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A HUMAN RELIABILITY ANALYSIS OF A NUCLEAR EXPLOSIVES DISMANTLEMENT

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ABSTRACT

This paper describes the methodology used in a human reliability analysis (HRA) conducted during a quantitative hazard assessment of a nuclear weapon disassembly process performed at the Pantex plant. The probability of human errors during the disassembly process is an extremely important aspect of estimating accident-sequence frequency for nuclear weapons processing. The methods include the systematic identification of potential human-initiated or -enabled accident sequences using an accident-sequence fault tree, the extensive use of walkthroughs and videotaping of the disassembly process, and hands-on testing of postulated human errors. THERP modeling of rule-based behavior and operational data analysis of errors in skill-based behavior are described. A simple method for evaluating the approximate likelihood of nonmalevolent violations of procedures was developed and used to examine the process. The HRA occurred concurrently with process design, so considerable interaction between the analysts and designers occurred and resulted in design changes that are discussed in the paper.

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 materials, providing the necessary conditions for the energetic release of toxic 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, 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 a human reliability analysis performed as a part of the hazard analysis for a new generation of nuclear weapon dismantlement process that includes new tooling and procedures.

Weapon dismantlement is heavily dependent on human activities, so human error must be considered in any hazard analysis of the process. Human error is a complex subject that can only be addressed approximately in a hazards assessment. This paper reports on the human reliability methods used in assessing the likelihood of such accidents during nuclear weapon dismantlement. The details of this analysis are by nature permeated with classified information. Therefore, only the methodology of the analysis can be presented in this forum.

Human reliability is a measure of the likelihood of human error in a system. Human Reliability Analysis (HRA) is a structured approach to identifying potential human errors and systematically estimating the probability of these errors using data, models, or expert judgment. The technique used to estimate error probability is highly dependent on the type of activity being analyzed. In this work, human activities were classified according to the Rasmussen taxonomy: rule-based, skill-based and knowledge-based (Reason, 1990). Rule-based activities were generally analyzed using the Technique for Human Error Rate Prediction (THERP) (Swain, 1983). Error probabilities for skill-based activities were mainly estimated using operational data collected during weapons processing in past years. A few skill-based activities could not be addressed by operational data. In these cases, estimates were based on the analyst's experience in HRA. Knowledge-based activities were not addressed quantitatively in this analysis, but some qualitative observations were made. The result of the analysis is a set of Human Error Probabilities (HEPs) for activities performed during the dismantlement process.

Weapon dismantlement presented the analysts with a set of human actions that had not been encountered in previous analyses of nuclear or chemical processes. Many of the activities were rule-based and eventually could be related to rule-based activities encountered in other technologies. However, a substantial number of activities were skill-based and had no counterpart in the experience of the analysts.

Estimation of HEP is a highly subjective endeavor, even when a methodology such as THERP is used. Different analysts can differ wildly in their probability estimates for the same activity because of their different perceptions of the likelihood of a given error. Analysts have to draw on their personal experience and previous analyses for their estimates. A "sanity check" should always be performed by the HRA analyst and several other analysts who are familiar with the process to look for inconsistencies and misconceptions. For this analysis, a peer review was solicited and evaluated by the analysts.

There is no generally accepted method for systematically determining all the important errors that can be made during a process. The analysts have used their experience with other systems and the experience of weapons technicians to construct a set of human errors using system fault trees and accident-sequence event trees. Human errors are woven into the fabric of this analysis from the beginning, and the analysis was performed by analysts with extensive HRA experience.

Basis for the HRA of Weapons Dismantlement

An HRA is critically dependent on the sources of data used in the analysis. It is possible to perform an HRA based solely on written materials such as procedures. However, this does not usually result in an accurate or insightful analysis. This weapon dismantlement HRA was based on several sources of information, including many first-hand observations. These sources of information include written dismantlement procedures, historical operating data, observations of dismantlement activities, videotapes of procedures, and interviews with technicians, engineers, training specialists, and supervisors.

The historical operating data used in this analysis included occurrence reports and log books. The historical operating data were used to develop estimates of human error rates for some skill-based activities, for example, hand-carrying components. This analysis is discussed more fully under the section on skill-based activities.

The analysts have observed a number of performances of the dismantlement process. These observations covered the entire history of the dismantlement procedure development. During these observations, the analysts were permitted to test or verify many of their assumptions concerning human errors. The analysts personally tried many of the more critical operations to determine if the error was actually credible and the potential for alerting factors and recovery.

The analysts heavily used videotapes of the weapon disassembly. These videotapes have proven invaluable as reference documents for the HRA. Activities were reviewed many times when necessary to fully understand the actions taken by the technicians. The videotapes also provided a means of discussing potential errors with a group of colleagues who could all review and stop the action as required until a consensus on a given error was reached.

