THOUGHTS ON RISK ESSENCE FROM PRA PRACTICE

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The scope of Probabilistic Risk Assessment (PRA) is so extensive that its study can include and model all technical aspects of the nuclear power plant implicitly or explicitly. This paper focuses on the risk importance, convolution of multiple events and the risk significance of the single initiating event in SDP. Three risk topics are based on the author's practice in the nuclear industry. (1) The first section repeats the risk importance used in the PRA and discusses the relationship and conversion among the risk importance (FV, RAW, RRW and Birnbaum) given the independence assumption of basic events including common cause events and the linear rare event approximation. The risk impact of a basic event can be represented by the risk surface. (2) The second section presents a method to simplify and evaluate the integration of the multiple time interdependent events in a cutset that is the combination of basic events (equipment failures, Loss of Offsite Power (LOOP) recovery action and operation actions etc.) in a parallel or serial manner. (3) The third section is to discuss how to evaluate the risk significance of an initiating event in the Significance Determination Process (SDP). Better understanding of these three topics could help a PRA analyst better support the plant operations and suggest modifications from risk perspective and keep continuously improving the safety and performance at a nuclear power plant.

I. CONVERSION OF RISK IMPORTANCE

Four risk importance measures are widely known and implemented in the daily PRA practice. The definitions of the risk importance of a basic event are repeated below in equations (1a~1d). Figure 1 illustrates the risk verse the basic event probability. With the rare event approximation, the risk is linear to the basic event probability. The surrogates of the public risk are Core Damage Frequency (CDF) and Large Early Release Frequency (LERF) in PRA. If choose to do so, other quantitative risk measure can be used to express other risk or safety considerations in another risk or safety dimension. Normally the CDF is the most limiting risk metric.

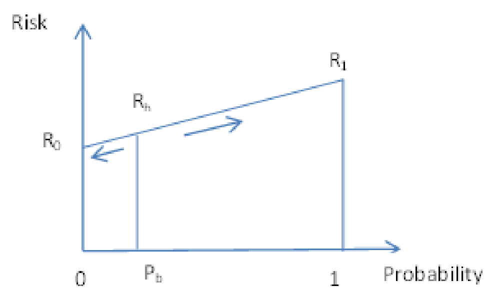

Fig. 1. The risk and the basic event probability using the rare event approximation.

$$FV = \frac{R_b - R_0}{R_b}. \qquad \text{(1a)}$$

$$B = \frac{R_1 - R_0}{1 - 0} = R_1 - R_0. \qquad \text{(1b)}$$

$$RAW = \frac{R_1}{R_b}. \qquad \text{(1c)}$$

$$RRW = \frac{R_b}{R_0}. \qquad \text{(1d)}$$

R_b is the baseline risk with the basic event of random probability; R_0 is the risk with the zero basic event probability, i.e. a guaranteed success condition; and R_1 is the risk with the basic event probability of 1.0, i.e. a guaranteed failure. The risk importance equations define Fussel-Vessel (1a), Birnbaum (1b), Risk Achievement Worth (RAW) (1c) and Risk Reduction Worth (RRW) (1d).

On example of other risk importance is Risk Worth, which is the risk increase due to the unreliability in terms of one function failure or the unavailability in terms of one out-of service hour as used in Mitigating System Performance Index (MSPI) program [1, 2, 6].

FV, RAW and RRW are relative risk importance measures of the risk change over the baselines risk. Birnbaum is not only a risk or risk change ratio like other risk importance, but also the risk change over the probability range, which measures the risk change between the guaranteed success and the guaranteed failure. Using the rare event approximation, the risk is a linear function of the probability, where the Birnbaum is the constant slope.

$$B = \frac{\Delta R}{\Delta P}. \qquad (2)$$

The results of the PRA quantification is normally a sum equation (logic OR) of tens of thousands of cutsets from an plant Level1/Level2 or CDF/LERF at-power logic model. It is practically very difficult for a computer to calculate precise values of the risk metrics (CDF, LERF) within a reasonable short period of time and cost. In a factored cutsets calculation the cutsets are factored in terms of initiators, the conditional risk is the production of the initiator frequency and the conditional probability. Take a very simple cutsets equation of 1 initiator and 2 cutsets F*C1, F*C2 as an example, the risk R is the product of the initiator frequency F and the probability of C1 OR C2:

$$R = F * \Pr(C1 + C2). \qquad (3)$$

where C1, C2 are basic event combinations that are the partial cutsets without including the initiator.

