Webinar – Part 1

Overview of Risk Assessment Guidelines contained in

Risk Assessment and Treatment of Wells
PHMSA Project DTPH56-17-RA-00002

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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
Intended Use of Guidelines

• By operators – to guide the selection, development and application of analysis methods and models for the assessment and management of well entry risk

• By regulators – to support evaluation of the suitability of the QRA methods and models develop and used by UGS well operators
Background to Guideline Development

The development process involved:

• Industry survey to enhance understanding
  – well configurations and key components
  – Well entry methods and reasons for entry
  – Industry concerns with development and application of risk-based methods

• Review of the application of risk in a range of industries
  – Underground storage
  – Other
    • Pipelines
    • Offshore oil & gas
    • Nuclear power generation
    • Power transmission
    • Aviation
Qualitative versus Quantitative Risk

• Defining characteristics of **Qualitative** Risk Methods
  – Risk is characterized using a **qualitative scale**
    • Involves **user-defined** parameters (e.g. Descriptive → low/medium/high, or Index values → between 1 and 10)
  – Both likelihood and consequences **ranked** on qualitative scales
  – Risk calculation is **context-specific** (based on developer’s judgment)
  – Risk estimate is relative and approach-specific (**subjective**)

• Defining characteristic of **Quantitative** Risk Methods
  – Risk is characterized on a **quantitative scale**
    • Consequences **quantified** by measurable loss parameters (e.g. lives lost, gas volume released)
    • Likelihood **quantified** by a mathematical probabilities or annual frequencies
  – Risk calculation yields expected value of loss, meaning is **universal** (based on probability logic)
  – Risk estimate is independently meaningful (**objective**)
Subjective versus Objective

<table>
<thead>
<tr>
<th>Information</th>
<th>Subjective</th>
<th>Objective</th>
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<tbody>
<tr>
<td>Risk measure</td>
<td>Qualitative</td>
<td>Quantitative</td>
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**Risk estimate**

- **Qualitative**
  - Typically based on subjective judgment (e.g. SMEs)
  - Objective data and models can provide guidance

- **Quantitative**
  - Can utilize subjective judgment and/or objective information
  - Typically maximize the use of objective data and models, but subjective judgment cannot be eliminated

Guidelines focus on Quantitative Risk Assessment (QRA)

Preferred basis for decision-making

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Risk Assessment Guidelines

The QRA Process

- Objectives
- Model Selection
- Data Collection
- Risk Assessment
- Documentation

Risk Assessment

- Well Definition
- Threat Identification
- Well Entry Scenario Definition
- Frequency Estimation
- Consequence Estimation
- Risk Estimation
- Risk Evaluation

Assessment Criteria
Risk Assessment Steps

1. **Well definition**: Define the configuration, including individual components that constitute barriers to gas releases for all credible gas release pathways

2. **Threat identification**: Identify applicable threats to well barrier component integrity during normal well operation

3. **Well entry scenario definition**: Define well entry activities to be evaluated and their intended impact on operational integrity of well components

4. **Frequency and consequence estimation**: Estimate failure frequencies and failure consequences during normal well operation before and after well entry, and during well entry

5. **Risk estimation**: Estimate required risk measures using the calculated failure frequencies and failure consequences

6. **Risk evaluation**: Compare results obtained from risk estimation to appropriate acceptance criteria where available, or compare to results obtained from analysis of alternative well entry scenarios
1. Well Definition - Pathway Identification

• The key to well risk estimation is identifying and characterizing credible gas release pathways

• Each pathway characterized by:
  – Likelihood that the pathway opens
  – Consequences of pathway opening

• Total well risk is calculated as the sum of the risks from all credible pathways

• Complicating factor - each pathway barrier can fail in different modes; and therefore many unique combinations of release rates and durations are possible depending on number of barriers and barrier failure sequence
2. Threat Identification

Good guidance provided in API 1171

- Failure of mechanical equipment
- Corrosion- or erosion-induced failure of casing or tubing string and associated mechanical connectors
- Unintentional damage to wellhead
- Intentional damage to wellhead
- Weather-related damage to wellhead
- Outside force damage to downhole components, particularly the well casing
- Incorrect well operation and maintenance activities ← Including well entry
3. Well Entry Scenario Definition

