A cost-savings methodology of panel enhancements
by Danna Gail Herbst

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Industrial and Management Engineering
Montana State University

Abstract:
Many currently-operating, industrial plants were built without an emphasis upon human engineering. Incorporating human factors into the re-design of existing control panels requires a capital investment. However, the application of human engineering design principles to existing panel designs reduces human error., A methodology for conducting a cost-savings analysis of incorporating human factor design principles into existing panel designs is presented. The cost-savings methodology integrates several existing methods, models, and techniques to enhance acceptance and application by industry. These methods, models, and techniques include panel enhancement techniques, economic cost models, task analysis, fault tree analysis, and a method for cost-benefit analysis. In addition, the methodology contains a new application of a linear additive utility model and a new procedure for determining the efficiency of funding allocation.

The cost-savings methodology proposes human engineering enhancements to existing panel designs. Enhancement costs and potential human error reduction are estimated. Potential human error reduction is quantified in terms of monetary risk reduction. Monetary risk reduction benefits and enhancement costs provide the basis for a cost-savings analysis, which consists of a cost-benefit and a funding allocation analysis.

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Master of Science

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Industrial and Management Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

September 1988

APPROVAL

of a thesis submitted by

Danna Gail Herbst

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ACKNOWLEDGEMENTS

I gratefully acknowledge James R. Wilson as well as the managers and staff of the Operational Safety Analysis Section of Westinghouse Idaho Nuclear Company for suggesting this study. I wish to extend my appreciation to Les Mitchell, Jill Cox, and the managers and staff of the Quality Assurance Department at Westinghouse Idaho Nuclear Company for their support. In addition, I would like to thank my husband, Scott Herbst, for his patience, encouragement, and support during the completion of this thesis.

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ABSTRACT

Many currently-operating, industrial plants were built without an emphasis upon human engineering. Incorporating human factors into the re-design of existing control panels requires a capital investment. However, the application of human engineering design principles to existing panel designs reduces human error.

A methodology for conducting a cost-savings analysis of incorporating human factor design principles into existing panel designs is presented. The cost-savings methodology integrates several existing methods, models, and techniques to enhance acceptance and application by industry. These methods, models, and techniques include panel enhancement techniques, economic cost models, task analysis, fault tree analysis, and a method for cost-benefit analysis. In addition, the methodology contains a new application of a linear additive utility model and a new procedure for determining the efficiency of funding allocation.

The cost-savings methodology proposes human engineering enhancements to existing panel designs. Enhancement costs and potential human error reduction are estimated. Potential human error reduction is quantified in terms of monetary risk reduction. Monetary risk reduction benefits and enhancement costs provide the basis for a cost-savings analysis, which consists of a cost-benefit and a funding allocation analysis.

INTRODUCTION

Background

Proper application of human engineering principles to design reduces human error and improves system reliability [6,14,18,22,27]. The importance of human factors in design was dramatically emphasized by the accident at Three Mile Island. Consequently, the application of human factors principles in the design of control panels has received increased attention in recent years [16]. However, most plants were built before this emphasis. To reduce human error and improve system reliability of currently operating plants, human engineering design principles must be applied to the re-design of existing control panels. The re-design of existing control panels has been termed retrofitting and backfitting [16,22].

Although retrofitting human factors into existing designs improves system reliability, it can be extremely expensive if hardware re-design is involved. Relocating instruments on a control panel is very expensive due to rewiring, drawing changes, engineering reviews, and safety reviews. However, human factor design principles can be applied to existing designs through surface enhancements. Surface enhancements are cosmetic additions, such as paint, tape, and labels applied according to information processing principles which reduce human error. The cost of retrofitting human factors via surface enhancements is substantially less than retrofitting via hardware re-design [22].

The cost of retrofitting human factors via surface enhancements represents a capital investment [16,22,31,32]. To justify a surface enhancement investment from an economic standpoint, monetary benefits of the human factor design inputs must outweigh the costs, and the investment must represent efficient allocation of available funds [10,33]. However, no systematic procedure exists at present to accomplish the complex integrative process necessary to quantify this type of human factor input to control panel design. The present study was initiated in an attempt to develop an economic analysis of panel enhancements that involves a cost-benefit analysis and a budget allocation analysis. The resulting methodology is entitled a Cost-Savings Analysis of Panel Enhancements (CSAPE). A CSAPE permits quantification of the benefits of surface enhancements in monetary terms, something human factors specialists are constantly under pressure from management to do.

Performing a cost-savings analysis of proposed panel enhancements will provide economic justification of the enhancement investment. Another advantage of conducting a CSAPE is the opportunity to evaluate the monetary benefits of panel enhancements before the enhancements are implemented. Both monetary benefits and reliability improvement benefits can be estimated.

A panel enhancement investment can be viewed as a safety investment. Methodologies that determine the cost-effectiveness of safety investments have been developed [2,3]. However, the previously developed methodologies evaluate cost versus a parameter, such as reliability, of a safety investment rather than cost versus monetary benefits [2,3,10,33]. These methodologies do not evaluate safety investments in terms of efficient budget allocation and do not deal with human factor design inputs [2,3]. A Cost-Savings Analysis of Panel Enhancements (CSAPE) evaluates safety investments in terms of cost versus monetary benefits, efficient budget allocation, and addresses human factor design inputs.

This study was conducted to develop a methodology for conducting a CSAPE. A CSAPE can be used to justify an investment in control panel enhancements and evaluate both the monetary and reliability improvement benefits of the investment. A CSAPE involves proposing surface enhancements for an existing panel design, quantifying the benefits of the enhancements in monetary terms, and performing a cost-saving analysis of the enhancements.

Objectives

The objective of this study was to integrate several established procedures into one methodology that would permit a Cost-Savings Analysis of Panel Enhancements (CSAPE). The CSAPE integrates established techniques of panel enhancements with economic cost models, task analysis, fault tree analysis, cost-benefit analysis, and a monetary risk definition [1,10,11,22,23,30,33]. Established procedures were used where possible to enhance acceptance and application by industry. However, the CSAPE also incorporates a new application of a linear additive utility model and a new approach to determine efficient funding allocation.

The Cost-Savings Analysis for Panel Enhancements (CSAPE) has been developed specifically for use in the chemical processing industry. However, with slight modifications, it could be used elsewhere as well.

Overview of the Methodology

The CSAPE involves proposing surface enhancements to an existing panel design, estimating the costs of implementing the enhancements, quantifying the benefits of the enhancements in monetary terms, and performing a cost-savings analysis of the enhancement investment.

The CSAPE begins with the identification of the control panel to be enhanced (see Figure 1). Surface enhancements are proposed for the existing design by using the surface enhancement process [22]. The costs for implementing the enhancements are identified and estimated using cost accounting and economic analysis principles [10,23,33].

The benefits of the proposed enhancements are quantified in monetary terms by calculating the risk reduction potential of the enhancements. The risk reduction potential is estimated by postulating an accident associated with the operation of the panel, and calculating the difference between the risk associated with the existing design and the enhanced design. Risk, as defined in the nuclear industry, is expressed in terms of expected cost of an accident. It is calculated by multiplying the economic consequences of the accident by the probability of the accident [1]. Consequently,

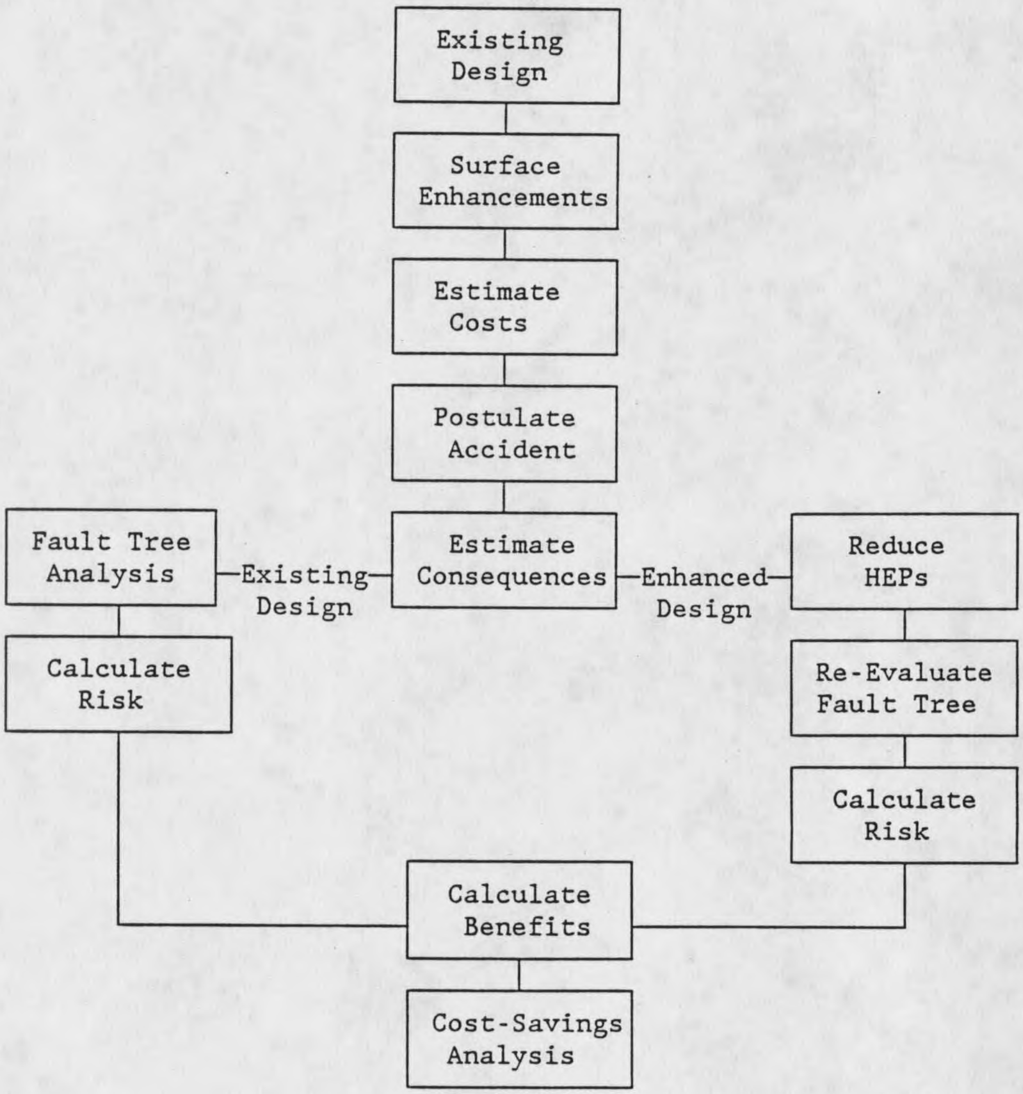


Figure 1. The methodology for a Cost-Savings Analysis of Panel Enhancements (CSAPE).

calculating the risk reduction potential requires estimating the financial consequences of the accident and estimating the probability of the accident with respect to both the existing and enhanced panel. The resulting risk reduction potential constitutes the monetary benefits of the proposed enhancements.

Estimating the probability of an accident with respect to the operation of the existing design involves conducting a fault tree analysis of the accident [11,17,28,30]. Fault tree analysis involves task analysis, fault tree construction, and fault tree evaluation. A task analysis of the operations involved in the accident provides the data base for the construction of the fault tree [27,30]. The quantitative evaluation of the fault tree provides the probability of the accident occurrence [11,17,28,30].

Estimating the probability of the accident with respect to the operation of the enhanced layout involves estimating the human error reduction potential of the enhancements and re-evaluating the fault tree. Surface enhancements reduce the human error probabilities (HEPs) associated with the accident [18,22,27]. A linear additive utility model is used to estimate the reducing factor for the human error probabilities (HEPs) [8,9,13,15,26]. The fault tree of the accident is re-evaluated using the reduced human error probabilities (HEPs) [7,11,30].

Risk reduction potential versus cost of the enhancements provide the basis for a CSAPE. The cost-savings analysis of the enhancement investment consists of a cost-benefit analysis and a funding allocation analysis. The benefit-cost ratio is used in the cost-benefit analysis [10,33]. The funding allocation analysis consists of determining the expected maximum yearly savings of the enhancement investment and using these savings to determine the efficiency of the funding allocation.

The CSAPE and an example illustrating its use are presented in subsequent sections.

PROPOSING ENHANCEMENTS

The methodology for a Cost-Savings Analysis of Panel Enhancements (CSAPE) begins with the identification of the panel to be enhanced and the surface enhancement process. A panel that needs to be enhanced can be identified once a distinction is made between a properly designed layout and a poorly designed layout. A panel layout survey is conducted to identify deviations in a layout from properly designed layouts. The surface enhancement process is then used to enhance poorly designed layouts [22].

Panel Layouts

There are several differences between proper panel designs and poor panel designs. A properly designed layout reduces display selection errors and unintentional control activation. Proper panel design aids an operator in locating, identifying, and selecting instruments quickly and accurately [22,27].

A properly designed layout will conform to the NUREG-0700 Guidelines [29]. The NUREG-0700 Guidelines recommend grouping displays and controls on a panel according to the principles of "task sequence" and "system function". The principle of task sequence groups instruments in order to minimize operator movement during task performance. Grouping displays and controls by system function refers to functional groups of instruments relating to system structure.

Further, groups of displays and controls should be assigned to panel locations according to their importance and frequency of use. Important and frequently used groups should be placed in the center visual area of the panel. Since it may be impossible to apply all of these design principles, design trade-offs will have to be made in allocating panel positions to instruments and groups of instruments [21,35]. Population stereotypes should be followed in arranging controls and displays within the groups as long as they do not conflict with the principle of task sequence. If a standard arrangement of components has been established, it should be maintained on other panels or sections of a panel. However, panel sections should not be mirror imaged. Control or display groups should be separated from one another using spacing or demarcation lines. If large groups of instruments are necessary, labeled coordinate axes should be used to facilitate the identification of an instrument within a grid. Control separation distances should be sufficient to allow for access and simultaneous activation of adjacent controls while preventing inadvertent activation. Color coding may be used to enhance the recognition and identification of displays, controls, or groups of instruments [29]. The above mentioned recommendations from the NUREG-0700 guidelines represent examples of areas that deal with a properly designed layout and are samples of what is meant by surface enhancement [22,29].

A panel layout survey should be conducted to identify deviations in the design from these guidelines. Table 1 illustrates a generic checklist that may be used in conducting such a survey [29].

Table 1. A checklist used in a panel layout survey.

	N/A	Complies With Guidelines	Does Not Comply With Guidelines	Comments
Panel Feature				

If a panel design deviates in major ways from these guidelines especially in terms of instrument location, it may be impossible to backfit recommendations by relocating instruments on the panel. Fire protection requirements may prohibit the separation of cables in order to relocate instruments. New cable or conduit installation is extremely expensive because of the requirements for engineering and seismic analyses, fire loading, safety reviews, and drawing changes [22]. However, improvements in the layout can be made through the use of surface enhancement techniques [22,31,32].

The Surface Enhancement Process

The surface enhancement process of proposing changes in panel layouts involves identifying the organizational structure of the panel, enhancing the organization structure, and verifying the enhancements [22].

Identifying the Organizational Structure

The organizational structure of an existing layout must be identified because the structure will govern the nature of design improvements possible. Existing panel designs may be based upon a number of organization structures or combinations thereof. The location of displays and controls on a panel may correspond to the functional relationships of plant subsystems and equipment. For example, a panel layout may be a mimic of the plant process, or the panel may be organized according to the relationships of plant support functions to major plant systems.

Components on a panel may be arranged according to the common activation and operation of equipment. Or, panel designs may be based on the functional relationships among the controls and displays. For example, instruments may be located on a panel to facilitate their simultaneous or sequential operation. Panel designs could also be based on the geographical relationships of the equipment.

The purpose of surface enhancement is to reduce inconsistencies and conflicts of the organizational structure in order to enhance the operability within the design. Careful attention should also be given to the manner in which operators mentally organize the panel in order to successfully enhance the design [22].

Enhancing the Organizational Structure

Enhancing the organizational structure involves making decisions concerning the surface enhancement techniques to be employed, component group formation, and elements of the component groups. Recommendations regarding these decisions should be obtained from the operating personnel [22].