Following Probability Rule of Addition Pr(C1+C2) equals to Pr(C1)+Pr(C2)-Pr(C1*C2), since the common cause events are treated separately as independent basic events for certain groups, the independence between C1 and C2 is assumed and the rare event approximation is reasonable for the numeric quantification, thus

$$R = F * \left[\Pr(C1) + \Pr(C2)\right]. \qquad (4)$$

In general, the equation has multiple initiators (i) and many associated cutsets (j) for each initiator, the risk can be expressed as

$$R = \sum_i F_i * \left[\sum_j \Pr\left(C_j\right)\right] \qquad (5)$$

For the at-power PRA model with the common causes treated as independent basic events, it is reasonable and conservative to assume all the basic events are independent and small enough such that the rare event approximation can provide conservative results with acceptable accuracy. For an initiator i, the partial cutset Cj has k basic events, so P(Cj)= P_1*P_2*…*P_k, therefore,

$$R = \sum_i F_i * \left[\sum_j \left(\prod_{k(j)} P_k\right)\right] \qquad (6)$$

Here k is a variable that varies with j. Without any performance deficiency this risk value is the baseline risk with random failure probabilities, nominal unavailabilities and standard human error probabilities. In order to demonstrate the relationship between the risk importance of a basic event, the baseline risk can be regroup into two parts, one with the basic event P_b of interest and one without it as equation (7).

$$R_b = (\text{Risk of cutsets with } P_b) + (\text{Risk of cutsets without } P_b) = B * P_b + C_0 \qquad (7)$$

Where $B = \Sigma_i F_i * [\Sigma_j(\Pi_{k\neq b} P_k)]$ and $C_0 = \Sigma_i F_i * [\Sigma_j(\Pi_k P_k)]$

Here is a simple example of 2 initiators (F_1, F_2) and 3 basic events (P_1, P_2, P_3), R is expressed as a function of P_1.

$$R = F_1*(P_1*P_2+P_1*P_3+P_2*P_3) + F_2*(P_1 + P_2) = (F_1*P_2+F_2*P_3+F_2)*P_1 + (F_1*P_2*P_3+ F_2*P_2) \quad (8)$$

In comparison with equation (7), thus $B = (F_1*P_2+F_2*P_3+F_2)$ and $C_0 = (F_1*P_2*P_3+ F_2*P_2)$

Given the guaranteed success, $P_1 = 0$, then the risk R_0 is

$$R_0= B *0 + C_0 = C_0 \quad (9)$$

Given the guaranteed failure, $P_1 = 1$, then the risk R_1 is

$$R_1= B *1 + C_0 = B + C_0 \quad (10)$$

Equation (1a) defines the FV value, substitute equation (7) and (9) for R_b, R_0,

$$FV = \frac{B*P_b + C_0 - C_0}{R_b} = \frac{B*P_b}{R_b} \quad (11a)$$

$$B = \frac{FV*R_b}{P_b}. \quad (11b)$$

From equation (9) and (10), it shows that the difference between R_1 and R_0 is B, which is the Birnbaum value as equation (1b) and (2).

Equation (1c) defines the RAW value, substitute equation (9) and (10) for R_0, R_1,

$$RAW = \frac{B*1 + C_0}{B*P_b + C_0} = \frac{B*(1-P_b) + B*P_b + C_0}{R_b} = \frac{B*(1-P_b)}{R_b} + 1. \quad (12a)$$

$$B = \frac{(RAW-1)*R_b}{(1-P_b)}. \quad (12b)$$

Equation (1d) defines the RRW value, substitute equation (7) and (9) for R_b, R_0,

$$RRW = \frac{B*P_b + C_o}{C_o} = \frac{R_b}{R_b - B*P_b} = \frac{1}{1 - B*P_b / R_b}. \quad (13a)$$

$$B = \left(1 - \frac{1}{RRW}\right)*\frac{R_b}{P_b}. \quad (13b)$$

Therefore, from equations (11b), (12b) and (13b) the risk importance B of a basic event can be expressed in terms of other risk importance as equation (14), which also can be used for the conversions between all of the 4 risk importance: FV, B, RAW, and RRW.

$$B = \frac{FV*R_b}{P_b} = \frac{(RAW-1)*R_b}{(1-P_b)} = \left(1 - \frac{1}{RRW}\right)*\frac{R_b}{P_b}. \quad (14)$$

A verification using the quantification of a hypothetical nuclear power plant risk logic model with CDF = 5.633E-6 per year is presented in Table I, which shows the ratios between one industry widely used risk evaluation software and the manual calculation are within the engineering accuracy (>99%). The risk importance of LERF has similar results. The experiments of basic events from PWR and BWR at-power PRA models show that almost all risk importance ratios are greater than 97%.