As part of the analysis process, the analysts discussed many human errors at length with technicians, supervisors, training specialists, and engineers associated with the program. The analysts have used the technicians' input to determine the appropriate THERP tables and Performance Shaping Factors (PSFs), and in some cases have based HEP estimates largely on the input from these experts. One of the most valuable aspects of these interviews was the insight they provided into such intangible, but important, factors as morale, attitude, motivation, and technician/management relationships.

Identification of Human Errors

Potential human errors that could lead to accidents with dispersal of toxic material were identified in the same manner as component failures—using an Accident Sequence Logic Diagram fault tree (ASLD). The dismantlement process was analyzed step by step to determine the location and weapon configuration of each step. Each step in the procedure was evaluated to identify potential errors that could be made, and the possible outcomes of the errors were analyzed. The errors that could result in accident conditions of interest in this study were analyzed further, and the human errors could be grouped into two main categories. Some errors initiated accident sequences; other errors enabled other accident-initiating events to proceed to accident conditions. The identification of human errors was greatly facilitated by the participation of the technicians, who helped identify error-likely situations, alerting factors, and recovery actions based on their extensive experience.

Estimates of HEPs for Rule-Based Activities

Many of the activities analyzed in this HRA were primarily rule-based. In a rule-based activity, the performer uses a set of stored rules to perform his actions. THERP is an analytical method principally useful in estimating HEPs for rule-based activities (Swain 1983). This methodology has been widely reviewed, and a considerable consensus has developed regarding its acceptability in the nuclear power industry. The use of this technique has expanded over the years to include chemical process industries, military activities, and other human endeavors. THERP was the method of choice for errors in rule-based activities for which there were no historical data.

The basic idea of THERP is to break complex tasks into a logically related set of simpler activities for which error probabilities can be more easily estimated. These simple error probabilities are referred to as Basic Human Error Probabilities (BHEPs). These BHEPs are modified to account for PSFs and then linked together using special rules to account for dependence between tasks or different performers and error recovery. The resulting computed HEPs are sometimes called Conditional HEPs. THERP has a set of models for different types of tasks often encountered in industrial applications that provide guidance for estimating the BHEPs. These BHEPs have received intense scrutiny during formal peer reviews and are probably the best currently available and most widely used estimates for these errors. The values of the BHEP generally range between 0.1 and 1.0E-4.

In general, a proper application of THERP, including dependence, produces error probabilities that are in the range of 1.0E-4 per opportunity or larger. An HEP is usually dominated by one or two relatively large failure modes. Occasionally, activities with good error recovery probabilities will have HEPs in the 1.0E-5 range. Any value less than 1.0E-5 requires special justification, including demonstration of independence between tasks.

In the THERP methodology, error probability estimates are modified to account for variations in work conditions. Variations encountered in work conditions at different facilities are represented by a set of PSFs. The THERP method assumes the average work conditions encountered in the US commercial nuclear power industry as nominal. When conditions that are significantly worse are encountered, the analyst multiplies the nominal HEP by a PSF value greater than 1.0, resulting in an HEP estimate greater than nominal. This PSF value may vary from 3.0 to 10.0 or more, depending on the PSF. Conversely, if the work conditions are significantly better than nominal, a PSF that is less than one may be applied to reduce the HEP below the nominal value. Often the effect of a PSF is to replace the nominal HEP value with the upper bound for adverse conditions or the lower bound for enhanced conditions. Typically, no more than one PSF multiplier is used on a given HEP because the PSFs are often interrelated and long strings of multipliers result in unrealistic values for the HEP.

A number of PSFs were considered explicitly in this THERP analysis. A fuller discussion of the basis for the evaluation is given in the following paragraphs.

Safety culture is a qualitative judgment concerning the commitment of the personnel at all levels in the organization to safety. The analysts' experience in safety analysis at numerous facilities indicates that safety culture has a significant effect on human performance at the plant. If the organization is permeated with feelings of impatience with safety-oriented procedures or administrative controls, the operational personnel will tend to be perfunctory in their adherence to safety standards, especially those they perceive as burdensome and unnecessary. This can lead to higher probabilities of error because of skipped procedural steps, neglected checks, or outright violations. An adverse safety culture will be reflected in adverse PSFs and higher error rates using such HRA methods as THERP.

The analysts evaluated the safety culture for weapon dismantlement during the observations and interviews. The analysts interacted with a number of technicians, supervisors, facility engineers, process designers, and management personnel and explored their attitude toward safety. The analysts were sensitive to any evidence of cynicism or contempt for safety rules. In addition, the processes for addressing safety procedures that were felt to be excessive were discussed among the engineers and technicians.

The analysts paid particular attention to the attitudes of the technicians and their supervisors toward violations of procedures, whether for perceived flaws in the procedures or for other reasons such as expediting production. This attitude was explored during many hours of informal interactions with the technicians and during formal interviews.

