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The work process analysis model (WPAM)

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The work process analysis model-I (WPAM-I) along with its products developed in a previous paper (Davoudian, K., Wu, J.-S. & Apostolakis, G., *Reliability Engineering and System Safety,* **45** (1994) 85–105 are used as inputs to WPAM-II. The goal is to provide the link between organizational factors (or dimensions), work processes, and probabilistic safety assessment parameters in order to facilitate the quantification of the impact of organizational factors on plant safety. This is achieved by calculating new (organizationally dependent) probabilities for minimal cut sets so that each new probability contains in it, either explicitly or implicitly, the effect of the pertinent organizational factors. A sample case is presented demonstrating the application of WPAM to a specific minimal cut set. Finally, sensitivity analyses are performed in order to explore the effectiveness of organizational improvements as a risk management strategy.

I INTRODUCTION

As was discussed in the first paper on this work,[1] the state of the art in current PSA methodology is such that organizational dependencies between hardware failures, between human errors, and between hardware failures and human errors are not modelled explicitly. Instead, the current methodology is confined mostly to models of isolated human errors and equipment failures.[2] Therefore, it was concluded that models are needed that can remedy the situation in not only a qualitative, but also a quantitative manner. WPAM was then proposed as one such integrated model.

The qualitative treatment in Ref. 1 included a discussion on both the importance of work processes to safe and reliable nuclear-power-plant (NPP) operation and the parameters which are used to evaluate plant safety. In this paper, the qualitative model is used, along with the products of WPAM-I, as inputs to the formalism of WPAM-II, which presents a mathematical algorithm for the quantification and incorporation of organizational factors into PSA.

The common-cause effect of organizational factors can potentially cause the PSA parameters, i.e. the candidate parameter groups (CPGs), to become coupled. Clearly, then, treating the CPGs as independent variables can lead to an underestimation of plant risk.[3] The present study proposes one way in which this potential underestimation can be avoided. Recognizing that, in PSA, each basic event in each minimal cut set (MCS) is represented by one or more CPGs, WPAM-II is used to recalculate basic-event probabilities in such a way that each new (organizationally dependent) probability accounts for (either explicitly and/or implicitly) the coupling among the CPGs. In other words, while WPAM-II recognizes that it is the CPGs that are coupled due to the influence of organizational factors, it calculates new probabilities for the events that are modelled by the CPGs as opposed to calculating a new value for each CPG.

It is again pointed out here that, in the present study, only pre-accident operations are considered, so that operator actions during a transient, for example, are not analyzed. However, as will be seen later, this does not preclude the analysis of dynamic situations which may have their roots in the routine operation of the plant.

Section 2 presents and discusses the details of WPAM-II. Following this discussion, in Section 3, a sample case is presented in which WPAM has been applied to human errors and organizational failures within the framework of the maintenance work process as one of several front-line work processes that are essential for the safe and reliable operation of a nuclear power plant. Section 4 contains sensitivity analyses for the example presented in Section 3 and

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includes suggestions for risk management. Finally, Section 5 presents some conclusions and suggestions for future research.

2 WORK PROCESS ANALYSIS MODEL-II (WPAM-II)

2.1 The structure of WPAM-II

Typically, PSA results include a set of major (dominant) accident sequences presented in logical combinations of minimal cut sets. The latter contain basic events, such as hardware failures, human errors, and common cause failures, as well as component/system unavailabilities due to testing and maintenance. Each of these basic events is represented in PSA by its corresponding parameter (e.g. λ, γ, τ, etc.) in the unavailability expressions (see Section 4.2 of Ref. 1). What is important, however, is that the treatment in PSA does not include the dependencies among the parameters that are introduced by organizational factors. To address this issue, WPAM-II has been designed to modify MCS frequencies to include organizational dependencies among the PSA parameters, i.e. the CPGs.

The primary purpose of WPAM-II is to address dependencies that might be introduced by organizational factors. As has been discussed previously, a point of concern has been whether the existing plant-specific data (e.g. failure rates) already contain in them the influence of organizational factors. For example, the individual plant examination (IPE) for a plant reports that, in determining the uncertainty in the probability of station battery depletion at a given time subsequent to the loss of ac power, experts (including a member of the operations and maintenance staff) were asked to consider 'the condition of the batteries at the time of the event' as one of the factors. Inasmuch as the condition of station batteries at any time is a strong indicator of the quality of maintenance at the plant,[4] it may be assumed that the distribution of battery depletion times has accounted for organizational factor(s) in a generic manner. However, the specific organizational factors that can result in reduced battery lifetime (e.g. ineffective maintenance procedures, deficient training, etc.) may also have an impact on the availability and/or success of other equipment in the plant. Therefore, while WPAM-II is capable of recalculating basic (organizationally independent) probabilities for basic events in each MCS (this has been performed by the Brookhaven National Laboratory,[5] for example), it concentrates primarily on capturing the common-cause effect of organizational factors on basic-event probabilities (and thus, on MCS frequencies). This, in effect, is analogous to the common-cause failure (CCF) analysis of hardware, where an additional term (containing, for example, the β factor) is introduced to account for the failure of redundant equipment due to a single cause.[6] However, in contrast to current CCF treatment, WPAM-II goes one step further by considering organizational common-cause failures of dissimilar systems and/or components.

WPAM-II is composed of two basic steps (see Fig. 1): minimal-cut-set screening and quantification. The former reduces the list of MCS for each dominant accident sequence by highlighting only those whose basic-event parameters (or, simply, parameters) show strong organizational dependence; this is achieved through an in-depth analysis of the basic events. Having this revised list, the quantification process then reassesses the MCS frequencies through the use of an approach similar to that of SLIM.[7,8] The details of the above steps are described in the sections that follow.

2.2 Minimal cut set screening

The number of minimal cut sets listed in PSAs typically runs into the thousands. Therefore, in an effort to reduce the number of MCS that need detailed analysis, a screening procedure has been devised which identifies and retains for further investigation only those MCS whose parameters show strong organizational dependence. This is done by defining a vector for each basic event, using these vectors to rate the organizational dependence of the basic events two (events) at a time, deriving an overall rating for each minimal cut set, and, finally, based on a cut-off rating, making a decision as to which MCS to retain for further analysis. The various steps of this procedure are described below.

2.2.1 The basic-event vector

Each minimal cut set normally contains two or more basic events. The screening process starts by defining a vector for each basic event. The purpose of the basic-event vector is to facilitate the assessment of the level of organizational dependence between two basic events. As shown below, this is achieved by defining four members for each vector, and then rating each set of two basic events based on the commonalities that are introduced through the four vector members. Of course, one of the vector members is the parameter which represents the basic event. This vector is (WP, CPG, WU, ID) where WP: work process; CPG: candidate parameter group; WU: working unit/department; and ID: system/component identification.

The first member, WP, refers to the work process, the details of which were discussed in Section 3 of Ref. 1. In this step, the objective is to identify the work process which most closely corresponds to the

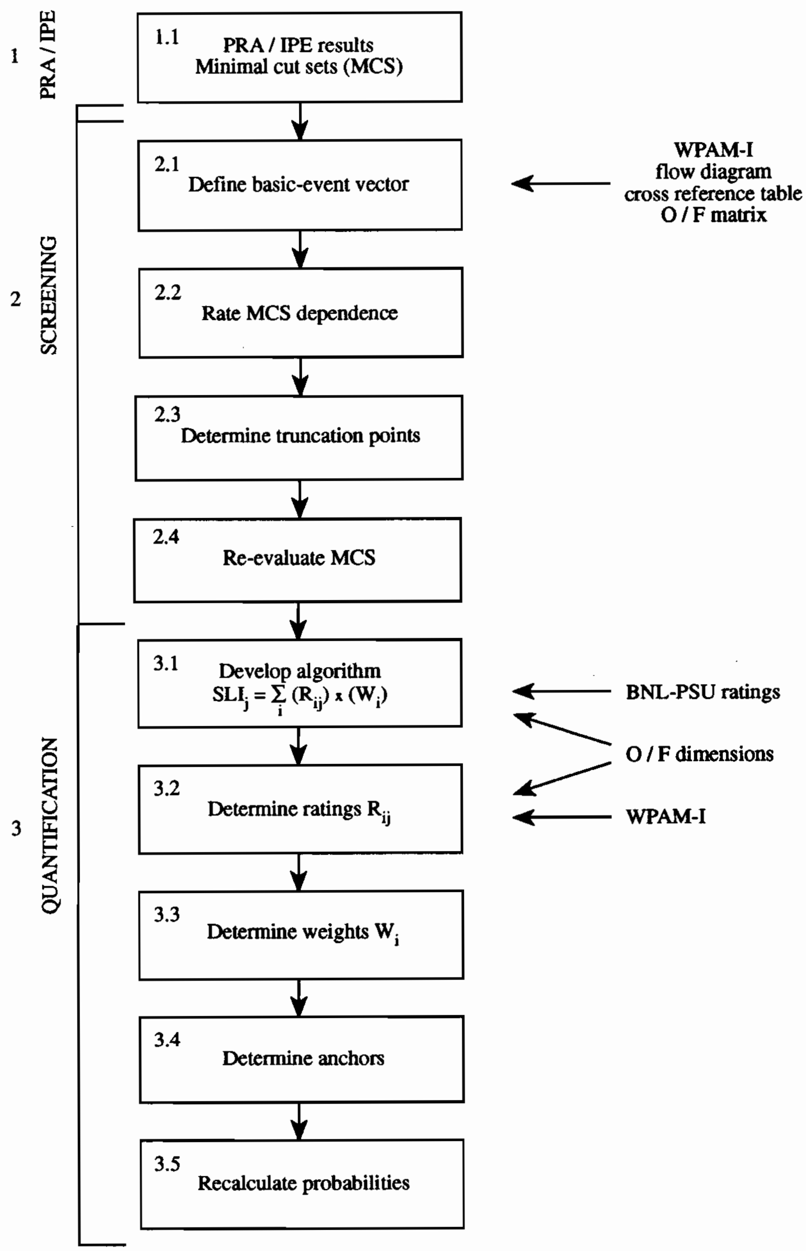

Fig. 1. Work process analysis model-II (WPAM-II).

context within which the failure in each basic event is set. Put another way, the question that must be answered at this point is 'what are the work processes that affect each parameter and, thus, its corresponding basic event the most?' (see also Section 4.2.3 of Ref. 1). For example, a basic event which appears frequently is the failure of a pump on demand. Usually, this failure is realized during normal or emergency operations. However, the work process which is identified for the basic-event vector is the maintenance work process, since this is where the pump may have been left in an inoperable state. In Reason's terminology, the work process that is sought here is the one in which the 'latent failure' (or the 'resident pathogen') is put into place, rather than the one in which the failure is realized.[9]

As was discussed in Ref. 1, candidate parameter groups (CPGs) are the groups of parameters whose numerical values might change due to the influence of organizational factors. In other words, the CPGs constitute a subset of what were called 'basic-event parameters' or simply 'parameters', above. For the present study, an examination of the PSA has resulted in the identification of six candidate parameter groups. It is important to mention here that this is not an exhaustive list; further research is needed before such a list of CPGs can be developed.