TABLE I. Risk Importance and Ratios

				Equation Calculation/Software Output			
Basic Event ID	Probability	CCDF (B*P)	C=CDF-B*P	B%	RAW%	FV%	RAW%
COMFR1_001	7.200E-05	1.364E-09	5.632E-06	100.00%	100.01%	100.91%	100.00%
COMFR1_002	7.200E-05	6.288E-09	5.627E-06	100.00%	100.00%	99.66%	100.00%
COMFR1_003	7.200E-05	2.633E-09	5.631E-06	100.00%	100.00%	99.45%	100.00%
COMFR1_004	1.110E-03	5.699E-09	5.628E-06	100.01%	100.02%	100.17%	100.00%
Risk Importance Calculation				Software Risk Importance Output			
C=CDF-B*P	B=B*P/P	RAW (12a)	FV(11a)	B	RAW	FV	RRW
1.895E-05	4.3634	2.422E-04	1.0002	1.895E-05	4.363	2.400E-04	1.0002
8.734E-05	16.5025	1.116E-03	1.0011	8.734E-05	16.502	1.120E-03	1.0011
3.657E-05	7.4917	4.674E-04	1.0005	3.657E-05	7.492	4.700E-04	1.0005
5.135E-06	1.9105	1.012E-03	1.0010	5.134E-06	1.91	1.010E-03	1.0010

The second application of the linear risk model (7) is the risk minimization of a mitigation design. Given all the initiators defined in advance, the risk of the unsuccessful mitigation is defined in equation (6). The influence of a basic event on the risk frequency is determined by the cutsets that include the combinations of the basic event with other mitigation basic events for certain or all initiators. For the extreme case where there is no any mitigation at all, the risk frequency equals to the total frequency of the initiators as equation (15).

$$R_{\max} = \sum_i F_i . \qquad (15)$$

If the risk from only one basic event with probability P_b is considered as a variable using equation (7), $B*P_b$ is the risk impact of the basic events along with other mitigation basic events, C_0 is the potion where the basic event has no impact at all. In this analysis, the logic operators AND and OR in the cutsets equation can be treated as the arithmetic operators MULTIPLICATION and ADDITION in the quantification. In other words, symbol * means either AND or MULTIPLICATION and symbol + means OR or ADDITION depend on it is for the logic or the quantification.

$$R_b = B * P_b + C_0 \qquad (7)$$

In general, the baseline risk can be treated as a linear function of the probability P_b, the slope is the baseline Birnbaum B, which is the summation of the products of the mitigation failures and initiators associated with the basic event of interest, while the constant C_0 is summation of the cutsets of the mitigation failures and initiator without that basic event.

Assume the mitigation failure combinations could be moved from summation B to summation C_0. If a combination is moved from B to C_0, it means the basic event of P_b becomes no impact or simply failed for the cutset. If a combination is moved from C_0 to B, it means the basic event P_b gets involved in the mitigation of the initiator. Mathematically the P_b can be replaced by another dummy basic event with same failure probability; the risk impact change can be defined by the cutsets change X between the portion of the cutsets that basic event involves, B, or the portion of no impact C_0. The generic basic model is presented in equation (16), P_b is a variable of the basic event probability, C_0 is the cutsets without the basic event P_b.

$$R = (B - X) * P_b + (C_0 + X) \qquad (16)$$

Where the X is the change of basic event combinations. When X>0, it is the basic event combinations that are removed from the baseline B and become part of C_0. When X<0, it is the basic event combinations that are added into the baseline B and removed from the C_0. When X = 0, the equation (16) is the baseline risk equation (7). Given the total number of initiators knows, the baseline Birnbaum is the sum of partial cutsets that involves the basic event P_b for the initiators, and C_0 is the combination that the other part of risk that has nothing to do with the basic event P_b. The symbol "-" is to remove some basic event combinations from the cusets equation, and eliminate some sequences associated with the basic event. The symbol "+" means the addition of some basic event combinations, and introduce more sequences.

The maximum risk with the consideration of the mitigation from all basic events except the basic event P_b of interest for all initiators is $B+C_0$. While all mitigation functions fail to mitigate all initiators, the maximum risk is the summation of the frequency of the initiators, $\Sigma_i F_i$ (equation 15). The equation (16) has two variables X, P_b, and represents a surface. Table II shows the baseline and limiting values of the risk surface.