Administrative controls are used in the weapon dismantlement process to reduce the probability of human error when a design fix is not possible or practical. Administrative controls are used to limit access to the cells, limit energy sources in the cells, and control the transportation of weapons and parts. The effectiveness of the administrative controls for weapon dismantlement were observed during operations and were evaluated based on occurrence reporting.

The Nuclear Explosive Operating Procedures (NEOPs) used in the disassembly process were analyzed to determine their effect on human error. Clarity and ease of use were evaluated. The effectiveness and usage of the reader-performer format and the check-off provisions for critical steps were evaluated during all the analysts' observations. The effectiveness of drawings and figures as aids to the technicians were analyzed as well.

Many special tools are used during dismantlement. Two of the most important tools are rotocages used for lifting and rotating the units and work stands with their associated holding fixtures. Each piece of tooling was examined to determine maintenance or operational errors that could lead to accidents. Rotocages are discussed in a later example, but our treatment of the work stand is discussed here because of its importance and interest in human reliability.

Much of the dismantlement of the weapon takes place on a rotating work stand. Some aspects of the work stand affect human reliability significantly. The stand is designed with simple, yet effective, multiple interlocks that prevent rotation of the assembly without positive support. In some circumstances, work-stand attachments prevent rotation in the wrong direction as well. The work stand provides positive support for the weapon assembly. In addition, the fixtures that hold the weapon assemblies in different configurations are designed with deep cups for the unit to rest in, greatly reducing the probability of knocking a unit from the stand. These design efforts reduce the probability of a weapon drop substantially. However, the probability of a fixture being dropped and striking the assembly is increased because of more opportunities, but the probability of an accident is generally lower for strikes than for weapon drops, so the overall result is a reduction in accident likelihood.

A longer range concern with the work stand and tooling involves the effects of wear on the interlocks. At the present, the probability of a spontaneous, inadvertent, or improper rotation appears very remote, because three independent mechanical stops would have to be failed or two stops overridden, respectively. The analysts have been unable to postulate a credible common-cause failure for these stops, so independent failures seem to be required. However, as the unit wears through use, the springs driving the trunnion locks and the springs and gears in the hand-wheel mechanism will wear. The springs may age at similar rates and eventually degrade past proper performance at relatively close times. Operational checks or inspections of the work stand interlocks were suggested as part of the pre-operational checks in the cell to minimize the time before an interlock fault is discovered. If the unit is not checked regularly, eventually both stop springs could enter a failed state, and it may be possible to inadvertently or improperly rotate the unit. The analysts observed that the technicians placed enormous reliance on the stops and interlocks. The technicians are then set up for a frequency-bias form error (Reason 1990) because of their strong expectations concerning the effectiveness of the interlocks. If the interlocks ever failed to operate as expected, a highly error-likely situation would occur with a possible drop of an assembly to the floor. Clearly, effective periodic checks of the stop and hand-wheel mechanisms would keep the probability of inadvertent rotation very low. The ergonomics of the stand were generally considered to be better than average for THERP analysis.

The physical environment of the cell has been analyzed in detail by human factors specialists (Alvarez 1993). The analysts in this study had a chance to evaluate the physical environment firsthand during many hours of observation as well. The goal of this observation was to identify environmental factors that could significantly increase the hazard over optimal conditions. Of particular interest were activities in the cells that compete for technician attention, such as interruptions, unexpected visitors, or the parallel dismantlement of another unit in the same room. Such events could distract technicians and could lead to higher error rates, especially for errors of omission. Interactions between the teams were evaluated based on anecdotal experience and observation. The tendency of technicians to leave their own unit occasionally to help the parallel effort and the possibility for confusion resulting from the simultaneous reading of NEOPs was explored.

Technician training was evaluated through discussions with trainers, reading training materials, and observation. The effectiveness of both structured training and apprenticeship instruction were examined. Examples of training records were studied as well.

The technicians were evaluated by the analysts for craftsmanship both as espoused and practiced. The craftsmanship (commonly called skill-of-the-craft in HRA) displayed by the technicians that the analysts observed was carefully noted. The handling of sensitive components, techniques for keeping track of the completed steps in the procedure, and checking for off-normal conditions were observed. A two-man coverage protocol is used to control access to the weapon during dismantlement. This two-man coverage rule has been analyzed from a human factors standpoint (Alvarez 1993). The analysts added their personal observations of the efficacy of this rule as a result of the their numerous walk-throughs. Every cell has a team of two technicians who both hold keys required to open the cell. The cell may not be opened without both keys. This makes it difficult for a single man to enter a bay or cell.

The effect of two-man coverage for the disassembly process is important in a THERP analysis. The analysts observed the second technician, as well as the reader when present, to evaluate their effectiveness in providing backup to the primary technician. The analysts looked for backup actions by the second technician, such as placing their hands beneath carried objects in a way that would protect against drops and second-checking important operations. Based on these observations, the level of dependence between the technicians was evaluated. Omissions of steps appeared to be the type of error most greatly affected by the two-man rule. The detailed performance of manual operations is probably less affected by the extra observers. The analysts particularly looked for instances of high levels of dependence between operators. Such dependence can occur when a task was so detailed that the observer or reader cannot adequately check it without significant effort or when the seniority of the technicians is widely different.