The six CPGs are defined as follows.

RE ≡ Failure to restore equipment to normal configuration after test/maintenance. This corresponds to γ in the unavailability equations.[1,10]

MC ≡ Miscalibration of equipment. This also corresponds to γ in the unavailability equations.

UM ≡ Unavailability due to maintenance (i.e. down time of component). This corresponds to τ_m in the unavailability equations.

FR ≡ Failure to function on demand (e.g. failure while running, failure to start, etc.). This corresponds to the failure rates λ_R and Q in the unavailability equations.

CCF ≡ Common cause failures (due to factors other than human errors). This corresponds to λ_C in the unavailability equations.

TR ≡ Available time for recovery. The parameter to which this CPG corresponds is determined by the accident sequence (or the MCS).

In general, the sixth candidate parameter group, TR, does not correspond to any one parameter in the unavailability expressions. This is, of course, expected since the available time for recovery is not part of system/component unavailability. However, in some MCS, recovery actions are included. For example, for most station blackout (SBO) accident sequences, the last basic event in each minimal cut set is 'the recovery of off-site power' (within a given number of hours). In this case, among the factors that are important in determining the available time for recovery is the condition of the station batteries at the time of the accident. The condition of the batteries, in turn, is determined by how well they are maintained on a regular basis. For example, Paula[4] reports that one reason for the occurrence of moisture-induced failures is the 'failure to properly seal the equipment following maintenance'. Therefore, even though it has been declared that the present version of WPAM excludes the treatment of dynamic situations, it is of utmost importance to include those events whose probability of occurrence may be affected by activities during normal operation. It is for this purpose that 'TR' has been included as a candidate parameter group. Again, for the recovery event mentioned above, the precondition for a failure (i.e. degraded batteries due to poor maintenance) is set during the maintenance work process, while the manifestation may come much later (i.e. during the actual SBO event).

The third member of the basic-event vector is 'the working unit involved'. This simply refers to the specific group of people who interact with a given piece of equipment during the course of the pertinent work process. That is, the working unit is the organizational unit which, within the context of the work process being studied, is involved with the particular equipment addressed in the basic event. For instance, in the case of a pump failing to run on demand (and considering the maintenance work process), the mechanics from the maintenance department would be identified as the 'working unit involved'. On the other hand, for a valve that has not been restored properly following maintenance, the operators from the operations department would be identified as the 'working unit involved'.

The analysis performed in WPAM-I for the corrective maintenance work process has resulted in (through the work process flow diagram and the cross-reference table) the identification of four working units which may interact with plant equipment. These are:

Operations	(OP)
Maintenance—mechanical	(MM)
Maintenance—electrical	(ME)
Instrumentation and control	(IC)

The fourth and last member of the basic-event vector is the 'system/component identification'. This is the identification that already exists in the basic-event description in each minimal cut set. The description includes the type (or nature) of failure (e.g. human error, pump failure, etc.), the failure mode (e.g. miscalibrated relay, failure of a pump to run on demand), and the component/system identification (e.g. pump No. 2 in loop A).

For example, one system/çomponent identification for the present analysis has been identified as 'XHE-MC-UVRLA'. The failure in this event involves a human error, designated by 'XHE', where a relay in train A (designated by 'UVRLA') is miscalibrated (designated by 'MC').

The main purpose of the 'system/component identification' is to help prevent the assignment of too much dependence between two basic events. This point may be clarified by the following example. Considering two events where one involves the failure of a pump to start and, the other, the failure of a valve, it will be apparent that the first three vector members for both events are identical. That is, within the framework of the maintenance work process, the first member is 'MP' (for maintenance process), the second member is 'FR' (for the CPG 'FR'), and the third member is 'MM' (for the maintenance-mechanical working unit). Based on this information alone, the combination of events would receive a very high dependence rating. This rating is reduced, however, once it is recognized that different pieces of equipment are involved. As will be described shortly, the rating for the 'system/component identification' allows a distinction to be made between not only different component types, but also different failure modes.

Based on the above descriptions for the members of the basic-event vector, a typical vector may look like the following:

(MP, MC, IC, XHE-MC-UVRLA)

which, in words, says that the miscalibration error mentioned above is set within the maintenance work process ('MP') by instrumentation and control personnel ('IC'), and is represented by the candidate parameter group 'MC' (for miscalibration).

2.2.2 MCS dependence ratings

Once a vector has been identified for each event in the minimal cut set, the basic events are rated two at a time based on the information contained in each of their vectors. For a MCS which contains three basic events, for instance, three overall ratings will be obtained: one for events No. 1 and 2 (R_{12}), one for events No. 1 and 3 (R_{13}), and one for events No. 2 and 3 (R_{23}). Clearly, for MCS with only two basic events, a single rating (R_{12}) is obtained.

The ratings are numbers between zero and one and are indicative of the degree of dependence between a given pair of basic events as pertains to each member of the basic-event vector. Complying with normal practice, a rating of zero indicates no dependence and a rating of one indicates complete dependence between the two events. In general, the vectors for the two basic events being rated are:

$$\text{EVENT 1:}\quad (\mathrm{WP}_1, \mathrm{CPG}_1, \mathrm{WU}_1, \mathrm{ID}_1)$$

$$\text{EVENT 2:}\quad (\mathrm{WP}_2, \mathrm{CPG}_2, \mathrm{WU}_2, \mathrm{ID}_2)$$

The procedure for rating any two events on the work process is fairly simple. Basically, if the two events under analysis involve the same work process, a rating of '1' is assigned (i.e. $R_{\mathrm{WP}} = 1$); otherwise, $R_{\mathrm{WP}} = 0$. For example, for a MCS in which one event involves the miscalibration of a relay and the other involves equipment being unavailable due to maintenance, R_{WP} would be set equal to 1·0 since, for the present analysis, the maintenance work process would be identified for both basic events. That is, for both modes of maintenance (i.e. testing and corrective maintenance) 'MP' is assigned as the first vector member and, for the combination, R_{WP} is set equal to 1. In effect, this says that the quality of maintenance is reflected equally in both of its modes, so that $R_{\mathrm{WP}} = 1$ no matter what combination of testing and corrective maintenance is assigned to WP_1 and WP_2.

A four-point scale has been constructed for the rating of two basic events on the candidate parameter group. Based on the judgment of the authors, the ratings are assigned as follows:

$R_{\mathrm{CPG}} = 1{\cdot}0$ for human actions represented by similar candidate groups (e.g. RE and RE),
0·5 for human actions represented by dissimilar candidate groups (e.g. RE and MC),
0·1 for hardware-related problems represented by similar candidate groups (e.g. FR and FR) or for one human action and one hardware related problem (e.g. MC and FR),
0·01 for hardware-related problems represented by dissimilar candidate groups.

Table 1 contains the ratings for all CPG combinations.

Several observations are made with regard to Table 1. First, in developing the table, the candidate parameter group 'CCF' was considered to be 'hardware related'. Furthermore, a rating of 0.1 was assigned to the CCF-CCF combination for completeness only; that is, during the course of the analysis, no minimal cut sets were found which contained more than one CCF basic event. Second, except for the UM-UM combination, 'UM' was conservatively taken to be human-action related. For the former, a rating of 0·5 (as opposed to 1·0) was assigned in order to account for those instances when equipment is down due to maintenance (for a longer period of time than is warranted) as a result of hardware related problems rather than human error(s). Finally, the candidate parameter group 'TR' was specialized to account for hardware related problems. This was done merely to set up the table so that it could be used for the sample calculation presented in the next section. It is again noted that all of the MCS which were analyzed (within the station blackout sequence) contained only one recovery action. Nevertheless, for completeness, a rating was included for the TR-TR combination.

The ratings for the working unit are based on a three-point scale:

$R_{\mathrm{WU}} = 1{\cdot}0$ for HIGH dependence,
0·5 for MODERATE dependence,
0·1 for LOW dependence.