The act of well entry constitutes a threat to well integrity
• Involves the temporary reconfiguration and/or addition of well components
• Temporary well configurations could failure during the well entry process

Reasons for well entry
• Monitoring or enhancing well production,
  • Performing well integrity diagnostics,
  • Repairing/replacing downhole or wellhead components
• Changing production or injection zones,
• Well suspension, or well abandonment

These actions can enhance operational reliability, but the act of entry introduces additional risk
3. Well Entry Scenario Definition

Entry scenarios defined in terms of:

• Type of entry
  – Wireline (including wireline or slickline operations)
  – Coiled tubing work
  – Work over (snubbing unit, drilling rig or service unit)

• Frequency of entry
  – One off
  – As required
  – Prescribed interval

• Intended outcome
  – How will it affect well operating risk

More frequent entry → higher entry-related well failure risk

- Increasing complexity/invasiveness
- Increasing chance for human error
- Increasing failure risk

Key consideration in decision making with respect to well entry
4. Frequency and Consequence Estimation

• Recall that key to UGS well risk estimation is identifying and characterizing all credible release pathways

• Each pathway characterized by:
  – The likelihood that the pathway opens
    • Depends on # of pathway barriers and failure frequency of individual barriers
  – The consequences of pathway opening
    • Depends on release rate and release volume
Frequency Estimation

• Data sources – for component or system failure frequencies
  – SME opinion
  – Historical data
  – Probabilistic models

• Models – for component failure frequency aggregation
  – Fault tress
  – Directed graphs
  – Bayesian networks
Data Sources

- SME opinion
  - Elicit information from subject matter experts
  - Translate knowledge and experience into frequency estimates

- Historical data
  - Frequency estimates based on past incident data, with or without ‘adjustments’

- Probabilistic models
  - Combine well component condition data and structural reliability methods to estimate component failure frequencies
SME Opinion

Advantages
• Limited implementation effort required
• Relatively simple process (structured approaches available for elicitation)
• Ability to leverage existing well specific knowledge and compensate for information gaps through experience

Disadvantages
• Uncertainty is high due to subjective nature of information obtained
• Lack of consistency in results obtained
• Not suitable for evaluating new or emerging threats
• Generally not be suitable for evaluating the effect of mitigation measures
Historical Data

• Approaches
  – Historical failure rates from incident databases
    • Failure rate = # incidents / [(# components) x (years of exposure)]
  – Historical failure rates with adjustment factors
    • Introduce multiplicative factors to account for individual well characteristics
    • Development of factors
      – SME opinion
      – Statistical and analytical methods
**Advantages**
- Limited implementation effort
- Higher confidence in results due to their empirical basis
- Repeatability
- Some ability to develop more well-specific estimates (i.e. with adjustment factors)

**Disadvantages**
- Generic incident data yields average failure frequency estimates
- More well-specific estimates require adjustments (often subjective) which increase uncertainty
- Generally not be suitable for evaluating effect of mitigation measures
- Not suitable for assessing new and emerging threats
- May not reflect future system or component performance (e.g. deterioration effects)
• Structural reliability methods
  – Uses engineering models that define conditions that result in component failure
  – Input parameters defined as distributions
  – Numerous generic software options
  – Examples
    • Monte Carlo simulation
    • FORM/SORM
Probabilistic Models

Advantages

• Directs data collection effort towards measurable parameters (e.g. casing wall loss)
• Results are well-specific
• Can address rare and emerging threats
• Can project failure frequency into the future based on damage growth projections
• Can reflect impact of specific integrity maintenance actions (e.g. casing corrosion repairs)

Disadvantages

• Appropriate engineering models are required
• Significant effort to characterize inputs
• Requires greater computational resources
• Some reliability analysis expertise required
• Complexity of models may lead to skepticism regarding results
Frequency Aggregation Models

• For complex systems where system failure can require concurrent failure of multiple components, various models are available:
  – Fault Trees
  – Directed Acyclic Graphs
  – Bayesian Networks

• All convey logical relationships or dependencies between events/parameters

• Each provides a different visual representation
Advantages

- **Fault Trees**
  - Well established approach offering a clear representation of component failures that lead to a release event
  - Generic software tools available for constructing and solving

