A Probabilistic Risk Assessment of Class I Hazardous Waste Injection Wells

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Approximately 150 underground injection wells exist in the United States that are categorized by the United States Environmental Protection Agency (U.S. EPA) as Class IH. These are wells that inject hazardous liquid waste. Based on figures from the U.S. EPA's Toxic Release Inventory (TRI), the volume of hazardous waste disposed of through Class IH deep well injection is about 220 million pounds. Since the primary goal of deep well injection is waste isolation, the primary risk to the environment is loss of waste containment. Surprisingly, no quantitative assessment of the risk of loss of waste isolation from Class IH injection, as currently practiced, has been performed by advocates, critics, or regulators of the industry. Using Failure Modes and Effects Analysis (FMEA), we identified and evaluated all the ways in which a deep well injection system can fail. Event and fault trees were developed for release to the lowermost underground source of drinking water (USDW), and frequencies were assigned to each event. Uncertainty about event frequencies was treated explicitly by developing probability distributions for each and propagating these through event sequences using Monte Carlo analysis and the Boolean algebra inherent to the trees. Based on the results of the analysis, it was estimated that the risk of loss of waste isolation from the accessible environment over the operating period of a Class IH injection well is less than one in one million (1E-6) at reasonable confidence levels.

INTRODUCTION

The disposal of the large volumes of industrial and municipal wastes has been a source of on-going concern throughout the latter half of the twentieth century. Over the past 20 years increasing stringent waste disposal regulations have improved environmental quality while limiting disposal options and raising costs. Since waste reduction techniques are equally subject to the law of diminishing returns, some waste will always result from human activities and disposal issues will remain to be addressed. From a societal viewpoint, the ideal disposal method should be (virtually) infinite, cheap, permanent, and result in no human or ecological exposures in the foreseeable future. Most current regulated methods of disposal, for example landfills or incineration, fail on one or more of these scores. Only deep well injection appears to satisfy all four requirements; however, the environmental risks associated with Class IH disposal technology remains a source of controversy.

Approximately 150 underground injection wells exist in the United States that are categorized by the United States Environmental Protection Agency (U.S. EPA) as Class IH[41]. These are wells that inject hazardous liquid waste. The majority of Class IH wells are located in the Great Lakes Region and the Gulf States, due to the favorable geology in these regions. Over half of Class IH wells are located in Texas and Louisiana, and almost 90% are in U.S. EPA Regions V and VI[41]. Based on figures from the U.S. EPA's Toxic Release Inventory (TRI)[42], the volume of hazardous waste disposed of through Class IH deep well injection is about 220 million pounds. This value is somewhat deceptive since the practice of deep well injection involves dilution of the waste with large amounts of water before it is pumped into the subsurface. Industries that practice deep well injection are sometimes singled out as major sources of pollutant releases to the environment. Since

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the intent of deep well injection is the permanent isolation of waste from the biosphere, it is unclear if the use of deep well injection is properly termed a release to the environment. While problems resulting from deep well injection have occurred, these incidents took place in the past and the conditions that caused them do not occur under current regulation and practice.

U.S. EPA promulgated regulations in 1980 governing all injection wells including those injecting hazardous waste (53 FR 28131). In 1988 U.S. EPA passed additional regulations requiring operators of Class IH wells to demonstrate that no migration of the waste constituents will occur from the injection zone while the waste remains hazardous (or for 10,000 years) (40 CFR Parts 146 and 148). Waste isolation is accomplished by a combination of:

- the application of strict siting criteria,
- the presence of multiple redundant engineered and geological barriers,
- practices to ensure chemical compatibility of waste with geology,
- operating restrictions and preventive maintenance during active injection operations,
- continual monitoring and testing of performance and confinement integrity, and
- the presence of alarms and a full-time operator.

These factors combine to assure that waste will be prevented from entering the accessible environment, i.e., that portion of the environment where human or ecological exposure can occur. In the absence of such exposure, no risk to health or welfare exists.

Studies published by both industry and the U.S. EPA in the past 10 years have concluded that the current practice of deep well injection is both safe and effective, and poses acceptably low risk to the environment[3,5,10,32,35,36,39,44]. Nonetheless, the effectiveness of deep well injection regulations has been challenged by various advocacy groups and the practice opposed on principle[15,19,28]. Studies purporting to examine the risks from deep well injection take as their starting point the assumption that release of waste from confinement to a drinking water aquifer has occurred and then model the transport time to a receptor well and the dose received by that receptor[31]. None to date has assessed the probability of the release occurring in the first place. Since the primary risk associated with deep well injection is that isolation from the accessible environment will fail, this probability must be examined before drawing any conclusions regarding health or environmental risks from such a release.

The purpose of this paper is to specifically examine this issue and to provide an objective and quantitative analysis of the risk of waste isolation loss from Class IH underground injection wells that will allow meaningful identification and comparison of waste isolation subsystems as contributors to that risk. Areas of uncertainty will be identified and quantified as to their possible contribution and importance to the risk estimates with a view of collecting additional data, identifying new sources of data, or stimulating new research to reduce these uncertainties. In doing so, we hope to provide all stakeholders with the type of rigorous scientific support needed to make appropriate decisions regarding deep well injection.

BACKGROUND

A review of available studies on Class I injection well failures over the past 20 years was conducted. These studies originated from a variety of sources including industry studies, peer-reviewed studies, trade association reports as well as reports from advocacy groups. Case studies and accident reports involving injection wells were reviewed as well. The relevant regulations were also carefully reviewed to determine the ways that regulatory requirements and restrictions affect siting, design, construction and operations. Numerous discussions and interviews were held with injection well operators and regulators. Based on this information, the critical factors to maintaining waste isolation were identified.

An important concept that appears throughout injection well risk studies and regulations is that of the underground source of drinking water (USDW). Releases from injection wells to the accessible environment (i.e., that portion of the environment where human or ecological exposures can occur) may occur either at the ground surface or into subsurface groundwater zones with potential human use. These groundwater zones are typically referred to as USDWs in studies and regulations. Surface releases are readily observed and remedied, and as such do not result in chronic exposures and have not been included in risk assessments. Potential releases to USDWs are the primary focus of risk assessments and regulations. Accordingly, in this assessment the relevant release point was assumed to be the lowermost USDW (i.e., closest to the injection zone).

In general, previous studies fall into four categories. The first category is case studies of injection well failures that have resulted in releases[4,6,12,17,25,34]. There are relatively few cases of this sort and none involving a release from a Class I well to a USDW since the U.S. EPA regulations took effect in 1980[35,39]. These historical incidents are confined without exception to issues of well siting, design, and operation that are no longer allowed under today's regulations, nor exist in today's population of Class I wells[5,12,17,25,34,39].

The second category is geologic fate and transport modeling studies[1,8,11,14,21,22,24,26,37,38,44]. These studies assume a release from an injection well and model the fate and transport of contaminants as they migrate through the typical geologic formations associated with injection wells. This includes modeling efforts performed for the "no migration petition" required for an operating permit. In general, such studies demonstrate that proper selection of the geologic formation creates an effective means to achieve waste isolation. While such studies can provide useful information on geologic factors important for maintaining waste isolation and the potential for failure of geologic barriers, they assume that a release has already occurred and do not account for waste isolation provided by engineered barriers of the well system. These studies can help with understanding mechanisms and general likelihood of failure of the geologic formations as one component of the loss of waste isolation, and can help in developing estimates of release volumes and concentrations to USDWs.

The third category is properly characterized as exposure studies[31]. One study of this type was found. In this study, it was assumed that a release occurred from the injection well to the USDW. The transport of this release in the USDW aquifer was modeled to a point of withdrawal for potable use. As with other modeling studies, a release was assumed without providing any information on how the release occurred and the probability of that release mechanism. Additionally, such studies do not take into account the effect of the containment or attenuation factors posed by geologic features (e.g., layers of low permeability rock) between the point of release and the USDW.

The final category is regulatory reviews and comparative risk studies. A 1989 U.S. EPA comparative risk evaluation of waste management alternatives by experts in the field concluded that deep well injection posed among the lowest environmental risks on a relative scale[36]. A 1991 U.S. EPA analysis of their restrictions on Class IH wells concluded that since 1980, Class IH wells are safer than virtually all other waste disposal practices[39]. U.S. EPA studied over 500 Class I wells in operation from 1988 to 1991 and found no failures known to have affected a USDW. In response to a 1992 House of Representatives subcommittee inquiry, U.S. EPA[40] provided state-by-state summaries of reported Class I well failure incidents between 1988 and 1992. This was defined as a breakdown or operational failure of components of the well system, whether waste isolation loss occurred or not. Although component failures were reported during the survey period, no waste isolation failure occurred and no waste from a Class I injection well reached a USDW. While these studies indicate the waste isolation effectiveness of current injection practices, they do not quantitatively address future risk.

In summary, no studies were identified that provide full quantitative characterization of the risk of Class I hazardous waste injection wells. Some describe release incidents for well systems that cannot and do not exist under today's regulations. Others characterize only a portion of the risk, for example, estimating exposures that might occur after presuming a release (often by mechanisms that have never occurred). Others demonstrate that releases have not occurred under current practices, but do not characterize the likelihood that releases might occur in the future. To properly assess the environmental risks posed by Class I injection wells, it is critical that the probability of loss of waste isolation be quantitatively assessed. Waste volumes and concentrations corresponding to realistic release scenarios should be included in the assessment.

METHODOLOGY

To quantitatively evaluate environmental risks posed by Class IH well injection, it was necessary to develop a detailed characterization of how the siting, construction, design, operation, testing and maintenance of a Class IH well system function together to create and ensure waste isolation[2,3,16,27,45]. The critical elements of this system that are important in maintaining waste isolation are singled out for special attention. Inherent in this approach is a systematic identification and depiction of events and conditions that could result in loss of waste isolation. This information was gathered from historical records on well failure events, and obtained from interviews with injection well construction, maintenance and testing practitioners, operators of injection wells, and the agencies that regulate them. From this information, a comprehensive set of scenarios was developed depicting the ways that a typical Class IH injection well system can fail to isolate waste. The probability of waste isolation loss in each of these scenarios was then quantified. Uncertainties in the analysis were given explicit quantitative treatment using Monte Carlo Analysis.

More specifically, the techniques of probabilistic risk assessment (PRA) were employed. PRA is a generally accepted approach for analyzing risks that arise through failure of engineered systems. In this case, PRA was used to identify sequences of events by which waste isolation could fail and result in waste reaching the lowermost USDW, and to characterize the probabilities of these event sequences. The results quantitatively and probabilistically demonstrate the degree of certainty that waste injected in this manner will effectively remain isolated and pose no future risk. The outcome of interest was the loss of waste isolation by release to the lowermost USDW from any cause. Factors considered included:

- errors in site selection or characterization, such as inappropriate or incompatible geology, unidentified abandoned wells, undetected geologic faults, or incorrect characterization of waste migration potential,
- geologic or engineered system failures, such as seismic fracturing of confining zones, tubing or casing breaches, annulus fluid pressure loss, or alarm failures,
- operator errors, such as failure to respond to alarms, failure to detect leaks during testing, over-pressurizing, or injecting incompatible waste, and
- other human errors, such as inadvertent extraction of waste in the future.

The following steps were taken and detailed discussion of each follows:

1. the Class IH well system, individual components, and conditions upon which the PRA is based were defined,
2. a Failure Modes and Effects Analysis (FMEA) was performed with the assistance of injection well experts,
3. based on the FMEA results, event and fault trees were developed, depicting the sequence of events that must occur for waste isolation to be lost,
4. based on historical or expert information, probability distributions characterizing the uncertainty in the frequency of occurrence of the various failures and other events were developed, and
5. Boolean logic and Monte Carlo analysis were used to combine the frequencies of independent and dependent events as depicted in the event and fault trees to estimate the overall probability of waste isolation loss for a Class IH well.

CLASS IH INJECTION WELL SYSTEM DEFINITION

In order to quantitatively assess the risk of loss of waste isolation from Class IH injection wells, the injection well system must be defined at a detailed enough level that specific event sequences can be identified and their frequencies quantified. At the similar time, the system definition must not be so unique that its methodologies and conclusions cannot be generalized to the population of Class IH wells at large. The Class IH well system definition used was based on the minimal design and operation features allowed under current regulations. This ensures the broadest applicability of the study results and conclusions. The regulatory system is sufficiently effective that there is no possibility that any Class IH injection wells exist and operate that do not meet at least the system definition used. This conclusion was verified by discussions with state and U.S.EPA officials, a review of the current U.S. EPA injection well database[41], and a random survey of Class I injection well operators involving about 20 percent of currently operating Class IH wells[47]. It is nonetheless appropriate to evaluate the possible failure of certain elements of the regulatory process that influence the effectiveness of waste isolation, and this was done. For instance, the possibility that an unplugged well in the area is unaccounted for in the site review was included.

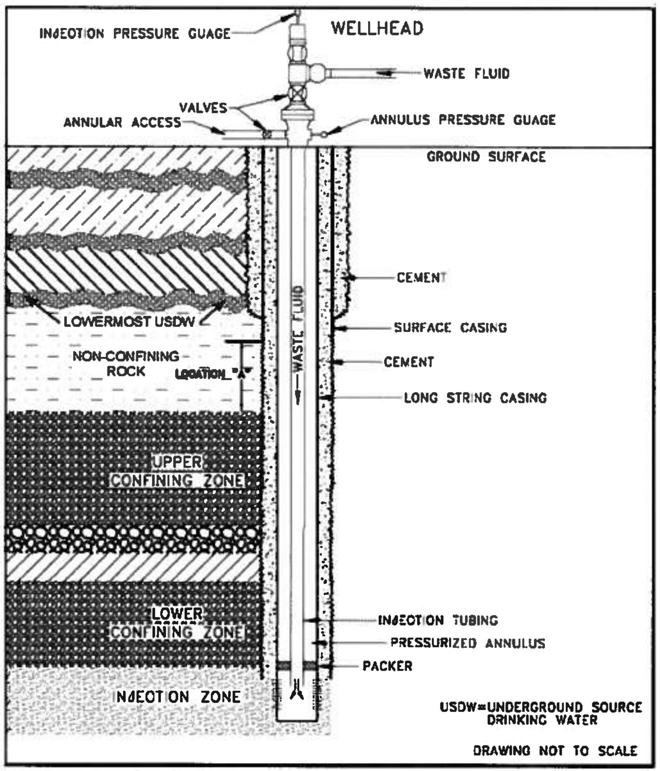


Figure 1 Simplified Class I Injection Well System Assumed for PRA

The design and operation features of the system analyzed are listed in Table 1 and a diagram of the system is shown in Figure 1. As a standard Class IH injection well, the system is assumed to comply with the requirements of the Code of Federal Regulations, Chapter 40, Parts 146 and 148 and Part 267, Subpart G. The salient features of these requirements with respect to waste isolation are listed in Table 1. It is assumed that the well operator has prepared a no migration petition, required to receive a permit to inject restricted wastes. The no migration petition results in a marked increase in site and system scrutiny by both the industry and the regulators. The operator must demonstrate through modeling that no migration of the waste will occur from the injection zone while the waste remains hazardous (or for 10,000 years). Such petitions extensively document the local geology and faults, the well design, the operation and maintenance procedures, comprehensive local well surveys, and fate and transport through mathematical modeling. In the process of characterizing the proposed injection site, an "area of review" (AOR) extending a two mile radius around the site must be investigated. The impact of these extensive analyses and investigations need to be considered in assessing the probability of release.

Table 1
CLASS IH WELL SYSTEM DEFINITION - DESIGN AND OPERATING FEATURES

WASTE ISOLATION ELEMENT	DESIGN OR OPERATING FEATURE
Applicable Regulation	Complies with 40 CFR 146 Subpart G
Site Selection and Characterization	Area of Review: 2 mile radius "No Migration Petition" for injection of restricted wastes
Geologic Barriers	Two confining layers between injection zone & lowermost USD
Engineered Barriers	Surface casing set below lower most USDW Casing completed with continuous cement Liquid-based annulus pressure barrier
Testing, Monitoring and Inspection	Equipped with auto alarm and a full time operator Annual Radioactive Tracer survey or OA log for fluid movement Temperature and noise logs once every five years

The geologic features of the system analyzed are depicted in Figure 1. The *injection zone* is the permeable subsurface rock that receives the waste. Class I injection well depths nationally range from 1,700 to 9,500 feet[41]. Typically, the USDW and injection zone are separated by several thousand feet[41]. The injection zone is required to be separated from the USDW by at least two confining zones consisting of dense rock or other geologic formations impermeable to fluid migration. For this assessment, it was assumed that only two confining zones exist. In actual practice, Class I injection wells have more than two confining layers[41], separated by non-potable water-bearing zones referred to as "buffer zones". Studies have shown that if waste fluid were to migrate through a confining zone, there would be significant dilution in each successive buffer zone[11,38]. This phenomenon has not been accounted for in exposure assessments to date[31], which generally assume that the waste inventory is released directly to a USDW.