Verifying the Enhancements

The proposed enhancements must be verified! Inappropriate changes in panel design may in fact degrade the man-machine interface. For example, the enhancements may violate existing design conventions, lead to negative transfer of learning, and may be inconsistent with the existing design. Therefore, modifications of an existing design must be thoroughly evaluated through the use of models and mock-ups. Three-dimensional models provide the most effective way of evaluating alternative designs in terms of colors, textures, color schemes, equipment arrangement, and operability. However, drawings may be adequate for the preliminary analyses.

Control panel mock-ups also allow for the safe testing of operator-equipment interfaces. In addition, they can be used as training tools after a design has been tested and approved. Models and mock-ups should be reviewed by operators, supervisors, engineers, and human factor specialists in order to disclose problem areas and provide direction for design trade-offs [22].

Surface Enhancement Techniques

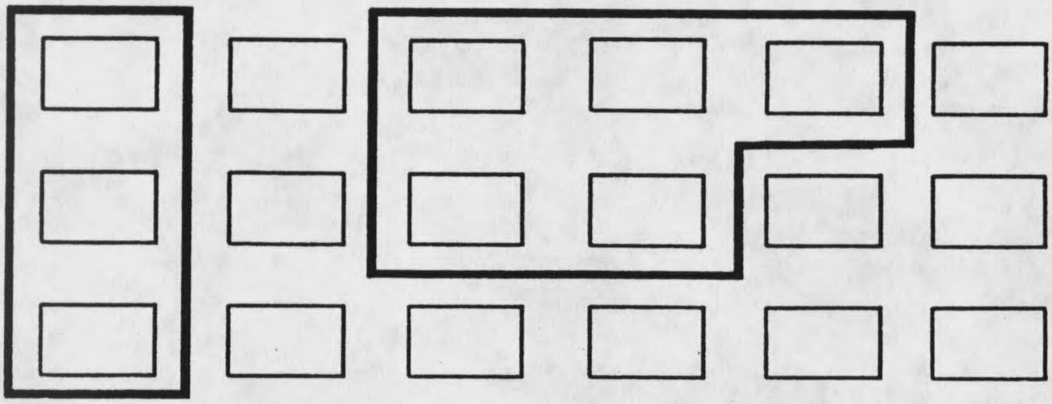
Surface enhancement involves the application of location aids. Location aids include demarcation, color shading, color coding, and mimic lines. These location aids are employed to enhance the perceptual organization of a panel's content. Surface enhancement techniques are based upon perceptual organization principles to provide an operator with visual location aids. The principles of perceptual organization include association, closure, dominance, and uniqueness. Implementation enhancement techniques must also include a concern for color selection and hierarchical labeling [22].

Association

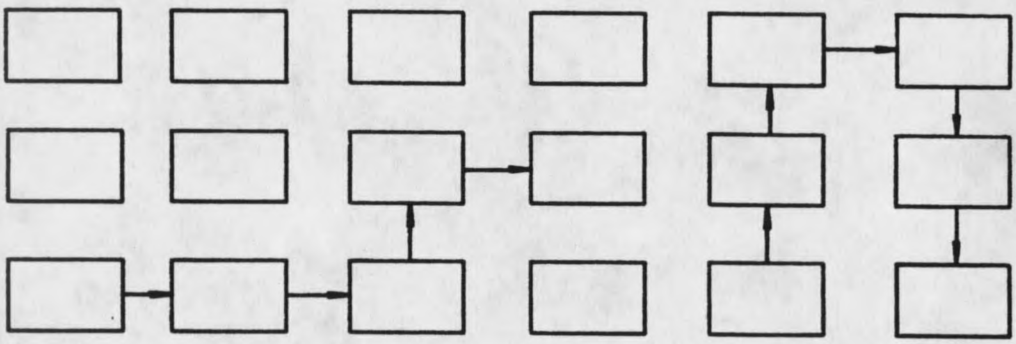
Association of displays and controls can be conveyed through the use of shape, color, and lines. For example, components with similar knob shapes or instrument cases can be perceived as forming a group. Color can convey association between physically separated components. In order to avoid a patchwork effect when using this technique, neutral color tones should be selected. Neutral color tones, such as greys and pastels, are more effective in conveying association. Strong colors can produce a conflicting organization principles of dominance. Strong colors also contribute to visual fatigue, clutter, and reduce contrast which leads to poor label readability [21,22,35].

A group of components can be associated by enclosing them with a line. Lines that enclose components groups are demarcation lines (see Figure 2). Demarcation lines with rounded or beveled corners tend to form stronger groups than ones with square corners. Demarcation lines should never cross and the lines should contrast well with the panel background color.

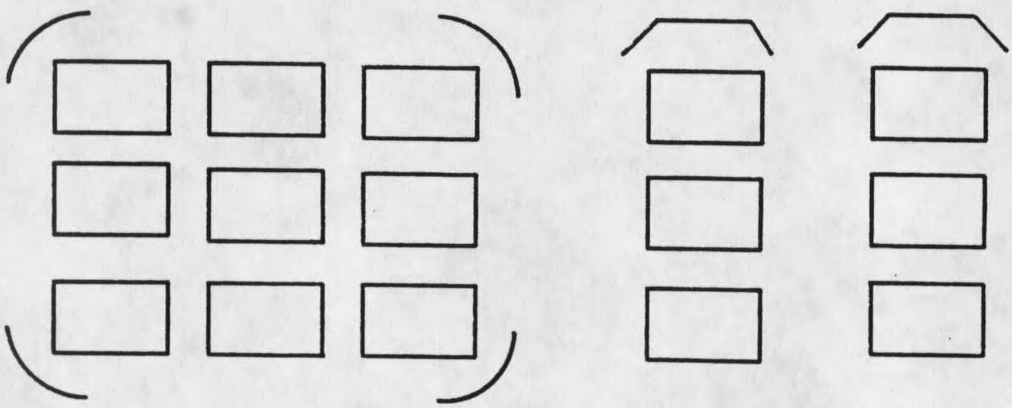
Instruments can also be visually linked by connecting them with a single line where the line indicates a task sequence or the process flow. Single lines that indicate task sequence or process flow are mimic lines. Mimic lines should never cross and arrows should indicate the direction of flow. A prerequisite of mimic line use is



Demarcation lines indicate association.



Mimic lines indicate association.



Rounded corners and brackets indicate closure.

Figure 2. Illustration of the perceptual organization principles of association and closure.

the appropriate physical arrangement of instruments to allow flow paths to be reflected (see Figure 2) [22].

Closure

The principle of closure is based upon the normal human perceptual tendency to visually extrapolate closure from existing graphic cues. For example, groups of instruments can be formed through the use of brackets or corners (see Figure 2). This bracket technique is only successful if the brackets are placed at the top of a group [22].

Dominance

Functional importance of components can be conveyed through the use of line width, contrast, or color. For example, wider demarcation lines convey a major group while narrower demarcation lines indicate subgroups (see Figure 3). Color can also convey dominance or importance when it is brighter or visually stronger than surrounding colors. However, care should be taken in applying color to denote dominance because strong or bright colors visually clutter the layout and reduce label contrast [22].

Uniqueness

The uniqueness or perceptual distinctiveness of an instrument can be conveyed through shape or color. A component with a different shaped knob or color than the surrounding components will appear unique (see Figure 3). A technique for making demarcation lines unique is using filled-in, rounded, or cut-off corners. Color can also be used to create mimic line uniqueness. However, this technique can be overused and the uniqueness lost. Uniqueness of mimic lines can also be lost by using too many mimic lines. Color shading may be used to make a group of instruments more distinctive. However, using too many colors can result in a "Christmas tree" effect [22].

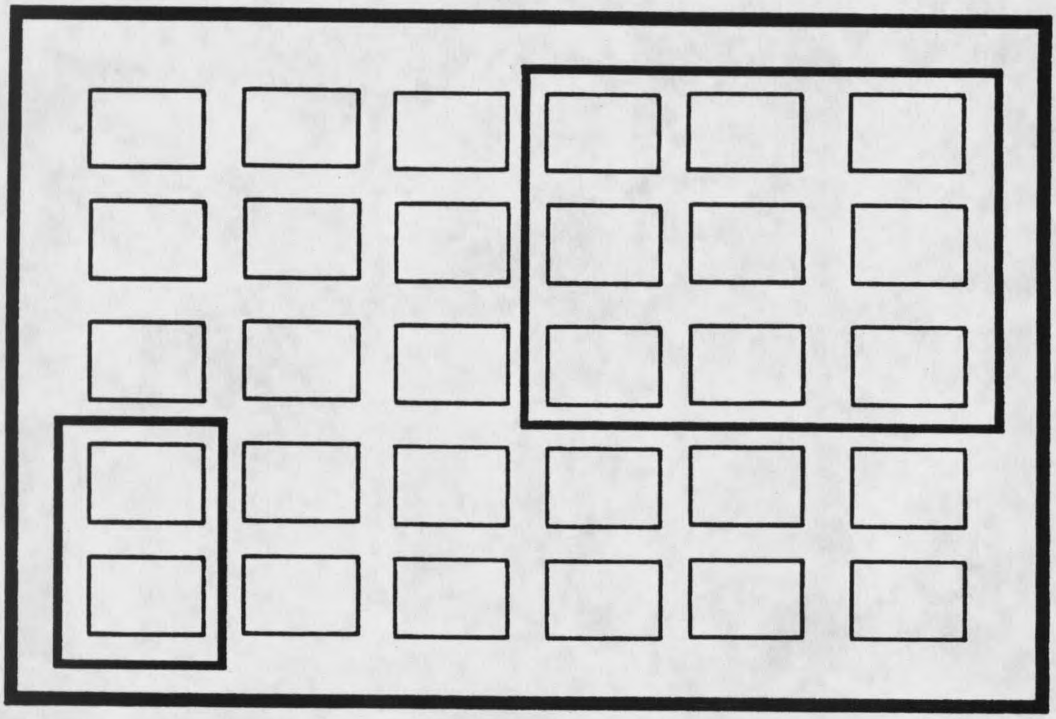
Color Selection

Color selection should be based on the type of hardware on the panel, panel board background color, and the colors of indicator lamps, CRT displays, and annunciators. Generally, large component groups require neutral tints while contrasting colors are used for smaller groups [22]. Light gull grey and dark gull grey are recommended for large and small component groups respectively [21,35].

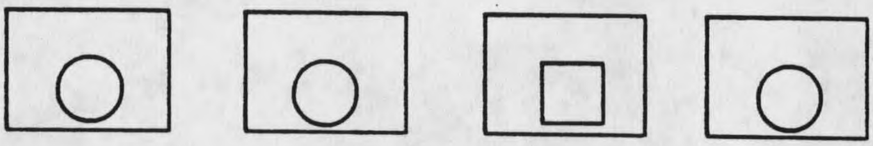
Hierarchical Labeling

Hierarchical labeling must be complementary to demarcation and color shading. The purpose of hierarchical labeling is to simplify and highlight the presentation of information in a manner that relates and integrates functionally similar component groups. Using a hierarchial labeling scheme, functionally related components are identified by general group labels. This reduces the verbiage on individual labels and consequently, reduces reading time [22].

Two important factors in the design of a hierarchical labeling scheme are levels of the hierarchy and letter size degradation. The four levels of a hierarchical labeling scheme are major, subordinate, component, and position identifier levels. A major level refers to a major system or work station while a subordinate level refers to subsystems or functional groups of instruments. The component and



Wide demarcation lines indicate dominance.



Shape indicates uniqueness.

Figure 3. Illustration of the perceptual organization principles of dominance and uniqueness.

position identifier levels refer to instrument labels and control selection labels, respectively. Appropriate letter size of the hierarchy must be determined from the appropriate letter size of the component label since the letter size increases 25% for each level of the scheme. Appropriate letter size for instrument labels depend upon the viewing distance and illumination levels. Larger character size is required for greater viewing distances and lower levels of ambient light. The guidelines of NUREG-0700 should be followed when selecting the letter size [22,29].

Other considerations in the design of a hierarchical labeling scheme include information of the major, subordinate, and component elements conveyed, and the nomenclature selection. The labels should not present redundant information and should only be used if unrelated components do not intrude into the area. Major labels should be located in the center, top edge of a panel, while the subordinate labels should be centered above the demarcation lines or shaded areas. Component labels should be located above the instruments to complete the top-down phenomenon created by the hierarchy. The NUREG-0700 guidelines regarding the placement, mounting, spatial orientation, visibility, information content, word selection, consistency, readability, and style should be applied to the labels [22,29].

ESTIMATING ENHANCEMENT COSTS

A cost-savings analysis of control panel enhancements requires the estimation of the enhancement costs. The total cost of implementing surface enhancements consists of several components. The cost components are initial costs, lost production costs, and incremental costs of operation and maintenance [2,10,23,33]. The cost components cannot simply be aggregated to arrive at a total cost estimate due to the difference in the timing of the cash flows. Money has a time value because of interest and inflationary effects [10,33]. Hence, only the value of the cash flows at the time of surface enhancement incorporation will be considered in the analysis. The time value used in the analysis will be denoted present worth. Once the cash flows or cost components have been converted to a present worth value, they can be aggregated to arrive at a total cost estimate. Consequently, each cost component will be analyzed in terms of a present worth value. A total cost estimate can be determined by summing the results [10,23,33].

Initial Costs

The initial costs of surface enhancements will consist of direct material, direct labor, and any overhead costs relating to the enhancements, mock-ups and models [23,33]. The overhead costs consist of administrative costs. Direct materials consist of paint, tape, and labels for the enhancements as well as the materials for the mock-ups or models [22]. The direct labor cost is composed of the labor cost necessary to implement surface enhancements and to construct the testing devices [22,23,33]. Since the timing of most of the cash flows is concurrent with implementation of surface enhancements, the cash flows are denoted as present worth values. Thus, the present worth value of the initial cost component is the sum of direct material, direct labor and any overhead costs related to the enhancements and testing devices [22,33].

Lost Production Costs

Another cost that may be incurred when implementing surface enhancements is lost production costs or costs due to plant downtime while incorporating the surface enhancements. Since it will be assumed that surface enhancements can be implemented in less than one year and end-of-year cash flows will be used in the analysis, the downtime costs can be aggregated and represented as a present worth, single sum value [10,33]. The estimate of lost production costs can be added directly to the initial cost component.

Although the lost production cost component is considered in the analysis, it could be avoided. Surface enhancement incorporation could be scheduled simultaneously with routine maintenance. Thus, surface enhancements could be incorporated while the plant was shut down for regularly scheduled maintenance. Eliminating the lost production costs would reduce the total cost of a surface enhancement investment, therefore, making the investment more attractive.

Incremental Operating and Maintenance Costs

The final cost component considered in the total cost of the surface enhancement investment is the incremental costs in maintenance and operation [2]. Additional costs might be incurred in the maintenance and operation of the plant due to surface enhancements. The incremental operation and maintenance costs may consist of the costs to revise written operating procedures due to the changes and the costs to refurbish the surfaces of the panel [22]. Such costs would be incurred throughout the remaining lifetime of the plant. For the purpose of this study, the average lifetime of an industrial plant will be assumed to be 40 years [4]. Thus, the incremental cash flows will be incurred over 40 minus n years, where n is the number of years the plant has been in operation. The incremental maintenance and operation costs will be modeled as discrete, end-of-year, cash flows (see Figure 4).

Since the timing of the incremental operating and maintenance cash flows is not concurrent with the incorporation of the surface enhancements, they must be converted to a present worth, single sum value. The present worth value, using then-current dollars, will be used in order to compensate for inflation and interest [4,33].