In contrast to the ratings for the candidate parameter groups, the ratings for the working unit do not pre-assign a degree of dependence to all possible combinations of working units. Rather, they allow the analyst to decide on the degree of dependence for these combinations. This is not in any way arbitrary; that is, in this case, the analyst has an additional

Table 1. Candidate-parameter-group ratings

		CPG_1					
		CCF	FR	UM	TR	RE	MC
	CCF	0·1	0·01	0·1	0·01	0·1	0·1
	FR	0·01	0·1	0·1	0·01	0·1	0·1
CPG_2	UM	0·1	0·1	0·5	0·1	0·5	0·5
	TR	0·01	0·01	0·1	0·1	0·1	0·1
	RE	0·1	0·1	0·5	0·1	1·0	0·5
	MC	0·1	0·1	0·5	0·1	0·5	1·0

source of guidance in that the work that has been done in WPAM-I (e.g. the task analysis and the development of the flow-diagram cross-reference table) helps greatly in assigning the ratings. Table 2 shows the ratings which were decided upon for the maintenance work process. As can be seen, it was judged that when two units from the maintenance department interact, the organizational dependence introduced (through common training, procedures, etc.) is stronger than when a maintenance unit interacts with a unit from the operations or the instrumentation and control department. For example, for a MCS containing a basic event where a pump fails to start and another basic event where a pump fails to continue running, a rating of 1·0 is assigned for the working unit since 'MM' would be assigned to both of their vectors. On the other hand, if the second event involves the restoration of a piece of equipment to its normal configuration, a rating of 0·1 is assigned since the realignment is performed by operators.

The final member of the basic-event vector that has to be rated is the component/system identification. Again, this member of the vector identifies the nature and type of failure and the specific component or system that is affected. Clearly, the more characteristics two basic events have in common, the more susceptible they are to a common-cause organizational failure. For example, two basic events, each of which involves the miscalibration of a relay in redundant trains, are believed to be more organizationally dependent than two basic events, where one involves the miscalibration of a relay, and the other involves the failure to return a piece of equipment to normal line-up. What is important to recognize is that examples such as the latter, even though they may be less dependent on organizational factors, are completely left out of the unavailability expressions.

The ratings for the member 'ID' are assigned as follows:

$R_{\mathrm{ID}} = 1{\cdot}0$ when both basic events involve the same component type and failure mode,

0·5 when the basic events share only the same component type or the same failure mode, but not both,

0·1 when neither the component type nor the failure mode is the same.

Table 2. Ratings for the working unit involved

	MM	ME	IC	OP
MM	0·1	0·5	0·1	0·1
ME	0·5	1·0	0·1	0·1
IC	0·1	0·1	1·0	0·1
OP	0·1	0·1	0·1	1·0

Once the ratings for each member of the vector have been determined, an overall rating needs to be calculated for all two-event combinations of each minimal cut set. At this point, the overall rating is taken to be simply the product of all the vector-member ratings (i.e. R_{WP}, R_{CG}, R_{WU}, and R_{ID}). That is

$$R_{ab} = R_{\mathrm{WP},ab} \cdot R_{\mathrm{CPG},ab} \cdot R_{\mathrm{WU},ab} \cdot R_{\mathrm{ID},ab} \quad (1)$$

where a and b are the event numbers and the value of R_{ab} will be between 0·0 and 1·0. For example, for a minimal cut set with three basic events, three values of the overall rating R_{ab} will be obtained. These are R_{12}, R_{13}, and R_{23}. Also, for MCS which contain more than two basic events, a low (or MIN) and a high (or MAX) value of R_{ab} will exist. As will be seen in the application of the truncation point, the MAX value of R_{ab} is chosen to represent the MCS.

It should be mentioned that R_{ab} in eqn (1) could have been equated to the sum of its terms or to the square root of the sum of the squares of its terms. However, the value of the ratings is relative, so that what matters ultimately is the truncation value for R_{ab}. This is the subject of the next section.

2.2.3 The truncation point

For every sequence, the list of MCS which has been obtained must be rearranged so that the MCSs will appear in order of descending values for R_{ab}. An important question is whether this should be done using the MAX or the MIN values of R_{ab}.

Of course, for MCSs with only two basic events, the above question does not apply. However, for MCSs with more than two basic events, there will be more than one value for the overall rating. Whereas the MIN value of the rating is indicative of the pair of basic events in the MCS which have the lowest degree of organizational dependence, the MAX value is indicative of the pair which are believed to have the highest degree of dependence. Keeping this in mind, if the truncation (or cut-off) value is applied to the MAX values, then for a given MCS, even if only one of the R_{ab} values is above the cut-off point, the minimal cut set survives the screening process. However, if the truncation value is applied to the MIN values, then, for the same minimal cut set, it takes only one of the R_{ab} values to be lower than the cut-off point in order for the whole MCS to be eliminated from further review. The latter, however, may result in the loss of important information regarding the dependence of basic events. For this reason, it is recommended that the truncation value be applied to the MAX values.

The determination of the actual truncation value depends on the amount of time, resources, and computer space that is available for the analysis. Therefore, the more scarce these resources become, the higher the truncation value will move. Clearly, the truncation value is a choice that will be made by the analyst as a function of the above mentioned factors.

2.2.4 Re-evaluation of the results
Once the minimal cut sets have been rated, it is recommended that the ones with high ratings be revisited. The purpose of this review is to eliminate some of the overconservative assumptions that may have been made in the original assessment. This usually means ascertaining that a MCS containing two similar events is kept for further analysis only if there is no other MCS accounting for the dependence between the two events. For example, a MCS with basic events involving the failure of two redundant pumps to run should survive the screening only if there is no MCS accounting for the common-cause failure of the two pumps—this, of course, assumes that the numbers that result from the CCF analysis are conservative enough so that they allow for some organizational dependence in a generic way. This situation is encountered in the example of the next section.

2.3 Quantification

With the organizationally less-significant minimal cut sets screened out, the reassessment of the MCS frequencies can now begin. First, WPAM-I is used to identify the organizational factors which may affect each candidate parameter group. Then, the success likelihood index methodology (SLIM)[7,8] is used to find new frequencies for each minimal cut set. This involves the determination of importance weights through the use of the analytic hierarchy process (AHP),[11] the determination of performance ratings using tools such as behaviorally anchored rating scales (BARS),[12–15] and the determination of calibration constants for the probabilities of similar and dissimilar events.

2.3.1 The use of WPAM-I
As was demonstrated earlier, the candidate parameter groups are chosen in such a way so as to highlight the paths through which organizational factors can affect system and component unavailabilities. There is, however, another advantage to introducing the candidate parameter groups. As will be discussed shortly, the frequency of each minimal cut set is modified through a recalculation of the (organizationally dependent) probabilities of its basic events. In order to do this, one would have to identify the pertinent organizational factors for each basic event of each minimal cut set, which could become cumbersome. This process could be avoided, however, by a one-time determination of the organizational factors that are of interest in each candidate parameter group. Then, every time a basic event is encountered, its vector will identify the candidate parameter group to which it belongs and this, in turn, will identify the organizational factors which will have to be considered. It should be mentioned that this treatment entails a certain degree of generalization. For example, an event involving the failure of a valve and one involving the failure of a pump would probably be assigned to the same CPG (i.e. 'FR'). This means that, based on the treatment proposed here, the same organizational factors would be assumed to influence these two events, even though this may not be the case.

The organizational factors matrix (see Ref. 1) already identifies the organizational dimensions that are relevant to each task. What needs to be done, then, is to identify the tasks (e.g. planning, execution, etc.) within the work process of interest which are relevant to each candidate parameter group. Once this has been accomplished, the organizational factors that may influence each CPG can be readily identified.

Table 3 was developed for the corrective maintenance work process using the flow chart and the cross-reference table (see Ref. 1), along with task procedures gathered from the plant. The following example illustrates the thinking behind the development of Table 3. As can be seen, 'scheduling coordination' was identified as one of the tasks which are deemed important to the candidate parameter group 'UM'. Scheduling/coordination is important in the following sense. In order for a maintenance job to be performed in a nuclear power plant, the work control center (WCC) has to schedule the work so that it does not interfere with other work that may be going on (see Section 3 of Ref. 1). The WCC is responsible for informing and, if need be, requesting the participation of other departments for all stages of the work. For example, in the initial stages, a lack of coordination could lead to a delay or a mistake in tagging out the component/system that is going to be worked on. In the middle of the process, the execution stage, a deficient effort in scheduling and coordination could lead to the absence of quality control personnel while the work is being performed. By the same token, when the job has been performed and the system tested, a lack of scheduling and/or

Table 3. Relevant tasks for the candidate parameter groups

	CCF	FR	UM	TR	RE	MC
Prioritization			X			
Planning	X		X			
Scheduling/ Coordination		X	X	X	X	X
Execution	X	X	X	X		X
Return to normal line-up	X	X	X		X	X

coordination may lead to either a delay in restoring the equipment to its original configuration or an incorrect assumption by plant personnel that the system is operable when, in reality, it may still be off-line.

To summarize then, the organizational factors that affect each task remain the same from one CPG to another; it is the tasks that change between CPGs and, thus, determine the relevant organizational factors for a given CPG.

2.3.2 The SLI methodology

Having the organizational factors that affect each CPG and, therefore, each basic event, WPAM-II proceeds by using the SLI procedure to calculate new MCS frequencies. In general

$$f_{\mathrm{MCS}} = f_{\mathrm{IE}} \cdot \prod_{i=1}^{n} p_i \qquad (2)$$

where

f_{MCS} = the core damage frequency contributed by a minimal cut set,
f_{IE} = the initiating event frequency,
p_i = the probabilities of basic events, allowing for the influence of organizational factors,
n = the number of basic events in a minimal cut set.