Injection wells are constructed by extending concentric pipes or *casings* down the drilled well boring. Corrosion resistant materials such as steel alloy or fiberglass are used in the casings. The upper and outermost casing (Figure 1) is called the *surface casing* and is required by regulation (Table 1) to extend below the base of the lowermost USDW. As shown in Figure 1, the surface casing may not extend into the uppermost confining zone. This may result in a section of the well without surface casing that passes through an area of non-confining rock below the lowermost USDW but above the confining zones (*Location A* on Figure 1). This area is important in the PRA because it is the location with the least number of barriers to loss of waste isolation.

Within the surface casing is the *long string casing* which extends to the injection zone. Chemically resistant cement or epoxy resin is used to fill the borehole space outside the surface casing, between the surface and long string casings, and the borehole space outside the long string casing from top to bottom. These casings were assumed to be completed with continuous cement (Table 1). This effectively binds the casings together and seals the well boring along its entire length, creating a single unit. Nonetheless, in this assessment the cement was conservatively considered to be a barrier for vertical but not horizontal fluid migration.

A smaller steel or fiberglass pipe, the *injection tube*, extends the length of the casings through a lower seal (the *packer*) into the injection zone. Waste pumped from above flows into and is forced out of the portion of the borehole that extends into the injection zone. This is known as the *injection interval*, and may be uncased or fitted with a perforated section to prevent loose material from entering and potentially clogging the borehole or injection tube.

The space between the long string casing and the injection tube (*the annulus*) is sealed at the surface by the wellhead and the base by the *packer*, and filled with a non-corrosive fluid under positive pressure in excess of the injection tube pressure. In Class IH wells the annulus fluid is required to function as an additional pressure barrier to prevent waste fluid from leaking through the injection tube or the packer. Measurement of the fluid pressure and volume within the annulus is used to monitor the mechanical integrity of the injection tube, long string casing, and packer.

An operating Class IH injection well system incorporates the redundancy of safety systems that typically characterize safe engineering design. The long string casing is continuously cemented from top to bottom. Along with the annulus fluid pressure, the casing is a barrier to an injection tube or packer leak and the cement provides a barrier to vertical migration of any fluid that would escape along the outside of the casing or the borehole. The surface casing presents another barrier to waste migration in the portion of the well passing through USDWs. Finally, the annulus is sealed at both ends and is pressurized. Since the pressure in the annulus is higher than the pressure used to inject the waste (positive pressure), any leaks in the injection tube would result in annulus fluid forced into the tube rather than waste fluid escaping into the annulus. The fluid pressure is required to be continuously monitored both by automated alarm systems and manually by a full-time operator for loss of pressure or volume that might indicate that the system integrity (*e*.g., pump failure, packer failure, casing failure, packer failure) is compromised. Most Class IH systems include automatic shutdown of the injection pumps upon alarm, although this auto-shutdown was conservatively assumed to not be present in the system assessed. Of course, the injection pumps shutdown upon loss of power events.

Class IH wells are monitored annually for a number of factors related to waste isolation including: injection zone pressure buildup, water quality monitoring in lower USDW in some cases, and required mechanical integrity testing to detect fluid movement outside of the long string casing. This testing includes annual radioactive tracer or oxygen activation logging, as well as temperature and noise logging at least once every five years. Casing inspection logs are required whenever the injection tube is removed. When migration or flaws are detected they are repaired.

In summary, the system assessed was a Class I hazardous waste injection well that minimally complies with 40 CFR 146 Subpart G requirements. The system components included in the PRA included geologic, engineered and human elements. Finally, the system was assumed to be operating, with an operating lifetime of 30 years. Post-operating risks analyzed included the possibility of inadvertent human extraction of waste and migration through breached geologic confining zones.

FAILURE MODES AND EFFECTS ANALYSIS

A Failure Modes and Effects Analysis (FMEA) were performed on the Class IH injection well system defined above. This is a systematic technique for identifying all means by which the injection well components could fail, and what the effect could be with respect to waste isolation. Each component and activity identified as important was evaluated by:

- identifying all possible failure modes of the component (*e.g.*, injection tube leaks, injection tube crushes, injection tube plugs, etc.),
- identifying the possible reasons for these failure modes (*e.g.*, corrosion, improper installation, etc.),
- assessing the possible consequences of the failure mode (*e.g.*, loss of annulus pressure, fracturing of injection zone, etc.), and
- identifying the system features that serve to prevent the failure or mitigate its consequences (*e.g.*, the annulus fluid is under positive pressure).

The FMEA process is a brainstorming activity that does not exclude events based on the probability of their occurrence. All plausible events are considered even if they are considered to be of very low probability. The results of the FMEA are qualitative in nature and are not in themselves suitable for quantifying risk. Since the process identifies all potential failure modes for the system, failure mechanisms of the components, and the safety systems designed to prevent or mitigate failures, it creates a level of understanding that can be used to develop the probabilistic framework to quantify risk (i.e., the event and fault trees).

The FMEA process in this assessment was one through a series of workshops with deep well injection operators and expert consultants. In addition, FMEA results were presented at a number of Ground Water Protection Council national meetings and refined based on input obtained there from injection well operators, maintenance and testing professionals, and state and U.S. EPA regulatory staff.

EVENT AND FAULT TREE DEVELOPMENT

Based on understanding gained from the FMEA, event trees were developed that identify potential sequences of events that could result in a release to the lowermost USDW. Seven possible initiating events were identified that characterize the overall risk of waste isolation loss for the Class IH injection well system defined. The seven initiating events identified were:

1. Packer Leak
2. Major Packer Failure
3. Injection Tube Leak
4. Major Injection Tube Failure
5. Cement Microannulus Leak
6. Confining Zone(s) Breach, and
7. Inadvertent Injection Zone Extraction.

Once initiated, the likelihood of waste isolation loss depends on the subsequent failure of additional components, barriers and back-up systems within a relevant time domain. The event tree is a diagram that depicts the sequence of events and component failures that must follow for a release to the lowermost USDW to occur. Pathway can be traced through the event tree along its branches, depicting different combinations of failures and successes of system components and operational events that function together to prevent or result in waste isolation loss.

Three events were of sufficient complexity, involving multiple events themselves, that fault trees were developed for them. These three events were: loss of the annulus pressure barrier, lower geologic confining zone breach, and upper geologic confining zone breach.

The event and fault trees for each initiating event sequence are discussed in more detail below, but first the development of estimated frequencies of occurrence for events in the trees is described.

EVENT FREQUENCY DISTRIBUTION DEVELOPMENT

Perhaps the most problematic part of this PRA was estimating frequencies of occurrence for events in the trees. For many of these events, occurrence is so rare and data are so sparse that a confident point estimate for the frequency of occurrence cannot be established. Consequently, uncertainty about occurrence frequencies was given explicit quantitative treatment in the assessment. Probability distributions of event occurrence frequencies were developed, either based on available occurrence data or expert judgement. These distributions are shown in Table 2, where the event names correspond to event names appearing on the event and fault trees in Figures 2 through 11. Simultaneous occurrence of the events in a sequence is required for a release to occur. The period of time during which simultaneous occurrence could feasibly happen before detection and remedy would occur was assumed to be one day. Thus, the frequencies shown in Table 2 are based on a daily time frame, unless they are on-demand probabilities of a failed state or response once a sequence is in progress (e.g., the probability that an alarm fails or the probability that a discontinuity is present in the confining zone).

Table 2

Event Probability Distributions Class I Hazardous Well

EVENT NAME	DESCRIPTION	PROBABILITY DISTRIBUTION TYPE	LOWER BOUND	MEDIAN	UPPER BOUND
ALARM	Automatic alarm fails	Uniform	5E-05	3E-04	5E-04
ANNPRESSLO	Annulus pressure drops below injection pressure	From Fault Tree	9E-14	7E-12	8E-11
CAPLOSS	Loss of injection zone capacity results in overpressurization	Uniform	1E-05	1E-04	1E-03
CHECKPA	Annulus check valve fails open	Triangular	1E-04	3E-04	1E-03
CONFINEBRCHL	Transmissive breach occurs through lower confining zone	From Fault Tree	6E-04	3E-03	1E-02
CONFINEBRCHU	Transmissive breach occurs through upper confining zone	From Fault Tree	6E-04	3E-03	1E-02
CONTROLPA	Annulus pressure control system fails resulting in underpressurization	Uniform	1E-06	1E-05	1E-04
CONTROLPI	Injection pressure control system fails resulting in overpressurization	Uniform	1E-06	1E-05	1E-04
DETECTWELL	Failure to identify abandoned well in AOR	Uniform	1E-03	5E-03	1E-02
DISCONT	Presence of unidentified transmissive discontinuity	Uniform	1E-04	1E-03	1E-02
EXTRACT	Extraction of injection zone groundwater	Uniform	1E-05	1E-04	1E-03
FLUIDTEST	Testing fails to detect injection fluid migration along outside of long string casing	Uniform	5E-04	3E-03	5E-03
INCOMPWASTE	Waste injected that is chemically incompatible with geology or previously injected waste	Uniform	1E-05	5E-05	1E-04
ITUBFAIL	Sudden/major failure and breach of injection tube	Poisson	3E-07	6E-07	8E-07
ITUBLEAK	Injection tube leak	Poisson	3E-05	6E-05	8E-05
LBUOYANCY	Injected fluid is sufficiently buoyant to penetrate lower confining zone breach	Single Value	1E+00	1E+00	1E+00
LOCATION A	Long string casing leak is located between surface casing and uppermost confining zone	Uniform	1E-02	3E-02	5E-02
LOCATION B	Long string casing leak is located above base of surface casing	Uniform	1E-02	5E-02	1E-01
LOCATION C	Long string casing leak is located below confining zone(s)	Uniform	9E-01	9E-01	1E+00
LSCASEFAIL	Sudden/major failure and breach of long string casing	Poisson	2E-07	3E-07	5E-07
LSCEMLEAK	Long string casing cement microannulus allows fluid movement along casing	Poisson	2E-06	6E-06	1E-05
LSTRINGLEAK	Long string casing leak	Poisson	2E-05	3E-05	5E-05
MIGRATION_A	Waste migrates up microannulus to Location A between surface casing and upper confining zone	Uniform	1E-04	1E-03	1E-02
NORECOGNIZE	Failure to recognize that groundwater extraction is located within injection waste zone	Uniform	1E-03	5E-03	1E-02
OPERINJ	Operator fails to recognize changes in confining zone capacity	Uniform*	5E-05	3E-05	5E-04
OPERRDET	Operator fails to detect/respond to unacceptable pressure differential	Uniform*	5E-05	3E-05	5E-04
OPERRFRAC	Operator error results in induced transmissive fracture through lower confining zone	Uniform*	5E-05	3E-04	5E-04
OPERRPA	Operator error causes annulus pressure below injection pressure	Uniform*	5E-05	3E-04	5E-04
OPERRPI	Operator error causes injection pressure above annulus pressure	Uniform*	5E-05	3E-04	5E-04
OUTAOR	Injection waste has migrated outside of Area of Review to unconfined zone	Uniform	1E-05	5E-05	1E-04
PACKFAIL	Sudden/major failure and breach of packer	Poisson	2E-07	4E-07	6E-07
PACKLEAK	Packer leak	Poisson	2E-05	4E-05	6E-05
PERMEA	Confining zone has unexpected transmissive permeability	Uniform	1E-05	1E-04	1E-03
PLUGFAIL	Identified abandoned well plug fails	Poisson	2E-04	8E-04	2E-03
PUMPPA	Annulus pump fails	Triangular	5E-05	5E-04	5E-03
RELDETECT	Groundwater monitoring fails to detect waste release outside injection zone	Single Value	5E-01	5E-01	5E-01
SEISMFAULT	Seismic event induces a transmissive fault or fracture	Uniform	1E-05	5E-05	1E-04
SURFCASELEAK	Surface casing leak	Poisson	2E-06	3E-06	5E-06
TRANSLCZ	Unidentified abandoned well is transmissive from injection zone through lower confining zone	Single Value	1E-01	1E-01	1E-01
TRANSUSDW	Unidentified abandoned well is transmissive through upper confining zone to USDW	Single Value	1E-01	1E-01	1E-01
UBUOYANCY	Injected fluid is sufficiently buoyant to penetrate upper confining zone breach	Same as OPERRDET	1E-05	5E-05	1E-04
WASTEPRESENT	Injected waste has not transformed into non-waste	Uniform	1E-02	1E-01	1E+00

Frequencies are per day or per demand

* Operator error event probability distributions are correlated (r=0.5) to account for same operator or similar training

QUANTITATIVE ANALYSIS OF EVENT TREES

In PRA, event frequencies are combined according to the logic of the event and fault trees using Boolean algebra. The result is the estimated frequency (or probability) of a release to the lowermost USDW over the lifetime of the Class I hazardous waste injection well. Since uncertain event frequencies in this assessment were characterized by probability distributions, these distributions were propagated through the Boolean algebra calculations using Monte Carlo analysis. The result is expressed as a distribution of the probability that waste isolation will be lost during the lifetime of the injection well. This approach enables one to draw conclusions as to the certainty of the waste isolation loss risk estimates and conduct sensitivity analyses to identify which individual events contribute the most uncertainty to the risk estimates. To facilitate such analysis, both fault and event tree probabilities were placed into Excel™ spreadsheets while the random sampling and generation of stochastic results was performed using Crystal Ball™. Latin Hypercube Sampling (LHS) was used to generate the input values for all distributions. The analysis was performed with 5,000 iterations to provide the best possible estimate of the percentiles. For operator errors likely to involve the same operator or similarly-trained operators, the frequency distributions were correlated. A parametric sensitivity analysis was also performed based on percent contribution of uncertain event frequencies to overall variance in the loss of waste isolation probability distribution.

PROBABILISTIC RISK ASSESSMENT (PRA) RESULTS

Using the event and fault trees, the risk of waste isolation loss and release to the USDW over the 30 year life of a Class IH hazardous waste injection well was characterized quantitatively. Most of the trees represent the daily probability of the event sequence, and their results are converted into 30 year probabilities for presentation below. Events that are independent of time (*i.e.*, inadvertent injection zone extraction) are presented as event probabilities. The cumulative percentile results of the analysis for each event sequence are presented in Table 3. Values shown in Table 3 are probabilities of the loss of waste isolation (i.e., release to the lowermost USDW) over the lifetime of the well. The cumulative percentile is the likelihood of being less than or equal to (i.e., of not exceeding) the corresponding loss of isolation risk.

Table 3
Cumulative Percent Results for Each Loss of Waste Isolation Event Class I Hazardous Well

Cumulative percentile is the likelihood of being less than or equal to (i.e., not exceeding) the corresponding loss of isolation risk.

Cumulative Percentile	Packer Leak	Packer Sudden Failure	Injection Tube Leak	Injection Tube Sudden Failure	Cement Microannulus	Confining Zones Fail	Inadvertent Extraction
0%	2.05E-20	7.73E-10	3.31E-20	1.15E-09	0.00E+00	5.05E-12	2.35E-10
10%	5.35E-19	2.05E-09	8.46E-19	3.22E-09	1.78E-08	6.37E-11	3.55E-09
25%	1.18E-18	2.82E-09	1.85E-18	4.45E-09	4.33E-08	1.20E-10	1.22E-08
50%	2.67E-18	4.08E-09	4.19E-18	6.35E-09	1.35E-07	2.38E-10	4.79E-08
75%	5.76E-18	5.53E-09	8.98E-18	8.54E-09	4.50E-07	4.80E-10	1.94E-07
90%	1.11E-17	7.00E-09	1.77E-17	1.06E-08	1.04E-06	8.98E-10	6.41E-07
100%	9.12E-17	1.32E-08	1.09E-16	2.08E-08	4.57E-06	6.39E-09	8.64E-06

Packer Leak

The initiating event in this sequence is the development of a leak in the packer at the base of the injection tube and pressurized annulus (See Figure 2). If the packer leaks during injection, containment is maintained as long as the annulus pressure is greater than the injection pressure. If the annulus pressure drops, containment will still be maintained by the long string casing. A leak in the long string casing may occur, but its location will be critical since this determines what additional failures must occur to lose containment. A long string casing leak in the area between the bottom of the surface casing and the upper confining zone (Location A) was assumed to result in a release to the lowermost USDW, even though current regulations require the surface casing to be set below the base of the lowermost USDW into a confining bed. Also there may actually be significant geologic interaction between this point and the USDW. If the long string casing leak is located above the base of the surface casing, a release to the USDW requires either a leak in the surface casing or a crack (microannulus) open in the long string casing cement to Location A. A leak below the confining layer(s) requires a breach of the geologic barrier(s) or a microannulus to Location A.