Stress can be an important PSF for human performance. Discussions with technicians concerning the fear stress levels for people involved in weapon disassembly was explored. In addition, the probability of dropping different objects was estimated from operational data, and some idea of the stress levels for handling different weapons components was gleaned.

The stress operators may feel because of production schedule pressures was more difficult to assess. Interviews with technicians, supervisors, engineers, and managers explored the relative precedence of safety and production as perceived by the technicians. Time stress driven by production pressures was evaluated based on interviews and observations, but the observations were admittedly artificial in this respect. Time stress could vary in the future if unrealistic production goals are set to comply with treaty-mandated weapon dismantlement.

The stress level experienced by operators during abnormal events was evaluated based primarily on occurrence reporting and interviews. In one incident that the analysts examined in detail, an abnormal occurrence caused an operator to flee the cell in panic. Abnormal events that could cause high operator stress are estimated to have a low frequency and do not contribute significantly to the overall accident likelihood.

THERP HEPs include errors of omission, errors of commission, and recovery errors. A common error of omission in a rule-based procedure is omission of a step. In this THERP analysis, the disassembly team is treated as a single unit because they will usually function with some dependence between technicians. A small tree for step omission was constructed and applied to all the errors for which step omission was a significant error mode. Recovery from an error could involve the technician who made the error recovering himself, the second technician, or the reader. The analysts always used THERP recovery values when they were available. When a specific THERP value was not available, they made estimates of recovery based on a number of factors including alerting.

This THERP analysis was conducted using a version of THERP programmed in *TOOLBOOK*. The *TOOLBOOK* THERP is identical to the handbook in all models and calculations. The difference is that the *TOOLBOOK* THERP is an object-oriented program. The analyst constructs the Human Reliability Event Tree (HRET) used in the THERP task analysis with drawing tools programmed in THERP. The analyst then refers to the THERP quick or algorithmic guides to determine which table to use. The THERP tables are programmed as interactive graphics that select the BHEP corresponding to the descriptions of the task chosen by the analyst.

To use the *TOOLBOOK* THERP, the analyst first draws an HRET using the program. As the tree branches are drawn, they are linked to blank HEP data pages that will contain the material needed to determine which THERP table to use, in addition to other information that may be useful in characterizing the error. The HEP page also provides capabilities for including recovery, PSFs, and dependence. The analysts choose the THERP models they wish to use, and when they are satisfied with the BHEP they have estimated, it is placed on the HEP page. When all the HEPs for the HRET have been calculated, the program performs the calculations for quantifying the HRET, including dependency effects between any specified tree levels and displays the results on an HRET summary sheet. In the THERP analyses that are described below, the HRET page, all the HEP pages, and the HRET summary pages were used to document the analysis. As an example for this paper, one set of pages consisting of an HRET, the HEP summary sheet, and an example HEP page for the activities on the HRET is included.

Many of the applications of THERP error estimates required considerable interpretation and extension of the human activities for which the HEP was originally intended. This is in the spirit of the THERP procedure as originally intended by Swain. The HEP estimates are for guidance and are a means of tapping into the tremendous reservoir of experience that these HEPs represent. These estimates of human error should not be taken too literally. They are highly uncertain and are only used here for guidance. The alternative would be blind guessing in many cases.

Generally, process steps that involve following a step-by-step procedure were analyzed using THERP. In some cases, the part of the process step that was rule-based was analyzed with THERP. For skill-based activities, the analysts used the operational data to estimate errors. Some of the THERP HRETs included hardware failure probabilities as well as HEPs.

Rule-Based Activity Example: Unit Hoist to Transport Cart

As an example of the THERP analysis used in this study, an analysis of a drop of a weapon during a hoist is included. A device called a rotocage is attached to the weapon to lift the assembly from the transportation cart to the center case transportation stand. Because of the unique nature of this device, an HEP for rotocage attachment was calculated in addition to the more conventional HEP for rigging errors used from industrial-lifting data (George 1980). Both errors, along with rigging and rotocage mechanical failure, were considered in computing a drop probability.

The rotocage is designed to grip the assembly while it is lying horizontally and allow it to be rotated to the vertical. Two failure modes are addressed in the THERP analysis. The rotocage may not be secured properly and the unit can fall when it is lifted, or the rotocage may be installed in the wrong location and the unit may rotate when lifted, allowing the assembly to strike the floor.

The task analysis includes selection of the rotocage, attaching the rotocage and locking the clamp, attaching the rotocage in the correct position, securing the rotocage to the center case with the safety screws, and checking load balance while hoisting.