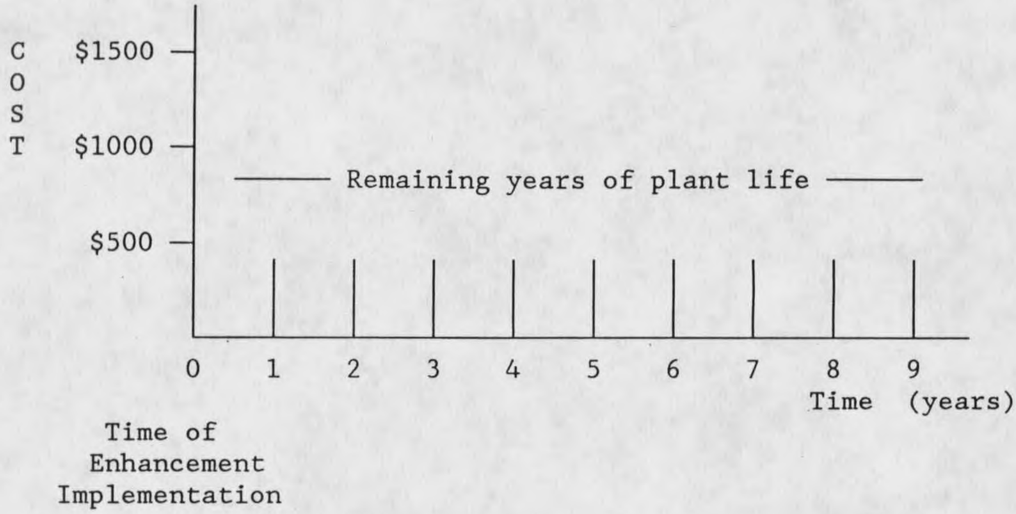


Figure 4. Cash flow profile of incremental operating and maintenance costs.

The present worth value using then-current dollars can be calculated as follows [4,33]:

$$P_i = \sum_{n=0}^{k} C_n(1 + i_r + j + i_r \cdot j)^{-n} \qquad (1)$$

where P_i = present worth value of the incremental costs
C_n = incremental cash flow in year n
i_r = interest or discount rate
j = inflation or escalation rate
n = year from year of enhancement completion
k = remaining years of plant lifetime

After all of the cost components have been estimated, a total cost estimate for the surface enhancement investment can be determined by summing the results [23].

POSTULATING AN ACCIDENT

The monetary benefits as well as the costs of the surface enhancement investment must be estimated before a cost-savings analysis can be performed. An accident must be postulated to determine monetary benefits of enhancements.

An accident associated with the operation of the layout must be postulated to determine the risk reduction potential of the surface enhancements. Careful selection of the accident or initial event is required. For example, if the initial event is too broad, then the analysis will become unmanageable [30]. On the other hand, if the initial event is too specific, then the full risk reduction potential of the surface enhancements will not be realized. Once the selection of the initial event has been made, the economic consequences can be estimated.

ESTIMATING ECONOMIC CONSEQUENCES

Economic consequences of an event are used in conjunction with the probability of the event to determine the risk reduction potential or monetary benefits of surface enhancements. The economic consequences of an initial event will be estimated based upon the economic analysis methods and estimates for light water reactors. The economic analysis methods and estimates are used in the regulatory decision-making process [4]. Therefore, an acceptable procedure for estimating financial consequences of an initial event has been incorporated in the methodology.

To estimate the financial impact of an initial event, the event is categorized into one of three event categories. The event categories are Event Category I, Event Category II, and Event Category III [4]. Event Category I consists of Type I Events or small consequence accidents [2,4]. Small consequence events occur routinely throughout the life of an industrial plant although they are not scheduled or planned events. Such events could be the result of plant trips, operator errors, unscheduled maintenance requirements, plant system failures or external events. Small consequence events consist of a period of zero plant production. However, no significant plant contamination, plant damage, or on-site health impact costs are incurred [4]. Thus, the economic consequences of Type I Events only consist of some on-site costs.

Event Category II consists of Type II Events or medium consequence events [2,4]. Medium consequence events result in substantial equipment damage and other on-site costs. Plant decontamination is required after an event in this category. Plant repair or decommissioning follows the decontamination. If the plant is repaired, a period of zero plant production may last for many years. However, these events do not result in a significant release of harmful material into the environment. Therefore, there is no significant off-site health impact or property damage costs associated with Type II Events [4].

Event Category III consists of Type III Events or severe accidents [2,4]. A Type III Event would result in severe plant damage and a significant release of a harmful material into the environment. Consequently, a Type III Event may result in off-site costs such as off-site health impacts and property damage as well as on-site costs such as on-site health effect costs, capital loss, perceived risk costs, litigation costs, and repair or decommissioning costs. Fortunately, Type III Events are very rare [4].

Off-Site Costs

Off-site costs are costs occurring at off-site locations, including the costs for measures taken to reduce population exposure after a contaminating event, property damage costs, and off-site health effect costs. Off-site costs also include indirect or secondary costs that occur outside a contaminated area [4]. An example would be the loss of tourism trade due to a severe industrial accident.

The countermeasure costs, off-site property damage costs, off-site health effect costs, and secondary costs represent general classifications of off-site costs. Specific off-site costs include population evacuation costs, temporary relocation costs, property decontamination, agricultural product disposal costs, population health effect and health care costs, off-site litigation costs, and permanent relocation costs [4].

Off-site costs are only incurred in Type III Events or very severe accidents. The probability of a Type III Event occurring is very small. In fact, the United States has never experienced a Type III Event [4]. Consequently, it has been determined that on-site costs generally dominate the economic consequences of potential accidents [25]. Therefore, in this study, only on-site costs or Type I and Type II Events will be considered in the analysis.

On-Site Costs

On-site costs are costs directly affecting the plant, industry, or that occur at on-site locations. There are several on-site cost components which are worker health effect costs, plant decontamination costs, repair costs, loss of production costs, capital investment loss, litigation costs, and perceived risk costs [4]. The cost components cannot simply be aggregated to arrive at a total on-site cost estimate because of the difference in the timing of the cash flows [4,10,33]. Adjustments must be made to account for this difference in the timing of these cash flows, i.e., compensating for the effects of interest and inflation. Compensating for the effects of interest and inflation will yield equivalent values which can be summed to arrive at a total on-site cost estimate [10,33]. In this study, the present worth value using then-current dollars will denote the equivalent value of these cash flows at the time of accident occurrence [4].

Worker Health Effect Costs

The assignment of a dollar value to health effects is the most controversial and difficult aspect of estimating the financial consequences of an accident. Actually, the value of life cannot be determined in a technical manner. The value of life is a political or social issue [25].

Rather than assigning a monetary value to the value of life, the "life shortening method" will be used. The life shortening method measures the number of lost years. Consequently, a lower value is assigned to delayed deaths or older persons, and a higher value is used for younger persons or immediate deaths [4,25]. Some estimates for radiation induced health effects are given below, which are based on a review of societal expenditures for life [4]:

$1,000,000	per early fatality
$100,000	per early injury
$100,000	per latent cancer fatality

The above estimates are based upon 1984 values. Consequently, these values must be adjusted for inflation and interest. To determine the present worth value for each of these estimates, use the following relation [10,33]:

$$E^* = E(1 + i_c)^n \quad \text{where } i_c = i_r + j + i_r \cdot j \tag{2}$$

and where E^* = adjusted estimate
E = estimate in 1984 dollars
i_c = compound inflation and interest rate
i_r = interest rate
j = inflation rate
n = the difference between the current year and 1984

Although worker health effect costs are incurred in a Type II Event, it is unlikely that worker health effect costs are a result of a Type I Event, since Type I Events are small consequence accidents [4].

Plant Decontamination Costs

In the case of a Type I Event, no significant plant contamination results. However, in the case of a Type II Event, plant decontamination is required before plant repair or decommissioning [4]. Therefore, when postulating a Type II Event, decontamination costs must be considered in the analysis.

The decontamination costs would include clean-up and waste disposal costs. Figure 5 is the cash flow profile for the estimated Three Mile Island-2 (TMI-2) decontamination and clean-up program in 1980 dollars [4].

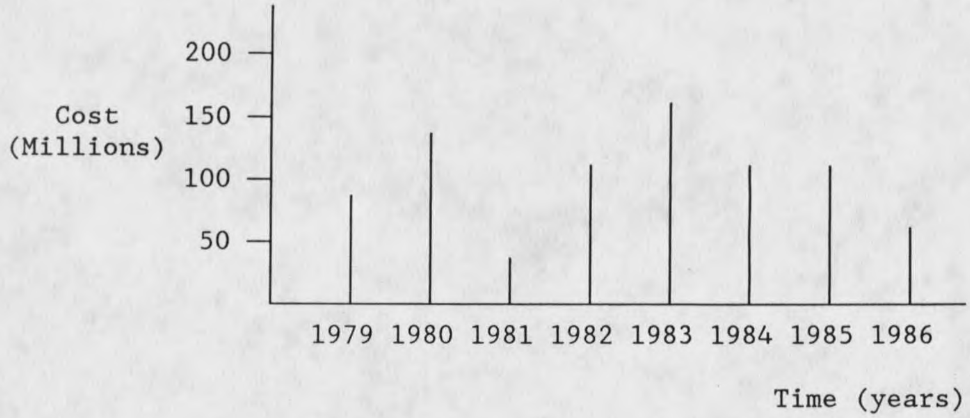


Figure 5. Cash flow profile of the Three Mile Island decontamination program.

The present worth of the decontamination costs using then-current dollars is computed as follows [4,10,33]:

$$D_c = \sum_{n=0}^{m} C_n(1 + i_r + j + i_r \cdot j) \quad (3)$$

where D_c = present worth of decontamination costs at the time of the event
C_n = undiscounted, uninflated program cost in year n after the event
n = year from the year of the event
m = completion year of the program
i_r = interest rate
j = inflation rate

Using an interest rate of 4% only, the present worth of the TMI-2 Recovery Program is approximately $750 million in 1980 dollars [4].

The duration of the decontamination program determines to some extent the cost of the decontamination operation. A longer program plan would result in higher costs due to the time value of money.

Based on studies of post-accident clean-up and decontamination programs, estimates of program duration are as follows [4]:

lower bound = 4 years
best estimate = 8 years
(based on TMI-2 Recovery Program)
upper bound = 12 years
(worst Type II Events)

Plant Repair Costs

Plant repair costs are often negligible in the case of a Type I Event because it is difficult to distinguish between routine maintenance costs and plant repair costs after a plant trip. In addition, the replacement parts needed after a Type I Event may be relatively inexpensive. Also, the repairs required after this type of event are probably performed by the normal operating crew. Consequently, repair costs may not need to be considered in a Type I Event [4].

In the case of a Type II Event, the plant will either have to be repaired or decommissioned after the decontamination program is completed. If the plant is repaired, the repair costs will include the labor and materials required to restore the plant to operational status. Such costs are incurred after the completion of the decontamination program [4]. Figure 6 illustrates the cash flow profile of a hypothetical repair program.

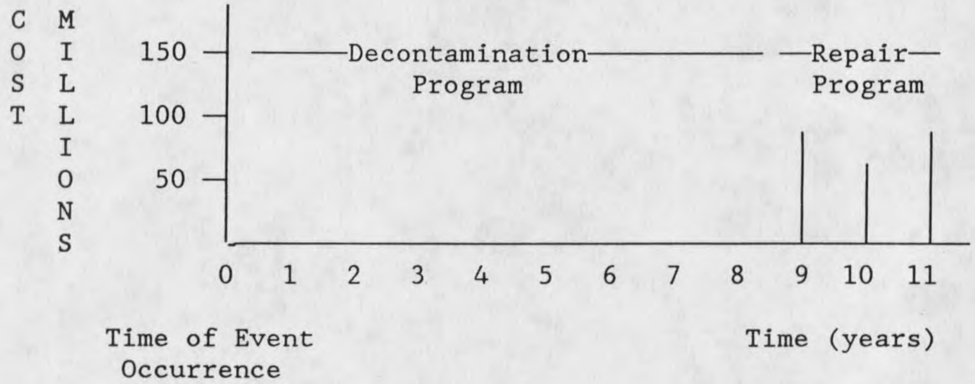


Figure 6. Cash flow profile of a hypothetical repair program.

The present worth of the repair costs, using then-current dollars, can be calculated as follows [10,33]:

$$R_c = \left[\sum_{n=l}^{m} C_n (1 + i_r + j + i_r \cdot j)^{-n} \right] \left[(1 + i_r + j + i_r \cdot j)^{-k} \right] \qquad (4)$$

where R_c = present worth of repair cost at the time of the event

C_n = undiscounted, uninflated repair cost year n

l = completion year of decontamination program

m = completion year of repair program

n = year from the completion year (l) of the decontamination program

k = number of years that the decontamination lasts

i_r = interest rate

j = inflation rate

The duration of the repair program will generally not be as long as the duration of the decontamination program. Estimates for the duration of repair programs are given below [4]:

lower bound = 1 year
best estimate = 2 years
upper bound = 3 years

Loss of Production Costs

Both Type I and Type II Events could result in loss of production costs. In the case of Type II Events, these costs are incurred until the decontamination and plant repair operations are completed [4]. An estimate of the downtime duration for a Type II event are obtained from the sum of the decontamination and repair duration. In the case of a Type I Event, the downtime duration is simply the time required to bring the plant back to operational status [4].

After the downtime duration and annual loss of production costs are estimated, the present worth of these costs are estimated as follows [10,33]:

$$P_c = \sum_{n=0}^{m} C_n(1 + i_r + j + i_r \cdot j)^{-n} \qquad (5)$$

where P_c = present worth using then-current dollars of the loss of production costs
C_n = uninflated, undiscounted loss of production costs in year n
n = year from the year of the event
m = completion year of repairs
i_r = interest or discount rate
j = inflation rate

Figure 7 portrays a cash flow profile of the loss of production costs for a hypothetical Type II Event.

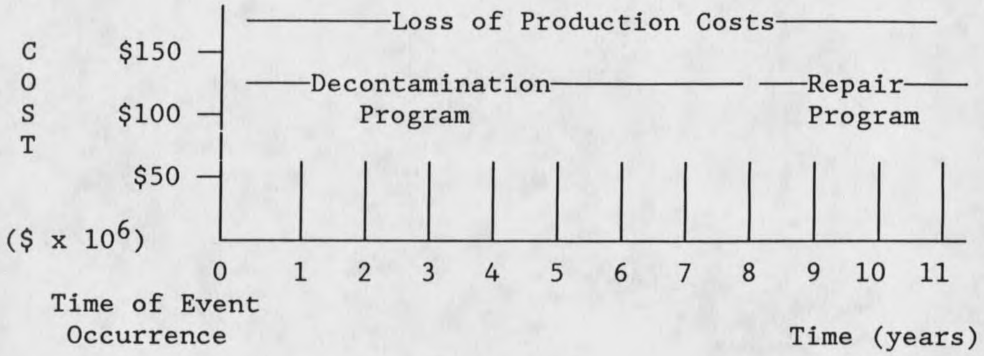


Figure 7. Cash flow profile for loss of production costs.

Figure 7 also illustrates the relation between a decontamination program, repair program, and loss of production costs.

Litigation Costs

After a severe Type II Event, the issues of liability and compensation are frequently settled through litigation. Litigation costs include the legal settlements and legal fees [4]. No estimate regarding the duration or magnitude of these costs are available. However, the present worth value using then-current dollars can be estimated by using the same technique used for estimating the present worth value of the loss of production costs [10,33].

Capital Investment Loss

Decommissioning the plant may be necessary after a severe Type II Event. Decommissioning will shorten the life of the plant. Consequently, the capital investment of the plant will not be fully recovered. Therefore, some part of the capital cost of the plant is lost [4].

The capital loss can be calculated by computing the depreciation schedule of the plant, determining the book value of the plant at the time of the shutdown, and then calculating the unrecovered balance. The unrecovered balance represents the capital loss. However, depreciation schedules are accelerated and plant lives are shortened in order to take more depreciation allowances in the early years. Consequently, the book value of the plant may be zero when the event occurs and, therefore, a capital loss will not be represented. Hence, this is not an accurate method for determining capital loss [4].

There is a more accurate method of calculating the capital loss. The replacement cost of the plant is estimated and annualized over the total expected life of the plant. In this study, the total expected life of an industrial plant is assumed to be 40 years. The capital loss is this annual cost over the remaining plant lifetime [4].

