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Enhanced Water Resources Risk from Collocation of Disposal Wells and Legacy Oil and Gas Exploration and Production Regions in Texas

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Research Impact Statement: Collocation of Texas Class II disposal wells and oil and gas activities increases failure likelihood by 2 times relative to generic Class II systems and 100 times relative to Class IH systems.

ABSTRACT: An existing probabilistic risk assessment (PRA) for Class I hazardous waste (Class IH) injection well systems is extended for dynamic risk analysis and modified for Class II disposal well systems, which inject large volumes of 'exempt' oil and gas exploration and production waste. Disposal system failure is release of waste to the biosphere, including underground sources of drinking water (USDW). Comparative PRA analysis of generic Class IH and generic Texas (TX) Class II disposal systems suggests Class II systems are 50 times more likely to fail than Class IH systems due to different requirements for pressure monitoring, waste migration monitoring, and number of confining layers. The generic TX Class II disposal well PRA was extended to portray a generic disposal system in Dimmit County, TX, which is a legacy oil and gas exploration and production region, and to account for the increased likelihood of waste migration pathways from unknown wells and plug failure of abandoned wells. Legacy oil-related activities increase the probability of waste migration pathways because well construction, regulatory protections, and information tracking technologies have improved during the last 40 years. The system failure likelihood for Class II disposal well systems, collocated with legacy and active oil and gas activities, is twice that for generic TX Class II disposal systems, and failure likelihood increases with the assumed proportion of unknown wells to known wells.

(**KEYWORDS**: probabilistic risk assessment; Underground Injection Control (UIC); Class II disposal well; unknown well; injection well; Dimmit County, TX.)

INTRODUCTION

Deep well injection has been, and continues to be, a successful method for long-term (> 10,000 years) isolation of waste from the biosphere (Clark *et al.*, 2005; Rish, 2005). In the US, injection wells are regulated by the Underground Injection Control (UIC) program, administered by the US Environmental Protection Agency (US EPA), to protect underground sources of drinking water (USDW) from endangerment by setting minimum requirements for injection well systems and the subsurface sequestration environment. The goal of UIC requirements is ensuring that injected waste stays within the design/target sequestration zone, does not directly or indirectly migrate to a USDW, does not cause a public water system to violate drinking water standards, and does not adversely affect public health in some other manner (US EPA, 2020c).

There are six classes of injection wells in the UIC program. Class-specific requirements and considerations apply to each type of injection well (US EPA, 2020a; c). Class I wells can be used to inject hazardous (Class IH) and non-hazardous (Class I) waste into deep, confined rock formations below all USDW. Hazardous waste is defined and delineated according to the Resource Conservation and Recovery Act (RCRA) (US EPA, 2016). Class II wells are used to inject fluids related to oil and gas (OG) exploration and production (E&P). Primary uses of Class II wells are enhanced recovery of OG and disposal of wastewater co-produced with OG (US EPA, 2021b).

Regulatory requirements for Class II diverged from Class I due to input from the OG industry. Drilling fluids, produced water, and other large volume wastes created as by-products during OG E&P are designated as “special wastes”, which are exempt from RCRA categorization as hazardous waste (US EPA, 1987), regardless of their content or toxicity. Implicit in the 'special wastes' designation is the assumption that these high-volume OG E&P waste products pose a lower threat of contamination per liter of 'typical' waste. Consequently, Class II wells may have different regulations relative to Class IH wells.

Produced water is the primary 'exempt' OG E&P waste by volume and is a byproduct of OG production (Clark and Veil, 2009). It often contains elevated salinity from salts that were in the water prior to introduction to the OG well, other chemicals introduced to the well to enhance production, and other constituents, like metals, scoured from underground formations during production (Allison and Mandler, 2018). Although exempt from categorization as 'hazardous', produced water is not safe for humans or the environment, and has been found to cause long-term environmental degradation when it reaches the surface surface (Lauer *et al.*, 2016; US EPA, 1987, 2019).

Produced water is generated in large quantities from OG production. In Texas (TX), a major OG producing state, produced water is abundant with a daily production estimate of three million cubic meters (25 million barrels, or bbls) in 2016. For context, three million cubic meters is roughly the combined net water use of Austin, Dallas, El Paso, Fort Worth, Houston, and San Antonio in 2014 (Collins, 2016). Generation of large volumes of produced water creates an equally large demand for disposal and generates extensive handling and management cost (Guerra *et al.*, 2011). In the Bakken shale region of North Dakota, 56 to 84% of produced water handling costs are attributed to transportation costs for moving produced water from the production location to the treatment or disposal location (Shrestha *et al.*, 2017). Consequently, there is a significant economic incentive to locate Class II disposal wells as close as possible to the OG production location.

The objective of this study is to analyze how differences in permitting and engineering requirements between Class IH and Class II disposal wells impact the risk of containment failure for disposal well systems located in active and legacy OG E&P regions. Risk of containment failure, which includes migration of injected fluids to the surface or to USDW, is assessed for generic Class II disposal wells in TX and for generic Class II disposal wells in TX that are collocated with active and legacy OG E&P activities. A Class IH probabilistic risk assessment (PRA) framework from Rish (2005) is modified to represent TX Class II wells and provides a reference point for comparison of risk management practice among Class IH injection and Class II disposal well systems. Results from this analysis highlight the relative risk of waste containment failure from different permitting requirements among Class IH injection well systems, TX Class II disposal well systems, and TX Class II disposal wells collocated with legacy and active OG E&P activities, where Dimmit County, TX is used as an example.

METHODS and DATA

Probabilistic Risk Assessment (PRA)

Probabilistic risk assessment (PRA) is a collection of techniques and methods to explicitly incorporate variability and uncertainty into risk analysis. PRA produces estimates of likelihoods for a range of consequence magnitudes and not a single answer. If un-addressed, variability and uncertainty result in misestimates (either underprediction or overprediction) of risk (US EPA, 2014).

A PRA focuses on risk evaluation to guide risk management. Reliability engineering assessment is used as the basis for PRA of complex engineered systems, like injection well systems. Reliability engineering provides quantitative modeling of component-level and system-level reliability, where the reliability of a component or system is the probability that it will not fail during a specified duration; reliability analysis focuses on the design basis for a system. The first comprehensive PRA was related to nuclear reactor (i.e., complex engineered system) safety; it built on reliability engineering analysis and provided insight into how relatively frequent and minor accidents could initiate a complex chain of events leading to more severe consequences than some infrequent and major accidents (Stamatelatos *et al.*, 2011).

Risk related to decision-making regarding complex, engineered systems encompasses scenarios, likelihoods, and consequences. Risk management is the reduction in frequency, or likelihood, of adverse scenarios, or accidents; adverse scenarios are those outcomes with negative consequences. Preventing accidents, or adverse scenarios, requires an understanding of the full chain of events that need to occur across multiple subcomponents to produce a system failure. The risk for a particular scenario is the probability for system failure, or negative consequences. Use of risk assessment in decision-making requires that uncertainty be addressed and quantified through assignment of likelihoods or probabilities to consequences (Stamatelatos *et al.*, 2011).

Accident scenarios begin with an initiating event that represents change from desired system operation. After initiation, the assessment proceeds by identifying pivotal events that may occur and that will exacerbate or mitigate scenario progression towards a full system failure and negative consequences. The sequence of pivotal events is represented with an event tree where each event represents a node in the progression of system failure from the initiating event. At each node, an event occurs, or does not occur, that propels, or mitigates, the final consequences of the accident scenario. An individual event in an event tree can be represented with a fault tree, which provides detailed logical relationships between complex and basic component failures (Stamatelatos *et al.*, 2011). In PRA, each event, in an event tree, and each fault, in a fault tree, is represented with a probability distribution to describe the likelihood of the event or fault occurring, and the uncertainty associated with occurrence, in isolation from the system.

PRA for Class IH Injection Wells

Rish (2005) presents a PRA for Class IH disposal of hazardous waste. A Class IH injection well is a complex engineered system, and the Rish (2005) PRA builds on a comprehensive reliability engineering analysis of a typical Class IH injection well and incorporates permitting requirements within the analysis. Our analysis of the risk management inherent in environmental permitting requirements for Class II disposal wells collocated with legacy and active oil and gas fields builds directly on the Rish (2005) PRA, uses the reliability engineering analysis in this PRA to represent complex, engineered, injection well systems, and extends this PRA to represent the permitting and environmental considerations unique to Class II disposal wells collocated with legacy and active OG E&P activities.

Deep well injection of waste isolates the hazardous material from the biosphere where the goal of isolation is to segregate the waste for as long as it remains hazardous; 10,000 years is the regulatory period during which waste, isolated in the subsurface using Class IH disposal wells, is assumed to remain hazardous (US EPA, 2016). The purpose of the Rish (2005) Class IH injection well PRA was to provide quantitative analysis of the risk of loss of waste isolation that provides identification and comparison of injection well component subsystems, including permitting considerations, as contributors to the overall risk.

System failure for a Class IH injection well is release of waste to USDW during the 10,000-year regulatory period. Two potential pathways for migration of injection fluid beyond containment are identified: 1) injection or disposal well failure where it has a loss of waste confinement and 2) existence of migration pathways near the injection or disposal well that produce loss of waste confinement and allow fluids to migrate to USDW. Rish (2005) employs failure modes and effects analysis (FMEA) of the entire Class IH well system to derive seven scenarios, where each scenario is represented by an event tree.

Each event tree (i.e., each scenario) has an initiating event and leads through a sequence of events to a full system failure; each event has an associated probability distribution. **Table 1** summarizes the event trees. Several of the individual events, which are a complex combination of multiple subcomponent accidents and failures, in the event trees are further divided into fault trees. **Figure 1** displays the event tree for an 'injection tube - containment' initiating event; this event represents an injection tube leak that causes loss of containment in one system component. The capitalized label 'ITUBLEAK' refers to the probability distribution for this event; probability distributions are defined in **Table S – 1** and **Table S – 2** in the supplementary materials. The same label (e.g., 'ITUBLEAK') is also used to identify the probability distribution in the companion, dynamic PRA models that are available on GitHub (https://github.com/nmartin198/class_II_UIC_PRA).

If an 'injection tube - containment' initiating leak event occurs (see **Figure 1**), then the annulus pressure is compared to the injection pressure on a probabilistic basis. For this decision (i.e., is the annulus pressure or the injection pressure greater?), ANNPRESSLO is the label that denotes the probability distribution that is used to determine if the annulus pressure is greater than the injection pressure. For this event, or decision, the ANNPRESSLO label refers to both a fault tree that can be used to calculate the probability distribution and the calculated probability distribution. The ANNPRESSLO fault tree is documented in Rish (2005); the ANNPRESSLO probability distribution is documented in **Table S – 1**, and the component probability distributions in the ANNPRESSLO fault tree are provided in **Table S – 2**. If the annulus pressure is greater than the injection pressure, then there is no possibility of a release of waste to USDW from the 'injection tube - containment', initiating leak event.

However, if the injection pressure is probabilistically determined to be greater than the annulus pressure, the analysis moves forward to the next event in **Figure 1**, 'long string casing - containment'. Occurrence of a 'long string casing - containment' leak is probabilistically determined using the LSTRINGLEAK probability distribution; this probability distribution is defined in **Table S – 1** and the LSTRINGLEAK label is also used to identify this distribution in the companion PRA models (https://github.com/nmartin198/class_II_UIC_PRA). If a 'long string casing - containment' leak does not occur, then there is no release of waste to USDW from the 'injection tube - containment', initiating leak event. If a 'long string casing - containment' leak event does occur, then the event tree analysis continues to the next event, 'leak location - release'. This event probabilistically determines the location of the 'long string casing – containment' leak event, and the outcome of 'leak location - release' event is release to USDW or additional analysis of events in the event tree.

Dynamic Probabilistic Event Tree Simulation

Class IH well PRA results provided in Rish (2005) are a static probabilistic assessment because the state of the system does not evolve during the 10,000-year analysis interval. Monte Carlo simulation techniques are used to propagate the uncertainty associated with each event in event trees and fault in fault trees to calculate likelihoods for system failure for each initiating event. For each realization, randomly selected probabilities are compared to event, probability distribution thresholds (see **Table S – 1** and **Table S – 2**) to determine if event or fault failure occurs during that realization.

Dynamic, probabilistic simulation is used for all PRAs (i.e., Class IH injection well and Class II disposal well PRAs) presented in this paper. These PRAs are implemented in GoldSim™ dynamic Monte Carlo simulation software (GoldSim Technology Group LLC, 2021). These models are available on GitHub at: https://github.com/nmartin198/class_II_UIC_PRA and can be executed and examined using the freely available GoldSim Player. Provision of the PRA models in this graphically queryable format, in conjunction with the event tree and fault tree schematics and the probability distribution definitions in **Table S – 1** and **Table S – 2** provides complete, transparent, and reproducible documentation for the analyses presented in this paper.

The dynamic component of the PRA analysis includes the conversion of Poisson distribution events in **Table S – 1** to randomly triggered events in the dynamic simulation models. Randomly triggered events maintain the same Poisson distribution of interarrival times as specified in **Table S – 1**, and the randomly occurring event representation is parameterized using the per day rate values (i.e., these representations use a Poisson distribution of interarrival times internally to generate randomly triggered events and a single rate parameter is sufficient to parameterize the Poisson distribution) in **Table S – 1**.

Table 2 provides the mean time to failure (MTTF) in years corresponding to the per day rate for each Poisson distribution event. Each Poisson distribution event in **Table S – 1** can occur zero or more times during each realization. PACKLEAK, ITUBLEAK, and LSTRINGLEAK are the Poisson events that have a MTTF below 100 years.

Dynamic simulation of the entire hazard interval for sequestered waste allows enhanced control on the PRA analysis including incorporation of design lifetimes for the disposal well facilities. The Class IH injection well is assumed to have an operating lifetime of 30 years. Inclusion of the operating lifetime of the well facilities allows the representation of event trees, pertaining to active well operations, to be analyzed for the operating lifetime instead of for the full hazard interval. Explicit in this representation is the assumption that injection and disposal wells will be properly plugged and abandoned after the operating lifetime.

In this approach, a failure initiated as part of well operations can only occur during the operating lifetime of an injection well. For example, an injection tube leak (see **Figure 1**) can only initiate a Class IH failure during the 30 years of active operations. After the active operations interval, inadvertent extraction of waste and confining zone breach (see **Figure S – 5** and **Figure 3**) initiating events can occur until 10,000 years have passed, and the waste is no longer a hazard to the biosphere. It should be noted that active operations initiating events need to occur during the operational period; however, system failure (the complete sequence of events in an event tree that leads to a release of waste to USDW) can occur later in the analysis period if a complete event pathway in an event tree produces a failure outcome.

The probability distributions in **Table 2** provide the description of time dependency included in this analysis, and the time to failure probability distributions are an input, not a solution, to the analysis. Although there is a 10,000-year analysis interval and decisions are made based on whether an event occurs during the operating lifetime of the injection well, the probabilistic simulations comprising the PRA analyses in this paper are event-based. This means the decision trees (like **Figure 1**) are analyzed when the initiating events occur and again whenever another event in the tree is probabilistically simulated to occur. There is no 'repair' included in this formulation; consequently, once a sub-event failure event has occurred that sub-event in the event tree will maintain its failure status for the remainder of the realization.

Purpose of PRA Analysis and Limitations

PRA provides a probabilistic analysis of failure risk for a complex, engineered system that can be used to guide risk management practice. The analysis is probabilistic because it is applied to 'future' scenarios and needs to explicitly represent and account for the uncertainty inherent in future conditions. If a forensic analysis is desired of the observed failure of a particular, complex, engineered system, then deterministic, physics-based analyses are generally more appropriate. PRA analysis, in this paper, is applicable to classes, or categories, of underground waste sequestration systems that include injection wells for waste emplacement and sequestration in the subsurface.