Selection of an improper rotocage could lead to improper installation, although a much more likely outcome is an inability to even attach it to the center case. This error involves an error by the tooling personnel in supplying the correct rotocage for the operation and a failure by the technician to recover when checking or subsequently attaching the incorrect rotocage. A negligible value was assigned to the probability of this error occurring and resulting in a center case drop because the rotocages differ so much in shape. The wrong rotocage would not physically fit on the unit and would with a high certainty alert the technicians to the problem .

The rotocage is designed to hold the center case by friction with the clamps hand tight. The safety screws will hold the unit even if the clamp is not secured. Thus, a drop requires that the technician neglect to secure the safety screws and neglect to tighten the clamps. The analysts judged a low dependence between the tasks of tightening the clamp and inserting the screws. This means that the HEPs are not independent. Having neglected to tighten the clamp makes it somewhat more likely that the technician will also neglect to install the safety screws. This reflects the analysts' judgment that an interruption is the most likely cause of neglecting to tighten hand screws and that an interruption would tend to affect both steps part of the time. The THERP analysis is summarized in the following figures. Figure 1. is an HRET for the activity. Figure 2 is a summary sheet that includes the estimated HEPs for different failure paths on the HRET.

Estimates of HEPs for Skill-Based Activities

In this analysis, applicable operational data were preferred over other data sources. Several HEPs for skill-based actions were estimated from weapon event and production data. Operational data were the preferred data source for constructing quantitative frequency and probability estimates, followed by surrogate data and then expert elicitation. In this analysis, errors in skill-based behavior were estimated using weapons processing data in most cases.

Surrogate operational data used in this HRA includes a Nuclear Regulatory Commission (NRC) lifting database. The NRC lifting data were used to estimate the approximate probability of rigging errors in lifting. These data are based on US Navy experience and are probably more conservative than need be for weapon dismantlement, where the lifts are more uniform and controlled. In addition, the analysts performed specific analyses for lifts using special fixtures so the surrogate data used in this context are not believed to introduce substantial problems in terms of applicability.

Event data for initiating-event frequency estimates were drawn principally from the Unusual Occurrence Reports (UORs), although some other sources were consulted as well. These reports address reportable events as defined by DOE Orders. The initiating events of interest to us are included in these reportable events. Counts of events drawn from event data provide the numerator for simple maximum likelihood estimators.

The UOR data were considered to be quite complete for most items of interest in this HRA. This is because the safety implications of these events are well recognized, and hence,

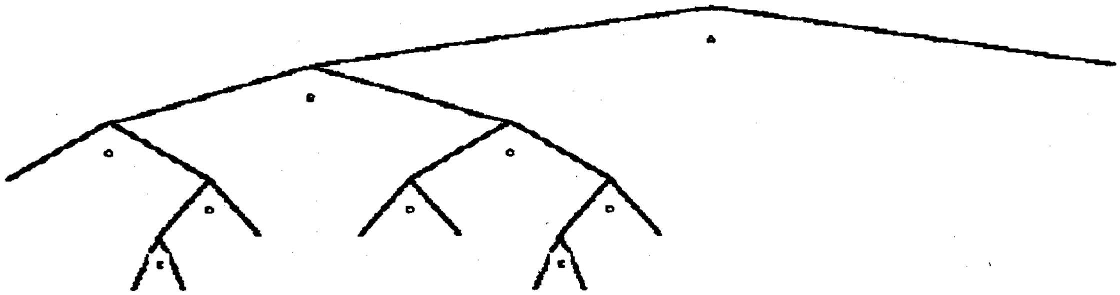
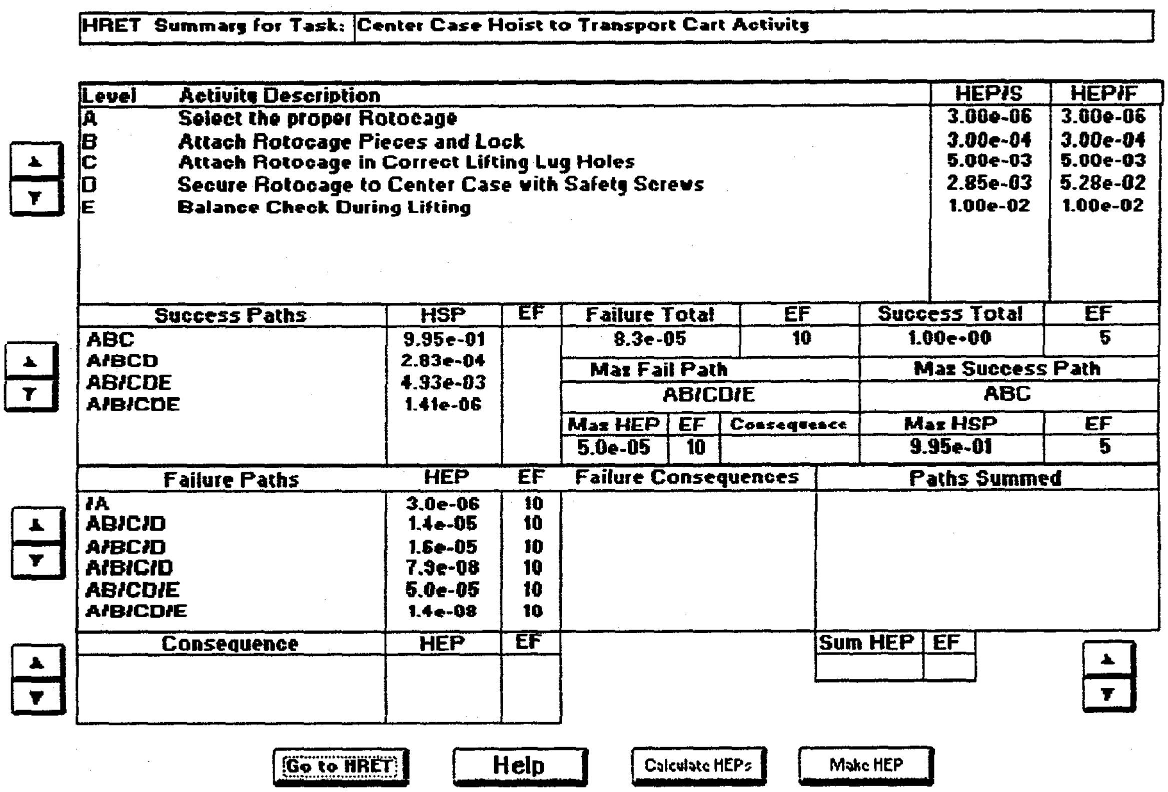