- **Directed Acyclic Graphs**
  - Provide a clear and intuitive visual representation of all possible flow pathways
  - Can accommodate multiple failure modes and mode combinations within a given pathway
  - Generic software tools available for constructing and solving

- **Bayesian Networks**
  - A form of directed acyclic graph that accommodates more general probabilistic relationships
  - Can accommodate component dependencies based on multiple information sources (qualitative and quantitative)

Disadvantages

- **Fault Trees**
  - Do not accommodate multiple modes of component failure therefore multiple fault trees are required
  - Become cumbersome and unwieldy for complex multi-barrier systems with components that can fail in different ways

- **Directed Acyclic Graphs**
  - Generally less familiar to risk practitioners than fault trees

- **Bayesian Networks**
  - Analytically complex and computationally intensive
  - Not generally amenable to development or routine use by operators
Consequence Estimation

Consequences of uncontrolled natural gas release

• Health and safety related
  – Acute hazard from fires \(\rightarrow\) threat to public safety: injury or fatality
  – Chronic hazard from harmful airborne compounds \(\rightarrow\) threat to public health: quality of life

• Environmental
  – Long term impact of methane release \(\rightarrow\) greenhouse effect: climate change

• Financial
  – Direct cost: damage repair / lost product / compensation / fines & penalties
  – Indirect cost: value of life / social cost of carbon
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Public and regulatory concern
Public and regulatory concern but not yet well understood
Relevant for cost benefit analysis and demonstrating ALARP
Safety Consequences

• Chance of injury or fatality given gas release depends on probability of ignition and thermal radiation dosage received by receptor
  – Probability of ignition
    • POI depends on gas release rate \( \leftrightarrow \) historical data on POI and models exist
  – Thermal radiation dose is a function of heat intensity and exposure time
    • Heat intensity depends on fire size and receptor location
      – Fire size depends on gas release rate \( \leftrightarrow \) release rate models exist
      – Heat intensity depends on receptor location \( \leftrightarrow \) heat intensity versus distance models exist
    • Exposure time depends on land use and ability to find shelter \( \leftrightarrow \) guidance available
Rate controlled by driving pressure, pathway geometry and barrier failure modes

• Simple approach assumes flow rate controlled by most restrictive element in pathway
  – E.g. Orifice Discharge models for failed barriers or Fanno Flow models for flow through casing or tubing

• Refined approach considers pathway in its entirety (a series of ducts and orifices)
  – Requires sophisticated models: e.g. Nodal Analysis software or CFD modeling

• Driving pressure considerations: caverns versus depleted reservoirs

Salt cavern well

Flow throttling by casing/tubing

Depleted reservoir well

Flow throttling by casing/tubing

← Lower release rate once reservoir constraints take effect

Additional flow throttling due to reservoir deliverability constraints
Thermal Hazard Estimation

Simplest approach – fatality area based on C-FER Potential Impact Radius formula*

*with release rate modification

- Heat intensity
- Chance of fatality
- Threshold heat intensity ($I_{th}$)
- Human effects model
- Actual
- One-step approximation

- Heat intensity
- Distance from hazard source
- Hazard versus distance model

- Hazard Zone Area

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Thermal Hazard Estimation

More refined approach – Based on probabilistic relationship between dosage and fatality

![Diagram showing probabilistic relationship between radiation dosage and chance of fatality]
Environmental Consequences

• Magnitude of environmental impact proportional to quantity of gas released
  – Volume or mass = release rate \times\text{ release duration}

• Release rate estimation - same as for safety consequence estimation

• Release duration estimation
  – Depends on mode of failure, failure location and other factors
  – Difficult to estimate using models
  – Suggested approach involves historical data and SME opinion \(\leftarrow\) some data available
• Safety Impact (fatalities and injuries)
  – Usually estimated based on the Value of a Statistical Life (VSL)
    • Guidance available: US DOT and UK HSE

• Environmental impact (quantity of gas released)
  – Usually estimated based on the Social Cost of Carbon (SCC)
    • Marginal cost of future impact per ton of greenhouse gas expressed as CO₂ equivalent
    • Guidance available: US EPA and US Office of Management and Budget (OMB)
5. Risk Estimation

