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A HAZARDS ANALYSIS OF A NUCLEAR EXPLOSIVES DISMANTLEMENT

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ABSTRACT

This paper describes the methodology used in a quantitative hazard assessment of a nuclear weapon disassembly process. Potential accident sequences were identified using an accident-sequence fault tree based on operational history, weapon safety studies, a hazard analysis team composed of weapons experts, and walkthroughs of the process. The experts provided an initial screening of the accident sequences to reduce the number of accident sequences that would be quantified. The accident sequences that survived the screening process were developed further using event trees. Spreadsheets were constructed for each event tree, the accident sequences associated with that event tree were entered as rows on the spreadsheet, and that spreadsheet was linked to spreadsheets with initiating-event frequencies, enabling event probabilities, and weapon response probabilities. The probability and frequency distribution estimates used in these spreadsheets were gathered from weapon process operational data, surrogate industrial data, expert judgment, and probability models. Frequency distributions were calculated for the sequences whose point-value frequency represented 99% of the total point-value frequency using a Monte Carlo simulation. Partial differential importances of events and distributions of accident frequency by weapon configuration, location, process, and other parameters were calculated.

INTRODUCTION

Nuclear weapon dismantlement processes are currently of great importance to the US Department of Energy (DOE) because of nuclear weapon arsenal downsizing in both the US and former Soviet Union nations. Nuclear weapons contain both high explosives (HE) and toxic and radioactive materials, providing the necessary conditions for the energetic release of hazardous materials to the environment in accident conditions. The DOE is working to reduce the likelihood of accidents during weapon dismantlement through an integrated program of tooling and procedural and training upgrades. An integral part of this program is a concurrent and iterative hazard analysis of the dismantlement process. Insights gained from this analysis are fed to the tooling and procedural designers to help them minimize the likelihood of dismantlement accidents. This work describes the hazards analysis methods developed for and applied to nuclear weapon dismantlement at the DOE Pantex Plant .

The hazards analysis initially was conceived as a semi-quantitative assessment of the frequency of transuranic material dispersal from the weapon with various accident sequences binned according to order-of-magnitude estimates of their frequency made by weapons experts. However, in practice, this approach did not work because knowledge concerning the various aspects of postulated accident sequences was divided among many experts, and no one expert could make a credible estimate of the likelihood of most accident sequences. For this reason, a more formal accident-sequence development and quantification akin to a probabilistic risk assessment was undertaken in this hazards analysis.

The HA approach is designed to provide systematic development of accident sequences from engineering and historical data sources. The methodology results in an analysis that can be traced from the results to the sources of all the models and data. A continuous chain of analyses is documented from event probabilities and frequencies through the final frequencies of different accident conditions. This traceability allows reviewers and users to inspect all assumptions and applications of models and data and to readily suggest corrections or substitutions.

The overall strategy adopted in this analysis is shown in Fig. 1. There are two main phases to the analysis. In the first phase, the consensus evaluation phase, a broad view of the process and facility was taken. Accident sequences were

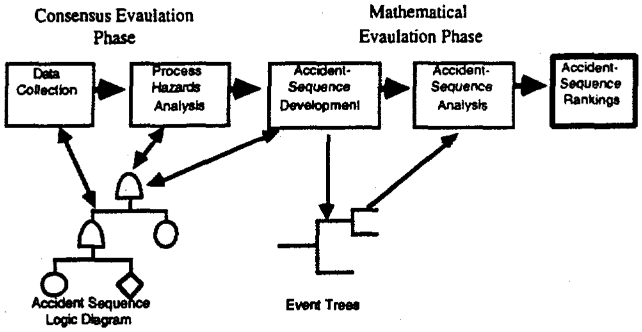

FIG. 1. HAZARDS ASSESSMENT OVERVIEW.

identified by a consensus of experts on an HA team. These accident sequences were evaluated by the experts to estimate their approximate frequency and outcomes. The consensus evaluation served as a screening tool to determine which accident sequences were subjected to the more rigorous mathematical and logical techniques used for the mathematical phase of the analysis.

In the mathematical evaluation phase, accident sequences that were determined to have a significant potential for leading to accident conditions were analyzed using powerful logical and probabilistic methods. The mathematical evaluation phase included a rigorous and documented probabilistic analysis of accident sequences resulting in frequency distributions, importances, and other probabilistic metrics that can be used to rank the accident sequences.