At this point, one approach for the determination of the p_i would be to recalculate the (independent) probability for each of the basic events. This approach was suggested by UCLA[16] and used, for example, by the Brookhaven National Laboratory (BNL).[5] However, as was mentioned before, WPAM is focused on modifying MCS frequencies due to organizational dependencies between basic events and considers changes in absolute basic-event probabilities to be second order effects. This, in effect, means that the first basic event is left alone and SLIM is used to reconsider the conditional probability of the second event given that the first event has occurred, and so on. For example, for a MCS with two basic events

$$f_{\mathrm{MCS}} = f_{\mathrm{IE}} \cdot p_1 \cdot p_{2|1} \qquad (3)$$

As was explained earlier, p_1 and $p_{2|1}$ are the probabilities of events that are modelled by candidate parameter groups. As such, they are expressed (in PSA) is terms of these CPGs. For example, for two events involving (consecutive) human errors, p_1 corresponds to γ_0 and $p_{2|1}$ corresponds to γ_1 in the unavailability expressions (see Section 4.2 of Ref. 1). On the other hand, if the second event involves the unavailability of equipment due to maintenance, for example, then the first event is still represented by γ, while the second is represented by the product $f\tau_{\mathrm{m}}$. Clearly, organizational factors can cause dependencies to exist among the CPGs (in this case, γ, f, and τ_{m}) that might not be easily quantifiable in an explicit manner. In cases where a basic event is represented by (a constant multiple of) one CPG only, it is fairly simple to determine the impact of organizational dependencies on CPG values. For the first case discussed above, for instance, $p_{2|1}$ is numerically equal to γ_1, so that the dependence between γ_0 and γ_1 is accounted for by the difference between the old (organizationally independent) and new (organizationally dependent) values of γ for the second event. However, in cases where multiple CPGs are involved, the analysis is not as straightforward. For example, for the second case mentioned above, $p_{2|1}$ corresponds to $f\tau_{\mathrm{m}}$, so that the kinds (and amount) of dependencies that are accounted for are not readily apparent.

There exist situations where $p_{2|1}$ is only an implicit function of the pertinent CPG. For example, for a basic event involving the recovery of offsite power in a station-blackout scenario, the probability of the event is a function of the amount of time that is available for recovery (T_A), which, in turn, is calculated as a function of variables, such as the condition of the station batteries at the time of the accident (see Section 3). In this case, the CPG for this event (T_A) and that for the previous event are coupled, and the dependence (through maintenance) must be accounted for in $p_{2|1}$. As will be discussed shortly, considerations such as this constitute the basis for determining the lower and upper bounds for $p_{2|1}$.

In order to determine the value of $p_{2|1}$, SLIM proceeds by defining a Success Likelihood Index ($\mathrm{SLI}_{2|1}$) as

$$\mathrm{SLI}_{2|1} = \sum_j R_j \, . \, W_j \qquad (4)$$

where

$W_j \equiv$ normalized importance weight with respect to the jth dimension (or organizational factor),
$R_j \equiv$ rating of the jth dimension.

The weights W_j are obtained by asking experts to 'rate' the pertinent organizational factors two at a time (i.e. perform a pairwise comparison) by using the computer-interactive Analytic Hierarchy Process (AHP).[11]

In Section 5 of Ref. 1, AHP was used to rank the pertinent organizational factors according to their importance to (i.e. their level or degree of influence on) the tasks of the work process under analysis. For the current application, another level is added where each task is, in turn, ranked with respect to the candidate parameter group of interest. This is shown pictorially in the hierarchical tree of Fig. 2. Figure 3 specializes this tree to the case where the CPG of interest is 'MC' (miscalibration). The tasks that are relevant to this CPG are scheduling/coordination, execution, and return to normal line-up (from Table 3), and the organizational factors that are deemed to

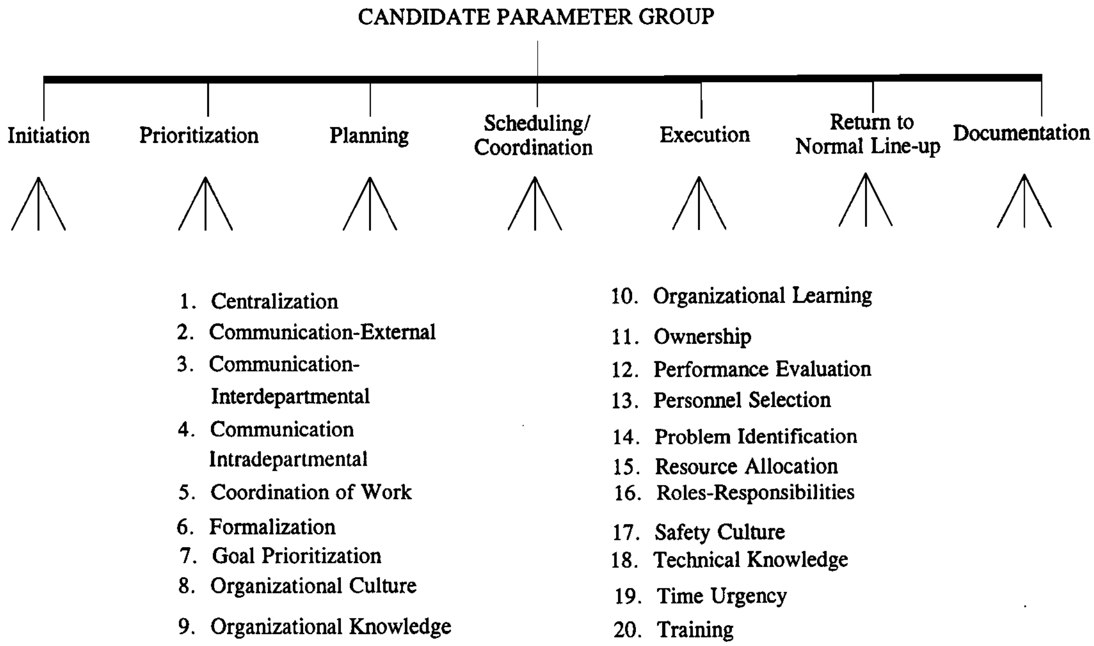

Fig. 2. Generic AHP tree for the candidate parameter group.

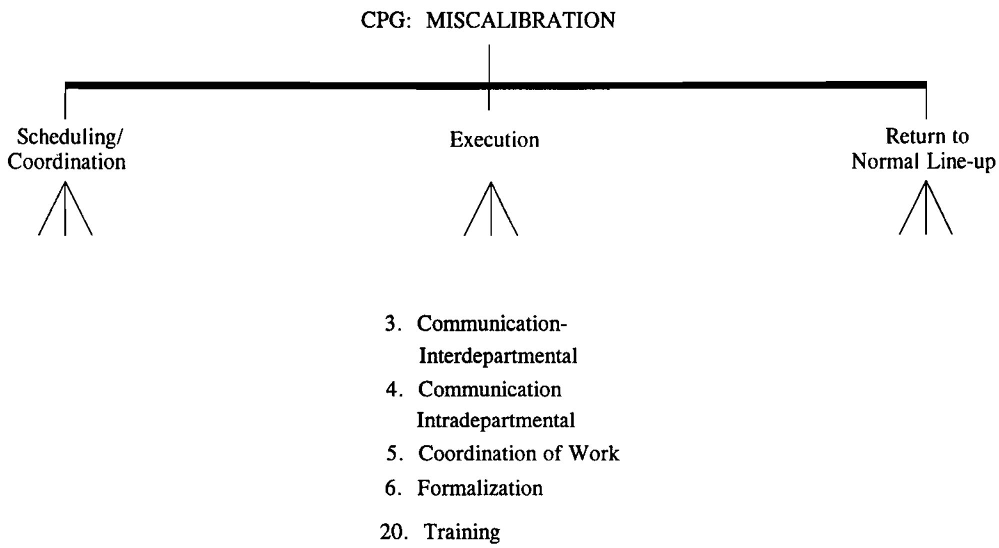

Fig. 3. Simplified AHP tree for 'miscalibration'.

be significant in the performance of these tasks are (narrowed down to) interdepartmental and intradepartmental communication, coordination of work, formalization, and training. Tables 4 to 8 show the entire AHP procedure, including the final weights for the candidate parameter group 'MC'. As before, in the language of AHP, a negative three (for instance) means three times as important, while a positive two means half as important.

The ratings R_j are found using measurement instruments such as Behaviorally Anchored Rating Scales (BARS), structured interviews, research surveys, and behavioral checklists[13,14,17,18] to rate the

Table 4. AHP for the 'MC' candidate parameter group

	Scheduling/ coordination	Execution	Return to normal line-up
Scheduling/ coordination	1.0	1.0	1.0
Execution		1.0	1.0
Return to normal line-up			1.0
Weights	1/3	1/3	1/3

$\lambda_{max} = 3.0$.
C.R. = 0.0.

Table 5. AHP for scheduling/coordination

	Interdepartmental communication	Intradepartmental communication	Coordination of work
Interdepartmental communication	1·0	2·0	−3·0
Intradepartmental communication		1·0	−6·0
Coordination of work			1·0
Weights	0·222	0·111	0·667

$\lambda_{max} = 3{\cdot}0$.
C.R. = 0·0.

Table 6. AHP for execution

	Intradepartmental communication	Formalization	Training
Intradepartmental communication	1·0	−5·0	−5·0
Formalization	—	1·0	1·0
Training	—	—	1·0
Weights	0·091	0·455	0·455

$\lambda_{max} = 3{\cdot}0$.
C.R. = 0·0.

Table 7. AHP for return to normal line-up

	Interdepartmental communication	Formalization	Training
Interdepartmental communication	1·0	1·0	1·0
Formalization		1·0	1·0
Training		1·0	
Weights	1/3	1/3	1/3

$\lambda_{max} = 3{\cdot}0$.
C.R. = 0·0.

performance of a plant on each of the organizational factors that are deemed relevant to plant safety. Normally, a 5-point scale is used, where 1 represents the lowest (worst) score, and 5 represents the highest (best) score. Table 9 (from Ref. 19) shows an example of these ratings for the 20 organizational factors which were used in this study. It is pointed out here that the ratings in Table 9 are fictional and are used for demonstration only.

It is important to note that the weights are obtained for each candidate parameter group, while the ratings are obtained for each department within the plant (Table 9). However, $SLI_{2|1}$ is still event-specific (for event 2) since, once the event is identified, the pertinent candidate group and department are set, as indicated in the event's vector.

