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A Hazard and Probabilistic Safety Analysis of a High-Level Waste Transfer Process

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Abstract

This paper describes a safety analysis of a transfer process for high-level radioactive and toxic waste. The analysis began with a hazard assessment that used elements of What If, Checklist, Failure Modes and Effects Analysis, and Hazards and Operability Study (HAZOP) techniques to identify and rough-in accident sequences. Based on this preliminary analysis, the most significant accident sequences were developed further using event trees. Quantitative frequency estimates for the accident sequences were based on operational data taken from the historical record of the site where the process is performed. Several modeling challenges were encountered in the course of the study. These included linked initiating and accident progression events, fire propagation modeling, accounting for administrative control violations, and handling mission-phase effects.

Introduction

This paper discusses a probabilistic safety assessment of a unique waste transfer process involving the potential release of flammable gases and the possible dispersion of radionuclides. In the course of the study, several unusual modeling situations were encountered that required extension of normal probabilistic safety assessment (PSA) techniques. The overall analysis is discussed, and the unique features of the study are described.

At the Hanford Site in Washington, there are 177 underground tanks in 18 separate tank farms containing accumulated liquid radioactive wastes from 50 years of weapons materials production activities. The total volume is about 60 million gallons containing approximately 500 million curies of radioactivity. The tanks vary in capacity from 55,000 to 1.2 million gallons and contain materials whose fluidity varies from relatively thick sludge to easily pumped liquids. Twenty-eight tanks that were built after 1970 are of a double-shell construction; the balance of the tanks, some of which were constructed as early as 1944, have only a thin single-shell steel liner inside the reinforced concrete shell. To date, there are no recorded liquid leaks for the double-shell tanks (DSTs), but about half of the single-shell tanks (SSTs) have leaked. The tanks are designed to confine the bulk of the aerosols that may be generated within them by "breathing" through a filtered stand pipe and have numerous penetrations or "risers" through their domes. These risers provide access to the tank interior for instruments, pumps, or other activities.

To prevent future leakage, many of the SSTs are pumped to remove water. This process is termed "salt-well pumping" because most of the waste in the tanks is in the form of salt cake with interstitial water. The salt-well pumping (SWP) process uses a jet pump placed above the tank in a pump pit to remove water that percolates from the salt cake and collects in a screen inserted into the waste by water lancing. The interstitial water in the salt cake is reduced gradually. SWP may be divided into an installation phase, a pumping phase, and a removal phase in which the salt-well screen and pump are installed, the interstitial water is pumped, and the salt-well pump and screen are removed, respectively. The installation phase tends to cause major disturbances in the waste; the pumping process is less intrusive. The removal phase also can cause substantial waste disturbances. A diagram of the physical setup of the process is shown in Fig. 1.

The SWP process poses potential hazards because the waste can retain flammable and toxic gases that could be released in significant quantities during SWP. In addition, contaminated water could be released to the environment accidentally during the transfer of liquid from the salt-well tanks.