TABLE II. Typical Cases of the Risk Surface.

	$X = -C_0$	$X = 0$	$X = B$
Risk equation	$R = (B+C_0)*P$	$R = B*P + C_0$	$R = B+C_0$
P=0	$R = 0$	$R = C_0$	$R = B+C_0$
$P = P_b$	$R= (B+C_0)*P_b$	$R = B*P_b+ C_0$	$R = B+C_0$
$P = 1$	$R = B+C_0$	$R = B+C_0$	$R = B+C_0$

In a design analysis, the basic event can be viewed as a mitigation or recovery action that could be applied to any cutsets in the equation. Logically the basic event can be in combination with basic event groups to mitigate initiators, numerically the degree of the involvement change of the basic event in the mitigation is expressed by the X. A risk surface example is shown in Figure 2. The parameters are listed in Table III.

TABLE III. Parameters of the Risk Surface Example

	B	C_0	P_b
COMFR1_001	1.895E-05	5.632E-06	7.200E-05

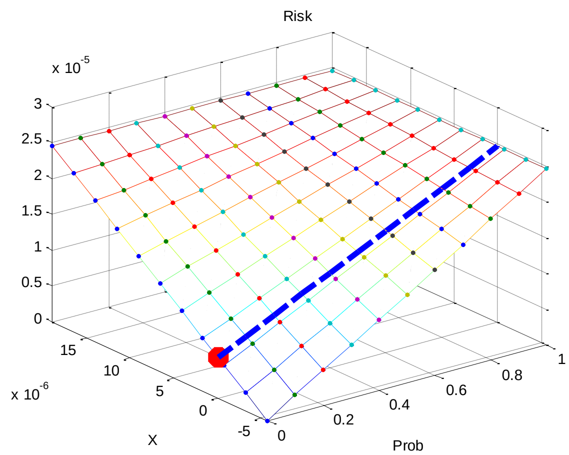

Fig. 2. Risk Surface.

The risk surface is a plane; the red dot is the baseline CDF (5.633E-6 per year); the blue bold dash line is the CDF change along with the probability. The top edges are a constant: the highest risk without the mitigation of P_b $R_1=B+C_b=2.458E\text{-}5$, where the probability is 1.0 and the basic event does not reside in the equation. The surface shows the risk change along with the extension of the residence of the basic event in the cutsets and its probability variation.

II. CONVOLUTION OF MULTIPLEEVENTS

The solved equation of the logic model could have tens of thousands or millions cutsets. Each cutset is the Boolean product (logic AND) of the initiator and a serial of failures of mitigation events E. For example, the kth cutset with the initiator IE_k and the basic events E_1 to E_n is

$$CS_k = IE_k*E_1*E_2*\ldots*E_n \qquad (17)$$

Logically, the cuset is the failure to mitigate the initiator.

In the risk calculation, the initiator can be factored out and the probability of partial cutset is calculated separately. The partial cutset of kth cutset is

$$C_k = E_1*E_2*\ldots*E_n$$

The cutset risk is the product of the initiator frequency and the failure probabilities of multiple events. So, the risk frequency of the kth cutset is

$R_k = F_k*P(C_k)$ (18)

Once the frequency of the initiator is obtained, what left is to calculate the probability of C_k. If all the events are independent, then

$P(C_k)=P(E_1)*P(E_2)*\ldots*P(E_n)$ (19a)

Given the assumption of independence, the rare approximation equation is normally used for the PRA risk quantification by using the multiplication of the failure probabilities of basic events as shown in equation (19a).

On the other hand, if the events are dependent, then the general multiplication rule applies,

$P(C_k)=P(E_1|E_2, E_3,\ldots,E_n)*P(E_2|E_3, \ldots,E_n)*\ldots*P(E_n)$ (19b)

In the risk cutsets equation, there are many time related basic events combined in the cutsets, e.g. pump fail to run, battery depletion etc. Their failure probabilities are a function of the mission time, normally 24 hours. In theory, the cutset probability needs to take the time interdependence into consideration. For a cutset, the initiator frequency is the pre-calculated initiating event frequencies in terms of event(s) per year, the partial cutset probability is actually a conditional probability of the logic product of a set of basic events following the occurrence of the initiator. Here two typical cases with the time dependence consideration are presented. The time to core damage after the failure of the mitigation and the coping time are omitted for the simplicity.

