RESIDUAL UNCERTAINTY IN CABLE LOCATIONS FOR FIRE HAZARD ASSESSMENTS

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ABSTRACT

In this work, a statistical model is constructed for the cable route locating process (CRLP) used in fire hazard assessments and probabilistic safety assessments for nuclear power plants. The objective is to estimate the probability of residual errors in the cable locations obtained from the process. The effect of the possible cable routing errors (CREs) on the fire hazard assessment is then quantified in terms of the probability of resulting failure of defence in depth on which the assessment is based. The potential risk due to the CREs is discussed in terms of the probability of a loss of redundant safety functions for the plant. Three strategies are proposed: to include the effect of CREs in the overall plant risk assessment, to mitigate the risk with conservative and proven measures in the fire hazard assessment, and to reduce the risk throughout the lifetime of the plant by improving and controlling the quality of the CRLP.

1. INTRODUCTION

Fire safety in nuclear power plants (NPPs) bears directly on the nuclear safety goal of protecting plant personnel, the public and the environment from undue radiological risk. In the event of an internal fire, the plant capability for shutting down the reactor and keeping it shutdown, removing decay heat, confining radioactive material, and monitoring plant status must be preserved [1, 2, 3]. To achieve this objective, the principle of defence in depth is applied in the fire safety program in NPPs, which can be stated as:

- To prevent fires from starting;
- To detect and extinguish quickly the fires that do start so as to limit the damage done; and,
- To prevent the spread of the fires that have not been extinguished so as to minimize their effect on systems performing the above essential safety functions.

The adequacy of the implementation of fire protection is verified quantitatively with a deterministic fire hazard assessment (FHA). This may be supplemented with a probabilistic safety assessment (PSA) for fires to identify dominant risk contributors and to balance the options for risk reduction by cost-benefit assessment. The IAEA guidance for performing a FHA or a fire PSA for NPPs is given in References [4, 5, 6].

The numerous power and instrument cables in an NPP are significant sources of fires, and their location has to be known to assess the fire protection measures. The potential failure of cables is a major nuclear safety concern in the event of a fire. If cables related to redundant safety functions have routing errors and are not adequately protected, the assessment will overlook the impact on nuclear safety due to damage of these cables during a fire. The objective of the fire protection program at the plant is then compromised. Ideally, the routes of all cables important to safety would be correctly identified during the assessment so that the cables are properly protected against the fire. However, it is difficult to achieve the ideal in practice. We have developed success criteria based on the residual errors that may remain in the cable locations. These residual errors arise from two sources – errors in plant documentation of cable location information and errors in establishing the cable location database for the FHA or fire PSA.

The possibility of making CREs is not a residual uncertainty associated with the FHA methodology. It is a quality assurance (QA) issue and the number of errors can be greatly reduced via rigorous process control and improvement during the CRLP. QA programs have been long enforced in NPPs to ensure quality fire safety programs at the plants [7, 8], which also applies to fire safety assessments. The project quality plan for determining cable locations is critical for controlling the residual errors.

In Section 2, the cause of the inherent cable routing errors, which is related to the statistical nature of the cable route locating process, is examined. A statistical model for the process is built to estimate the probability of correct cable routing from the process. In Section 3, the effect of possible CREs on a FHA is quantified in terms of the probability of resulting failure of defence-in-depth for fire protection. In Section 4, the impact on plant safety due to CREs is discussed in terms of the probability of loss of redundant safety functions for the plant. In Section 5, three strategies to address the risk from CREs are identified: to absorb the risk into the overall risk assessment of the plant, to mitigate the risk with conservative and proven measures in the FHA, and to reduce the risk by continuously improving and controlling the CRLP.

2. NATURE OF CABLE ROUTE LOCATING

Based on good practice, locating cable routes consists of two necessary steps, identifying the cable route for a device (e.g. from cable registers and tray drawings) then verifying it as built (e.g. through plant walkdown). Here, the output from the identifying step is assumed to always be recorded in the cable routing database (CRD) – verification should always be performed on the actual entry recorded in the database so that possible clerical error can be detected and corrected. These two steps are repeated for every cable route. Locating all the potentially tens of thousands cable routes required for a FHA is a ‘time-consuming’ process.