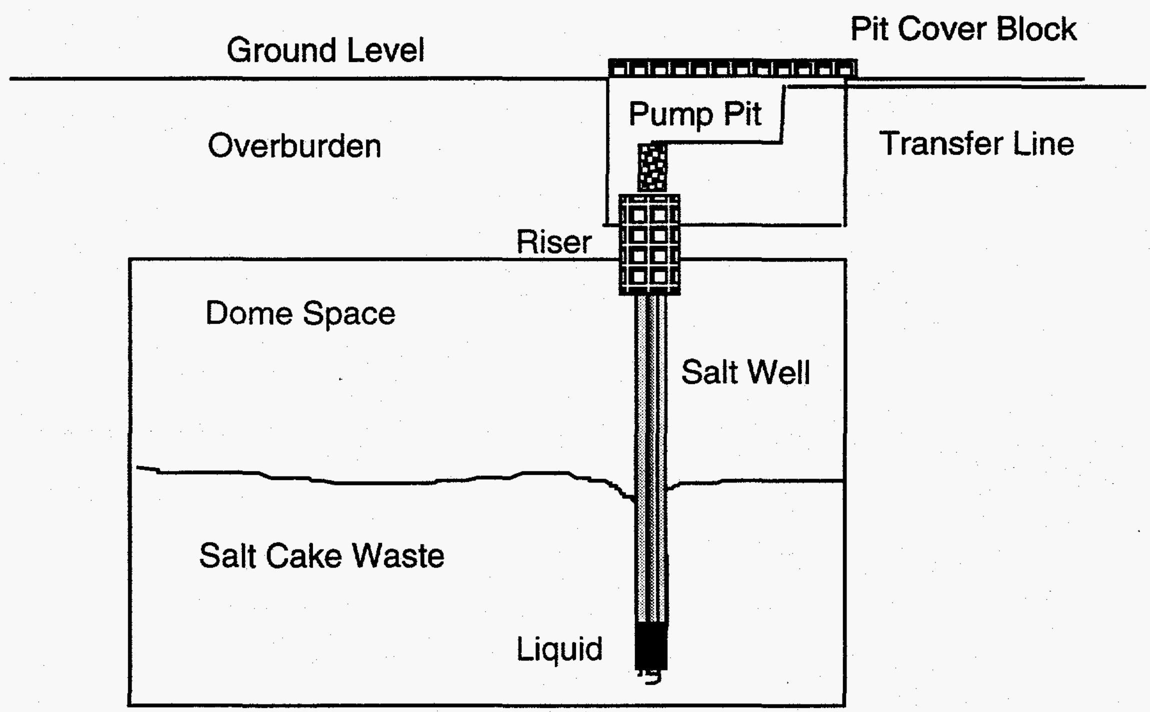


Fig. 1. Salt-Well Pumping

The PSA systematically identified high-consequence accident sequences that had potentially high frequency and determined what characteristics of the tanks or processes made those accident frequencies relatively high. The accident sequences identified by the PSA led to additional equipment or operational changes that would reduce the accident sequence frequencies.

Methodology

The time constraints placed on this analysis required an efficient use of expert personnel and existing data. The overall analysis is shown in Fig. 2. The analysis began with a hazard assessment that used elements of What If, Checklist, Failure Modes and Effects Analysis (FMEA), and Hazards and Operability Study (HAZOP) techniques to identify and rough-in accident sequences. The hazard assessment team included engineers and operational personnel from Hanford who were very familiar with SWP and safety analysts from Los Alamos who were experienced in analyzing many types of systems. The hazard assessment provided a quick and efficient way to incorporate the operational expertise of the engineers and operators at Hanford into the safety analysis models developed by Los Alamos analysts.

The Los Alamos analysts prepared for the hazard assessment phase of the analysis by developing a fault tree to identify accident sequences. This fault tree was developed by studying operating records to identify actual accidents or accident precursors and by deducing accident sequences based on tank operations and the hazards and energy sources found in the tanks. This fault tree served as a prompt in the hazard assessment to spur investigation of a wide range of accident sequences by the hazard assessment team. An important aspect of the hazard assessment was a flow chart of the SWP process. This flow chart was developed by the Los Alamos analysts with technical input from the Hanford members of the hazard assessment team. The flow chart was helpful in organizing the accident sequences and in taking into account the changes in operations and accident frequency that occur as SWP progresses.