Each SLI will result in the probability of an event conditional upon the occurrence of its prior event(s). Considering the first two events of a MCS, a SLI will be calculated for the second event using the performance rating for the second event (i.e. no dependence is accounted for in the ratings). This leaves the weight to show the organizational dependence between the two events. In other words, in calculting the SLI for the second event, neither the weight for event No. 1 nor that for event No. 2 can be used independently. Instead, a combination of these weights has to be used which will bring out the dependence between the two events. In order to accomplish this task, WPAM-II uses the following expression for the effective weight, $W_{2|1,j}$,

$$W_{2|1,j} = \frac{W_{1j} \, . \, W_{2j}}{\sum_j W_{1j} \, . \, W_{2j}} \tag{5}$$

where the subscript $2\,|\,1, j$ means 'the weight for event No. 2 given event No. 1, with respect to the jth organizational factor'. When a third event exists, two effective weights, $W_{3|1,j}$ and $W_{3|2,j}$, are calculated according to eqn (5). For each set of $W_{3|i}$'s, the conditional probabilities $p_{3|1}$ and $p_{2|1}$ are calculated according to the procedure described below; in order to be conservative, the higher $p_{3|i}$ is selected.

Equation (5) is simply one way in which an effective weight can be determined; it was chosen because it has several attractive characteristics. First, by renormalizing the weights, eqn (5) ensures that, when

Table 8. Overall AHP results for the candidate parameter group 'MC'

Weights	Organizational factors	Scheduling/coordination	Execution	Return to normal line-up
0·074	Interdepartmental communication	0·222	0·0	0·0
0·178	Intradepartmental communication	0·111	0·091	0·333
0·222	Coordination of work	0·667	0·0	0·0
0·263	Formalization	0·0	0·455	0·333
0·263	Training	0·0	0·455	0·333

Table 9. An example of the ratings used in the SLI methodology*

	Operations	Instrumentation and control	Maintenance—electrical	Maintenance—mechanical
Centralization	2	2	2	2
External communication	2	2	2	2
Interdepartmental communication	2	2	2	2
Intradepartmental communication	3	2	2	2
Coordination of work	2	2	2	2
Formalization	2	2	1	1
Goal prioritization	2	1	1	1
Organizational culture	1	2	2	2
Organizational learning	1	1	1	1
Organizational knowledge	2	2	2	2
Ownership	1	2	1	1
Performance evaluation	2	2	2	2
Personnel selection	2	3	3	3
Problem identification	2	1	1	1
Resource allocation	2	1	1	1
Roles—responsibilities	2	2	2	2
Safety culture	2	2	2	2
Technical knowledge	3	3	2	2
Time urgency	2	2	1	1
Training	2	2	2	2

* Based on a scale from 1 (worst) to 5 (best).

two events have high importance weights for a given organizational factor, the effect of the similarity will be magnified. That is, a high amount of dependence is accounted for between the two events. Conversely, when a given organizational factor is important for one event and not for the other, eqn (5) reduces the effect, so that a lower amount of dependence exists between the two events. Also, as a check, if both $W_{1,j}$ and $W_{2,j}$ are equal to 0·5, then $W_{2|1,j}$ will also be equal to 0·5. Lastly, if the weight is 0·0 for one event (i.e. the organizational factor is not important at all) and 1·0 for the other (i.e. the organizational factor is extremely important), then $W_{2|1,j}$ will be 0·0 since no (organizational) dependence exists. This means that, in this case, the original basic-event probabilities can be used.

Having determined $\mathrm{SLI}_{2|1}$ with the aid of eqns (4) and (5), the conditional probability of the second event, $p_{2|1}$, is calculated as

$$\log(p_{2|1}) = a \,.\, \mathrm{SLI}_{2|1} + b \tag{6}$$

where a and b are calibration constants (or anchor points) and are determined by

$$\log(p_2) = a \,.\, (\mathrm{SLI}_{2|1} = 5) + b \tag{7}$$

and

$$\log(p_u) = a \,.\, (\mathrm{SLI}_{2|1} = 1) + b \tag{8}$$

with

$p_2 \equiv$ the lower anchor point, which is assumed to be equal to the organizationally independent probability of event 2,

$p_u \equiv$ the upper anchor point.

Equations (7) and (8) are interpreted as follows: if the ratings for the plane are the best that they can be, i.e. equal to five, then $p_{2|1} = p_2$, its independent probability with no organizational dependence. On the other hand, if the ratings are the worst that they can be, i.e. equal to one, then $p_{2|1} = p_u$, containing the highest degree of organizational dependence.

As a general rule in this analysis, the value of p_u is assumed to be equal to 0·5, if events one and two involve similar activities, and 0·1, if they involve different activities. It is worth mentioning that, within the framework of the methodology presented in Ref. 20, the former corresponds to a high level of dependence (HD) and the latter corresponds to a level of dependence that is slightly lower than moderate (MD ≡ 0·14). The rationale behind the assignment of these numbers is that, since a nuclear power plant is governed by an overall 'culture', it is quite difficult for two activities within the same work process (and department) to be completely organizationally independent. For the case of similar activities, for example, it is judged that, although complete dependence (i.e. $p_u = 1{\cdot}0$) may be uncalled for, complete independence is also not realistic, since there is a fairly high amount of dependence that is introduced through factors such as shared procedures, common training programs, and the like. Still, as will be shown in the example of the next section, allowances are made for specific cases to deviate from the general 'rules' discussed here.

Clearly, the determination of the anchor points involves a certain degree of subjectivity and could very well be case-specific (see Section 3, for example). However, even if case-specific anchor points are determined, the following question might still exist: 'what if p_2 is already assigned a value that is higher than its independent value?' In other words, what if, for two similar human actions, p_1 is assumed to have the value 0·001, for example, and p_2 the value 0·14, corresponding to the case of moderate dependence in Ref. 20. In this case, could WPAM still be applied without double-counting? That is, if the lower and upper anchor points are taken to be 0·14 and 0·5, respectively, then $p_{2|1}$ would have a value that is greater than 0·14. This, of course, may be fine, if the value 0·14 contains no allowances for organizational dependence between the two human actions. On the other hand, if such a dependence is reflected in this value for p_2, then the use of WPAM could result in double-counting the dependence.

A major problem that arises in resolving this issue is that the factors that go into the determination (and conversion to numerical values) of the various levels of dependence, such as those presented in Ref. 20, are not explicit. Therefore, on face value, it cannot be deciphered whether the use of WPAM would cause certain influences to be double-counted. One method of reconciliation, of course, would be to start the whole analysis from the beginning. That is, one could take p_1 and p_2 to be completely (organizationally) independent (i.e. $p_2 = p_1 = 0{\cdot}001$ in this example) so that one could apply WPAM knowing that, *a priori*, no organizational dependencies are accounted for—this, in fact, happens to be the case in the example of Section 3. Obviously, more research needs to be performed, before this matter can be resolved in a definitive manner.

Once the minimal-cut-set frequencies in all sequences have been modified, a new core damage frequency (CDF) must be calculated. As has been mentioned before, the number of MCS in a typical PSA or IPE runs into the thousands, which makes the need for computational tools indispensable. At present, only a preliminary computer code has been developed which does not allow a comprehensive recalculation of all the MCS frequencies and, thus, the CDF. For this reason, in the sample case presented in the next section, the frequency of only one (dominant) MCS is recalculated.

3 SAMPLE CASE

3.1 Background

In order to demonstrate the methodology of WPAM-II, a sample case is presented in this section. The example which is used is taken from an IPE and involves the analysis of a MCS contained in one of the station blackout dominant accident sequences leading to core damage.

The IPE contains 16 dominant accident sequences, with a total of about two thousand minimal cut sets. In particular, the station blackout accident sequence contains 150 MCS, with a (sequence) frequency of $6{\cdot}17 \times 10^{-7}$ per reactor year. For demonstration purposes, only this accident sequence was chosen and, for this sequence, only the top 25 and the bottom 25 MCS were retained for further analysis. As they stand, the bottom 25 MCS contribute the least to the overall sequence frequency; the purpose for re-examining them was to determine whether the potential impact of organizational factors on their frequencies could be large enough so that they would move to the top of the sequence (i.e. whether, due to organizational dependencies, they would have the potential to make a larger contribution to the sequence frequency).

In the analysis that follows, the treatment is guided by the procedure that was outlined in the previous section and which is shown pictorially in Fig. 1.