For a production process involving large volume it is almost impossible to have zero defects. Likewise, it is difficult to have a CRLP that produces thousands of cable routes with zero errors. The identifying step of the CRLP is idealized as follows:

Procedure 1: Match a cable to a cable tray

The power or signal cable for a device is laid along within cable trays. Therefore, if the routes of the trays are determined, so is the route of the cable. The matching records for all cables can be obtained from the plant.

Procedure 2: Trace the route of the cable tray

A cable tray is routed through room(s) in the plant – note that the rooms here are not necessarily the fire zones defined in a FHA or fire PSA to separate safety systems by space and barriers. The layouts of all cable trays can be traced from relevant plant drawings.

Assuming that the output from the matching or tracing procedure of the identifying step is recorded separately in the CRD, the verifying step of the CRLP shall be also carried out separately for the two procedures. During the entire CRLP, errors are possible with each procedure while reading or recording the plant information, or while checking the information via plant walkdown. Nevertheless, the number of errors, including those made when creating the original plant information, can be reduced through continuous improvement of the process depicted in Figure 1. The improvement can be achieved by reducing variation in process output so that a good process capability, the range over which the natural variation of a process occurs as determined by the system of common causes, is always maintained [9].

The process capability has three important components that are defined for each procedure of the CRLP (refer to Figure 2). The 'design specification' here is strictly the correctness of relevant routing information for every cable, however, statistically, this cannot be met. Since the product is only judged with attributes, i.e. the routing is either correct or incorrect, the probability of correct output (PCO) is used to control the process. In this way, a relaxed specification would be a minimum PCO, $P_{min,\ p,\ s}$, leading to a minimum probability of correct cable routing (PCCR) in the CRD acceptable 'temporarily' for a given FHA. The subscripts $p = 1$ or 2 for the matching or tracing procedure and $s = 1$ or 2 for the identifying or verifying step. Thus, the 'centering of the natural variation' would be the average PCO, $P_{p,\ s}$, from the procedure, as can be expected from a consistent QA program executed by qualified people. The 'range of variation', the last component of the process capability, shall be always controlled within the specifications of $P_{min,\ p,\ s}$ and unity (see the block arrow). When the overall process quality of the procedure is improved, the average probability $P_{p,\ s}$ moves toward the unity and the range becomes narrower (see the line arrows), thus the minimum probability $P_{min,p,\ s}$ tolerated can be raised. The range of variation is usually measured with a sample-based confidence interval selected according to the control target for a process (e.g. $\pm 3\sigma$).

For the CRLP, however, a meaningful confidence interval may not be derived from samples collected during each procedure of the process, even if possible, since the CRLP is critical where the number of cable routing errors is very limited.

