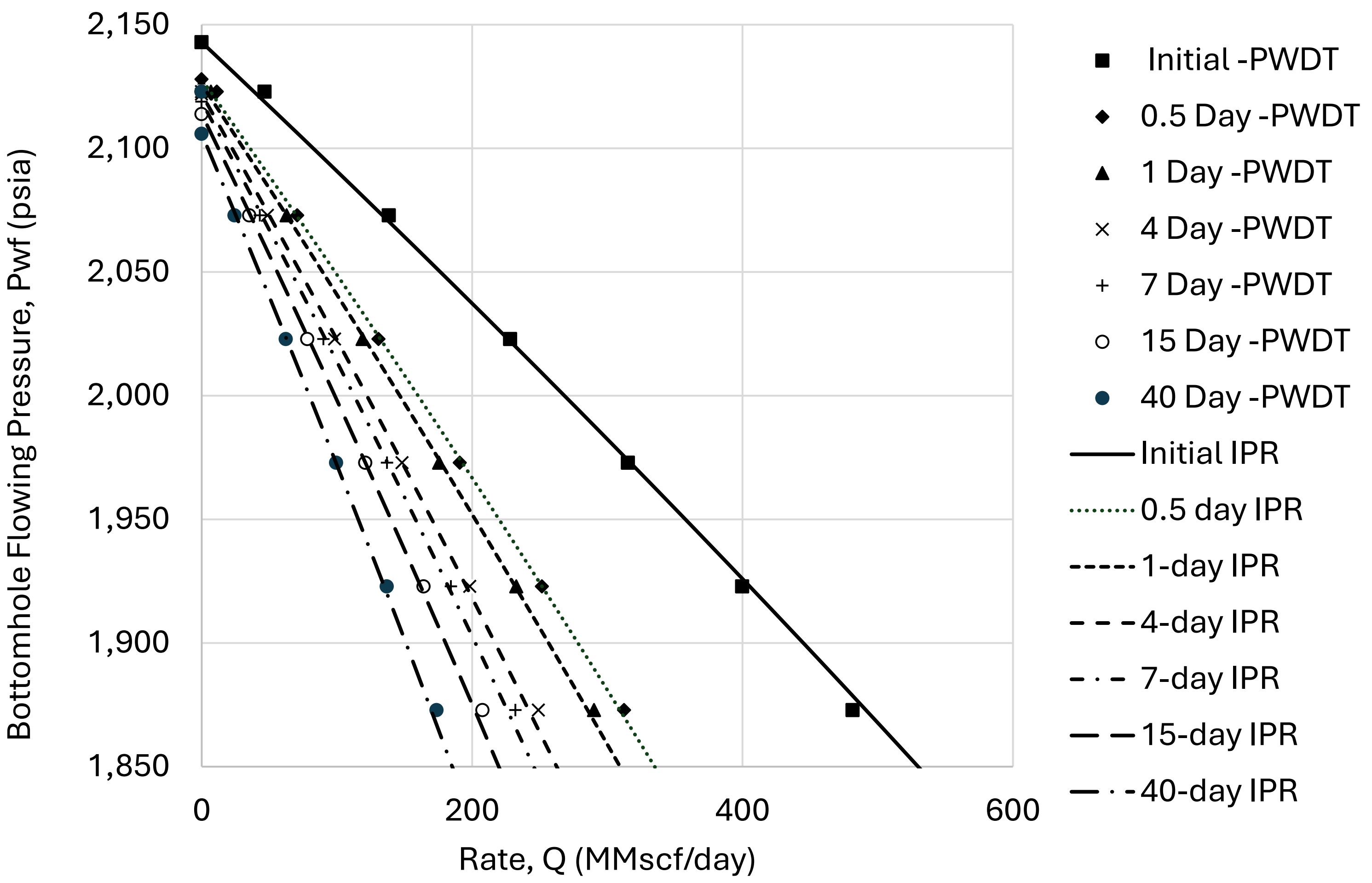
$$Q_g = J\left({P_r}^2 - {P_{wf}}^2\right)$$