The annual replacement cost can be calculated as follows [4,10,33]:

$$A_r = P\left[\frac{i(1+i)^n}{1+i)^n - 1}\right] \tag{6}$$

where A_r = annual replacement cost n = 40 yrs
P = plant replacement cost i = interest rate

The capital loss is calculated as given below [4,10,33]:

$$C_l = A_r \left[\frac{(1 + i)^n - 1}{i(1 + i)^n} \right] \tag{7}$$

where A_r = annual replacement cost; n = no. of yrs remaining on plant life; C_l = capital loss; i = interest rate

Perceived Risk Costs

The most severe costs of a Type II Event are those of perceived risk. Perceived risk costs result when the plant operation is viewed as being out of control. Thus, perceived risk costs are the result of loss of confidence by both the public and regulatory agencies [4,5].

If plant operation is viewed as being out of control after an accident, the company can experience higher costs for borrowing capital. This altered perception of risk can also lead to a higher demanded return on capital. In addition, the loss of confidence can affect the policy decisions made by the regulatory agencies and may therefore lead to a rapid shutdown or phasing out of the facility. The company will then experience cash flow limitations due to the loss of income. This will result in insufficient coverage on existing financial commitments [4]. Consequently, the company's stability will be jeopardized.

If the facility is not shutdown or phased out due to the altered perception of risk after an accident, the future of the facility will still be uncertain. The decisions made by the regulatory agencies will affect the restart or rehabilitation alternatives. In addition, these decisions will affect the technical characteristics of the feasible options regarding the facility's future. The regulatory decisions will also regulate the plan proposed for the facility's future with respect to timing, safety and environmental characteristics [5].

It is uncertain whether a company will ever be able to regain the confidence of the regulatory agencies or the public after an accident. In fact, the altered perception of risk can spread as it did after the accident at Three Mile Island. The attitudes of people unaffected by Three Mile Island changed due to the media's continual coverage of the accident. The people unaffected by Three Mile Island began to resent the fact that Three Mile Island was ever built [5].

The loss of confidence can halt the growth in the industry. For example, after the accident at Three Mile Island, there were many plant cancellations and no new plant orders [5]. The perceived risk costs can literally devastate the industry and the company. Due to the potential magnitude of the perceived risk costs, these costs can engulf all other costs associated with an accident [4,34].

The perceived risk costs can result in plant shutdown or an uncertain future for the company depending upon the severity of the accident and the perception of risk associated with the plant. Consequently, there is a great deal of variation in the magnitude and duration of these costs. Therefore, the perceived risk cost will be viewed as a variable, present worth value.

FAULT TREE ANALYSIS

The methodology for a CSAPE utilizes fault tree analysis to determine the probability of a postulated accident. Fault tree analysis consists of a task analysis, fault tree construction, and fault tree evaluation. A task analysis of an accident provides the data necessary to construct a fault tree. Constructing a fault tree provides a cause and effect structure of an accident. Quantitative fault tree evaluation provides an estimate of accident probability [11,27,30]. The role of human reliability is emphasized to determine the effect the enhancements will have upon improving system reliability.

Task Analysis

The methodology for a Cost-Savings Analysis of Panel Enhancements (CSAPE) utilizes task analysis to identify potential human errors that would contribute to the occurrence of an accident [6,27]. An accident in a fault tree is referred to as an initial event or failure. Consequently, all the human operations or tasks involved in the failure are analyzed in order to estimate the potential for human error. Potential human errors are basic events in a fault tree of an initial event [20,21,27].

A task analysis consists of identifying and analyzing the tasks involved in the failure. Potential human errors are identified by evaluating each task in terms of the accuracy, quality, and time requirements of the task [24]. Evaluating other task characteristics will also aid in the identification of potential human errors [18,24].

A very fine level of detail is needed in the analysis because tasks must be broken into their behavioral elements to identify the potential human errors. This may require breaking tasks into subtasks. Thus, task analysis is an iterative procedure [18,27].

Fault Tree Structure

The logical tree-type structure or fault tree is constructed by identifying the initial event or accident and then working backwards in time [27]. The events directly contributing to the initial event are connected to it through the use of logical links. Then, the events contributing to higher order events are identified and connected to the tree. This process continues until the lowest level events are part of the tree [11].

Components of a fault tree are "primary events", "intermediate events", and "logic gates". Primary events consist of "basic events", "undeveloped events", "conditioning events", and "external events". Basic events are human tasks. Undeveloped events represent hardware failures. A conditioning event is a primary event used to record conditions or restrictions that may apply to a logic gate. An external event is an event that is expected to occur, such as a phase change in a dynamic system [30]. An intermediate event is the result of one or more antecedent causes acting through logic gates [30].

There are two basic types of logic gates used in a fault tree: AND-gates and OR-gates. The OR-gate is used when an event occurs only if one or more of the input or lower level events occur. The OR-gate, denoted by a shield with a curved base, represents the union of events connected to the gate (see Figure 8). The OR-gate is equivalent to the Boolean operation "+". Consequently, the output event of an OR-gate can be represented as the sum of the input events [30].

The AND-gate is used when the output event occurs only if all of the input or lower level events occur [11,30]. The AND-gate, represented by a shield with a flat base, represents the intersection of events connected to the gate. The AND-gate is equivalent to the Boolean operation "•", and the output event is the product of the input events [30].

The initial event probability is estimated by assigning error probabilities to the faults in the tree and performing a quantitative analysis [30].

Assigning Human Error Probabilities

To estimate the probability of the initial event occurring with respect to the operation of the existing layout, error probabilities are assigned to events in the tree and the fault tree is evaluated [30]. Human reliability data tables are used to assign error probabilities to the tasks or basic events in the fault tree [17].

Human reliability is a measure of the probability of successful task performance. Human error rate is the complement of human reliability; human error rate is one minus human reliability.

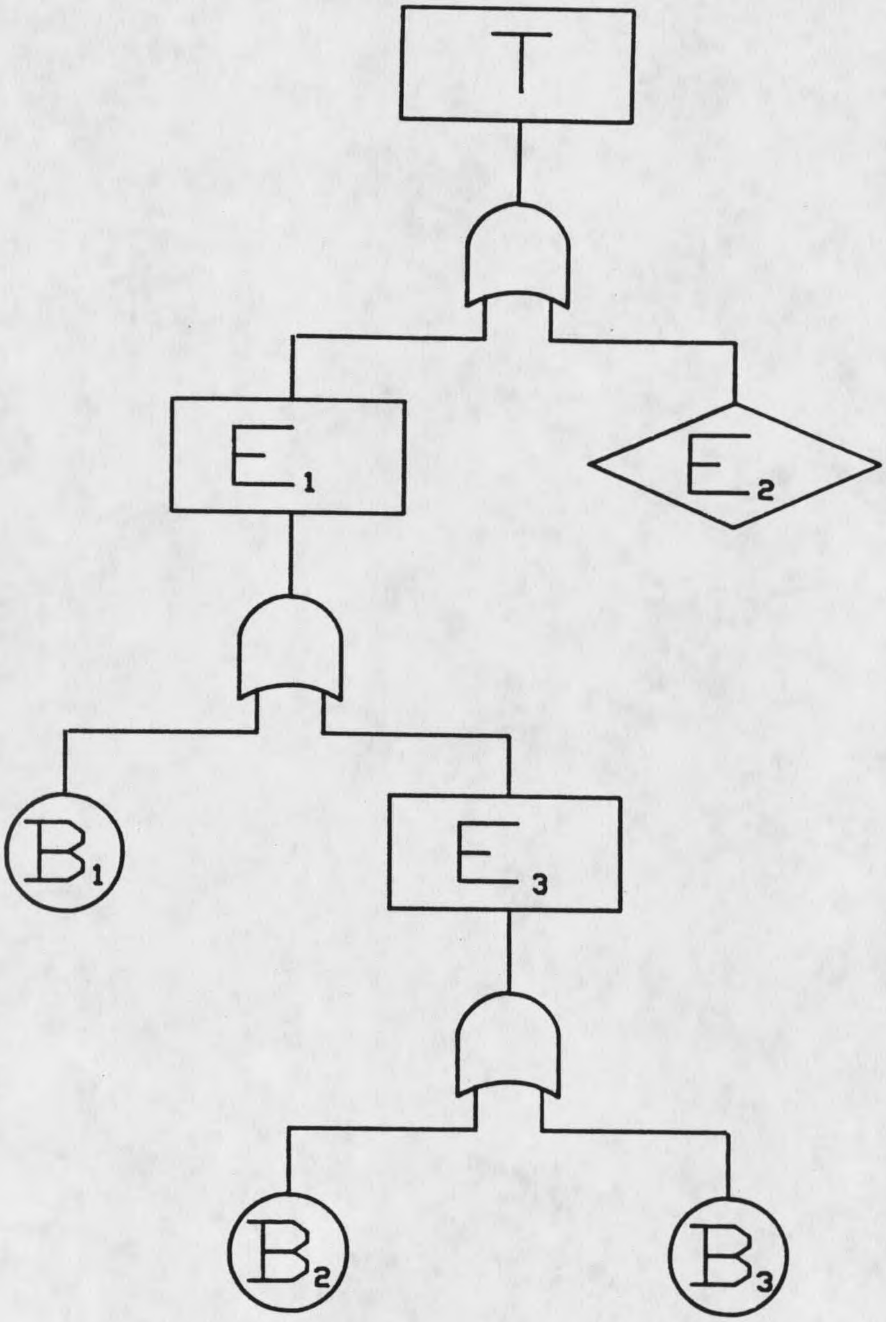


Figure 8. A fault tree. T denotes the initial event. E_1, E_2, and E_3 represent intermediate events. B_1, B_2, and B_3 represent basic events.

The Technique for Human Error Rate Prediction (THERP) is a method for predicting human error rates [20,27]. The outputs of the THERP model include estimated human error probabilities (HEPs) for selected tasks (see Appendix A) [14,27]. The HEPs selected will reflect the probability of human error with respect to the operation of the existing layout.

The HEPs

The HEP values in the THERP Tables are demand dependent. Demand refers to the demand per year of a process sequence associated with an initial event. The yearly demand for task performance or a process sequence is not reflected in the HEP values [27].

Performance Shaping Factors

The Technique for Human Error Rate Prediction (THERP) is based upon the theoretical concept that human error is modified by performance shaping factors (PSFs) [20,27]. One of the performance shaping factors is human factors engineering [6,27]. Control panel enhancements will improve the human engineering performance shaping factor [22,27]. If this performance shaping factor is improved, lower HEP values are used in the analysis [27].

Dependence

Dependencies between tasks must be incorporated into the analysis, otherwise the failure probability of the initial event will be underestimated. Two tasks are dependent if the probability of failure of one task is influenced by the success or failure of the other task.

These tasks do not necessarily need to be performed by the same person to be dependent [27].

Task dependency may range from zero to complete dependence. If two tasks have zero dependence, they are independent. Likewise, if two tasks have complete dependence, failure on one task will insure failure on the other task. There are several levels of dependence between zero and complete dependence. These dependence levels in ascending order are zero dependence, low dependence, moderate dependence, high dependence, and complete dependence. Guidelines for assigning dependence levels between tasks are given in Appendix A. Data tables that present equations and values to be applied to HEPs to allow for the effects of dependence can also be found in Appendix A [27].

Uncertainty Bounds

The uncertainty of the estimated HEP value is denoted by uncertainty bounds (UCBs). Uncertainty bounds do not represent statistical confidence limits because uncertainty bounds are based upon judgement and not statistics [27].

The proposed distribution for the HEPs is a log normal distribution i.e., the log of the HEPs represent a normal distribution [7,11,27]. The lower uncertainty bound represents the 5^{th} percentile, the upper bound represents the 95^{th} percentile, and the nominal HEP represents the median, with respect to a log normal distribution. The uncertainty bounds (UCBs) are represented by an error factor (EF) since they are symmetrical about the nominal HEP. The lower bound is determined by dividing the nominal HEP by the error factor. Likewise, the upper bound is determined by multiplying the nominal HEP by the error factor. Due to the amount of variation in the HEP estimates, the EF is large for a small HEP value while the EF for a large HEP value is small. Table 16 in Appendix A can be used in determining the error factor associated with an initial event [27].

Fault Tree Evaluation

The fault tree is evaluated once the error probabilities have been assigned to the events in the tree. This is accomplished by translating the fault tree structure to a set of equivalent Boolean algebraic expressions, and determining and evaluating the "minimal cut sets" of the tree [30].

A fault tree is a graphic representation of the Boolean relationships among the events [30]. To determine the set of equivalent Boolean algebraic equations of a fault tree, the higher order events are equated to their lower level events using the Boolean operation of "+" or "•" for the OR-gate and AND-gate, respectively [11,30].

The minimal cut sets of a fault tree are the smallest irreducible set of basic events required to insure the occurrence of the initial event [11,30]. The minimal cut sets are determined by first expanding one of the Boolean equations of the tree. This equation is expanded by substituting the remaining equations into it. Consequently, the fault tree is then described as one equation instead of a set of equations [30].

Once the fault tree has been converted to an equivalent Boolean equation, this equation is reduced by applying the laws of Boolean algebra. The reduced Boolean equation represents the minimal cut sets. The initial event probability is determined by evaluating the minimal cut sets [30].

CALCULATING RISK: THE EXISTING LAYOUT

The methodology for a Cost-savings Analysis of Panel Enhancements (CSAPE) requires calculating the risk associated with the operation of an existing layout.

The HEP values are assigned to the basic events in the fault tree to reflect the probability of human error with respect to the operation of the existing layout. The risk associated with a Type II event is calculated as follows [1,4]:

$$R_e = P(I)[\ E' + Dc + Rc + Pc + L_c + C_l + P_r] \tag{8}$$

where R_e = risk associated with the operation of the existing layout
$P(I)$ = probability of the initial event
E' = present worth of worker health effect costs
D_c = present worth of decontamination costs
P_c = present worth of loss of production costs
R_c = present worth of repair costs
L_c = present worth of litigation costs
C_l = capital loss
P_r = perceived risk costs

Since a Type I Event will only result in lost production costs, a Type I risk calculation will differ from that of a Type II risk calculation. The monetary risk associated with a Type I Event is calculated as follows [1,4]:

$$R_e = P(I)[\ P_c\ ] \tag{9}$$

where R_e = risk associated with the existing design
$P(I)$ = initial event probability
P_c = present worth of the loss of production costs

CALCULATING RISK: THE ENHANCED LAYOUT

Surface enhancements will reduce human error probabilities (HEPs) associated with the operation of an enhanced layout [22,27]. Surface enhancements will improve the human engineering performance shaping factor and consequently, lower HEP values are used in the analysis [27].

The recommended reducing factor for improved human engineering design ranges from a value of 2 to 10 [27]. A quantitative approach is needed to estimate the magnitude of the reducing factor. The approach used in this analysis consists of a linear additive utility model [8,9,13,15,26].

Determining the Reducing Factor

The magnitude of the reducing factor should be based upon the utility of the combination of surface enhancement techniques that will enhance the reliability of the layout operation. Consequently, the reducing factor is a direct measure of the perceived utility. Utility is used to identify the measure of the relative contribution to layout improvement. The method presented for judging the magnitude of the reducing factor is derived from the Simple Multi-Attribute Rating Technique (SMART). The method derived from SMART has been used extensively and is an effective, reproducible technique [9].

The linear additive model is a method of obtaining and aggregating subjective judgments [8,9,13,15,26]. To determine the reducing factor, the utility of each attribute or surface enhancement technique is evaluated to identify the relative contribution to potential error reduction. Consequently, surface enhancements are incorporated into the assessment procedure in a systematic manner [8].

The reducing factor is determined by first ranking the surface enhancements in order of improvement or in terms of the contribution towards adherence of the layout to the NUREG 0700 Guidelines [29]. A weight is assigned to each surface enhancement ranging from 1 to 100, where a weight of 100 denotes total adherence to the guidelines and 1 denotes a negligible contribution to the adherence of the guidelines. After weights have been assigned to each surface enhancement, the weights are normalized [8,9,13,15,26].

The basic events in the minimal cut sets, that are affected by the enhancements, are evaluated in terms of each of the surface enhancements. A rate is assigned to the basic events in terms of the effect each surface enhancement will have upon reducing the likelihood of the event. The rate can be interpreted as the perceived percent in error reduction. The assigned rates will range from 1.0 to 0, where 1 denotes that the surface enhancement will completely reduce the likelihood of the event and 0 signifies the likelihood of the event will not be reduced at all by the surface enhancement. If a surface enhancement is unrelated to an event, the symbol N/A can be used to denote this relationship.