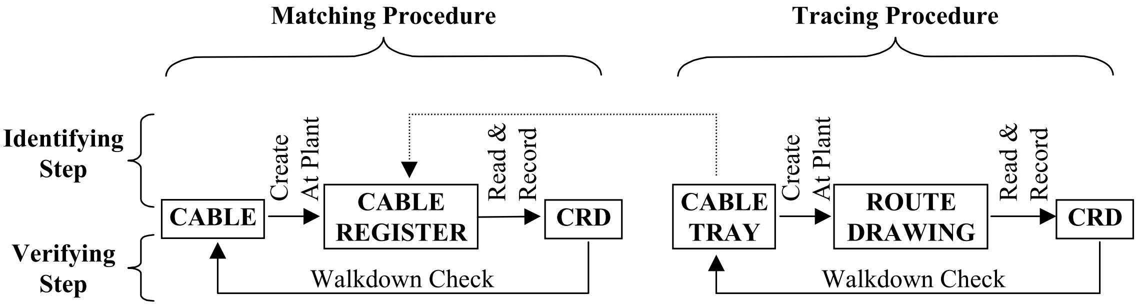

Figure 1 The CRLP model

For the purpose of this work, the confidence interval and associated confidence level (CL) will be used as two qualitative management measures during the CRLP. For a given average probability of correct output $P_{p,\,s}$, as expected from the existing QA program and training, a higher level of confidence as felt by, or seen from, one in performing the work following the QA requirement would result in a product quality near the average. That is, a narrower confidence interval is formed – this is consistent with the relation between the width of a confidence interval and the associated confidence level, as derived from samples. Thus, if the confidence level is $CL_{p,\,s}$ for a procedure, the confidence interval can be defined as $P_{p,\,s} \pm (1-CL_{p,\,s})xP_{p,\,s}$. In this work, the conservative lower confidence limit $P_{p,\,s}xCL_{p,\,s}$ is used.

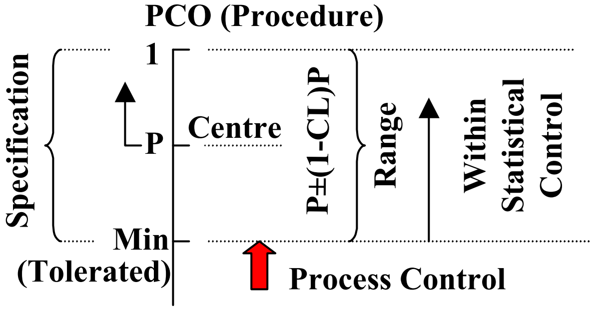

Figure 2 Control and improve a procedure of the CRLP

Therefore, for the procedure 'p' during the identifying step, the probability of incorrect output is $1 - P_{p,\,1}xCL_{p,\,1}$. During the corresponding verifying step, the probability of correct output is $P_{p,\,2}xCL_{p,\,2}$. Here, it is vital that any inconsistency between the outputs from the identifying and verifying steps be resolved, after which, the PCO from the procedure increases to:

$$P_P = P_{P,1} x CL_{P,1} + (1 - P_{P,1} x CL_{P,1}) x P_{P,2} x CL_{P,2} \quad (2.1)$$

Thus, the probability of correct cable routing from the locating process is

$$P_{CCR} = P_1 x P_2 \quad (2.2)$$

That is, for a cable route to be correct, its matching (between cable and cable tray) and routing (of the cable tray) information must be correct at the same time.

A good QA program is always expected for a nuclear related process. Assuming 95%/95% (PCO/CL) for each of the two procedures during the two steps leads to a low PCCR from the process (0.9811 – see the first three columns of Table 1). A stricter QA program is required, for example, 99%/99% which would result in a PCCR of 0.9992, i.e. a defective rate of 8.0E-4 in the CRD. Namely, with tens of thousands cable routes, there still may be dozens of errors in the final database that is to be based by an assessment, or even more considering possible variations in the process due to special causes. For example, if the intended walkdown verification for the matching procedure can not be carried out, the PCCR will dramatically drop to 0.9797. In reality, this may often be the case. As a result, a superior quality for the matching procedure during the identifying step becomes the key. That is, refer to Figure 1, a combined QA level of 99.98%/99.98% in creating (at the plant) then reading and recording (during the FHA) the matching information is needed for the overall process quality to go back to 0.9992 in the above example.

Table 1 Probabilities of loss of the third level of fire defence at different QA levels and potential risks of loss of redundant safety functions

PROCEDURE PCO/CL(%/%)	**PCCR From CRLP**	**RATE Of CRE In The CRD**	**NO Of CREs (N_{CRE})**	**P_{D3F} & P_{LoRSF}**
CREs From Same Safety Group In The Fire Zone (Case A)				
95/95	0.98107787	0.018922131	662	0.1931634
96/96	0.98774466	0.01225534	429	0.1251066
97/97	0.99302658	0.00697342	244	0.071187
98/98	0.99686614	0.003133861	110	0.0319915
99/99	0.99920814	0.000791863	28	0.0080836
99.8/99.8	0.99996806	3.19358E-05	1	0.000326
CREs From Both Safety Groups In The Fire Zone (Case B)				
95/95	0.98107787	0.018922131	662	0.547805
96/96	0.98774466	0.01225534	429	0.2300513
97/97	0.99302658	0.00697342	244	0.07442
98/98	0.99686614	0.003133861	110	0.015125
99/99	0.99920814	0.000791863	28	0.00098
99.8/99.8	0.99996806	3.19358E-05	1	1.25E-06