The consequence evaluation phase began with data collection and evaluation. Using this information, the HA analysts developed a process model consisting of a detailed flow chart and breakdown of activities or process steps. From this process model, a preliminary version of a large fault tree called the Accident-Sequence Logic Diagram (ASLD) was developed. A team of process experts was convened, and viewed a process walkthrough on video. During the walkthrough, the team of process experts identified potential accident sequences and evaluated their frequency and consequences. This activity is called the Process Hazards Assessment (PHA) in this study. The accident-sequence information generated during the PHA was stored on the ASLD by updating its logic models. The result of the PHA was an updated ASLD with a very extensive set of accident sequences and a determination of which accident sequences are worthy of further analysis.

The mathematical evaluation phase operated on the results of the PHA using more detailed and complex analytical tools. The accident sequences identified in this PHA as having the highest potential plutonium dispersal frequencies were analyzed in more detail with event-tree construction to provide a probabilistic framework for estimating accident-sequence frequencies. The event-tree construction process led to further development of the logic of the ASLD for significant accident sequences. Frequency estimates for the accident sequences considered in the mathematical evaluation phase were developed based on the event trees. Probabilistic estimation of accident-sequence frequencies, quantitative estimates of the uncertainty of accident-sequence frequencies, and a quantitative analysis of the importance were developed based on the accident-sequence models. The result of this analysis is a systematically determined and well-documented ranking of the most significant identified accident sequences for the process. A by-product of the analysis, and probably the most significant result, is an identification of risk-reduction measures that can be applied to dominant accident sequences to increase the safety of the process.

This HA was conducted in parallel with the Seamless Safety program (Fischer 1994) for upgrading the tooling and procedures used in the weapon disassembly process. The Seamless Safety program combines safety and hazards analyses with design activities seamlessly to develop new procedures and tooling. As a result, the significant findings of the HA were addressed by tooling or procedure changes as they were identified.

Disassembly Process Data Collection

In this HA, the data collection activities consisted of document reviews, observations of the process, and interviews with experts in different weapon-related technologies Documentary data on the process were voluminous. Event data describe accident or accident precursor events that have occurred or could occur. Process data describe the disassembly process. Response data describe the response of weapon energy sources or hazards to different environments. All of these data feed into the analysis either through the ASLD fault tree or through the process model that was used to organize the PHA sessions. The disassembly process was observed in person and on videocassette as part of the data collection effort. These observations proved invaluable for the construction of the ASLD.

Technical and engineering experience at the Pantex Plant (where the weapon disassembly process occurs), Los Alamos (the nuclear design laboratory), and Sandia National Laboratory (the electrical and mechanical design laboratory) was extremely useful in constructing the ASLD for accident-initiating events. The anecdotal experience of the technicians was particularly useful in determining the performance-shaping factors for various human errors and in identifying human errors that have or nearly have occurred. In addition, their experience helped us understand accident progression for some accidents.

Interview data were fed into the analysis both through accident-sequence construction and through the estimates of frequencies and probabilities. In the course of the analysis, so many experts were interviewed that they could not all be accommodated on the PHA team. However, their input was documented and presented to the PHA team for consideration when it was applicable to an accident sequence under consideration.

Accident-Sequence Logic Diagram Methodology

A well-known technique for systematically and exhaustively identifying accident-initiating events is accident-sequence fault-tree construction. An accident-sequence fault tree has cut sets that are accident sequences and uses the powerful deductive logic of fault-tree construction to develop accident sequences. However, it is often easier to visualize accident sequences using inductive structures such as event trees or cause-consequence diagrams. In addition, event trees provide a means of grouping many similar initiating events together and stimulating a different type of thinking about an accident progression than the deductive logic used in fault trees. Addressing the problem from different points of view leads to an enhanced understanding of the accident sequences. This analysis includes both event- and fault-tree modeling, accepting the redundancy as the price required for more rigorous analysis.

The type of accident-sequence fault tree constructed for this analysis has been confused with the Master Logic Diagram (MLD). The term ASLD is used because the traditional MLD is limited to initiating events only. ASLDs are accident-sequence fault trees constructed so that the cut sets of the fault tree are accident sequences. This method is used because of its stimulus to deductive reasoning and organization provided by the hierarchical structure of the fault tree.