3.2 Minimal cut set screening

The fifty MCS which were retained were assigned basic-event vectors and rated for organizational dependence as described in Section 2.2 above. Tables 10 and 11 contain the overall dependence ratings for all basic-event combinations along with the minimum

Table 10. Overall ratings for the top 25 minimal cut sets

MCS No.	R (1–2)	R (1–3)	R (2–3)	R (MIN)	R (MAX)
1	0·0005	—	—	0·0005	0·0005
2	0·0005	—	—	0·0005	0·0005
3	0·005	0·0005	0·005	0·0005	0·005
4	0·005	0·005	0·0005	0·0005	0·005
5	0·025	0·005	0·001	0·001	0·025
6	0·005	0·001	0·005	0·001	0·005
7	0·005	0·0005	0·005	0·0005	0·005
8	0·025	0·005	0·001	0·001	0·025
9	0·005	0·001	0·005	0·001	0·005
10	0·100	0·0005	0·0005	0·0005	0·100
11	0·005	0·005	0·0005	0·0005	0·005
12	0·0005	—	—	0·0005	0·0005
13	0·0005	—	—	0·0005	0·0005
14	0·001	0·0005	0·001	0·0005	0·001
15	0·001	0·001	0·0005	0·0005	0·001
16	0·001	0·0005	0·001	0·0005	0·001
17	0·001	0·001	0·0005	0·0005	0·001
18	0·005	0·0005	0·005	0·0005	0·005
19	0·0005	0·0005	0·010	0·0005	0·010
20	0·005	0·0005	0·0005	0·0005	0·005
21	0·005	0·0005	0·0005	0·0005	0·005
22	1·00	0·001	0·001	0·001	1·00
23	0·005	0·001	0·001	0·001	0·005
24	0·005	0·001	0·001	0·001	0·005
25	1·00	0·001	0·001	0·001	1·00

Table 11. Overall rating for the bottom 25 minimal cut sets

MCS No.	R (1–2)	R (1–3)	R (2–3)	R (MIN)	R (MAX)
126	0·005	0·005	0·001	0·0005	0·005
127	0·005	0·001	0·0005	0·0005	0·005
128	0·001	0·0005	0·001	0·0005	0·001
129	0·001	0·001	0·0005	0·0005	0·001
130	0·005	0·005	0·0005	0·0005	0·005
131	0·005	0·0005	0·005	0·0005	0·005
132	0·005	0·0005	0·001	0·0005	0·005
133	0·005	0·0005	0·001	0·0005	0·005
134	0·005	0·0005	0·001	0·0005	0·005
135	0·005	0·0005	0·001	0·0005	0·005
136	0·005	0·001	0·0005	0·0005	0·005
137	0·005	0·001	0·0005	0·0005	0·005
138	0·005	0·005	0·001	0·001	0·005
139	0·050	0·0005	0·0005	0·0005	0·005
140	0·050	0·0005	0·0005	0·0005	0·050
141	0·005	0·005	0·001	0·001	0·005
142	0·005	0·005	0·001	0·001	0·005
143	0·001	0·0005	0·001	0·0005	0·001
144	0·001	0·001	0·0005	0·0005	0·001
145	0·001	0·0005	0·001	0·0005	0·001
146	0·001	0·001	0·0005	0·0005	0·001
147	0·005	0·005	0·0005	0·0005	0·005
148	0·010	0·0005	0·0005	0·0005	0·010
149	0·010	0·0005	0·0005	0·0005	0·010
150	0·010	0·0005	0·0005	0·0005	0·010

and maximum values of R for each MCS. Furthermore, Table 12 shows is descending order, the ranking of each MCS according to its R(MAX). Several comments must be made with regard to these tables. First, the MCS which have moved to the top involve similar as well as dissimilar actions and/or components. For example, MCS No. 22 involves two human actions of miscalibration and a third event involving the recovery of offsite power within 13 h. Similarly, MCS No. 25 contains two human failures in restoring manual valves after testing and the same recovery action as in No. 22. Second, as was suspected, at least two MCS, No. 139 and 140, moved up. This is due to the fact that the first two basic events in each of these MCS involve the failure of a pump to start and the failure of a redundant pump to continue running. Again, common test and maintenance practices are regarded as the factors that cause these basic events to be coupled. Finally, the four MCS ranked 47 to 50 involve common-mode failures of equipment, so that, as compared to the rest of the MCS, they would be expected to show lower amounts of organizational dependence.

As was discussed in Section 2, the truncation (or cut-off) point is determined as a function of many variables. For example, based on Table 12, a truncation value of 0·05 would eliminate 45 of the original 50 MCS from further analysis. On the other hand, if the cut-off value is lowered to 0·005, only 14

Table 12. Minimal cut set ranks according to R (MAX)

MCS RANK	MCS NO.	R (MIN)	R (MAX)
1	22	0·0010	1·00
2	25	0·0010	1·00
3	10	0·0005	0·100
4	139	0·0005	0·050
5	140	0·0005	0·050
6	5	0·0010	0·025
7	8	0·0010	0·025
8	19	0·0005	0·010
9	148	0·0005	0·010
10	149	0·0005	0·010
11	150	0·0005	0·010
12	3	0·0005	0·005
13	4	0·0005	0·005
14	6	0·0010	0·005
15	7	0·0005	0·005
16	9	0·0010	0·005
17	11	0·0005	0·005
18	18	0·0005	0·005
19	20	0·0005	0·005
20	21	0·0005	0·005
21	23	0·0010	0·005
22	24	0·0010	0·005
23	126	0·0005	0·005
24	127	0·0005	0·005
25	130	0·0005	0·005
26	131	0·0005	0·005
27	132	0·0005	0·005
28	133	0·0005	0·005
29	134	0·0005	0·005
30	135	0·0005	0·005
31	136	0·0005	0·005
32	137	0·0005	0·005
33	138	0·0010	0·005
34	141	0·0010	0·005
35	142	0·0010	0·005
36	147	0·0005	0·005
37	14	0·0005	0·001
38	15	0·0005	0·001
39	16	0·0005	0·001
40	17	0·0005	0·001
41	128	0·0005	0·001
42	129	0·0005	0·001
43	143	0·0005	0·001
44	144	0·0005	0·001
45	145	0·0005	0·001
46	146	0·0005	0·001
47	1	0·0005	0·0005
48	2	0·0005	0·0005
49	12	0·0005	0·0005
50	13	0·0005	0·0005

of the original 50 MCS will be screened out. As was mentioned before, for the present example, only one MCS was kept for requantification, namely, MCS No. 22.

It is important to re-evaluate the screening results before continuing with the quantification process (step 2.4 in Fig. 1). In this example, it is apparent from Table 12 that any truncation value that is less than or equal to 0·10 will not screen out MCS No. 10. This is significant in that MCS No. 10 involves the failure of two redundant pumps to continue running. As such, it has already been modelled as a single common-cause event (in MCS No. 1) and, thus, should be eliminated from further analysis.

With the truncation value applied and the re-evaluation performed, the methodology proceeds with the quantification process. As was mentioned before, in this analysis, only one MCS (No. 22) is taken through this process.

3.3 Quantification

Minimal cut set No. 22 can be represented as follows

$$T1 * MC1 * MC2 * \text{NR-LOSP-13HR}$$

In words, the MCS starts with the loss of offsite power (T1), followed by the loss of emergency ac power (MC1 * MC2), and the failure to recover offsite power within 13 hours (NR-LOSP-13HR), where the 13-hour time period accounts for the depletion of the station batteries in 8 hours followed by core damage 5 hours later. The cause of the loss of emergency ac power is the miscalibration of relays on redundant busses. Both MC1 and MC2 are failures due to miscalibration, which occur most often during the maintenance work process. Both activities are conducted by the instrumentation and control department and the two events involve identical procedures and similar execution steps. It is expected that these two events will be strongly coupled. On the other hand, MC1 and NR-LOSP-13HR (or MC2 and NR-LOSP-13HR) are only similar to the extent that their occurrence is maintenance-process related. Consequently, loose coupling is expected in this case.

The basic-event vectors are:

event No. (MC1): (MP, MC, IC, MC1)
event No. 2 (MC2): (MP, MC, IC, MC2)
event No. 3 (NR-LOSP-13HR): (MP, TR, ME, NR-LOSP13HR)

where

MP ≡ Maintenance Process (for the work process)
MC ≡ Miscalibration (for the CPG)
TR ≡ Available time for recovery (for the CPG)
IC ≡ Instrumentation and control (for the working unit)
ME ≡ Maintenance-electrical (for the working unit)

In the IPE, the same probability (3×10^{-3}) is used for both events Nos 1 and 2. That is, the failures to correctly calibrate component No. 1 (MC1) and component No. 2 (MC2) are assumed to be independent. As mentioned before, in WPAM-II, the first basic event is left alone and SLIM is used to reconsider the conditional probability of the second event given that the first event has occurred.

In order to calculate $p_{2|1}$, an effective weight must be determined which, in turn, requires the calculation of weights for the candidate parameter groups representing the two basic events. Table 13 contains a simplified representation of the weights for all of the CPGs. The weights were calculated by following the same AHP procedure that generated the results in Tables 4 through 8, so that a table analogous to Table 8 was obtained for each of the six CPGs. For example, the weights for the CPG 'MC' (in the last column of Table 13) are taken from the first column in Table 8. Table 13 is called 'simplified' because, in this example,

Table 13. Final candidate-parameter-group weights

Organizational factor	CCF	FR	UM	TR	RE	MC
Centralization						
External communication						
Interdepartmental communication	0·079	0·086	0·121	0·167	0·141	0·074
Intradepartmental communication	0·087	0·047	0·073	0·106	0·027	0·178
Coordination of work		0·114	0·148	0·50	0·090	0·222
Formalization	0·338	0·290	0·263	0·114	0·292	0·263
Goal prioritization						
Organizational culture						
Organizational learning						
Organizational knowledge						
Ownership						
Performance evaluation						
Personnel selection						
Problem identification						
Resource allocation	0·049		0·023			
Roles—responsibilities						
Safety culture						
Technical knowledge	0·167	0·172	0·155		0·158	
Time urgency			0·062			
Training	0·280	0·290	0·156	0·114	0·292	0·263

only a limited number of organizational factors were considered for each CPG.

The weights in Table 13 must now be used in conjunction with eqn (5) in order to calculate an effective weight. From the basic-event vectors shown above, the CPG for both events Nos 1 and 2 is 'MC', so that, using the last column in Table 13, the effective weight with respect to each organizational factor (OF) is calculated as shown in Table 14, where OFs Nos 3, 4, 5, 6, and 20 are interdepartmental communication, intradepartmental communication, coordination of work, formalization, and training, respectively (see Table 13).

