C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Webinar – Part 2

An Overview of Demonstration Analysis Results

contained in

Risk Assessment and Treatment of Wells

PHMSA Project DTPH56-17-RA-00002

November 17, 2020

Presented by Mark Stephens

m.stephens@cfertech.com

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

PHMSA Project Objectives

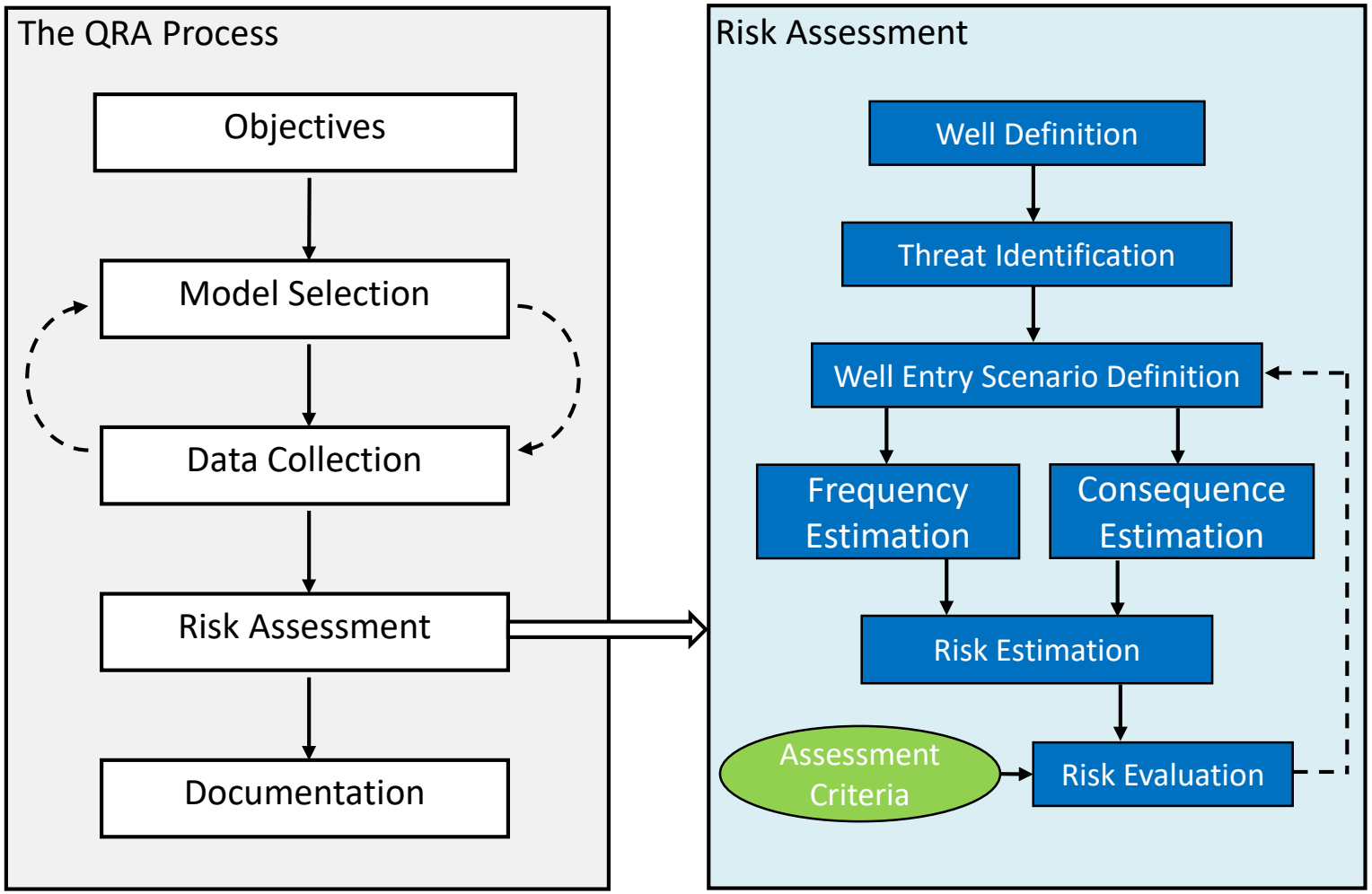
- **Guidelines -** Develop guidance for risk assessment of underground gas storage (UGS) wells subject to periodic entry
  - Focus on quantitative risk assessment (QRA) approaches
  - Explicit guidance for assessing risk to public safety and the environment

- **Demonstration -** Evaluate risk associated with well operation and periodic entry for typical depleted reservoir and cavern well configurations
  - To illustrate application of the QRA guidelines
  - To provide a basis for development and/or updating of best practices

Focus of Webinar – Part 2

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

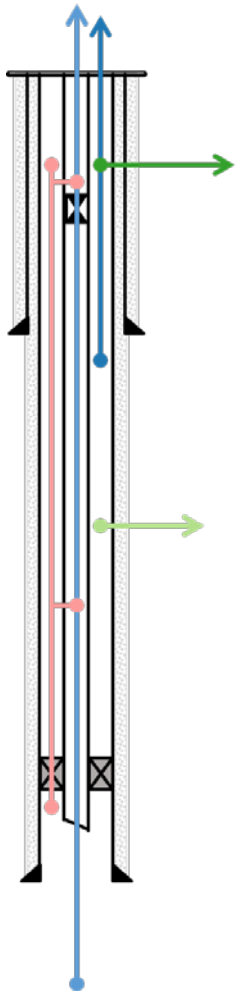
Risk Assessment - Guidelines



C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Risk Assessment - Background

- Pathway Identification and characterization
  - Well risk estimation involves identifying and characterizing all available release pathways
  - Each pathway defined by
    - Probability that pathway opens
    - Consequences of pathway opening
      - Release rate → safety consequences
      - (Release rate) x (Release duration) → environmental consequences



Risk Assessment - Background

- Risk is the expectation of loss (i.e. probability-weighted loss estimate)
  - Risk = Probability x Consequence
  - Risk* = Frequency x Consequence

    where Risk is the risk within a prescribed time period*

- Risk estimation for wells that can fail in multiple ways with consequences that depend on how pathway failure occurs
  - Risk for pathway '*i*' failing by mode '*j*'
    - $Risk_{ij} = Freq_{ij} \times Cons_{ij}$
  - Total risk from all '*n*' pathways failing by all '*m*' modes
    - $\text{Risk} = \sum_i^n \sum_j^m (Freq_{ij}) \bullet (Cons_{ij})$

Risk Assessment - Background

- Continuous versus point-in-time risk
  - Well operation – ongoing risk in each year of well operation
    - operating risk / year
  - Well entry – additional point-in-time risk
    - (entry risk / entry) x (well entries / year) = entry risk / year
  - Combined well risk - the sum of annualized operating risk and entry risk
    - (operating risk / year) + (entry risk / year) = combined risk / year

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Risk Assessment - Background

- Relevant combined well risk measures for decision-making
  - Annual risk ← focus on maximum value within the prescribed period
  - Cumulative risk over the prescribed period
    - $\text{Cumulative Risk} = \sum_{i}^{n} Annual\ Risk_{\ i}$ where n = years

- Risk Evaluation
  - Option 1 (where acceptance criteria exist)
    - Compare calculated risk level to prescribed acceptable level → Acceptable scenarios do not exceed threshold
      - For safety risk evaluation compare maximum annual risk to acceptance criteria
  - Option 2 (where acceptance criteria do not exist)
    - Compare calculated risk for various operating scenarios → Preferred scenario has lowest risk level
      - For environmental risk compare cumulative risk over n-year evaluation period to alternative scenarios

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Demonstration Analysis - Framework

- Risk estimation
  - Risk under normal operational conditions → operating risk
  - Risk due to typical periodic well-entry activities → baseline entry risk

  ] Baseline risk
  - Risk due to additional entry activities intended to enhance well integrity → additional entry risk

- Risk evaluation
  - Baseline risk due to operation + baseline entry are combined and evaluated on an annual basis
    - Safety and Environment risk
  - Total combined risk (operational + baseline entry + additional entries) are aggregated over prescribed evaluation periods (2, 5, 10 and 20 years) and compared
    - Environmental risk

Demonstration Analysis – Risk Measures

Chosen risk measures

- Life-Safety Risk
  - The generally accepted safety risk measures are Individual Risk (IR) and Societal Risk (SR)
  - Focus on Location Specific Individual Risk (LSIR)
    - Annual likelihood of fatality for an individual at a specified location (assuming full-time outdoor occupancy)
- Environmental Risk
  - Total expected release volume

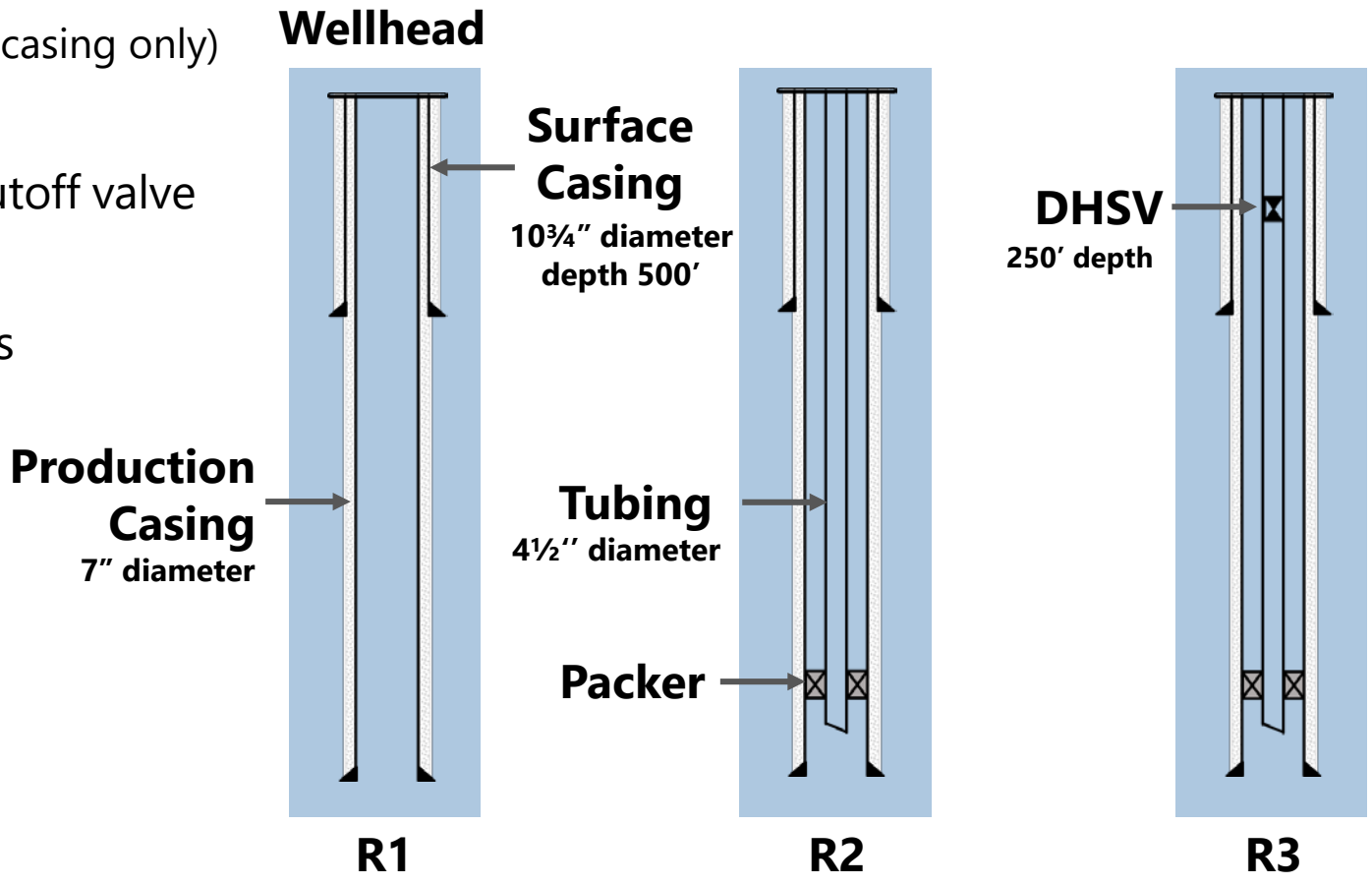
Well Configurations

Reservoir wells

- **R1** – Base configuration (production and surface casing only)
- **R2** – R1 with tubing and packer
- **R3** – R2 with tubing, packer and downhole shutoff valve

Well attributes common to all well configurations

- **Pressure:** 2000 psi
- **Temperature:** 100°F
- **Well depth:** 5000 ft
- **Fracture depth:** 4000 ft