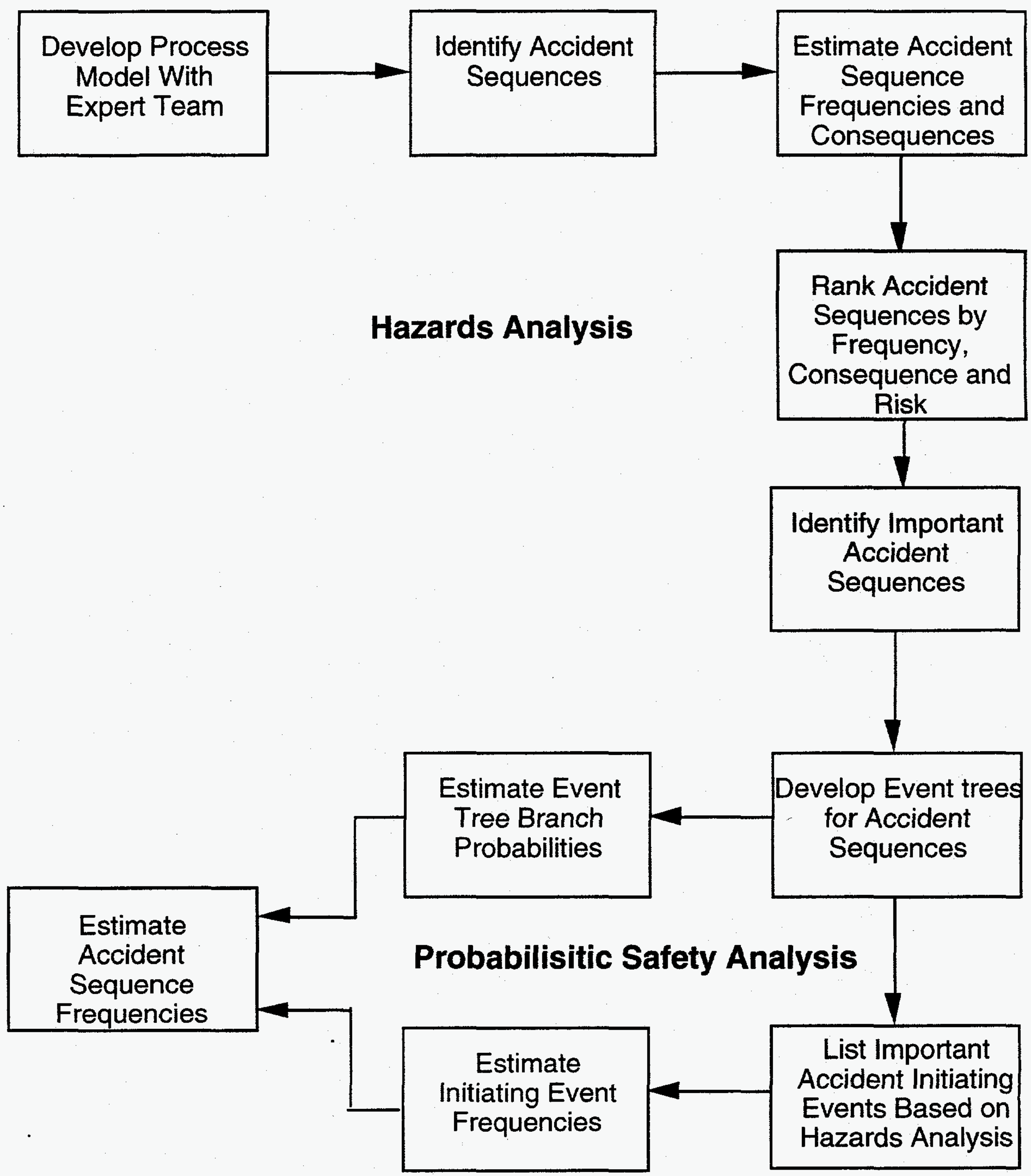


Fig. 2. Analysis Process

The result of the hazard assessment was a set of accident sequences with rough estimates of frequency and consequences for potential accidents throughout the SWP process. These accident sequences were collected and analyzed using spreadsheets. The analysis included binning the accident sequences by consequence type and ranking them by frequency, consequence, and risk.

The accident sequences in the hazard assessment spreadsheet were analyzed further using event trees. Each accident sequence produced an accident initiating event. Related initiating events were grouped to produce a set of eight event trees. These event trees resulted in an expanded set of accident sequences based on the initiating events identified by the hazard assessment. Each initiating event was quantified based on historical data, gas-release models, surrogate data sources, or expert judgment using interactive group elicitation techniques (Meyer and Booker, 1991). The historical data were taken mainly from an extensive data base of tank farm initiating-event frequencies developed previously (Bott, 1993). Surrogate data were used for the frequency of lifting accidents (George et al, 1980). Gas-release frequency models were developed by safety analysts at Los Alamos and Hanford using historical data, tank waste characterization models, and expert judgment.