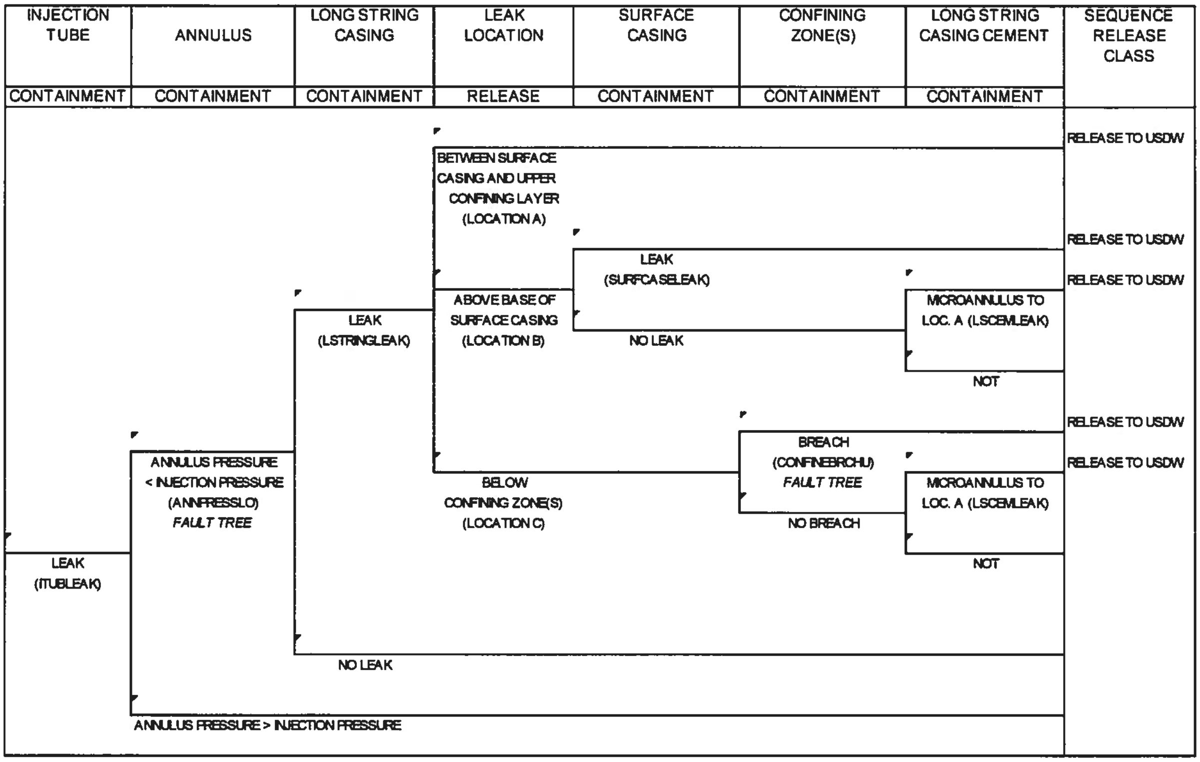


Figure 2
Packer Leak Event Tree Class I Hazardous Well

Two component failures in the event tree are described by fault trees: the first quantifies the probability that the annulus pressure is less than the injection pressure while the second addresses the probability that the confining zone is breached. These fault trees are presented in Figures 3 and 4, respectively, while the event probabilities associated with these fault trees can be found in Table 2.

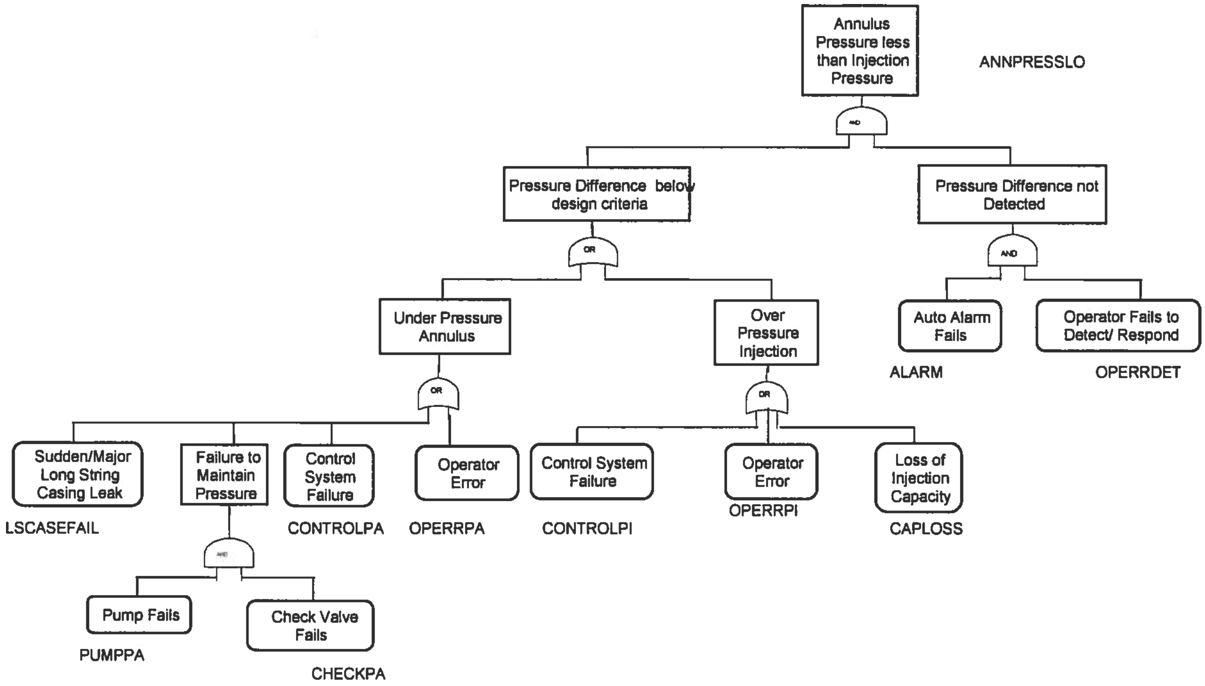


Figure 3
Annulus Pressure Barrier Failure Fault Tree Class I Hazardous Well

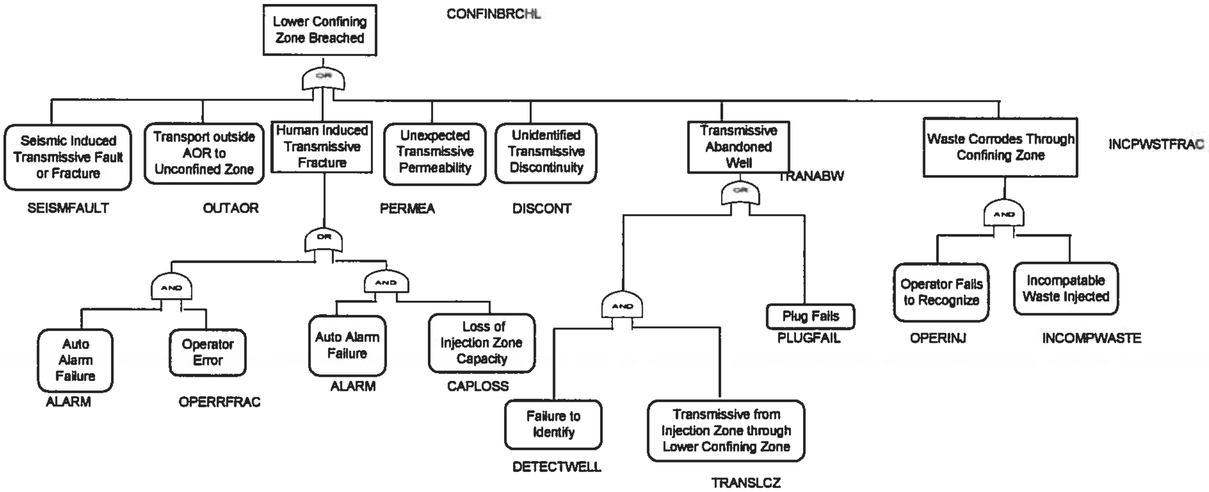


Figure 4
Lower Confining Zone Breach Fault Tree Class I Hazardous Well

The PRA results of the packer leak scenario indicate that the probability of waste isolation loss over the life of the well from this initiating event is on the order of 10^{-17} to 10^{-18} (see Table 3). The annulus pressure is the primary barrier to loss of containment and the probability of pressure loss is extremely low since it would require simultaneous alarm and full-time operator failures. In fact, the difference in pressure between the annulus and injection fluids do occur, but the high reliability of the redundant auto-alarm and full-time operator keep the probability of this resulting in a pressure barrier loss during injection extremely low. Additionally, the location of a long string casing leak is a critical factor to waste isolation loss as it determines the presence or absence of additional barriers.

Major Packer Failure

This event is distinguished from the "Packer Leak" event in that it involves a complete and sudden loss of the packer and the subsequent rapid loss of annulus pressure (See Figure 5). Without the annulus pressure barrier, the containment now depends on the integrity of the long string casing and associated components. The sequence of component failure leading to waste isolation loss thereafter is similar to the packer leak tree except there is no annulus pressure barrier.

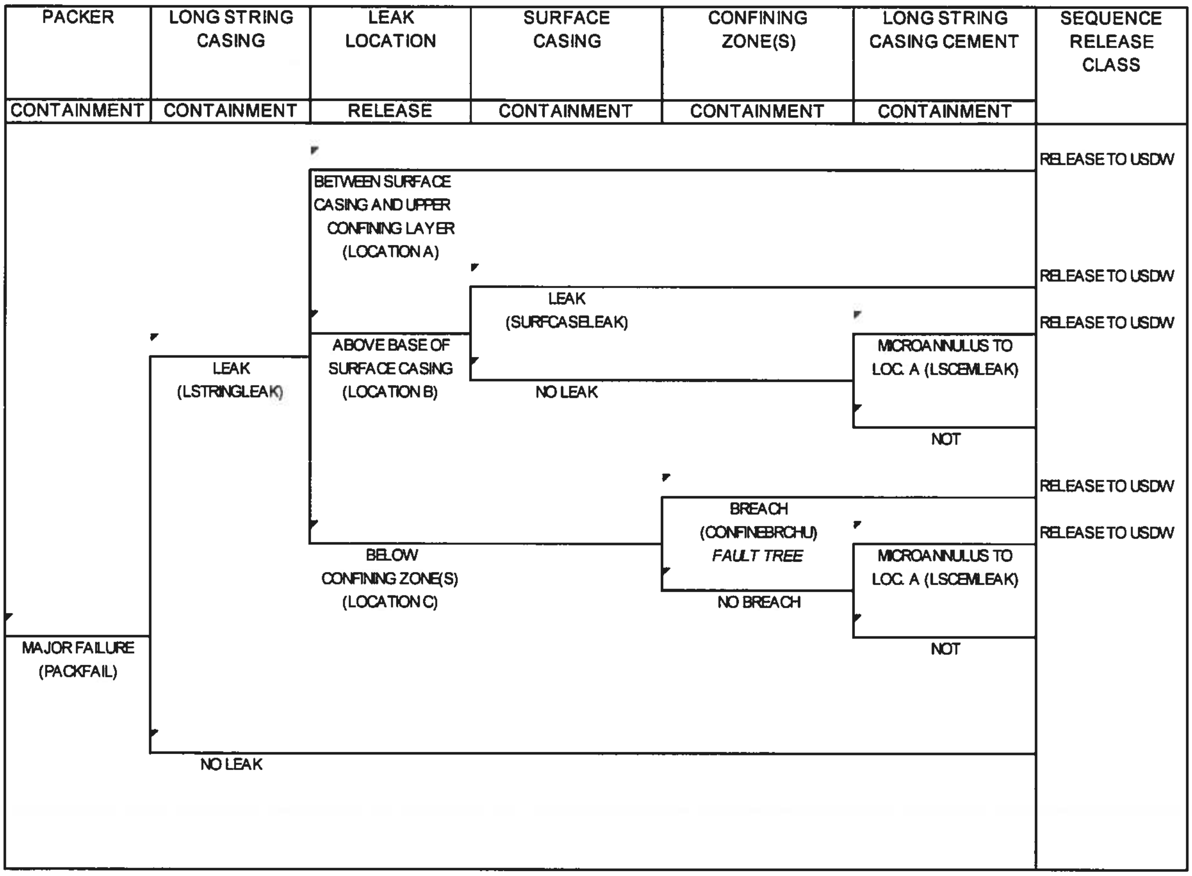


Figure 5
Packer Major Failure Event Tree Class I Hazardous Well

A major packer failure is a lower probability event than a packer leak. Despite this, the assumed absence of annulus pressure eliminates an important barrier to waste isolation loss and results in a higher risk than for a simple packer leak, on the order of 10^{-8} to 10^{-9} (see Table 3). With the loss of pressure, the waste is assumed to mix in the annulus fluid in the column. As above, the location of the long string casing is a critical factor to waste isolation loss.

Injection Tube Leak

This initiating event involves a leak in the injection tube above the packer (See Figure 6). Since it is not a catastrophic failure, annulus pressure is maintained. Aside from the location of the leak, the events and the sequence leading to containment loss is identical to that of the packer leak scenario. Similar to the packer leak, the results indicate that the probability of waste isolation loss over the life of the well is extremely low, on the order of 10^{-17} to 10^{-19} (see Table 3). As with the packer leak, the annulus pressure is the primary barrier to loss of containment. Additionally, the location of the long string casing remains a critical factor to waste isolation loss to the accessible environment.

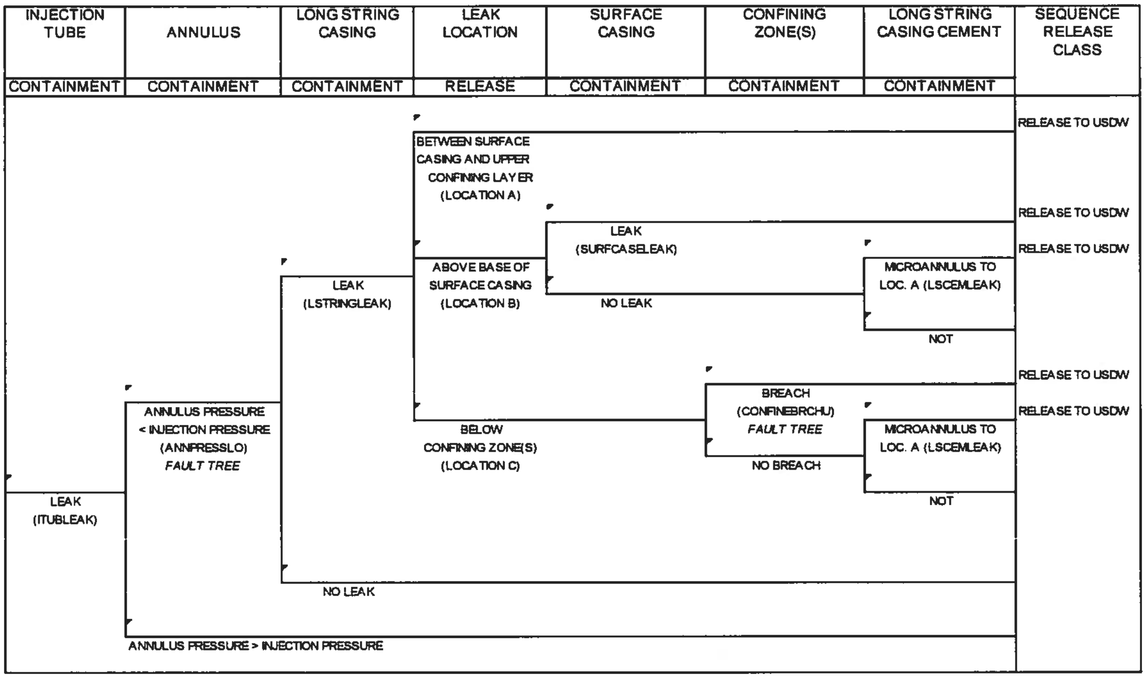


Figure 6
Injection Tube Event Tree Class I Hazardous Well

Major Injection Tube Failure

This initiating event is similar to the major packer failure and characterized by a catastrophic failure of the injection tube above the packer with the resulting loss of annulus pressure (See Figure 7). Aside from the location of the failure, the events and the sequence leading to possible containment loss is identical to that of the major packer failure scenario discussed above.