The ASLD process is complex, involving one or more large fault trees carefully constructed to give initiating events and their enabling events, hostile environments, and responses as cut sets. The ASLD for the weapon disassembly process was constructed in stages based on numerous information sources, including process experts, previous safety analyses, process documentation, and the experience of the ASLD analysts. As the analysis progressed from the data collection effort through the PHA team meetings and finally to event-tree construction, the ASLD was amended to include newly identified accident sequences. Although the ASLD continuously evolved during the course of the analysis, it went through two main phases. The first phase was the preliminary ASLD that was constructed based on the data collection effort before the first meeting of the PHA team. As a result of the team's evaluation meetings, the ASLD was modified and expanded to reflect the information developed from the team of experts.

The ASLD was used as a means of organizing and understanding the accident sequences for the disassembly process. It was constructed with completeness as a major aim. Every identifiable accident sequence that could be deduced was included in the ASLD unless the accident was clearly impossible.

The ASLD was used during the PHA team discussions as a framework for considering possible accident sequences at each step in the dismantlement procedure in an organized and systematic manner. After discussion of a particular step, the ASLD was consulted to ensure that no previously identified possibilities had been skipped in the discussion. Any accident sequences identified as insignificant were noted but retained on the ASLD so that a record of their consideration was preserved. In addition, any accident sequences that had been missed in the ASLD were noted and later added to the fault tree.

The ASLD was finalized as a result of the PHA team meetings followed by some subsequent additions as a result of process changes, further accident-sequence development, or newly discovered accident sequences. The PHA process expanded the ASLD considerably. In addition, a standard set of external initiating events modified to reflect the specific nature of the Pantex site was taken from previous Pantex safety analyses (Pierce 1993). Together, these sources provided an extensive set of initiating events, enabling conditions, and weapon responses from which to construct accident sequences.

The output of the ASLD is a set of Boolean equations in disjunctive normal form called minimal cut sets. Each term in the cut sets is an event, and each cut set is the conjunction of the events represented by its terms. The cut sets are found by Boolean manipulation of the Boolean equation for the ASLD fault tree. The SETS computer code (Stack 1984) generated the cut sets of the ASLD. The cut sets appear as a group of events described in natural language sentences and hence are readily understood by engineers. A large number of accident-sequence cut sets were generated by the Boolean solution of the ASLD. One of the first tasks performed with the accident-sequence cut sets was to generate a screening list of accident sequences that had very low initiating-event frequency or very low probability of resulting in significant plutonium release given initiating-event occurrence. These judgments were based on discussions with the experts included in the PHA teams. The initiating events and the accident sequences that included a screening list were documented, but not considered further in the analysis. The screening was done at this point to avoid constructing extraneous event trees as part of the accident modeling process.

Process Hazards Assessment Methodology

It is typically advantageous to focus the quantitative effort in a HA relatively quickly on a subset of possible accident sequences that are most likely to be significant contributors to plutonium dispersal frequency. Unless this focusing occurs early in the analysis, much effort can be wasted by considering events that are later found to be insignificant. This focusing, or screening, effort is rather tricky because it implies a certain amount of "knowing the answer" before the analysis. One of the great concerns in this type of screening is the potential for overlooking and screening out a potentially significant accident sequence that has not been recognized as such.

The identification and screening functions described above were accomplished in this analysis through a method called a PHA, which is used to identify the hazards and provide a preliminary listing of dominant accident sequences for the system or process. The PHA used in this effort was a relatively rigorous and formalized process. This analysis used the knowledge of weapons experts and the event-oriented thinking of the HA analysts to both systematically identify accident sequences and provide preliminary estimates of their frequency. Thus, this approach used the best available systematic methods for identifying accident sequences and the best available information for screening out insignificant accident sequences.

As discussed previously, two analytical methods not normally combined were used synergistically in the PHA. A preliminary ASLD was used to help organize the PHA, and the PHA in turn provided new accident sequences that were added to the ASLD. In addition, the PHA provided a systematic means of identifying the accident sequences on the ASLD that warranted further analysis. The PHA has been described in detail previously (Fischer 1994).