(1) After the initiator occurred, it assumes that the mitigation events start at time zero and are independent of each other. Take a loss of offsite power (LOOP) scenario as an example, the conditional probability of unfavorable outcome $P(C_k)$ is the probability of failure to mitigate LOOP event and lead to core damage (CD), this occurs only if the diesel generator A fails to run (event A) with failure rate λ1, the turbine driven auxiliary feedwater pump fails to run (event B) with failure rate λ2 and the offsite power fails to recover (event C), C_k = A*B*C. All events are parallel in time and progress independently as shown in Figure 3(a). For simplification, other basic events of demand failure are not considered, for example the failure to start involving the motor driven auxiliary feedwater pump, train B diesel.

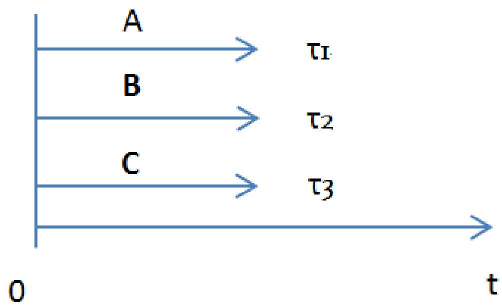

Fig. 3(a). Events in parallel manner.

The running failures are assumed the exponential probability density function (PDF) and the probability of fail to recovery probability is the LOOP non-recovery probability as a lognormal probability density function Φ(t) [NUREG/CR-6928] . So the probability of each event is the integral over the interval from 0 to the time equal to mission time T. The variables τ1, τ2 and τ3 are the time designators of the events A, B, C respectively.

$$P(C_k) = P(A) * P(B) * P(C) = \int_0^T \lambda 1 e^{-\lambda 1 \tau 1} d\tau 1 * \int_0^T \lambda 2 e^{-\lambda 1 \tau 2} d\,\tau 2 * \int_0^T \Phi(\tau 3) d\tau 3 \quad (20a)$$

(2) In this case, after the initiator occurred, it assumes that the events start at time zero and are dependent on each other. There are events of a standby system that only starts and runs upon the failure of the operating system. Take another loss of offsite power scenario as an example, the unfavorable outcome occurs only if the diesel generator A fails to run (event A) and

the diesel generator B starts successfully after the diesel A failed and then fails to run (event B) and the offsite power fails to recover (event C), $C_k = (A*B)*C$. Events A and B are time dependent in serial manner and C is independent event as shown in Figure 3(b).

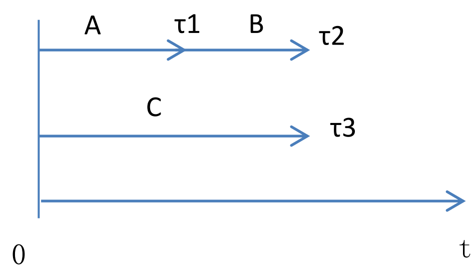

Fig. 3(b). Events in Series manner.

So the probability of events A*B and C is the product of integrals over the interval from 0 to the time equal to the mission time T and the failure probability of event C. The interdependence of A (operating) and B (standby) can be treated by using the convolution. The diesels have the failure rate λ.

$$\mathrm{P(R)} = P(A * B) * P(C) = * \int_0^T \left(\int_0^{\tau 2} \lambda e^{-\lambda \tau 1} * \lambda e^{-\lambda(\tau 2 - \tau 1)} d\tau 1 \right) d\,\tau 2 * \int_0^T \Phi(\tau 3) \mathrm{d}\tau 3 \qquad \text{(20b)}$$

The PDF of the standby system of multiple components can be expressed as the convolution of the PDF of the individual component. The order has no impact on the results of the convolution [5]. The rare event approximation of multiple events is conservative and the convolution method can be used when more realistic modeling is favored.

III. RISK ANALYSIS OF THE SIGNLE INITIATING EVENT IN SDP

Significance Determination Process (SDP) is part of the US regulatory Reactor Oversight Process (ROP) to determine the risk significant of the inspection finding under the ROP regulatory framework that consists of three key strategic performance areas: reactor safety, radiation safety, and safeguards. “The process used by the NRC staff to evaluate inspection findings to determine their safety significance. This involves assessing how the inspection findings affect the risk of a nuclear plant accident, either as a cause of the accident or the ability of plant safety systems or personnel to respond to the accident.” [7]. The appropriate regulatory action may follow in accordance with the ROP action matrix.