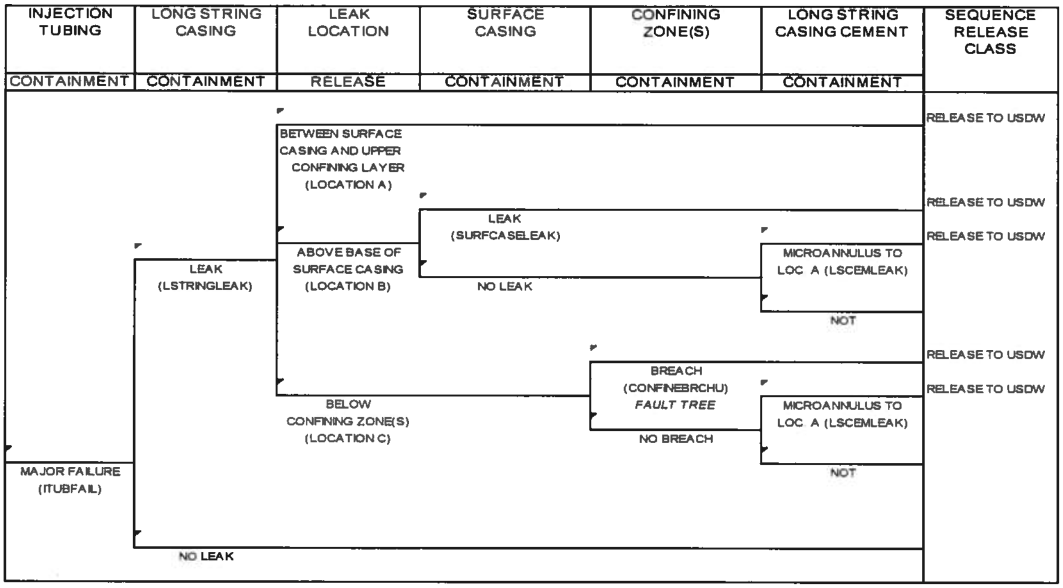


Figure 7
Injection Tubing Major Failure Event Tree Class I Hazardous Well

A major injection tube failure is a lower probability event than an injection tube leak. As with the major packer failure, the assumed immediate loss of annulus pressure eliminates an important barrier to waste isolation loss and results in a higher risk than a simple leak of the injection tube, on the order of 10^{-8} to 10^{-9} (see Table 3). With the loss of positive pressure, the waste is assumed to mix in the annulus fluid and escapes through the leak in the long string casing. As in all these scenarios, the location of the long string casing is a critical factor to waste isolation loss.

Cement Microannulus Failure

Radiotracer studies are performed annually on Class IH wells to detect migration. This event sequence involves the possibility that an extended vertical opening (i.e., microannulus) in the cement surrounding the long string casing remains undetected and results in waste isolation loss (See Figure 8). The cement extends from the surface through all confining layers to the injection zone. Should a microannulus crack open in the cement, extend from the injection zone through the upper confining zone and remain undetected, waste injected under pressure could possibly migrate up to Location A and then to the USDW. Alternatively, waste could migrate only up to a location below the upper confining zone, then the upper confining zone could breach. An additional fault tree is needed to estimate the probability that the upper confining zone will be breached. This fault tree is presented in Figure 9 with the corresponding probabilities presented in Table 2.

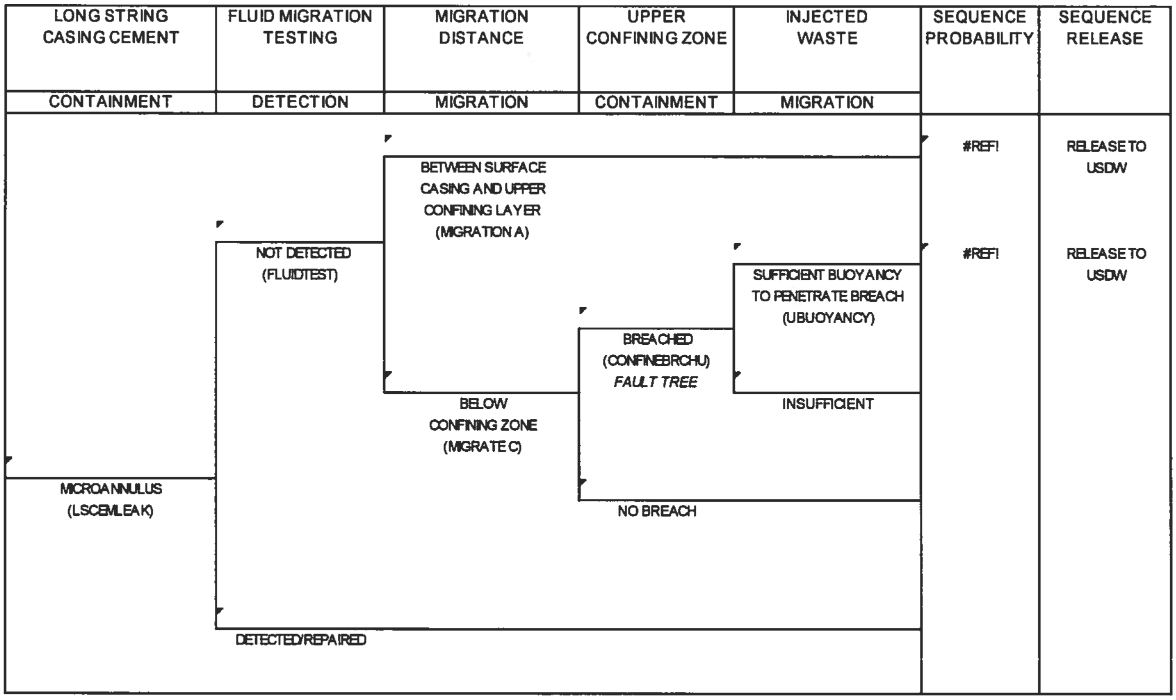


Figure 8
Cement Microannulus Event Tree Class I Hazardous Well

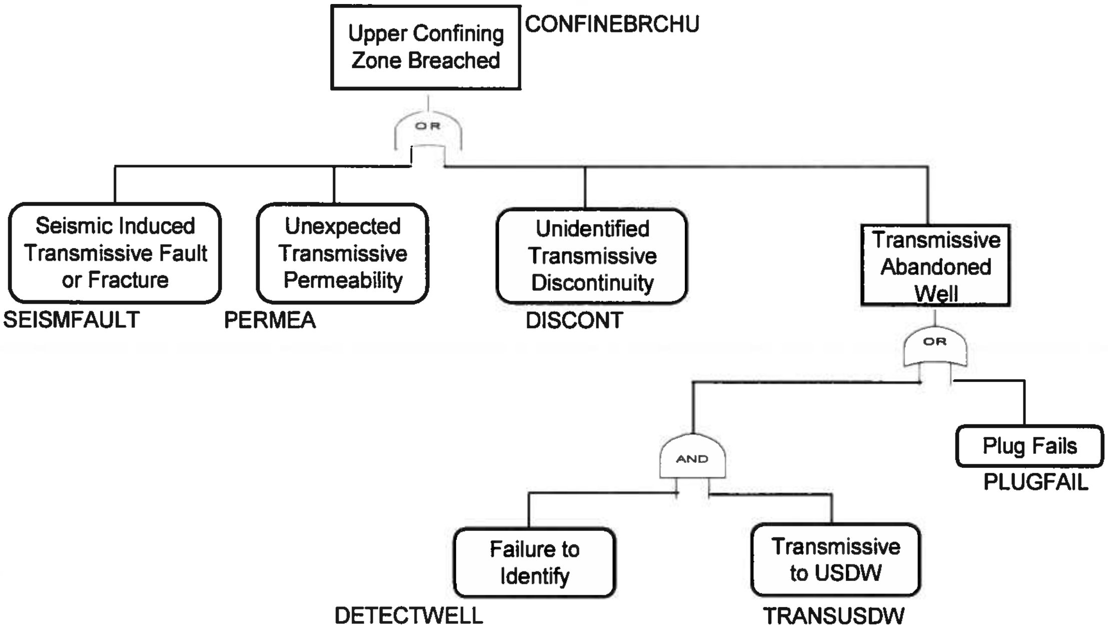


Figure 9
Upper Confining Zone Breach Fault Tree Class I Hazardous Well

The probability that loss of waste isolation will result under this scenario was calculated to be on the order of 10^{-6} to 10^{-8} (see Table 3). The event sequence is controlled by the location to which the microannulus extends. In this case, it was assumed to extend from the injection zone to the USDW. The greatest uncertainty lies in whether such an extended and transmissive microannulus will occur and if the waste fluid can travel that far given that the injection zone represents the path of least resistance to the pressurized waste stream. Additionally, the annual testing for fluid migration also limits the risk to loss through this mechanism.

Confining Zone Breach

The initiating event in this scenario is a transmissive breach of the lower confining zone (directly above the injection zone) (See Figure 10). The probability of this event is based on the fault tree analysis first developed for the packer leak (Figure 4). Once the lower confining zone is breached, the remaining barriers to waste isolation loss are:

1. the waste is sufficiently buoyant to penetrate the lower confining zone breach;
2. groundwater monitoring fails to detect waste outside of the injection zone;
3. the upper confining zone is breached; and
4. the waste is sufficiently buoyant to penetrate the upper confining zone breach.

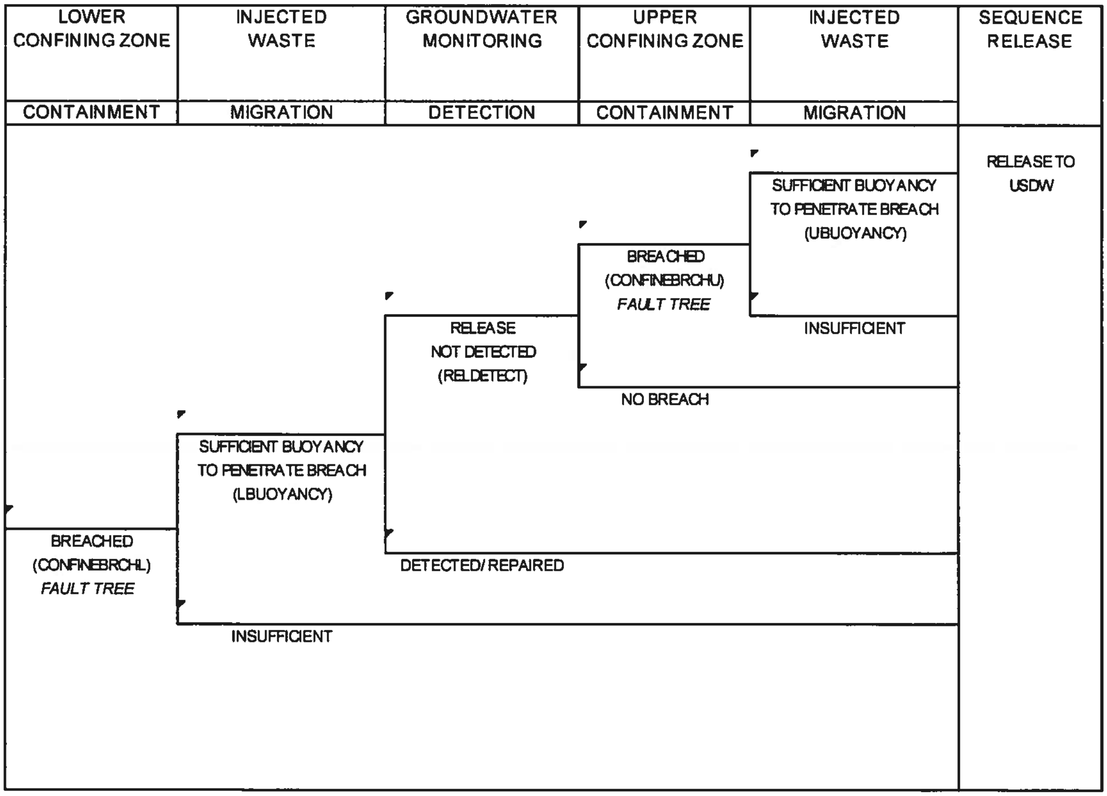


Figure 10
Confining Zone (s) Breach Event Tree Class I Hazardous Well

A breach in the confining zone requires that all confining zones must be completely breached with transmissive openings. This must remain undetected in spite of on-going monitoring of pumping pressure and volumes, injection zone pressure and groundwater quality. Additionally, the waste must have a driving force in all zones in order to be sufficiently buoyant to penetrate to the USDW above, and no bleed-off must occur into the buffer aquifers between the confining zones. This scenario has a probability of loss of waste isolation on the order of 10^{-10} (see Table 3).

Inadvertent Injection Zone Extraction

Given the depth of most injection wells, future human intrusion into the injection zone is unlikely (See Figure 11). An extraction scenario also does not rely on any additional components of the operating system. The initiating event assumes extraction of injected waste with the additional sequence probabilities included to assess the possibility that the extraction of the injection zone material goes unnoticed by the well user. The time domain is not relevant as all such activities are assumed to be post-closure of the system.

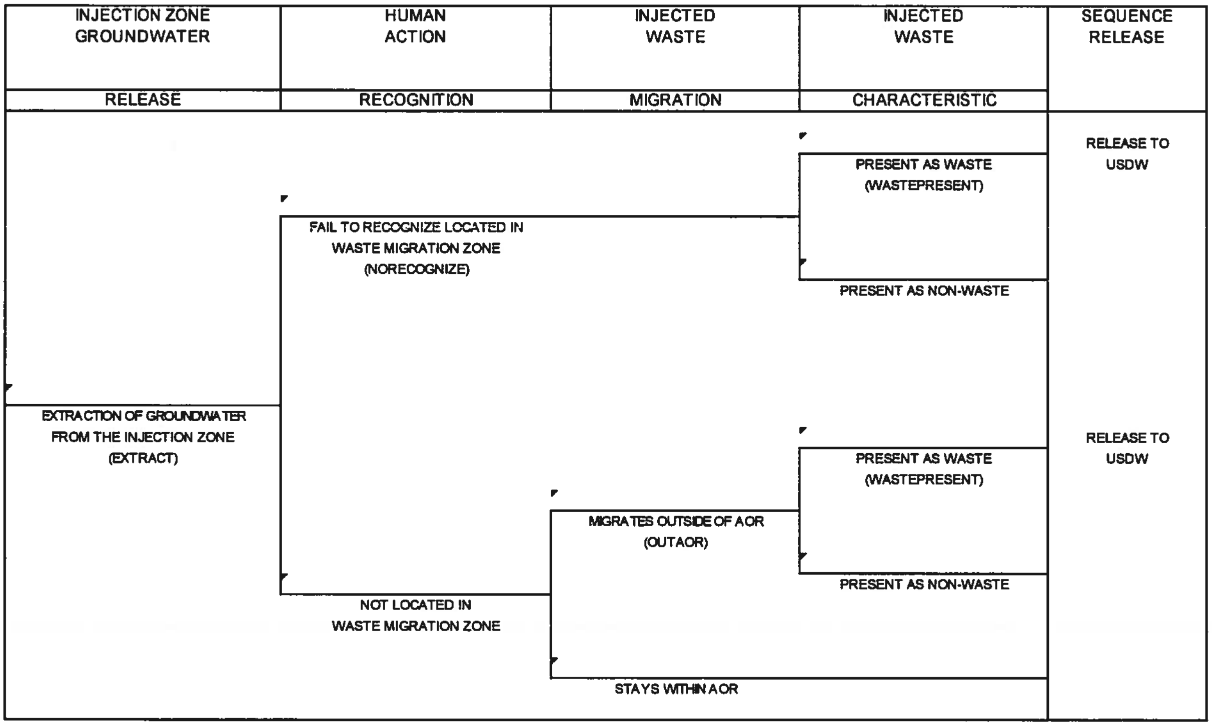


Figure 11
Inadvertent Injection Zone Water Extraction Event Tree Class I Hazardous Well

This scenario is the most difficult to estimate the probability of occurrence. Even so, the possibility that extraction of isolated waste will occur post-closure was calculated to be less than 10^{-6} (see Table 3). Since injection zones are more than 1,000 feet deep and presumably underlie most accessible and higher quality aquifers, it is unclear why water from the injection zone would be extracted by anyone. Depending on timing and location, the waste may no longer present a potential hazard or the plume may not be intersected by the extraction wells.