ASSUMPTION: $N = 35000$, $L = 150$, $L_{2GRP} = 100$, $L_{2GRP,S} = 10$,
$f = 0.75$ and $P_{D1F} = 0.1$

3. EFFECT OF CABLE ROUTING ERROR ON FIRE HAZARD ASSESSMENT

From Section 2, the number of possible CREs from a CRLP is linked to the QA level in the process. If a total M safety related cables are included in an assessment, N cables ($N \leq M$) can be assumed associated with the two redundant safety groups at the plant, which must be protected against the fire so as not to disable redundant systems within both groups. At a probability of correct cable routing from the CRLP, P_{CCR}, as calculated from Equation (2.2), the number of CREs important to availability of the redundant safety groups would be

$$N_{CRE} = Nx(1 - P_{CCR}) \tag{3.1}$$

The impact on a fire hazard assessment due to these CREs, in terms of the probability of failure of the defence-in-depth levels for fire protection, is estimated with the following assumptions:

- Only a single major fire is postulated for the plant at a time, which is defined as one with high economic losses or a threat to safety [1];
- The major fire that presumably can not be extinguished quickly will damage all systems in the zone;

  The second level of fire defence is intended to limit damage done by the fire. The requirement for its adequacy, for the purpose of nuclear safety, is not set as long as no redundant safety systems are damaged at the same time, i.e. within the same zone. Therefore, the conservative assumption of loss of all safety systems (maybe not all components) present within the zone is desired in this work. Nevertheless, any successful local protection and separation measures for particular systems, which may have been accounted for in a FHA, will certainly reduce the nuclear risk from the level estimated in this work. For example, if only the systems affected with the CREs are damaged in a zone, the risk associated with Case A, discussed later, would have been removed, and the risk from Case B reduced considerably.

- Separation of all redundant safety systems by distance and barriers (as verified with the assessment) is always adequate to prevent fire spreading across zones;
- The number of zones for each safety group is in proportion to the number of systems in the group;

  While redundant safety systems are not permitted in a same zone, non-redundant systems from the two groups are allowed. The total number of zones for the two groups, L_{2GRP}, after excluding the number of shared zones, $L_{2GRP,S}$, is divided between the groups according to the ratio, f, of the number of systems in Group 1 over the total number for the two groups. Therefore, the numbers of Group 1, Group 2 and shared zones are respectively $fx(L_{2GRP}-L_{2GRP,S})$, $(1-f)x(L_{2GRP}-L_{2GRP,S})$ and $L_{2GRP,S}$.

In the plant design, separation, by space or orientation, of the two redundant safety groups is already considered so that a few zones for either group can be assured not to have misplaced cables from the other group. In this case, such zones are excluded from the scope of the L_{2GRP} discussed above, but still, they are part of the total zones for the plant. The total number of systems in each group can be assumed not changed.

- One safety system can only have one cable routing error in a zone – multiple CREs in a zone for a same system are considered not statistically significant.

- The cable routing errors are distributed between the two safety groups according to the ratio f.

First, the probability of failure of the first level for fire defence, P_{D1F}, is measured with the frequency of a single major fire anywhere in the plant. Statistics of fire incidents from Canada and other NPP operations indicate that major fires have a frequency of less than once per ten reactor years of operation [1]. Namely, $P_{D1F} = 0.1$ per reactor year.