PRA for Class II Disposal Wells

The Class IH injection well PRA (Rish 2005) is adapted and modified to produce PRAs for 1) generic Class II disposal wells and 2) generic Class II disposal wells collocated with legacy and active OG E&P activities. Two main differences between Class IH and Class II wells are the 1) type of waste and 2) volume of disposal. The nomenclature of 'disposal well' is used with Class II wells to differentiate among types of Class II wells. For Class II, 'injection' denotes wells that inject E&P waste to produce enhanced recovery of older (and possibly relatively depleted) OG fields. 'Disposal' denotes Class II wells that inject E&P wastes for sequestration from the biosphere and water resources (Railroad Commission of Texas, 2021a).

Modifications of the Class IH PRA focus on differences in permitting requirements and differences in expected injection volume between Class IH and Class II disposal wells. The reliability engineering analysis of the injection well system from Rish (2005) is used for Class IH and Class II wells. In the UIC program, the US EPA delegates primary enforcement authority, or primacy, to state, territory, or tribal organizations (US EPA, 2022). Consequently, detailed permitting requirements for Class II wells are set at the state level. Class II well permitting considerations for TX are used in this paper because TX has Class II disposal well guidelines, legacy and active OG E&P regions, and Class II disposal wells collocated with legacy and active OG E&P activities. The Railroad Commission of TX (RRC) provides the EPA-approved UIC program for Class II wells for TX (Railroad Commission of Texas, 2021c).

Table 3 lists the primary differences in permitting requirements, which result in event tree modification, between a generic Class IH well and a generic TX Class II disposal well. These two differences were used to adjust the event trees and create a generic TX Class II disposal well PRA. No attempt was made to institute a full FMEA specifically for Class II disposal wells under the assumption that basic permitting requirements would be more important to overall risk than differences in well construction methods and materials. Results of the Rish (2005) FMEA are applied to Class II disposal wells with the exception of two items listed in **Table 3**. The reader is referred to Rish (2005) for details of the FMEA and definitions of well system components.

The first difference in **Table 3** pertains to differences in pressure monitoring regimes. Expression of the different pressure monitoring requirements in PRA event trees results in the removal of the 'annulus pressure - containment' event from Class II PRA event trees (see **Figure 2** relative to **Figure 1**). The probability of a 'annulus pressure – containment' loss event is described by the ANNPRESSLO fault tree and resultant probability distribution in the Class IH PRA (see **Figure 1**, **Table S – 1**, and **Table S – 2**). For a Class II disposal well, one confining zone is required for separation from the lowermost USDW. In contrast, a Class IH well requires two confining zones with monitoring between the confining zones. These differences in confining zone requirements result in the truncation of the 'Confining Zone Breach' initiating event scenario for the Class IH PRA, shown on **Figure 3**, to only an 'Upper Confining Zone Breach' initiating event scenario for the Class II PRA as shown on **Figure 4**.

Differences in expected injection volume and rate are also incorporated into the Class II PRAs. It is expected that Class II disposal wells will inject relatively large volumes of produced water because Class II wells were differentiated from Class I wells for handling relatively large volume 'exempt' E&P waste. This injection volume-related expectation is represented in **Figure 4** with the different treatment of the 'injected waste migration - containment' event between panel a) and b). **Figure 4a** includes the assumption that sufficient waste volume is injected during active operations to promote enough pressurization within the sequestration interval that vertical migration of waste outside of containment will occur if there are flaws in containment. The initiating event in **Figure 4** is loss of containment (i.e., the existence of a flaw in sequestration interval containment). **Figure 4b** denotes the assumption that elevated pressurization within the sequestration interval will dissipate rapidly when injection stops. After active operations (i.e., **Figure 4b**), sequestered waste will need to be relatively buoyant to migrate upwards through any flaws in containment. The UBUOYANCY label in **Figure 4b** denotes the probability distribution used to characterize the 'injected waste - migration' event in the Class IH PRA.

Special Considerations for Class II Disposal Wells Collocated with Legacy and Active OG E&P Activities

The purpose of waste disposal via deep injection (using either Class IH or Class II disposal wells) is to sequester harmful substances in a location isolated from the biosphere and water resources for sufficient fate and transformation time. Two conceptual routes to loss of waste containment are mechanical failure of the injection well itself and existence of migration pathways near, but unrelated to, the injection well.

Special considerations for Class II disposal wells collocated with legacy and active OG E&P activities relate to increased likelihood for migration pathways. Examples of migration pathways related to OG E&P are improperly plugged or completed wells and properly plugged wells whose plugs have failed. Plugging a well involves sealing the well in such a way as to confine oil, gas, and water in the strata in which they are found and prevent them from escaping to other strata (Williams *et al.*, 2000). Abandoned wells are inactive wells that have been plugged in accordance with applicable standards and retired in a compliant manner. Unknown wells are inactive wells for which there are no records, or the records have been lost; unknown wells are assumed to be unplugged for this analysis.

Legacy and active OG E&P regions have a long history of installing boreholes to find and extract OG and so have numerous deep wells. Legacy OG E&P regions have enhanced likelihood of unknown wells that have been forgotten across the decades prior to the institution of detailed well tracking procedures, and legacy regions have increased likelihood of plug failure due to historic use of what are now considered antiquated plugging methods and materials. Active OG E&P regions, especially those that use non-conventional production techniques, generate significant volumes of produced water and thus increased demand for disposal wells.

Part of UIC Class I and II permit requirements are completion of geologic studies in an area of review (AoR) to identify and analyze the possibilities for migration pathway existence (US EPA, 2001, 2016). For Class II wells in TX, the fixed radius of the AoR for disposal wells is 402 m (0.25 mi) (Railroad Commission of Texas, 2021c); this is equivalent to the required AoR radius for Class I nonhazardous wells and municipal wells (US EPA, 2001). For Class IH wells in TX, the radius for the AoR is extended to 4.0 km (2.5 mi) (US EPA, 2001), and Rish (2005) uses an AoR radius of 3.2 km (2 mi) in the Class IH PRA. The TX Class II AoR analysis includes confirmation that all (known) inactive wells within the AoR are (properly) abandoned according to the applicable standards at the time of abandonment (Railroad Commission of Texas, 2021c).

Figure 5 depicts the adverse consequences to water resources from UIC injection for waste disposal in conjunction with unknown wells and plug failure of abandoned wells. This figure shows discharge of injected waste to both the surface and USDW. Technically discharge to the surface is not covered under the UIC program and would be covered under the National Point Discharge Elimination System (NPDES) program. For Class II PRA analysis, system failure is defined as discharge of waste to the surface and migration of waste to USDW.

Two PRA scenarios have initiating events, and a subsequent sequence of events in the event tree, that are unrelated to the injection well: 1) 'Inadvertent Injection Zone Extraction' initiating event scenario (see **Figure S – 5**) and 2) 'Confining Zone Breach' initiating event scenario (see **Figure 3**). In these two failure scenarios, the injection well and the plug installed as part of injection well abandonment maintain mechanical integrity throughout the analysis period, and injected waste impacts the biosphere via a route that is unconnected to the injection well. The remaining five failure scenarios have an initiating event related to the injection well; however, waste migration to USDW can only occur in conjunction with a 'confining zone – containment', loss of containment event within the event tree (see **Figure 1**, **Figure 2**, and **Figure 3**). For six of the seven failure scenarios, all except for the 'Inadvertent Injection Zone Extraction' scenario, system failure likelihood is directly augmented by an increase in likelihood for migration pathways and a corresponding increase in probability for a 'confining zone – containment' loss of containment event.

Class IH injection well systems require two confining zones with active monitoring for waste migration between the confining zones, see **Table 3**. In **Figure 3**, these requirements are implemented using a 'lower confining zone – containment' breach initiating event, which is represented with the CONFINEBRCHL fault tree and resultant probability distribution (see **Table S – 1** and **Table S – 2**). Because there are two required confining zones, there is an 'upper confining zone - containment' event in the **Figure 3** event tree, which is represented with the CONFINEBRCHU fault tree that is shown on **Figure 6** (see **Table S – 1** and **Table S – 2** for component fault probabilities).

The Class II PRA version of the event tree for the 'confining zone - containment' breach, initiating event is shown on **Figure 7**; only one confining interval is required for TX Class II disposal wells. For the TX Class II disposal well PRA (i.e., not collocated), the CONFINEBRUCHU fault tree, shown on **Figure 6**, generates the probability of the 'upper confining zone – containment' breach, initiating event. Special considerations for Class II disposal wells collocated with legacy and active OG E&P regions are incorporated into the PRA analysis in the mCONFINEBRCHU fault tree shown in **Figure 7**. The mCONFINEBRCHU fault tree provides the likelihood for the 'upper confining zone - containment' breach, initiating event for the Class II collocated disposal well PRA. The change between the Class IH injection and TX Class II disposal well PRAs CONFINEBRCHU fault tree (**Figure 6**) and the collocated Class II disposal well PRA mCONFINEBRCHU fault tree (**Figure 7**) is the representation of the 'transmissive abandoned well' fault.

For the collocated Class II disposal well PRA, the ‘transmissive abandoned well’ fault can occur from two compound faults: 1) plug failure of a deep well (i.e., deeper than the sequestration interval) within the AoR and 2) a deep, unknown well within the AoR. The component fault likelihoods, for these two compound faults, need to be determined for a specific case study region that is a legacy and activate OG E&P area because the component faults rely on the spatial distribution of wells, distribution of well depth, and distribution of plug age.

Data

Probabilistic analysis is employed when insufficient data exist for deterministic analysis. Data are important to PRA to define scenarios and to derive probability distributions. Specific information required for this analysis are: 1) Class II disposal well permitting requirements, 2) spatial distribution of wells, 3) distribution of well depth, and 4) distribution of plug age. As mentioned previously, the case study region is in TX, and TX Class II disposal well permitting requirements are used to formulate modified event and fault trees. A focused case study region is used to derive the required probability distribution information related to well location and depth and installed plug ages.

Case Study Region

To facilitate analysis of collocation of a generic Class II disposal well with legacy and active OG, a case study region was selected to provide existing well data sets. The selected study region is Dimmit County, TX which is at the southwestern end of the Eagle Ford Shale region (see **Figure 8**). Dimmit County has a long history of oil and gas production and has ‘legacy’ oil and gas exploration and production activities. The first producing oil wells were drilled in the 1940s. Production subsequently increased in the 1950s, and total oil production from Dimmit County was 513,000 barrels in 1958. Production continued to increase into the mid-1970s when the oil industry became the largest source of income in the region, outperforming agriculture. The industry experienced a temporary dip in output in the 1980s. Although oil production increased overall from the 1940s to 2000, historical maximum production was modest compared with the Eagle Ford Shale boom starting in 2008 which was driven by the advent of novel hydraulic fracturing techniques (Leffler, 2020). The Eagle Ford Shale boom generates ongoing active OG E&P activities in Dimmit County.

More than 8,445 active, abandoned, and orphaned OG wells are in Dimmit County as shown on **Figure 8**. These wells represent the legacy of 80 years of continuous OG production in combination with the hydraulic fracturing boom from 2008 to 2016. Because these wells are for OG E&P, they are deep relative to water wells and may extend thousands of meters into the subsurface. The combination of many deep wells and a long history means that there are thousands of inactive wells. Most inactive wells are abandoned but some of the inactive wells are orphaned wells. An orphaned well is an inactive well that is non-compliant and has been inactive for a minimum of 12 months. Non-compliant means that the well has not been plugged.

To derive information concerning the spatial distribution of wells, distribution of well depth, and distribution of plug age for the study area, a dataset of oil- and gas-related boreholes located in Dimmit County was created by synthesizing publicly available digital datasets. The datasets used in this analysis were acquired from the RRC on 24 August 2020. The Dimmit County dataset is made up of boreholes with digitally available spatial information and well characteristic information including total well depth and, if the well has been abandoned, plug installation date.

The underlying RRC datasets synthesized for this study suffer from data quality issues common to OG wells in TX and the United States. Digitization of borehole data has only started in the last ten years; OG wells completed prior to the time of current digitization practices are only recorded in the digital database if they were plugged, recompleted, re-permitted or repurposed after the instatement of digitization practices. Consequently, the likelihood that digital data are available for a given well depends on the time when it was completed and operated. It is safe to assume that the database is missing a significant number of older boreholes.

Figure 9 displays the histogram of total well depths from the Dimmit County OG well dataset. In application of **Figure 7** within the PRA, a randomly sampled total well depth from **Figure 9** is compared to the assumed average disposal interval depth of 1,524 m (5,000.0 ft). Only when the randomly sampled total well depth exceeds 1,524 m can an unknown well or a plug failure fault occur. In **Figure 9**, 78% of the wells have depths exceeding 1,524 m.

Histograms of plug installation years and minimum distance to the nearest known well are shown on **Figure 10** and **Figure 11**, respectively. The plug installation date histogram was calculated directly from the dataset. However, the minimum distance to the nearest known well was determined using 10,000 randomly selected point locations within the boundaries of Dimmit County. For each random point, the distance to the nearest known well was calculated. **Figure 11** was generated from the collection of 10,000 minimum distances.

In **Figure 7**, the mean time to failure (MTTF) for an installed plug is probabilistically estimated by randomly sampling a plug age from the cumulative mass function form of the histogram shown on **Figure 10**; the mean plug installation date from **Figure 10** is 1998. Plug installation practices for various epochs are then used to assume a MTTF based on the plug date from **Table 4**, assuming that the plug will have been installed according to the construction procedures and guidelines applying at the time of abandonment. Plug installation date, randomly sampled from **Figure 10**, is used to determine a MTTF from **Table 4**, which provides the average rate used to specify a Poisson distribution of interarrival times (as discussed for injection well component failures in relation to **Table 2**) created at the start of each realization in the companion PRA models (available at https://github.com/nmartin198/class_II_UIC_PRA). The expected MTTF based on the mean plug installation date of 1998 is 5,000 years. Plug failure event interarrival times are then randomly selected (i.e., sampled) in series (each time a failure is simulated to occur the next failure arrival time is randomly selected) from this Poisson distribution.

Basic technologies used for plugging wells have not changed much since the 1970s. While modern wells have a low risk of failure if completed according to regulation, wells completed and/or plugged prior to 1970 were subject to less rigorous standards and regulation and thus have greater probability of failure. In TX, the history of well construction and plugging regulation shows the progression of no regulation a century ago to the current, modern safety standards. The focus on early well plugging requirements was to protect oil and gas resources from escaping. Well plugging to protect water resources and the environment was not a consideration until the 1960s (Technology Subgroup of the Operations & Environment Task Group, 2011).

Furthermore, "{t}here is plenty of anecdotal evidence that well abandonment was not always executed in the spirit of the regulations until recently. Out of 19 penetrations in the area of review {AoR} of the well drilled for limited CO2 injection at the Frio Experiment site {study site is South Liberty Salt Dome near Houston, TX (Hovorka *et al.*, 2006)}, only 3 had been plugged with cement below the lowermost USDW {i.e., properly abandoned}. Most of these wells had been drilled in the 1950s and plugged in the 1970s (Nicot 2009, p. 1634)."

Nicot et al. (2006) and Nicot (2009) grouped abandoned wells in TX into four time/age categories by abandonment year to describe relative likelihood of plug failure and well integrity issues as shown on **Table 4**. These four intervals represent thresholds of improvement in well construction and abandonment technology as well as in permitting regulation and enforcement. In the years 1935 and 1967, the RRC issued specific plugging instructions which significantly changed the method of well abandonment. In 1983, oversight by the state was greatly increased by introducing fees and penalties and more specific plugging and abandonment rules were defined.