C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

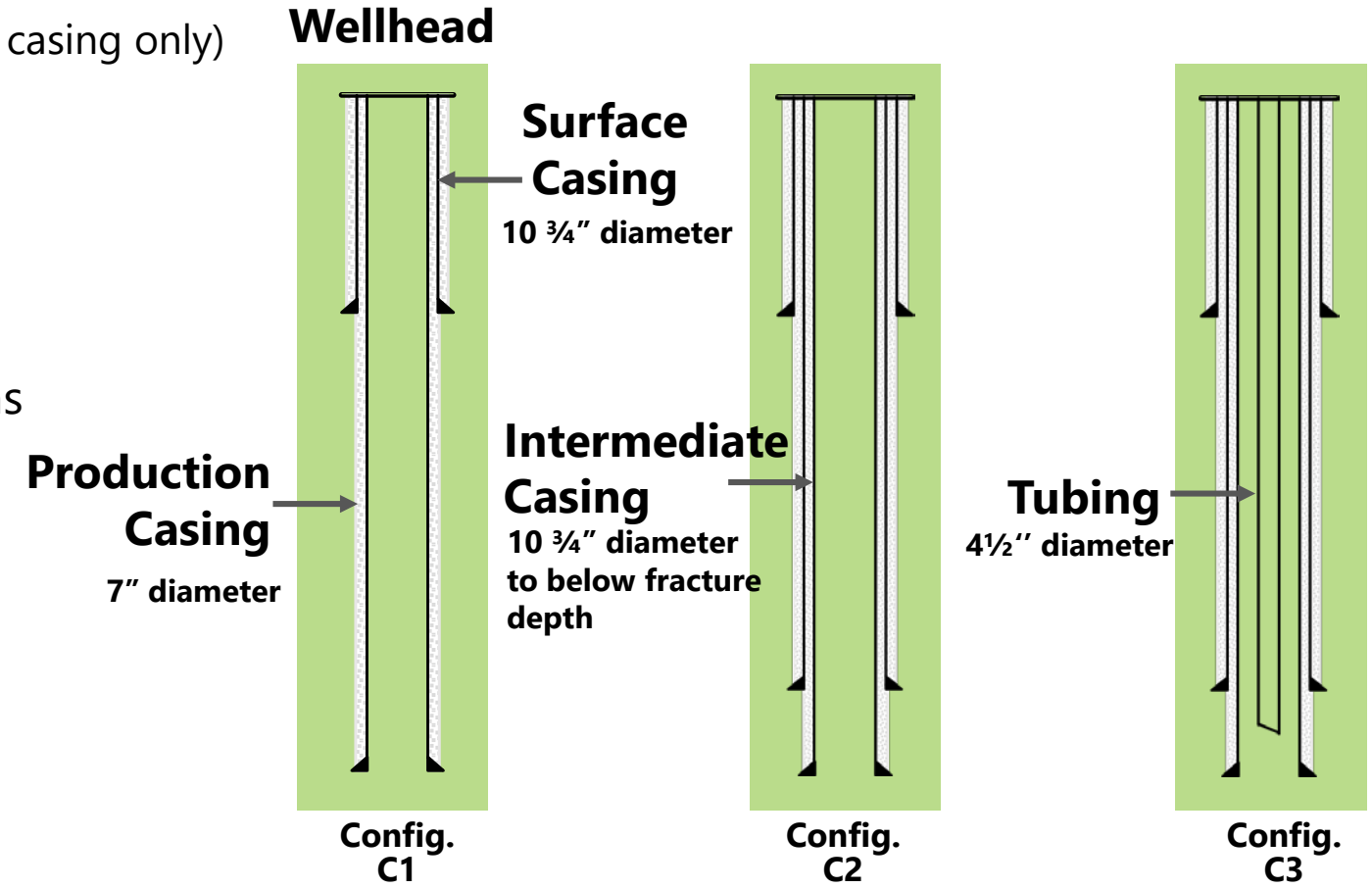
Well Configurations

Cavern wells

- **C1** – base configuration (production and surface casing only)
- **C2** – C1 with intermediate casing
- **C3** – C2 with suspended tubing string

Well attributes common to all well configurations

- **Pressure:** 2000 psi
- **Temperature:** 100°F
- **Well depth:** 5000 ft
- **Fracture depth:** 4000 ft

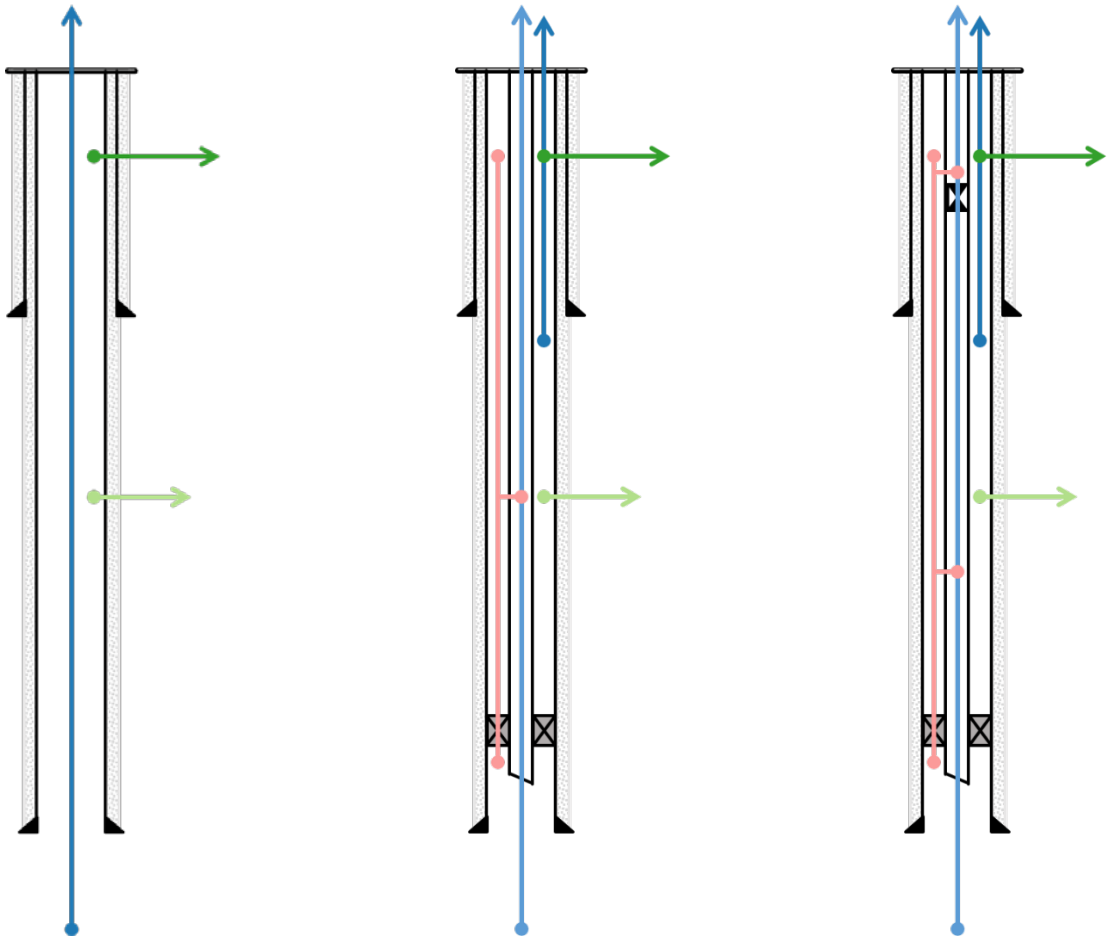


Baseline Risk

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Frequency Estimation: Operational

- Frequency estimation considerations
  - Pathways for release to atmosphere
  - Barriers in each pathway
  - Failure modes for each barrier
    - Small opening (small leak)
    - Medium opening (large leak)
    - Large opening (component rupture)
- Modeling approach
  - Fault-tree analysis
  - Historical data for individual barrier failure rate estimation ← informed by engineering judgement



R1 R2 R3

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Frequency Estimation: Operational

- Individual barrier failure rates obtained from multiple sources
- Values selected from data specific to UGS wells where possible

Barrier	Data Source	Failure Frequency (per well-year)
Surface casing (SC)	GRI - inferred	8.0×10^{-6}
Production and intermediate casing (above SC shoe)	GRI	8.0×10^{-6}
Production and intermediate casing (below SC shoe)	GRI	7.2×10^{-5}
Wellhead Assembly	GRI	5.4×10^{-5}
Tubing	AGA	2.3×10^{-5}
Packer	SINTEF	2.9×10^{-3}
DHSV	AGA	2.0×10^{-5}

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Frequency Estimation: Operational

Barrier failure modes and relative likelihoods of occurrence

Barrier	Failure Mode Likelihood			Data Source
	Small Leak	Large Leak	Rupture	
Surface casing (SC)	83%	12%	5%	(CAPP)
Production and intermediate casing - above SC shoe	83%	12%	5%	(CAPP)
Production and intermediate casing - below SC shoe	83%	12%	5%	(CAPP)
Wellhead Assembly	79%	17%	4%	(HSE)
Tubing	91%	7%	2%	(SINTEF)
Packer	85%	10%	5%	(Engineering judgement)
DHSV	0%	56%	44%	(SINTEF)

Frequency Estimation: Operational

Reservoirs wells

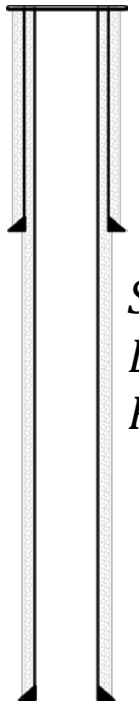
$FoF_{operational}$: $1.3 \times 10^{-4} \frac{failures}{well\ year}$

$5.4 \times 10^{-5} \frac{failures}{well\ year}$

0.4 times less R1

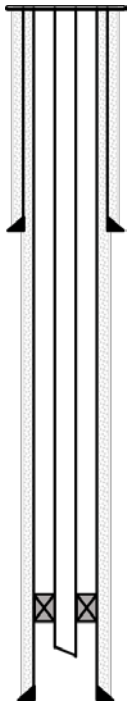
$3.7 \times 10^{-7} \frac{failures}{well\ year}$

0.003 times R1



$SL = 1.0 \times 10^{-4}$
$LL = 1.8 \times 10^{-5}$
$RU = 5.7 \times 10^{-6}$

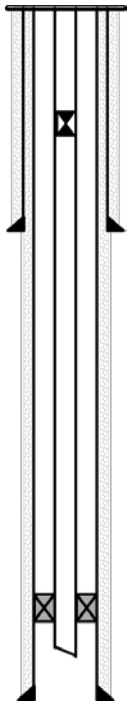
R1



$SL = 4.3 \times 10^{-5}$
$LL = 9.1 \times 10^{-6}$
$RU = 2.1 \times 10^{-6}$

0.4 times R1

R2



$SL = 3.6 \times 10^{-7}$
$LL = 9.8 \times 10^{-9}$
$RU = 8.7 \times 10^{-10}$

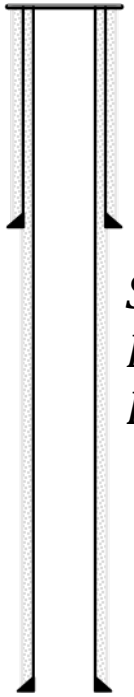
0.0002 times R1

R3

Frequency Estimation: Operational

Caverns wells

$FoF_{operational}$: $1.3 \times 10^{-4} \frac{failures}{well\ year}$

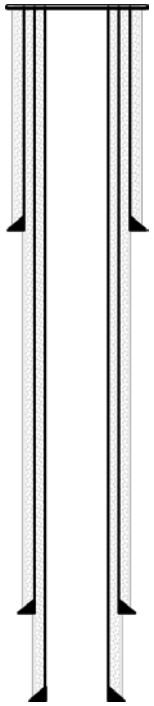


$SL = 1.0 \times 10^{-4}$
$LL = 1.8 \times 10^{-5}$
$RU = 5.7 \times 10^{-6}$

C1

$5.4 \times 10^{-5} \frac{failures}{well\ year}$

0.4 times R1



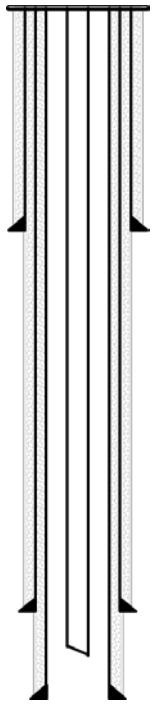
$SL = 4.2 \times 10^{-5}$
$LL = 9.1 \times 10^{-6}$
$RU = 2.1 \times 10^{-6}$