Incompatible Waste Injection

The issue of incompatibility of wastes and well components or geologic formations was covered under the outcomes of the other event trees. Carbon dioxide or other gas formation may result in packer blow-out, rupture of the injection tube, transmissive geologic fracturing, or well head blow-out. Each of these events are covered by the event trees for packer or injection tube failure, the fault tree for confining zone breaches, or are considered spills and not relevant to this evaluation. Corrosion of rock or other system components are covered under the fault tree for the lower confining zone breach or the event tree for the relevant system component (*i.e.*, injection tube leak or failure). A chemical interaction may also result in a plug forming in the system resulting again in packer blow-out, failure of the injection tube, or fractures of the different confining zones in response to a pressure build-up. These are addressed by the event trees for the confining zone breach, the packer or injection tube failure, or the fault tree for the breach of the lower confining zone.

OVERALL LOSS OF WASTE ISOLATION RESULTS

Based on the PRA conducted for Class IH wells, the 90th percentile risks for the individual scenarios detailing the potential loss of waste isolation range from a low of 10^{-17} (packer leak) to a high of 10^{-6} (cement microannulus) (See Figure 12). The probability for all events combined (assuming that these risks are additive) resulting in loss of waste isolation is between 10^{-6} and 10^{-8} (Figure 12). The event sequences that are predominant contributors to overall risk are the microannulus failure and the possibility of inadvertent future extraction. The sensitivity analysis (Figure 13) identified the following contributions to overall uncertainty about probability of loss of waste isolation:

- distance that waste migrates along a vertical cement microannulus (52% of the variance);
- likelihood of future extraction from the injection zone (17% of the variance);
- probability that at the time of future extraction the waste is no longer hazardous or the plume is not present (15% of the variance);
- likelihood that the fluid testing fails to detect migration (8% of the variance); and
- likelihood that the extracted material is unrecognized as waste by the well user (3% of the variance).

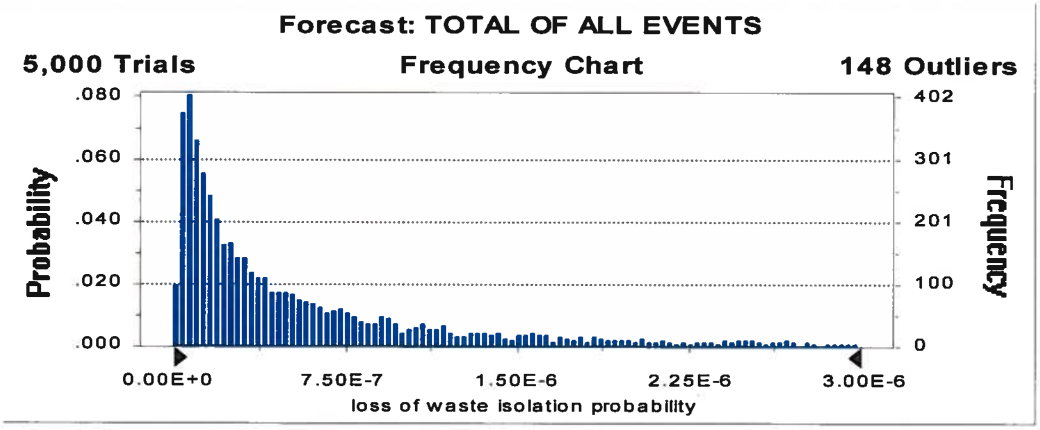


Figure 12. Probability Distribution Loss of Waste Isolation Total Risk Class I Hazardous Well

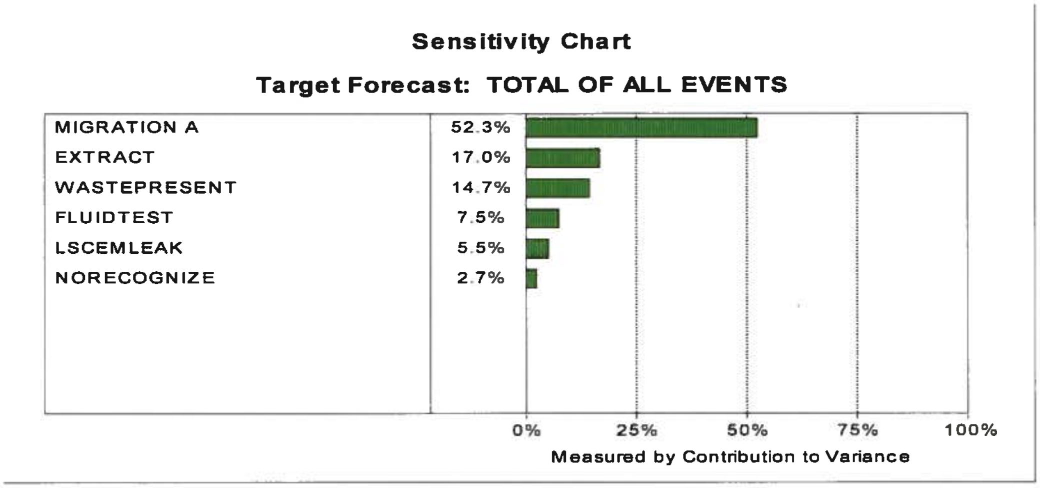


Figure 13
Sensitivity Chart Relative Contributions to Overall Uncertainty About Loss of Waste Isolation Risk

CONCLUSIONS AND RECOMMENDATIONS

Because of the conservative assumptions used for failure event probabilities and the explicit treatment given to uncertainties in this analysis, we believe that the risk of loss of waste isolation from Class IH wells is less than 10^{-6}. The low risk is due in large measure to the use of redundant engineered systems and geology to provide multiple and diverse barriers to prevent release to the accessible environment. This is aided in part by the fact that deep well injection is a simple design relying on passive systems to limit failure modes and frequencies to a minimum. The annulus pressure is a critical barrier and performance monitor, but displays high reliability due to the presence of automatic alarms, shut-offs, and full-time operators.

The risk that waste isolation is lost is dominated by two failure scenarios:

1. the possibility that a transmissive microannulus develops in the cemented borehole outside of the long string casing and it extends from the injection zone up past the geologic confining zones, and
2. the possibility of inadvertent future extraction of injected waste.

Uncertainty about the overall risk to waste isolation is also dominated by events associated with these two scenarios. For example, in developing the frequency distribution for the microannulus initiating event (LSCEMLEAK in Figure 8), it was conservatively assumed that "vertical migration detected" events in the well failure database[40] were equivalent to the occurrence of a transmissive microannulus extending from the injection zone through one or both of the confining layers. Class IH well operators contend that microannulus extending from the injection zone through the confining layers are not found. Thus, a highly uncertain event initiates the highest risk sequence, and is therefore treated with significant conservatism in the PRA. This points to the need for more complete data on the location, duration and length of detected microannulus, rather than just noting the number of times that vertical migration is detected.

Numerous conservative assumptions were used in this PRA that, combined with the explicit treatment of uncertainty given (i.e., the Monte Carlo analysis) lend confidence to the conclusions of low risk. Credit was not taken for any cement as a horizontal barrier to waste migration. Likewise, in using the well failure database[40], all events termed "failure" for packers, tubing and casing were assumed to be breaches of sufficient size and duration to transmit waste. As explained above, "vertical migration detected" events were similarly assumed to represent a complete transmissive pathway from the injection zone up past the geologic confining layer(s). In the event of a breach of the confining layers, the buoyancy of the waste and the injection pressure was assumed to be high enough to drive migration through breaches of multiple confining layers. The significant bleed-off and attenuation that occurs in the intervening buffer aquifers was not taken into account. Only two geologic confining layers were assumed throughout this PRA when survey information indicates that three or more confining zones are usually present. Published human error data were used as the lower bound on probability distributions for these events that assumed equal probability that error rates can be an order of magnitude higher than published rates. Automatic shutdown of the injection well pumps is a usual operating feature of most Class IH wells. For this PRA, no automatic shutdown was assumed. It was further assumed that a release between the surface casing and the upper confining zone was equivalent to a release to the USDW, and that releases below the confining zones involved only one confining zone barrier to the USDW. Finally, the timing between independent occurrences in the various event and fault trees was assumed to be coincident for sufficient duration prior to detection and corrective action that a release could occur.

Since the failure location and timing of the individual events are critical to the development of these release scenarios, uncertainty would be reduced and knowledge improved if this information was collected and included in the databases maintained on Class I well failures. The presence, degree of training, and diligence of the human operator is important to preventing system failure and loss of waste isolation. This is especially critical in maintaining the annulus pressure, which is a major barrier to loss of waste from the system. Uncertainty over the existence and transmissivity of extended vertical cement breaches is important. Experimental or field data on the microannulus assumed to exist in these scenarios would assist in reducing this uncertainty and improving the risk estimates. Finally, we recommend that future assessments of the potential environmental risks associated with deep well injection explicitly take into account the probability of release and the amount of waste that could be released by the mechanisms of feasible system failure scenarios.

REFERENCES

1) Buss, D.R. et al. *A Numeric Stimulation Study of Deep-Well Injection in Two Hydrogeologic Settings -- Texas Gulf Coast, Great Lakes Basin.* GeoTrans, Inc. (June 20, 1984).
2) Buttram, J.R. *Operation and Maintenance of Underground Injection Wells.* Ground Water Monitoring Review. pp. 64-67 (Summer 1986).
3) CH2M Hill. *A Class I Injection Well Survey. Phase II Report - Performance Evaluation.* Prepared for Underground Injection Practices Council. Oklahoma City, OK. D19976.S2.00 (May 1986).
4) CH2M Hill. *A Class I Injection Well Survey Phase I Report. Survey of Selected Sites.* Prepared for Underground Injection Practices Council. Oklahoma City, OK. D19976.S1 (April 1986).
5) Clark, J.E. *Environmental Scoring Without Risk Assessment.* Presented at Clean Texas 2000 - Environmental Trade Fair. E.I. du Pont de Nemours and Co., Inc. (April 14, 1994).
6) Clark, J.E. *Factors That Can Cause Abandoned Wells to Leak as Verified by Case Histories from Class II Injection,*

Texas Railroad Commission Files. Underground Injection Practices Council, Proc. of the International Symposium on Substance Injection of Oilfield Brines (May 1987).

7) Clement, R.T. Making Hard Decisions: An Introduction to Decision Analysis. pp. 253-254 (PWS-KENT Publishers, 1991).

8) Davis, S. *Responses to Questions from the Chemical Manufacturers Association.* Submitted to Chemical Manufacturers Association by Department of Hydrology and Water Resources. University of Arizona. Tucson, Arizona (April 10, 1987).

9) Davis, M.L. and D.G. Satterwhite. *Summary Procedures Guide for Application of Risk and Hazards Analysis Techniques.* EG&G, Idaho (1988).

10) Department of Energy and Natural Resources et al. *Illinois Scientific Surveys Joint Report 2. Evaluation of Underground Injection of Industrial Waste in Illinois* (1989).

11) Don L. Warner, Inc. and Engineering Enterprises, Inc. *Confining Layer Study.* Prepared for U.S. EPA Region V (December 1984).

12) Engineering Enterprises, Inc., Geraghty & Miller, Inc. and Ken E. Davis Associates. *Class I Hazardous Waste Injection Wells Evaluation of Non-Compliance Incidents.* Prepared for U.S. Environmental Protection Agency. Washington, D.C. (September, 1986).

13) Envirosphere Company. *Draft Task Report. Below Regulatory Concern Waste Accident Scenario Dose Assessment Task 1: Unexpected Event/Accident Identification.* Prepared for Electric Power Research Institute, Palo Alto, California (February 1988).

14) Goolsby, D.A. *Geochemical Effects and Movement of Injected Industrial Waste in a Limestone Aquifer.* U.S. Geological Survey, Tallahassee, FL. (1972).

15) Gordon, W. and J. Bloom. *Deeper Problems: Limits to Underground Injection as a Hazardous Waste Disposal Method.* Natural Resources Defense Council, Inc. (1985)

16) *Journal of the Underground Injection Practices Council. Vol. 1* (1986).

17) Ken E. Davis Associates. *Conclusions and Recommendations on the Assessment of Fourteen Alleged Class I Well Failures.* Keda Project No. I 001633. Houston, TX (May 1986).

18) Lannoy and Procaccia. *European Industry Reliability Databank* (1996).

19) MacLean, A. and R. Puchalsky. *Where the Wastes Are: Highlights from the Records of the More than 5,000 Facilities that Receive Transfers of TRI Chemicals.* OMB Watch and Unison Institute (April 1994).

20) McCormick. Reliability and Risk Analysis. Chapter 3. (Academic Press, Inc., San Diego, 1981).

21) Meritt, M.L. *Digital Simulation of the Regional Effects of Subsurface Injection of Liquid Waste Near Pensacola, Florida.* U.S. Geological Survey. Prepared in cooperation with the Florida Dept. of Environmental Regulation. Tallahassee, FL (1984).

22) Miller, C. et al. *Flow and Containment of Injected Wastes.* Ground Water Monitoring, Review. pp. 37-47 (Summer 1986).

23) Morgan, P.G. *A Closer Look at "Deeper Problems" - A Response to Those Who Would Ban Hazardous Waste Disposal by Underground Injection: The New Mexico Experience.* New Mexico Environmental Improvement Division, Underground Injection Control Program (1985).

24) Morganwalp, D.W. and R.E. Smith. *Modeling of Representative Injection Sites.* (1988).

25) Paque, M.J. *Class I Injection Well Performance Survey.* Ground Water Monitoring Review. pp. 68-69 (Summer 1986).

26) Scrivner, N.C. et al. *Chemical Fate of Injected Wastes.* Ground Water Monitoring Review. pp. 53-57 (Summer 1986).

27) SCS Engineers. *Final Report. Summary of Chemical Manufacturers Association Underground Injection Well Survey.* Prepared for CMA UIC Work Group. Washington, D.C. (February 1985).

28) Sierra Club Legal Defense Fund. E. P. Jorgensen, editor. The Poisoned Well. New Strategies for Groundwater Protection. Island Press. Washington, D.C. (1989).

29) Swain, A.D. and A.L. Guttman. *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications*. NUREG/CR-1278. Scandia National Laboratories (1980).

30) Swain, A.D. *Accident Sequence Evaluation Program: Human Reliability Analysis Procedure*. NUREG/CR-4772, SAND86-1996 (February 1987).

31) The Cadmus Group, Inc. *Regulatory Impact Analysis of Proposed Hazardous Waste Disposal Restrictions for Class I Injection of Phase III Wastes*. Prepared for U.S. EPA, Office of Ground Water and Drinking Water, Jan. 12, 1995.

32) Underground Injection Practices Council. *A Class I Injection Well Survey. Phase II Report - Survey of Operations*. Oklahoma City, OK (December 1987).

33) Underground Injection Practices Council. *Injection Well Bibliography*. Oklahoma City, OK (January 1989).

34) Underground Resource Management, Inc. *Evaluation of a Subsurface Waste Injection System near Vickery, Ohio*. Prepared for the Ohio EPA (March 1984).

35) U.S. Environmental Protection Agency. *Report to Congress on Injection of Hazardous Waste*. EPA 570/9-85-003. U.S. EPA Office of Drinking Water. (May 1985).

36) U.S. Environmental Protection Agency. *OSWER Comparative Risk Project Executive Summary and Overview Report*. Washington, D.C. (September 1989).

37) U.S. Environmental Protection Agency. *Assessing the Geochemical Fate of Deep-Well-Injected Hazardous Waste. A Reference Guide*. EPA/625/6-89/025a. U.S. EPA Office of Research and Development. (June 1990).

38) U.S. Environmental Protection Agency. *Assessing the Geochemical Fate of Deep-Well-Injected Hazardous Waste. Summaries of Recent Research*. EPA/625/6-89/025b. U.S. EPA Office of Research and Development. (July 1990).

39) U.S. Environmental Protection Agency. *Analysis of the Effects of EPA Restrictions on the Deep Injection of Hazardous Waste*. EPA/570/9-91-031. U.S. EPA Office of Ground Water and Drinking Water. (October 1991).

40) U.S. Environmental Protection Agency. Letter from Martha G. Prothro, Acting Assistant Administrator, U.S. EPA Office of Water to Honorable John D. Dingell, Chairman, Subcommittee on Oversight and Investigations, Committee on Energy and Commerce, U.S. House of Representatives. Attachment W. (April 19,1993).

41) U.S. Environmental Protection Agency. *Draft UICWELLS Database*. U.S. EPA Office of Water, Underground Injection Control Branch. (April 1996).