MTTF values in **Table 4** are allocated to an age category to produce a progression of increasing plug reliability to reflect the improvements in materials and methods with technological advances from the 1930s to present day. The goal with the progressive reliability improvement representation was to ensure that the present-day estimates represent the expected durability for advanced technology OG wells designed to withstand harsh conditions and deep environments. Most wells in the study area database tend to be recently abandoned (i.e., the mean plug age is 1998). Recently installed OG wells are generally for non-conventional production and designed to leverage advanced technologies and materials.

It should be noted that there are only about 100 years of possible data available for collection from a well plugged in the 1920s which is only half the shortest MTTF estimate of 200 years. The concept of data collection also suggests some degree of regular monitoring across the plug lifetime; plug competency monitoring is generally not required or instituted in the study area. Even if data had been collected in the study area, 100 years is not a sufficient analysis period to effectively constrain reliability engineering based MTTF estimates, which range from 200 to 5,000 years, with observations. The longest MTTF estimate of 5,000 years (Arild *et al.*, 2019) is still only half of the 10,000-year analysis interval, which means that significantly more than half of all plugs are expected to fail during the analysis interval. The MTTF values in **Table 4** should be considered unconstrained estimates that were selected to represent the hypotheses that cutting-edge materials and technologies should produce a MTTF more than ten times that of pre-1935 materials and technologies and that all plugs are expected to fail during the 10,000-year analysis interval because the expected time to plug failure (i.e., the MTTF) is at most 5,000 years.

Unknown Wells

As discussed previously, unknown wells are legacy orphan wells whose existence has been forgotten or was never recorded in regulatory records. Because they are forgotten orphan wells, unknown wells have the potential to provide injected waste migration pathways to the biosphere. Unknown wells are a known issue of unknown magnitude in legacy OG E&P regions of TX (Corso, 2019). Currently, orphaned wells are tracked in permitting databases and are unlikely to be forgotten; however, this has only been feasible, from an available technology perspective, for the last two or three decades. These databases actively track a significant number of orphaned wells and wells that are not active and not considered fully abandoned. For example, there were approximately 3.2 million known abandoned wells in the U.S. as of 2018. Around two thirds of these abandoned wells are orphaned or improperly abandoned and do not have a plug (US EPA, 2020b). In Texas, there were more than 13,840 orphaned wells in 2005, reduced to 6,799 as of February 2021; the numbers are reduced from 2005 to 2021 because TX has a program where the state pays to abandon orphaned wells. 31 of the remaining orphan wells in 2021 were in Dimmit County (Railroad Commission of Texas, 2021d).

As part of required AoR analysis for TX Class II disposal wells, databases of known wells are searched for orphan wells within the AoR. A Class II disposal permit will not be approved if there is an orphan well within the proposed AoR unless the orphan well is abandoned (i.e., plugged in accordance with applicable standards) as part of the permit application process. The AoR can contain abandoned wells (Railroad Commission of Texas, 2021c).

Our assumption is that unknown wells that are likely to be deeper than the sequestration interval present an important risk management issue for Class II disposal wells. Unknown wells that are relatively shallow (i.e., water wells instead of OG E&P wells) pose limited risk because there should be at least one confining interval (see **Figure 3** and **Figure 4**) that separates the waste sequestration interval from any shallow, unknown wells. Information about unknown wells is currently unknown by definition; consequently, it is assumed for this analysis that the count of unknown wells is a percentage (0 to 20%) of the count of known wells and that all unknown wells are unplugged.

The percentage of unknown wells to active and abandoned wells is a specified value, one of 0%, 5%, 10%, 15%, or 20% (see **Figure 7**). The specified value generates a 'scenario' for the collocated Class II disposal well PRA. The scenario representation is conceptually different from including a probability distribution to represent the 'unknown well' fault in **Figure 7**.

Observed Injection Well System Failure

Class IH injection wells are viewed as a successful and safe disposal method for hazardous waste. Only four significant cases of waste migration occurred due to Class IH well operations prior to development of the UIC program in the 1980s. No cases of USDW contamination have been attributed to Class IH injection wells since the start of the UIC program due to stringent siting, construction, operation, and testing requirements (Clark *et al.*, 2005). Containment monitoring between the geologic confining zones is required for Class IH injection well systems; consequently, there can be some degree of confidence that there is no currently unobserved waste migration. The Rish (2005) Class IH injection well system PRA quantitatively estimates the risk of loss of waste containment and subsequent migration to be less than one in one million.

For Class II disposal wells, which are the focus of this assessment, monitoring for waste migration is not required. For these waste sequestration systems, a concern is that there is unobserved and undocumented waste migration. One goal of PRA is to prevent accidents (like waste migration outside of sequestration) from occurring by examining the likelihood for adverse consequences when data directly describing adverse consequence likelihood are not available.

Class II well failures have been observed in the past. Nicot et al. (2006) surveyed well leaks in TX and uncovered reports of seven contamination events of underground drinking sources by Class II wells from 1996 to 2003. In 2011, an abandoned (i.e., plugged) well in Dimmit County experienced an approximately 41 m^3 (260 bbl) breakout attributed to a nearby Class II disposal well (Malewitz, 2015). This represents one documented failure in the case study region, which contains 42 disposal wells (see **Figure 8**), and a 2.4% (1 observed failure / 42 disposal wells) likelihood of disposal well system failure.

For the documented failure in the study area, the plug that failed was installed in 1949, about 60-years prior to the failure. A breakout occurs when the injected waste, produced water in this instance, is forced up a nearby borehole by injection pressures and discharges to the ground surface. This breakout was sufficient in magnitude to kill the grass and shrubs affected by produced water discharge. The abandoned well that had the plug failure was more than 402 m (0.25 mi) from the nearby disposal well; consequently, there was not a requirement to include it in the AoR analysis because it was outside of the required radius (Malewitz, 2015). The result of this breakout was discharge to the ground surface. Although the breakout fluids had adverse consequences to the biosphere, there is no direct evidence that waste impacted USDW. However, it is possible that some amount of produced water (i.e., waste) migrated to one or more USDW as the waste moved up the borehole of the failed, abandoned well.

Assumptions

All assumptions in this analysis are explicitly documented in the event tree schematics, probability distributions (see **Table S – 1** and **Table S – 2**), and companion dynamic simulation PRA models (see https://github.com/nmartin198/class_II_UIC_PRA).

The following bullets provide a relisting of the most important assumptions.

- Buoyancy is not a factor/consideration during Class II disposal well operations for the 'injected waste - migration' event shown on **Figure 4**. It is assumed that the relatively large volume of injected waste produces sufficient pressure within the sequestration interval and within the AoR to provide for an 'injected waste - migration' event if migration pathways exist within the AoR.
- Uniform spatial distribution across Dimmit County is assumed for existing deep wells and deep well construction and abandonment characteristics because individual histograms/probability distributions are used for the entire county as shown on **Figure 9**, **Figure 10**, and **Figure 11**.
- Class IH injection and Class II disposal wells will be properly plugged and abandoned after the operating lifetime of the injection well using methods and materials with MTTF exceeding 10,000 years. The Class IH injection well is assumed to have an operating lifetime of 30 years, and the Class II disposal well is assigned an operating lifetime of 10 years. Failure initiated as part of well operations can only occur during the operating lifetime of the well. For example, an injection tube leak can only initiate a Class IH

failure during the 30 years of operation or a Class II failure during the ten years of operation.

- Specified probability values for proportion of unknown to known wells is used as a 'scenario' and sensitivity analysis parameter and is a member of [0, 0.05, 0.10, 0.15, 0.20].

RESULTS

Three PRAs are used to analyze and compare risk management: 1) Class IH PRA, 2) generic TX Class II PRA, and 3) generic collocated Class II PRA based on OG well data from Dimmit County, TX. **Table 5** shows the total system failures from 100,000 realizations of the generic Class IH injection well, TX Class II disposal well, and collocated, in Dimmit County, Class II disposal well system PRAs. Without consideration of collocation and unknown wells, a generic TX Class II disposal well is 50 times more likely to fail that a generic Class IH injection well. The simulated increases in failure counts are attributed to the changes in requirements, listed in **Table 3** and shown on **Figure 4**. When collocation of the disposal well with legacy and active OG E&P activities is considered in conjunction with the possibility of unknown wells, simulated failure counts increase with increasing proportion of unknown to known wells. In **Table 5**, each 0.05 increase in proportion of unknown wells provides a failure count increase of between 1.1 and 1.5 times. The simulated number of failures increases by between 1,100 and 1,500 across 100,000 realizations for each 0.05 increase in proportion of unknown wells.

When no unknown wells are assumed for a generic, collocated in Dimmit County, Class II disposal well, the simulated failure count is lower than the simulated failure count for a generic TX Class II disposal well. Because Dimmit County (i.e., the Eagle Ford Shale region) is the location of active OG E&P, there are relatively more new and recently constructed and abandoned, deep wells that are assumed to be constructed, or abandoned, with advanced methods and improved materials; this produces the expectation for a longer MTTF (based on **Table 4** and **Figure 10**) for well plugs relative to the generic Class IH and generic TX Class II disposal well system PRAs. The different expectations for abandoned well plug MTTF result in a larger number of 'Upper Confining Zone Breach' initiating event failures for generic TX Class II disposal wells relative to generic, collocated in Dimmit County, Class II disposal wells (see **Table 6**) with zero unknown wells.

The number of system failures by initiating event and event tree are compared in **Table 6**. The "Upper Confining Zone Breach" event tree (see **Figure 4**) accounts for most of the generic TX Class II disposal well system failure count for both collocated and not collocated systems, as expected from the assumptions embodied in the analyses. For Class IH wells, "Confining Zone Breach" (see **Figure 3**) provides about the same order of magnitude of system failures as generated from 'Packer Failure' (see **Figure S – 2**) and "Injection Tube Failure" (see **Figure S – 3**) scenarios. The 'Packer Failure' and 'Injection Tube Failure' initiating events are more likely to occur during the 30-year operating lifetime of the Class IH well as opposed to the 10-year operating lifetime of the Class II well based on the MTTF values shown in **Table 2**. Leaks, like "Packer Leak" (see **Figure S – 1**) and "Injection Tube Leak" (see **Figure 2**), are more likely to initiate complete system failure in Class II well systems because of the limited monitoring of annulus pressure and requirement for only one confining layer (see **Table 3**) in conjunction with increased likelihood of injected waste migration during the Class II well operating lifetime due to the relatively small AoR and large injection volume.

The 'injected waste – migration' event impacts the 'Confining Zone Breach' initiating event scenarios shown in **Figure 3** and **Figure 4**. This migration event must occur for a 'Transmissive and Abandoned Well (e.g., represented with TRANABW probability distribution in Rish (2005) or the mTRANABW compound fault in **Figure 7**)' fault to produce a system failure. **Table 7** provides summaries of simulated 'Transmissive and Abandoned Well' fault and 'injected waste - migration' event occurrences. 'Transmissive and Abandoned Well' faults occur often in Class IH realizations because of the short MTTF for plugs of 1,300 years (see **Table 2**) relative to the 5,000-year MTTF (see **Table 4** and **Figure 10**) for a generic, collocated in Dimmit Count, Class II system. The 'injected waste - migration' event, in contrast, occurs much more frequently in the Class II disposal well PRAs because migration is assumed to occur within the AoR when a pathway exists during active Class II well operations due to the relatively large disposal/injection volumes. After Class II disposal well operation concludes, the 'injected waste - migration' fault can only occur based on the likelihood for the disposal fluid to be relatively buoyant (i.e., the UBUOYANCY probability distribution from Rish (2005)), as shown in **Figure 7**.

DISCUSSION

Two main definitional differences between Class IH and Class II wells are the type of waste and expected volume of disposal. Class II wells handle 'exempt', relatively large volume OG E&P waste fluids. Class II waste is not inventoried, and waste composition is unknown. Because Class IH injection and Class II disposal wells are separate categories under the UIC program, there are different regulatory requirements. In TX, Class II disposal well operators must report monthly average injection rates, total monthly volumes, and maximum wellhead injection pressures while 24-hour, automated annulus pressure monitoring in the injection well is required for Class IH injection wells (see **Table 3**). The annulus pressure monitoring system is a critical component in Class IH injection wells for preventing contamination to USDW, and it has provided high reliability in practice due to requirements for automatic alarms, shut offs, and full-time operators (Clark *et al.*, 2005; Rish, 2005). Regulations for Class II disposal well systems in TX require that one confining layer separate the waste sequestration interval from USDW; monitoring for waste migration is not required. For Class IH injection wells, two confining layers must separate the injection zone from lowermost USDW with required monitoring between confining layers.

Relaxation of pressure monitoring, confining layer, and waste migration requirements for Class II disposal wells relative to Class IH injection wells conceptually contradicts the risk management practice expected for disposal of relatively large volumes of waste; larger volume disposal logically suggests enhanced pressure monitoring and increased confining layer and waste migration monitoring requirements. Comparison of PRA results in **Table 5**, **Table 6**, and **Table 7** identifies that generic TX Class II disposal well systems are 50 times more likely to fail than generic Class IH injection systems because of relaxed pressure monitoring, confining layer, and waste migration monitoring requirements.

From the permitting perspective, a generic TX Class II disposal well system is equivalent to a generic TX collocated Class II disposal well system. Special risks posed by collocation of waste disposal systems with legacy and active OG activities relate to the possible existence of 'additional' migration pathways generated by the existence of large numbers of deep wells that pierce the disposal interval, increased possibility of plug failure with increased abandoned well counts in the AoR, and increased likelihood of unknown, and thus unplugged, wells bequeathed by a legacy of OG E&P activity that spans many decades (see **Figure 5**).

Table 5, **Table 6**, and **Table 7** describe the expected increase in failure risk due to the 'additional' migration pathways expected from legacy and active OG activities. When the assumed proportion of unknown to known wells is between 0.05 and 0.20, a generic, collocated

Class II disposal well system in Dimmit County, TX is expected to be 1.5 to 5 times more likely to fail than a generic TX Class II disposal well system (i.e., not collocated) and 80 to 250 times more likely to fail than a generic Class IH injection well system. When no unknown wells are assumed, the generic, collocated Class II disposal well system in Dimmit County is less likely to fail (0.4 times) than a generic TX Class II disposal well because of the expectation for an increase in average well plug MTTF for wells abandoned using modern practices and materials.

Disposal well system failure observations and data are limited because monitoring for waste migration is not required. However, there has been at least one documented disposal well system failure in Dimmit County, TX out of the 42 disposal wells (see **Figure 8**), providing an expected failure rate of 2.4% of well systems. 100,000 realizations are used to generate the results in **Table 5**, **Table 6**, and **Table 7**; 2.4% corresponds to a failure count of 2,400 in **Table 5**. Generic, collocated Class II disposal well system in Dimmit County, TX PRA results reproduce the 2.4% observed failure rate for a proportion of unknown to know wells between 0.05 and 0.10. The observed well system failure was attributed to plug failure, which is conceptually part of the 'Transmissive and Abandoned Well' fault in **Figure 7**. Using failure counts of 2,400 for generic, collocated TX Class II disposal well systems, 1,300 for generic TX Class II disposal well systems (see **Table 5**), and 25 for generic Class IH injection well systems (see **Table 5**), a collocated Class II disposal well in Dimmit County, TX is 1.8 times more likely to fail than a TX Class II disposal well (i.e., not collocated) and is 96 times more likely to fail than a Class IH injection well.