NRC Inspection Manual Chapters IMC 0308 “Reactor Oversight Process Basis Document”, IMC 0609 “Significance Determination Process” and Risk Assessment Standardization Project (RASP) handbook provides manuals, methods and guidance to achieve more consistent results when performing inspections or risk assessments for inspection findings, operational events and performance issues. This paper focuses on at-power SDP quantitative risk analysis of internal initiating event (IE) and presents a method of how to estimate the risk significance of an initiating event (e.g. reactor trip, turbine trip or loos of offsite power) and/or degraded conditions (e.g. a system or component failure or operation error) by taking into consideration of the time window. A performance deficiency (PD) has been identified for the SDP evaluation, which is the proximate cause or direct cause of an observed SSC unavailability and/or the consequential initiating event that has tripped the reactor.

In respect of an inspection finding that was the proximate cause of an initiating event that actually tripped the reactor, there is a different professional option from the industry that the use of ΔCDF instead of CCDP (Conditional Core Damage Probability) is more appreciate as an SDP metric and the safety significance should be accounted for by Bayesian update of the IE frequency increase. While NRC maintains ΔCDF metric that is the difference between the CCDP from IE occurrence caused by the inspection fining and the baseline CDP.

From the author’s perspective, the baseline PRA model represents the as-build, as-operated and as-maintained nuclear power plant with only random failures and normal or standard operation practice, which means there is no deficiency of the

SSCs and operation actions, only random failure. Random failure is also called chance failure. One example is the sudden breakdown without preceding degrade condition, a sudden accumulation of stresses may act on and in the component beyond its design strength and cause the failure. Chance failures occur at random intervals, irregularly and unexpectedly and even the good detect technique and the best maintenance cannot eliminate it. The spectrum of the root cause of the random failure is evaluated in the uncertainty analysis since it is very difficult to enumerate all the root causes. In addition, the human being is not perfect, it is expected that the operators may make mistakes by chance even with the proper training and good performance history. In SDP, such assumption is invalid since the deficiency comes into play. Thus, it is inappropriate to use the actual occurrence of the IE due to a deficiency to Bayesian update the random IE frequency. Essentially the deficient IE is different from the random IE with different frequency of occurrence. This Bayesian practice tends towards the underestimation of the risk significance. On the other hand, it is conservative to include such event in the data analysis to calculate and update the baseline IE frequency in the PRA model revision.

A crucial concept to evaluate the deficiency is the time window. A time window is the time period of the existence of the condition of interest. It has different meanings in the different programs. In the MSPI (Mitigating System Performance Index) program, the time window is 36 months. The time window of the unavailability due to a degraded condition is represented by the exposure time "t/2" in SDP when the inception of the condition being assessed is unknown. If there were successful cases before, t is the time period since the last successful functional operation of the component. If this event never happened previously, the time window of the at-power risk of a power plant starts from the beginning of the commercial operation but no later than the date of permanent shutdown, because outside the max time window it is not physical feasible for the core damage to occur.

Since the baseline model should target the expected or standard performance based on the design and operation history, the deficiency should not be part of the baseline and the initiating event caused by the PD could be treated as a special kind of IE even it has the same plant response and accident sequence as the random IE. In such a way, the baseline tend to represent the expected normal or "best" practice of the plant, the poor and deficient performance can be caught in the SDP by the risk increase in the risk assessment. No plant should be operated continuously with the repetitive risk significant deficient performances. The poor performance of a plant history should be captured in the PRA model as the higher baseline risk due to the higher failure probabilities and the initiator frequencies.

If the root cause of the deficiency is not corrected, the frequency of an initiating event due to PD shall be much higher than the frequency of the same initiating event due to a random failure. If the same PD existed before and caused a repeat IE, the time window is the time period from the last occurrence. If the PD is the first time of its kind and its inception is unknown, the time window should be the time period starting from the start of the commercial operation, and the exposure time is one-half of that time period. For a plant of 40 year design life, the time window T is 40, and the exposure time will be no more than 20 years (<20 yr) for an initiating event due to the assumed only one event of such kind of PD and the unknown inception. The usage of the exposure time 't/2' can account for the uncertainty and previous corrective actions and be conservative for such rare event.