The reducing factor is obtained by combining the improvement weights and the likelihood reduction rates. The reducing factor is calculated as follows [8,9,13,15,26]:

$$R = \sum_{i=1}^{m} \sum_{j=1}^{n} w_i \cdot x_{ij} \tag{10}$$

where R = reducing factor
w_i = improvement weight for the i^{th} surface enhancement
x_{ij} = the likelihood reduction rate for the i_{th} surface enhancement and j_{th} basic event
n = number of affected basic events
m = number of surface enhancements

Table 2 illustrates a format that may be used in determining the reducing factor for the human error probabilities [26].

Table 2. A format used to calculate the reducing factor.

Improvement Weight	Surface Enhancement	Basic $Event_1$	....	Basic $Event_n$
W_1	Description of m Surface Enhancements	X_{11}	....	X_{1n}
.		.	....	.
.		.	....	.
.		.	....	.
.		.	....	.
.		.	....	.
W_m		X_{m1}	....	X_{mn}

The reduced HEPs are calculated by dividing the affected HEP in the minimal cut sets by this reducing factor [27]. The reducing factor can be calculated from the above format as follows:

$$R = W_1 \cdot X_{11} + \ldots + W_1 \cdot X_{n1} + \ldots + W_m \cdot X_{m1} + \ldots + W_m \cdot X_{mn}$$

In order to calculate the risk associated with the enhanced design, the fault tree must be re-evaluated using the reduced human error probabilities. After the probability of the initial event associated with an enhanced layout is determined, the risk associated with the enhanced layout is determined in the same manner as the risk associated with an existing layout.

BENEFITS: RISK REDUCTION

Benefits of surface enhancements are in terms of risk reduction. The risk reduction potential of enhancements in a layout is determined by calculating the difference between the risk associated with an existing layout and the risk associated with the enhanced layout. More precisely, benefits are calculated as follows:

$$R_r = R_e - R_i \tag{11}$$

where R_r = risk reduction potential of the surface enhancements
R_e = risk associated with the existing layout
R_i = risk associated with the enhanced layout

Monetary risk may be viewed as the expected cost of the accident per demand [1]. The expected costs are costs per demand because the probability of the initial event is dependent upon the frequency of task performance (see The HEPs) [27]. The risk reduction potential of the surface enhancements, therefore, is the probabilistic reduction in the cost of the accident per demand. Consequently, the benefits of the surface enhancements are in monetary terms.

COST-SAVINGS ANALYSIS

A surface enhancement safety investment must be justified economically before a decision regarding its implementation can be made [2,3,10,33]. The safety investment should insure efficient allocation of the safety budget. In addition, benefits of the investment should outweigh its costs [10,33]. Consequently, an enhancement investment is analyzed in terms of efficient budget allocation and costs versus benefits.

Safety Budget Allocation

An annual safety budget can be viewed as being allocated efficiently if the yearly returns on an investment are greater than the investment expenditures. A surface enhancement investment represents efficient allocation of a safety budget if the probabilistic maximum yearly savings exceed the investment expenditures. The probabilistic maximum yearly savings of an enhancement investment is the difference between the probabilistic upper bound of yearly costs of an event and the probabilistic lower bound of the yearly costs of the event. The upper bound of yearly costs is with respect to the operation of the existing layout while the lower bound of yearly costs is with respect to the operation of the enhanced layout. The probabilistic yearly costs are determined by multiplying the expected costs per demand, or risk, by the demand per year. This can be described as follows:

$$M_s = UCB_e \cdot d \cdot E_c - LCB_i \cdot d \cdot E_c \qquad (12)$$

where M_s = maximum yearly savings of the enhancement investment
UCB_e = upper uncertainty bound of an initial event with respect to the existing layout
d = demand per year of the process sequence associated with the initial event
E_c = the economic consequences of the event
LCB_i = lower uncertainty bound of the initial event with respect the enhanced layout

Thus, the probabilistic maximum yearly savings is the difference between the upper bound per year associated with the operation of existing layout and the lower bound per year associated with the operation of the enhanced layout. The yearly demand of the process sequence associated with the event must be estimated in order to compute the probabilistic cost per year.

The surface enhancement investment represents efficient allocation of the safety budget as long as the following condition is satisfied:

$$M_s \geq I_e \qquad (13)$$

where M_s = maximum yearly savings
I_e = the total investment expenditures

The above condition requires that the probabilistic yearly savings of an enhancement investment must be greater than or equal to the total investment expenditures (see Estimating Enhancement Costs). The condition insures efficient allocation of a safety budget because the probabilistic yearly savings will continue to accrue throughout the remaining lifetime of the facility and these savings exceed the investment expenditures.

Cost-Benefit Analysis

The surface enhancement investment can be justified economically if the monetary benefits the company receives from the investment exceed its costs. The application of this criterion of acceptability is known as a cost-benefit analysis from an organization's viewpoint [10,33].

The benefits of a surface enhancement investment are the potential monetary risk reduction of an accident per demand. The costs of the investment consist of costs associated with the implementation of the enhancements. The costs and benefits are stated in equivalent terms since the present worth values of both the costs and benefits may occur simultaneously (see Estimating Enhancement Costs and Estimating Economic Consequences). Stating the costs and benefits of the enhancement investment in equivalent monetary terms is a prerequisite of performing a cost-benefit analysis [10,33].

The cost-benefit acceptance criterion implies that the ratio of benefits to costs must exceed one to economically justify the investment [10,33]. For the enhancement investment, this acceptance criterion is stated as follows:

$$\frac{I_e}{R_r} > 1 \qquad (14)$$

where $I_e = I_c + P_l + M_c$ and $R_r = R_e - R_i$

and I_e = present worth of the total investment costs
I_c = present worth of the initial investment costs
P_l = present worth of the loss of production costs of the investment
M_c = present worth of the incremental operating and maintenance costs of the investment
R_r = present worth of the incremental risk reduction potential of the enhancements
R_e = present worth of the risk associated with the existing layout
R_i = present worth of the risk associated with the enhanced layout

To apply the acceptance criterion, only the absolute magnitudes of the costs and benefits are considered in the analysis. Cost implies a negative monetary value or a negative cash flow [10,33]. Consequently, the absolute value of the cost measure is used in the analysis.

The cost-benefit analysis consists of comparing the enhancement investment against a "do nothing" option. If the benefit-cost ratio exceeds one, the investment is preferred to the "do nothing" option [10,33].

Several mutually-exclusive alternative enhancement investments can be evaluated and compared using the cost-benefit method. The alternatives are compared in a pairwise manner using a common planning horizon and the benefit-cost ratio acceptance criterion to determine the economically preferred alternative. To perform this analysis, the alternative investments must be ordered from lowest to highest costs. During this pairwise comparison, only the incremental costs and incremental benefits, or the differences between the alternatives' costs and benefits, are considered in the analysis. The highest cost investment is preferred to the lower cost investment as long as the benefit-cost ratio is greater than one. The preferred alternative is then compared to the next higher ordered alternative and this process continues until all of the alternatives have been exhausted. The surviving alternative of this exhaustive pairwise comparison is the preferred alternative [10,33].

After the preferred alternative has been determined, it should be implemented. The implementation of a surface enhancement alternative will require scheduling labor and equipment time. Lost production costs can be avoided by scheduling the implementation during regularly scheduled maintenance. Since the lost production costs of an enhancement investment outweigh the material costs, this would make the investment much more attractive economically [22].

EXAMPLE: ENHANCEMENT RISK REDUCTION IMPACT ON INADVERTENT TRANSFERS

This example examines the risk reduction potential of panel enhancements on inadvertent transfers at a chemical processing plant. An inadvertent transfer consists of the transfer of toxic materials from a vessel to an unintended area such as a sump, floor, or vessel [17]. The risk reduction potential of panel enhancements on inadvertent transfers is illustrated through a Cost-Savings Analysis of Panel Enhancements (CSAPE).

Surface enhancements are proposed for a control panel within an extraction facility of a chemical processing plant. Estimates for the costs of these enhancements are provided in order to conduct a cost-savings analysis of the investment.

The benefit-cost ratio acceptance criterion is used in the cost-benefit analysis of the panel enhancements. In addition, the enhancement investment is analyzed in terms of efficient safety budget allocation.

Surface Enhancements

The Panel

The control panel under investigation is organized functionally by cells. However, groups of instruments are not visually distinguishable except by color coded labels. Also, functionally related controls and displays within the cell groups are not easily identified (see Figure 9). Some functionally related controls and displays are separated by large distances. In addition, some controls are operated in a manner contrary to the expectations of the operators. For example, some control levers are pushed to open valves and pulled to close valves while similar controls are operated in the opposite manner [12].

Implications

The undelineated functional groups of instruments will increase operator response and search times as well as increase the potential for unintentional selection and activation errors. The controls that are operated in a manner contrary to operators expectations will increase the potential for incorrect control manipulation [22, 27].

Enhancement Objectives

Functional groups of instruments will be clearly identified and separated. A hierarchical labeling scheme will be employed to complement the identification of the functional groups on the panel. The uniqueness of the controls that are operated in a manner contrary to operators' expectations will be enhanced [22].

Enhancement Description

One-inch demarcation lines are used to differentiate functional cell groups. The color of the demarcation lines contrasts with the panel backboard color. Where sufficient spacing between components is unavailable for these lines, top brackets of a similar width are used

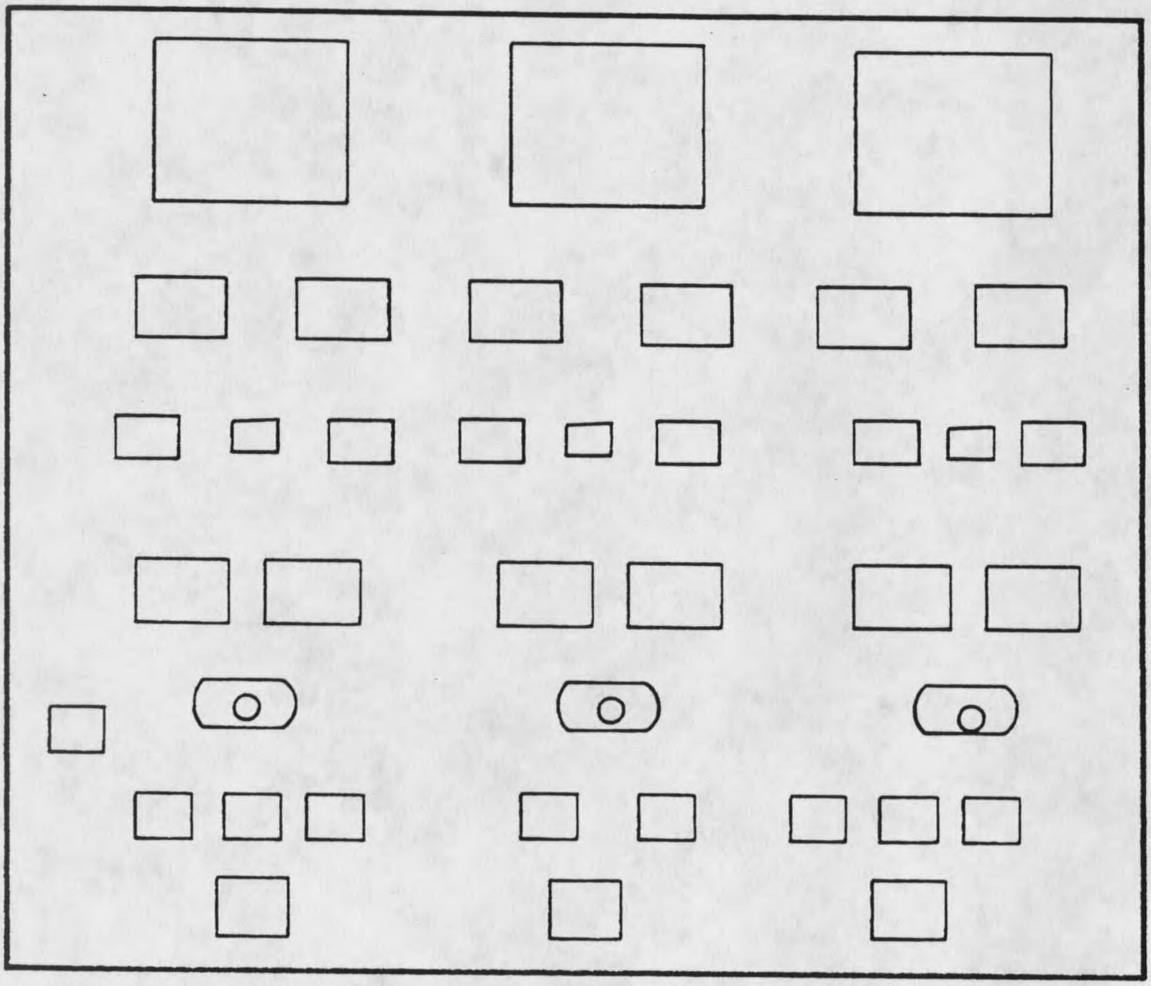


Figure 9. The existing panel layout in the extraction facility.

to designate these functional groups. Narrower one-half inch demarcation lines of a similar color are used in delineating subgroups of instruments within the cell groups. Top brackets of a similar width and color are employed to designate subgroups where sufficient space is unavailable for these demarcation lines (see Figure 10) [22]. A top down hierarchical labeling scheme is used to facilitate the identification and location of specific components on the panel. The major cell groups, subgroups, and components are all labeled. The labels are located above the respective groups and components to complete the top-down phenomenon. The labels adhere to the NUREG-0700 Guidelines [22,29].

Association between physically separated instruments is conveyed through the use of color shading. The component and the panel backboard surrounding the associated group or subgroups is shaded using a neutral color such as light green [22].

Shape coding is used to convey the uniqueness of the controls that are operated in a manner contrary to the operators' expectations. Square knobs designate the unique controls while the existing round knobs designate the conventionally operated controls [22].

The above enhancements must be verified through the use of a panel mock-up or model before implementation [22].