Next, eqn (4) is used to calculate $SLI_{2|1}$. Again, referring to the basic-event vectors, it can be seen that instrumentation and control is identified as the working unit for both events. Then, using the ratings given in Table 9 for the I & C department, $SLI_{2|1}$ is calculated as

$$\begin{aligned} SLI_{2|1} &= (2)(0{\cdot}0243) + (2)(0{\cdot}1410) + (2)(0{\cdot}2193) \\ &\quad + (2)(0{\cdot}3077) + (2)(0{\cdot}3077) \\ &= 2{\cdot}0 \end{aligned}$$

As was discussed before, for the case of similar actions

$$p_2 = 3 \times 10^{-3} < p_{2|1} < p_u = 0{\cdot}50$$

Therefore, using eqns (6) through (8), a value of 0·139 is calculated for $p_{2|1}$. It is interesting to note that, with regard to the Handbook of Human Reliability Analysis,[20] this value corresponds to moderate dependence (MD). As can be seen, the value of $p_{2|1}$ increased from 0·003 to 0·139 due to the influence of organizational factors only. This means that it could rise even higher with the inclusion of other types of dependencies. This, again, hints to the importance of the way in which the anchor points are derived, i.e. the considerations that are included in the numerical values of the anchor points.

Before continuing with the calculation of the conditional probability for the third event, it is important to note that what is being coupled here is the available time for recovery, represented by the CPG 'T_A' ('TR'), and a human error of miscalibration, represented by 'γ' ('MC'). However, T_A itself is a function of the life of the station batteries and is calculated using several factors, including the condition of the batteries at the time of the accident. This makes sense because, if station batteries are not maintained well, they may become depleted much faster than expected. This hastens the occurrence of core damage which, in turn, means that the actual time that is available for the recovery of offsite power is not 13 hours (for this example), but less. This, of course, translates into a higher probability for the non-recovery event. This is why Paula states,[4] with regard to battery-terminal-connection-detail faults, that 'the likelihood of these failure mechanisms occurring is directly related to the quality of the utility's checking, testing, and maintenance activities; human errors (either of commission or omission) are likely to be involved, if these failure mechanisms cause battery unavailability.' The same author further states that 'actual battery failures that are due to internal faults are also related to the quality of the checking, testing, and maintenance activities of the utility; again, human errors are likely to be involved if these failure mechanisms cause battery unavailability.' Clearly, the quality of maintenance is the underlying factor that causes T_A and γ to be coupled.

The conditional probability for the third event (i.e. the non-recovery of loss of offsite power within 13 h) is calculated in a similar fashion as that for $p_{2|1}$. In the present version of WPAM-II, this conditional probability is determined by computing two conditional probabilities ($p_{3|1}$ and $p_{3|2}$) for the third event and then conservatively using the one with the larger value. In general, this involves two separate calculations. However, for the present example, only one calculation is needed since events Nos 1 and 2 are identical and, thus, $p_{3|1} = p_{3|2}$.

Using Table 13 (for the CPGs 'MC' and 'TR') and eqn (5) again, the resultant effective weights are as shown in Table 15.

As was discussed in Section 2.3.2, no dependence is accounted for through the ratings, so that the working unit of the dependent event is always used in determining the ratings. Therefore, using Table 9 (for the maintenance-electrical unit) along with eqn (4),

Table 14. Calculation of the effective weights $W_{2|1,j}$

OF No.	MC1	MC2	$W_{1j} * W_{2j}$	$W_{2|1,j}$
3	0·074	0·074	0·0055	0·0243
4	0·178	0·178	0·0317	0·1410
5	0·222	0·222	0·0493	0·2193
6	0·263	0·263	0·0692	0·3077
20	0·263	0·263	0·0692	0·3077

$\sum W_{1j} * W_{2j} = 0{\cdot}2248$

Table 15. Calculation of the effective weights $W_{3|1,j}$

OF No.	MC1/MC2	NR-LOSP-13HR	$W_{1j} * W_{3j}$	$W_{3|1,j}$
3	0·074	0·167	0·0123	0·061
4	0·178	0·106	0·0189	0·094
5	0·222	0·500	0·1110	0·549
6	0·263	0·114	0·0300	0·148
20	0·263	0·114	0·0300	0·148

$\sum W_{1j} * W_{3j} = 0{\cdot}2022$

$SLI_{3|1}$ is calculated as:

$$\begin{aligned} SLI_{3|1} &= (2)(0{\cdot}061) + (2)(0{\cdot}094) + (2)(0{\cdot}549) \\ &\quad + (1)(0{\cdot}148) + (2)(0{\cdot}148) \\ &= 1{\cdot}852 \end{aligned}$$

The IPE value for the probability of the third event is $1{\cdot}3 \times 10^{-2}$. As mentioned above, this value (through the CPG 'T_A') is a function of the condition of the station batteries. The relationship may be clarified as follows: In the IPE, the station batteries are assumed to run (with a probability of 1·0) for at least 8 h. Then, allowing 5 hours between the time of battery depletion and core damage, Fig. 4 is used to determine the probability of non-recovery of loss of offsite power within the total of 13 h.

The upper bound suggested earlier for p_u was 0·1, However, this is too high a value since, as can be seen from Fig. 4 (which reflects industrial experience), it corresponds to a total time of about 2·5 hours, a situation which is not likely to be encountered within the context of the sequence that is being studied. However, pursuant to the above discussions, some dependence must be accounted for. It is also mentioned in passing (since the present analysis does not deal with dynamic situations) that another factor for which credit is usually taken by IPEs in the calculation of T_A is the shedding of excess loads off the dc busses, so that battery life can be extended for as long as possible. That is, the batteries are not designed for 8 hours. Since in shedding the loads the operators must act under accident conditions, it is not clear whether it can be taken for granted that they will shed the correct loads, at the correct time, and in a timely manner.

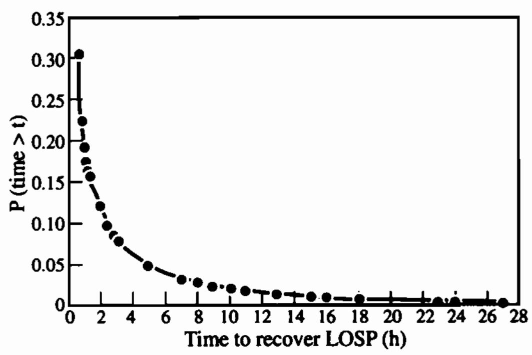

Fig. 4. Recovery curve for loss of offsite power (LOSP).

In the sensitivity analyses performed in the IPE, one of the calculations involves the reduction of battery depletion time by one half. That is, battery depletion is assumed to occur at 4 hours, with core damage (i.e. non-recovery of offsite power) occurring at 8 hours into the accident. For the purposes of the present example, this case was used as the worst-case scenario, so that, referring to Fig. 4, the value of the upper anchoring point was determined to be $2{\cdot}7 \times 10^{-2}$ for a total time of 8 hours. Therefore,

$$p_2 \times 1{\cdot}3 \times 10^{-2} < p_{3|1} < p_u = 2{\cdot}7 \times 10^{-2}$$

and, using eqns (6) through (8), a value of $2{\cdot}31 \times 10^{-2}$ is obtained for $p_{3|1}$, i.e. the probability of non-recovery of loss of offsite power within 13 h, given the miscalibration in event No. 1.

As can be seen from Table 16, based on the values just obtained, the new MCS frequency (accounting for the initiating event T_1) is $5{\cdot}5 \times 10^{-7}$ as compared to the IPE value of $6{\cdot}7 \times 10^{-9}$, a factor of about 100, which is due primarily to the increase in the probability of MC2.

The impact of the increase in the MCS frequency on the overall core damage frequency (CDF) is estimated in three ways. First, method 1 determines the effect of this MCS alone on the CDF. In this case, the old MCS frequency is subtracted from, and the new MCS frequency is added to the IPE CDF. For this example, this results in a new CDF of $2{\cdot}44 \times 10^{-6}$ as opposed to the IPE CDF of $1{\cdot}90 \times 10^{-6}$. The second method is based on preliminary studies that were done only on the sequence under analysis which showed that, if the top 4 or 5 MCS that survived the screening process were requantified, then the overall sequence frequency would be comparable to about 2·5 times the probability of the top MCS (i.e. No. 22). Therefore, for the second estimate, the new MCS probability is multiplied by a factor of 2·5 to give the new sequence frequency. The difference between this value and the

Table 16. Comparison of results from the IPE and the sample case

	IPE quantification	Present analysis
T1	$5{\cdot}7 \times 10^{-2}$	5.7×10^{-2}
MC1	$3{\cdot}0 \times 10^{-3}$	$3{\cdot}0 \times 10^{-3}$
MC2	$3{\cdot}0 \times 10^{-3}$	$1{\cdot}4 \times 10^{-1}$
NR-LOSP-13HR	1.3×10^{-2}	2.3×10^{-2}
MCS frequency (per ryr)	6.7×10^{-9}	$5{\cdot}5 \times 10^{-7}$
Core damage frequency (per reactor year)	$1{\cdot}9 \times 10^{-6}$	$2{\cdot}4 \times 10^{-6}$ (Est. No. 1) $2{\cdot}7 \times 10^{-6}$ (Est. No. 2) $4{\cdot}2 \times 10^{-6}$ (Est. No. 3)

IPE sequence frequency is then added to the IPE CDF to give the new CDF. For the present example, this method resulted in a CDF of $2{\cdot}66 \times 10^{-6}$. Finally, for the third estimate, all sequences were assumed to be affected by the same factor that was calculated for the sequence under investigation. Therefore, the new CDF was obtained by multiplying the IPE CDF by the ratio of the new sequence frequency (with the 2·5 factor) to the IPE sequence frequency. This yielded a new CDF of $4{\cdot}23 \times 10^{-6}$. Estimate No. 3, then, resulted in the largest change, where the IPE CDF basically doubled.

4 RISK MANAGEMENT

Sensitivity analyses were performed on both the ratings (Table 9) and the anchor points. Whereas the former is useful in risk management, the latter gauges the effects of changes in p_u on the CDF. The analyses were performed using the example of the previous section as the base case. Also, estimate No. 3 was used for the CDF value. Of course, in a real application, the results should include an uncertainty analysis before the sensitivity calculations are done. Such an uncertainty analysis, however, is not within the scope of this work.