The PHA was useful in screening out accident sequences that were not important contributors to plutonium dispersal frequency at the initiating-event level. A huge number of initiating events were identified during the systematic analysis used in an ASLD. Many of these were estimated by the PHA team members to contribute negligibly to plutonium dispersal frequency. These events were eliminated early in the analysis so that analytical resources were concentrated on more important contributors. Thus, initiating events with a low probability of resulting in significant plutonium dispersal or with a low frequency of occurrence were eliminated from further consideration based on the expert judgment of the PHA team.

Accident-Sequence Development

Accident-sequence development is the analytical process that takes the ASLD accident-sequence cut sets determined by the PHA to be worthy of further analysis and develops finished accident sequences through event-tree construction. The structure of all the event trees could be represented by a single common accident model. This common structure made it possible to perform the frequency point-estimate calculations for the accident sequences on spreadsheets.

This analysis envisions each accident as a sequence of events that results in a consequence. The accident model is a set of events like links in a chain. Each set of events has to occur for the accident condition to be reached. The first link in every accident sequence is an initiating event. If an initiating event occurs, then the next link that must occur is a set of enabling conditions. If both of these events occur, then the weapon assembly is subjected to a hostile environment. The weapon's response to this hostile environment is the next link in the accident-sequence chain. The result of the weapon response is the accident condition and is the last link in the accident-sequence chain.

To help comprehensively identify accident-initiating events, the environment surrounding the pit (the nuclear material at the center of the weapon) was divided into four nested levels. This division made it conceptually easier to organize a systematic search for accident-initiating events and their associated accident sequences.

The focus of this analysis is the plutonium pit, so all environments are relative to the pit. The innermost environment is the weapon, containing a collection of components that are potential energy sources. All energy sources are potential sources of accident-initiating events and can serve as energy amplifiers for lower energy precursor events. At any step in the dismantlement process, the weapon will include energy sources and energy transmission paths to the pit. The energy sources may actuate spontaneously or be actuated by some other energy source.

The weapon is a constantly changing system as a result of the dismantlement process. As the disassembly progresses, changes occur that can have a major effect on potential accident sequences. For example, the HE may be surrounded by heavy metal casing when first received, but the HE may be exposed later in the process. The collection of components that constitute the weapon at any given time is called the weapon configuration. The weapon configuration determines what weapon energy sources are present, what weapon safety features are operable, what weapon hazards are present, and what weapon mitigating features are present. All of these features will affect the probability of accident-initiating events resulting in various hostile environments and the probability of various weapon responses to these hostile environments.

During the disassembly process, a large number of weapon configurations are realized. Many of these are nearly equivalent from a safety point of view, so a subset of all configurations is actually used in this analysis.

The weapon also is affected by the process environment. The process can be envisioned as a tube through which the weapon flows. Components leave the process tube during the dismantlement process as the weapon is moved or as the parts are transported away from the weapon. The process includes all human actions that are part of the dismantlement, all equipment, and all material used in the process. Human actions and equipment events occurring as part of the process may act as initiating events or as enabling conditions for accident sequences. For example, dropping a lifting fixture on a hemisphere lying on a table is an initiating event, whereas the act of placing the hemisphere on the table over which the strongback is carried is an enabling condition. The process environment varies for each step of the dismantlement procedure. The process environment was determined by observations of the process and by study of the dismantlement procedure.

The facility environment surrounds the weapon and the process. The facility offers both safety features (such as fire suppression systems) and energy sources (such as high-pressure gas system piping). The facility also may enable accident-initiating events to damage the weapon by acting as conduits or amplifiers of energy. Collapse of a structure following an earthquake is an example of an enabling condition for a seismic initiating event. The facility environments are determined by the location of the pit.

The facility is surrounded by the external environment. The external environment acts mainly as a source of energy sources and thus accident-initiating events. "Tornado" and "aircrash" are examples of natural and manmade external environment accident-initiating events. These accident-initiating events are discussed below.

The list of initiating events and their enabling conditions generated through the hazards analysis, ASLD, and external event list was examined to determine which initiating events were likely to result in identical event trees. Initiating events that followed similar accident sequences then were lumped together, and an event tree was constructed for them. Branching for different weapon responses was added to the accident sequence, and an event tree that modeled the accident from initiating event to plutonium release was constructed.

Groups of initiating events with similar accident progressions were combined to construct a relatively small number of different accident-sequence event trees. Thus, any one event tree may represent the accident sequences for many distinct initiating events. Some details of individual accident sequences may be lost in this process of combining, and care must be taken not to lose important distinctions among accident-initiating events.