Enhancement Costs

Initial Costs

The direct material and labor costs for the enhancements and the mock-up are estimated to be $40,000. The administrative or overhead

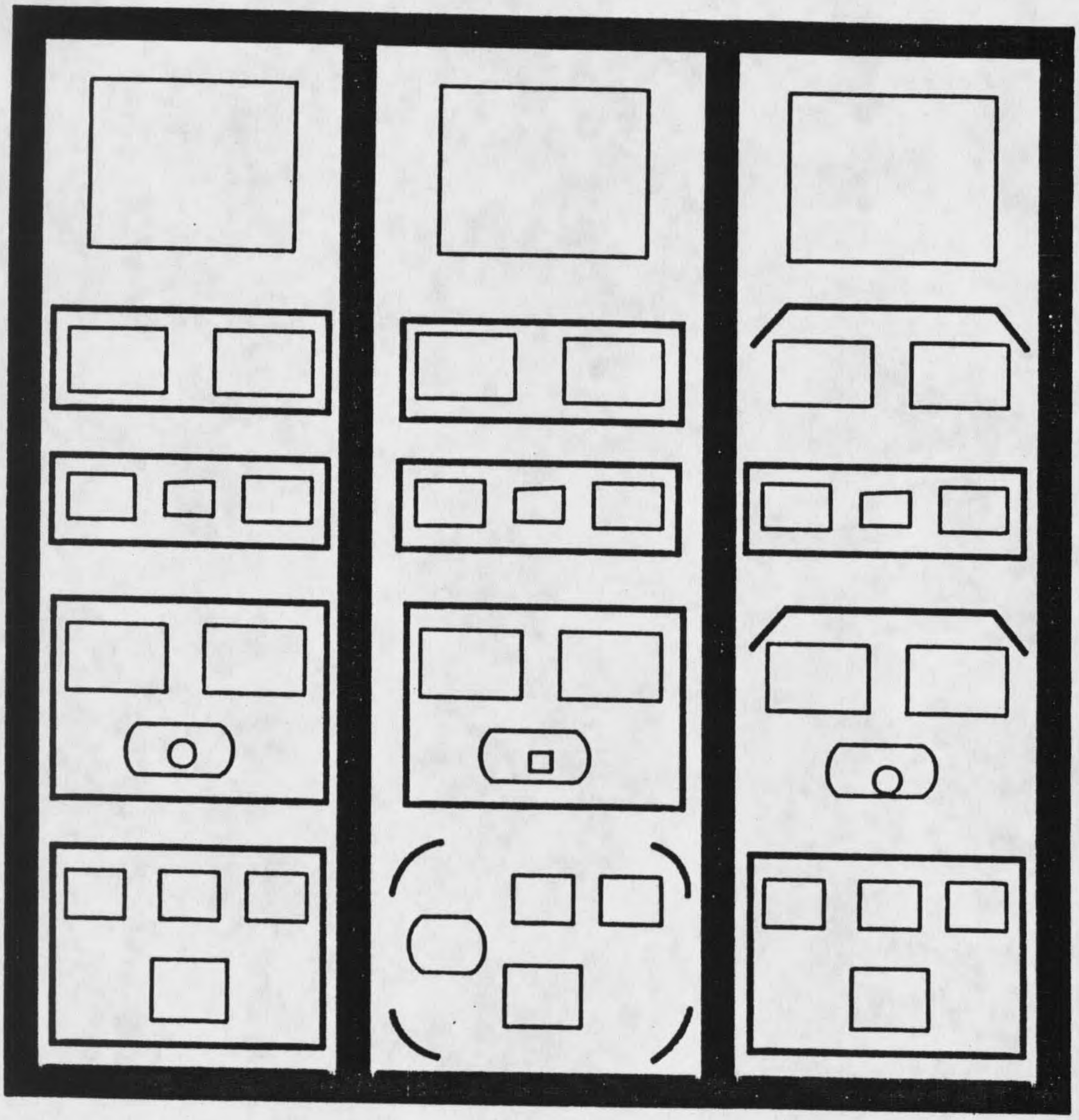


Figure 10. The enhanced panel layout in the extraction facility.

costs are estimated at $10,000 in this example. Thus, the present worth of the initial costs is estimated at $50,000.

Lost Production Costs

The implementation of the surface enhancements is scheduled simultaneously with routine maintenance or a planned shutdown. Consequently, costs associated with plant downtime are not considered in the investment expenditures of this example.

Incremental Operating and Maintenance Costs

Incremental costs of operating and maintenance associated with the enhancements are estimated at $10,000 annually. This estimate includes the costs of revising written operating procedures due to the changes and the costs to refurbish the enhancements [2,22]. Since the extraction facility has been in operation for 35 years, its remaining lifetime is 5 years, consequently, these costs will be incurred annually for the next 5 years. The present worth of the incremental operating and maintenance costs at the time of enhancement implementation is computed using Equation 1. The present worth value of the costs using an interest rate of 4% and a 3% inflation rate is $40,800.

Total Cost Estimate

The total cost estimate for the panel enhancements is the sum of the present worth values of the initial costs, lost production costs, and incremental maintenance and operating costs. In this example, the total cost estimate for the surface enhancements is $90,800. This is only a hypothetical estimate.

Economic Consequences

In this example, an inadvertent transfer is classified as a Type II Event. Consequently, only on-site costs are considered in the analysis. It is assumed that such an event would result in the death of one person and the injury of two others. Although the inadvertent transfer results in significant facility contamination, the facility is repaired rather than decommissioned after the event [34]. Consequently, capital investment loss is not a cost component in this example.

Worker Health Effect Costs

The worker health effect costs are determined using estimates for radiation induced health effects as given in previous section, Estimating Economic Consequences [4]. The present worth value of these costs are calculated using Equation 2 [4,10,33]. The present worth value of the fatality costs using a 4% interest rate and a 3% inflation rate is approximately $1,316,700. The present worth value of the health effect costs for the two injured workers using the same interest and inflation rate is approximately $263,300. The total health effect costs are $1,580,000.

Plant Decontamination Costs

After the event, the plant is decontaminated before it is repaired. The duration of the decontamination program is based upon the lower bound estimate of the clean-up program duration estimates as given in the previous section, Estimating Economic Consequences.

Consequently, the decontamination program duration is estimated at 4 years [4]. The annual cost of the decontamination program is estimated at $25,000 annually [34]. The present worth value, $84,450, is calculated using Equation 3, an interest rate of 4%, and a 3% inflation rate [4].

Plant Repair Costs

The plant repair program is estimated to last one year and cost $4.2 million. The program duration estimate is based upon the lower bound estimate for repair programs as given in the previous section, Estimating Economic Consequences. The present worth value is calculated using Equation 4 [4,10,33]. This estimate is approximately $3 million [34].

Loss of Production Costs

The duration of the plant downtime due to the inadvertent transfer is the sum of the decontamination program duration and the repair duration. Consequently, it is assumed that the loss of production costs will last for 5 years. The annual loss of production costs are estimated at $100,000 per year [34]. The present worth of these costs at the time of the accident occurrence is calculated using Equation 5, a 4% interest rate, and a 3% inflation rate [4,10,33]. The resulting present worth value is $408,700.

Litigation Costs

In this example, it is assumed that the inadvertent transfer will result in litigation costs. The estimates of these costs are based upon the worker health effect costs since the issues of liability and compensation may arise due to the worker health effects. The litigation cost estimates, therefore, reflect the total worker health effect costs of $1,580,000.

Perceived Risk Costs

Although repair of the extraction facility is planned after the event, the future of the plant may still be uncertain due to the political ramifications of the event. The plant may be slowly phased out because the plant process is perceived as being out of control [4.5]. Therefore, the company may lose its mission. In this example, this perceived risk cost is estimated at $25 billion [34].

Total Cost Estimate

The total cost estimate of the economic consequences for an inadvertent transfer is the sum of the present worth values of the worker health effect cost, decontamination costs, repair costs, litigation costs, and perceived risk costs [4,10,33]. The total cost estimate is approximately $25.006 billion. The economic consequences of the event can be multiplied by its probability to determine the associated risk.

Risk Calculations

The Existing Layout

The demand probability of the inadvertent transfer is estimated by performing a task analysis of the transfer operation, constructing a fault tree for the event, and evaluating the fault tree. The task analysis provides the data necessary to construct the fault tree [27]. The fault tree, which is composed of the most credible faults that insure the occurrence of the event, is evaluated by determining the minimal cut sets of the tree [17,30].

A task analysis of the transfer operations in the extraction facility is performed in order to determine the most credible faults that would insure the occurrence of the event. A list of the tasks performed during a typical transfer operation is given in Appendix B [17].

A fault tree for the inadvertent transfer is constructed from the faults associated with the event. See Figure 11 [17]. The role of human reliability in the reliability of the system is emphasized by the undeveloped hardware failures. Human error probabilities (HEPs) are assigned to the human tasks to reflect the probability of the event associated with the operation of the existing panel layout. The human error probability estimates are based on the nominal HEP values given in the THERP Tables (see Appendix A) [27]. The failure estimates and assumptions used in the fault tree analysis are given in Table 3 [17].

The probability of the inadvertent transfer is estimated by evaluating the minimal cut sets of the tree with respect to the error probabilities [17,30]. A description and list of the minimal cut sets are given in Appendix B. The resulting demand probability of the event with respect to the existing layout is .00101 [17]. Using Equation 6, the resulting risk estimate is approximately $25,256,700 per demand.

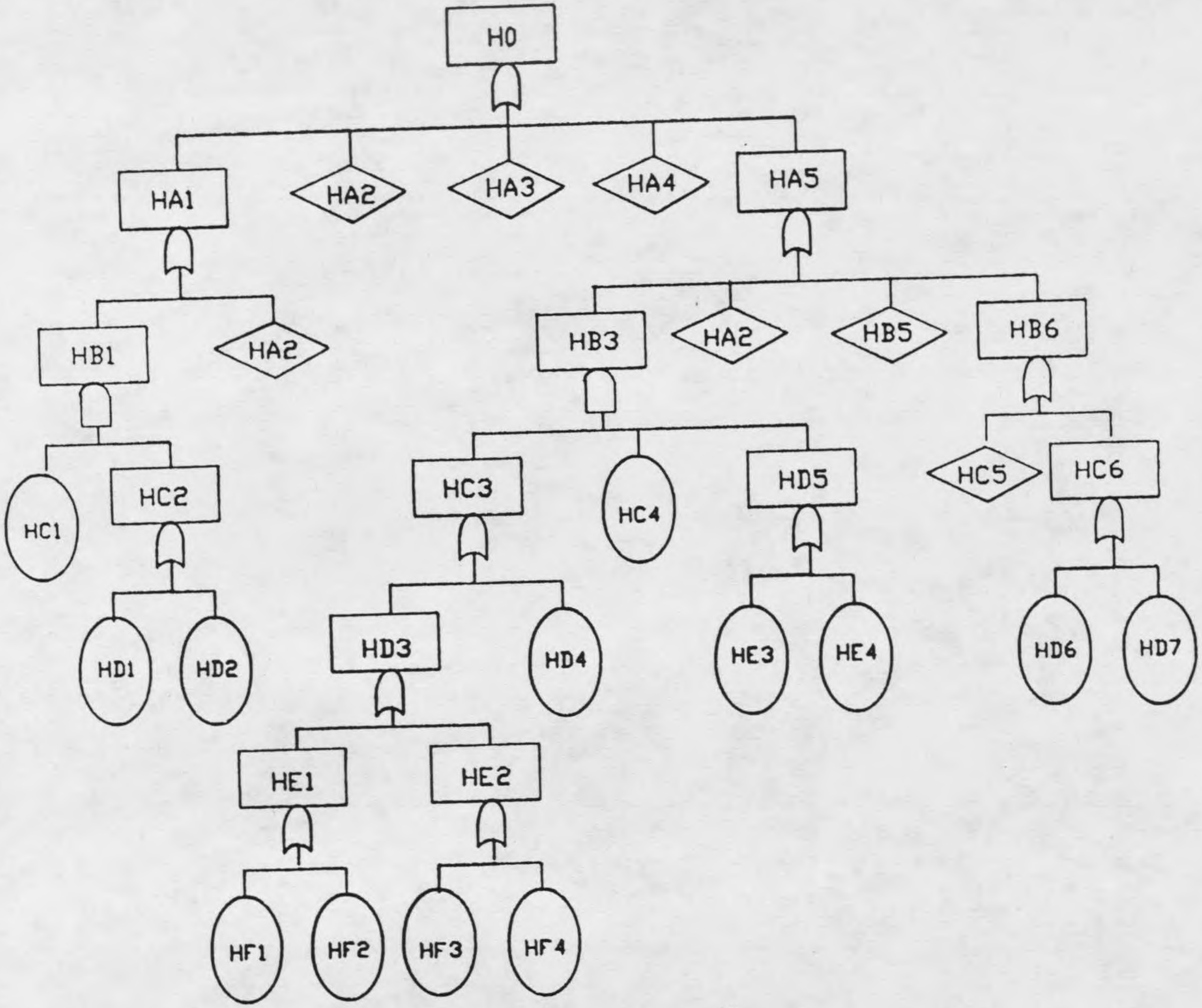


Figure 11. Inadvertent transfer fault tree.

Table 3. Failure estimates and assumptions for an inadvertent transfer.

Event Name	Event Description	Table Or Source	Result	Assumptions
HA2	Valves mislabeled	Arbitrary	.00003	System Error
HA3	Unknown routes exist	Arbitrary	.00005	System Error
HA4	Abnormal occurrence	Arbitrary	.00005	System Error
HB5	Previous line-ups incorrect	Arbitrary	.00005	System Error
HC1	Supervisor fails to detect error	16	.1	Initial Operator
HC4	Operator/supervisor fails to detect error	16	.1	Initial Operator
HC5	Errors in drawings	Arbitrary	.00005	System Error
HD1	Wrong sending vessel chosen	8	.001	Operator Error
HD2	Wrong vessel input into computer	9	.004	Operator Error
HD4	Wrong vessel input into computer	9	.004	Operator Error
HD6	Procedures wrong	6	.0001	Human Error
HD7	Procedures wrong	6	.0001	Human Error
HE3	Displays misread	11	.006	Human Error
HE4	Wrong displays are read	10	.003	Operator Error
HF1	Checklist used incorrectly	7 8	.0005	Operator Error
HF2	Operator omits a step	7 8	.0005	Operator Error
HF3	Valves operated incorrectly	13	.001	Operator Error
HF4	Wrong valve manipulated	12	.08	Operator Error

The Enhanced Layout

Enhancing the layout will result in lower human error probabilities [22,27]. To calculate the probability of the inadvertent transfer with respect to the enhanced layout, a reducing factor for the HEPs is determined, the affected human error probabilities of the minimal cut sets are reduced, and the fault tree is re-evaluated.

A linear additive utility model is used in quantifying the subjective judgments regarding the reducing factor for the human error probabilities. Normalized improvement weights are assigned to each surface enhancement. Likelihood reduction rates are assigned to the basic events in the minimal cut sets that are affected by the enhancements as shown in Table 4. Using Equation 10, the resulting reducing factor is approximately 2. The HEPs of the basic events HD1, HE4, HF3, and HF4 are divided by the reducing factor. The resulting values and probability of the initial event as compared to those of the

Table 4. Format used in calculating the reducing factor.

Improvement Weight	Surface Enhancement Description	HD1	HE4	HF3	HF4
.24	Large Demarcation Lines	.8	.8	N/A	.8
.22	Small Demarcation Lines	.7	.7	N/A	.7
.20	Color Shading	.6	.6	N/A	.6
.19	Shape Coding	N/A	N/A	.9	N/A
.15	Hierarchical Labeling	.8	.8	N/A	.8

existing layout are given in Table 5. The demand probability of an inadvertent transfer associated with the operation of the enhanced layout is .000946. Using Equation 8, the risk of an inadvertent transfer with respect to the enhanced layout is approximately $23,656,300 per demand. This result is obtained from multiplying the economic consequences of the event by its demand probability [1].

Budget Allocation

The surface enhancement investment is analyzed to determine if it represents efficient allocation of the safety budget. To represent efficient use of the safety funds, the probabilistic maximum annual savings from this investment must exceed the costs of the investment as stated in Equation 13. The probabilistic maximum annual savings of the enhancement investment is the difference between the probabilistic upper bound of yearly costs of an inadvertent transfer and the probabilistic lower bound of yearly costs of an inadvertent transfer. The upper bound is with respect to the operation of the existing layout while the lower bound is with respect to the enhanced layout.

The probabilistic yearly costs are determined by referring Equation 12. The yearly demand of transfer operations for the extraction facility is estimated at 10^4 transfer operations per year [34]. Using this demand, Equation 12, and Table 15 in Appendix A to determine the upper and lower uncertainty bounds, the upper bound of yearly costs is approximately $7.6 million per year and the lower bound of yearly costs is $2.4 million per year. The probabilistic maximum yearly savings, $5.2 million per year, exceed the investment

Table 5. Probabilities of an inadvertent transfer.

Event Name	Existing Layout	Enhanced Layout
HA2	.00003	.00003
HA3	.00005	.04
	.00005	.00005
HB5	.00005	.00005
HC1	.1	.1
HC4	.1	.1
HC5	.00005	.00005
HD1	.001	.0005
HD2	.004	.004
HD4	.004	.004
HD6	.0001	.0001
HD7	.0001	.0001
HE3	.006	.003
HE4	.003	.003
HF1	.0005	.0005
HF2	.00015	.00015
HF3	.001	.0005
HF4	.08	.04
Probability of Inadvertent Transfer	.00101	.000946

costs of $90,800. Therefore, the enhancement investment represents efficient use of the safety funds since the condition of Equation 13 is satisfied.

Cost-Benefit Analysis

A cost-benefit analysis of the safety investment involves determining the benefit-cost ratio of the investment. If the benefit-cost ratio is greater than one, the benefits exceed the costs and this implies that the surface enhancements should be implemented [10,33].