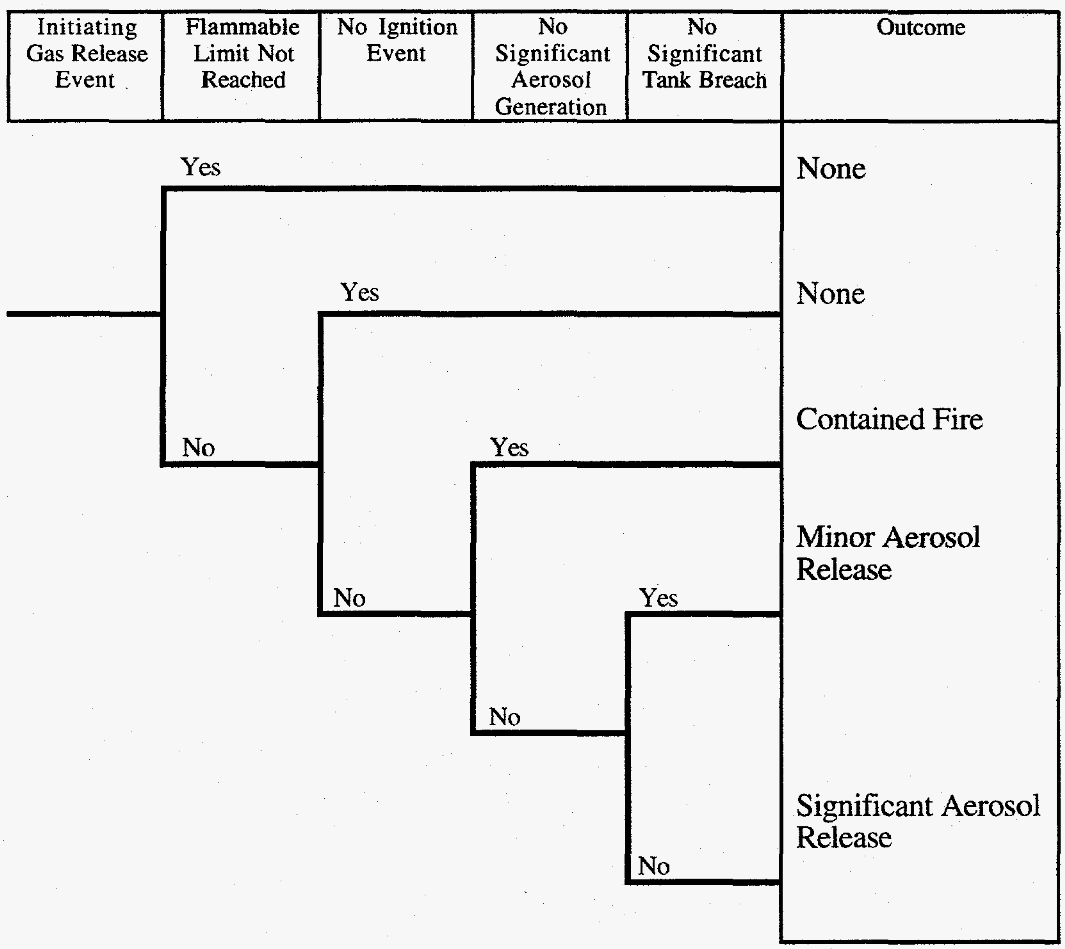
Eight event trees were used to model all the SWP accident initiating events. For a given event tree, the branch probabilities vary according to the initiating event. Thus, dependencies between accident initiating events and branch probabilities are addressed explicitly. This explicit treatment increased the analysis effort but provided more differentiation between accident progression for different accident initiating events. Several important safety concerns were identified by this more detailed treatment of accidents.

The outcomes of the different accident sequences discussed above were binned into several different consequence categories. These categories depended on the waste-release quantity, the energy of the release, and the position of the release. These consequence categories were based on previous calculations of radionuclide and toxic chemical effects on both the on-site and off-site population around Hanford. In this way, a few consequence calculations served to characterize the risk for a large number of accident sequences.