Based on the event trees, the analysts constructed an accident-sequence model for the HA accident analysis, modified to account for the unique features of the dismantlement process as shown diagramatically in Fig. 2. In this accident model, an initiating event (typically actuation or realization of an energy source) begins the accident sequence. A set of conditions beyond the initiating event are required for many accident sequences to occur. These are called enabling conditions. If required enabling conditions are present, then the accident progresses to create a hostile environment that the weapon assembly experiences. The weapon responds to the hostile environment, potentially creating an accident condition.

This HA uses the logical model discussed above to estimate the frequency with which different accident sequences occur. Each of the steps in the accident sequence is represented by a probability of occurrence. In general, successive stages in the accident sequence will depend on preceding stages. Thus, the accident sequences are chains of dependent, conditional probabilities. These probabilities may be combined using proper care to account for dependencies and to estimate the frequency of the consequence occurrence.

In this model, every accident sequence is started by some event. As a general rule, an initiating event was an abnormal event associated with an energy source. For example, if a tank has a flammable mixture of hydrogen as a normal condition, then a spark would be an initiating event for a tank fire accident. On the other hand, if a tank has a continuous sparking source, and the hydrogen concentration is normally below the flammable limit, then a tank liquid gas release that causes the hydrogen concentration to exceed the flammable limit would be an initiating event for a tank fire. When an accident sequence consisted of more than one abnormal event, the most dynamic event was selected as the initiating event, and the other, more temporally extended events were made enabling conditions.

The initiating events were grouped on the basis of the level of environment from which they arose. This type of organization was first used in the construction of the ASLD to help us ensure exhaustive consideration of possible accident sequences. Weapon initiating events were generated through interviews, DoD Unusual Occurrence Reports (UORs), and surveillance reports. Process initiating events were identified by observation of the process, interviews with weapon process technicians, and Pantex UORs. Facility initiating events were compiled from facility safety analyses, Pantex UORs, industrial experience, interviews with plant personnel, and walkdowns of the facilities. There are standard lists of external events that have been developed for a wide variety of processes and locations. Such lists were consulted and specialized for the Pantex location.

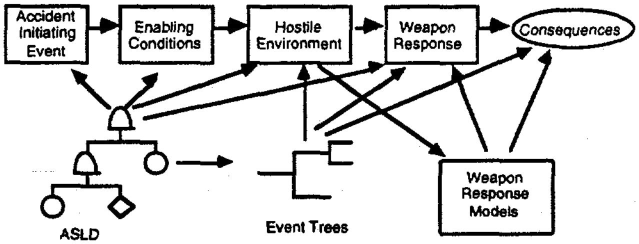

FIG. 2. ACCIDENT MODEL.

Often, an initiating event can only lead to an accident if other, often pre-existent, conditions are met. These conditions are called enabling conditions in this model. The location and configuration of the weapon are special enabling conditions. The location determines the facility hazards to which the weapon is subject, and the configuration determines the weapon response. The probabilities associated with the location and configuration branch points in the event trees represent the probability that a weapon is in a configuration or location given the occurrence of an initiating event. Other examples of enabling conditions were protective feature failures and geometric considerations.

A hostile environment is experienced by the weapon assembly as a result of an accident-initiating event and requires enabling conditions. The hostile environment acts on the assembly to produce a response. This response may be an actuation of an amplifying energy source or a direct release of plutonium from the pit. The weapon assembly response is modeled by approximating the continuum of physical responses of the weapon assembly to hostile environments with a few discrete events. In the weapon assembly response model, a discrete cause-and-effect approximation for complex physical phenomena is constructed. The weapon assembly response is one of the greatest sources of uncertainty in the discrete event model of weapon dismantlement. A major contributor to this uncertainty is the response of the weapon's main charge HE to various insults. In this HA, the response of HE was modeled as a probability distribution of the occurrence of an HEVR, given insult energy.

A unique aspect of this HA was the overriding importance of the weapon response, especially the HE, in determining plutonium dispersal frequency. In more traditional HAs of large systems, the responses often are assumed to occur with a probability of 1, given the occurrence of an accident sequence. In this HA, the accident sequence produces an environment that is hostile to the weapon. The weapon assembly responds to a hostile environment by absorbing, transmitting, or amplifying energy. The pit, which is the focus of this analysis, will respond to the energy incident upon it. The pit response determines the outcome of interest in this study.