The benefits of the surface enhancements are stated in terms of risk reduction per demand. The risk reduction potential of the panel enhancements is determined by subtracting the risk associated with respect to the enhanced layout from the risk with respect to the existing layout as stated in Equation 11. The resulting benefits of the panel enhancement are $1,600,400, and the benefit-cost ratio, 1,600,400 : 90,800 is 17.6. Since this ratio is greater than one, the enhancement investment is the preferred alternative.

Recommendations

This example illustrates the monetary rewards of surface enhancements to a control panel within an extraction facility. Before realistic enhancements can be proposed, the panel must be thoroughly evaluated. These proposed improvements must be verified through the use of models or mock-ups [22]. These procedures will insure that the monetary rewards of surface enhancements are fully realized.

Summary

The example of risk reduction potential of surface enhancements on inadvertent transfers illustrates the monetary benefits that can be realized from panel enhancements.

Enhancement costs are estimated to conduct a cost-savings analysis of the proposed enhancements. The enhancement costs for the control panel within the extraction facility include the following:

Initial Costs	$50,000
Incremental Operating and Maintenance Costs	40,800

The total cost of the proposed enhancements is $90,800. The total cost estimate of the economic consequences of an inadvertent transfer is $25.006 billion. This result is obtained from the following cost components of an inadvertent transfer:

Worker Health Effect Costs	$1,580,000
Plant Decontamination Costs	84,450
Plant Repair Costs	3,000,000
Loss of Production Costs	408,700
Litigation Costs	1,580,000
Perceived Risk Costs	25,000,000,000

The risk associated with the existing panel layout and the enhanced layout are as follows:

Existing Layout	$25,256,700 per demand
Enhanced Layout	23,656,300 per demand

The risk reduction potential of the panel enhancements is $1,600,400 per demand. The resulting benefit-cost ratio is 17.6. This ratio indicates that the enhancements represent an economically preferred investment alternative.

The upper and lower bound of yearly costs of an inadvertent transfer are given below:

Upper bound of yearly costs	$7.6 million
Lower bound of yearly costs	2.4 million

Since the maximum yearly savings of $5.2 million exceed the investment costs, the enhancement investment represents efficient use of the safety budget funds. This result, coupled with the benefit-cost ratio result, support the recommendation for implementing the panel enhancements.

CONCLUSIONS

The Cost-Savings Analysis of Panel Enhancements (CSAPE) is an integration of established methods that permits an economic analysis of panel enhancements. Panel enhancements reduce human error and improve system reliability. The CSAPE is used to quantify these benefits in monetary terms and economically justify an enhancement investment. Performing a CSAPE involves proposing panel enhancements, estimating enhancement costs, quantifying enhancement benefits in monetary terms, and conducting a cost-savings analysis.

The distinction between properly designed panels and poorly designed panels is used to identify panels that must be enhanced. Features of properly designed panels are presented as well as the surface enhancement process and techniques used to improve existing panel designs. The CSAPE provides established methods for the cost analysis of the enhancement investment.

The CSAPE methodology quantifies enhancement benefits in monetary terms. Monetary benefits of enhancements are expressed in terms of risk reduction. Risk reduction potential is determined by postulating an accident scenario associated with the operation of a layout and performing a sensitivity analysis of the existing design versus an enhanced design. The sensitivity analysis utilizes a new application of a linear additive utility model to quantify the benefits in monetary terms.

The costs and monetary benefits of proposed enhancements provide the basis for a cost-savings analysis. A cost-savings analysis consists of a cost-benefit analysis and a budget allocation analysis. A new approach to determine efficient funding allocation is presented and illustrated.

The CSAPE is demonstrated through an example. The example provides an illustration of possible enhancements to a panel within an extraction facility of a chemical processing plant. The proposed enhancement investment is economically justified. The validity of the CSAPE methodology is endorsed through the results of this example, although no validation is required since CSAPE is based on established methods, models and techniques.

The Cost-Savings Analysis of Panel Enhancements (CSAPE) is flexible in the sense that any type of initial event can be postulated in the analysis. The CSAPE is also flexible in terms of application. CSAPE can be used in industries other than the chemical processing industry with only slight modifications. The modifications required for application to other industries involve only the restatement of economic consequences of an initial event.

CSAPE illustrates that panel enhancements can be economically justified in terms of cost versus benefits and efficient budget allocation. CSAPE could also be used to justify the economics of incorporating human factor design principles in new designs. The cost-savings analysis for new designs would differ from CSAPE. For example, rather than proposing surface enhancements to existing designs, human factor design recommendations would be proposed for new designs. Task analysis would replace the surface enhancement process since human factor design recommendations are derived from task analysis. However, quantifying the benefits of the human factor design recommendations in monetary terms would be similar to quantifying the benefits of panel enhancements in monetary terms. The cost-savings analysis of human factor recommendations would be performed in the same manner as the cost-savings analysis of the surface enhancements.

The CSAPE could be improved and further developed. A major and continuing need for improvement lies with the human error probability estimates. The human error estimates used in the CSAPE are based on the THERP data tables. These human error estimates are based on judgement rather than statistics [27]. Any improvement in the human error estimates would improve the risk estimates used in a CSAPE. The CSAPE could be developed further to include Type III Events. Currently, only Type I and Type II Events are considered in a CSAPE.

Although CSAPE could be improved and developed further, it provides an initial methodology for quantifying the monetary benefits of human factors safety investments. The CSAPE also provides procedures for a cost-benefit and safety budget allocation analysis of human factors safety investments. Methodologies have been developed for a cost-effectiveness analysis of hardware safety investments [2,3]. However, CSAPE complements and extends the previously developed methodologies rather than parallels them. Used together, the economics of both hardware and human factors safety investments can be evaluated.

GLOSSARY

GLOSSARY

Backfit	Changes to an existing design.
Backfitting	The re-design of existing designs.
Basic Event	A primary event in a fault tree that consists of human tasks.
Conditioning Event	Conditions or restrictions that apply to a fault tree logic gate.
Cost-Benefit	An economic analysis of an investment that involves evaluating the benefit-cost ratio of the investment.
Cost-Savings	An economic analysis that incorporates a cost-benefit analysis and efficient budget allocation analysis.
Demand	The demand per year of the process sequence associated with the initial event.
Efficient Budget Allocation	The allocation of funds in which the maximum yearly savings of an investment exceed the investment costs.
External Event	A fault tree event that is expected to occur.
Failure	An accident or unusual occurrence.
Inadvertent Transfer	A transfer of materials from a vessel to an unintended area.
Initial Event	See failure.
Intermediate Event	One or more antecedent causes of an event acting through a logic gate.
Life Shortening Method	A method of estimating the value of human life that measures the number of lost years.
Logic Gates	Logical connectors of AND and OR used between fault tree events.

GLOSSARY-Continued

Minimal Cut Sets	The smallest irreducible set of basic events required to insure the occurrence of an initial event.
Perceived Risk Cost	Costs of an accident due to the loss of the public's and regulatory agencies' confidence.
Primary Events	Events in a fault tree that are not developed further.
Probabilistic Lower Bound of Yearly Costs	The lower bound of expected yearly costs of an initial event.
Probabilistic Maximum Yearly Savings	The upper bound of probabilistic yearly costs of an accident minus the lower bound of probabilistic yearly costs of an accident.
Probabilistic Upper Bound of Yearly Costs	The upper bound of expected yearly costs of an initial event.
Reducing Factor	A number used to reduce human error probabilities.
Retrofit	See backfit.
Retrofitting	See backfitting.
Risk	The expected cost of an accident.
Surface Enhancements	Cosmetic changes to an existing design which consist of paint, tape and labels.
System Function Principle	A human engineering design principle of grouping functionally related instruments together on a control panel.
Task Sequence	A human engineering design principle that involves locating instruments on a panel to minimize operator movement.

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REFERENCES CITED

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APPENDICES

APPENDIX A

HUMAN ERROR DATA

Table 6. Estimated HEP per item (for perceptual unit) in preparation of written material.

Item	Potential Errors	HEP	EF
(1)	Omitting a step or important instruction from a formal or ad hoc procedure* or a tag from a set of tags	.003	5
(2)	Omitting a step or important instruction from written notes taken in response to oral instructions+	Negligible	
(3)	Writing an item incorrectly in a formal or ad hoc procedure or on a tag	.003	5
(4)	Writing an item incorrectly in written notes made in response to oral instructions+	Negligible	

* Formal written procedures are those intended for long-time use; ad hoc written procedures are one-of-a-kind, informally prepared procedures for some special purpose.

+ A maximum of five items is assumed. If more than five items are to be written down, use .001 (EF = 5) for each item in the list.

Table 7. Estimated HEPs related to failure of administrative control.

Item	Task	HEP	EF
(1)	Carry out a plant policy or scheduled tasks such as periodic tests or maintenance performed weekly, monthly, or at longer intervals	.01	5
(2)	Initiate scheduled shiftly checking or inspection function	.001	3
	Use written operations procedures under		
(3)	Normal operating conditions	.01	3
(5)	Use a valve change or restoration list	.01	3
(6)	Use written test or calibration procedures	.05	5
(7)	Use written maintenance procedures	.3	5
(8)	Use a checklist properly*	.5	5

* Read a single item, perform the task, check off the item on the list. For any item in which a display reading or other entry must be written, assume correct use of the checklist for that item.

Table 8. Estimated probabilities of errors of omission per item of instruction when use of written procedures is specified.*

Item**	Omission of Item	HEP	EF
	When procedures with checkoff provisions are correctly used:+		
(1)	Short list, <10 items	.001	3
(2)	Long list, >10 items	.003	3
	When procedures without checkoff provisions are used, or when checkoff provisions are incorrectly used:++		
(3)	Short list, <10 items	.003	3
(4)	Long list, >10 items	.01	3
(5)	When written procedures are available and should be used but are not used++	.05#	5

* The estimates for each item (or perceptual unit) presume zero dependence among the items (or units) and must be modified by using the dependence model when a nonzero level of dependence is assumed.

** The term "item" for this column is the usual designator for tabled entries and does <u>not</u> refer to an item of instruction in a procedure.

\+ Correct use of checkoff provisions is assumed for items in which written entries such as numerical values are required of the user.

++ Table 9 lists the estimated probabilities of incorrect use of checkoff provisions and of nonuse of available written procedures.

\# If the task is judged to be "second nature," use the lower uncertainty bound for .05, i.e., use .01 (EF = 5).

Table 9. Estimated probabilities of errors in recalling oral instruction items not written down.*

HEPs as a function of number of items to be remembered**

Item+	Number of oral instruction items or perceptual units	Pr[F] to recall item "N," order of recall not important (a) HEP	EF	Pr[F] to recall all items, order of recall not important (b) HEP	EF	Pr[F] to recall all items, order of recall not important (c) HEP	EF
	Oral instructions are detailed:						
(1)	1++	.001	3	.001	3	.001	3
(2)	2	.003	3	.004	3	.006	3
(3)	3	.01	3	.02	5	.03	5
(4)	4	.03	5	.04	5	.1	5
(5)	5	.1	5	.2	5	.4	5
	Oral instructions are general:						
(6)	1++	.001	3	.001	3	.001	3
(7)	2	.006	3	.007	3	.01	3
(8)	3	.02	5	.03	5	.06	5
(9)	4	.06	5	.09	5	.2	5
(10)	5	.2	5	.3	5	.7	5

* It is assumed that if more than five oral instruction items or perceptual units are to be remembered, the recipient will write them down. If oral instructions are written down, use Table 9 for errors in preparation of written procedures and Table 8 for errors in their use.

** The first column of HEPs (a) is for individual oral instruction items, e.g., the second entry, .003 (item 2a), is the Pr[F] to recall the second of two items, given that one item was recalled, and order is not important. The HEPs in the other columns for two or more oral instruction items are joint HEPs, e.g., the .004 in the second column of HEPs is the Pr[F] to recall both of two items to be remembered, when order is not important. The .006 in the third column of HEPs is the Pr[F] to recall both of two items to be remembered in the order of performance specified. For all columns, the EFs are taken from Table 15.

+ The term "item" for this column is the usual designator for tabled entries and does not refer to an oral instruction item.

++ The Pr[F] in rows 1 and 6 are the same as the Pr[F] to initiate the task.

Table 10. Estimated probabilities of errors in selecting unannunciated displays (or annunciating displays no longer annunciating) for quantitative or qualitative readings.

Item	Selection of Wrong Display	HEP*	EF
(1)	When it is dissimilar to adjacent displays**	Negligible	
(2)	From similar-appearing displays on DCS which conforms to the human factor guidelines regarding computer systems as given in NUREG 0700	.0005	10
(3)	From similar-appearing displays that are part of well-delineated functional groups on a panel	.001	3
(4)	From an array of similar-appearing displays identified by labels only	.003	3

* The listed HEPs are independent of recovery factors. In some cases, the content of the quantitative or qualitative indication from an incorrect display may provide immediate feedback of the selection error, and the total error can be assessed as negligible.

** This assumes the operator knows the characteristics of the display for which he is searching.

Table 11. Estimated HEPs for errors of commission in check-reading displays.*

Item	Display or Task	HEP	EF
(1)	Digital indicators (these must be read there is no true check-reading function for digital displays)	.001	3
	Analog meters:		
(4)	Without limit marks	.003	3
	Analog-type chart recorders:		
(6)	Without limit marks	.006	3
(7)	Confirming a status change on a status lamp	Negligible .003**	3
(8)	Misinterpreting the indication on the indicator lamps	Negligible	

* "Check-reading" means reference to a display merely to see if the indication is within allowable limits; no quantitative reading is taken. The check-reading may be done from memory or a written checklist may be used. The HEPs apply to displays that are checked individually for some specific purpose, such as a scheduled requirement, or in response to some developing situation involving that display.

** If operator must hold a switch in a spring-loaded position until a status lamp lights, use HEP = .003 (EF = 3).

Table 12. Estimated probabilities of errors of commission in operating manual controls.*

Item	Potential Errors	HEP	EF
(1)	Inadvertent activation of a control		
(1A)	Select wrong control when it is dissimilar to adjacent controls	Negl.	
	Select wrong control on a panel from an array of similar-appearing controls:		
(2)	Identified by labels only	.003	3
(3)	Arranged in well-delineated functional groups	.001	3
(4)	On DCS which conforms to the human factor guidelines as given in NUREG 0700	.0005	10
	Turn rotary control in wrong direction (for two-position switches, see item 8)		
(6)	When design violates a strong populational stereotype and operating conditions are normal	.05	5
	Turn a two-position switch in the wrong direction or leave it in the wrong setting		
(7)	When there is no violation of population stereotypes	.0001	10
(8)	When design violates a strong population stereotype and operating conditions are normal	.01	5
(9)	Set a rotary control to an incorrect setting (for two-position switches, see item 8)	.001	10
(10)	Failure to complete change of state of a component if switch must be held until change is completed	.003	3
	Select wrong circuit breaker in a group of circuit breakers		
(11)	Densely grouped and identified by labels only	.005	3
(13)	Improperly mate a connector (this includes failures to seat connectors completely and failure to test locking features of connectors for engagement)	.003	3

* The HEPs are for errors of commission only and do not include errors of decision as to which controls to activate.

Table 13. Estimated HEPs for selection errors for locally operated valves.

Item	Potential Errors	HEP	EF
	Making an error of selection in changing or restoring a locally operated valve when the valve to be manipulated is		
(2)	Clearly and unambiguously labeled, part of a group of two or more valves that are similar in <u>one</u> of the following: size and shape, state, or presence of tags	.003	3
(4)	Unclearly or ambiguously labeled, part of a group of two or more valves that are similar in <u>one</u> of the following: size and shape, state, or presence of tags	.008	3

Table 14. Estimate HEPs in detecting stuck locally operated valves.

Item	Potential Errors	HEP	EF
	Given that a local operated valve sticks as it is being changed or restored,* the operator fails to notice the sticking valve, when it has		
(3)	A rising stem but no position indicator**	.005	3

* Equipment reliability specialists have estimated that the probability of a valve's sticking in this manner is approximately .001 per manipulation, with an error factor of 10.

** A position indicator incorporates a scale that indicates the position of the valve relative to a fully opened or fully closed position. A rising stem qualifies as a position indicator if there is a scale associated with it.