Initial			0.5 days			1 day			4 days			7 days		
P_r	2,143	psi	P_r	2,128	psi	P_r	2,126	psi	P_r	2,122	psi	P_r	2,119	psi
P_{wf}	Q	J	P_{wf}	Q	J	P_{wf}	Q	J	P_{wf}	Q	J	P_{wf}	Q	J
Psi	MMscf/d	MMscf/d *psi^2	Psi	MMscf/d	MMscf/d *psi^2	Psi	MMscf/d	MMscf/d* psi^2	Psi	MMscf/d	MMscf/d* psi^2	Psi	MMscf/d	MMscf/d *psi^2
2,123	46.5	0.00054	2,123	11.1	0.00052	2,123	6.8	0.00053	2,123	0.0	0.00000	2,123	0.0	0.00000
2,073	138.4	0.00047	2,073	70.8	0.00031	2,073	62.8	0.00028	2,073	48.6	0.00024	2,073	43.0	0.00022
2,023	228.0	0.00046	2,023	130.7	0.00030	2,023	119.1	0.00028	2,023	98.3	0.00024	2,023	90.0	0.00023
1,973	315.2	0.00045	1,973	191.0	0.00030	1,973	175.7	0.00028	1,973	148.2	0.00024	1,973	137.1	0.00023
1,923	399.8	0.00045	1,923	251.6	0.00030	1,923	232.7	0.00028	1,923	198.4	0.00025	1,923	184.4	0.00023
1,873	481.4	0.00044	1,873	312.5	0.00031	1,873	290.1	0.00029	1,873	249.1	0.00025	1,873	232.1	0.00024

Generating the IPR Curve

$$Q_g = J\left({P_r}^2 - {P_{wf}}^2\right)$$

Average "J" Values	
Initial	0.00045
0.5	0.00030
1	0.00028
4	0.00024
7	0.00023
15	0.00021
40	0.00018