FIG. ~~2~~ 1 A HUMAN RELIABILITY EVENT TREE FOR A THERP ANALYSIS.



HRET Summary for Task:	Center Case Hoist to Transport Cart Activity

Level	Activity Description	HEP/S	HEP/F
A	Select the proper Rotocage	3.00e-06	3.00e-06
B	Attach Rotocage Pieces and Lock	3.00e-04	3.00e-04
C	Attach Rotocage in Correct Lifting Lug Holes	5.00e-03	5.00e-03
D	Secure Rotocage to Center Case with Safety Screws	2.85e-03	5.28e-02
E	Balance Check During Lifting	1.00e-02	1.00e-02

Success Paths	HSP	EF
ABC	9.95e-01	
A/BCD	2.83e-04	
AB/CDE	4.93e-03	
A/B/CDE	1.41e-06	

Failure Total	EF	Success Total	EF
8.3e-05	10	1.00e-00	5

Max Fail Path	Max Success Path
AB/CD/E	ABC

Max HEP	EF	Consequence	Max HSP	EF
5.0e-05	10		9.95e-01	5

Failure Paths	HEP	EF	Failure Consequences	Paths Summed
/A	3.0e-06	10		
AB/C/D	1.4e-05	10		
A/BC/D	1.6e-05	10		
A/B/C/D	7.9e-08	10		
AB/CD/E	5.0e-05	10		
A/B/CD/E	1.4e-08	10		

Consequence	HEP	EF

Sum HEP	EF

Go to HRET | Help | Calculate HEPs | Make HEP

FIG. ~~3~~ 2 SUMMARY OF THERP ANALYSIS.

they are required to be reported by the UOR system. The analysts do not believe that a substantial number of incidents go unreported or are hidden based on their observations of dismantlement processes.

Uncertainties in the data are introduced by the search methods, which often use titles for the UORs and may be misleading. The analysts tried to err on the side of checking more reports than they thought would be of interest, but some may have escaped their attention. This problem was exacerbated

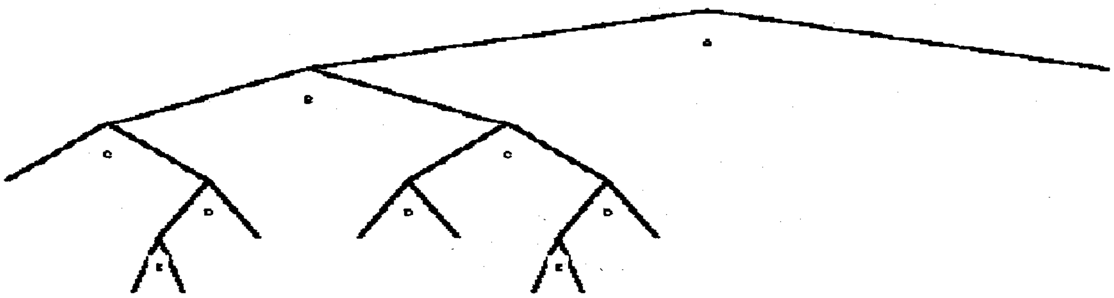


FIG. 1. A HUMAN RELIABILITY EVENT TREE FOR A THERP ANALYSIS.