The third level of fire defence is originally intended to prevent common cause failures of redundant safety systems from the two groups. However, if the CREs are assumed to occur in any 'L_{2GRP}' zone including the shared zones, failure of this level then becomes possible in any 'L_{2GRP}' zone without fire spreading. Therefore, failure of this level is defined more generally in this work as the first step toward estimating the probability of loss of redundant safety functions. That is, the failure is indicated with the loss of multiple systems in the two groups (redundant or not) in the same zone as the major fire. The two groups end up within the same zone due to the CREs for either or both groups – the probability of failure of this level is discussed below with two different approaches.

A. Cable routing errors related to one safety group in the fire zone

First, for Group 1, the fxN_{CRE} cable routing errors are located in $fxN_{CRE}/N_{EPZ,1}$ different zones out of a total L_{2GRP} zones within the total L zones for the plant ($L_{2GRP} \leq L$). It is assumed here that, if any zone has the errors for Group 1, it will only have $N_{EPZ,1}$ errors ($1 \leq N_{EPZ,1} \leq fxN_{CRE}$). The probability of having Group 1 errors within Group 2 zones is then $Y_1 = [fxN_{CRE}/(N_{EPZ,1}xL_{2GRP})]x\{[(1-f)x(L_{2GRP}-L_{2GRP,S})+L_{2GRP,S}]/L_{2GRP}\}$. Since the fire can start in any of the L zones, the probability of the fire within one of the 'mistaken two group' zones is $L_{2GRP}xY_1/L$.

Then, for Group 2, the $(1-f)xN_{CRE}$ cable routing errors are located in $(1-f)xN_{CRE}/N_{EPZ,2}$ different zones out of a total L_{2GRP} zones. It is assumed here that, if any zone has the errors for Group 2, it will only have $N_{EPZ,2}$ errors ($1 \leq N_{EPZ,2} \leq (1-f)xN_{CRE}$). The probability of having Group 2 errors within Group 1 zones is then $Y_2 = [(1-f)xN_{CRE}/(N_{EPZ,2}xL_{2GRP})]x\{[fx(L_{2GRP}-L_{2GRP,S})+L_{2GRP,S}]/L_{2GRP}\}$. Since the fire can start in any of the L zones, the probability of the fire within one of the ‘mistaken two group’ zones is $L_{2GRP}xY_2/L$.

Therefore, the total probability of the fire within one of the ‘mistaken two group’ zones is $L_{2GRP}x(Y_1+Y_2)/L$. If all the safety systems within the zone are damaged, the probability of failure of the third level for fire defence is thus

$$P_{D3F,A} = \frac{P_{D1F}xNx(1-P_{CCR})}{LxL_{2GRP}}\left[2f(1-f)(L_{2GRP}-L_{2GRP,S})+L_{2GRP,S}\right] \tag{3.2}$$

with Equation (3.1) considered. To simplify the equation, the errors per zone $N_{EPZ,1}$ and $N_{EPZ,2}$ were already assumed to be 1. This is the limiting scenario for the largest P_{D3F}. For example, if N = 35000, $P_{CCR} = 0.9992$, f = 0.75, L = 150, $L_{2GRP} = 100$ and $L_{2GRP,S} = 10$, Equation (3.2) gives a probability of failure of 0.0081 per reactor year (see Table 1).

B. Cable routing errors related to both safety groups in the fire zone

For Group 1, the fxN_{CRE} cable routing errors are located in $fxN_{CRE}/N_{EPZ,1}$ different zones out of a total L_{2GRP} zones within the total L zones for the plant ($L_{2GRP} \leq L$). For Group 2, the $(1-f)xN_{CRE}$ cable routing errors are located in $(1-f)xN_{CRE}/N_{EPZ,2}$ different zones within the same L_{2GRP} zones. It is assumed here that, if any zone has the errors, it will have $N_{EPZ,1}$ or $N_{EPZ,2}$ errors for Group 1 or 2 ($1 \leq N_{EPZ,1} \leq fxN_{CRE}$ and $1 \leq N_{EPZ,2} \leq (1-f)xN_{CRE}$). The probability of having errors related to both groups within one of the L_{2GRP} zones is then $Y=[fxN_{CRE}/(N_{EPZ,1}xL_{2GRP})]x[(1-f)xN_{CRE}/(N_{EPZ,2}xL_{2GRP})]$.