0.4 times R1

C2

$5.4 \times 10^{-5} \frac{failures}{well\ year}$

0.4 times R1



$SL = 4.2 \times 10^{-5}$
$LL = 9.1 \times 10^{-6}$
$RU = 2.1 \times 10^{-6}$

0.4 times R1

C3

Frequency Estimation: Well-entry

Well entry failures modeled predominantly wellhead failures

- Failure rate defined as function of entry type (IOGP offshore data with adjustments based on GRI data for onshore UGS wells)

$$FoF_{workover} > FoF_{coiled\ tubing} > FoF_{wireline}$$

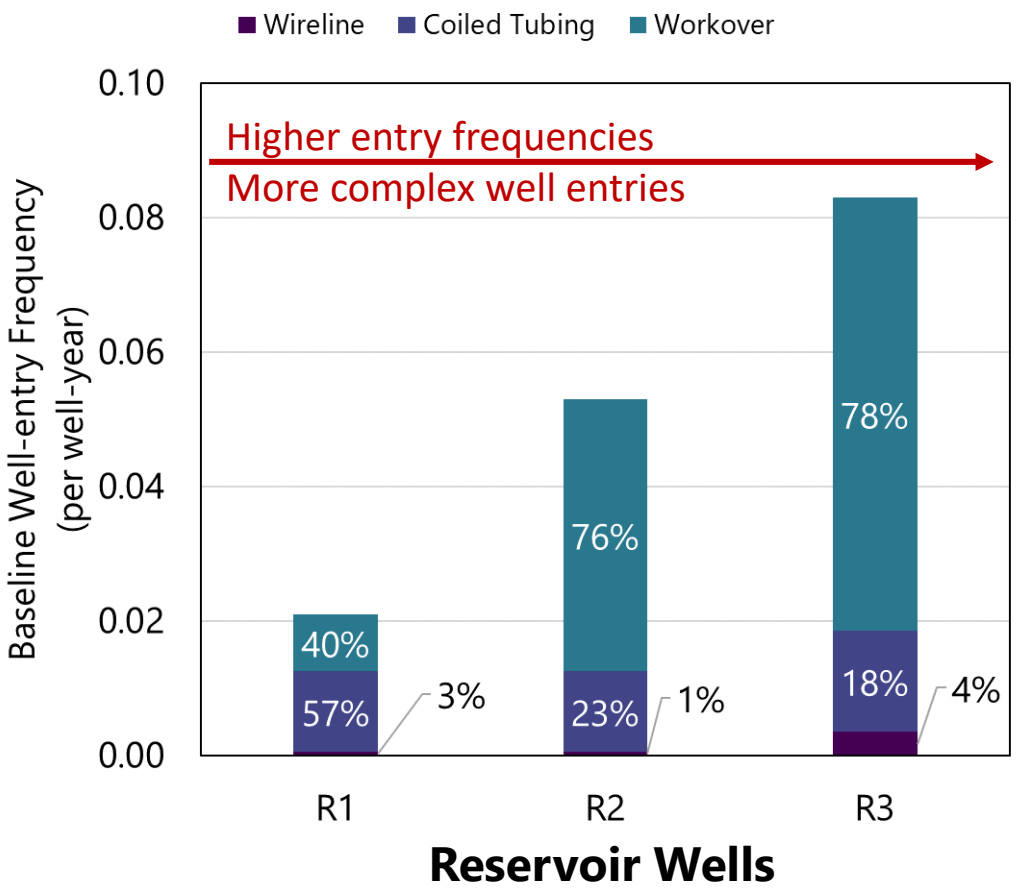
Entry Type	Failure Rate (per entry)	
	IOGP	Baseline (1/2 IOGP)
Workover	4.0×10^{-4}	2.0×10^{-4}
Coiled Tubing	1.1×10^{-4}	5.5×10^{-5}
Wireline	9.0×10^{-6}	4.5×10^{-6}

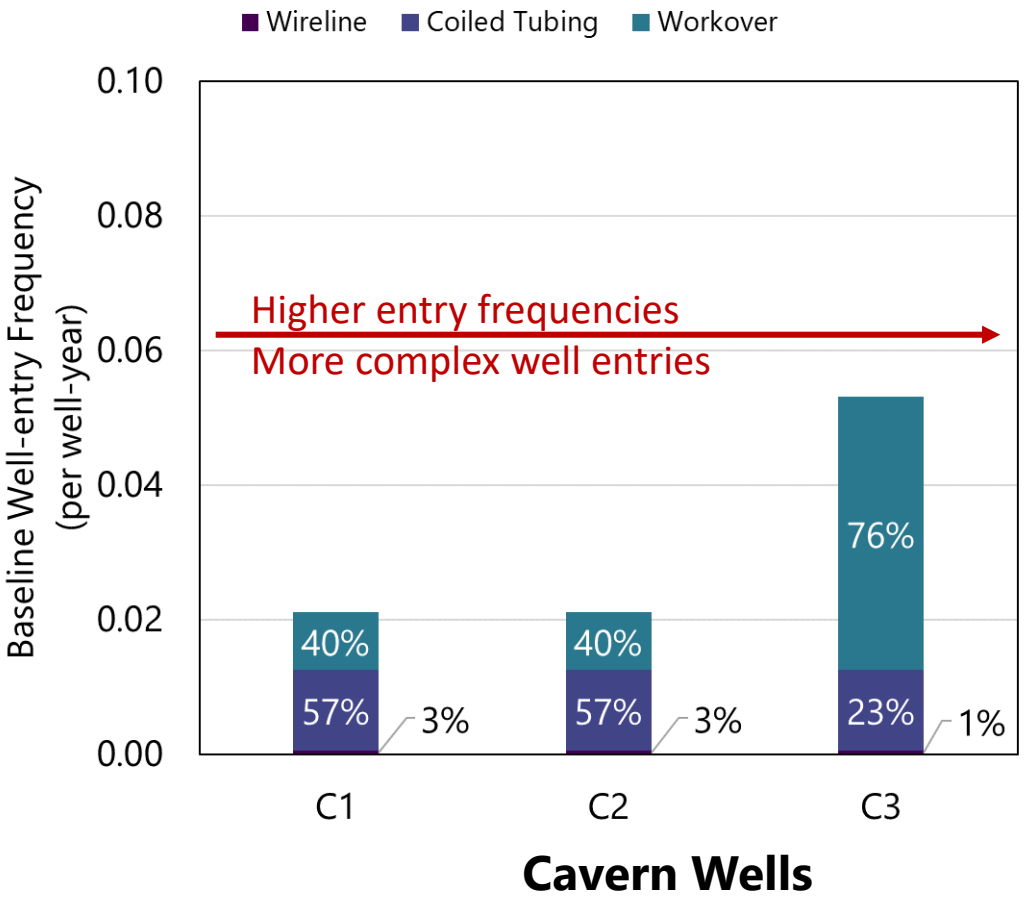
- Failure mode likelihood taken to be independent of entry type (UK HSE data)

Failure Mode	Mode Splits
Small Leaks	9%
Large Leaks	73%
Ruptures	18%

Frequency Estimation: Baseline Well Entry

- Frequencies from UGS industry data: API, AGA, INGAA & Project survey



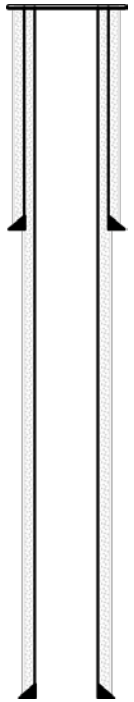


Frequency Estimation: Baseline Well-entry

Reservoir wells

$FoF_{well-entry}$: $2.4 \times 10^{-6} \frac{failures}{well-year}$

$SL = 2.1 \times 10^{-7}$
$LL = 1.7 \times 10^{-6}$
$RU = 4.2 \times 10^{-7}$



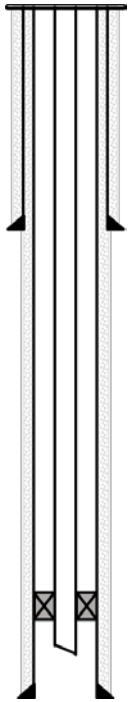
R1

$8.8 \times 10^{-6} \frac{failures}{well-year}$

4 times R1

$SL = 7.9 \times 10^{-7}$
$LL = 6.4 \times 10^{-6}$
$RU = 1.6 \times 10^{-6}$

4 times R1



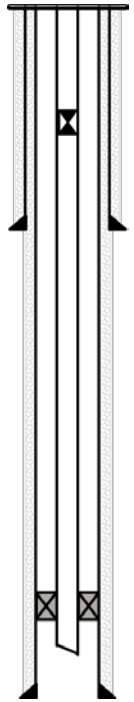
R2

$1.4 \times 10^{-5} \frac{failures}{well-year}$

6 times R1

$SL = 1.2 \times 10^{-6}$
$LL = 1.0 \times 10^{-5}$
$RU = 2.5 \times 10^{-6}$

6 times R1

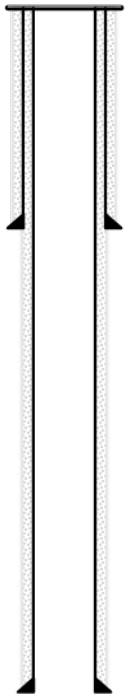


R3

Frequency Estimation: Baseline Well-entry

Cavern wells

$PoF_{well-entry}$: $2.4 \times 10^{-6} \frac{failures}{well-year}$

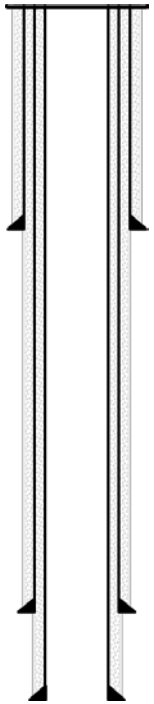


$SL = 2.1 \times 10^{-7}$
$LL = 1.7 \times 10^{-6}$
$RU = 4.2 \times 10^{-7}$

C1

$2.4 \times 10^{-6} \frac{failures}{well-year}$

Same as R1



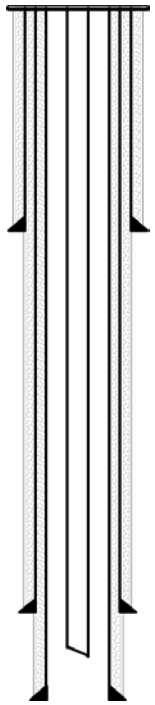
$SL = 2.1 \times 10^{-7}$
$LL = 1.7 \times 10^{-6}$
$RU = 4.2 \times 10^{-7}$

Same as R1

C2

$8.8 \times 10^{-6} \frac{failures}{well-year}$

4 times R1



$SL = 7.9 \times 10^{-7}$
$LL = 6.4 \times 10^{-6}$
$RU = 1.6 \times 10^{-6}$

4 times R1

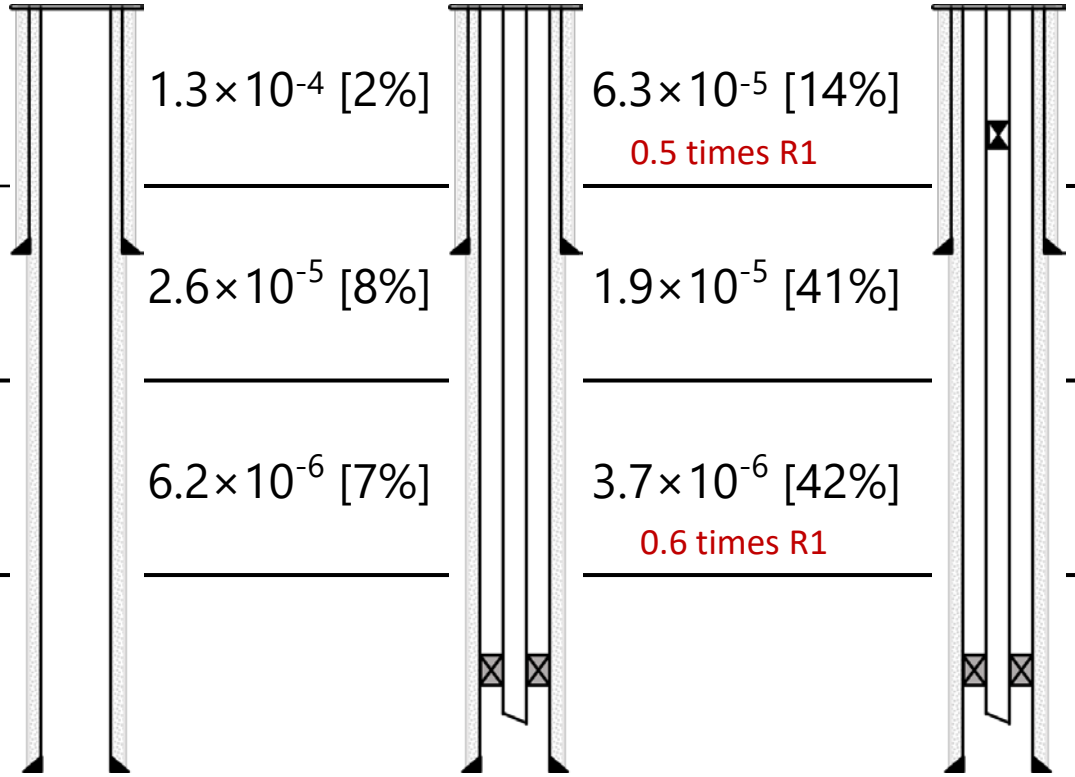
C3

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Frequencies: Operational + Baseline Well-Entry

Reservoir wells - failures per well year [% entry related]