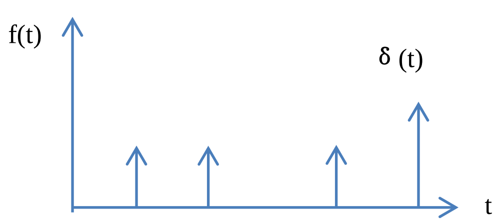

Fig. 4(a)

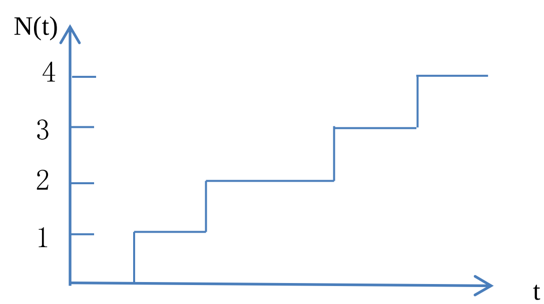

Fig. 4(b)

Assume the event occur in a very short period of time and it can be treated as a Dirac Delta function that represents a initiating event happened at the instantaneous time point, Figure 4(a) shows the IE occurrence function f(t), i.e., the occurrences of the initiating events along the time. The short line means the a random case IE and the long line is a PD causes IE with higher CCDP. The length difference is for illustration purpose only.

Once the plant is built and in operation, the total number of IE is the integral of the function f(t) over the time, and at the instant of the occurrence the step increases 1. N(t) in Figure 4(b) is the history of the total number of IEs along the time. The simply classic estimation of the IE frequency $\lambda_{IE}(t)$is N(t)/(t), which is normally treated as a constant in the PRA model in practice.

For an individual IE event, normally the most limiting risk metric is the CCDP of a period of time; numerically CCDP is the Birnbaum values of an IE in the PRA model. Mathematically and logically there is no direct conversion between CDP and CDF. In SDP, ΔCDP approximates ΔCDF with the assumption the IE frequency of 1/yr.. This usage of the CDP difference to approximate the ΔCDF implicates the exposure time of the IE is 1 year, i.e., the deficiency IE frequency is 1/yr, which is arbitrary and has the potential of overly conservative or non-conservative.

The risk significance should be evaluated on the existence of the PD itself, which has the same plant response and can be modeled as the random IE accident sequence. Actually the PD should be treated as a special IE which uses the random IE model as its surrogate. The exposure time interval should be T/2 where T is time of being in operation if it is the first time occurrence or be the time period from the last occurrence if it is a repeat PD. This is conservative and consistent for both cases since the frequency is inverse proportion to the exposure time.

Normally the baseline CDP of an initiating event is evaluated over a time window, IE_CDP0= P(IE)*P(CD|IE)= λ_{IE}*T*CCDP. The possibility of the initiating event occurrence P(IE) can be modeled by the exponential distribution or the Poisson distribution. If the random variable is the time interval between the two events, the exponential distribution is appropriate. If the interest is the probability of the certain numbers of occurrence in a time window, the Poisson distribution shall be used. For a single initiating event, P(IE) = λ_{IE}*T is the rare event approximation of the exponential distribution. The same probability can be derived from both distributions.

Regarding the risk of an individual IE in terms of CDP, if the IE actually happened during the time period t, the risk IE_CDP1 = P(CD|IE) = CCDP, then the delta CDP of a single IE occurrence ΔIE_CDP = (1-λ_{IE}*T)*CCDP for the random reason. For a PD caused initiating event, since the performance deficiency is not allowed in design and licensing, the baseline CDP is expected to be zero, so ΔIE_CDP = CCDP for the PD case.

Considering the CDFs of all potential IEs, since all the other IE frequencies except the PD caused IE are irrelevant to the PD, their frequencies are unchanged. With the rare event approximation of the exponential distribution, the total baseline CDP during the exposure time period t is

$$CDP0 = CDF0*t, \qquad (21)$$

where CDF0 = sum(λ_{IE}*CCDP), the CDF0 from all initiating events is the summation of the products of the IE frequencies and corresponding CCDPs. Given the occurrence of the PD caused IE, the risk probability increases to CDP1

$$CDP1 = CDF1*t , \qquad (22)$$

where CDP1 = CDP0+CCDP = sum(λ_{IE}*CCDP)*t +CCDP. Here CDP1 is the case where other IEs are nominal. Then equation (22) –(21),

$$\Delta CDP = CCDP =\Delta CDF *t \qquad (23)$$

where ΔCDF = CDF1-CDF0. Therefore the relationship between ΔCDF and CCDP can be easily derived from (23).

$$\Delta CDF = \Delta CDP /t = CCDP/t \qquad (24)$$

The exposure time period t is T/2 if the beginning of PD is unknown. If the event is a repetitive PD, the ΔCDF could increase significantly. The CCDP of an IE is numerically same as Birnbaum value; therefore the safety significance is able to be determined in advance once the PRA model is finalized. The Birnbaum has a wide range, since the risk significant criterion is 1E-6 for CDF, an example of ΔCDF using Birnbaum 1E-1 to 1E-7 is calculated. The results are provided in Table VI and illustrated in Figure 5. The red fields are the cases of non-green risk.