Since the fire can start in any of the L zones, the probability of the fire within one of the ‘both group error’ zones is $L_{2GRP}xY/L$. This could be a Group 1, Group 2 or shared zone. If all the safety systems within the zone are damaged, the probability of failure of the third level for fire defence is

$$P_{D3F,B} = \frac{P_{D1F}x[Nx(1-P_{CCR})]^2xf(1-f)}{LxL_{2GRP}} \tag{3.3}$$

after Equation (3.1) is considered. This is already the limiting scenario for the largest P_{D3F}, with the errors per zone $N_{EPZ,1}$ and $N_{EPZ,2}$ assumed to 1. For example, if N = 35000, $P_{CCR} = 0.9992$, f = 0.75, L = 150 and $L_{2GRP} = 100$, Equation (3.3) indicates a probability of failure of 0.00098 per reactor year (see Table 1).

4. RESULTING IMPACT ON PLANT SAFETY

Common cause failures of safety groups due to a fire occur at various probabilities depending on the number of cable routing errors related to each safety group that may potentially exist within the zone of the fire. However, failures of multiple safety systems within the two groups do not necessarily mean the loss of redundant safety functions. On one hand, the risk of loss of redundant safety functions due to failures of multiple safety systems will increase if the number of CREs within a zone increases. On the other hand, the probability of a fire within a zone with the CREs will decrease as the number of CREs per zone increase, if the total number of CREs is given. Therefore, the impact on plant safety can not be measured alone by the probability of failure of the third level for fire defence. Rather, the risk can be measured by the probability of the loss of redundant safety functions.

With the CREs per zone for both groups assumed as 1, Equation (3.2) or (3.3) represents the largest probability of the fire in a zone with CREs for Case A or B in Section 3, which causes multiple system failures from the two safety groups. The probability of loss of redundant safety functions from the two groups can be conservatively expressed as

$$P_{LoRSF,A} = P_{RSS,Max} x P_{D3F,A} \tag{4.1}$$

or

$$P_{LoRSF,B} = P_{RSS,Max} x P_{D3F,B} \tag{4.2}$$

where P_{RSS} is the probability of redundancy among the safety systems being failed in a zone due to the fire, and the subscript Max indicates the maximum P_{RSS} among all the L_{2GRP} fire zones for the two safety groups. Theoretically, the more safety systems each with more components within a zone, the larger the P_{RSS} for the zone is. That is, a flattened profile, over the L_{2GRP} zones, of the number of safety systems per zone is preferred, as it tends to lower the $P_{RSS,\ Max}$. However, since the correct identification of all components for each system is the very concern in this work, the plant specific $P_{RSS,\ Max}$ can only be estimated with a sufficient 'safety factor' covering possible errors in component layout information. Therefore, the $P_{RSS,\ Max}$ should be usually taken as unity.

Following the examples in Section 3, the P_{LoRSF} at different P_{CCR} is shown in Table 1. Within the expected range of P_{CCR}, Case A dominates P_{LoRSF} while Case B is clearly preferred (see Figure 3). Limiting the number of zones at the plant that are shared by non-redundant systems in the two safety groups, a unique parameter affecting Case A, would reduce the P_{LoRSF} (Figure 4). This requires that more fire zones be defined – such a conservative measure, i.e. larger L and L_{2GRP}, also significantly reduces the overall P_{LoRSF}, as can be seen from Equations (3.2) and (3.3), not to mention the flattening benefit just discussed above.

The probabilities in Table 1 apply to all possible losses of redundant safety functions from the two safety groups. For example, a postulated severe scenario during a major fire may be the damage of a process control cable coupled with the damage of the redundant safety systems from the two groups needed for mitigating the resultant process failure. In addition, the risk due to coincidence of a major fire with another unrelated initiating event is also increased, if redundant safety functions from the two groups are unexpectedly lost during the fire. The consequence of such failures is assessed toward the overall nuclear safety goal of the plant – core damage frequency. This is done in the fire PSA.