HRET Summary for Task:	Center Case Hoist to Transport Cart Activity

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B	Attach Rotocage Pieces and Lock	3.00e-04	3.00e-04
C	Attach Rotocage in Correct Lifting Lug Holes	5.00e-03	5.00e-03
D	Secure Rotocage to Center Case with Safety Screws	2.85e-03	5.28e-02
E	Balance Check During Lifting	1.00e-02	1.00e-02

Success Paths	HSP	EF
ABC	9.95e-01	
A/BCD	2.83e-04	
AB/CDE	4.93e-03	
A/B/CDE	1.41e-06	

Failure Total	EF	Success Total	EF
8.3e-05	10	1.00e+00	5

Max Fail Path	Max Success Path
AB/CD/E	ABC

Max HEP	EF	Consequence	Max HSP	EF
5.0e-05	10		9.95e-01	5

Failure Paths	HEP	EF	Failure Consequences	Paths Summed
/A	3.0e-06	10		
AB/C/D	1.4e-05	10		
A/BC/D	1.6e-05	10		
A/B/C/D	7.9e-08	10		
AB/CD/E	5.0e-05	10		
A/B/CD/E	1.4e-08	10		

Consequence	HEP	EF

Sum HEP	EF

Go to HRET | Help | Calculate HEPs | Make HEP

FIG. 2. SUMMARY OF THERP ANALYSIS.

they are required to be reported by the UOR system. The analysts do not believe that a substantial number of incidents go unreported or are hidden based on their observations of dismantlement processes.

Uncertainties in the data are introduced by the search methods, which often use titles for the UORs and may be misleading. The analysts tried to err on the side of checking more reports than they thought would be of interest, but some may have escaped their attention. This problem was exacerbated by a series of missing UORs in the period 1986 to 1988. The titles of these UORs were preserved, but the reports themselves were destroyed accidentally by Pantex during microfilming.

Another uncertainty that plagues operational data is the question of the applicability of previous data to current situations. Often, a fault will occur from a human error that will result in a design change to address that fault. This makes the occurrence of that event less likely in the future than it was in the past. The analysts have not tried to take this effect into account unless they specifically knew of design fixes to the problem because it tends to lead to overestimation of events.

Estimates of skill-based human performance can be profoundly influenced by the work conditions—similar to the rule-based behavior discussed previously. To account for varying work conditions, the match between the work conditions for the period covered by the operational data used in our estimates of skill-based HEPs and the work conditions encountered in the activity being analyzed were considered. The safety culture current at the dismantlement site is significantly enhanced over that extant during the historical period upon which the operational data are based. This is considered a major factor in determining human error rates, especially for rule-based behavior. The experience level for the technicians may have declined somewhat because of retirements, but the effect on skill-based behaviors was judged to be slight because many very experienced younger technicians are still employed. Based on these considerations, the error rates predicted from operational data are estimated to be roughly applicable to future dismantlements.

Population data provide the denominator for calculating rates or probabilities using simple maximum likelihood estimators. Population data may be a time on test, a number of opportunities for error, or a number of cycles. Production data for the Pantex Plant were used to estimate the number of opportunities for certain types of production errors. The production data were divided into activities. Activities that involved both assembly and disassembly usually were combined when opportunities for HE drops or strikes were calculated.

Each weapon assembly/disassembly presents a certain number of opportunities (on average) for error, called opportunity multipliers. An estimate of this number of opportunities was based on discussions with technicians and engineering personnel. These opportunity multipliers are the number of opportunities per weapon. For example, based on interviews, the analyst may determine that there is a definable number of hand lifts of HE per weapon dismantlement . Thus, the approximate probability of a hand-lifted HE drop per opportunity is the average number of drops per weapon dismantlement divided by the average number of opportunities per weapon dismantlement.

An interesting result of the operational data analysis involved drops of-hand carried objects. The data indicated a very low probability of dropping hand-carried HE per opportunity. The same data indicate a considerably higher probability of dropping special nuclear material components. Interviews and discussions with operators indicated that HE drops are viewed as directly threatening to the life of the technician, whereas drops of nuclear materials are viewed as an administrative nightmare as opposed to a physical threat. The operational data indicate that special carefulness akin to a facilitative stress level is exercised by workers handling HE. Extrapolating this effect, the analysts reasoned that fixture drops would be even less feared than pit drops. For drops of fixtures or tools, the analysts assumed that the lower stress resulted in less care in handling and adjusted the HEPs for nuclear component drops further upwards according to the THERP model for adjusting HEPs for very low stress. This results in an HEP for dropping tools that is a factor of 3 higher than the nuclear material drop HEP.

Multiple-Process-Step Human Errors

Errors in some steps in the NEOP do not immediately result in an accident-initiating event but set the stage for later accidents. This type of error is difficult to detect. The analysts have used dismantlement experts and flow charts of the process to help to identify errors that could set up later accidents in the NEOP. As an example of this type of human error, a specific error is discussed.