Failure Modes	Failure Type	R1	R2	R3
Rupture + Large Leak+ Small Leak	Operational + Baseline entry	1.3×10^{-4} [2%]	6.3×10^{-5} [14%] 0.5 times R1	1.4×10^{-5} [97%] 0.1 times R1
Rupture + Large Leak	Operational + Baseline entry	2.6×10^{-5} [8%]	1.9×10^{-5} [41%]	1.3×10^{-5} [100%]
Rupture	Operational + Baseline entry	6.2×10^{-6} [7%]	3.7×10^{-6} [42%] 0.6 times R1	2.5×10^{-6} [100%] 0.4 times R1

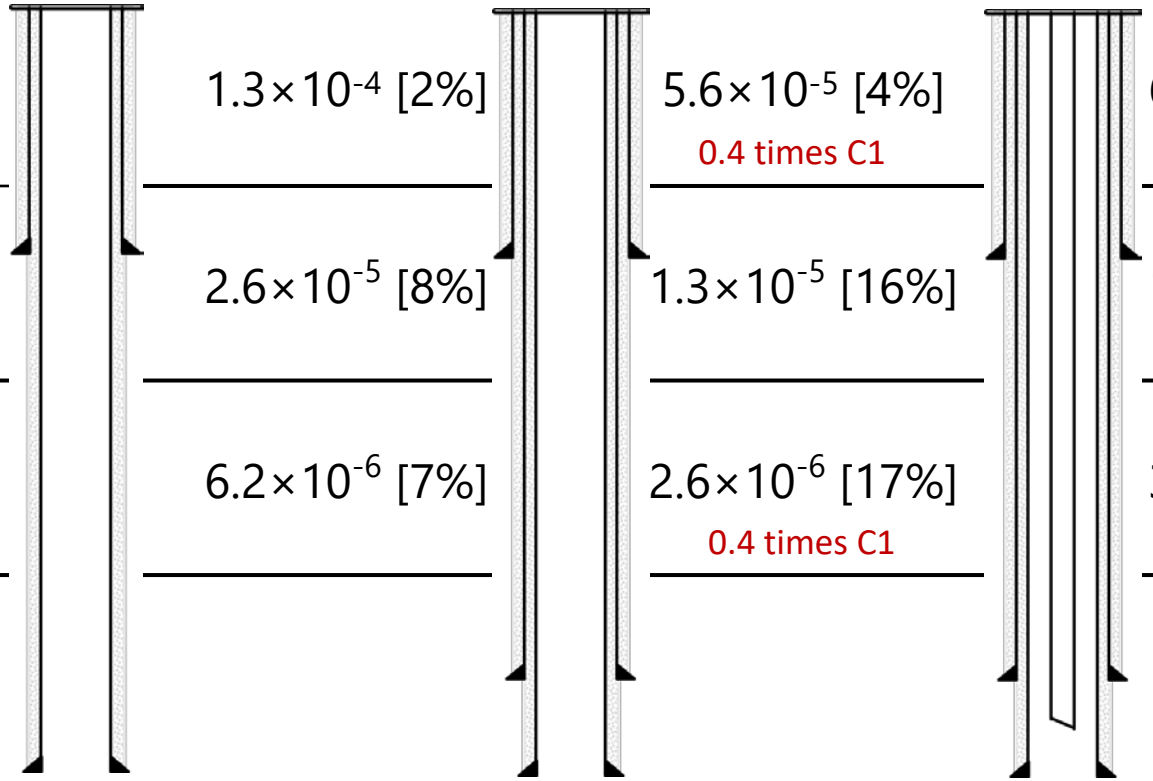


C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Frequencies: Operational + Baseline Well-Entry

Cavern well - failures per well year [% entry related]

Failure Modes	Failure Type	C1	C2	C3
Rupture + Large Leak+ Small Leak	Operational + Baseline entry	1.3×10^{-4} [2%]	5.6×10^{-5} [4%] 0.4 times C1	6.2×10^{-5} [14%] 0.5 times C1
Rupture + Large Leak	Operational + Baseline entry	2.6×10^{-5} [8%]	1.3×10^{-5} [16%]	1.9×10^{-5} [42%]
Rupture	Operational + Baseline entry	6.2×10^{-6} [7%]	2.6×10^{-6} [17%] 0.4 times C1	3.7×10^{-6} [42%] 0.6 times C1



Consequences Measures and Estimation

- **Life Safety Consequences** – Chance of fatality caused by exposure to thermal radiation from an ignited gas release, given well failure and gas ignition
  - Thermal radiation intensity dependent on gas release rate
    - Use models for estimating release rate as a function of failure pathway characteristics
  - Chance of fatality dependent on thermal radiation intensity and exposure duration
    - Use models for estimating fatality likelihood as function of release rate and distance from well

- **Environmental Consequences** – Long term impact resulting from global warming potential of greenhouse gas release, given well failure
  - Impact proportional to volume released
  - Release volume is dependent on release rate and release duration
    - Same as models used for estimating release rate for safety consequence estimation
    - Use historical data and simple statistical models to estimate release duration

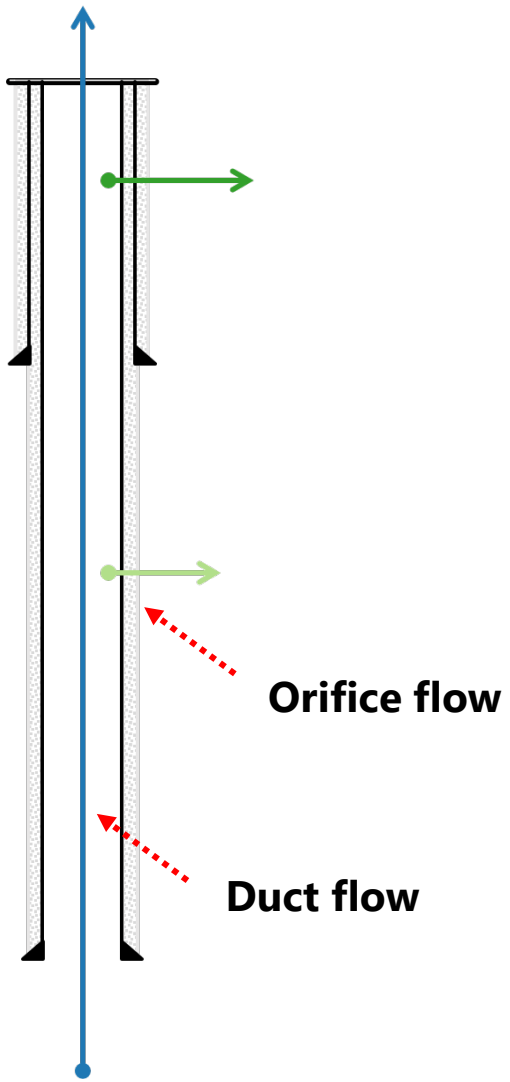
C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Consequences: Release Rate Estimation

- Release rate depends on the failure pathway between the cavern/reservoir and the atmosphere

- Idealize each flow pathway as series of ducts and orifices
  - **Duct flow -** Modeled with an adiabatic compressible flow
  - **Orifice flow -** Modeled as choked flow through an orifice

- Modeling approach:
  - **Simplified method -** Flow through each component calculated separately assuming flow driven by effective cavern/reservoir pressure and limiting (minimum) release rate is taken as release rate for pathway under consideration



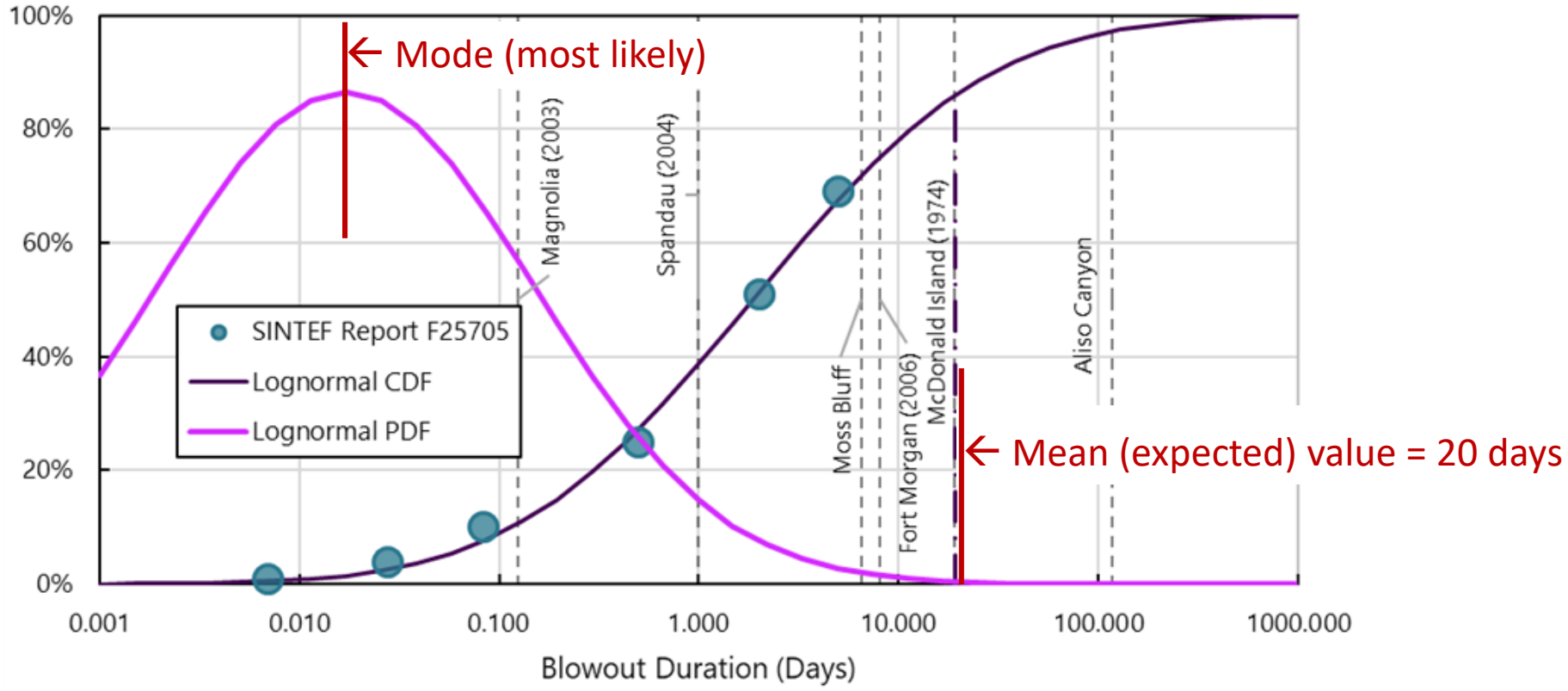
C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Consequences: Release Rates and Well Deliverability Considerations

Flow Path	Failure Mode	Orifice Diameter (mm)	Release Rate (kg/s)
Wellhead release (flow through tubing)	*Small Leak*	*1*	0.012
	Large Leak	*11*	1.5
	Rupture	*110*	29 (25)
Casing hole release	*Small Leak*	*2*	0.048
	Large Leak	*18*	3.9
	Rupture	*44*	24
Wellhead release (flow through casing)	*Small Leak*	*2*	0.048
	Large Leak	*18*	3.9
	Rupture	*180*	90 (55)

- Release rates in parenthesis are reduced to account for reservoir flow throttling due to reservoir deliverability limit as determined from IPR curve for typical well with 350 MMSCF open flow
- Initial flow from reservoir wells not limited by reservoir deliverability to the same degree as longer-term releases
  - unlimited flow rates used to assess safety-risk (for all wells)
  - deliverability-limited flow rates used to assess environmental risk where applicable (for reservoir wells only)