For a given configuration, the response probability varies according to the hostile environment energy level. For example, a drop from a greater height is ranked higher in probability of plutonium dispersal than a similar drop from a lower height. However, there was no attempt to differentiate between relatively fine gradations in hostile environments.

An important aspect of weapon response is the action of energetic components within the weapon. These components can act as amplifiers on the incident energy that constitutes a hostile environment.

Several sources for weapons response probabilities were used. The favored method, when available, was testing data. These data were available for weapons responses to drops, fires, and impacts in many configurations but required some interpretation. As a last resort, expert opinion concerning the probability of the response was used. This approach was avoided whenever possible because of the difficulty in accounting for or avoiding expert biases in the estimates and because of the intrinsic difficulties experts encounter in quantifying frequencies or probabilities of events, especially rare ones. However, the bulk of the response data came from such expert opinion. The development of the HE response data is discussed in a companion paper in this conference (Eisenhawer 1995).

The consequence of concern in this HA was transuranic material release from the confinement of the pit. Health and environmental consequences were not considered. This HA is comparable to a Level I PRA effort encountered in the nuclear power industry, which means that no health or other effects arising from plutonium dispersal are considered. Thus, this analysis ends with the occurrence of plutonium release, and specific confinement attributes associated with the ramps, bays, and cells are not considered. The range of plutonium releases possible from the pit is very large. This continuum was divided into a discrete number of plutonium release bins. These bins then were used to group the accident sequences according to the type of plutonium release that occurs.

Accident-Sequence Analysis Methodology

A number of initiating events were identified through an ASLD. Many of these can be readily shown to contribute negligibly to plutonium dispersal frequency and were eliminated early in this analysis by means of the PHA. This allowed analytical resources to be concentrated on more important accident sequences. Initiating events that either had a very low probability of resulting in significant plutonium dispersal or would be very unlikely to happen at all were eliminated from further consideration. Thus, the analysts screened on both frequency and consequence.

Point estimates of the frequency were calculated for all accident sequences that survived the PHA screening process. The accident sequences that represented 99% of the total accident-sequence frequency for each plutonium dispersal class were analyzed further using Monte Carlo techniques to determine accident-frequency distributions.

The calculation of a frequency estimate for an accident sequence is based on the Boolean equation that represents that accident sequence. The Boolean equation is a representation of the event-tree path for that accident sequence The Boolean equations for the event-tree paths all had a similar structure, which closely reflects the accident model discussed previously. The quantitative analysis of the accident sequences was performed with spreadsheets, with the analysts being careful to check for dependencies or common-cause events that linked terms in an accident sequence. This method was used because of its simplicity and because all the accident sequences could be represented by very similar accident-sequence equations.

The analysts elected to use spreadsheets for the point-value accident-sequence-frequency and uncertainty calculations. This method was chosen because it allowed automatic updating throughout the entire calculation when an initiating-event frequency, enabling condition probability, or response probability was changed. It also allowed us to make the analysis more traceable by providing space for copious annotation of each frequency and probability used.

The use of spreadsheets had the advantage of allowing linking between the database and the accident sequences, thus providing a means for changing a single accident sequence without re-running the entire analysis when changing an initiating-event frequency, enabling condition probability or weapon response probability. A disadvantage to spreadsheet calculations is the rigid structure imposed on the accident-sequence equations.

Several types of spreadsheets were used in this analysis to make it more manageable and modular. Three initiating-event spreadsheets contained all the initiating events taken from the ASLD and the external-event list. The enabling condition spreadsheet contained all the enabling events that appear in the accident sequences. The initiating-event and enabling-condition spreadsheets are linked into the probability calculations, operational database calculations, and human-reliability calculations. Thus, changes in these calculations are reflected automatically in the accident-sequence frequencies. The weapon-response spreadsheet contains the weapon-response probabilities. These response probabilities are linked to the spreadsheets used to combine expert and test data for the weapon response probabilities. The time-fraction spreadsheet includes the time fractions used to convert initiating events expressed as frequency per unit time to frequency per weapon. All these spreadsheets were linked to the accident-sequence spreadsheets, one for each event tree, to provide a calculation of the point value of the accident-sequence frequency with automatic updating of the results. These spreadsheets were, in turn, linked to a summary spreadsheet that summarized the results of the accident-sequence spreadsheets by plutonium dispersal class, configuration, location, and other groupings. The spreadsheet linking structure used in this analysis is shown in Fig. 3.