The ratings, such as those in Table 9, are indicative of the 'well being' of an NPP organization. When the ratings are moderate to high (i.e. 3, 4, or 5), plant risk, as indicated by the CDF, is minimized. On the other hand, when the ratings are low (i.e. 1 or 2) the plant faces a higher amount of risk. The purpose for performing sensitivity analyses on the ratings is to rank the organizational factors in terms of their effect on plant risk. Once this is done, the results can be used to guide the direction of organizational improvements and the allocation of resources. Similar procedures are employed in other areas as well. For example, in fire risk analysis, PRA results are used to identify different levels of contributors to (fire) risk which, then, allows for the evaluation of possible options for the reduction of this risk.[21] In the present study, the organizational factors are the 'contributors to risk'.

Table 17 contains the results of the sensitivity analysis on the ratings. As can be seen, when all of the ratings are raised to a value of '3', the CDF is already reduced to its lowest value (i.e. the IPE CDF). Normally, this would be expected to occur when the ratings are all raised to 4 or 5 (for the case in which the anchor point for the IPE values is set at plant ratings corresponding to 5). However, it must be remembered that the estimates used in this analysis are very coarse.

It may be argued that, if the ratings are in fact indicative of the NPP's well being, then improving all

Table 17. Sensitivity analysis on the ratings using estimate No. 3 for the VDF

	MCS frequency	Core damage frequency
IPE results	$6{\cdot}7 \times 10^{-9}$	$1{\cdot}9 \times 10^{-6}$
Base case—original rates	$5{\cdot}5 \times 10^{-7}$	$4{\cdot}2 \times 10^{-6}$
All ratings raised to '3'	$1{\cdot}24 \times 10^{-7}$	$1{\cdot}9 \times 10^{-6}$
Interdepartmental communication (3)	$5{\cdot}3 \times 10^{-7}$	$4{\cdot}1 \times 10^{-6}$
Intradepartmental communication (3)	$4{\cdot}5 \times 10^{-7}$	$3{\cdot}5 \times 10^{-6}$
Coordination of work (3)	$3{\cdot}8 \times 10^{-7}$	$2{\cdot}9 \times 10^{-6}$
Formalization (3)	$3{\cdot}5 \times 10^{-7}$	$2{\cdot}7 \times 10^{-6}$
Training (3)	$3{\cdot}6 \times 10^{-7}$	$2{\cdot}8 \times 10^{-6}$
Inter- & intradepartmental communication (3)	$4{\cdot}3 \times 10^{-7}$	$3{\cdot}3 \times 10^{-6}$
Formalization and training (3)	$2{\cdot}3 \times 10^{-7}$	$1{\cdot}9 \times 10^{-6}$

of the ratings to '5' should result in a value for the CDF that is lower than that in the IPE. In other words, why should the IPE value be the lower limit? The answer to this question points again to the level of subjectivity that is involved in the determination of the anchor points, since the ratings and the anchor points are intimately connected through eqns (6), (7), and (8). For the purposes of the sample case, the IPE was assumed to represent the best (organizational) scenario, where the probabilities reflect zero organizational dependence among the basic events. However, improvements beyond the IPE level of risk are not inconceivable. For example, it could be that the numbers used in the IPE represent more than a zero level of organizational dependence. In this case, these numbers would not be used as the lower anchor points. This would mean that risk reduction beyond the IPE would be possible by making organizational improvements in the most important areas.

In this example, improvements in formalization, training, and co-ordination of work seem to be more advantageous in terms of risk reduction than improvements in communications (Table 17). For instance, if formalization (e.g. the quality of procedures, etc.) in the plant can be improved enough so that it can receive a rating of 3 (as compared with the current 2), then, this action alone would decrease the CDF from $4{\cdot}2 \times 10^{-6}$ per ryr. to $2{\cdot}7 \times 10^{-6}$ per ryr., an improvement of about a factor of 2. On the other hand, when cost effectiveness is considered, a utility might decide that some improvement in several factors is more effective.

Tables 18 and 19 contain sensitivity analyses for the upper anchor points for the two kinds of events encountered in the base case. In each table, the MCS frequency and the CDF are calculated by varying only one of the upper anchor points at a time. For example, in Table 18, the upper anchor point for the third event is kept constant at its base-case value of

Table 18. Sensitivity on the upper anchoring point for the miscalibration event

	MCS frequency	Core damage frequency
IPE results	$6{\cdot}7 \times 10^{-9}$	$1{\cdot}9 \times 10^{-6}$
Base case ($p_u = 0{\cdot}5$)	$5{\cdot}5 \times 10^{-7}$	$4{\cdot}2 \times 10^{-6}$
$p_u = 0{\cdot}003$	$1{\cdot}2 \times 10^{-8}$	$1{\cdot}9 \times 10^{-6}$
$p_u = 0{\cdot}050$	$9{\cdot}8 \times 10^{-8}$	$1{\cdot}9 \times 10^{-6}$
$p_u = 0{\cdot}100$	$1{\cdot}6 \times 10^{-7}$	$1{\cdot}9 \times 10^{-6}$
$p_u = 0{\cdot}200$	$2{\cdot}8 \times 10^{-7}$	$2{\cdot}1 \times 10^{-6}$
$p_u = 0{\cdot}300$	$3{\cdot}7 \times 10^{-7}$	$2{\cdot}9 \times 10^{-6}$
$p_u = 0{\cdot}400$	$4{\cdot}7 \times 10^{-7}$	$3{\cdot}6 \times 10^{-6}$
$p_u = 0{\cdot}600$	$6{\cdot}3 \times 10^{-7}$	$4{\cdot}9 \times 10^{-6}$
$p_u = 0{\cdot}750$	$7{\cdot}5 \times 10^{-7}$	$5{\cdot}7 \times 10^{-6}$
$p_u = 0{\cdot}900$	$8{\cdot}5 \times 10^{-7}$	$6{\cdot}6 \times 10^{-6}$
$p_u = 1{\cdot}000$	$9{\cdot}2 \times 10^{-7}$	$7{\cdot}1 \times 10^{-6}$

Table 19. Sensitivity analysis on the upper anchoring point for the non-recovery event

	MCS frequency	Core damage frequency
IPE results	$6{\cdot}7 \times 10^{-9}$	$1{\cdot}9 \times 10^{-6}$
Base case ($p_u = 0{\cdot}027$)	$5{\cdot}5 \times 10^{-7}$	$4{\cdot}2 \times 10^{-6}$
$p_u = 0{\cdot}013$	$3{\cdot}1 \times 10^{-7}$	$2{\cdot}4 \times 10^{-6}$
$p_u = 0{\cdot}020$	$4{\cdot}3 \times 10^{-7}$	$3{\cdot}3 \times 10^{-6}$
$p_u = 0{\cdot}025$	$5{\cdot}2 \times 10^{-7}$	$4{\cdot}0 \times 10^{-6}$
$p_u = 0{\cdot}030$	$6{\cdot}0 \times 10^{-7}$	$4{\cdot}6 \times 10^{-6}$
$p_u = 0{\cdot}035$	$6{\cdot}7 \times 10^{-7}$	$5{\cdot}2 \times 10^{-6}$
$p_u = 0{\cdot}040$	$7{\cdot}5 \times 10^{-7}$	$5{\cdot}8 \times 10^{-6}$
$p_u = 0{\cdot}045$	$8{\cdot}2 \times 10^{-7}$	$6{\cdot}3 \times 10^{-6}$
$p_u = 0{\cdot}050$	$8{\cdot}9 \times 10^{-7}$	$6{\cdot}9 \times 10^{-6}$

0·027. As can be seen from both tables, the CDF rises almost linearly with corresponding increases in p_u.

5 SUMMARY AND DISCUSSION

In this paper, the details of WPAM-II were discussed and, using WPAM-I and its products, the entire Work Process Analysis Model was applied to a sample case in order to both qualitatively describe and quantitatively determine the degree to which organizational factors act as common causes of hardware and/or human failures. It was made clear that, within the framework of WPAM, organizational factors are perceived to exert their influence on plant safety through the work processes which, themselves, influence the candidate parameter groups used in the assessment of risk in PSA. With this as the theoretical background, the actual dependence among the candidate parameter groups was accounted for by recalculating the probabilities of the basic events that are represented by the CPGs. It was shown that, based on preliminary estimates, the common-cause effect of organizational factors on basic-event probabilities could cause the overall core damage frequency to double.

Admittedly, the quantification process contains a certain amount of subjectivity, especially with regard to the determination of the anchor points. In order to explore the effects of the choice of anchoring points on the core damage frequency, sensitivity analyses were performed which showed that the relationship between the upper anchor point and the CDF is almost linear. Sensitivity analyses were also performed for the ratings and the results illustrate the potential utility of this method in the allocation of resources in risk management. For example, it was shown that, in this specific case, a simultaneous improvement in both formalization and training would reduce plant risk significantly. On the other hand, improving inter- and intradepartmental communication together would have lower risk-reduction potential.

At this point, several suggestions are made for future research. First, no uncertainty analysis was performed in this study. It is expected that the uncertainty in the WPAM results will be large because the data for the analysis are largely obtained through expert judgment. Even though what has been proposed and demonstrated in the present study may be considered a good start, it is clear that the performance of an uncertainty analysis is essential to the furtherance of what has been accomplished so far. Second, computational tools are needed which can carry out the procedure in a more comprehensive manner. This, of course, goes hand in hand with the development of rigorous algorithms through which the impact of organizational factors on a single minimal cut set can be translated to the impact on the overall core damage frequency. Finally, an important task for the future involves the extension of this work to a broader range of work processes and even non-work-process related scenarios.

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