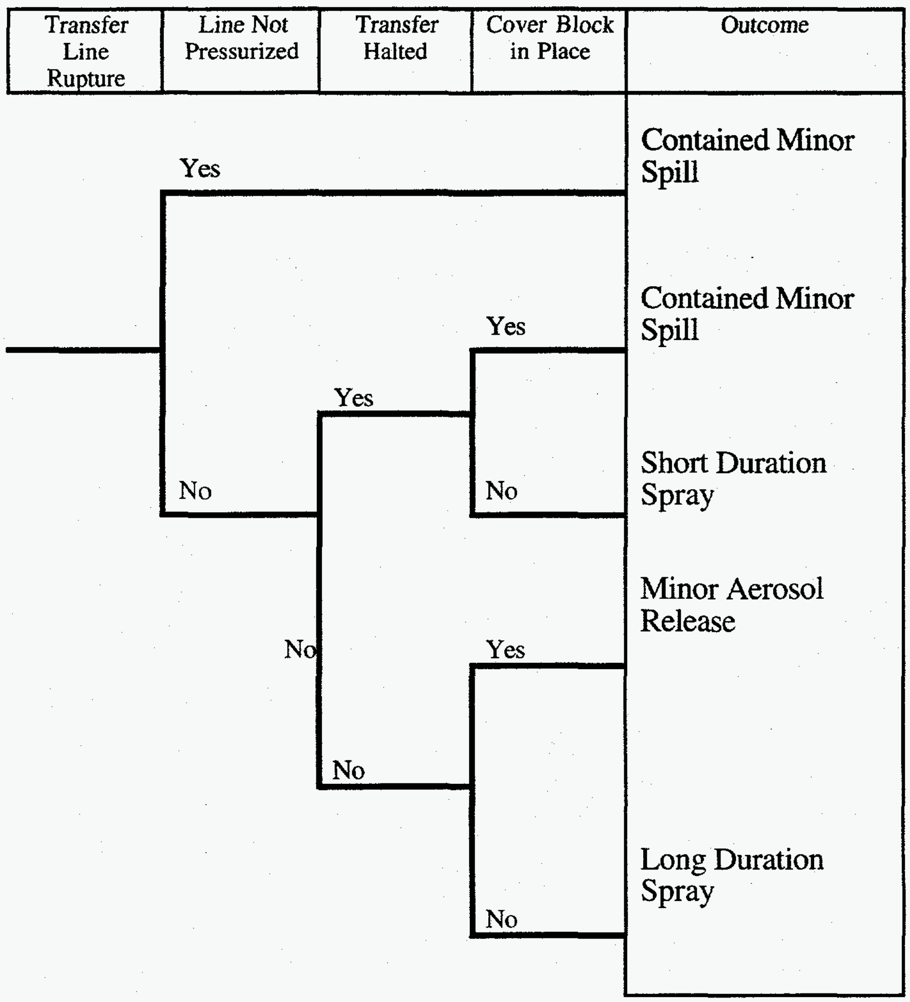
Significant Accident Sequences

The most important accidents during SWP are flammable gas burns in the waste tank dome space. Flammable gases are always generated in wastes that have water, organic compounds, and radionuclides. Hydrogen and organic-decomposition-product gases are generated by thermolysis, radiolysis, and tank liner corrosion. This generated gas potentially can be trapped within the waste and build up to considerable volumes. The gas then can be released spontaneously, or a release can be induced by disturbing the waste. Flammable gas that is released continuously or periodically can form a flammable mixture in the entire tank ullage, in a localized area, or even outside of the tank confinement boundary. The flammable mixture can be ignited by electrical, mechanical, or thermal energy sources, and a gas burn or, in some cases, a detonation can result. A burn of gas inside the tank dome space is very serious because the tank is likely to collapse, generating a significant amount of radioactive aerosol as well as toxic gases.