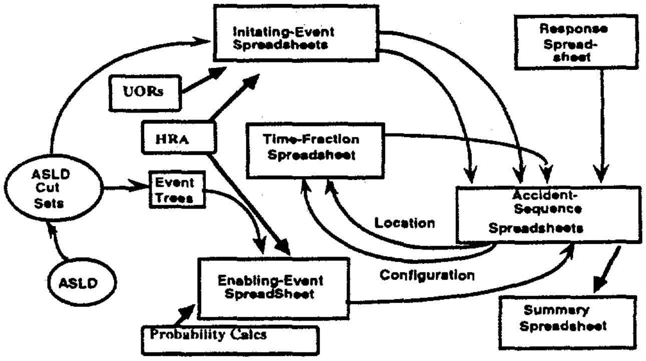

FIG. 3. SPREADSHEET LINKS.

In addition, a dominant accident-sequence spreadsheet that included the top contributors (about 90% of the frequency) was included. Plots based on these spreadsheets provided a visual representation of the relative contribution of the various categories of accident sequences.

This analysis included point estimates of the frequency of accident sequences that result in plutonium dispersal to allow the analysts to determine which accident sequences are most likely to result in plutonium dispersal. The accident sequences with the highest point estimates then were analyzed using Monte Carlo simulation to determine a frequency distribution instead of a point estimate.

In this study, all estimates are given in probability per unit that is disassembled. This basis was chosen because of the potential variability in the number of units disassembled per year and because most of the accident-initiating events are more easily expressed in these units. This is readily seen for disassembly human errors, for which a given number of opportunities for error on each weapon are given.

Estimated frequencies and probabilities for events are based on the best data available. In many cases, several different sources of data were considered. Instances of occurrence for many accident-initiating or similar events found in the ASLD could be found in the historical records of Pantex and DoD activities involving nuclear weapons. In many instances, the analysts also were able to approximate the population data required to estimate frequencies or probabilities.

If operational data could not be found or were considered inapplicable, then surrogate sources of data were considered. These sources included industrial databases for the chemical and nuclear industries. If no experiential data were available, then calculations using accepted models could be used. The use of the THERP for human-reliability analysis and the use of correlations for missile penetration into the bays and cells are examples of this type of data analysis (Swain 1983). Finally, as a last resort, expert elicitation was used when no other data sources were available. Many of the weapon-response probability estimates are derived from expert opinion.

The analysts considered uncertainty at several different levels in this study, including inherent test data variability, phenomenological model uncertainty, and applicability uncertainty. Uncertainty in HE response phenomena represents the greatest uncertainty in plutonium dispersal frequency for the disassembly process. The analysts have tried to include uncertainty estimates with all the frequency and probability estimates used in this analysis. The uncertainty bands on the accident-sequence frequencies are some indication of the pervasive lack of data on the events and phenomena that are important in this weapon disassembly process.

The point value is used as the mean of the assumed distribution. The uncertainty range may be expressed as an error factor, quantiles or percentiles of the distribution, or distribution parameters such as the standard deviation. A point value is calculated for each accident sequence using the probability equation implied by the accident-sequence cut set. The accident-sequence frequencies were estimated using the rare-event approximation. The accident-sequence frequency values in this HA are all low enough to justify use of this approximation.

A subset of the accident sequences for which point-value frequency estimates were calculated was selected for further analysis. The accident sequences chosen were those with the highest frequency values. Those accident sequences whose combined frequency represented 99% of the total accident frequency for each consequence category were chosen for this more extensive analysis. This set of accident sequences is called the dominant accident-sequence set.

The dominant accident-sequence set was analyzed using a Monte Carlo simulation that produced accident-sequence frequency distributions rather than point-value frequency estimates. The simulation was performed on the accident-sequence equations used in the point-value frequency calculations. To determine the frequency distribution, probability distributions were used for each term in the accident-sequence equations instead of the point values used in the accident-sequence point-value calculation. These probability distributions were developed as part of the event data construction discussed previously. These uncertainties are included on the initiating event, enabling condition, and response spreadsheets.