A special fixture with screw-in wedges is used at one point in the process to separate tightly joined components. If the separation wedges are not backed out far enough, they can remain engaged with the weapon components, and one of the components could be lifted inadvertently in later steps with a high probability of dropping out of the separation fixture and striking the floor.

Identification of Potential Violations

Violations of technical specifications and procedures have been important culprits in many major disasters. For this reason, the analysts have screened many of the critical steps in the NEOP to identify steps that have a high potential for violation with relatively high-probability safety consequences.

It is impossible to estimate probabilities of violation with current understanding. Instead, the analysts have set up criteria to help us identify violation-prone steps. This criteria includes the perceived payoff for the violation and the perceived expectation of consequences from the violation. A table summarizing the criteria is shown in Table 1.

TABLE 1
VIOLATION ATTRACTIVENESS MATRIX

Perceived Payoff	Perceived Probability of Payoff	Perceived Penalty	Perceived Probability of Penalty
Personal Comfort	Nearly Certain	Personal Punishment	Nearly Certain
Personal Safety	High	Personal Injury	High
Increased Job Performance	Low	Job Impact	Low
Increased Process Performance	Nearly Impossible	Process Impact	Nearly Impossible

A violation with a high probability of occurring would have a high-perceived pay-off with high probability and a low-perceived penalty with low probability. Using this criterion, the analysts tried to identify any violation-prone steps. In general, the technicians principally perceived low personal benefit and a relatively high-perceived consequence for violating procedures, both from the safety and the job security standpoints.

Analysis of Knowledge-Based Activities: Emergency Procedures

Normally, the technicians are not confronted with situations that require extensive knowledge-based behavior. When an abnormal situation arises during a disassembly, operating instructions specify that the weapon state be stabilized, further process work halted, and cognizant assembly and safety engineers notified. In a nuclear emergency situation, the technicians evacuate the cell or bay as well. If the situation is not deemed too serious, then engineers develop an operating procedure. If the safety concerns are greater, the procedures typically are produced in an *ad hoc* manner by a panel of experts assembled for that purpose. This type of activity relies on knowledge-based behavior, which is typically error-prone (Reason 1990). The potential for error is aggravated by the possibility of relatively high stress on the decision-makers and the technicians if the situation is perceived as dangerous.

Because of the great number of potential abnormal conditions that could be encountered, most with little true safety significance, it is probably inevitable that some form of *ad hoc* emergency procedure process is required. Some potential measures to increase the probability of success for these procedures are discussed below.

There are advantages to formalizing the emergency procedure process to provide a more structured analysis of the problem. Perhaps a tiered approach could be adopted, where an abnormal situation is screened by assembly engineering, nuclear safety, and the design laboratory. If necessary, a team could be assembled to evaluate the conditions and determine the safest method for proceeding.

The assembly engineering personnel should work to ensure that all foreseeable and relatively likely conditions are covered by specific alternative steps the NEOP or that separate, pre-existing operating procedures are available. This will allow the technicians or the engineers to function in a rule-based mode as often as possible.

For processes in which relatively likely emergencies can be predicted, emergency drills with trainers may be useful in working out the "kinks" in the process. A full dress rehearsal of the emergency procedure process also could be useful. This could be run as an exercise in which an emergency is postulated and a team of engineers is assembled from the Laboratories and other sources. The team then could work through the emergency. A great deal probably could be learned from this type of exercise.

CONCLUSIONS

This work describes an HRA performed as a part of the development of a weapon dismantlement procedure. In the course of this HRA, the analysts discovered many activities that could be made safer by changing tooling, procedures, or training. Fro example, the HRA analysis suggested that the NEOPs could be improved by more careful differentiation between warnings, cautions, and notes that are used to emphasize specific steps or requirements in the procedures. It appeared that a warning was supposed to address critically important requirements that potentially affect worker and public safety. Cautions and notes addressed progressively less significant safety items. However, when the analysts inquired about some of the warnings, the staff were unable to provide a satisfactory reason for their inclusion. Some of the warnings seemed to be almost boiler plate, added to all NEOPs out of historical habit or to satisfy some now-lost directive. This practice dilutes the effectiveness of the *bona fide* warnings that are present. Overrated or inapplicable warnings should be removed from the procedure or replaced by cautions or notes. This would help to reinforce the effect of a warning on the technicians. As a result of the input of the HRA, the NEOPs were improved as suggested in the above discussion.

Another suggestion was that the procedures direct the technicians to remove hazardous and energetic components from the cell immediately after disassembly rather than relying on the operator to take that initiative on his own. This practice was generally followed anyway because it reduces potential hazards by limiting the time the weapon is at risk from energy sources associated from these parts of the weapon, but a specific requirement was felt to be more certain to maximize safety.

This HRA on nuclear weapon dismantlement produced many interesting results that were reflected in the final procedures. This study broke new ground in applications of THERP and resulted in new human error estimates based on operational data that will be applicable in future weapon studies.

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