42) U.S. Environmental Protection Agency. *1997 Toxics Release Inventory Public Data Release Report*. U.S. EPA Office of Prevention, Pesticides and Toxic Substances. (April 1999).

43) Visocky, A.P. et al. *Study of Current Underground Injection Control Regulations and Practices in Illinois*. Ground Water Monitoring Review. pp. 59-63 (Summer 1986).

44) Ward, D.S. et al. *A Numerical Evaluation of Class I Injection Wells for Waste Containment Performance*. GeoTrans, Inc. Prepared for U.S. EPA Office of Drinking Water, Underground Injection Control Program. (September 30, 1987).

45) Warner, D.L. and J.H. Lehr. *An Introduction to the Technology of Subsurface Wastewater Injection*. University of Missouri - Rolla and National Water Well Association. Prepared for Robert S. Kerr Environmental Research Lab, Ada, OK. (December 1977).

46) Wesson, R.L. and C. Nicholson. *Earthquake Hazard Associated with Deep Well Injection*. Prepared for U.S. EPA. U.S. Geological Survey. (June 1987).

47) Woodward Clyde Consultants. *Underground Injection Well Questionnaire*. Survey prepared for Chemical Manufacturers Association. (August 1995).

APPENDIX A

Basis for Event Frequency Probability Distributions

There are 39 events identified in the PRA (listed in Table 2 of the paper) for which failure rates are needed to calculate event tree and fault tree probabilities. For many of these events, occurrence is so rare and data are so sparse that a confident point estimate for the frequency of occurrence cannot be established. Directly applicable compilations of data on the frequency of most events were not found. In common practice, most component failure modes are identified and corrected during required testing and maintenance, and thus may not be recorded as a failure event per se. More than one third of the events involve some type of human error. There are available compilations of human error frequency data[29,30]; however, their direct applicability to the human tasks involved here is uncertain.

Consequently, uncertainty about occurrence frequencies was given explicit quantitative treatment in the PRA. Probability distributions of event occurrence frequencies were developed, either based on available occurrence data or expert judgement. In general, probability distributions for event frequencies were derived as follows.

1. A 1993 U.S. EPA reply to a House of Representatives subcommittee inquiry[40] provided state-by-state summaries of certain reported types of Class I injection well failure events between 1988 and 1992. Numbers of events were reported for 469 Class I wells (hazardous and nonhazardous) located in twelve states. Events reported included tubing leaks, casing leaks, packer leaks and waste migration on the outside of the long string casing (i.e., cement microannulus). The number of reported events was divided by 855,925 well-days (469 wells x 5 yrs x 365 days/yr) to derive an estimate of the average daily occurrence rate for each type of event. Since nonhazardous wells have less regulatory restrictions than hazardous, it was a conservatism to include these data.

   Modeling these failure rates with a binomial distribution, it is possible to determine the confidence intervals for a given average failure rate. Estimations of the 90th percentile upper confidence limit of the average failure rates were calculated using methods outlined by McCormick[20]. These are shown in the following table.

Component	Number of Reported Failures	90th Percentile Confidence Limit Of Average Failure Rate (day^{-1})
Tube	48	6.80E-05
Casing[1]	28	4.20E-05
Packer[1]	31	4.60E-05
Waste Migration[2]	5	1.10E-05

1. Three recorded "annulus leak" events were included because it could not be determined

if these were casing or packer related.
2. This category is assumed to be a surrogate for casing cement leak events.

Probability distributions representing uncertainty about the frequency rate of these events (ITUBLEAK, LSTRINGLEAK, PACKLEAK, LSCEMLEAK) were developed by using these upper confidence limits for the average rate as the rate parameter in a Poisson distribution. The Poisson distribution is commonly used in reliability analysis to describe random failures in a system that cause irreversible transitions in the system[20], such as a loss of waste isolation. The Poisson distribution requirements[20], which are met for this application, include:

- Events can happen at any time within the day
- The probability of an event is small
- Events can happen independently of other events
- The average number of events per day does not change with time

2. For events involving typical components of any industrial system such as valve, pump, control system or alarm failures, occurrence frequencies were obtained from available industrial reliability databases[9,13,18].

3. Most human errors rates were derived from available human reliability data for similar activities. Usually, these human error data have been compiled for highly trained and scrutinized occupations such as nuclear power plant operators[29,30] and firemen[9,13]. While Class I hazardous injection well operators arguably fall into this same category, in the assessment these rates were conservatively assigned as the lower bound of the distribution with an upper bound set at an order of magnitude higher rate.
4. For events in which data are entirely lacking, the authors relied on professional judgement, shaped in part by the experience of deep well operators and regulators elicited during workshops held in conjunction with Ground Water Protection Council national meetings. To account for uncertainty in professional judgement, relatively large bounds of uncertainty were applied to frequencies derived in this manner. When the uncertainty was high, the range of the distribution may span several orders of magnitude. In some cases the frequency was set at a maximum value, for example the probability that injected fluid is sufficiently buoyant to penetrate a lower confining zone breach was assumed to be 1.

The probability distributions representing uncertainty about event frequencies are summarized in Table 2 of the paper and discussed individually below.

Event:	ITUBLEAK
Description:	Injection tube leak
Probability:	Poisson distribution with 6.8E-05/day rate
Basis:	This event quantifies the probability that the injection tube carrying waste to the injection zone will develop a leak. Based on compilation of state-by-state data analyzed as discussed above.
Event:	ITUBFAIL
Description:	Sudden and major failure and breach of the injection tube

Probability: 1/100th of ITUBLEAK probability
Basis: ITUBFAIL assumes a sudden and major failure of the injection tube such that the annulus pressure is lost simultaneously. Based on professional judgement, the likelihood of the injection tube failing catastrophically was estimated to be 1/100th the probability of a leak. Thus the ITUBFAIL probability was assigned a value 0.01 times ITUBLEAK.

Event: ANNPRESSLO
Description: Annulus pressure drops below injection pressure
Probability: Determined by Fault Tree Analysis
Basis: Due to the multiple components associated with this failure event, an ANNULUS PRESSURE BARRIER FAILURE FAULT TREE (Figure 3 in paper) was developed and used to evaluate the event probability. The resulting cumulative distribution for this event frequency is:

10th percentile	1.5E-12
20th percentile	2.6E-12
30th percentile	3.8E-12
40th percentile	5.2E-12
50th percentile	7.0E-12
60th percentile	9.3E-12
70th percentile	1.2E-11
80th percentile	1.7E-11
90th percentile	2.4E-11

Event: LSTRINGLEAK
Description: Long string casing leak
Probability: Poisson distribution with 4.2E-05/day rate
Basis: Based on compilation of state-by-state data analyzed as discussed above.

Event: LSCASEFAIL
Description: Sudden and major failure and breach of the long string casing
Probability: 1/100th of LSTRINGLEAK probability
Basis: LCASEFAIL assumes a sudden and major failure of the long string casing such that the annulus pressure is lost simultaneously. Based on professional judgement, the likelihood of the long string casing failing catastrophically was estimated to be 1/100th the probability of a leak. Thus the LCASEFAIL probability was assigned a value 0.01 times LSTRINGLEAK.

Event: SURFCASELEAK
Description: Surface casing leak
Probability: Poisson distribution with 4.2E-06/day rate
Basis: The surface casing surrounds the long string casing and provides one of the final engineered barriers to the Underground Source of Drinking Water (USDW). Failure probabilities are derived from LSTRINGLEAK with a correction of 0.1 to account for the fact that the surface casing is subject to less stress than the long string casing, and it is shorter and closer to the surface making it less likely to be subject to

construction failure modes.

Event: LSCEMLEAK
Description: Long string casing cement micro-annulus allows fluid movement along casing
Probability: Poisson distribution with 1.1E-05/day rate
Basis: Surrounding the entire length of the long string casing is cement which fills the void between the casing and the surrounding geology. Given that there may be discontinuities in the cement pack, there is the probability that waste may migrate up the outer length of the casing through a micro-annulus discontinuity in the cement. Based on the state-by-state data responses for "waste migration", a failure rate parameter for the distribution was determined using the methodology described above.

Event: LOCATION A
Description: Long string casing leak is located between surface casing and uppermost confining zone
Probability: Uniform distribution from 1.0E-02 to 5.0E-02
Basis: Given that a long string casing leak has occurred, the exact location along its entire length determines the likely migration route. If the leak occurs within the bounds defined by LOCATION A, migration to the USDW is assumed to be immediate and complete. Estimation of probability is based on professional judgement taking into account the length of casing in this location relative to typical overall long string casing length. In addition, consideration was given to the fact that stresses on the casing increase with depth.

Event: LOCATION B
Description: Long string casing leak is located above the bottom of the surface casing
Probability: Uniform distribution from 1.0E-02 to 1.0E-01
Basis: The same logic applied to the determination of LOCATION A probability is used here.

Event: LOCATION C
Description: Long string casing leak is located below the confining zone(s)
Probability: 1-Prob(LOCATION A)-Prob(LOCATION B)
Basis: The final section of the casing string extends from the top of the upper most confining zone to the injection zone. This represents the largest fraction of the casing length and stresses increase with depth, so the likelihood for a casing leak is higher in this location. Given that a long string casing leak has occurred, the probabilities for LOCATION A, LOCATION B, and LOCATION C must sum to unity. Thus, an algorithm is included in the event tree for the Monte-Carlo simulation that calculates the probability of LOCATION C based on the probabilities selected at each iteration for LOCATION A and LOCATION B.

Event: PACKLEAK
Description: Packer leak

Probability: Poisson distribution with 4.6E-05/day rate

Basis: This event quantifies the probability that the packer will develop a leak. The packer seals the bottom of the annulus between the long string casing and the injection tube. The probability is based on compilation of state-by-state data analyzed as discussed above.

Event: PACKFAIL

Description: Sudden and major failure and breach of packer

Probability: 1/100th of PACKLEAK probability

Basis: Using the same basis applied to other catastrophic failure events, a professional judgement of 1/100th of the probability of a leak was used for complete packer failure.

Event: FLUIDTEST

Description: Testing fails to detect injection fluid migration along outside of long string casing

Probability: Uniform distribution from 5.0E-04 to 5.0E-03

Basis: Regular testing is required to detect migration fluid along the outside of the casing material. Generally, the probability of failing to detect a leak is most likely due to operator error either in the procedure or in the interpretation of results. Thus, the probability of failing to detect fluid migration is based on the probability of operator and hence human error. A primary source of human error rates is studies prepared for nuclear power plant reliability analysis[29,30]. These studies show that errors of omission for nonpassive tasks (maintenance, test, or calibration) occur at a rate of approximately 1.0E-03 per demand, with a range from 5.0E-04 to 5.0E-03. It is assumed that a single failure to detect on demand (i.e., at the time of the test) results in significant fluid migration.

Event: CONFINEBRCHL

Description: Transmissive breach occurs through lower confining zone

Probability: Determined by Fault Tree Analysis

Basis: Due to the multiple components associated with this failure event, a LOWER CONFINING ZONE BREACH FAULT TREE (Figure 4 in paper) was developed and used to evaluate the event probability. The resulting cumulative distribution for this event frequency is:

10th percentile	1.7E-03
20th percentile	1.9E-03
30th percentile	2.2E-03
40th percentile	2.5E-03
50th percentile	2.9E-03
60th percentile	3.4E-03
70th percentile	4.3E-03
80th percentile	5.8E-03
90th percentile	8.2E-03

Event: CONFINEBRCHU

Description: Transmissive breach occurs through upper confining zone

Probability: Determined by Fault Tree Analysis

Basis: Due to the multiple components associated with this failure event, an UPPER CONFINING ZONE BREACH FAULT TREE (Figure 9 in paper) was developed and used to evaluate the event probability. The resulting cumulative distribution for this event frequency is:

10th percentile	1.6E-03
20th percentile	1.8E-03
30th percentile	2.1E-03
40th percentile	2.4E-03
50th percentile	2.7E-03
60th percentile	3.3E-03
70th percentile	4.2E-03
80th percentile	5.6E-03
90th percentile	7.9E-03

Event: LBUOYANCY
Description: Injection fluid is sufficiently buoyant to penetrate lower confining zone breach
Probability: 1.0
Basis: Since fluid is being injected under pressure below the lower confining zone, it is conservatively assumed that this provides sufficient buoyancy to penetrate a breach. In general, in the absence of active injection pressure it is unlikely that buoyancy would be sufficient to transmit injected fluid completely through a breach.

Event: UBUOYANCY
Description: Injection fluid is sufficiently buoyant to penetrate upper confining zone breach
Probability: Uniform Distribution from 1.0E-05 to 1.0E-04
Basis: It is assumed that fluid injection would need to be maintained (while losing pressure to the breach in the confining zones) or even over-pressurized to provide a sufficient force to drive fluid through breaches in both the lower and upper confining zones. For this to occur, there would need to be an operator error in failing to detect an injection pressure loss or over-pressurization. As explained above, human reliability data show that errors of omission for non-passive tasks occur within a range of 5.0E-04 to 5.0E-03 per demand. While pressure is checked continuously during injection, it is conservatively assumed that a single failure to detect a pressure change results in significant fluid movement up through the breaches.

Event: RELDETECT
Description: Groundwater monitoring fails to detect waste release outside injection zone
Probability: 0.5
Basis: This probability is based on professional judgement. Given a release of waste fluid through postulated confining zone breaches, required groundwater monitoring should detect a release. At that detection the injection would be ceased and the driving force for upward fluid movement would be eliminated. This sequence could fail if the monitoring locations are not at or downgradient of the location of the breach in the confining zone, or if the time between release and detection is long enough that a significant release occurs before corrective action is taken.

Event: EXTRACT
Description: Extraction of groundwater from same saturated zone as injection zone
Probability: Uniform Distribution from 1.0E-05 to 1.0E-03
Basis: This probability is based on professional judgement. Deep well injection zones contain non-potable water, usually of high salinity, with no attractive resource value. A number of more useful water bearing zones occur at shallower depths that can be accessed much more cost-effectively. The probability of this event occurring near an existing or former deep injection well at any time in the foreseeable future is considered to be very low.

Event: NORECOGNIZE
Description: Failure to recognize that groundwater extraction is located within injected waste plume
Probability: Uniform Distribution from 1.0E-03 to 1.0E-02
Basis: Assuming that someone in the future screens an extraction well at injection zone depth, this is the probability that they do not recognize the well has intercepted an injected waste plume. This event would require both failure to recognize the well is located within a documented Class I hazardous waste injection well Area or Review (AOR) and failure to recognize that the extracted water contains waste. The distribution is based on professional judgement, taking into consideration significant uncertainties associated with time frames in the thousands of years as well as the small area of the plume relative to the entire saturated zone.

Event: OUTAOR
Description: Injection waste has migrated outside of the AOR to an unconfined zone
Probability: Uniform distribution from 1.0E-05 to 1.0E-04
Basis: Migration of the injected waste plume outside the Area of Review (AOR) is assigned a low probability of occurrence given the extensive characterization efforts required for the no-migration petition. It is conservatively assumed in the PRA that if this event occurs and the injected material is still characteristically hazardous then a release to a USDW occurs. Horizontal and upward migration of injected fluid very far out of predicted ranges would be necessary for this to occur.

Event: WASTEPRESENT
Description: Injected waste has not transformed into non-waste
Probability: Uniform distribution from 1.0E-02 to 1.0
Basis: This event addresses the probability that injected waste has not transformed into a non-hazardous form at a future time when either (a) groundwater is inadvertently extracted from the injected waste plume or (b) the plume has migrated outside of the Area of Review to an unconfined zone. The assigned probability distribution takes into consideration (a) it is not uncommon to render the waste non-hazardous by pretreatment and dilution prior to or during injection, (b) injected waste attenuates in the plume, and (c) biodegradation and other transformation/loss processes may decrease hazardous constituents over time. Inadvertent extraction and migration outside the AOR are events with long time frames, and there is reasonable likelihood

that these factors could have transformed the waste by the time of these event sequences.

Event: PUMPPA
Description: Annulus pump fails
Probability: Triangular distribution with min=5.0E-05; mode=3.0E-04; max=5.0E-03
Basis: The European Industry Reliability Data Bank[18] provides a resource of compiled data for equipment failure rates. Based on the failure rates per hour (5.0E-07 to 5.0E-04) for pumps with long operating times, the daily (assuming a 10 hr daily operating period) probability of pump failure is between 5.0E-06 and 5.0E-03 day^{-1}. This data is supported in general, by similar mechanical failure rates from PRAs performed for the nuclear power industry. Range estimates for pump failures from a number of nuclear industry resources[20] provide a median value of 3.0E-05 failures/hour (3.0E-04 failures/day). For the nuclear industry, redundancies and routine replacement ensures that the failure rates and consequences of pump failure are minimal. A triangular distribution was used for annulus pump failure rate, using the nuclear power industry value of 3.0E-04 failures/day as the mode and assigning the European database values as the extreme range values.