An important component of risk management and PRA is identification of consequence magnitude. Adverse consequences for the generic Class IH PRA are waste migration, or release, to USDW. For the generic Class II disposal well system PRAs, adverse consequences are waste migration to USDW and the ground surface. If waste composition for Class II disposal were known, it would be possible to differentiate consequence magnitude among the PRAs based on typical waste inventory and expected clean-up and mitigation costs.

Another cost-associated, risk management practice that is not captured in these PRA analyses is the possibility for use of bonding requirements, or other fees, for the waste disposal system operators/owners to offset risk. Waste disposal system operators garner revenue from providing the disposal service. Conceptually, bonding requirements (or other fees) could be set (or increased) to account for, or address, increased risk from operating and permitting practice. Ideally, bonding requirements would be determined based on combined considerations of permitting risk management and expected clean-up and mitigation costs for adverse consequences with the goal of removing any hidden state provided subsidies to waste disposal. A state providing a permit for waste disposal operations that are known to entail a risk of adverse consequences without congruent requirements for risk sharing with the operators is an example of a possible hidden subsidy; in this case, the state would likely be left with the major portion of clean-up bills resulting from adverse consequences even though the operators accrue the major portion of the revenue from the disposal services. A second possible hidden subsidy example would be a state paying to abandon orphan wells when the state does not receive offsetting fees from the entities that originally constructed and operated the well or from future disposal system operators.

A final limitation of the generic Class II disposal well PRAs employed in this study is that they only consider adverse consequences that occur after the waste enters the injection well. There is no consideration of risk related to the surface facilities of a disposal well system. In future augmentations to the comparative PRA analyses, cost considerations and risk from surface facilities operations and produced water transport will be included to provide a complete risk management practice analysis through analysis of surface facility-based risks, examination of relative bonding requirements, and estimation of clean-up and mitigation costs for adverse consequences.

CONCLUSIONS

Risk management, embodied in engineering and permitting practices, for waste disposal systems utilizing Class II disposal wells is examined regarding unique risks posed by collocation of waste isolation facilities with legacy and active OG E&P activities. PRA is used to analyze and compare risk management practices among generic Class IH injection wells, generic TX Class II disposal wells, and generic TX Class II disposal wells collocated with legacy and active OG activities in Dimmit County, TX.

The unique risk for Class II disposal facilities collocated with OG E&P is enhanced likelihood for waste migration pathways generated by numerous relatively deep wells (i.e., deeper than the waste sequestration interval). Migration pathways of concern are provided by unknown and unplugged wells and by plug failure in abandoned wells. With assumed proportions of unknown and unplugged to known wells ranging from 0.05 to 0.20, Class II disposal well systems collocated with legacy and active OG activities are 1.5 to 5 times more likely to fail, and release waste to USDW or the biosphere, than Class II disposal well systems located away from OG activities.

Class II facilities are utilized for disposal of special ‘exempt’, relatively large volume E&P wastes. Because Class II and Class IH are separate categories, there are different permitting requirements regarding injection well pressure monitoring, number of confining layers segregating the waste disposal interval from USDW, and monitoring for possible waste migration. TX Class II disposal well systems have relatively relaxed pressure monitoring, confining layer configuration, and waste migration monitoring requirements relative to Class IH systems. Consequently, PRA analysis suggests that a generic TX Class II disposal well system is 50 times more likely to fail than a generic Class IH disposal well system.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Tables with probability distribution definitions for event and fault trees (**Table S – 1** and **Table S – 2**) and additional event tree figures (**Figure S – 1**, **Figure S – 2**, **Figure S – 3**, **Figure S – 4**, and **Figure S – 5**) for event trees that were not modified as part of this study.

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DATA AVAILABILITY

Data that support the findings of this study are available in 'Datasets Available for Download' from the Railroad Commission of Texas at https://www.rrc.texas.gov/resource-center/research/data-sets-available-for-download/. These data were derived from this resource that is available in the public domain: https://www.rrc.texas.gov/resource-center/research/data-sets-available-for-download/. Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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TABLES

Table 1: Event trees and initiating events in Rish (2005) PRA

ID	Initiating Event	Figure
1	Packer leak	**Figure S – 1**
2	Major packer failure	**Figure S – 2**
3	Injection tube leak	**Figure 1**
4	Major injection tube failure	**Figure S – 3**
5	Cement microannulus leak	**Figure S – 4**
6	Confining zone breach	**Figure 3**
7	Inadvertent injection zone extraction	**Figure S – 5**

Table 2: Poisson distribution definitions from Rish (2005), see Table S – 1 and Table S – 2

Probability Distribution Label	Description	Rate (1/day)	MTTF (yrs)
PACKLEAK	Packer leak	4.6E-05	60
LSTRINGLEAK	Long string casing leak	4.2E-05	65
SURFCASELEAK	Surface casing leak	4.2E-06	650
LSCEMLEAK	Long string casing cement microannulus allows fluid movement along casing	1.1E-05	250
PACKFAIL	Sudden/major failure and breach of packer	4.6E-07	6,000
ITUBLEAK	Injection tube leak	6.8E-05	40.
ITUBFAIL	Sudden/major failure and breach of injection tube	6.8E-07	4,000
LSCASEFAIL	Sudden/major failure and breach of long string casing	4.2E-07	6,500
PLUGFAIL[+]	Identified abandoned well plug fails	2.2E-06	1,300

[+] PLUGFAIL provided per well per year and converted to per day. One well is used to limit the number of PLUGFAIL events (to 1) that can occur during a realization.

Table 3: Primary differences between Class IH PRA and Class II disposal well permitting

ID	Rish (2005) Class IH injection well		Class II disposal well in Texas	
1	24-hour, automated annulus pressure monitoring in the injection well	**Figure 1**	Operators must report monthly average injection rates, total monthly volumes, and maximum wellhead injection pressures	**Figure 2**
2	Two confining layers separate injection zone from lowermost USDW with monitoring between confining layers	**Figure 3**	One confining zone of 250 feet of clay or shale or other relatively impermeable strata must separate the injection interval from lowermost USDW	**Figure 4**

Table 4: Important well age divisions after Nicot et al. (2006) with MTTF estimates by plug age category

Age category	Historical Context	Estimated Mean Time-to-Failure (MTTF)
Pre-1935	While abandoned wells were mandated to be plugged by the RRC starting in 1919, the practice was not regulated nor followed. Plugging materials were various from mud to wood and cement.	**200 years [1,2]**
1935-1967	In 1935 plugging was required to be done by cement across producing formations. However, several different methods were employed to various degrees of success.	**1,000 years [4]**
1967-1983	Well plugging requires cement using the circulation method and a plug top as well as 100-foot cement plug above the uppermost perforated horizon. Wells plugged post-1967 are thought to have a high probability of having been plugged properly (Nicot 2009)	**2,000 years [4]**
1983-present	RRC has increased scrutiny and only approved cementers are permitted to plug wells. There are few known well plug failures from recently plugged wells (Rish 2005).	**5,000 years [3]**

[1] Woodyard (1982) estimates a MTTF of 144 years for the well itself when unplugged (surface and production casing)

[2] Thompson et al. (1996) estimates 200 years until the failure of cement well plugs in depth less than 305 m (1,000 ft)

[3] Arild et al. (2019) expect plugged wells to fail in 2,000-5,000 years for offshore wells in the North Sea using a Bayesian modeling framework

4 1,000 years for 1935-1967 and 2,000 years for 1967-1983 MTTF are assumed to provide a progression across the age divisions showing an improvement in expected plug performance due to improvements in construction materials and methods and more stringent permitting requirements.

Table 5: Comparison of system failures simulated for 10,000 years and 100,000 realizations

PRA Model	Proportion of Unknown Wells	Total Realizations with Failures*				Failure Count Increase Relative to Class IH	Collocated Class II Relative to Class II
		5th CI+ Bound (%)	Count	Mean (%)	95th CI+ Bound (%)		
Generic Class IH	NA	0.02	25	0.03	0.03	1	NA
Generic TX Class II	NA	1.24	1,299	1.30	1.36	52	1
Generic, collocated in Dimmit County, TX, Class II	0.00	0.45	491	0.49	0.53	20	0.4
	0.05	1.91	1,989	1.99^	2.06	80	1.5
	0.10	3.34	3,436	3.44^	3.53	137	2.6
	0.15	4.72	4,839	4.84	4.96	194	3.7
	0.20	6.19	6,317	6.32	6.45	253	4.9

* Percentage values can be converted to number of failures by multiplying the percentage by 100,000 (i.e., the number of realizations)

+ CI = confidence interval; CI bounds show that sufficient realizations were used in the analysis to provide non-overlapping failure counts among the PRAs and unknown well scenarios

^ Observed likelihood of disposal well system failure in Dimmit County, TX is 2.4%, which falls between the mean failure counts for 0.05 and 0.10 proportion of unknown wells

Table 6: Comparison of system failures by initiating event

Event Tree Listed by Initiating Event		Generic Class IH	Generic TX Class II	Generic, Collocated in Dimmit County, TX, Class II				
				Proportion of Unknown Wells				
				0.00	**0.05**	**0.10**	**0.15**	**0.20**
Packer Leak	5th (%*)	0.00	0.07	0.07	0.08	0.10	0.10	0.12
	Count	0	87	80	99	113	123	138
	Mean (%)	0.00	0.09	0.08	0.10	0.11	0.12	0.14
	95th (%)	0.00	0.10	0.09	0.12	0.13	0.14	0.16
Packer Failure	5th (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Count	9	0	0	1	1	1	1
	Mean (%)	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	95th (%)	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Injection Tube Leak	5th (%)	0.00	0.08	0.08	0.10	0.12	0.15	0.17
	Count	0	102	99	117	144	173	193
	Mean (%)	0.00	0.10	0.10	0.12	0.14	0.17	0.20
	95th (%)	0.00	0.12	0.12	0.14	0.16	0.20	0.22
Injection Tube Failure	5th (%)	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	Count	14	0	0	0	1	1	1
	Mean (%)	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	95th (%)	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Cement Microannulus Leak	5th (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Count	0	0	0	0	0	0	0
	Mean (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	95th (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Confining Zone Breach+	5th (%)	0.00	1.06	0.28	1.70	3.09	4.43	5.86
	Count	2^	1,110^	312^	1,765^	3,177^	4,541^	5,984^
	Mean (%)	0.00	1.11	0.31	1.77	3.18	4.54	5.98
	95th (%)	0.00	1.16	0.34	1.83	3.27	4.65	6.11
Inadvertent Extraction	5th (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Count	0	0	0	0	0	0	0
	Mean (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	95th (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00

* Percentage values can be converted to number of failures by multiplying the percentage by 100,000 (i.e., the number of realizations)

+ Generic Class IH require a 'Lower Confining Zone Breach' to occur before an 'Upper Confining Zone Breach' can occur. Only one confining zone (i.e., an 'Upper Confining Zone') is required for Class II disposal wells in TX

^ 'Confining Zone Breach', initiating event system failures are directly dependent on the abandoned well plug MTTF used in evaluation of the event tree and scenario. Generic Class IH and TX Class II PRAs use a MTTF of 1,300 years (see **Table 2**). The Generic, collocated in Dimmit County, TX Class II PRA has an expected abandoned well plug MTTF of 5,000 years based on the average abandonment date of 1998 from **Figure 10**.

Table 7: Comparison of important fault and event occurrence in 'Confining Zone Breach' initiating event scenarios

Failures by Component Fault or Event			'Transmissive and Abandoned Well' Fault				'injected waste – migration' Migration Event			
			5th CI Bound (%*)	**Count**	**Mean (%*)**	**95th CI Bound (%*)**	**5th CI Bound (%*)**	**Count**	**Mean (%*)**	**95th CI Bound (%*)**
Realizations with Failures (out of 100,000)	Class IH		99.95	99,964	99.96	99.97	0.00	2	0.00	0.00
	TX Class II		99.95	99,964	99.96	99.97	1.06	1,110	1.11	1.16
	Collocated Class II	0.00	24.71	24,939	24.94	25.16	0.28	312	0.31	0.34
		0.05	24.89	25,120	25.12	25.35	1.70	1,765	1.77	1.83
		0.10	25.07	25,294	25.29	25.52	3.09	3,177	3.18	3.27
		0.15	25.24	25,467	25.47	25.69	4.43	4,541	4.54	4.65
		0.20	25.42	25,649	25.65	25.88	5.86	5,984	5.98	6.11

* Percentage values can be converted to number of failures by multiplying the percentage by 100,000 (i.e., the number of realizations)

FIGURE CAPTIONS

Figure 1: **'Injection tube leak' initiating event scenario, adapted from Rish (2005)**. Labels with all letters capitalized like 'ITUBLEAK' refer to a probability distribution defined in Rish (2005) and listed in **Table S – 1** in the supplementary materials. Accident or failure scenarios are described with event trees in PRA. Subcomponent fault probability distributions for fault trees are defined in **Table S – 2**.

Figure 2: **'Injection tube leak' initiating event scenario for generic TX Class II wells**. This event tree is equivalent to the injection tube leak initiating event, event tree in **Figure 1** with the removal of the 'annulus pressure - containment' event which is described by the ANNPRESSLO fault tree and resultant probability distribution. The removal of the 'annulus pressure - containment' event from Class II PRA event trees replicates the difference in pressure monitoring requirements between Class IH wells and Class II disposal wells.

Figure 3: 'Confining zone breach' initiating event scenario, adapted from Rish (2005). Labels with all letters capitalized like 'UBUOYANCY' refer to a probability distribution defined in Rish (2005) and listed in **Table S – 1** in the supplementary materials. The 'Upper Confining Zone Containment' and 'Lower Confining Zone Containment' events are represented with fault trees.

Figure 4: 'Upper confining zone breach – containment' initiating event scenarios for TX Class II disposal wells. Only one confining zone is required and so only the upper confining zone is included in these event trees. Panel a) shows the event tree that pertains during active injection operations. Class II wells were differentiated because of the relatively large volumes of waste produced by oil and gas activities. It is assumed that this concern translates into relatively large injection volumes. Panel b) displays the event tree that is used after well closure and plugging. This event tree is equivalent to the upper confining zone portion of **Figure 3**.

Figure 5: Schematic of consequences to water resources from open wells. Open wells include unknown wells (which were never abandoned even though they are inactive) and wells with plug failures. Open wells provide migration pathways to USDW (see the "Aquifer" in the schematic) and the ground surface. "Open Wells and Plug Failure" by Southwest Research Institute is licensed under CC BY 4.0.

Figure 6: Class IH hazardous waste injection well CONFINEBRCHU fault tree after Rish (2005). Capitalized labels within parentheses denote a probability distribution defined in **Table S – 2**.

Figure 7: mCONFINEBRCHU fault tree for Class II disposal well in Dimmit County, TX. Capitalized labels within parentheses are quantities with probability distributions defined in **Table S – 2**. Shaded boxes identify portions of the fault tree that are customized for Class II disposal wells collocated with legacy and non-conventional oil and gas opportunities. The quantities in the shaded boxes require a specific case study location for derivation because they describe the likelihood of spatial relationships among a generic disposal well and a known collection of deep wells.

Figure 8: Dimmit County, TX with known oil and gas wells and existing Class II disposal wells. Overall location along with the full extent of the Eagle Ford Shale region is shown on the inset in the top left. 8,445 oil and gas wells are shown along with 42 Class II disposal wells.