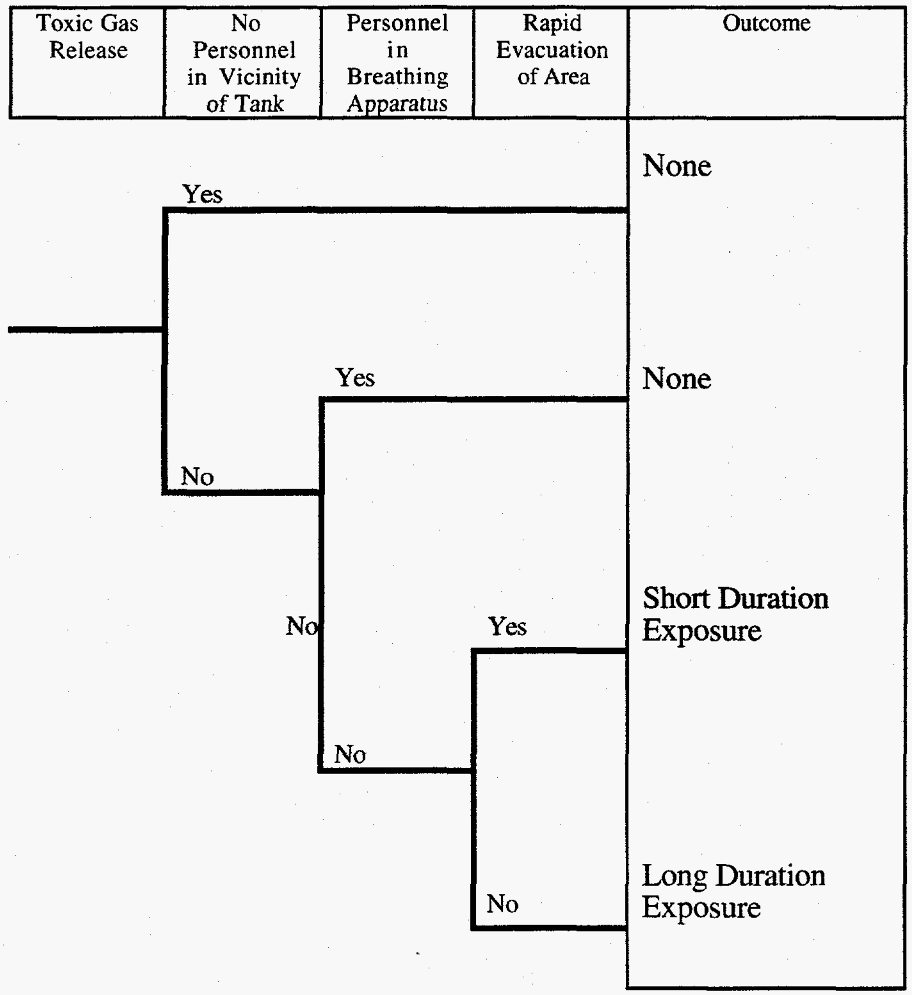
The modeling of flammable gas burns in the tank dome was a complex undertaking. A simplified event tree that shows the major features of gas burn accidents is shown in Fig. 3. Several features of gas burn accident progression that had not been recognized previously were identified by this analysis. These features include linking between gas-release events and ignition sources, gas fire propagation from outside the tank, and the importance of the phase of SWP on accident frequency.



Another important class of SWP accidents is the spill of wastes. A simplified event tree for a transfer-line rupture showing the major considerations in the analysis, is shown in Fig. 4. The transfer of SWP water provides the conditions for spills of waste to the environment through misrouting of the water, transfer-line breaks, or improper hookup of movable piping (called jumpers at Hanford). The transfer-line spill event tree captures this class of accident. The tree includes the possibility of discovering and stopping a spill in progress. Many of the likely places for spills to occur are underground structures called pits. These pits are supposed to be covered with a concrete block during waste transfer, but a much more serious release can occur if the block is left off. The possibility that a cover block may be left off is modeled in the event tree as well.



Toxic gas releases form another important class of accidents for SWP. A simplified event tree for toxic gas release that shows the types of events considered in the analysis is shown in Fig. 5. Toxic gases can accumulate and be released in a manner analogous to flammable gases. These gases can seriously affect personnel in the vicinity of a tank. An event tree to model this accident class was developed to include the presence of personnel near the tank, the wearing of protective apparatus, and the timely evacuation of the area.



Each of these accidents posed challenges in modeling that required innovative solutions. Some of these modeling achievements are discussed below.