The multiplication of event probabilities to estimate an overall accident-sequence frequency assumes statistical independence between the events. Often this assumption is grossly violated by common-cause failures of multiple components, dependence on human actions, or linking between initiating events and mitigating system failures. Human reliability dependence was treated in the THERP analysis (Swain 1983).

Common-cause failures usually occur when a complex system has redundant components. Many or all of the components may fail because of a common causal event and thus defeat what appears to be high reliability if the components truly failed independently. The analysis included a search for common-cause events using accepted guidelines for identifying such occurrences (Stack, 1991b). This approach did not identify common-cause events of significance.

Accident-initiating events may cause failures of systems or features designed to protect against accidents (Stack, 1991a). Thus, the initiating event initiates the accident and defeats all protection against it as well. In this disassembly process, the absence of important accident-prevention systems reduced the importance of linked initiating events. An example of a linked initiating event is an aircrash. An aircrash is often accompanied by a ground fire, and the air crash would often disable the fire suppression system. Thus, the fire would be started with a high probability of the suppression system being unavailable from the same event.

There was initial concern about the potential for increased plutonium dispersal frequency for disassembly of weapons that were in an abnormal or damaged condition when they were received for disassembly. Although the frequency of receiving such a weapon might be small, the probability of plutonium dispersal, given such a weapon, might be much higher than for a normal weapon, and therefore, such weapons might make a significant contribution to disassembly plutonium dispersal frequency. For this reason, this analysis included a search for abnormal weapons conditions.

This analysis also considered the effects of HE damage, including cracking or sensitization, and treated the previous firing of the system valves. These abnormal weapon conditions are included as part of the analysis. This analysis did not include disassembly of weapons that had been involved in severe accidents in the field, such as fires or severe mechanical damage.

The weapon in this study is relatively old, so aging concerns were addressed. This analysis examined the effects of aging on the sensitivity of HE. In addition, this analysis considered aging effects on other energetic components in the weapon. No attempt was made to account for aging deterioration of casings or foams that offered protection from mechanical damage.

Aging of the disassembly work stand was considered as a means of defeating the interlock system. Possible aging scenarios that could increase the probability of interlock failure are included in this analysis. In addition, the possibility of fatigue failure of the fixtures as a result of thousands of cycles was considered.

Accident-Sequence Ranking

After the frequency distributions are calculated for the dominant accident sequences, ranking the sequences is relatively simple. In this analysis, the dominant accident sequences were ranked according to mean and median frequency estimates for several locations, and events were ranked by partial differential importance. Location was included as a parameter because different locations in the weapon processing complex afforded different mitigation levels for plutonium dispersal. These rankings indicated the accident sequences that dominated this estimate of plutonium dispersal frequency and the events whose probability or frequency estimates had the highest effect on plutonium dispersal frequency.

The accident sequences can be readily ranked by sorting the frequency distributions according to the mean and median. For the dominant accident sequences, the mean and point-value estimates were very similar. The median tended to be significantly lower than the mean, but the relative ranking between sequences was similar for both statistics.

In addition to a simple ranking of frequency estimates, event importance was calculated for many events. The importance of an event in this HA is a measure of the contribution it makes to the overall plutonium dispersal frequency. A number of different importance measures are used in HA. The partial differential method was used in this study. The partial differential importance of an event A in a Boolean equation D, is found by (Olman, 1982):

$$I_{D,A}=\frac{\partial D}{\partial A} .$$

Events that have high importance are generally in accident sequences with few terms or several terms with high probabilities. An examination of the accident sequences leads one to expect that certain types of events will tend to have high importance. These events are human errors that lead directly to impacts on HE and high explosive violent reaction (HEVR) probabilities that appear in relatively high-frequency accident sequences.

CONCLUSIONS

The hazard assessment of weapon dismantlement required extension and modification of many traditional hazard assessment tools. The traditional approach to identifying accident sequences was formalized using an accident-sequence fault tree. An accident-sequence model was developed that was specific to weapon dismantlement and included the effects of changing weapon configurations and locations. Event trees were used to group accident-initiating events into a small number of models, and the failure paths through the event trees were modeled using spreadsheets. These techniques proved to be efficient and useful in documenting the analysis and provided the means for readily updating the analysis as procedures or other data changed.

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