Event: CHECKPA
Description: Annulus check value fails open
Probability: Triangular distribution with min=1.0E-04; mode=3.0E-04; max=1.0E-03
Basis: Given that the annulus pump fails, CHECKPA is the probability that the check valve, designed to keep the annulus fluid contained and pressurized in the annulus, stays open. This an on-demand failure rate in that failure only occurs when the component is called upon to function. Data from McCormick[20] gives an on-demand failure rate for check values (fail open) of 1.0E-04 to 1.0E-03 per demand (median of 3.0E-04). Since CHECKPA is conditional upon PUMPPA, and both are represented by the same AND gate within the fault tree, the on-demand probability is used directly.

Event: CONTROLPA
Description: Annulus pressure control system fails resulting in under-pressurization
Probability: Uniform distribution from 1.0E-06 to 1.0E-04
Basis: Control system failures are usually the result of electronic or electrical failures resulting from loss of signal function. Lannoy and Procaccia[18] list the range of electrical/electronic failures from the compiled databases to be between 5.00E-08 and 1.00E-05 per hour. For a one-day operating period, this range converts to a failure probability of 1.2E-06 to 2.4E-04 day^{-1}. Since this range has no point of central tendency a uniform distribution is selected for the PRA.

Event: CONTROLPI
Description: Injection pressure control system resulting in over-pressurization
Probability: Uniform distribution of 1.0E-06 to 1.0E-04
Basis: This is a similar control system failure as was described for CONTROLPA. Similar logic is used to specify a probability distribution.

Event: OPERRPA
Description: Operator error causes annulus pressure to drop below injection pressure
Probability: Uniform distribution from 5.0E-05 to 5.0E-04
Basis: Swain[30] provides data on human error showing a frequency of 1.0E-05 error per action. Assuming the operator is performing 5 critical actions per day that could lead to a potential pressure drop, the daily failure rate is 5.0E-05. A uniform distribution is used which assumes this estimate is the lower bound and it is equally likely to be up to an order of magnitude higher frequency of human error. Since all operator errors in this PRA may be performed by either the same or a similarly-trained operator, this and the other operator error event probability distributions were correlated in the Monte Carlo simulation using a correlation coefficient of 0.5.

Event: OPERRPI
Description: Operator error causes injection pressure to rise above annulus pressure
Probability: Uniform distribution from 5.0E-05 to 5.0E-04
Basis: The same basis applies as for event OPERRPA above.

Event: OPERRDET
Description: Operator fails to detect/respond to unacceptable pressure differential
Probability: Uniform distribution from 5.0E-05 to 5.0E-04
Basis: The same basis applies as for event OPERRPA above.

Event: OPERRFRAC
Description: Operator error results in induced transmissive fracture through lower confining zone
Probability: Uniform distribution from 5.0E-05 to 5.0E-04
Basis: The same basis applies as for event OPERRPA above.

Event: OPERINJ
Description: Operator fails to recognize changes in confining zone capacity
Probability: Uniform distribution from 5.0E-05 to 5.0E-04
Basis: The same basis applies as for event OPERRPA above.

Event: CAPLOSS
Description: Loss of injection zone capacity results in over-pressurization
Probability: Uniform distribution from 1.0E-05 to 1.0E-03
Basis: The capacity of injection zone rock is carefully studied for a Class I well as part of the site selection process and no-migration petition. Given the extent of the characterization efforts involved, it is unlikely that a lack of capacity will be overlooked. This would be the result of a human error of omission, which occur at a rate of approximately 1.0E-03 per demand. Since at least one additional independent review of this factor would be performed (e.g., by the regulatory agency), this frequency is assumed to be the upper bound of the distribution.

Event: PERMEA
Description: Confining zone has unexpected transmissive permeability
Probability: Uniform distribution from 1.0E-05 to 1.0E-03

Basis: The permeability of confining zone rock is carefully studied for a Class I well as part of the site selection process and no-migration petition. Given the extent of the study efforts involved, it is unlikely that permeability will be incorrectly characterized. This would be the result of a human error of omission, which occur at a rate of approximately 1.0E-03 per demand. Since at least one additional independent review of this factor would be performed (e.g., by the regulatory agency), this frequency is assumed to be the upper bound of the distribution.

Event: DISCONT
Probability: Uniform distribution from 1.0E-04 to 1.0E-02
Description: Presence of unidentified transmissive discontinuity
Basis: As per the discussion on the characterization efforts outlined above for PERMEA, it is unlikely that the geologic properties of the confining zone were not completely described. However, irregularities in the geological characteristics of the confining zone are possible given the lateral extent of the injection zone. Thus a factor of ten higher probability is used than was assigned to PERMEA.

Event: DETECTWELL
Description: Failure to identify abandoned well in AOR
Probability: Uniform distribution from 1.0E-03 to 1.0E-02
Basis: Based on similar arguments as used for PERMEA and DISCONT, it is unlikely that the presence of abandoned wells within the AOR would remain undetected. However, records for abandoned wells can be missing or in error. The distribution range used is higher in error frequency to reflect this added consideration.

Event: ALARM
Description: Automatic alarm fails
Probability: Uniform distribution: 1.00E-05 to 1.00E-03
Basis: The frequency of alarm failures were analyzed by Davis and Satterwaite[9] for fire hazards associated with the management and storage of radioactive waste. A failure probability of 5.00E-05 was determined. However, this assessment was based on alarms with high reliability requirements specified for nuclear facilities. To account for the possibility that less reliable equipment may exist at an injection well facility, this value was used as the lower bound of a uniform distribution that includes an equal probability that the alarm failure rate can be as much as a factor of 100 higher.

Event: SEISMFAULT
Description: Seismic event induces a transmissive fault or fracture
Probability: Uniform distribution: 1.00E-05 to 1.00E-04
Basis: Avoidance of areas prone to seismic activity is carefully studied for a Class I well as part of the site selection process and no-migration petition. In addition, seismic factors are part of the design criteria for the well. Given the extent of the study efforts involved, it is unlikely that the well will be located where seismic activity has been incorrectly characterized. The event would more likely be a rare event that heretofore had not occurred at such a magnitude in the region of the well site, and therefore is not reflected in historical seismic event data. In addition, the seismic

event would need to be of a nature that it results in a transmissive fault or fracture penetrating entirely through the confining zone. This event was assigned, by judgement, a probability of occurrence in the range of 1 in 100,000 to 1 in 10,000.

Event: PLUGFAIL
Description: Identified abandoned well plug fails
Probability: Poisson distribution with 8E-04/well rate
Basis: Assignment of failure probability is based on TRC proper plug hearing files in Clark[6]. In this study, 2531 oil and gas fields were examined for plug leakage incidents from abandoned wells. Two leakage incidents were found. The number of abandoned wells may exceed the number of fields by a factor of ten. A conservative failure rate was estimated as 2 plug failures per 2531 fields, or 8E-04 plug failures per abandoned well (assuming only one well per field). Since this event meets the Poisson distribution requirements (see above in introductory remarks), a Poisson distribution was assumed using the failure rate determined here.

Event: TRANSUSDW
Description: Unidentified abandoned well is transmissive through upper confining zone to USDW
Probability: 0.1
Basis: There are no data upon which to base this event frequency. The probability assumed here of 0.1 is believed to be very conservative considering that the event requires the abandoned well to provide a pathway, other than plug failure, to transmit injected waste through the entire confining zone.

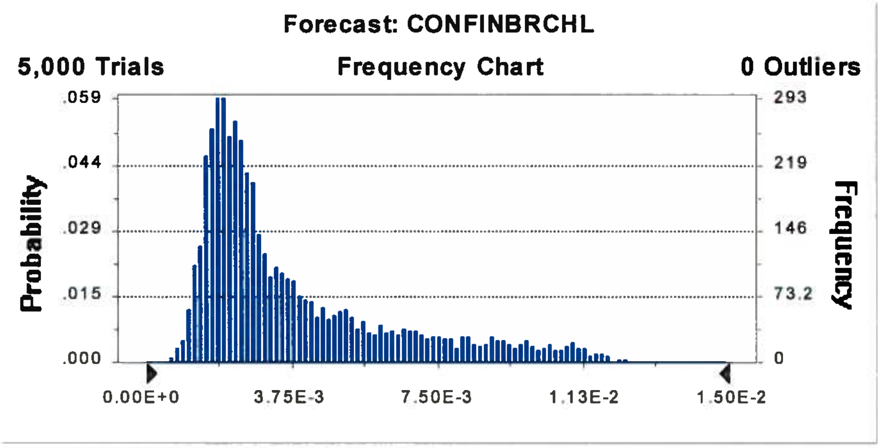
Event: TRANSLCZ
Description: Unidentified abandoned well is transmissive from injection zone through lower confining zone
Probability: 0.1
Basis: There are no data upon which to base this event frequency. The probability assumed here of 0.1 is believed to be very conservative considering that the event requires the abandoned well to provide a pathway, other than plug failure, to transmit injected waste through the entire confining zone.

Event: INCOMPWASTE
Description: Injected waste is incompatible with previously injected material
Probability: Uniform distribution: 1.00E-05 to 1.00E-04
Basis: Material that is injected is well characterized to ensure that no chemical or physical reactions can take place that can sufficiently alter the properties of the material in the injected zone. In addition, the no migration petition process requires study of waste-host rock compatibility. This event also assumes sufficient waste volume and reaction with confining zone rock to result in a complete breach of the confining zone. This event was assigned, conservatively by judgement, a probability of occurrence in the range of 1 in 100,000 to 1 in 10,000.

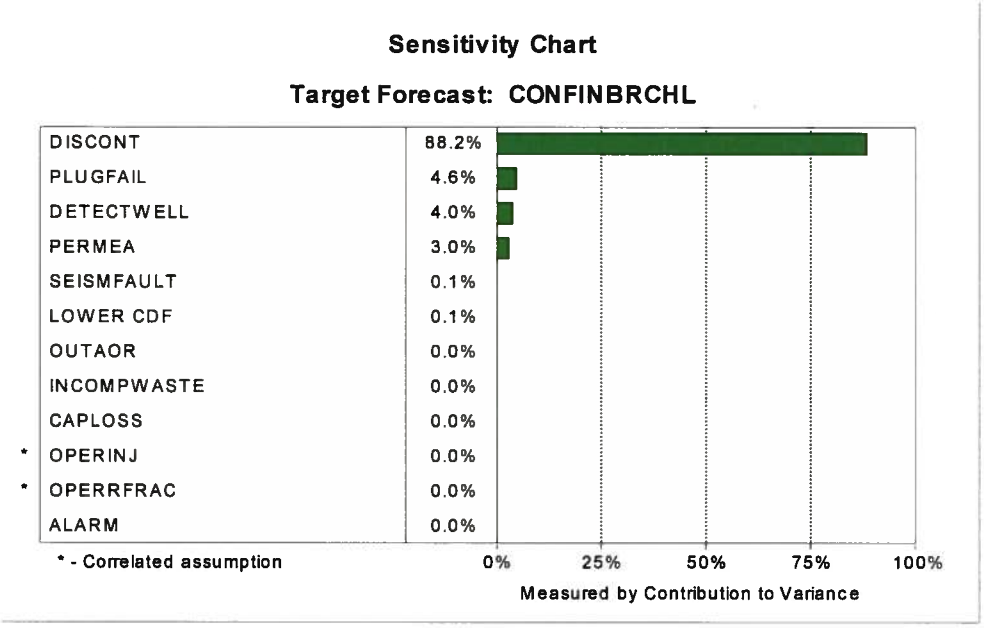
Figure 3 - Supporting Documents

Forecast: CONFINBRCHL

Statistics:	Value
Trials	5000
Mean	3.82E-03
Median	2.76E-03
Mode	---
Standard Deviation	2.55E-03
Variance	6.52E-06
Coeff. of Variability	0.67
Mean Std. Error	3.61E-05



Cumulative Percentile	Failure Frequency
0%	6.17E-04
10%	1.60E-03
25%	2.01E-03
50%	2.76E-03
75%	4.91E-03
90%	8.00E-03
100%	1.31E-02

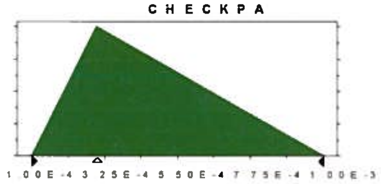


Assumptions

Assumption: CHECKPA **[FT_ANPRF.XLS]ANNPRESSFAIL - Cell: E28**

Triangular distribution with parameters:

Minimum	1.00E-04
Likeliest	3.00E-04
Maximum	1.00E-03

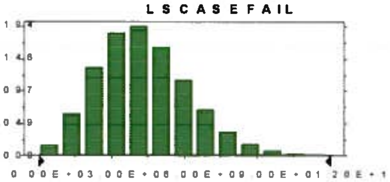


Selected range is from 1.00E-4 to 1.00E-3
Mean value in simulation was 4.67E-4

Assumption: LSCASEFAIL **[FT_ANPRF.XLS]ANNPRESSFAIL - Cell: A20**

Poisson distribution with parameters:

Rate	4.20E+00

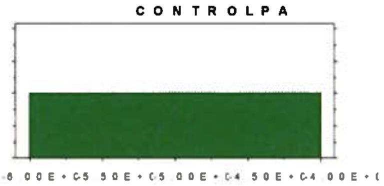


Selected range is from 0.00E+0 to +Infinity
Mean value in simulation was 4.18E+0

Assumption: CONTROLPA **[FT_ANPRF.XLS]ANNPRESSFAIL - Cell: E20**

Uniform distribution with parameters:

Minimum	-6.00E+00
Maximum	-4.00E+00

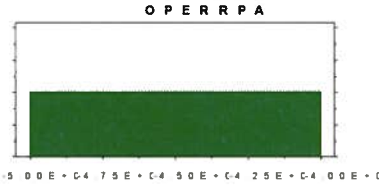


Mean value in simulation was -5.00E+0

Assumption: OPERRPA **[FT_ANPRF.XLS]ANNPRESSFAIL - Cell: F20**

Uniform distribution with parameters:

Minimum	-5.00E+00
Maximum	-4.00E+00



Mean value in simulation was -4.50E+0

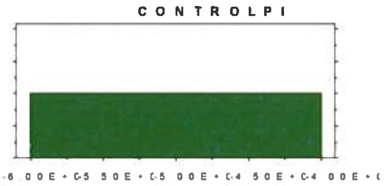
Correlated with:

OPERRPI (J20)	0.50
OPERRDET (O13)	0.50

Assumption: CONTROLPI **[FT_ANPRF.XLS]ANNPRESSFAIL - Cell: H20**

Uniform distribution with parameters:

Minimum	-6.00E+00
Maximum	-4.00E+00

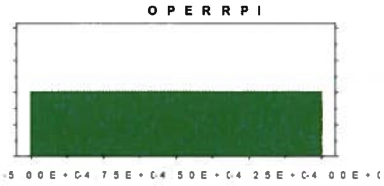


Mean value in simulation was -5.00E+0

Assumption: OPERRPI **[FT_ANPRF.XLS]ANNPRESSFAIL - Cell: J20**

Uniform distribution with parameters:

Minimum	-5.00E+00
Maximum	-4.00E+00



Mean value in simulation was -4.50E+0

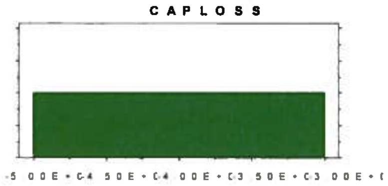
Correlated with:

OPERRPA (F20)	0.50

Assumption: CAPLOSS [FT_ANPRF.XLS]ANNPRESSFAIL - Cell: M20

Uniform distribution with parameters:

Minimum	-5.00E+00
Maximum	-3.00E+00

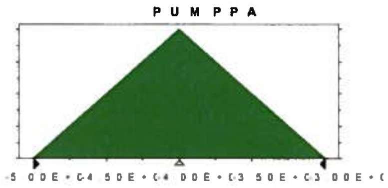


Mean value in simulation was -4.00E+0

Assumption: PUMPPA [FT_ANPRF.XLS]ANNPRESSFAIL - Cell: B28

Triangular distribution with parameters:

Minimum	-5.00E+00
Likeliest	-4.00E+00
Maximum	-3.00E+00

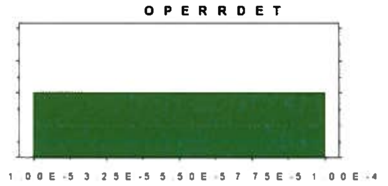


Selected range is from -5.00E+0 to -3.00E+0
Mean value in simulation was -4.00E+0

Assumption: OPERRDET [FT_ANPRF.XLS]ANNPRESSFAIL - Cell: O13

Uniform distribution with parameters:

Minimum	1.00E-05
Maximum	1.00E-04



Mean value in simulation was 5.50E-5

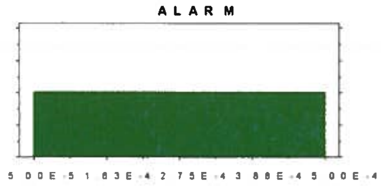
Correlated with:

OPERRPA (F20)	0.50

Assumption: ALARM [FT_ANPRF.XLS]ANNPRESSFAIL - Cell: M13

Uniform distribution with parameters:

Minimum	5.00E-05
Maximum	5.00E-04



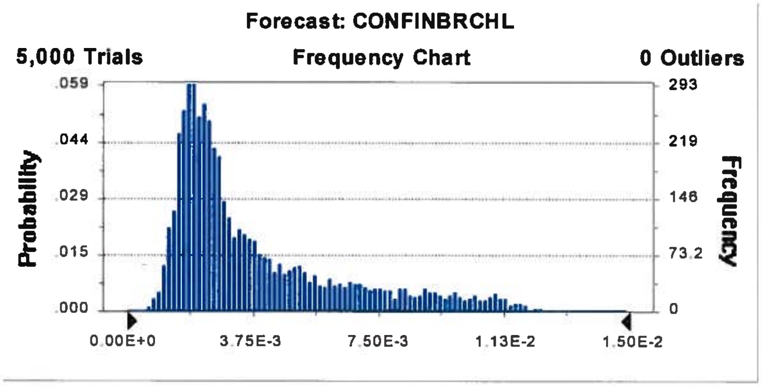
Mean value in simulation was 2.75E-4

1.2E-13	0%
9.8E-13	5%
1.5E-12	10%
2.1E-12	15%
2.6E-12	20%
3.2E-12	25%
3.8E-12	30%
4.5E-12	35%
5.2E-12	40%
6.0E-12	45%
7.0E-12	50%
8.0E-12	55%
9.3E-12	60%
1.1E-11	65%
1.2E-11	70%
1.4E-11	75%
1.7E-11	80%
2.0E-11	85%
2.4E-11	90%
3.1E-11	95%
7.6E-11	100%

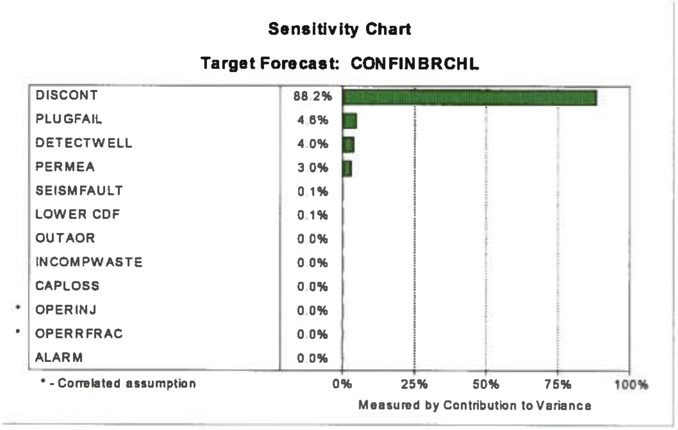
Figure 4 - Supporting Documents

Forecast: CONFINBRCHL

Statistics:	Value
Trials	5000
Mean	3.82E-03
Median	2.76E-03
Mode	---
Standard Deviation	2.55E-03
Variance	6.52E-06
Coeff. of Variability	0.67
Mean Std. Error	3.61E-05



Cumulative Percentile	Failure Frequency
0%	6.17E-04
10%	1.60E-03
25%	2.01E-03
50%	2.76E-03
75%	4.91E-03
90%	8.00E-03
100%	1.31E-02

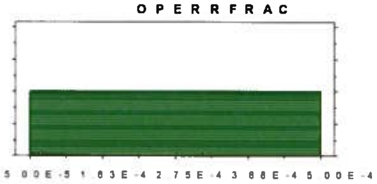


Assumptions

Assumption: OPERRFRAC **[FT_LOWCF.XLS]lowerconf-layer IH - Cell: C27**

Uniform distribution with parameters:

Minimum	5.00E-05
Maximum	5.00E-04



Mean value in simulation was 2.75E-4

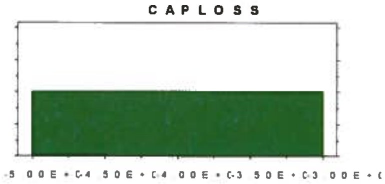
Correlated with:

OPERINJ (M24)	0.50

Assumption: CAPLOSS **[FT_LOWCF.XLS]lowerconf-layer IH - Cell: F26**

Uniform distribution with parameters:

Minimum	-5.00E+00
Maximum	-3.00E+00

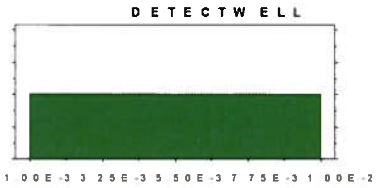


Mean value in simulation was -4.00E+0

Assumption: DETECTWELL [FT_LOWCF.XLS]lowerconf-layer IH - Cell: G32

Uniform distribution with parameters:

Minimum	1.00E-03
Maximum	1.00E-02

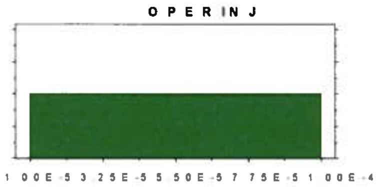


Mean value in simulation was 5.50E-3

Assumption: OPERINJ [FT_LOWCF.XLS]lowerconf-layer IH - Cell: M24

Uniform distribution with parameters:

Minimum	1.00E-05
Maximum	1.00E-04



Mean value in simulation was 5.50E-5

Correlated with:

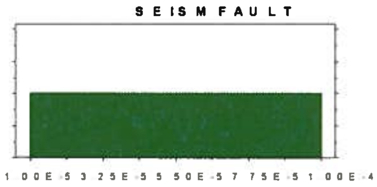
Assumption: OPERINJ (cont'd) [FT_LOWCF.XLS]lowerconf-layer IH - Cell: M24

OPERRFRAC (C27)	0.50

Assumption: SEISMFAULT [FT_LOWCF.XLS]lowerconf-layer IH - Cell: A15

Uniform distribution with parameters:

Minimum	1.00E-05
Maximum	1.00E-04

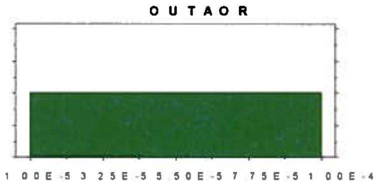


Mean value in simulation was 5.50E-5

Assumption: OUTAOR [FT_LOWCF.XLS]lowerconf-layer IH - Cell: C15

Uniform distribution with parameters:

Minimum	1.00E-05
Maximum	1.00E-04

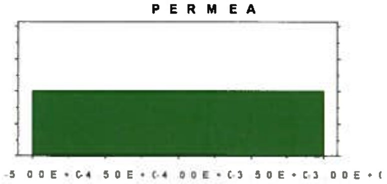


Mean value in simulation was 5.50E-5

Assumption: PERMEA **[FT_LOWCF.XLS]lowerconf-layer IH - Cell: E15**

Uniform distribution with parameters:

Minimum	-5.00E+00
Maximum	-3.00E+00

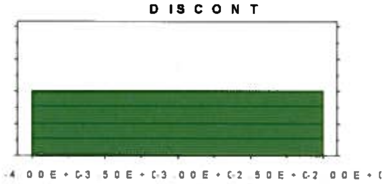


Mean value in simulation was -4.00E+0

Assumption: DISCONT **[FT_LOWCF.XLS]lowerconf-layer IH - Cell: G15**

Uniform distribution with parameters:

Minimum	-4.00E+00
Maximum	-2.00E+00

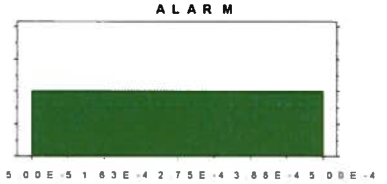


Mean value in simulation was -3.00E+0

Assumption: ALARM **[FT_LOWCF.XLS]lowerconf-layer IH - Cell: A27**

Uniform distribution with parameters:

Minimum	5.00E-05
Maximum	5.00E-04



Mean value in simulation was 2.75E-4

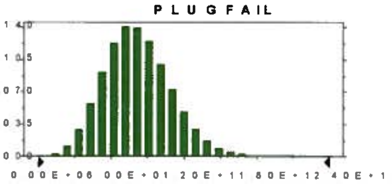
Assumption: PLUGFAIL **[FT_LOWCF.XLS]lowerconf-layer IH - Cell: K24**

Poisson distribution with parameters:

Rate	8.00E+00

Selected range is from 0.00E+0 to +Infinity

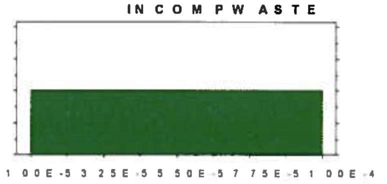
Mean value in simulation was 7.98E+0



Assumption: INCOMPWASTE **[FT_LOWCF.XLS]lowerconf-layer IH - Cell: O24**

Uniform distribution with parameters:

Minimum	1.00E-05
Maximum	1.00E-04

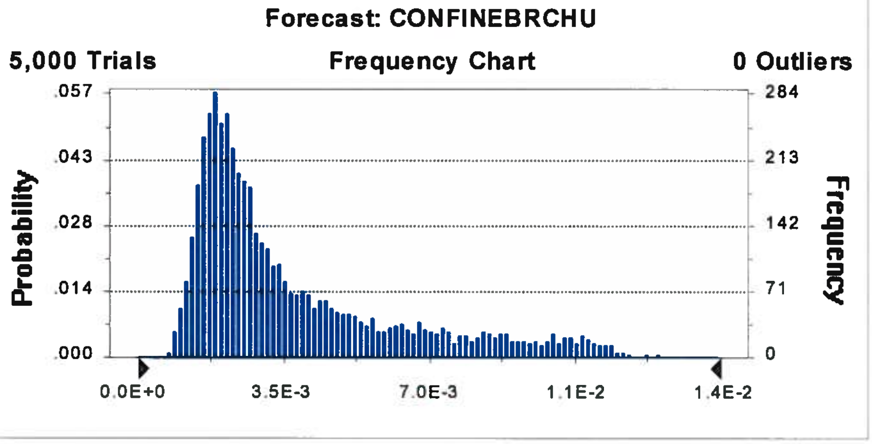


Mean value in simulation was 5.50E-5

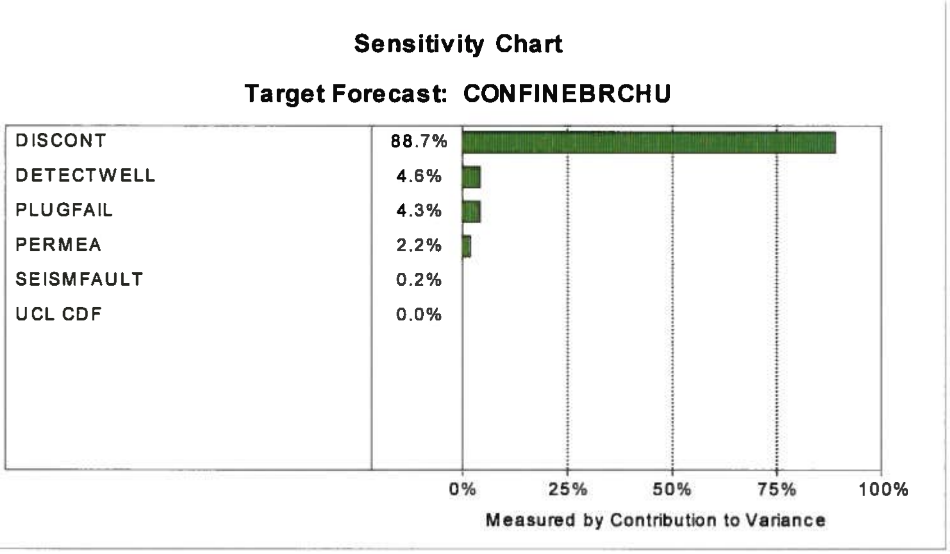
Figure 9 - Supporting Documents

Forecast: CONFINEBRCHU

Statistics:	Value
Trials	5000
Mean	3.8E-03
Median	2.7E-03
Mode	—
Standard Deviation	2.6E-03
Variance	6.5E-06
Coeff. of Variability	0.68
Mean Std. Error	3.61E-05



Cumulative Percentile	Failure Frequency
0%	6.2E-04
10%	1.6E-03
25%	2.0E-03
50%	2.7E-03
75%	4.8E-03
90%	8.0E-03
100%	1.3E-02


Sensitivity Chart

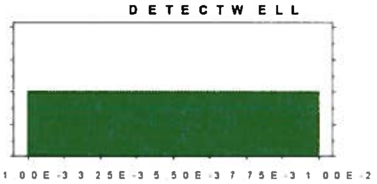
Target Forecast: CONFINEBRCHU

Assumptions

Assumption: DETECTWELL **[FT_UPPCF.XLS]upperconf-layer IH - Cell: D26**

Uniform distribution with parameters:

Minimum	1.00E-03
Maximum	1.00E-02

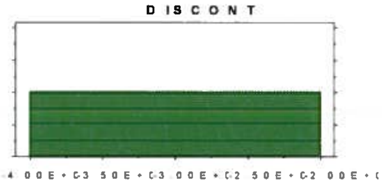


Mean value in simulation was 5.50E-3

Assumption: DISCONT **[FT_UPPCF.XLS]upperconf-layer IH - Cell: E15**

Uniform distribution with parameters:

Minimum	-4.00E+00
Maximum	-2.00E+00



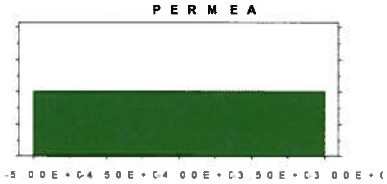
Mean value in simulation was -3.00E+0

Assumption: PERMEA **[FT_UPPCF.XLS]upperconf-layer IH - Cell: C15**

Uniform distribution with parameters:

Minimum	-5.00E+00
Maximum	-3.00E+00

Mean value in simulation was -4.00E+0

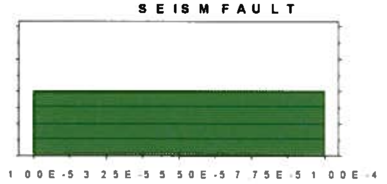


Assumption: SEISMFAULT **[FT_UPPCF.XLS]upperconf-layer IH - Cell: A15**

Uniform distribution with parameters:

Minimum	1.00E-05
Maximum	1.00E-04

Mean value in simulation was 5.50E-5



Assumption: PLUGFAIL **[FT_UPPCF.XLS]upperconf-layer IH - Cell: I21**

Poisson distribution with parameters:

Rate	8.00E+00

Selected range is from 0.00E+0 to +Infinity
Mean value in simulation was 7.99E+0

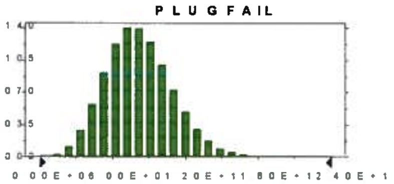


Figure 12 - Supporting Documents

Statistics:	Value
Trials	5000
Mean	6.48E-07
Median	3.23E-07
Mode	---
Standard Deviation	8.70E-07
Variance	7.57E-13
Coeff. of Variability	1.34E+00
Mean Std. Error	1.23E-08

Cumulative Percentile	Loss of waste isolation probability
0%	9.27E-09
5%	4.38E-08
10%	6.25E-08
15%	8.13E-08
20%	1.01E-07
25%	1.23E-07
30%	1.52E-07
35%	1.84E-07
40%	2.24E-07
45%	2.69E-07
50%	3.23E-07
55%	3.86E-07
60%	4.62E-07
65%	5.51E-07
70%	6.58E-07
75%	7.92E-07
80%	9.78E-07
85%	1.23E-06
90%	1.63E-06
95%	2.43E-06
100%	8.94E-06