Gas Release-Ignition Linking

Gas release events in flammable-gas-retaining waste tanks can be caused by intrusive actions or energetic events that break up the crystal structure that retain the gases. A comparison of events that cause ignition sources capable of igniting flammable gases with gas-release events shows an important linkage. Many of the same events that have a high probability of causing a gas release also have a high probability of causing ignition sources. Thus, in many gas-burn accidents, the accident initiating event is linked to an event in the accident progression. The importance of linked

initiating events has been discussed elsewhere (Bott 1989), but in this instance, the linking is less than complete. The initiating event in this case does not ensure the occurrence of the later event, but it does increase the probability of the later event by several orders of magnitude.
The linking was handled in this study by constructing two version of the gas-burn event trees. In the "random" version of the tree, the occurrence of an ignition is treated as a random occurrence that must occur at the proper location and during the time the gas is above the flammability limit. Other versions of the gas-burn event tree are called the "linked" versions. The ignition probability in these trees reflects the probability that the event that caused the gas release will also result in an ignition source.

The gas-burn accident sequences with the highest frequency were all of the linked type. Most of these accidents would occur during the installation of the SWP equipment. The installation process would significantly disturb waste that had potentially lain undisturbed for a long period and thus would have a high probability of inducing a significant gas release that could result in either a tank-wide or a localized flammable gas mixture. In addition, the installation activities that are most likely to cause a gas release, such as water lancing to form a salt well, are also quite likely to cause a mechanical ignition source for the flammable gas from metal-on-metal or metal-on-concrete sparks.

One high-frequency accident began with a water-lancing gas release that is not large enough to cause a flammable mixture in the entire dome but rose as a plume upward to the riser through which the water lance was being operated. Water lancing could result in sparks when the lancing pipe strikes the riser, so there is a finite probability of igniting a plume of gas released during water lancing. This type of plume probably would not be detected until it was too late to stop the water lancing. Thus, the gas release and spark source are dependent, resulting in a high frequency of gas burn. A similar situation could occur if the induced gas release filled the entire tank dome space, but this could be detected more readily and ignition probability could be reduced by timely action.

Gas Fire Propagation

The number of ignition sources in the tank dome is limited, but ignition sources are much more numerous in some areas adjacent to the tanks, for example, the pump pit. Through event-tree development, the potential for a flammable gas concentration in the salt well or pump pit to ignite and propagates back into the dome space was demonstrated. The event-tree models highlighted the requirements for these accidents resulting in a dome-space burn.

Determining the probability of gas fire propagation required investigation into several areas. Areas where gas could accumulate had to be identified, and communication pathways between the accumulation area and the tank dome had to be evaluated for their capability to propagate a flame. Experts from tank operations and gas fire dynamics were brought together to determine the probabilities that a flammable gas concentration would occur in a pit or salt well simultaneously with a flammable concentration in the tank dome space. Tank operators were used to estimate the probability of an ignition source under different operating conditions. This estimate was complicated by the possibility of monitoring for flammable gas during some operations such as opening the pump pit or opening the salt-well cover, times when ignition sources are readily generated. The potential for burn-back from the pump pit or salt well into the dome space is complicated further by the possibility of deflagration-to detonation transition in these relatively confined spaces. A detonation would greatly increase the probability of burn-back into the dome space.

One potential accident that was identified by event-tree development was burn-back from outside the tank into the tank dome space. This can occur if the tank dome space contains a flammable mixture of gas that leaks outside the tank through a filtered breather tube or one of numerous other penetrations and forms a local flammable mixture outside the tank. A unique aspect of an external fire is that it could cause radionuclide dispersal without damaging the tank structurally by burning the exhaust filter and dispersing its small radionuclide burden.

Administrative Control Violations

The event trees for both toxic gas releases and spills demonstrated the importance of administrative controls in reducing the risk to on-site workers during salt-well pumping. These event trees provided an unusual opportunity for risk analysts to demonstrate the importance of compliance with controls. Violations of both these strictures seemed inconceivable to the operational personnel, but a study of tank farm history and human error provided a quantitative demonstration of their reality.

A dominant accident sequence involving spills during salt-well liquid transfer was a transfer-line leak under pressure in a transfer or valve pit with the cover block removed. This accident sequence resulted in a relatively high consequences to workers in the vicinity. Underground transfer-line leak and leaks in pits with the cover block in place released very little respirable radionuclides to the atmosphere. The cover blocks are supposed to be in place during any transfer. However, a study of incidents at the tank farm reveals instances in which a buried transfer line was uncovered for maintenance. Tank farm operators, unaware of the uncovered line, transferred waste, which resulted in the exposure of the workmen at the excavation site to moderate levels of radiation. A similar type of violation of controls could result in leaving a cover block off a transfer pit during a SWP transfer. The probability of such a violation was estimated using standard human reliability analysis techniques.