Consequences: Release Duration

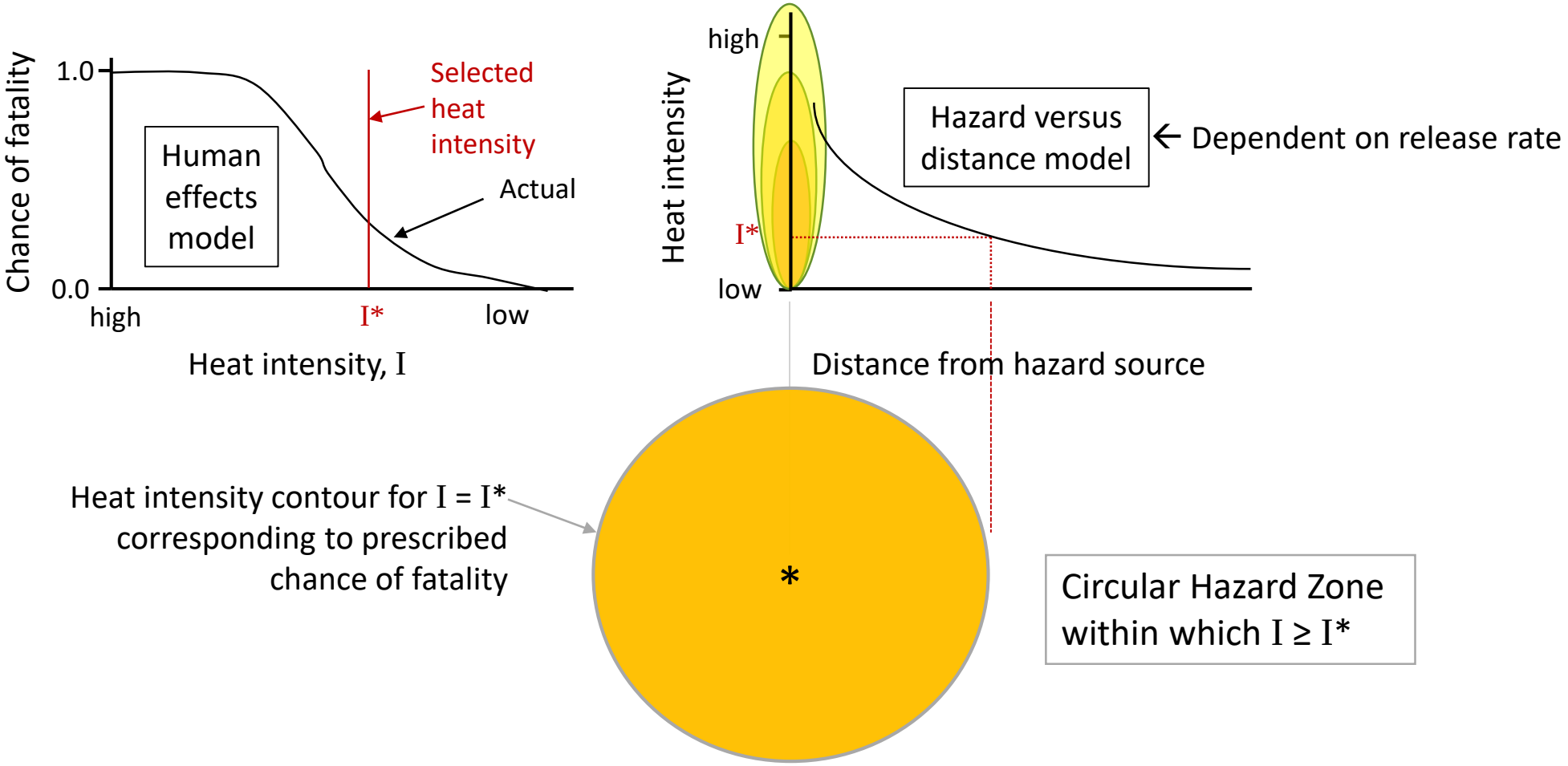


The expected release duration determined by 'distribution fitting' to historical release duration data

- Distribution is heavily skewed log-normally: mean >> mode

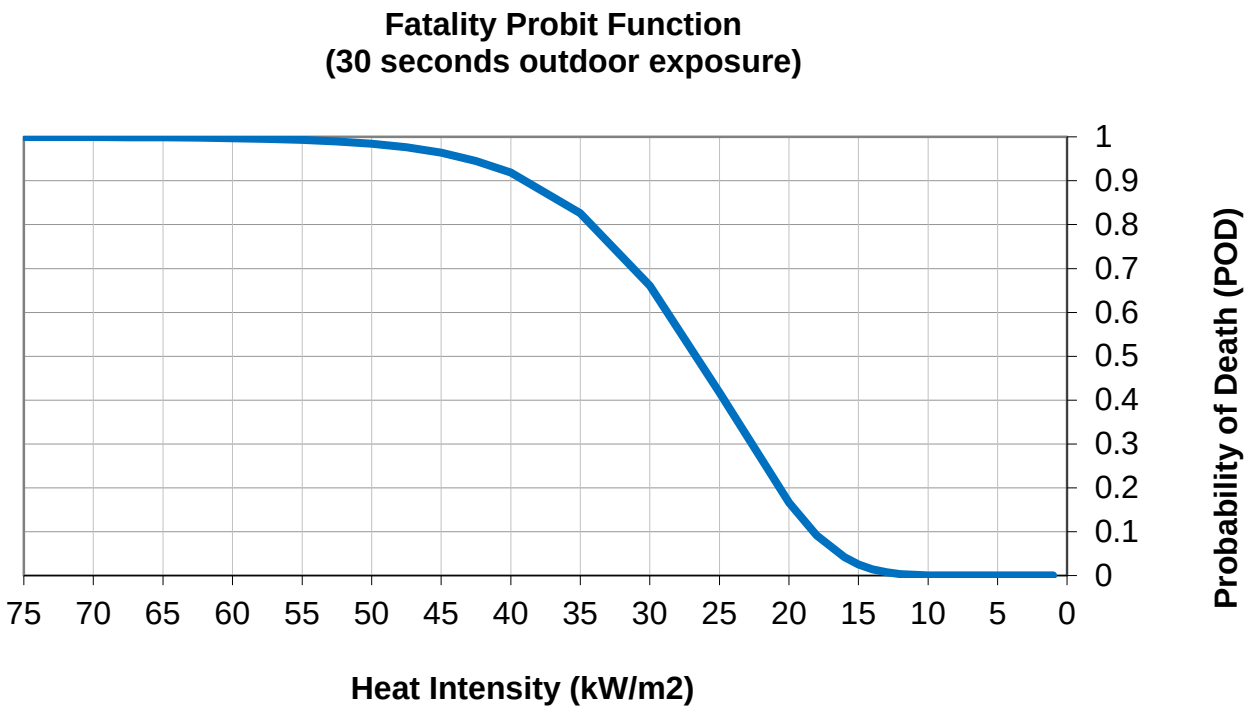
Safety Consequence Modeling: General Approach

Thermal radiation hazard resulting from gas jet ignition



Safety Consequence Modeling: Probability of Death (POD)

- **Human effects model** - chance of fatality as a function of radiation intensity at location of interest



Safety Risk Estimation

- Location Specific Individual Risk

$$LSIR = \sum_{i=1}^{n} \sum_{j=1}^{m} FOF_{ij} \text{ x } POI_{ij} \text{ x } POD_{ij}$$

where: FOF_{ij} = frequency of failure of pathway *i* by mode *j*

POI_{ij} = probability of ignition, given failure of pathway *i* by mode *j*

POD_{ij} = probability of death at point of interest, given failure of pathway *i* by mode *j* *and* ignition

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Probability of Ignition (POI)

Release Rate (kg/s)	Probability of Ignition	
	Operational	Well-entry
<1	1%	5%
1 to 50	3%	15%
>50	10%	50%

- **Operational** – POI values from UKOAA study
- **Well-entry** – Operational POIs increased by factor of 5 to account for increased ignition sources in vicinity of well during well entry*

**based on GRI well risk study which suggests significant UGS well releases have a POI of ~50%*

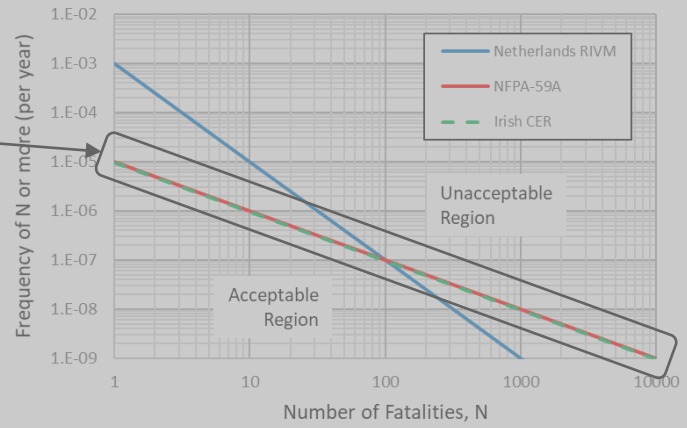
Safety Risk Acceptance Criteria

Based on C-FER review of relevant criteria from various jurisdictions and industries suggested criteria are:

- Individual Risk - threshold level for Personal IR*
  - 10^{-6} to 10^{-5} per year (subject to land use considerations and well status, e.g. new vs existing)

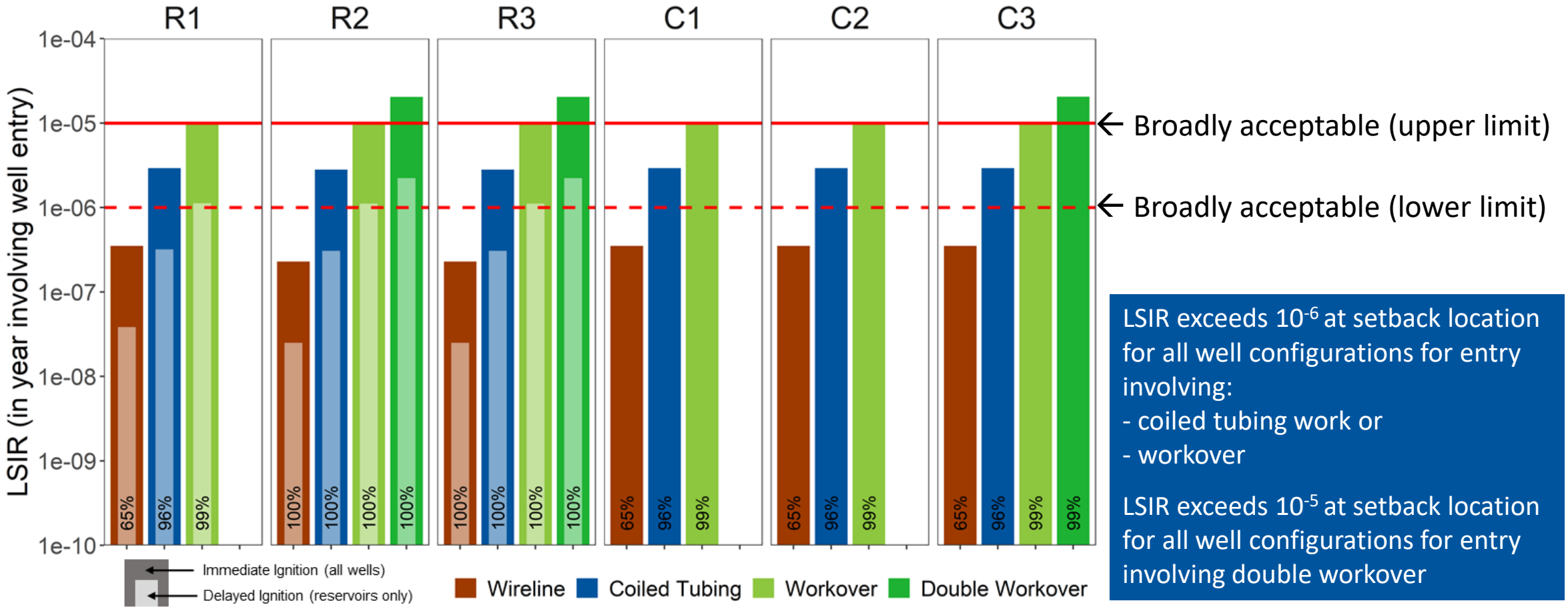
    **conservative for evaluating LSIR*

- Societal Risk – threshold F-N curve
  - Adopt NFPA 59A curve



Safety Risk : Location Specific Individual Risk

- LSIR for each well configuration by entry type – 30 m (100 ft) setback

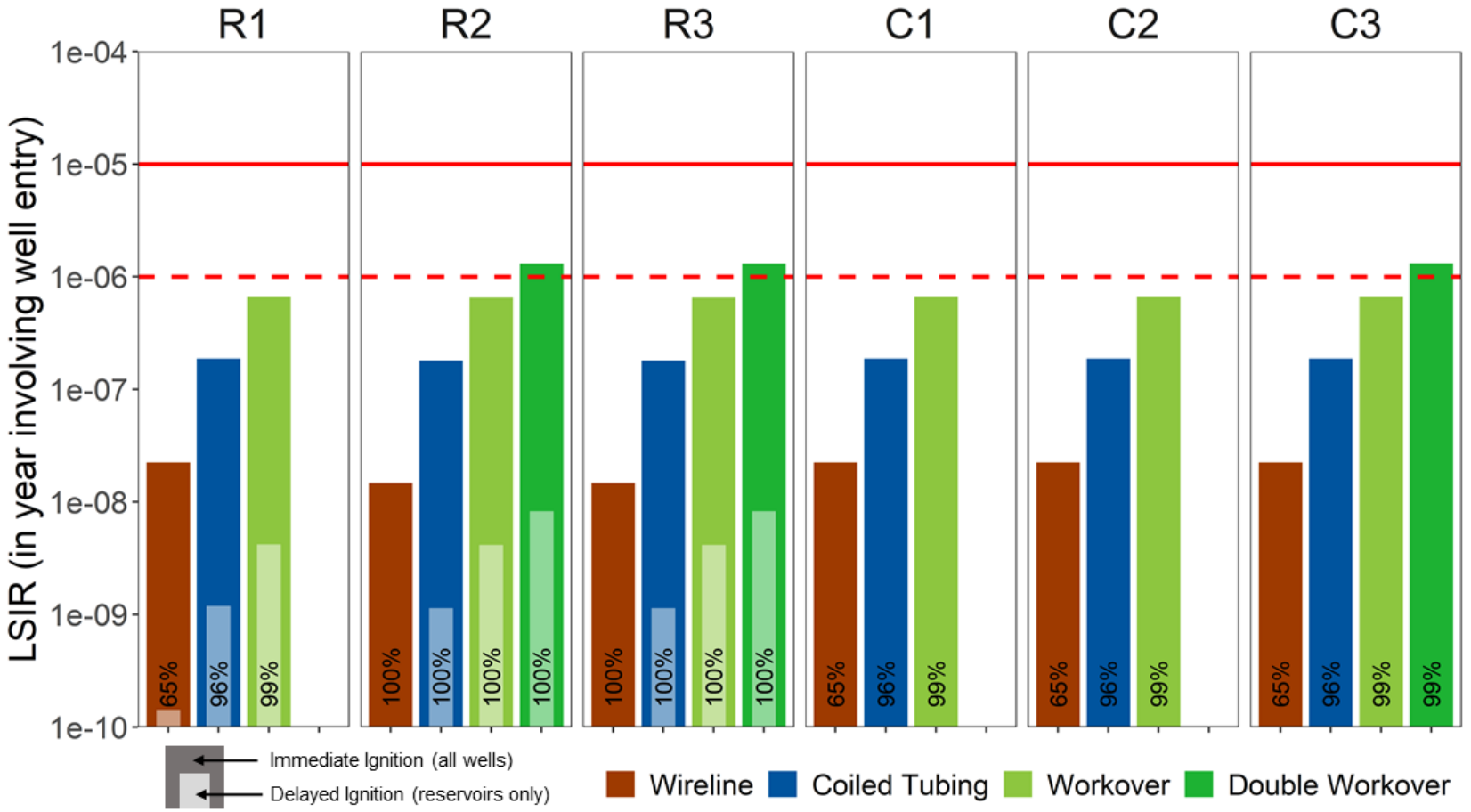


LSIR exceeds 10^{-6} at setback location for all well configurations for entry involving:
- coiled tubing work or
- workover