• 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

• 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
    • $Risk = \sum_{i}^{n} \sum_{j}^{m} (Freq_{ij}) \cdot (Cons_{ij})$
• Well operation risk – ongoing risk in each year of well operation
  – operating risk / year

• Well entry risk – 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

• Relevant well risk measures for decision-making
  – Annual risk ← focus on maximum value
  – Cumulative risk over prescribed period (n years): Cumulative Risk = $\sum_{i}^{n} Annual Risk_{i}$
Consensus exists that two complimentary measures of risk should be considered

- **Individual risk**: annual probability of fatality† for a person living or working in proximity to a hazardous facility
- **Societal risk**: expected number of annual fatalities† associated with the population living or working in proximity to a hazardous facility

### Individual risk (IR) measures

- Personal IR* – individual risk accounting for time spent indoors, outdoors and away
- Location specific IR* – individual risk assuming continuous outdoor occupancy

### Societal risk (SR) measures

- Expected fatalities – total expected fatalities accounting for time in, out and away
- Expectation represented by an F-N curve*

† Can also be estimated in terms of injury rather than fatality
Consensus exists that two complimentary measures of risk should be considered
- Individual risk: annual probability of fatality† for a person living or working in proximity to a hazardous facility
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• Societal risk (SR) measures
  - Expected fatalities – total expected fatalities accounting for time in/out and away
  - Expectation represented by an F-N curve*
Safety Risk Measures

• Societal risk measures, continued

F-N Curves
• An established means to reflect risk aversion, i.e. society’s progress aversion to incident causing large numbers of casualties
Based on review of relevant criteria from various jurisdictions and industries (in particular: UK HSE, Irish CER, Netherlands RIVM and NFPA 59A) 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 Location Specific IR

- **Societal Risk** – threshold F-N curve
  - Adopt Irish CER / NFPA 59A curve
  - Choose risk neutral over risk averse
    - Risk neutral approach minimizes expected fatalities
The most basic objective measure of long-term environment impact is the total expected quantity of gas released.

Currently no established criteria for evaluating environmental risk posed by UGS well operation.
Risk Evaluation

• Evaluation when acceptance criteria are available → Safety Risk
  – Compare calculated risk to acceptance criteria
    • If Risk ≤ Risk acceptance threshold
      – No action required
    • If Risk > Risk acceptance threshold
      – Implement measures to lower risk to acceptable level, or
      – Demonstrate that risk is as low as reasonably practicable (ALARP)
        » Cost of risk reduction is grossly disproportionate to benefit gained
Risk Evaluation

- Evaluation when acceptance criteria do not exist $\rightarrow$ Environmental Risk
  - Conduct comparative scenario analysis
    - Identify operating and maintenance scenarios that demonstrate a net reduction in risk over a prescribed evaluation period
    - Preferred scenario has lowest cumulative risk over the evaluation period
1. **Frequency estimation** - Efforts should be made to expand the reporting and analysis of UGS well and well component failure incident data. The reporting of failures of UGS wells has been a PHMSA requirement since 2017; however both the reporting requirements for, and the granularity of the information provided on, UGS well failures should be revisited.

2. **Consequence estimation** - Gas flow upwards through the casing cement and/or the surrounding formation in the event of a casing breach is not well understood and further work is required to enable better estimation of gas flow rates to the surface though these pathways.

3. **Setback distances** - To enhance public safety and promote greater consistency in defining setbacks, explicit guidance is required to define well-specific setback distances that adequately reflect the possible extent of the hazard zone that would develop in the event of a credible worst-case release followed by gas ignition. **Need a PIR formula specific to UGS wells.**

4. **Safety risk acceptance criteria** - To facilitate the broader use of QRA for safety-based decision making, a widely accepted, consensus-based set of safety risk acceptance criteria is required. Effort should be made to assemble a group of informed stakeholders to review options and decide on what set of criteria should be adopted for use in assessing UGS well safety.

5. **Well entry interval optimization** - True optimization of well entry frequency requires methods and models that can convert downhole component condition and inspection data into defensible estimates of component reliability over time. Such methods, involving the use of structural reliability models, have been developed for use in other industries (e.g. pipeline industry) and are adaptable to UGS wells (e.g. casing corrosion). Work in area is ongoing, but efforts to accelerate the development and application of such methods are warranted.
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