Administrative controls on tank farm personnel also played a major role in determining the consequences of toxic gas release. The event-tree model for toxic gas release accidents includes the presence of personnel in the vicinity of the tank as a branch point. Tank farm controls seek to limit access to the vicinity of flammable gas tanks. The toxic gas accident sequence demonstrates the wisdom of this control from a risk perspective in a graphic manner and argues forcibly for its strict enforcement. Similarly, workers in the vicinity of flammable gas tanks are required to wear breathing apparatus in most cases. The toxic gas event tree again stresses the importance of enforcing this control to reduce the risk from toxic gas exposure

Mission Phase

The phase of the SWP process in which an accident occurred had a major effect on the accident probability and consequences. The probability of a gas-release event declined as the amount of interstitial water was reduced because gas retention was reduced. The probability of ignition of a flammable gas mixture was strongly dependent on the phase of the process; that is, it is higher during installation or certain types of maintenance than during steady pumping. The expected number of personnel exposed to toxic gas releases was also a strong function of the time of the accident; it is much higher during installation or removal than during normal pumping.

The effects of mission phase were handled by using different versions of the event trees for different phases of the SWP process. Ignition probabilities depended on the activities under way at the time of the gas release. Gas detection probability depended on the requirement for portable detection at the time of interest. The use of breathing apparatus and the expected number of personnel present depended on the administrative controls appropriate to the activity in progress. The gas-release initiating events were also strongly dependent on the phase of the mission. Probabilities of reaching a flammable concentration were much lower after SWP than before. This method of handling mission-phase effects resulted in producing versions of the same event trees with different branch probabilities depending not only on the initiating event but on the time of occurrence as well.

Risk Reduction

The ultimate goal of most risk analysis is risk reduction, but it is easy to lose sight of this during the course of a study. Often the emphasis shifts to trying to achieve certain levels of risk to meet risk acceptance guidelines. The uncertainties are so large in risk analysis that absolute risk estimates are usually not meaningful. However, the relative risk ranking of accident sequences can be very useful and is difficult to achieve in any other way.

Risk reduction was addressed by first ranking the accident sequences by risk and then examining the highest ranking accident sequences to determine which events in the accident sequence were contributing the most to the frequency. The events that made significant contributions to frequency were evaluated to determine administrative controls, procedural changes, or engineering alterations that could reduce the frequency of the accident sequence. Some effective risk reduction suggestions were stimulated by the analysis.

The dominant accident sequences for dome-space burn included sparks caused by water lancing. Several strategies for reducing the ignition probability were proposed. Nitrogen purging of the riser used for lancing was proposed as a way to inert a flammable gas plume. Administrative limits on the rate of lance movement were proposed to reduce the likelihood of striking the riser with the lance and causing a spark. Another suggested ignition-source preventive was continually flowing a film of water over the riser so that a strike by the lance would not create a spark.

Methods to reduce dome-space fire frequency were proposed, including using ventilation to reduce the time after a gas release that a flammable gas mixture remains in the dome space. Moving current gas monitors to more representative locations or adding extra instruments also was proposed, as was increased sampling before entering pump pits or opening.

To reduce spill accident consequences, requiring a walkdown of the transfer route periodically to ensure no cover blocks have been removed from pits and to look for the telltale signs of transfer-line leakage were proposed.

Conclusions

Hazard assessment techniques were used to bring together safety analysts, operational personnel, and engineers to rapidly identify accident sequences and estimate their frequencies and consequences for a waste-transfer process. A rapid and efficient hazard assessment followed by a more detailed event-tree analysis identified significant accident sequences in the SWP process for transferring waste. In a period of about a month, the dominant accidents were identified and roughly quantified. The events in the dominant accident sequences that were the main contributors to risk were identified, and a number of preventive and mitigating features were proposed.

Several modeling challenges made the analysis interesting and required some innovative solutions. Linked initiating events, mission-phase dependencies, fire propagation, and administrative control violations complicated the analysis.

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