TABLE VI. ΔCDF with various CCDP (Birnbaum) and T

ΔCDF	IE Birnbaum						
T	1.00E-01	1.00E-02	1.00E-03	1.00E-04	1.00E-05	1.00E-06	1.00E-07
2	1.00E-01	1.00E-02	1.00E-03	1.00E-04	1.00E-05	1.00E-06	1.00E-07
10	2.00E-02	2.00E-03	2.00E-04	2.00E-05	2.00E-06	2.00E-07	2.00E-08
20	1.00E-02	1.00E-03	1.00E-04	1.00E-05	1.00E-06	1.00E-07	1.00E-08
40	5.00E-03	5.00E-04	5.00E-05	5.00E-06	5.00E-07	5.00E-08	5.00E-09

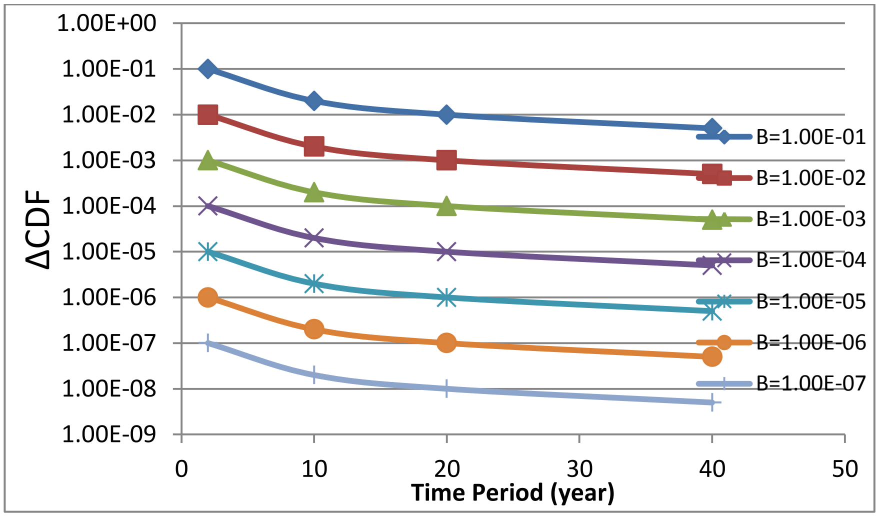

Fig. 5. ΔCDF with various B and T.

The ΔCDF is the product of the IE frequency and CCDP. If it is determined that PD exists and leads the initiating event, 1/t is the IE frequency, and the following is the IE for the different time windows. For a 40-year time window, the ΔCDF = 0.05*CCDP. Thus this process is more realistic. Since given the IE occurred, the risk significance is lower for longer operation where the frequency of 1 event/year is overly conservative, while the risk significance will increase significantly for the repetitive PD where the frequency of 1 event/year assumption is non-conservative especially for the PD repeated less than two years.

TABLE V. The suggested IE frequency due to PD

Time Window T (year)	IE Frequency (1/year)
1	1/(1/2) = 2.0
2	1/(2/2) = 1.0
10	1/(10/2) = 0.2
20	1/(20/2) = 0.1
40	1/(40/2) = 0.05

IV. CONCLUSIONS

This paper summarized a few thoughts about the risk assessment in the nuclear power plant from the author's PRA experience. (1) The risk importance can be converted from one form to another with the assumption of the rare event approximation and the basic event independence including the common cause events. The risk impact of a basic event can be represented by the risk surface. (2) The convolution of multiple time interdependent events, caution should be exercised to assure the time interdependence modeled in series or in parallel manner, and the order of the events should not affect the numeric convolution results as long as the integral limit in time has been accounted for. (3) In SDP, the 1 event per year assumption could be over-conservative for the individual long term rare PD-caused initiating event and be non-conservative for the risk of the short term repetitive initiating event (repeat in less than two years). A suggestion of conversion of ΔCDF from ΔCDP and CCDP is presented.

Overall, the author hopes these insights would be helpful for the PRA practitioner to better understand the risk and improve the risk assessment in the associated programs for safer nuclear power plants.

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