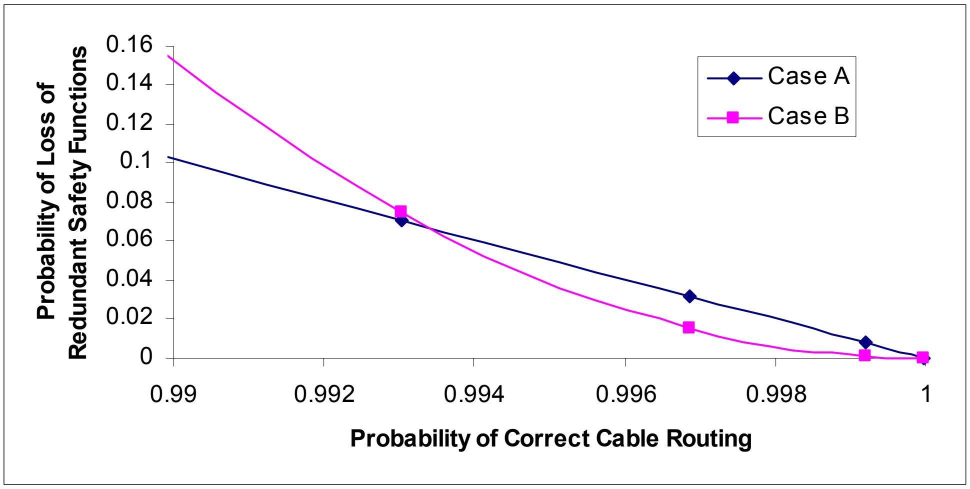

Figure 3 Comparison of the probability of loss of redundant safety functions

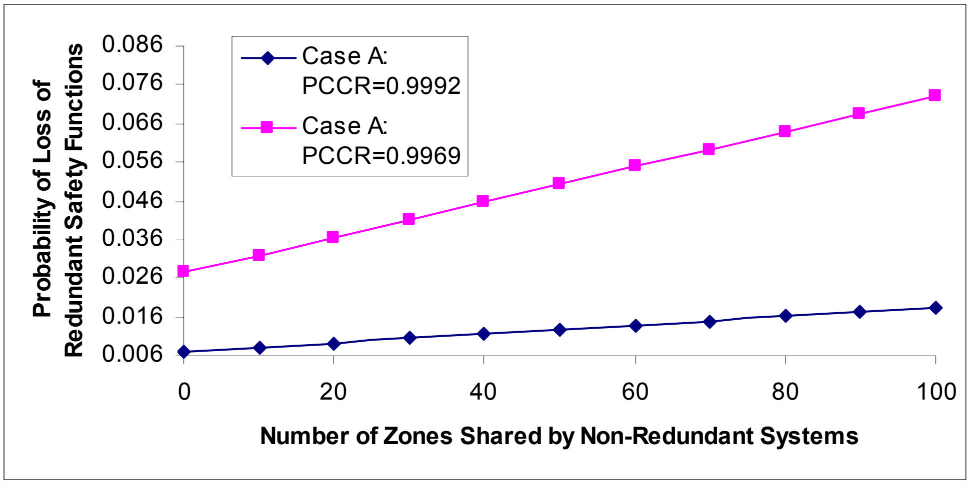

Figure 4 Effect of the number of zones shared by non-redundant systems

Equations (4.1) and (4.2) can be also used to determine the required minimum probability of correct cable routing from the CRLP at a given P_{LoRSF} by the plant. The target P_{CCR} can be then achieved by applying the control and improvement mechanism illustrated in Figure 2 to all component procedures of the process following the QA model expressed by Equations (2.1) and (2.2).