Figure 9: Histogram of oil and gas well depths in Dimmit County

Figure 10: Histogram of Plug Installation Years

Figure 11: Histogram for distance to nearest known well

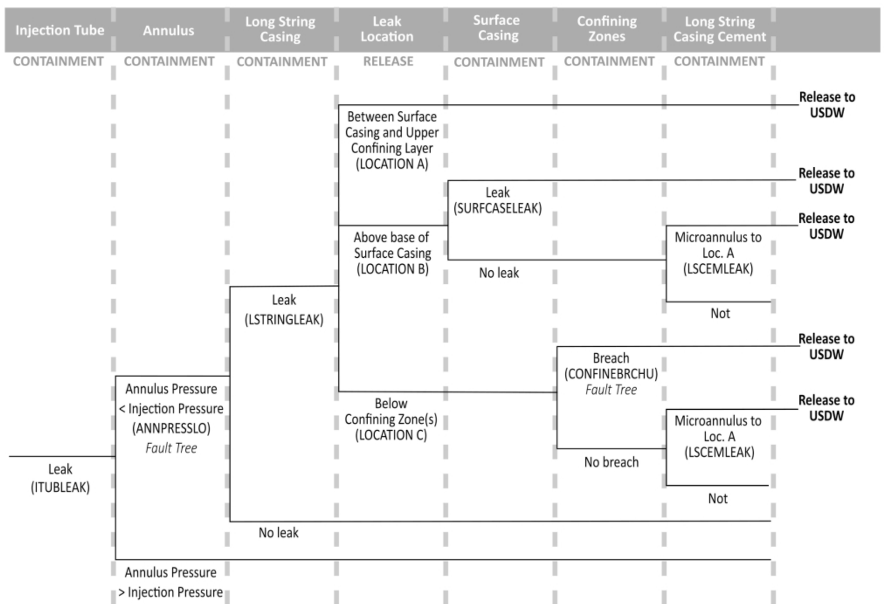

Figure 1: 'Injection tube leak' initiating event scenario, adapted from Rish (2005). Labels with all letters capitalized like 'ITUBLEAK' refer to a probability distribution defined in Rish (2005) and listed in Table S – 1 in the supplementary materials. Accident or failure scenarios are described with event trees in PRA. Subcomponent fault probability distributions for fault trees are defined in Table S – 2.

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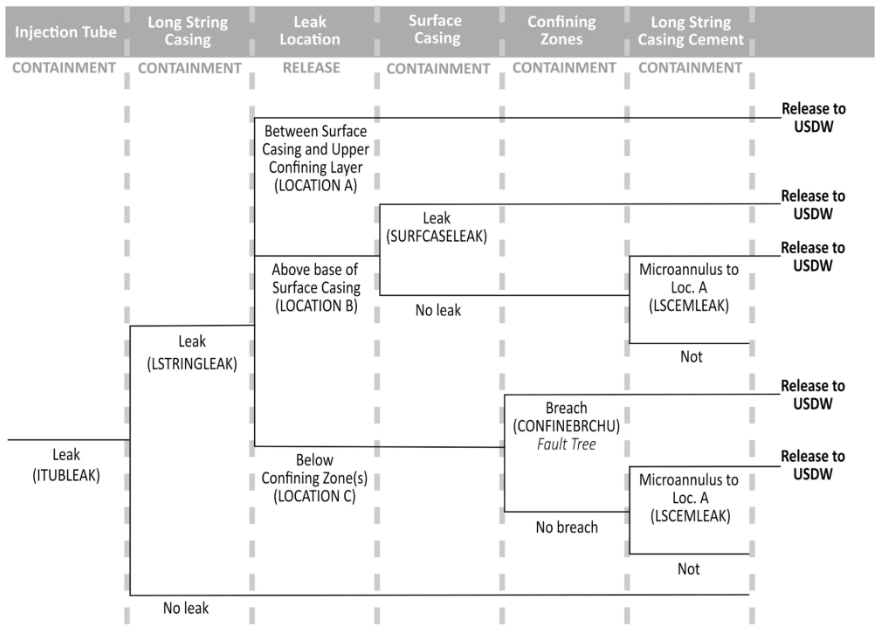

Figure 2: 'Injection tube leak' initiating event scenario for generic TX Class II wells. This event tree is equivalent to the injection tube leak initiating event, event tree in Figure 1 with the removal of the 'annulus pressure - containment' event which is described by the ANNPRESSLO fault tree and resultant probability distribution. The removal of the 'annulus pressure - containment' event from Class II PRA event trees replicates the difference in pressure monitoring requirements between Class IH wells and Class II disposal wells.

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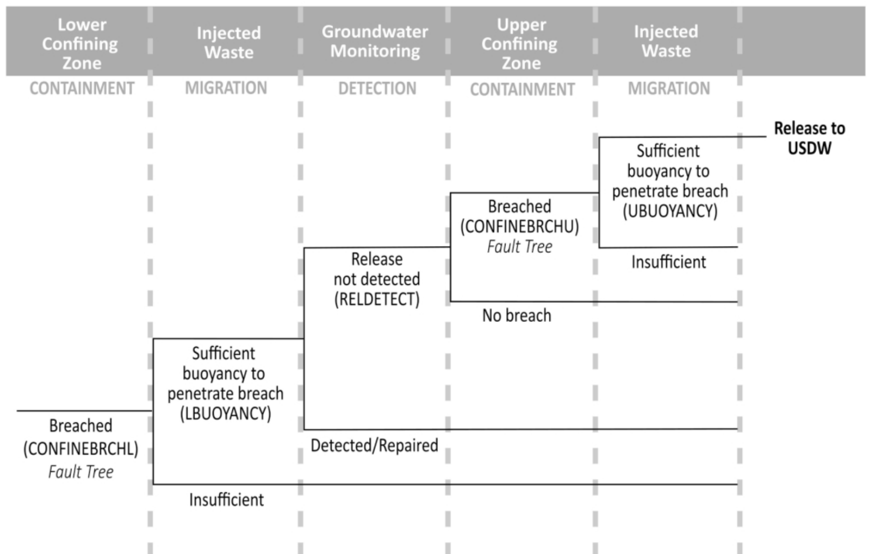

Figure 3: 'Confining zone breach' initiating event scenario, adapted from Rish (2005). Labels with all letters capitalized like ‘UBUOYANCY’ refer to a probability distribution defined in Rish (2005) and listed in Table S – 1 in the supplementary materials. The ‘Upper Confining Zone Containment’ and ‘Lower Confining Zone Containment’ events are represented with fault trees.

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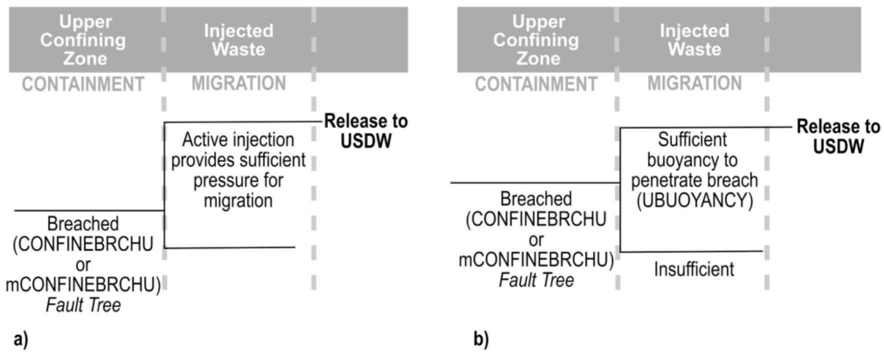

Figure 4: 'Upper confining zone breach – containment' initiating event scenarios for TX Class II disposal wells. Only one confining zone is required and so only the upper confining zone is included in these event trees. Panel a) shows the event tree that pertains during active injection operations. Class II wells were differentiated because of the relatively large volumes of waste produced by oil and gas activities. It is assumed that this concern translates into relatively large injection volumes. Panel b) displays the event tree that is used after well closure and plugging. This event tree is equivalent to the upper confining zone portion of Figure 3.

190x92mm (300 x 300 DPI)

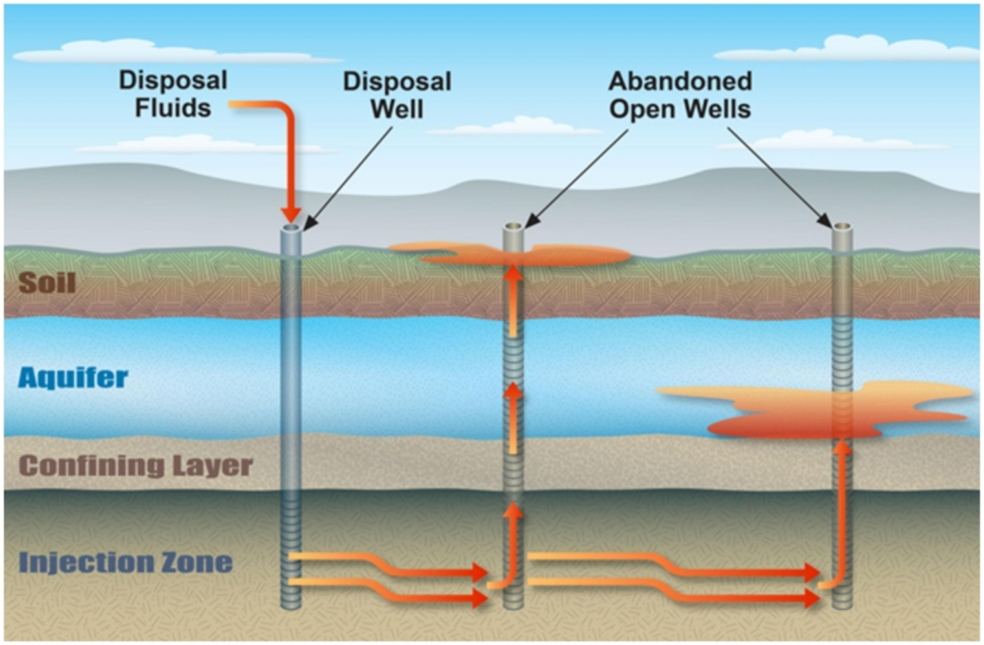

Figure 5: Schematic of consequences to water resources from open wells. Open wells include unknown wells (which were never abandoned even though they are inactive) and wells with plug failures. Open wells provide migration pathways to USDW (see the "Aquifer" in the schematic) and the ground surface. "Open Wells and Plug Failure" by Southwest Research Institute is licensed under CC BY 4.0.

135x90mm (300 x 300 DPI)

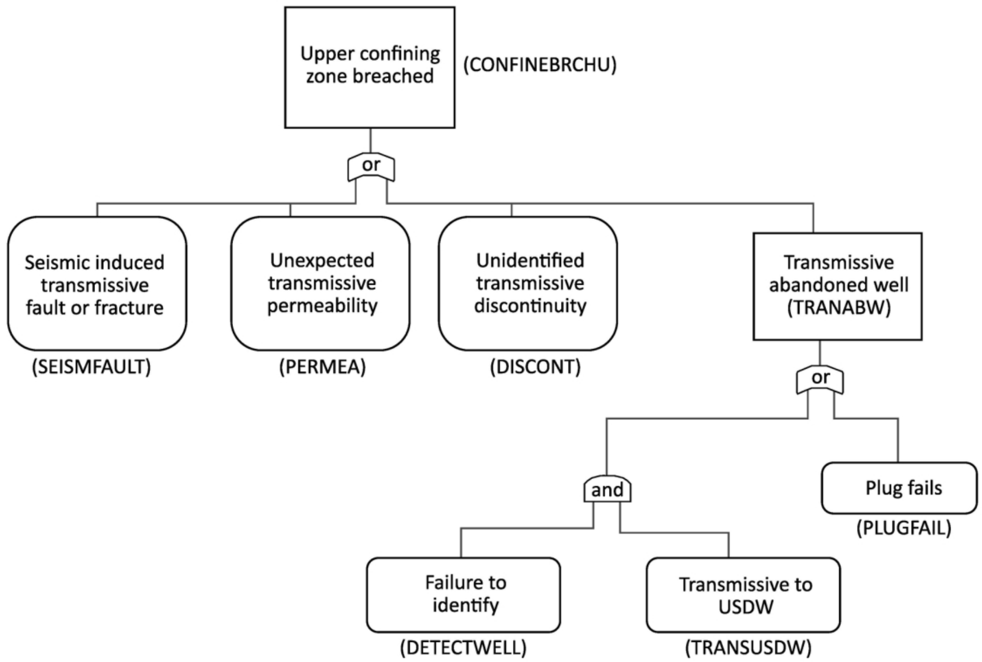

Figure 6: Class IH hazardous waste injection well CONFINEBRCHU fault tree after Rish (2005). Capitalized labels within parentheses denote a probability distribution defined in Table S – 2.

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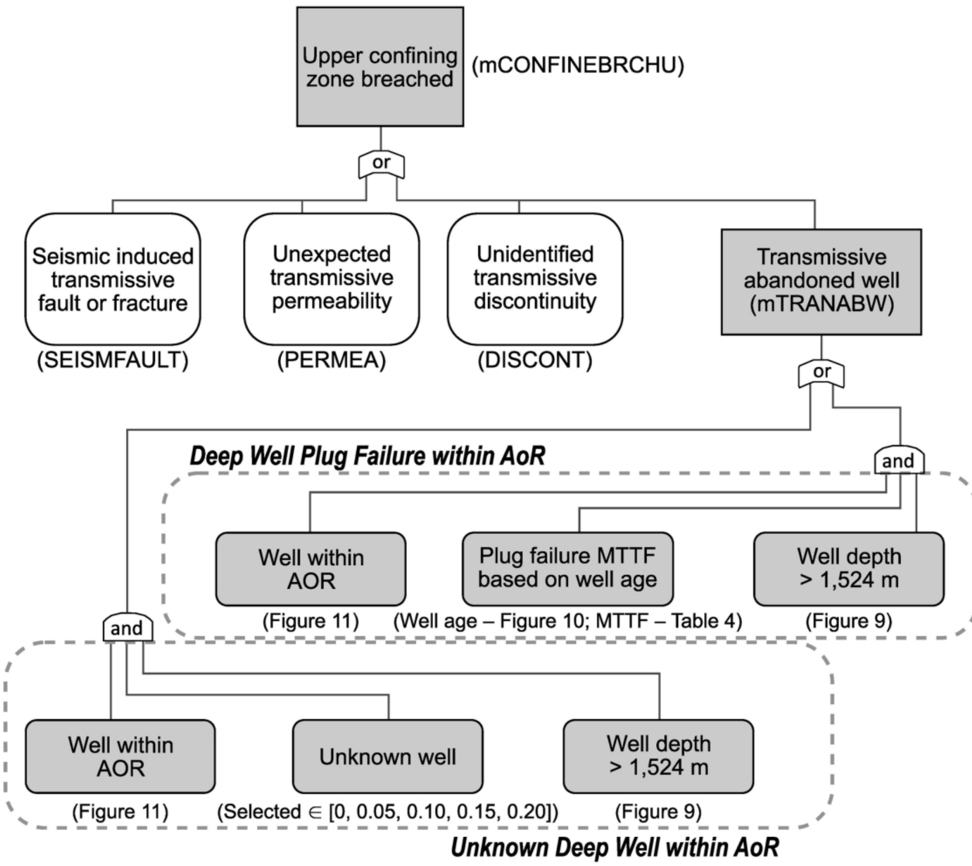


Figure 7: mCONFINEBRCHU fault tree for Class II disposal well in Dimmit County, TX. Capitalized labels within parentheses are quantities with probability distributions defined in Table S – 2. Shaded boxes identify portions of the fault tree that are customized for Class II disposal wells collocated with legacy and non-conventional oil and gas opportunities. The quantities in the shaded boxes require a specific case study location for derivation because they describe the likelihood of spatial relationships among a generic disposal well and a known collection of deep wells.