LSIR exceeds 10^{-5} at setback location for all well configurations for entry involving double workover

Safety Risk : Location Specific Individual Risk

- LSIR for each well configuration by entry type – 40 m (130 ft) setback



← Broadly acceptable (upper limit)

← Broadly acceptable (lower limit)

LSIR under 10^{-6} at setback location for all well configurations <u>except</u> for entry involving double workover

LSIR under 10^{-5} at setback location for all well configurations

Risk level very sensitive to setback distance

Environmental Risk Estimation

- Expected annual release volume

$$V_{release} = \sum_{i=1}^{n} \sum_{j=1}^{\mathrm{m}} FOF_{ij} \times Rate_{ij} \times Duration_{ij}$$

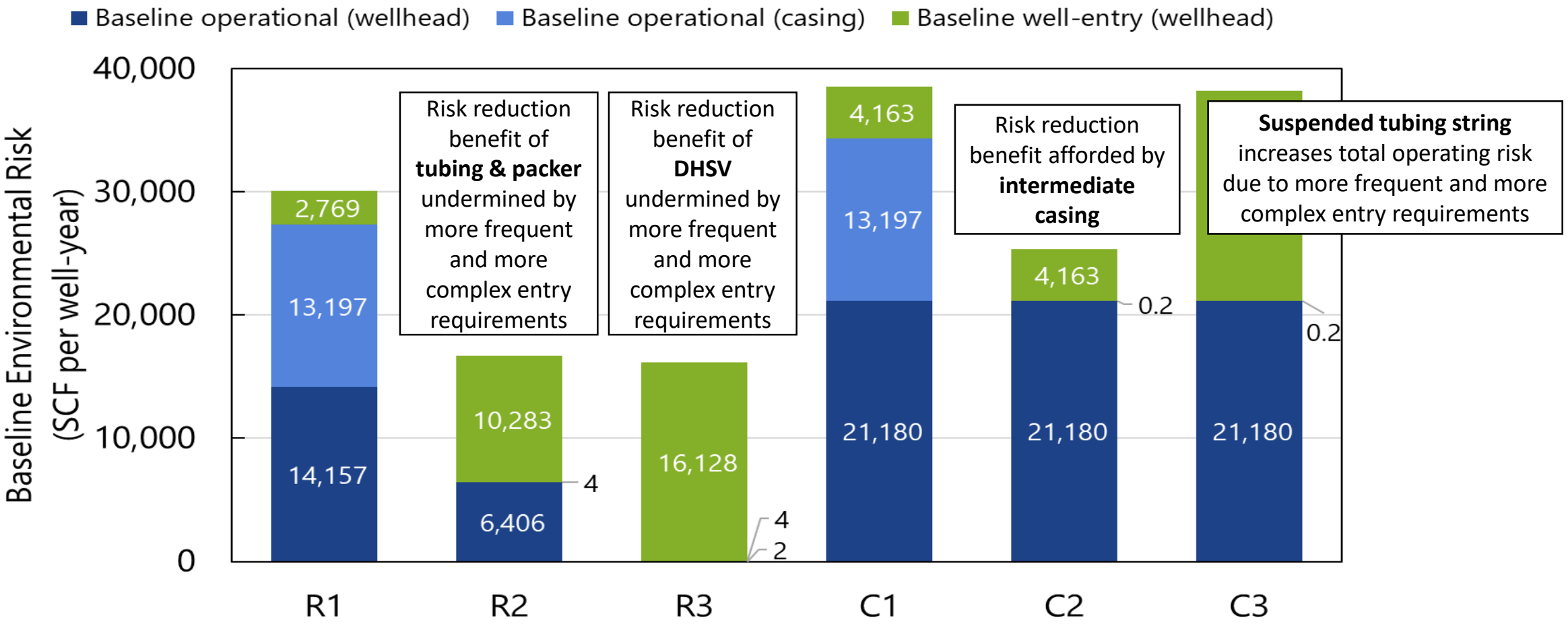
where: FoF_{ij} = frequency of failure of pathway *i* by mode *j*

$Rate_{ij}$ = rate of gas release, given failure of pathway *i* by mode *j*

$Duration_{ij}$ = duration of gas release, given failure of pathway *i* by mode *j*

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Risk Estimation: Environmental Risk



Integrity Management Through Additional Well Entry

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Well Entry Scenarios Evaluated

R1 and C1 – single barrier casing (no tubing)
R2 – double barrier casing (tubing in place)

Case	Intent	Well config.	Inspection entry type	Well condition	Condition	Action taken	Benefit
1	Casing inspection	R1 and C1 R2	Wireline Workover	Typical	Typical	None	None
2a	Casing inspection and repair	R1 and C1 R2	Wireline Workover	Typical	Typical	Casing repair	Casing POF reduced by factor of 10 to 0.1 x typical
2b	Casing inspection and repair	R1 and C1 R2	Wireline Workover	Casing POF 10 x typical		Casing repair	Casing POF reduced by factor of 100 to 0.1 x typical
3	Wellhead replacement	R1 and C1 R2	N/A N/A	Typical	100% 100%	Wellhead replacement	Wellhead POF reduced by factor of 10 to 0.1 x typical

Additional considerations

- Well entry failure rates (multipliers on IOGP rates: 4.0×10^{-4} workover, 1.1×10^{-4} coiled tubing, 9.0×10^{-6} wireline)
  - 1.0 x IOGP (2 x base case)
  - 0.5 x IOGP (base case)
  - 0.25 x IOGP (1/2 x base case)
  - 0.1 x IOGP (1/5 x base case)
- Integrity benefits evaluated over 2, 5, 10 and 20 yr periods (assuming benefit sustained for period duration)

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Cumulative Risk Evaluation

Operational risk + Baseline well entry + Periodic Integrity-related well entry

For evaluation periods = 2, 5, 10 and 20 yrs

Baseline risk evaluated previously in terms of annual risk

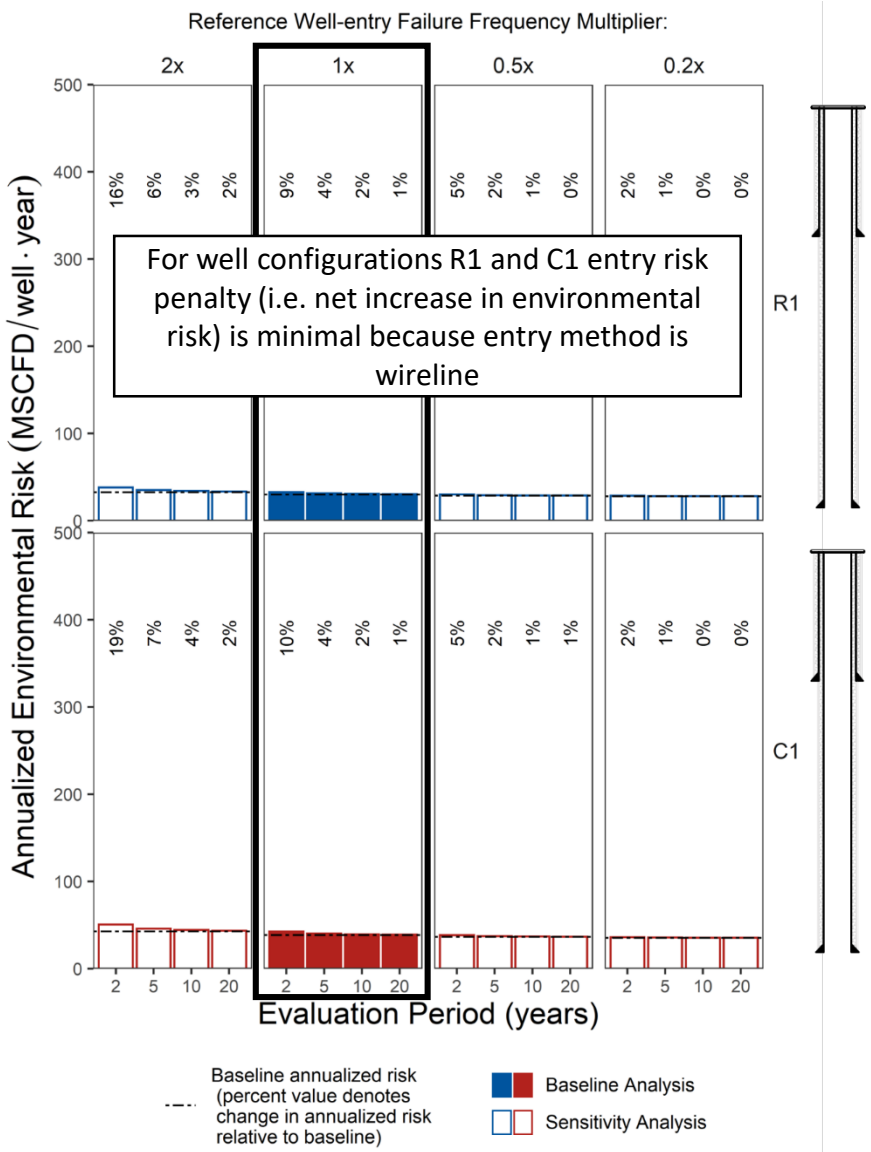
Evaluated in following examples in terms of cumulative risk over evaluation period
(annualized to enable comparison of scenarios with different evaluation periods)

Well Entry Scenarios: Cumulative Risk

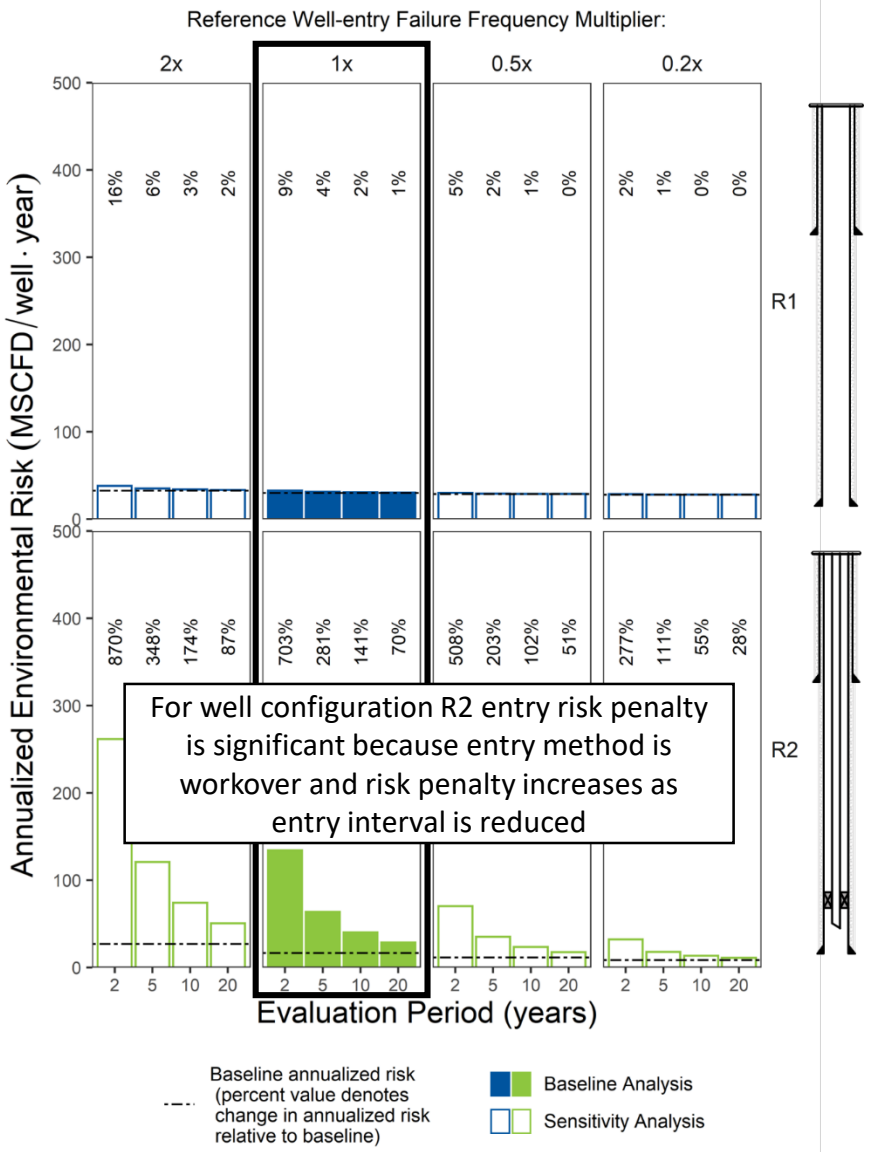
Example Case 1

- Well entry for casing inspection assuming typical casing integrity (i.e. casing POF = baseline)
- No remediation performed
- Evaluation period analogous to reinspection interval

$$\text{Annualized Risk} = \frac{\sum_i^n Annual\ Risk}{Evaluation\ Period}$$



For well configurations R1 and C1 entry risk penalty (i.e. net increase in environmental risk) is minimal because entry method is wireline