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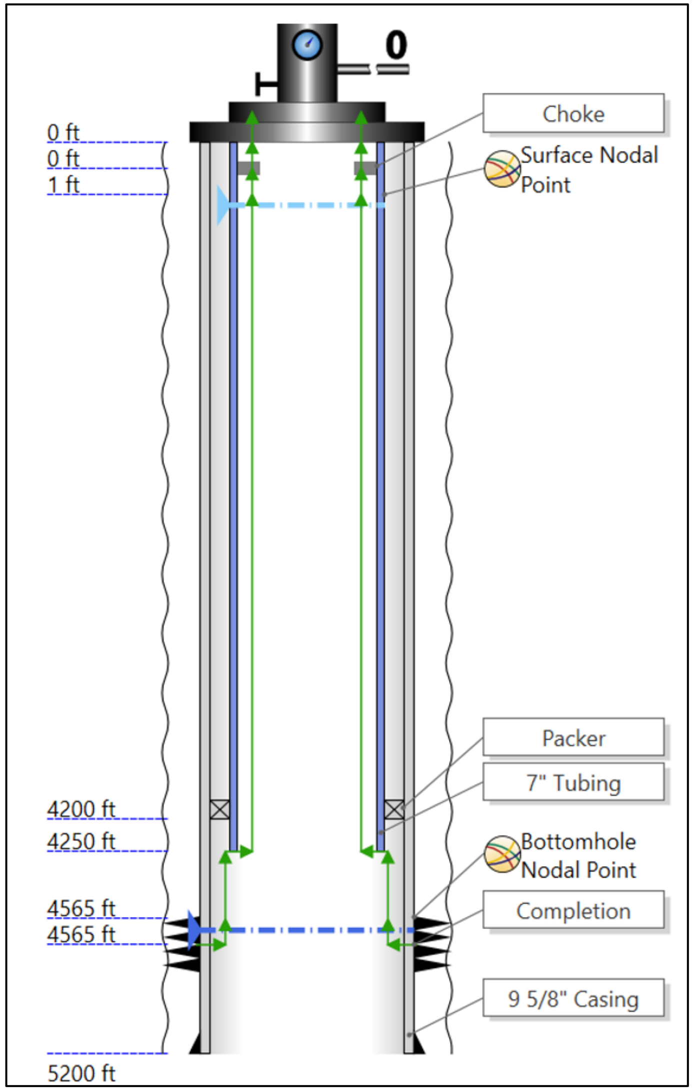
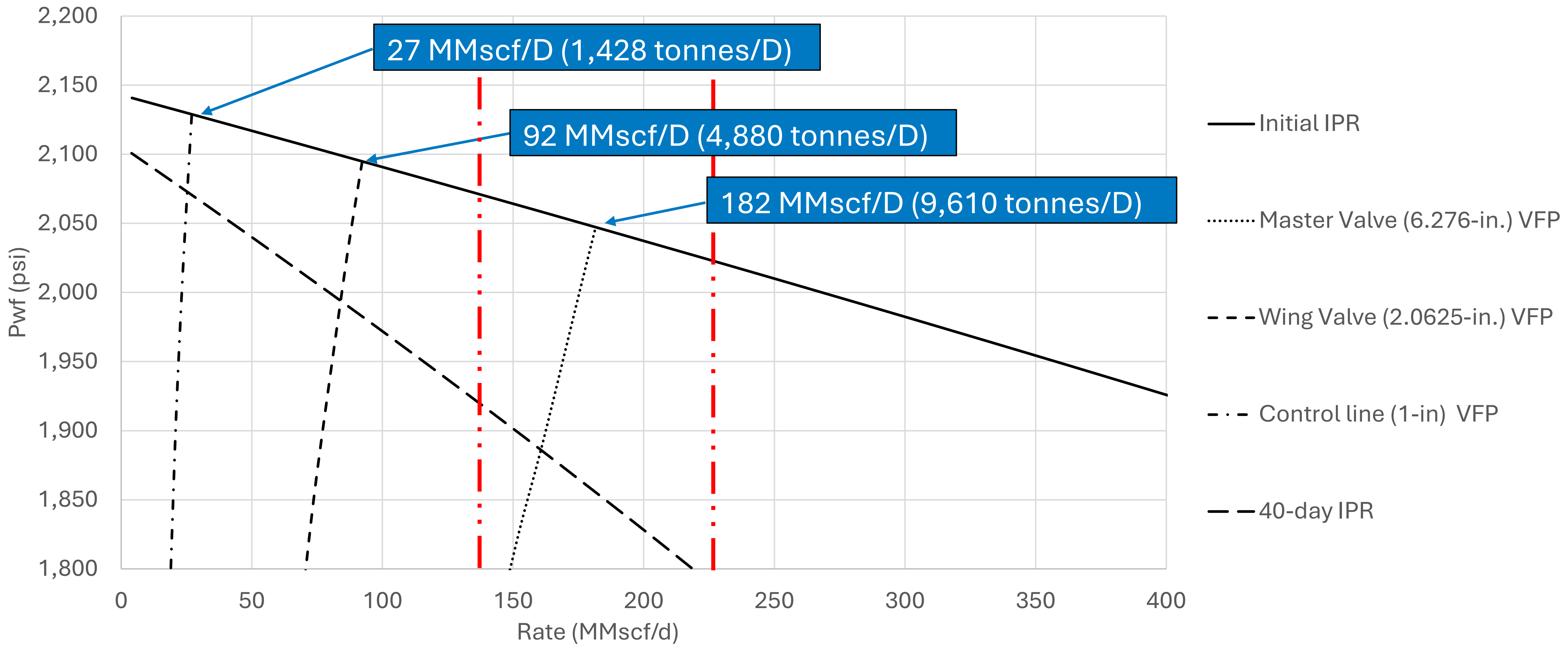
Modeling Leakage Rate

- Resulting IPR curves were input into Pipesim for nodal analysis
  - (any readily nodal software can be used for this)
- Leakage orifice size was approximated by placing a choke at the surface
- Wellhead pressure was set to 14.7 psia (0 psig)
- Wellbore model was used to generate vertical flow performance (VFP) curves

Equipment Failure	Release Orifice Diameter (in)
Tubing Annulus Wing Valve	2.0625
Control Line Port	1
Full Bore Release	6.276



Estimated Leakage Rate



Conclusion

- This proposed methodology provides a readily accessible methodology for estimating injection well leakage rates
  - Industry standard methods of critical failure point analysis
  - Industry standard IPR methods
  - Industry standard (and usually existing) modeling software
- Rates are subject to error based on assumptions required to complete the calculations.
- The methodology provides comparable leakage rate estimates to that of know well-based atmospheric releases such as Sheep Mountain or Alfina 1.
- The estimated rates can be used directly in risk analysis or for further modeling such as atmospheric dispersion.

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