157x140mm (300 x 300 DPI)

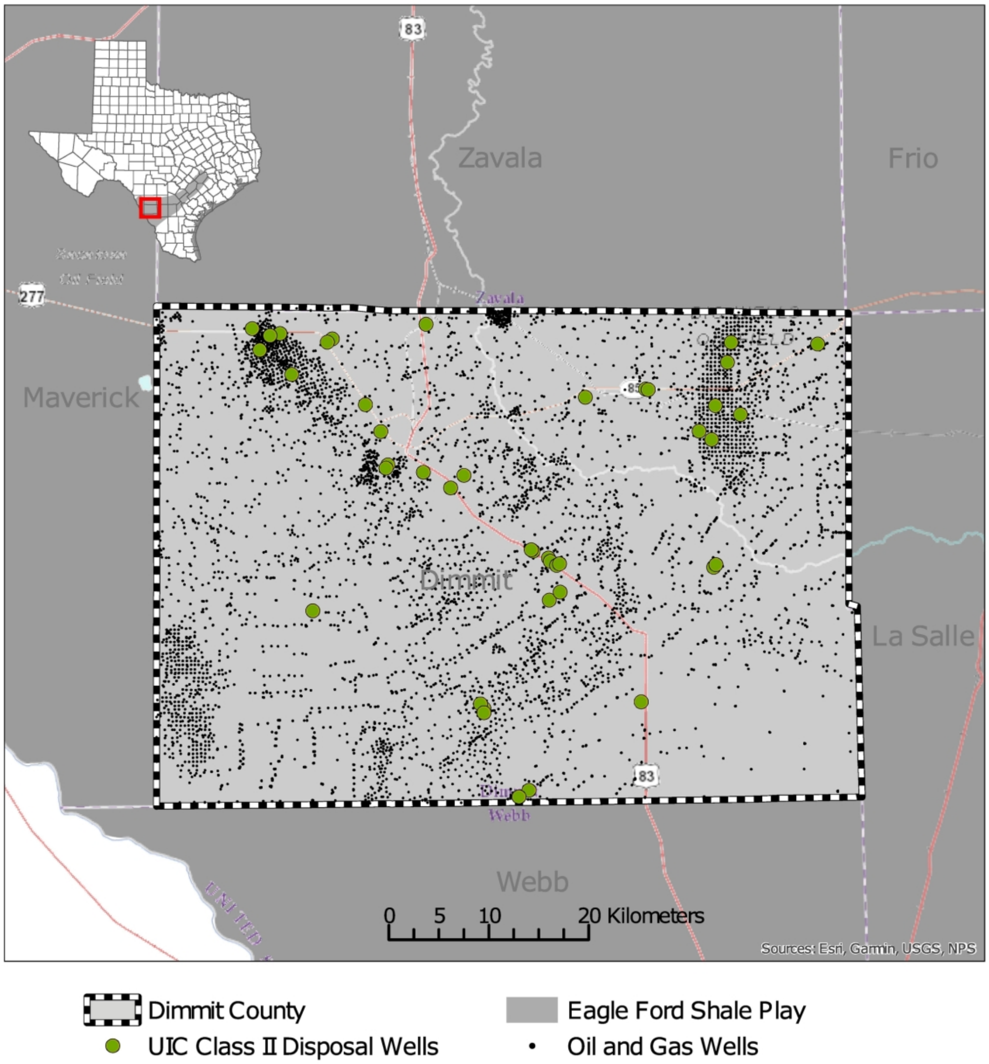


Figure 8: Dimmit County, TX with known oil and gas wells and existing Class II disposal wells. Overall location along with the full extent of the Eagle Ford Shale region is shown on the inset in the top left. 8,445 oil and gas wells are shown along with 42 Class II disposal wells.

196x215mm (300 x 300 DPI)

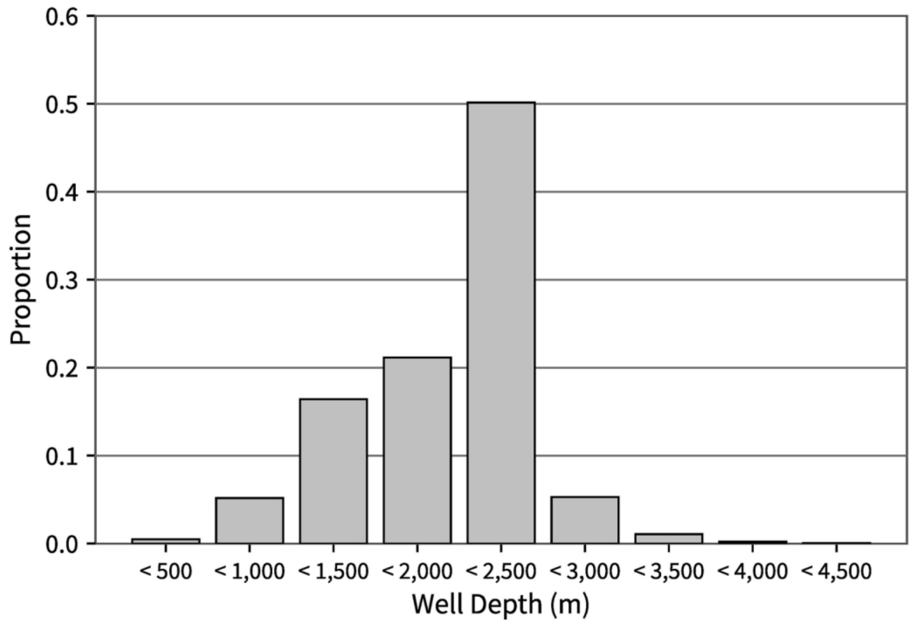


Figure 9: Histogram of oil and gas well depths in Dimmit County

145x94mm (300 x 300 DPI)

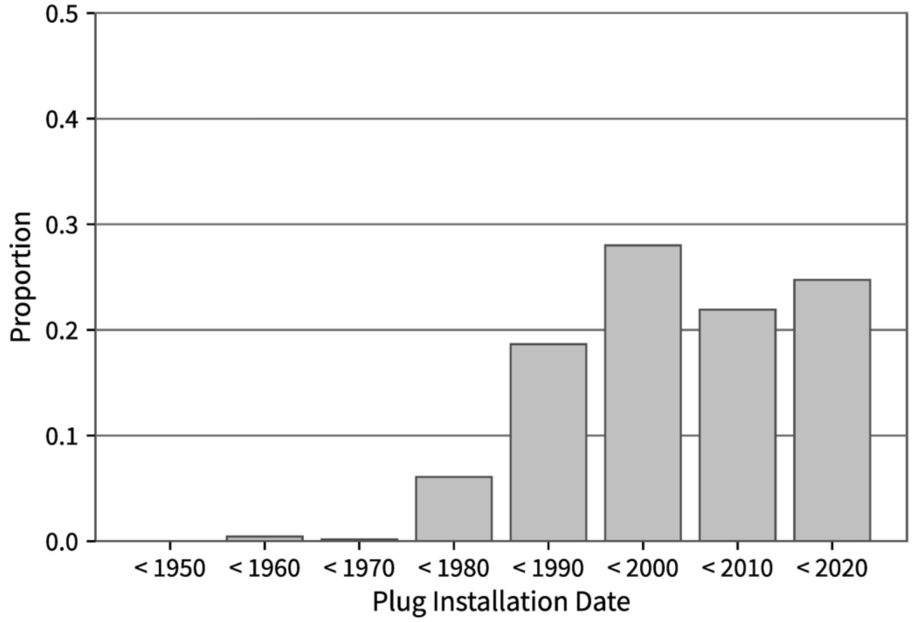


Figure 10: Histogram of Plug Installation Years

145x94mm (300 x 300 DPI)

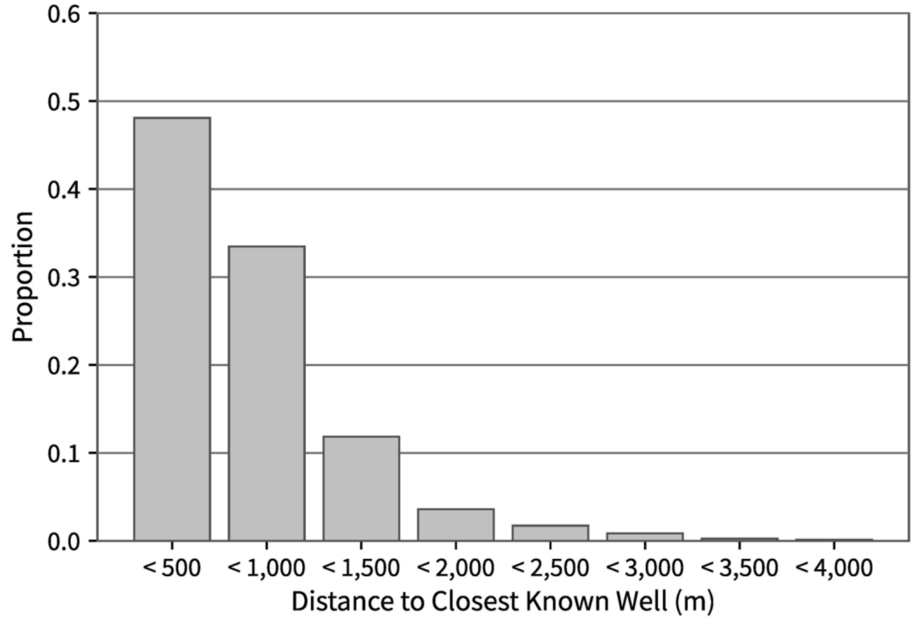


Figure 11: Histogram for distance to nearest known well

145x94mm (300 x 300 DPI)

SUPPLEMENTARY INFORMATION

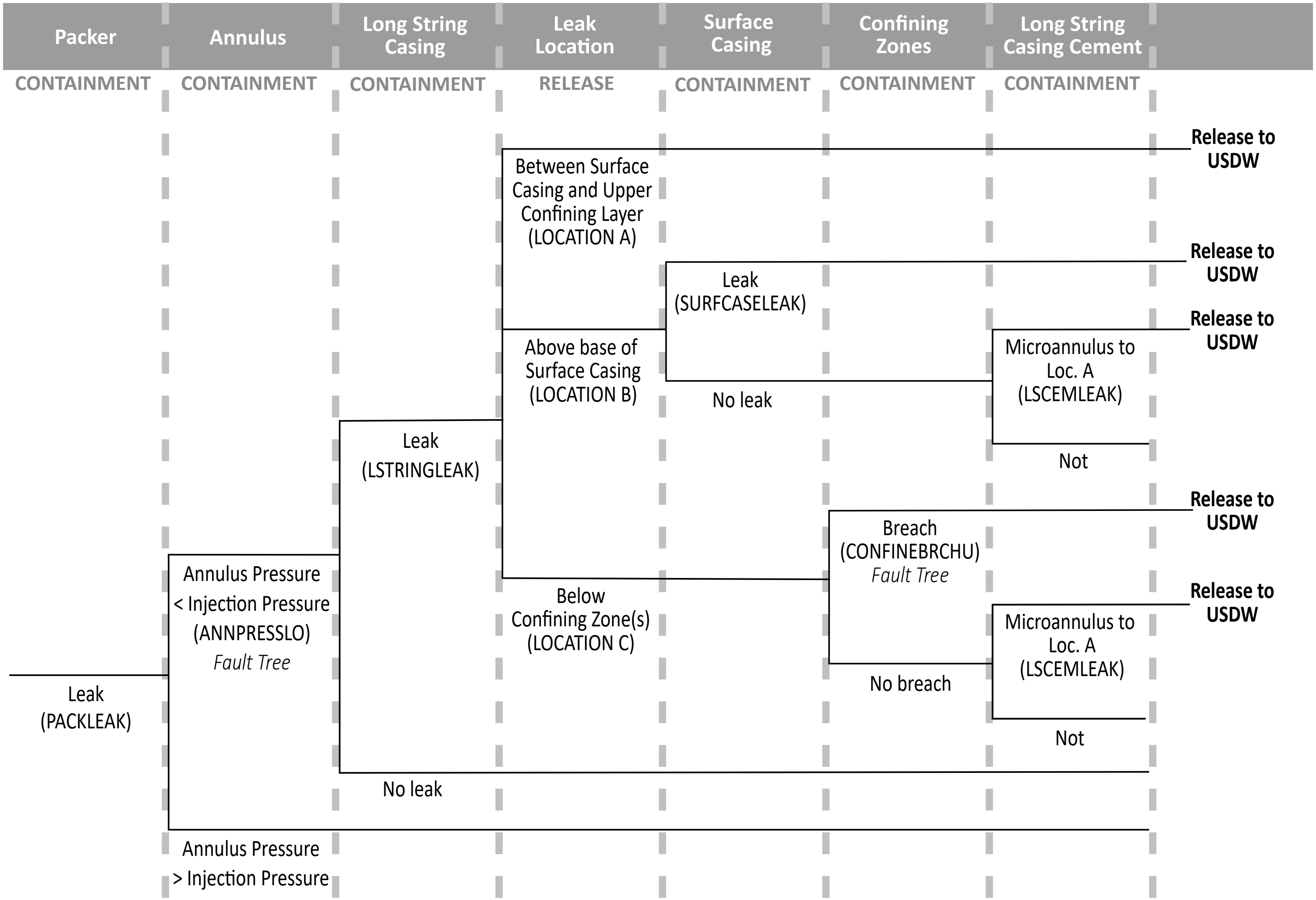
The dynamic PRA simulation models used in this study are available online at:
https://github.com/nmartin198/class_II_UIC_PRA