For well configuration R2 entry risk penalty is significant because entry method is workover and risk penalty increases as entry interval is reduced

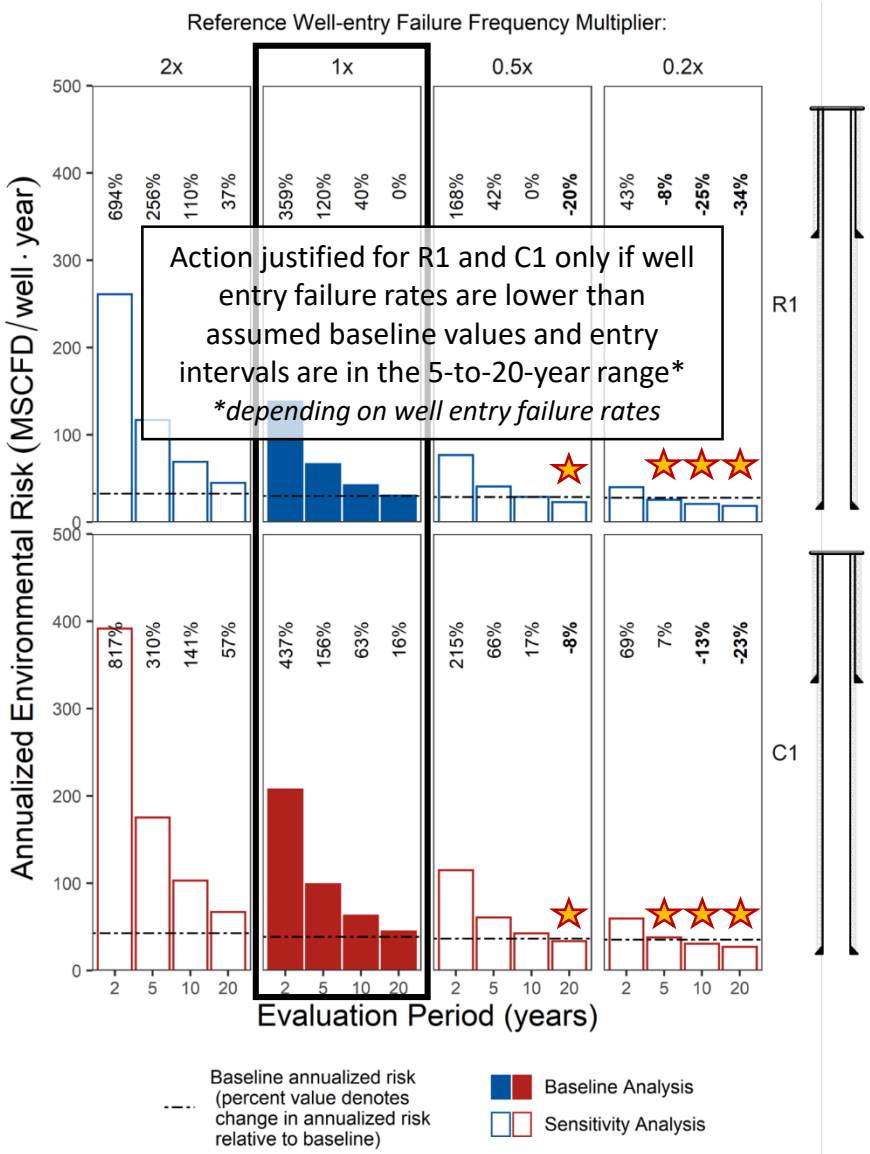
Well Entry Scenarios: Cumulative Risk

Example Case 2a

- Well entry for casing inspection assuming typical casing integrity (i.e. casing POF = baseline)
- Casing remediation performed (i.e. casing POF = 0.1 times baseline)
- Evaluation period analogous to reinspection interval

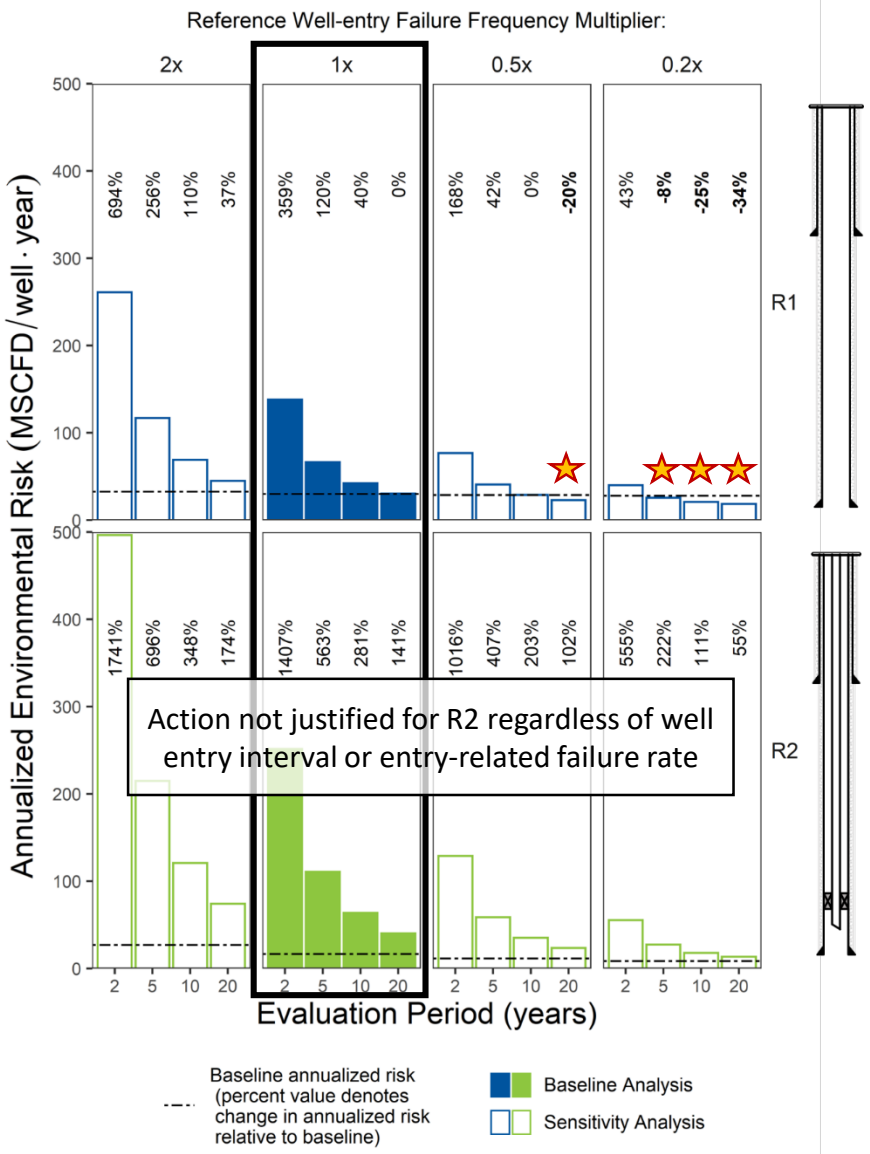
★ - Outcomes yielding net reduction in environmental risk

$$\text{Annualized Risk} = \frac{\sum_i^n \textit{Annual Risk}}{\textit{Evaluation Period}}$$



Action justified for R1 and C1 only if well entry failure rates are lower than assumed baseline values and entry intervals are in the 5-to-20-year range*

**depending on well entry failure rates*



Action not justified for R2 regardless of well entry interval or entry-related failure rate

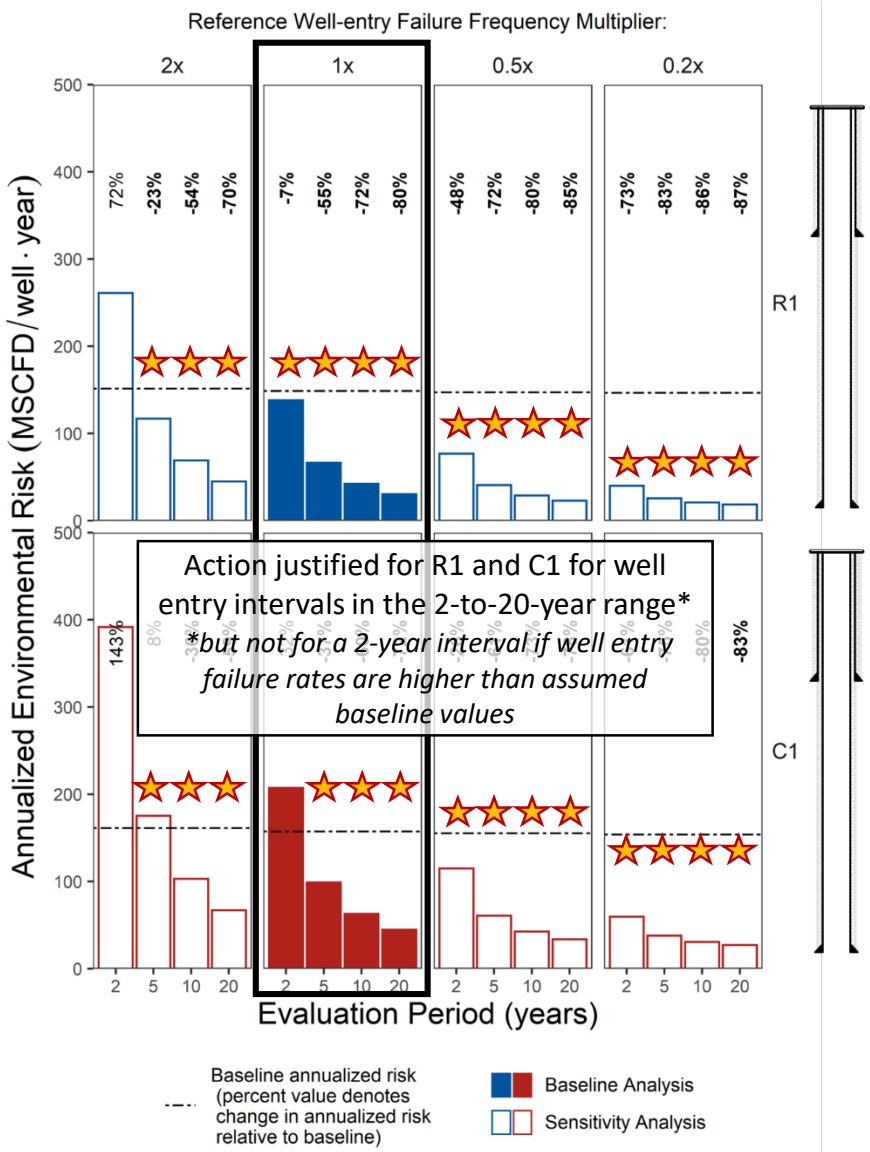
Well Entry Scenarios: Cumulative Risk

Example Case 2b

- Well entry for casing inspection assuming poor casing integrity (i.e. casing POF = 10 times baseline)
- Casing remediation performed (i.e. casing POF = 0.1 times baseline)
- Evaluation period analogous to reinspection interval