Table 15. General guidelines for estimating uncertainty bounds for estimated HEPs.*

Item	Task and HEP Guidelines**	EF$^+$
	Task consists of performance of step-by-step procedure conducted under routine circumstances (e.g., a test, maintenance, or calibration task); stress level is optimal:	
(1)	Estimated HEP < .001	10
(2)	Estimated HEP .001 to .01	3
(3)	Estimated HEP > .01	5

* The estimates in this table apply to experienced personnel.

** For UCBs for HEPs based on the dependence model, see Table 17.

$^+$ The highest upper bound is 1.0.

Table 16. Estimated probabilities that a checker will fail to detect errors made by others.*

Item	Checking Operation	HEP	EF
(1)	Checking routine tasks, checker using written materials (includes over-the-shoulder inspections, verifying position of locally operated valves, switches, circuit breakers, connectors, etc., and checking written lists, tags, or procedures for accuracy)	.1	5
(2)	Same as above, but without written materials	.2	5
(3)	Special short-term, one-of-a-kind checking with alerting factors	.05	5
(4)	Checking that involves active participation, such as special measurements.	.01	5
	Given that the position of a locally operated valve is checked (item 1 above), noticing that it is not completely opened or closed:		
(6)	A rising stem with or without a position indicator**	.5	5
(8)	Checking by reader/checker of the task performer in a two-man team, <u>or</u> checking by a <u>second</u> checker, routine task (no credit for more than 2 checkers)	.5	5
(9)	Checking the status of equipment if that status affects one's safety when performing his tasks	.001	5
(10)	An operator checks change or restoration tasks performed by a maintainer	Above HEPs 5	5

* This table applies to cases during normal operating conditions in which a person is directed to check the work performed by others either as the work being performed or after its completion.

** A position indicator incorporates a scale that indicates the position of the valve relative to a fully opened or fully closed position. A rising stem qualifies as a position indicator if there is a scale associated with it.

Table 17. The Annunciator Response Model: Estimated HEPs* for multiple annunciators alarming closely in time.**

Item	Number of ANNs	Pr[F] for each annunciator (ANN) (or completely dependent set of ANNs) successively addressed by the operator										$\overline{Pr[F_i]}$#
		1	2	3	4	5	6	7	8	9	10	
		(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
(1)	1	.0001										.0001
(2)	2	.0001	.001									.0006
(3)	3	.0001	.001	.002								.001
(4)	4	.0001	.001	.002	.004							.002
(5)	5	.0001	.001	.002	.004	.008						.003
(6)	6	.0001	.001	.002	.004	.008	.016					.005
(7)	7	.0001	.001	.002	.004	.008	.016	.032				.009
(8)	8	.0001	.001	.002	.004	.008	.016	.032	.064			.02
(9)	9	.0001	.001	.002	.004	.008	.016	.032	.064	.13		.03
(10)	10	.0001	.001	.002	.004	.008	.016	.032	.064	.13	.25	.05
(11)	11-15											.10
(12)	16-20											
(13)	21-40	$Pr[F_i]$ for each additional ANN beyond 10 = .25										
(14)	>40											.25

Table 17. (Continued).

* The HEPs are for the failure to initiate some kind of intended corrective action as required. The action carried out may be correct or incorrect and is analyzed using other tables. The HEPs include the effects of stress and should not be increased in consideration of stress effects.

EF of 10 is assigned to each $Pr[F_i]$ or $\overline{Pr[F_i]}$.

** "Closely in time" refers to cases in which two or more annunciators alarm within several seconds or within a time period such that the operator perceives them as a group of signals to which he must selectively respond.

$\overline{Pr[F_i]}$ is the expected Pr[F] to initiate action in response to a randomly selected annunciator (or completely dependent set of annunciators) in a group of annunciators competing for the operator's attention. It is the arithmetic mean of the $Pr[F_i]$s in a row, with an upper limit of .25. The $Pr[F_i]$ column assumes that all of the annunciators (or completely dependent sets of annunciators) are equal in terms of the probability of being noticed.

Table 18. Estimated HEPs for annunciated legend lights.*

Item	Task	HEP	EF
(1)	Respond** to one or more annunciated legend lights	See Table	
(2)	Resume attention to a legend light within 1 minute after an interruption (sound and blinking cancelled before interruption)	.001	3
(3)	Respond to a legend light if more than 1 minute elapses after an interruption (sound and blinking cancelled before interruption)	.95	5
(4)	Respond to a steady-on legend light during initial audit	.90	5
(5)	Respond to a steady-on legend light during other hourly scans	.95	5

* No written materials are used.

** "Respond" means to initiate some action in response to the indicator whether or not the action is correct. It does not include the initial acts of cancelling the sound and the blinking; these are assumed to always occur.

Table 19. Estimated probabilities of failures to detect one (of one) unannunciated deviant display* at each scan, when scanned hourly.**

Item	Display Type	Initial Audit	Hourly Scans+						
		1	2	3	4	5	6	7	8
		(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
	Analog meters:								
(2)	without limit marks	.15	.47	.67	.80	.87	.92	.95	.97
	Analog-type chart recorders:								
(4)	without limit marks	.30	.58	.75	.85	.91	.94	.97	.98
(5)	Annunciator light no longer annunciating	.9	.95	.95	.95	.95	.95	.95	.95
(6)	Legend light++ other than annunciator light	.98	.98	.98	.98	.98	.98	.98	.98
(7)	Indicator lamp++	.99	.99	.99	.99	.99	.99	.99	.99

* "One display" refers to a single display or a group of completely dependent displays, i.e., a perceptual unit.

** For error factors, refer to Table 15.

+ Written materials not used.

++ These displays are rarely scanned more than once per shift, if at all. Hourly HEPs for each are listed for completeness only.

Table 20. Estimated probabilities of failing to detect at least one* of one to five unannunciated deviant displays as a function of the BHEP for detection of a single deviant display during periodic scanning.

	Number of Deviant Indications				
	1	2	3	4	5
	BHEP	Pr[F] to detect at least one deviant display+			
Item	(a)	(b)	(c)	(d)	(e)
(1)	.99	.985	.98	.975	.97
(2)	.95	.93	.90	.88	.86
(3)	.90	.85	.81	.77	.73
(4)	.80	.72	.65	.58	.52
(5)	.70	.59	.51	.43	.37
(6)	.60	.48	.39	.31	.25
(7)	.50	.37	.28	.21	.16
(8)	.40	.28	.20	.14	.10
(9)	.30	.19	.13	.08	.05
(10)	.20	.12	.07	.04	.03
(11)	.10	.05	.03	.02	.01
(12)	.05	.03	.01	.007	.004
(13)	.01	.005	.003	.001	.001

* To estimate the HEP for failure to detect other concurrent unannunciated deviant displays when one has been detected, use the HEP for the initial audit for those displays that are not functionally related to the display detected (from Table 10) and use the annunciator response model for those displays that are functionally related to the display detected (from Table 17). The HEPs apply when no written materials are used.

+ For EFs, refer to Table 15.

Table 21. Estimated probabilities that the basic walk-around inspection* will fail to detect a particular deviant indication of equipment outside of the control room within 30 days.**

Item	Number of days between walk-arounds per inspector+	Cumulative Pr[F] within 30 days given one inspection per shift++
(1)	1 (daily walk-around for each inspector)	.52
(2)	2	.25
(3)	3	.05
(4)	4	.003
(5)	5	.0002
(6)	6	.0001
(7)	7 (weekly walk-around for each inspector)	.0001

* Assumption is that no written procedure is used; if a written procedure is used for a walk-around, use the tables related to errors of omission and commission for performance of rule-based tasks.

** Three shifts per day are assumed.

+ It is assumed that all inspectors have the same number of days between walk-arounds.

++ For EFs, use EF = 10 as an approximation.

DEPENDENCE ASSESSMENT GUIDELINES

FOR DATA TABLES 22, 23, AND 24

Evaluate the influence of the failure or success on the immediately preceding task on the task of interest.

Use the higher of two levels of dependence when there is doubt about which one of them is more important.

Evaluate the spatial and time relationships among all events. Dependence between any two events increases as the events occur closer in time and space.

Evaluate the functional relationships among events. Dependence between any two events increases with their functional relatedness.

Evaluate the effects of stress on dependence among personnel. Dependence increase with stress.

Evaluate the similarities among personnel with respect to all relevant factors. Dependence increases with similarity in status, training, and responsibility.

Evaluate tasks that must be accomplished within a given time frame for dependence.

Zero dependence is not a valid assumption for errors of omission if all of the following exist:

(a) the displays are adjacent
(b) the pointers on the displays are parallel
(c) policy is to check displays sequentially

Zero dependence can be assumed if the check readings are performed at different times.

DEPENDENCE ASSESSMENT GUIDELINES

FOR DATA TABLES 22, 23, AND 24-Continued

Assume zero dependence when using written procedures and checklists.

Assign low dependence if there is any doubt about zero dependence.

Assign moderate dependence when there is an obvious relationship between the performance on one task and on a subsequent task.

Assign high dependence when the performance on one task very substantially affects performance on a subsequent task.

Assign complete dependence to those tasks performed simultaneously, paired together in the written procedures, or those tasks that are perceives as one task.

Assume complete dependence if two check-readings must be performed simultaneously and are covered in the same step, or when control are manipulated in pairs.

Table 22. Conditional probabilities of success or failure for Task "N" for the five levels of dependence, given SUCCESS on preceding Task "N-1."

	Task "N" Conditional Probabilities									
	ZD**		LD		MD		HD		CD	
	S	F	S	F	S	F	S	F	S	F
Item	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
(1)	.75	.25	.76	.24	.79	.21	.87	.13	1.0	0
(2)	.9	.1	.9	.1	.91	.09	.95	.05	1.0	0
(3)	.95	.05	.95	.05	.94	.06	.97	.03	1.0	0
(4)	.99	.01	.99	.01	.991	.009	.995	.005	1.0	0
(5)	.995	.005	.995	.005	.996	.004	.997	.003	1.0	0
(6)	.999	.001	.999	.001	.999	.001	.9995	.0005	1.0	0
(7)	.9995	.0005	.9995	.0005	.9996	.0004	.9997	.0003	1.0	0
(8)	.9999	.0001	.9999	.0001	.9991	.0009	.99995	.00005	1.0	0
(9)	.99999	.00001	.99999	.00001	.99991	.00009	.999995	.000005	1.0	0

* All conditional probabilities are rounded. The values in the F columns were obtained by subtraction.

** The conditional probabilities, given ZD, are also the basic probabilities for Task "N."

Table 23. Conditional probabilities of success or failure for Task "N" for the five levels of dependence, given FAILURE on preceding Task "N-1."

	Task "N" Conditional Probabilities									
	ZD**		LD		MD		HD		CD	
	S	F	S	F	S	F	S	F	S	F
Item	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
(1)	.75	.25	.71	.29	.64	.36	.37	.63	0	1.0
(2)	.9	.1	.85	.15	.77	.23	.45	.55	0	1.0
(3)	.95	.05	.9	.1	.81	.19	.47	.53	0	1.0
(4)	.99	.01	.94	.06	.85	.15	.49	.51	0	1.0
(5)	.995	.005	.95	.05	.85	.15	.50	.50	0	1.0
(6)	.999	.001	.95	.05	.86	.14	.50	.50	1.0	0
(7)	.9995	.0005	.95	.05	.86	.14	.50	.50	1.0	0
(8)	.9999	.0001	.95	.05	.86	.14	.50	.50	1.0	0
(9)	.99999	.00001	.95	.05	.86	.14	.50	.50	1.0	0

* All conditional probabilities are rounded. The values in the S columns were obtained by subtraction.

** The conditional probabilities, given ZD, are also the basic probabilities for Task "N."

Table 24. Approximate CHEPs and their UCBs for dependence levels* given FAILURE on the preceding task.

Item	Levels of Dependence	BHEPs		
		(a)	(b)	(c)
(1)	ZD**	< .01	.05 (EF = 5)	.1 (EF = 5)
		(d)	(e)	(f)
		.15 (EF = 5)	.2 (EF = 5)	.25 (EF = 5)

Item	Levels of Dependence	Nominal CHEPs and (Lower to Upper UCBs)		
		(a)	(b)	(c)
(2)	LD	.05 (.015 to .15)	.1 (.04 to .25)	.15 (.05 to .5)
(3)	MD	.15 (.04 to .5)	.19 (.07 to .53)	.23 (.1 to .55)
(4)	HD	.5 (.25 to 1.0)	.53 (.28 to 1.0)	.55 (.3 to 1.0)
(5)	CD	1.0 (.5 to 1.0)	1.0 (.53 to 1.0)	1.0 (.55 to 1.0)
		(a)	(b)	(c)
(2)	LD	.19 (.05 to .75)	.24 (.06 to 1.0)	.29 (.08 to 1.0)
(3)	MD	.27 (.1 to .75)	.31 (.1 to 1.0)	.36 (.13 to 1.0)
(4)	HD	.58 (.34 to 1.0)	.6 (.36 to 1.0)	.63 (.4 to 1.0)
(5)	CD	1.0 (.58 to 1.0)	1.0 (.6 to 1.0)	1.0 (.63 to 1.0)

* Values are rounded. All values are based on skilled personnel (i.e., those with >6 months experience on the tasks being analyzed).

** ZD = BHEP. EFs for BHEPs should be based on Table 15.

APPENDIX B

INADVERTENT FAULT TREE DATA

TRANSFER TASK LIST

Verbal instruction to perform transfer.

Operator inputs sending and receiving vessel names into computer.

Operator requests 3 batch transfer forms.

Operator checks computer for other transfers currently occurring.

Supervisor approves transfer.

Operator identifies displays for the vessels.

Operator adjusts control.

Operator closes 3 valves.

Supervisor verifies lineup and breaks seal on valve.

Operator verifies seal breakage in log.

Supervisor turns control to ON position.

Operator turns control ON.

Operator opens 2 valves.

Supervisor verifies lineup.

Operator monitors other potential receiving vessels.

Operator records transfer data for each vessel.

Testing request from filled out for receiving vessel.

Operator monitors displays to verify transfer completion.

Operator performs post transfer valve lineup.

Supervisor verifies post transfer valve lineup.

TRANSFER TASK LIST-Continued

Supervisor closes 3 valves.

Operator closes valve.

Operator records transfer data on forms.

Valve resealed and recorded.

Final paperwork finished.

MINIMAL CUT SETS

Cut Set	Description
HA2	The valves are mislabeled.
HA3	There is an unknown configuration which allows the transfer to occur via an unknown route.
HA4	An abnormal condition exists.
HB5	Previous post-transfer lineups performed incorrectly.
HC5	Errors in drawings used by instruction writers that cause information in procedures to be incorrect.
HD6	A procedure writer omits a step.
HD7	A procedure writer makes a writing error.
HC8	An operator chooses the wrong sending vessel for a transfer and the supervisor fails to detect this error.
HC1 HD2	An operator inputs the wrong sending vessel into the computer and the supervisor fails to detect this error.
HC4 HD4 HE3	The operator inputs the wrong receiving vessel into the computer, the checker and the supervisor fail to detect this error.
HC4 HD4 HE4	The operator inputs the wrong receiving vessel into the computer, the checker and the supervisor fail to detect this error, and the operator monitors the wrong display.
HC4 HE3 HF1	The operator omits part of the procedure, the checker fails to detect the omission, and the operator reads the displays incorrectly.
HC4 HE3 HF2	The operator omits part of the procedure, the checker fails to detect the omission, and the operator reads the displays incorrectly.
HC4 HE3 HF3	The operator manipulates the valves incorrectly, the checker fails to detect this error, and the operator reads the displays wrong.

MINIMAL CUT SETS-Continued

HC4 HE4 HF1	The operator omits part of the procedure, the checker fails to detect this error, and the operator reads the wrong displays.
HC4 HE4 HF2	The operator omits part of the procedure, the checker fails to detect this error, and the operator reads the wrong displays.
HC4 HE4 HF3	The operator manipulates the valves incorrectly, the checker fails to detect this error, and the operator reads the wrong displays.
HC4 HE4 HF4	The operator manipulates the wrong valves, the checker fails to detect this error, and the operator reads the wrong displays.