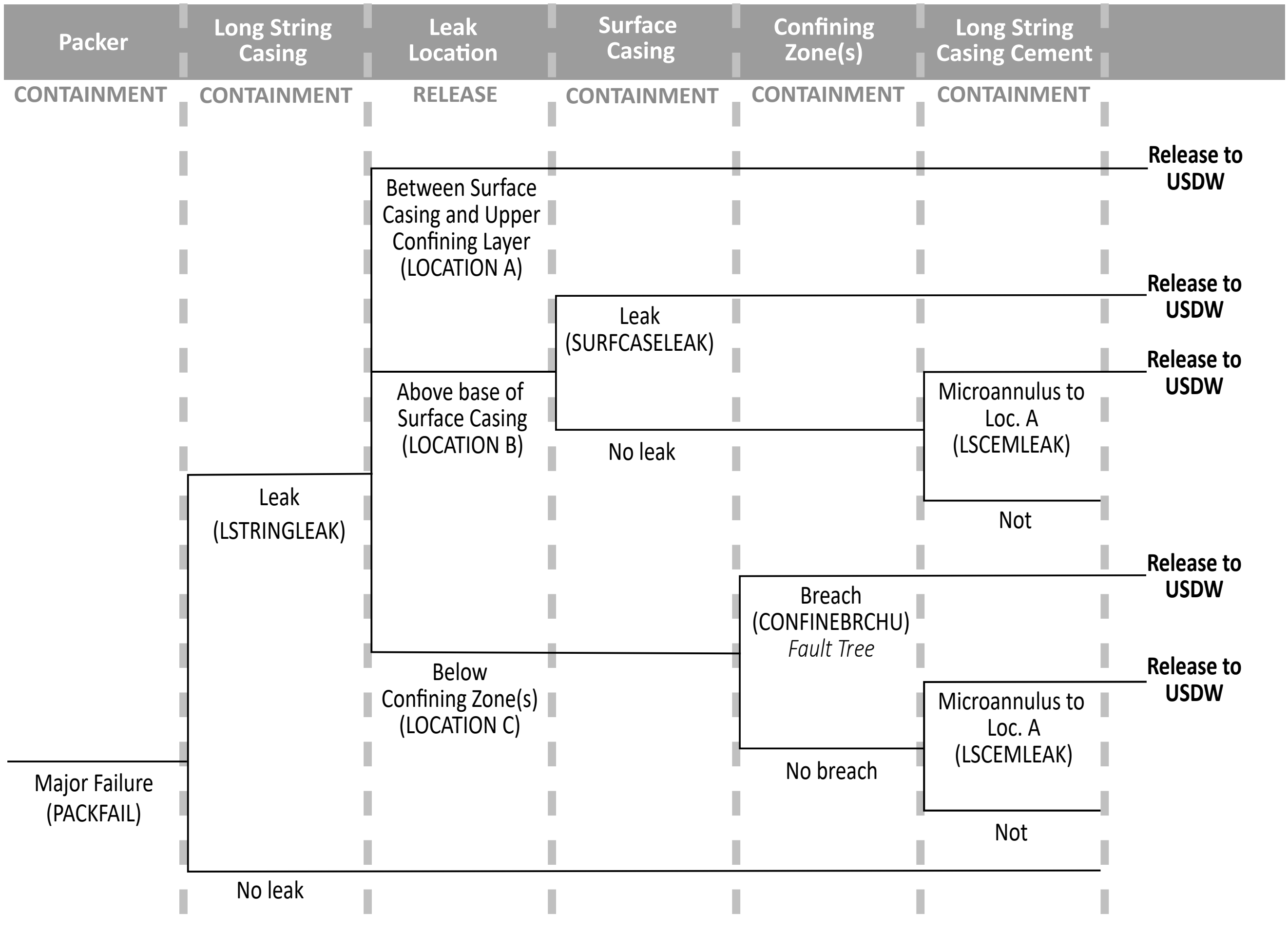
Event Tree and Initiating Event	Distribution										Notes
	Name	Description	Type	units	Parameters						
					Param 1 Name	Param 1 Value	Param 2 Name	Param 2 Value	Param 3 Name	Param 3 Value	
Packer Leak	PACKLEAK	Packer leak	Poisson	day^{-1}	Lower bound	2E-05	Median	4E-05	Upper bound	6E-05	Rish (2005) uses a Poisson distribution with 4.6E-5/day rate
	ANNPRESSLO	Annulus pressure drops below injection pressure	CMF	probability	Lower bound	9.00E-14	Median	7.00E-12	Upper bound	8.00E-11	Rish (2005) provides both a probability distribution as a cumulative mass function (CMF) and a fault tree. The provided probability distribution calculated using Monte Carlo simulation of the fault tree. The CMF is used in the Class I PRA and the fault tree is not simulated.
	LSTRINGLEAK	Long string casing leak	Poisson	day^{-1}	Lower bound	2E-05	Median	3E-05	Upper bound	5E-05	Rish (2005) uses Poisson distribution with 4.2E-5/day rate
	LOCATION_A	Long string casing leak located between surface and	Uniform	probability	Lower bound	1E-02	Median	3E-02	Upper bound	5E-02	
	LOCATION_B	Long string casing leak located above base of surface casing	Uniform	probability	Lower bound	1E-02	Median	5E-02	Upper bound	1E-01	
	LOCATION_C	Long string casing leak located below confining zone	Uniform	probability	Lower bound	9E-01	Median	9E-01	Upper bound	1E+00	
	SURFCASELEAK	Surface casing leak	Poisson	day^{-1}	Lower bound	2E-06	Median	3E-06	Upper bound	5E-06	Rish (2005) uses Poisson distribution with 4.2E-6/day rate
	CONFINEBRCHU	Transmissive breach occurs through upper confining zone	CMF	probability	Lower bound	6E-04	Median	3E-03	Upper bound	1E-02	Rish (2005) provides both a CMF and a fault tree. The provided probability distribution calculated using Monte Carlo simulation of the fault tree. Class I PRA simulates the fault tree.
	LSCEMLEAK	Longstring casing cement microannulus allows fluid movement along casing	Poisson	day^{-1}	Lower bound	2E-06	Median	3E-05	Upper bound	5E-05	Rish (2005) uses Poisson distribution with 1.1E-5/day rate
Packer Failure	PACKFAIL	Sudden/major failure and breach of packer	Poisson	day^{-1}	Lower bound	2E-07	Median	4E-07	Upper bound	6E-07	Rish (2005) uses Poisson distribution with 4.6E-7/day rate
	LSTRINGLEAK	Long string casing leak	Poisson	day^{-1}	Lower bound	2E-05	Median	3E-05	Upper bound	5E-05	Rish (2005) uses Poisson distribution with 4.2E-5/day rate
	LOCATION_A	Long string casing leak located between surface and	Uniform	probability	Lower bound	1E-02	Median	3E-02	Upper bound	5E-02	
	LOCATION_B	Long string casing leak located above base of surface casing	Uniform	probability	Lower bound	1E-02	Median	5E-02	Upper bound	1E-01	
	LOCATION_C	Long string casing leak located below confining zone	Uniform	probability	Lower bound	9E-01	Median	9E-01	Upper bound	1E+00	
	SURFCASELEAK	Surface casing leak	Poisson	day^{-1}	Lower bound	2E-06	Median	3E-06	Upper bound	5E-06	Rish (2005) uses Poisson distribution with 4.2E-6/day rate
	CONFINEBRCHU	Transmissive breach occurs through upper confining zone	CMF	probability	Lower bound	6E-04	Median	3E-03	Upper bound	1E-02	Rish (2005) provides both a CMF and a fault tree. The provided probability distribution calculated using Monte Carlo simulation of the fault tree. Class I PRA simulates the fault tree.
	LSCEMLEAK	Longstring casing cement microannulus allows fluid movement along casing	Poisson	day^{-1}	Lower bound	2E-06	Median	3E-05	Upper bound	5E-05	Rish (2005) uses Poisson distribution with 1.1E-5/day rate
Injection Tube Leak	ITUBLEAK	Injection tube leak	Poisson	day^{-1}	Lower bound	3E-05	Median	6E-05	Upper bound	8E-05	Rish (2005) uses a Poisson distribution with 6.8E-05/day rate
	ANNPRESSLO	Annulus pressure drops below injection pressure	CMF	probability	Lower bound	9.00E-14	Median	7.00E-12	Upper bound	8.00E-11	Rish (2005) provides both a CMF and a fault tree. The provided probability distribution calculated using Monte Carlo simulation of the fault tree.
	LSTRINGLEAK	Long string casing leak	Poisson	day^{-1}	Lower bound	2E-05	Median	3E-05	Upper bound	5E-05	Rish (2005) uses Poisson distribution with 4.2E-5/day rate
	LOCATION_A	Long string casing leak located between surface and	Uniform	probability	Lower bound	1E-02	Median	3E-02	Upper bound	5E-02	
	LOCATION_B	Long string casing leak located above base of surface casing	Uniform	probability	Lower bound	1E-02	Median	5E-02	Upper bound	1E-01	
	LOCATION_C	Long string casing leak located below confining zone	Uniform	probability	Lower bound	9E-01	Median	9E-01	Upper bound	1E+00	
	SURFCASELEAK	Surface casing leak	Poisson	day^{-1}	Lower bound	2E-06	Median	3E-06	Upper bound	5E-06	Rish (2005) uses Poisson distribution with 4.2E-6/day rate
	CONFINEBRCHU	Transmissive breach occurs through upper confining zone	CMF	probability	Lower bound	6E-04	Median	3E-03	Upper bound	1E-02	Rish (2005) provides both a CMF and a fault tree. The provided probability distribution calculated using Monte Carlo simulation of the fault tree. Class I PRA simulates the fault tree
	LSCEMLEAK	Longstring casing cement microannulus allows fluid movement along casing	Poisson	day^{-1}	Lower bound	2E-06	Median	3E-05	Upper bound	5E-05	Rish (2005) uses Poisson distribution with 1.1E-5/day rate

Injection Tube Failure	ITUBFAIL	Sudden/major failure and breach of injection tube	Poisson	day^{-1}	Lower bound	3E-07	Median	6E-07	Upper bound	8E-07	Rish (2005) uses Poisson distribution with 6.8E-7/day rate
	LSTRINGLEAK	Long string casing leak	Poisson	day^{-1}	Lower bound	2E-05	Median	3E-05	Upper bound	5E-05	Rish (2005) uses Poisson distribution with 4.2E-5/day rate
	LOCATION_A	Long string casing leak located between surface and	Uniform	probability	Lower bound	1E-02	Median	3E-02	Upper bound	5E-02	
	LOCATION_B	Long string casing leak located above base of surface casing	Uniform	probability	Lower bound	1E-02	Median	5E-02	Upper bound	1E-01	
	LOCATION_C	Long string casing leak located below confining zone	Uniform	probability	Lower bound	9E-01	Median	9E-01	Upper bound	1E+00	
	SURFCASELEAK	Surface casing leak	Poisson	day^{-1}	Lower bound	2E-06	Median	3E-06	Upper bound	5E-06	Rish (2005) uses Poisson distribution with 4.2E-6/day rate
	CONFINEBRCHU	Transmissive breach occurs through upper confining zone	CMF	probability	Lower bound	6E-04	Median	3E-03	Upper bound	1E-02	Rish (2005) provides both a CMF and a fault tree. The provided probability distribution calculated using Monte Carlo simulation of the fault tree. Class I PRA simulates the fault tree.
	LSCEMLEAK	Longstring casing cement microannulus allows fluid movement along casing	Poisson	day^{-1}	Lower bound	2E-06	Median	3E-05	Upper bound	5E-05	Rish (2005) uses Poisson distribution with 1.1E-5/day rate
Cement Microannulus Leak	LSCEMLEAK	Longstring casing cement microannulus allows fluid movement along casing	Poisson	day^{-1}	Lower bound	2E-06	Median	3E-05	Upper bound	5E-05	Rish (2005) uses Poisson distribution with 1.1E-5/day rate
	FLUIDTEST	Testing fails to detect injection fluid migration along outside of long string casing	Uniform	probability	Lower bound	5E-04	Median	3E-03	Upper bound	5E-03	
	MIGRATION_A	Waste migrates up microannulus to Location A between surface casing and upper confining zone	Uniform	probability	Lower bound	1E-04	Median	1E-03	Upper bound	1E-02	
	CONFINEBRCHU	Transmissive breach occurs through upper confining zone	CMF	probability	Lower bound	6E-04	Median	3E-03	Upper bound	1E-02	Rish (2005) provides both a CMF and a fault tree. The provided probability distribution calculated using Monte Carlo simulation of the fault tree. Class I PRA simulates the fault tree.
	UBUOYANCY	Injected fluid is sufficiently buoyant to penetrate upper confining zone breach	Uniform	probability	Lower bound	1E-05	Median	5E-05	Upper bound	1E-04	
Confining Zone Breach	CONFINEBRCHL	Transmissive breach occurs through lower confining zone	CMF	probability	Lower bound	6E-04	Median	3E-03	Upper bound	1E-02	Rish (2005) provides both a CMF and a fault tree. The provided probability distribution calculated using Monte Carlo simulation of the fault tree. Class I PRA simulates the fault tree.
	LBUOYANCY	Injected fluid is sufficiently buoyant to penetrate lower confining zone breach	Single value	probability	1E+00						
	RELDETECT	Groundwater monitoring fails to detect waste release outside injection zone	Single value	probability	5E-01						
	CONFINEBRCHU	Transmissive breach occurs through upper confining zone	CMF	probability	Lower bound	6E-04	Median	3E-03	Upper bound	1E-02	Rish (2005) provides both a CMF and a fault tree. The provided probability distribution calculated using Monte Carlo simulation of the fault tree. Class I PRA simulates the fault tree.
	UBUOYANCY	Injected fluid is sufficiently buoyant to penetrate upper confining zone breach	Uniform	probability	Lower bound	1E-05	Median	5E-05	Upper bound	1E-04	
Inadvertant Extraction	EXTRACT	Extraction of groundwater from the injection zone	Uniform	probability	Lower bound	1E-05	Median	1E-04	Upper bound	1E-03	Log uniform required to obtain the stated median.
	NORECOGNIZE	Failure to recognize groundwater extraction located within injection waste zone	Uniform	probability	Lower bound	1E-03	Median	5E-03	Upper bound	1E-02	
	OUTAOR	Injection wast has migrated outside of Area of Review to unconfined zone	Uniform	probability	Lower bound	1E-05	Median	5E-05	Upper bound	1E-04	
	WASTEPRESENT	Injected waste has not transformed into nonwaste	Uniform	probability	Lower bound	1E-02	Median	1E-01	Upper bound	1E+00	Log uniform required to obtain stated median