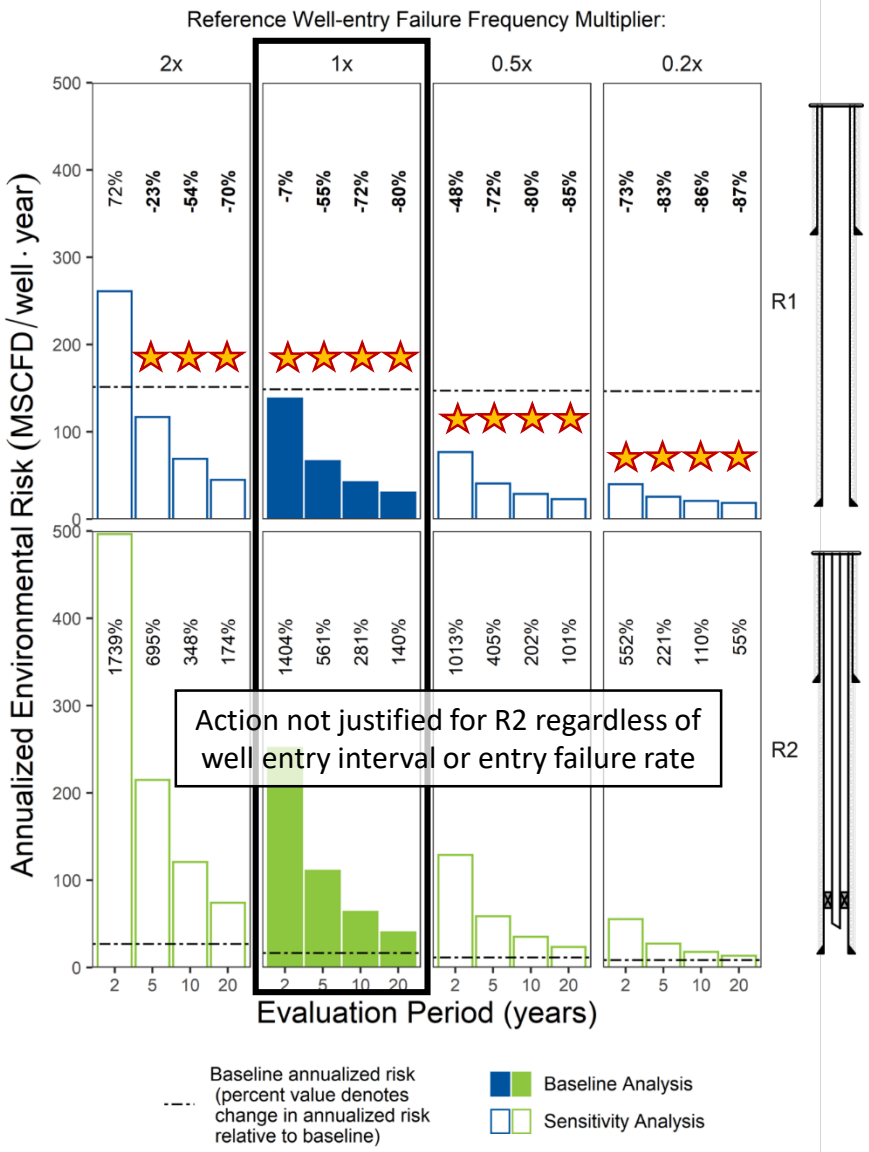
★ - Outcomes yielding net reduction in environmental risk

$$\text{Annualized Risk} = \frac{\sum_i^n \textit{Annual Risk}}{\textit{Evaluation Period}}$$



Action justified for R1 and C1 for well entry intervals in the 2-to-20-year range*

**but not for a 2-year interval if well entry failure rates are higher than assumed baseline values*



Action not justified for R2 regardless of well entry interval or entry failure rate

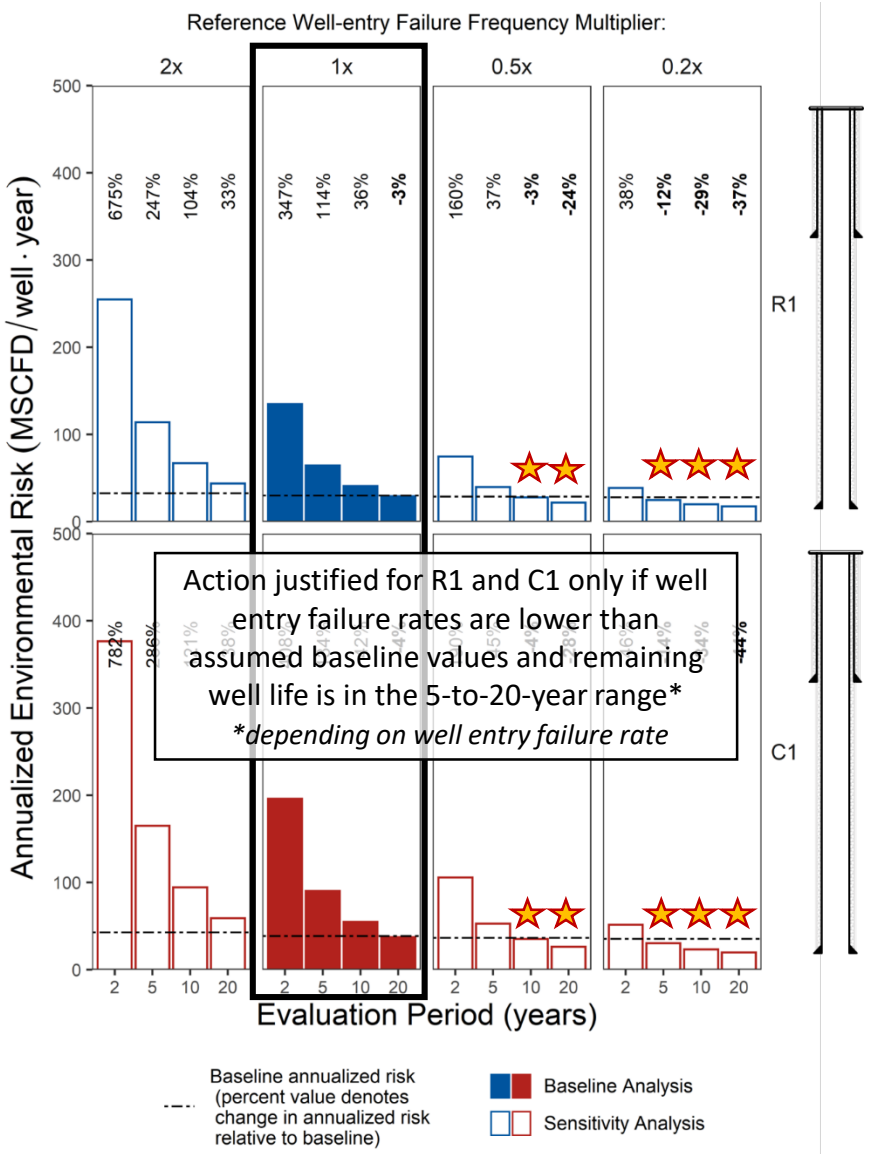
Well Entry Scenarios: Cumulative Risk

Example Case 3

- Well entry for wellhead replacement (assumed wellhead POF = baseline)
- Replacement wellhead installed (wellhead POF = 0.1 times baseline)
- Evaluation period analogous to remaining well life

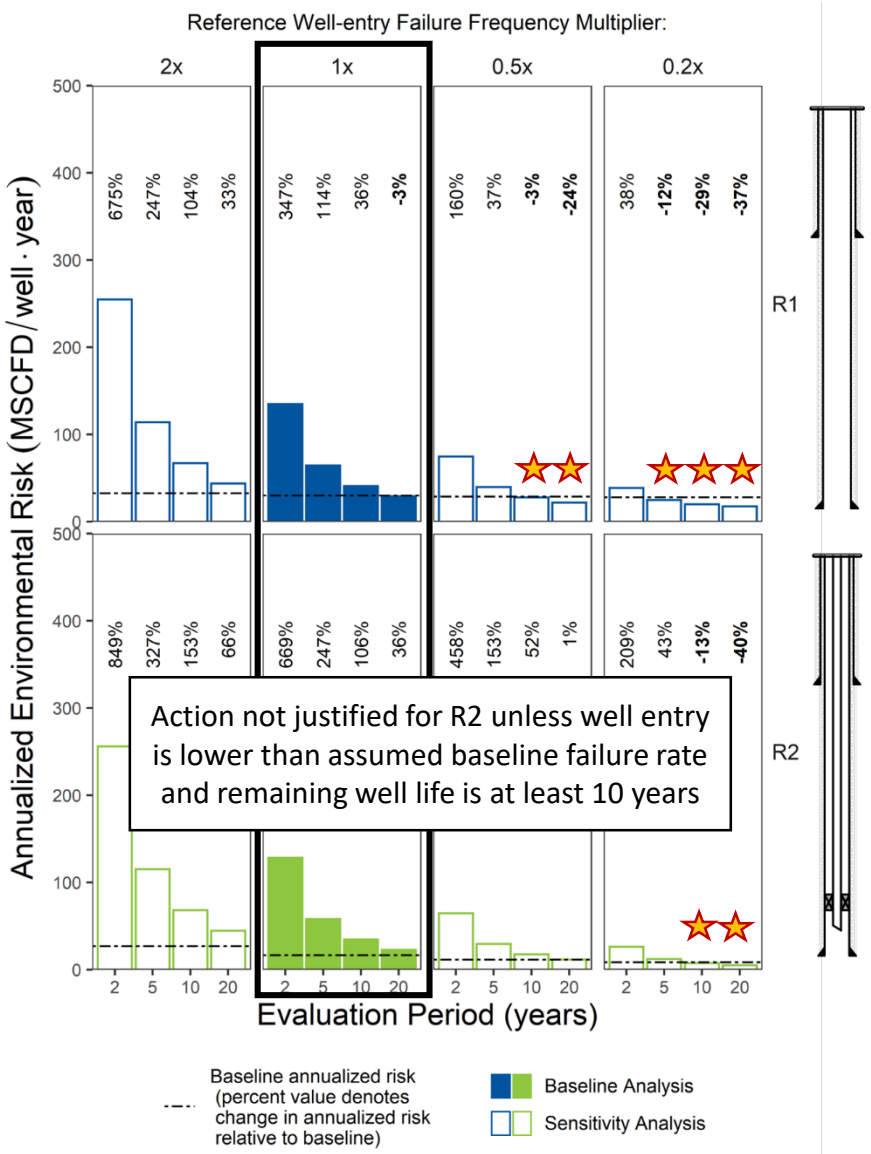
★ - Outcomes yielding net reduction in environmental risk

$$\text{Annualized Risk} = \frac{\sum_i^n \textit{Annual Risk}}{\textit{Evaluation Period}}$$



Action justified for R1 and C1 only if well entry failure rates are lower than assumed baseline values and remaining well life is in the 5-to-20-year range*

**depending on well entry failure rate*



Action not justified for R2 unless well entry is lower than assumed baseline failure rate and remaining well life is at least 10 years

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Key Findings from Demonstration Analyses

General

- Results highlight sensitive of findings to the failure probabilities for key well components and activities
  - Wellhead failure during operation and well entry
  - Production casing failure during operation (if it is the only downhole barrier)
- Cavern wells can be associated with higher safety and environmental risk levels than reservoir wells
  - Designed for higher operating flow rates so release rates resulting from well failure are similarly higher
  - No flow throttling due to reservoir deliverability limits
  - Higher flow rates → greater failure consequences

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

Key Findings from Demonstration Analyses

Well Safety Risk – for typical UGS wells

- Wells do not pose an acute safety risk to public unless routinely occupied locations are near wellhead
- Modest setback distances can achieve broadly acceptable levels of safety risk
  - Explicit guidance required to define appropriate setback distances that adequately account for impact of key well attributes on hazard zone size (i.e. casing diameter, well depth and gas storage pressure)
    - Guidance could consist of a variation on the PIR formula currently used for identifying HCAs for pipelines (the PIR model for pipelines can be adapted to UGS wells by revising the gas release rate model)
- Highest contributor to annual safety risk is well entry, particularly entry events involving a workover
  - Additional precautions (i.e. temporary setbacks) during workovers for existing wells in proximity to occupied areas may be warranted

Key Findings from Demonstration Analyses

Well Entry Risk

- Well entry for integrity management purposes is most beneficial if efforts target components that serve as single barriers to gas release
  - The wellhead or the production casing when used without intermediate casing or production tubing
- Periodic well entry for inspection and remediation of production casing, when it is the sole downhole barrier, is difficult to justify on a frequent basis unless casing condition known to be poor
  - Remediation work if performed should maximize the time to next inspection
- Periodic well entry for inspection and remediation of production casing, when it is not the sole downhole barrier, is difficult to justify in typical situations
  - May become more justifiable, particularly for casing integrity confirmation in wells employing production tubing, when reliable casing integrity evaluation can be performed without removal of the tubing string
- Well configurations that support well entry for inspection and remediation by means other than a workover are generally associated with lower life cycle operating risk

C-FER Technologies
A SUBSIDIARY OF ALBERTA INNOVATES

This research was funded under the Department of Transportation, Pipeline and Hazardous Materials Safety Administration's Pipeline Safety Research and Development Program.

The views and conclusions contained in this presentation are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Pipeline and Hazardous Materials Safety Administration, or the U.S. Government.