5. CONCLUSIONS

The cable routing errors are an inherent part of locating cable routes as required for a deterministic fire hazard assessment. This would impair the principle of defence in depth, which is used to ensure adequate fire protection for a nuclear power plant. As a result, the nuclear safety of the plant may be compromised. Three strategies are suggested to address the potential increased risk:

- Include the cable routing errors in the overall risk assessment for the plant;
- Mitigate the risk with conservative and proven measures considered in the FHA;
- Limit the incremental risk by reducing the possibility of making CREs, when creating, collecting and using the plant information.

A continuous effort over the lifetime of the plant is required to improve and control the quality of the cable route locating process for the FHA or fire PSA, thus enhancing the confidence in the assessment.

LIST OF ACRONYMS

CL	Confidence Level	NPP	Nuclear Power Plant
CRD	Cable Routing Database	PCCR	Probability of Correct Cable Routing
CRE	Cable Routing Error	PCO	Probability of Correct Output
CRLP	Cable Route Locating Process	PSA	Probabilistic Safety Assessment
FHA	Fire Hazard Assessment	QA	Quality Assurance

NOMENCLATURE

$CL_{p,\,s}$	Confidence level expected from a procedure of the CRLP, with subscripts p = 1 or 2 for the matching or tracing procedure and s = 1 or 2 for the identifying or verifying step
f	Ratio of the number of systems in Group 1 over the total number for the two redundant safety groups at a plant
L	Total number of fire zones defined for an assessment over a plant
L_{2GRP}	Number of zones for the two redundant safety groups at a plant ($L_{2GRP} \leq L$)
$L_{2GRP,S}$	Number of zones shared by the two redundant safety groups at a plant
M	Total number of safety related cables included in an assessment
N	Number of cables in an assessment that are related to the two redundant safety groups at a plant ($N \leq M$)
N_{CRE}	Number of CREs related to the two redundant safety groups at a plant
$N_{EPZ,1/2}$	Number of Group 1/2 CREs per zone
P_{CCR}	PCCR from the CRLP
P_{D1F}	Probability of failure of the first level for fire defence

$P_{D3F,\ A/B}$	Probability of failure of the third level for fire defence, for Case A/B in Section 3
$P_{LoRSF,\ A/B}$	Probability of loss of redundant safety functions from the two safety groups at a plant, for Case A/B in Section 3
$P_{min,\ p,\ s}$	Minimum PCO specified for a procedure of the CRLP – see $CL_{p,\ s}$ above for the subscripts p and s
P_p	PCO from a procedure of the CRLP after the verifying step, with subscript p = 1 or 2 for the matching or tracing procedure
$P_{p,\ s}$	Average PCO expected from a procedure of the CRLP – see $CL_{p,\ s}$ above for the subscripts p and s
$P_{RSS,\ Max}$	Maximum (among all fire zones for the two redundant safety groups at a plant) probability of redundancy among the safety systems being failed in a zone due to the fire

REFERENCES

1. CAN/CSA-N293-95, Fire Protection for CANDU Nuclear Power Plants, 1997.
2. IAEA Safety Standards Series No. NS-R-1, Safety of Nuclear Power Plants: Design, 2000.
3. IAEA Safety Standards Series No. NS-R-2, Safety of Nuclear Power Plants: Operation, 2000.
4. IAEA Safety Reports Series No. 8, Preparation of Fire Hazard Analyses for Nuclear Power Plants, 1998.
5. IAEA Safety Series No. 50-P-9, Evaluation of Fire Hazard Analyses for Nuclear Power Plants, 1995.
6. IAEA Safety Reports Series No. 10, Treatment of Internal Fires in Probabilistic Safety Assessment for Nuclear Power Plants, 1998.
7. CNSC Draft Regulatory Standard S-213, Quality Assurance Program Requirements for Nuclear Facilities, 2004.
8. CAN/CSA-N286.0-92, Overall Quality Assurance Program Requirements for Nuclear Power Plants, 1992.
9. Evans, J.R. & Lindsay, W.M., The Management and Control of Quality, 2nd Ed., West Publishing Company, 1993.