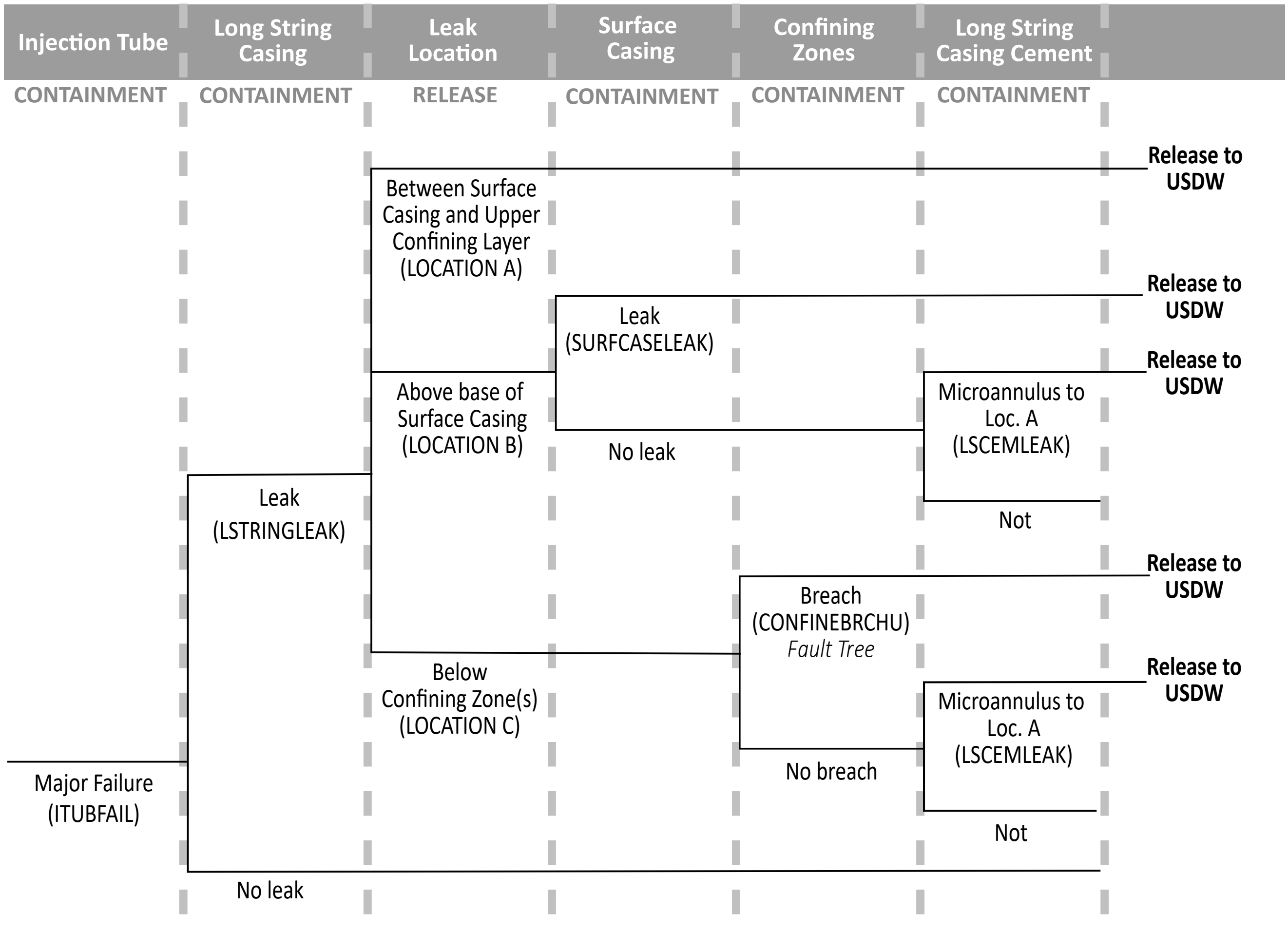
Fault Tree	Distribution										Notes
	Name	Description	Type	units	Parameters						
					Param 1 Name	Param 1 Value	Param 2 Name	Param 2 Value	Param 3 Name	Param 3 Value	
ANNPRESSLO	PUMPPA	Annulus pump fails	Triangular	probability	Lower bound	5E-05	Median	5E-04	Upper bound	5E-03	
	CHECKPA	Annulus check valve fails to open	Triangular	probability	Lower bound	1E-04	Median	3E-04	Upper bound	1E-03	
	LSCASEFAIL	Sudden/major failure and breach of long string casing	Poisson	day^{-1}	Lower bound	2E-07	Median	3E-07	Upper bound	5E-07	Rish (2005) uses Poisson distribution with 4.2E-7/day rate
	CONTROLPA	Annulus pressure control system fails, resulting in overpressurization	Uniform	probability	Lower bound	1E-06	Median	1E-05	Upper bound	1E-04	Requires log uniform to obtain the median
	OPERRPA	Operator error causes annulus pressure below injection pressure	Uniform	probability	Lower bound	5E-05	Median	3E-05	Upper bound	5E-04	All operator failures are correlated using r=0.5
	CONTROLPI	Injection pressure control system fails, resulting in overpressurization	Uniform	probability	Lower bound	1E-06	Median	1E-05	Upper bound	1E-04	Requires log uniform to obtain the median
	OPERRPI	Operator error causes injection pressure above annulus pressure	Uniform	probability	Lower bound	5E-05	Median	3E-05	Upper bound	5E-04	All operator failures are correlated using r=0.5
	CAPLOSS	Loss of injection capacity result in overpressurization	Uniform	probability	Lower bound	1E-05	Median	1E-04	Upper bound	1E-03	
	ALARM	Automatic alarm fails	Uniform	probability	Lower bound	5E-05	Median	3E-04	Upper bound	5E-04	
	OPERRDET	Operator fails to detect/respond to unacceptable pressure differential	Uniform	probability	Lower bound	5E-05	Median	3E-05	Upper bound	5E-04	All operator failures are correlated using r=0.5
CONFINBRCHL	DETECTWELL	Failure to identify a well in AOR	Uniform	probability	Lower bound	1E-03	Median	5E-03	Upper bound	1E-02	
	TRANSLCZ	Unidentified abandoned well transmissive through lower confining zone	Single Value	probability	1E-01						
	ALARM	Automatic alarm fails	Uniform	probability	Lower bound	5E-05	Median	3E-04	Upper bound	5E-04	
	OPERRFRAC	Operator error results in induced transmissive fracture through the lower confining zone	Uniform	probability	Lower bound	5E-05	Median	3E-05	Upper bound	5E-04	All operator failures are correlated using r=0.5
	ALARM	Automatic alarm fails	Uniform	probability	Lower bound	5E-05	Median	3E-04	Upper bound	5E-04	
	CAPLOSS	Loss of injection zone capacity	Uniform	probability	Lower bound	1E-05	Median	1E-04	Upper bound	1E-03	
	PLUGFAIL	Identified abandoned well plug fails	Poisson	day^{-1}	Lower bound	2E-04	Median	8E-04	Upper bound	2E-03	Rish (2005) uses a Poisson distribution with 8E-4/well rate
	OPERINJ	Operator fails to recognize changes in confining zone capacity	Uniform	probability	Lower bound	5E-05	Median	3E-05	Upper bound	5E-04	All operator failures are correlated using r=0.5
	INCOMPWASTE	Injected waste is chemically incompatible with geology or previously injected waste	Uniform	probability	Lower bound	1E-05	Median	5E-05	Upper bound	1E-04	
	SEISMFAULT	Seismic induced transmissive fault or fracture	Uniform	probability	Lower bound	1E-05	Median	5E-05	Upper bound	1E-04	
	OUTAOR	Injection wast has migrated outside of Area of Review to unconfined zone	Uniform	probability	Lower bound	1E-05	Median	5E-05	Upper bound	1E-04	
	PERMEA	Confining zone has unexpected transmissive permeability	Uniform	probability	Lower bound	1E-05	Median	1E-04	Upper bound	1E-03	Need log uniform to obtain the median
	DISCONT	Unidentified transmissive discontinuity	Uniform	probability	Lower bound	1E-04	Median	1E-03	Upper bound	1E-02	
	DETECTWELL	Failure to Identify	Uniform	probability	Lower bound	1E-03	Median	5E-03	Upper bound	1E-02	
	TRANSUSDW	Unidentified abandoned well transmissive through upper confining zone to USDW	Single value	probability	1E-01						

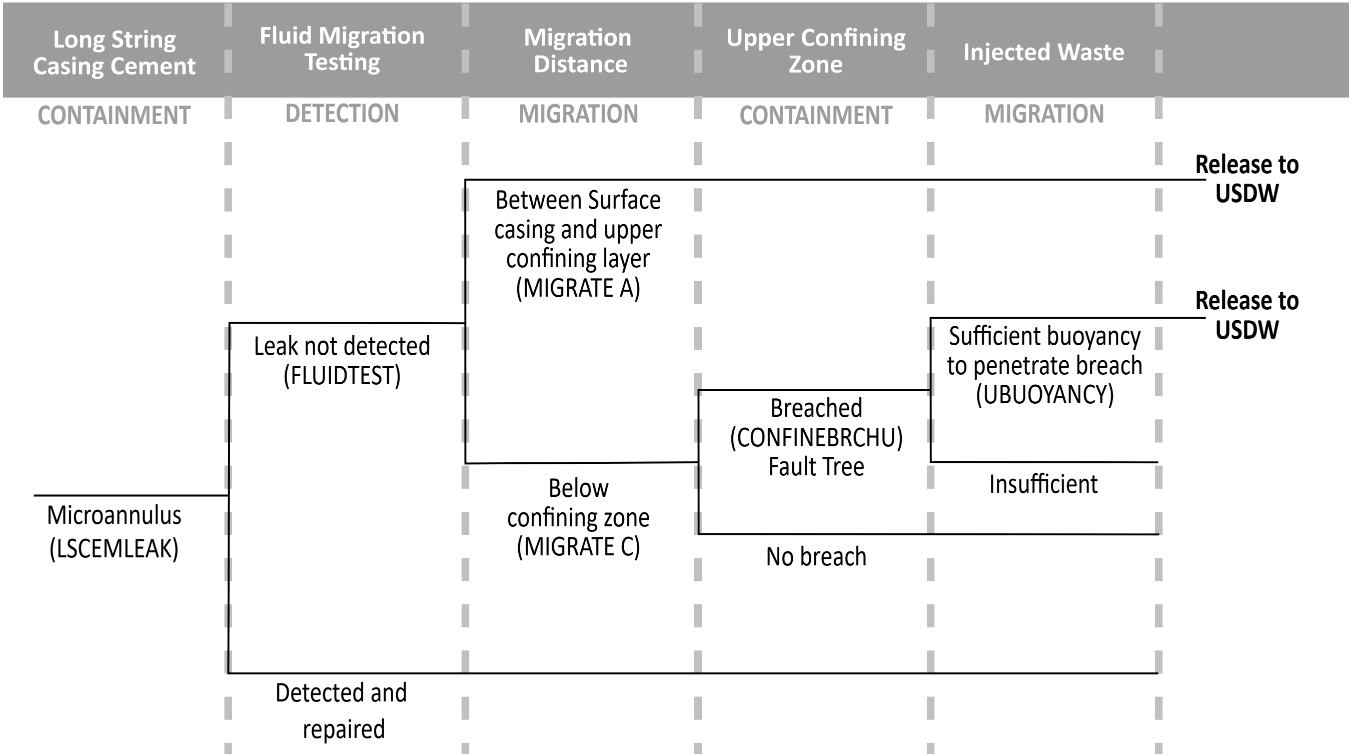
CONFINEBRCHU	PLUGFAIL	Identified abandoned well plug fails	Poisson	day^{-1}	Lower bound	2E-04	Median	8E-04	Upper bound	2E-03	Rish (2005) uses a Poisson distribution with 8E-4/well rate
	SEISMFAULT	Seismic induced transmissive fault or fracture	Uniform	probability	Lower bound	1E-05	Median	5E-05	Upper bound	1E-04	
	PERMEA	Confining zone has unexpected transmissive permeability	Uniform	probability	Lower bound	1E-05	Median	1E-04	Upper bound	1E-03	Need log uniform to obtain the median
	DISCONT	Unidentified transmissive discontinuity	Uniform	probability	Lower bound	1E-04	Median	1E-03	Upper bound	1E-02	

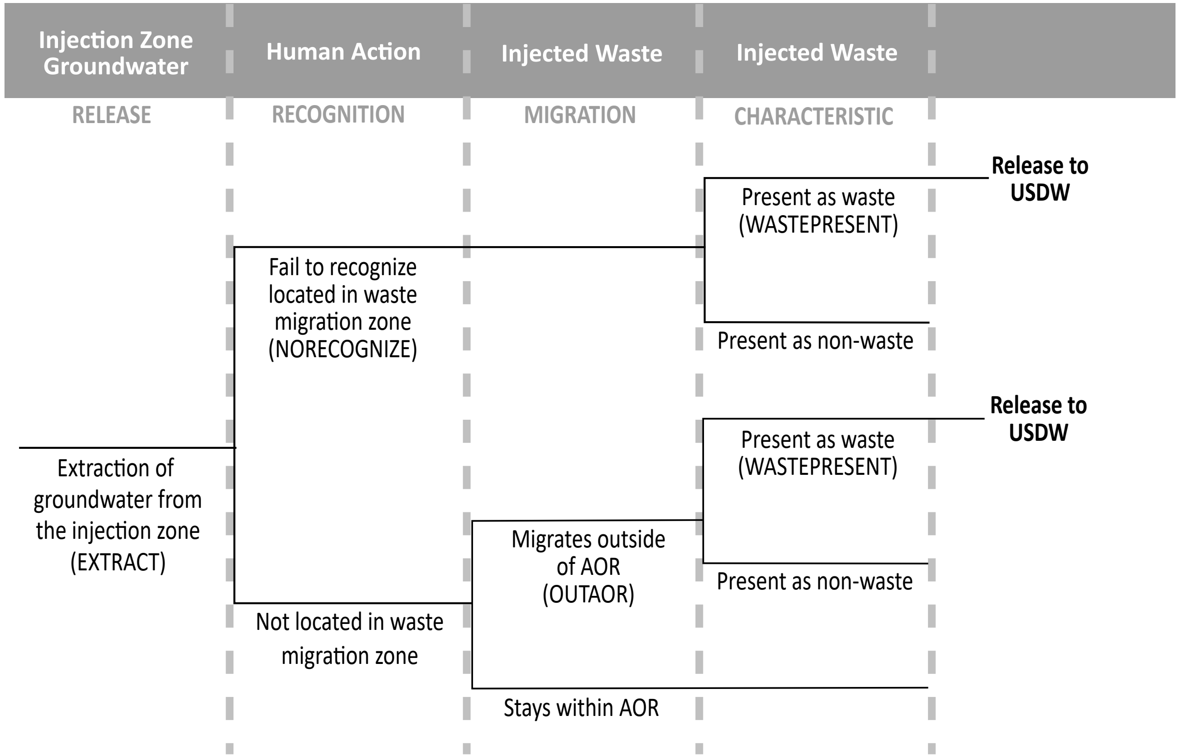

Packer
Annulus
Long String Casing
Leak Location
Surface Casing
Confining Zones
Long String Casing Cement
CONTAINMENT
CONTAINMENT
CONTAINMENT
RELEASE
CONTAINMENT
CONTAINMENT
CONTAINMENT
Release to USDW
Between Surface Casing and Upper Confining Layer (LOCATION A)
Release to USDW
Leak (SURFCASELEAK)
Release to USDW
Above base of Surface Casing (LOCATION B)
No leak
Microannulus to Loc. A (LSCEMLEAK)
Not
Leak (LSTRINGLEAK)
Release to USDW
Breach (CONFINEBRCHU) Fault Tree
Release to USDW
Below Confining Zone(s) (LOCATION C)
Microannulus to Loc. A (LSCEMLEAK)
No breach
Not
Annulus Pressure < Injection Pressure (ANNPRESSLO) Fault Tree
Leak (PACKLEAK)
No leak
Annulus Pressure > Injection Pressure



Packer
Long String Casing
Leak Location
Surface Casing
Confining Zone(s)
Long String Casing Cement
CONTAINMENT
CONTAINMENT
RELEASE
CONTAINMENT
CONTAINMENT
CONTAINMENT
Release to USDW
Between Surface Casing and Upper Confining Layer (LOCATION A)
Release to USDW
Leak (SURFCASELEAK)
Release to USDW
Above base of Surface Casing (LOCATION B)
Microannulus to Loc. A (LSCEMLEAK)
No leak
Leak (LSTRINGLEAK)
Not
Release to USDW
Breach (CONFINEBRCHU)
Fault Tree
Below Confining Zone(s) (LOCATION C)
Release to USDW
Microannulus to Loc. A (LSCEMLEAK)
No breach
Major Failure (PACKFAIL)
Not
No leak


Injection Tube
Long String Casing
Leak Location
Surface Casing
Confining Zones
Long String Casing Cement
CONTAINMENT
CONTAINMENT
RELEASE
CONTAINMENT
CONTAINMENT
CONTAINMENT
Major Failure (ITUBFAIL)
Leak (LSTRINGLEAK)
No leak
Between Surface Casing and Upper Confining Layer (LOCATION A)
Above base of Surface Casing (LOCATION B)
Below Confining Zone(s) (LOCATION C)
Leak (SURFCASELEAK)
No leak
Breach (CONFINEBRCHU) Fault Tree
No breach
Microannulus to Loc. A (LSCEMLEAK)
Not
Microannulus to Loc. A (LSCEMLEAK)
Not
Release to USDW
Release to USDW
Release to USDW
Release to USDW
Release to USDW


Long String Casing Cement
Fluid Migration Testing
Migration Distance
Upper Confining Zone
Injected Waste
CONTAINMENT
DETECTION
MIGRATION
CONTAINMENT
MIGRATION
Release to USDW
Between Surface casing and upper confining layer (MIGRATE A)
Release to USDW
Sufficient buoyancy to penetrate breach (UBUOYANCY)
Leak not detected (FLUIDTEST)
Breached (CONFINEBRCHU) Fault Tree
Insufficient
Below confining zone (MIGRATE C)
Microannulus (LSCEMLEAK)
No breach
Detected and repaired


Injection Zone Groundwater
Human Action
Injected Waste
Injected Waste
RELEASE
RECOGNITION
MIGRATION
CHARACTERISTIC
Release to USDW
Present as waste (WASTEPRESENT)
Fail to recognize located in waste migration zone (NORECOGNIZE)
Present as non-waste
Release to USDW
Present as waste (WASTEPRESENT)
Extraction of groundwater from the injection zone (EXTRACT)
Migrates outside of AOR (OUTAOR)
Present as non-waste
Not located in waste migration zone
Stays within AOR